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SIX DECADES OF GUIDED MUNITIONS AND BATTLE NETWORKS: PROGRESS AND PROSPECTS

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Six Decades of Guided Munitions and Battle Networks: Progress and Prospects

by

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March 2007

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The Center for Strategic and Budgetary Assessments (CSBA) is an independent, nonprofit, public policy research institute established to make clear the inextricable link between near-term and long-range military planning and defense investment strategies. CSBA is directed by Dr. Andrew F. Krepinevich and funded by foundations, corporations, government, and individual grants and contributions.

This report is one in a series of CSBA analyses on the emerging military revolution. Previous reports in this series include *The Military-Technical Revolution: A Preliminary Assessment* (2002), *Meeting the Anti-Access and Area-Denial Challenge* (2003), and *The Revolution in War* (2004). The first of these, on the military-technical revolution, reproduces the 1992 Pentagon assessment that precipitated the 1990s debate in the United States and abroad over revolutions in military affairs.

Many friends and professional colleagues, both within CSBA and outside the Center, have contributed to this report. Those who made the most substantial improvements to the final manuscript are acknowledged below. However, the analysis and findings are solely the responsibility of the author and CSBA.

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Acknowledgements

Since early 2003, numerous individuals have made contributions, some large, some small, to this report. The technical and tactical content of the case studies dictated many narrowly focused discussions with colleagues and friends on specific details, and these contributions are mostly acknowledged in footnotes. There were, however, others whose insights, suggestions, or criticisms eventually affected the overall structure, framework, and conclusions in this report.

Foremost was Andrew W. Marshall, the Director of the Office of Net Assessment (ONA), Office of the Secretary of Defense (OSD). He insisted from the outset on a wide range of cases spanning the various military services and war-fighting communities. Having been involved in the controversy between OSD and the US Army that culminated in cancellation of the planned replacement for the Paladin self-propelled howitzer, Crusader, I was already aware that some US military communities had embraced guided-munitions much earlier than others. Nevertheless, Marshall's insistence that I needed to explore cases that went well beyond the experience of any single military service or mission area proved to be wise counsel.

Most of the substantive conclusions about guided munitions and battle networks in the summary and concluding chapter coalesced during discussions with my CSBA colleague Robert Work during 2006. The original draft of this report had been completed in 2004 and then was set aside during most of 2005. When I returned to the

manuscript in early 2006, it quickly became painfully clear that considerable restructuring was needed. In the end, three of five chapters were virtually rewritten from a clean sheet of paper and most of the cases studies in the other two chapters were substantially reworked. What made the discussions with Bob Work so valuable was the experience he brought to the table from several years of observing and participating in ONA-sponsored war games, especially those in the Future Warfare 20XX and Strategic Challenge series of games. These games had explored future US force structures in the 2025 timeframe across a range of scenarios. As it turned out, the patterns I was seeing by this time in the guided-munitions case studies resonated with those Work was seeing in many of the 20XX and Strategic Challenge games. On the pivotal issue of a causal explanation for why some war-fighting communities had been early adopters of guided munitions and battle networks, Bob was in fact a step or two ahead of me in seeing the deeper pattern.

Two outside readers, Christopher Bowie at Northrop Grumman and Dave Johnson at RAND, were willing to plow through the evolving manuscript. Bowie's global comments precipitated both the addition of a summary and the inclusion of "Battle Networks" in the title. Johnson provided line-by-line editorial suggestions on the entire manuscript, virtually all of which improved the clarity of the original text. His diligence was astonishing—Dave's attention to detail even extended to updating an out-of-date url in a footnote.

At CSBA, Chris Sullivan and Ben Fink went through successive drafts, catching typos and flagging awkward prose. Their patience in putting up with months of ongoing changes and revisions was greatly appreciated—especially Chris' willingness to give the entire report, including the index, one final read. In addition, Bob Work restructured an entire chapter and one point, and, toward the end of the editing process, Andrew Krepinevich, CSBA's executive director, provided inputs on the entire draft.

I cannot resist mentioning how much of a learning experience this project turned out to be. At the outset in 2003, the task of exploring of the impact guided munitions had exerted on war's conduct since the late 1980s appeared to be a straightforward one. I had been actively exploring this subject since running the Gulf War Air Power Survey's task force on operations and effects under Eliot Cohen during 1991-1993. Having continued to follow guided-weapons developments, I presumed that I had a solid grasp of the broad issues involved and their implications for the future conduct of war. In hindsight, I was profoundly mistaken in this presumption. The judgments in the summary turned out to go far beyond anything I had envisioned in 2003. Intellectually and analytically, this project turned out to be both a humbling and a refreshing experience.

Finally, I want to thank Boeing, Lockheed Martin, the Naval Undersea Museum, Northrop Grumman, Russell "Bud" Taylor, and Textron for granting CSBA permission to use company and personal photographs.

Summary

The research and analysis underlying this report began in 2003 and aimed at answering the following question. How has the maturation of *non-nuclear* guided munitions during the late 1980s and early 1990s affected the conduct of warfare by advanced militaries, especially by the various combat arms of the US armed forces? In this context, *guided munitions* were understood to be those that could actively home on their targets or aim-points after being fired, released, or launched.

While the basic question at issue seemed relatively straightforward, it soon emerged that the overall subject encompassed considerably more than this initial working definition indicated. The resulting complications led to several early insights:

- First and foremost, guided munitions constitute too narrow a category. Because "precision munitions" require detailed data on their intended targets or aim-points to be militarily useful—as opposed to wasteful—they require "precision information." Indeed, the tight linkage between guided munitions and "battle networks," whose primary reason for existence is to provide the necessary targeting information, was one of the major lessons that emerged from careful study of the US-led air campaign during Operation Desert Storm in 1991. Consequently, the proper topic of this report is *guided*

munitions together with the targeting networks that make these munitions "smart."

- Second, while the initial inclination was to date the origins of recognizably modern guided munitions from either the 1980s or, at the earliest, the initial successes with laser-guided bombs during 1968-1973, it soon became apparent that both the munitions and their associated targeting networks date back at least to the Second World War. In the end, the years 1940 and 1943 were chosen as somewhat arbitrary, but defensible, start dates for the beginning of the still-unfolding guided-munitions *era*. The 1940 Battle of Britain witnessed the first successful exploitation of a modern battle network using long-range sensors (radar), and 1943 saw initial combat successes with recognizably modern guided munitions. Hence, the title of this report: *Six Decades of Guided Munitions and Battle Networks: Progress and Prospects*. Both guided munitions and battle networks have been emerging for over a half century and the reference to prospects in the subtitle implies that there is still a ways to travel down this particular road.

- Third, some war-fighting communities in the US military enthusiastically embraced guided munitions years, or even decades, before others. As the case studies in Chapter III reveal, the US Navy's submarine community began turning to guided torpedoes for submarine-versus-submarine engagements even before World War II had ended, whereas the tank communities in the US Army and US Marine Corps currently still rely primarily on aimed fire for tank-on-tank engagements.

These early observations led to both deeper problems and to deeper insights regarding the evolving guided-munitions/battle-networks era. The principal problems were two. The first concerns the conceptual categories used to characterize this era or regime. By the early 1980s, Soviet military leaders and theorists had concluded that ongoing advances in precision munitions, wide-area sensors, and automated command-and-control would give rise to non-nuclear "reconnaissance-strike complexes" whose destructive potential would approach that of nuclear weapons. This prospect had been considered in the mid-1970s by American analysts such as Albert Wohlstetter as a possible alternative to nuclear use. It was given further voice in the United States during the late 1980s by Andrew Marshall's hypothesis of an emerging "revolution in military affairs." While Marshall has consistently stressed that new operational concepts and organizational adaptations would be more important than technology per se in the likely changes in war's conduct, he hypothesized that one direction these changes might take would be toward the emergence of long-range precision strike as the dominant operational approach. The problem that this speculation posed for the present study is that a *revolution* already six decades in the making, with more still to come, could just as readily be characterized as *evolutionary*. While much will be said about this problem in what follows, the eventual solution offered is to describe the guided-munitions era as dispassionately as possible and leave final judgment to the reader. For now, suffice it to say that the preceding, industrial-age war-fighting regime, in which most munitions missed whatever they were aimed at, is profoundly different from one in which most munitions hit their targets or aim-points—or at least come close enough to achieve the desired effects.

The second problem that emerged was that of developing a persuasive answer to the question: Why were some war-fighting communities early adopters of relatively immature guided munitions while others long resisted adopting them even after they had proven their worth in combat? In the case of early adopters such as the US Navy's submarine community after World War II, the answer lies in the number of dimensions in which the opposing platform or target could maneuver to avoid being hit in conjunction with whether any viable unguided alternatives were available. In engagements between submerged submarines able to maneuver in three dimensions and remain deep underwater for extended periods of time, non-homing torpedoes aimed on constant azimuths and running at constant depths offered little chance of hitting the opponent. For this particular tactical problem, guided torpedoes were, and remain, the only viable solution using non-nuclear explosives—a nuclear warhead being able to compensate for substantial aiming error.

By contrast, fixed targets like a hardened aircraft shelter obviously do not maneuver at all. Yet they are "elusive" in the broader sense that, even with a penetrating warhead, accuracies in the neighborhood 3-4 meters are needed to be consistently able to breach them and destroy any aircraft inside. Laser-guided bombs demonstrated the requisite accuracy as early as 1968-1969, and in 1972 they proved spectacularly effective against a range of point targets during air operations in Southeast Asia. Yet it was not until the 1991 Persian Gulf War that the US Air Force wholeheartedly embraced guided munitions as the backbone of future strike operations. The point here is that institutional cultures matter—particularly as a mediating influence in situations in which the targets are not free to maneuver in three dimensions. In the case of the air-to-ground attack of predominately fixed surface targets, it was not difficult for an Air Force fighter community that highly valued individual pilot skill in dive bombing to find reasons to ignore the potential of laser-guided bombs to transform air warfare—even after these munitions had proven themselves reliable and effective in combat. Indeed, there is evidence that cultural resistance to guided air-to-ground munitions persisted within the US Navy's attack community as recently as 2001 during Operation Enduring Freedom against the Taliban and al Qaeda in Afghanistan.

As for war-fighting communities that have still have not embraced guided munitions, consider tank units in US Army and Marine Corps. For tank-on-tank engagements out to ranges of 3,000-4,000 meters, the 120-millimeter cannon of the M1 main battle tank remains accurate and lethal enough to have a high probability of reliably achieving "first-round" kills against an opposing tank moving on an essentially two-dimensional plane. With thermal imaging gun-sights and depleted-uranium/discarding-sabot rounds, aimed fire from tank main guns remains a viable alternative to guided munitions, and the American tank communities have yet to embrace missiles in lieu of cannons.

The critical role of target maneuverability in the early adoption of guided munitions is further borne out by the case of missiles for air-to-air combat. The fighter communities in both the US Air Force and Navy embraced the medium-range Sparrow III air-intercept missile prior to major US military involvement in Vietnam (1965-1973), lived through the AIM-7's dismal performance in Southeast Asia, and then persisted with the missile after Vietnam long enough for the availability of solid-state electronics to turn it into a lethal, reliable, beyond-visual-range weapon. The main differences between the surface-attack and air-to-air combat cases are not only that enemy fighters could maneuver in three dimensions but, even against less-agile Soviet long-range bombers attacking targets in the continental United States, the urgency of intercepting them before they could release nuclear weapons, regardless of weather or time of day, strongly motivated a guided solution. These factors appear to explain the willingness of the Air Force and Navy to persevere through the period of the poor-performing AIM-7D/E/E-2 Sparrow IIIs, with their vacuum-tube and hand-soldered electronics, until the appearance of the solid-state AIM-7Ms that proved so effective in 1991.

Turning to the deeper insights that emerged from working through these problems, a central theme in the maturation of guided munitions and battle networks is, of course, the quest for dependable accuracy—"near zero miss" as one American study put it in 1975. In Southeast Asia, for example, American aircrews alert enough to acquire visually North Vietnamese air-to-air or surface-to-air missiles early in the engagement could generally use evasive maneuvers to force the missiles to miss. That day has passed. A similar pattern occurred with the US Navy's principal post-World War II high-explosive torpedoes for submarine-versus-submarine engagements. While the Mark-37's guidance, which included active-sonar inside 1,000 yards, was a considerable advance over earlier torpedoes, the first-generation Soviet nuclear-powered attack submarines turned out to be capable of higher submerged speeds than the US torpedo. The 55-knot Mark-48 and its deeper-diving, faster Mark-48 Advanced Capability (ADCAP) successor eventually eliminated the possibility of Soviet nuclear submarines outrunning or out-diving US heavy torpedoes, but the first Mark-48s did not enter service until the early 1970s and the Mark-48 ADCAPs not until the late 1980s. As for surface targets, from the first combat experiments in 1968, laser-guided bombs yielded hit-rates approaching 50 percent and overall accuracies in the vicinity of 10-15 feet. Granted, the requirement of laser-guided munitions for clear air was a major drawback and partially explains Air Force reluctance to emphasize them after Vietnam in other theaters such as Europe. However, the advent of the Joint Direct Attack Munition, which was first used against Serbian targets in 1999, finally overcame even this limitation.

There is, however, one important caveat that warrants mention regarding the signal success of munitions that home on target coordinates based on location and timing information from the US constellation of Global Positioning System (GPS) satellites. The annual infrastructure costs of maintaining this constellation have turned out to be so expensive that only the United States has had the wherewithal to sustain the availability of GPS-quality navigation information worldwide since the end of the US-Soviet Cold War. This point is important because it goes far to explain why only the US military has been able to field the guided munitions and battle networks for prompt precision-strike on a global basis—at least so far. At least somewhat unexpectedly, reconnaissance-strike complexes have proven far more challenging and costly for other nations to emulate than armored divisions and *Blitzkrieg* tactics were during 1939-1945.

These sorts of observations eventually led to a number of other insights regarding the evolving guided-munitions/battle-network regime and its future prospects. The following points highlight five of the more salient findings discussed in Chapters IV and V:

- For most targets, the problem of accuracy can be considered largely solved. Regarding the attack of surface targets, those that are emergent, time-sensitive, mobile, fleeting, hardened, or deeply buried still present challenges to US forces, although progress is being made. The key to effectiveness in most of these cases is the quality and timeliness of the targeting information provided to the munitions, and such precision information increasingly depends more on the targeting networks than on the guided munitions themselves.

- To push the preceding point a step further, the US military has achieved accuracy "independent of range to the target." In other words, a long-rang e cruise missile such as the Tomahawk Land Attack Missile is as accurate against a target 1,000 nautical miles from its launch point as a laser-guided bomb is against an aim-point only a few miles away from the attacking aircraft. However, the Tomahawk is nearly one-hundred-fold more expensive per round than a Paveway II laser-guided bomb, which reveals that cost independent of range to the target cannot yet be considered a solved problem.

- The German development of *Blitzkrieg* (or mobile, armored operations) during the interwar years 1918-1939 is rightly viewed as having restored the ascendancy of the offense over the defense in air-land operations. In this sense, *Blitzkrieg* was an industrial-age solution to the stalemated trench warfare that had dominated the Western Front during World War I. By and large, the emergence of guided munitions and battle networks appears to have increased the offense's ascendancy over the defense, although the concept of mass has been radically transformed. With unguided munitions, the basic approach to taking out most targets has been to deliver sufficiently massive quantities of ordnance for the "law of large numbers" to compensate for the lack of accuracy. Again, most unguided munitions effectively miss their targets or aim-points. With reliable guided munitions, by comparison, it only takes one or two rounds getting through to the target to achieve the desired "kinetic" effect. In this sense, guided munitions truly are more like nuclear weapons than unguided conventional ones. Mass in the guided-munitions era, therefore, becomes a matter of achieving sufficient salvo density against active defenses to get one or two munitions through to the target. Even when the defenses employ guided munitions to prevent this from happening, it has seldom been difficult for the attacker to achieve sufficient salvo density to "leak through" to the targets or aim-points. Hence this report's judgment that guided munitions and battle networks have increased the offense's ascendancy over the defense.

- One of the hallmarks of a revolution in military affairs highlighted by Andrew Marshall and Andrew Krepinevich in the early 1990s was that the old way of fighting stands little chance in open battle against the new approach. The major-combat phase of Operation Iraqi Freedom in March-April 2003 appears to provide strong support for this point. The contest pitted industrial-age armored forces relying on the massive employment of aimed fires against superior Coalition ground forces backed by a range of guided munitions and targeting networks. As Robert Work has observed, in this grossly uneven contest between an old and new way of fighting, the heavy forces of the Iraqi army were virtually reduced to an array of targets and aim-points waiting to be serviced.

- In hindsight, the maturation of guided munitions and battle networks has not turned out the way most observers anticipated during early discussions of "near zero miss" munitions and reconnaissance-strike complexes. While the broad trend within the US military has been for most (but not all) warfighting communities to move away from close combat and toward engagement at a distance with guided munitions,

> Marshall's early-1990s vision of opposing reconnaissance-strike complexes dueling one another at long ranges has not yet materialized. The most obvious reason is that since the late-1980s, only the United States has had the resources to field the requisite guided munitions *and* battle networks. The unintended consequence of this unusual situation has been that adversaries willing to employ lethal force against US interests or forces have been constrained to two main options: acquiring nuclear weapons in hopes of precluding the use of America's dominant conventional capabilities against them, especially for regime change; or, resorting to the brutal ambush tactics of insurgents and terrorists, including suicidal jihadists. Thus, the maturation of US guided munitions and battle networks has, so far, had the unintended and unexpected consequence of leaving near-term military opponents with rather unpleasant asymmetric options. Presently only China appears to have to resources to consider competing symmetrically with US guided munitions and battle networks, and even then only in the longer term.

Looking ahead, what are the prospects for significant changes in the current guided-munitions regime? One possibility is that the currently tight constraints on robotic systems will relax sufficiently to permit the appearance of autonomous combat systems in future combat arenas. One insight that emerges from the guided-munitions cases in Chapter III is the realization that such systems already exist. Once fired, a Sidewinder air-to-air missile is entirely autonomous. Yes, the constraints on its autonomy tightly restrict its freedom of action. But after a Sidewinder leaves the launch rail, it is both lethal and on its own. No further intervention by the pilot firing the missile is possible. The question, then, is: How soon might the tight constraints evident in the case of guided munitions such as the Sidewinder be relaxed? Here, however, cultural constraints again come to the fore. While the Defense Advanced Research Projects Agency has been actively pursuing sufficient machine intelligence to permit lethal systems to find and attack a range of targets within a sizeable area, the military services have been reluctant to embrace such weapons. In the case of the Low Cost Autonomous Attack System, Air Force leaders actually insisted that a data link be added to provide human monitoring and intervention after release.

While autonomous combat systems might substantially alter the conduct of operations within the current guided-munitions/battle-networks regime, the appearance of directed-energy weapons could well push the conduct of warfare into a different regime entirely. A fundamental feature of the current regime is that guidance is needed at ranges-to-target beyond 3-4 kilometers because the speeds of bombs, projectiles, and missiles generally do not allow them to reach their targets quickly enough to preclude the target or opposing platform getting out of the way. Speed-of-light, line-of-sight lasers with sufficient power and beam quality to be tactically effective over long distances would obviously change this situation, opening the door to the reemergence of aimed fires. Thus, while directed-energy combat systems have not yet been fielded, their appearance certainly has the potential to exert far-reaching changes on the conduct of modern warfare.

These then are the principal insights that emerge from the detailed case studies at the heart of this report. As a final observation, it may be useful to mention a few points about the structure of what follows. Chapter I concentrates mainly on the past history of guided munitions with an eye toward justifying the view that both the munitions and targeting networks reach back at least six decades. As already indicated, the detailed case studies are in Chapters III and IV, and Chapter V draws out their main implications. What, then, is in Chapter II? It is essentially a discussion of how to think about guided munitions (and their associated targeting networks). While the author and Andrew Marshall view the effort to frame the subject as essential, it covers some theoretical issues that may not be everyone's cup of tea. Readers anxious to get to the case studies could, of course, skip the second chapter. The downside of doing so is that a number of the theoretical issues covered in Chapter II have been subject to widespread confusion and misunderstanding. For example, the experience of the Spanish conquistadors in Peru in the early 1500s really does shed light on the widely held belief that superior technology, greater numbers, or some combination of the two, usually drive combat outcomes by highlighting the important, even primary, role played by human and cultural factors. Nevertheless, in light of the American aversion to theory, the author recognizes that those with no patience for such matters may wish to skim through Chapter II or even skip directly the Chapter III.

Glossary

AAA	Anti-aircraft artillery
AAC	Army Air Corps
AAW	Anti-air warfare
ABL	Airborne Laser
ACEVAL	Air Combat Evaluation
ACM	Advanced cruise missile
ACMR	Air combat maneuvering range
ADC	Air/Aerospace Defense Command
ADCAP	Advanced Capability
AFB	Air Force Base
AFV	Armored fighting vehicle
AGM	Air-to-ground munition
AIM	Air intercept missile
AIR	Air intercept rocket
AIRS	Advanced Inertial Reference System
ALCM	Air Launched Cruise Missile
AMRAAM	Advanced Medium-Range Air-to-Air Missile
AMSTE	Affordable Moving Surface Target Engagement
APFSDS	Armor piercing, fin stabilized, discarding sabot
APL	Applied Physics Laboratory
ARM	Anti-radiation missile
ARPA	Advanced Research Projects Agency
ASM	Anti-ship missile
ASROC	Anti-submarine rocket
ASW	Antisubmarine warfare

ATACMS	Army Tactical Missile System
ATD	Advanced technology demonstration
ATR	Automatic target recognition
AWE	Advanced warfighter experiment
AZON	Azimuth only
AWACS	Airborne Warning and Control System
AWOS	Air War Over Serbia
BCT	Brigade combat team
BDA	Bomb damage assessment/Battle damage assessment
BDM	Braddock, Dunn and MacDonald
Bf	*Bayerische Flugzeugwerke*
BMW	Bavarian Motor Works (*Bayerische Motoren Werke*)
BVR	Beyond visual range
C2	Command and control
CALCM	Conventional Air Launched Cruise Missile
CAOC	Combined Air Operations Center
CAP	Combat air patrol
CAS	Close air support
CBO	Congressional Budget Office
CBU	Cluster bomb unit
CERTEX	Certification exercise
CVGB	Carrier battle group
CEC	Cooperative Engagement Capability
CENTCOM	Central Command
CENTAF	Central Command Air Forces
CCIP	Continuously computed impact point
CEP	Circular error probable
CIC	Combat information center
CILTS	Commission on Integrated Long-Term Strategy
CIWS	Close-in Weapon System
CNO	Chief of Naval Operations
CONUS	Continental United States
CSBA	Center for Strategic and Budgetary Assessments
DARPA	Defense Advanced Research Projects Agency
DC	District of Columbia
DEW	Directed-energy weapon (or weapons)
DoD	Department of Defense
DoN	Department of the Navy
DNA	Defense Nuclear Agency
DSMAC	Digital scene matching area correlation
DU	Depleted uranium
EFOGM	Enhanced fiber optic guided missile

ENIAC	Electronic Numerical Integrator and Computer
EO	Electro-optical
FAC	Forward air controller or fast attack craft
FPB	Fast patrol boat
FEBA	Forward edge of the battle area
FLIR	Forward-looking IR
fn	Footnote
FY	Fiscal year
GAM	GPS-aided munition
GAO	Government Accounting Office
GAR	Guided Aircraft Rocket
GATS	GPS-Aided Targeting System
GBU	Guided bomb unit
GCI	Ground controlled intercept
GLONASS	Global Navigation Satellite System
GNAT	German Naval Acoustic Torpedo
GPS	Global Positioning System
G/VLLD	Ground/vehicular laser locator designator
GWAPS	Gulf War Air Power Survey
HARM	High-Speed Anti-radiation Missile
HEAT	High explosive anti-tank
HQ	Headquarters
HMMWV	High Mobility Multi-purpose Wheeled Vehicle
IAF	Israeli Air Force
IAM	Inertially aided munition
ICAF	Industrial College of the Armed Forces
ICBM	Intercontinental ballistic missile
ICC	International Control Commission
IDF	Israeli Defense Forces
IFF	Identification friend or foe
INS	Inertial navigation system
IOC	Initial operational capability
IOT&E	Initial operational test and evaluation
IR	Infrared
JASSM	Joint Air-to-Surface Standoff Missile
JCS	Joint Chiefs of Staff
JDAM	Joint Direct Attack Munition
Joint STARS	Joint Surveillance Target Attack Radar
JPF	Joint Programmable Fuze
JRTC	Joint Readiness Training Center
KE	Kinetic energy
KH	KEYHOLE

Km	Kilometer (or kilometers)
Ladar	Laser detection and ranging
LAM	Loitering attack munition
LANTIRN	Low Altitude Navigation and Targeting InfraRed for Night
Laser	Light amplification by stimulated emission of radiation
lb (lbs)	Pound (pounds)
LGB	Laser guided bomb
LOCAAS	Low Cost Autonomous Attack System
LRA	Long Range Aviation
LRRDPP	Long Range Research and Development Planning Program
MICOM	(US Army) Missile Command
MiG (МиГ)	Mikoyan-Gurevich
MIL	Milliradian
MIT	Massachusetts Institute of Technology
MLRS	Multiple Launch Rocket System
mm	Millimeter (or millimeters)
MTI	Moving target indicator
MTR	Military technical revolution
MTT	Multiple-target track
MULE	Modular universal laser equipment
NATO	North Atlantic Treaty Organization
NCTR	Non-cooperative target recognition
NDRC	National Defense Research Committee
NLOS-LS	Non-Line-of-Sight Launch System
nm	Nautical mile (or nautical miles)
NOTS	Naval Ordnance Test Station
NSC	National Security Council
NVN	North Vietnam
NWC	Naval Weapons Center
OAF	Operation Allied Force
ODS	Operation Desert Storm
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
ONA	Office of Net Assessment
OPEVAL	Operational evaluation
OSD	Office of the Secretary of Defense
OSD/NA	Office of Net Assessment, Office of the Secretary of Defense
OSRD	Office of Scientific Research and Development
OTRI	Operational Theory Research Institute

OUE	Operational Utility Evaluation
PGM	Precision guided munition
P_k	Probability of kill
PRC	People's Republic of China
PRF	Pulse recurrence frequency
PSAB	Prince Sultan Air Base
QED	Quantum electrodynamics
RADAR	Radio detection and ranging
RAF	Royal Air Force
RAM	Random access memory
RAND	Research ANd Development [Corporation]
RMA	Revolution in military affairs
ROE	Rules of engagement
RSTA	Reconnaissance, surveillance, and target-acquisition
RUK	Reconnaissance-strike complex (рекогносцировк-удара комплекс)
SA	Situation awareness (also: situational awareness)
SAC	Strategic Air Command
SAIC	Science Applications International Corporation
SAGE	Semi-Automatic Ground Environment
SAM	Surface-to-air missile
SAR	Synthetic aperture radar (also Selected Acquisition Report)
SDB	Small Diameter Bomb
SEA	Southeast Asia
SFW	Sensor Fuzed Weapon
SIOP	Single Integrated Operational Plan
SLBM	Submarine launched ballistic missile
SOSUS	Sound Surveillance System
SSBN	Ballistic missile submarine, nuclear
SSN	Submarine, nuclear
SSGN	Guided missile submarine, nuclear
STT	Single-target track
TAC	Tactical Air Command
TERCOM	Terrain contour matching
TFS	Tactical Fighter Squadron
TFW	Tactical Fighter Wing
THEL	Tactical High-Energy Laser
TI	Texas Instruments
TLAM	Tomahawk Land Attack Missile
TOW	Tube-launched, Optically tracked, Wire-guided
TRAM	Target-Recognition/Attack Multi-sensor

TRW	Tactical Reconnaissance Wing
TST	Time-sensitive targeting
U-boat	*Unterseeisch-Boot*
UN	United Nations
USA	US Army
USAF	US Air Force
USAFE	US Air Forces in Europe
USMC	US Marine Corps
USN	US Navy
USNTS	US Naval Torpedo Station
VF	USN designation for a fighter squadron
VLS	Vertical launch system
VPAF	Vietnamese People's Air Force
WMD	Weapons of mass destruction
WP	Warsaw Pact
WVR	Within visual range

I. Introduction

This report has two basic aims: (1) to assess the influence terminally guided, non-nuclear (or "conventional") munitions have exerted on the conduct of warfare since their initial use during World War II; and (2) to anticipate the influence further advances in conventional guided munitions are likely to have on military operations in coming decades. Following Christopher J. Bowie's suggestion, the term *guided munitions* will hereafter refer to projectiles, bombs, missiles, torpedoes and other weapons that can actively correct for initial-aiming or subsequent errors by homing on their targets or aim-points after being fired, released, or launched. Prominent examples of guided munitions in US combat experience during the past six decades include naval surface-to-air missiles (SAMs) such as the American Talos, the Soviet-built SA-2 SAM, laser guided bombs (LGBs), the Sidewinder and Sparrow III air-intercept missiles (AIMs), the Tomahawk Land Attack Missile (TLAM), the Conventional Air Launched Cruise Missile (CALCM), and the Joint Direct Attack Munition (JDAM).

The heart of this report consists of historical case studies that span a wide variety of the guided munitions developed since the beginning of the Second World War by various war-fighting communities and military services, predominately American ones. The reason for surveying a broad range of cases is straightforward. Insofar as a principal aim is ultimately to suggest how further advances in guided munitions may affect the future conduct of military operations, a detailed understanding is needed of the actual changes in tactics, doctrines, operational concepts, military organizations, and combat outcomes these weapons have caused to date, and why. For example, fixed targets are far easier to hit than targets maneuvering in three dimensions and, when the target can maneuver freely in two or three dimensions, the incentives to adopt guided weapons in place of aimed fires are correspondingly stronger. However, this pattern only emerges from examining a fairly diverse set of cases.

This introductory chapter presents some of the study's more prominent findings. Three overarching themes have been selected from among the various conclusions suggested by the guided-munitions case studies in Chapters III and IV. First, munitions able to correct for initial aiming errors by homing on their targets or aimpoints have, more often than not, experienced long, uneven, often-troubled gestation periods prior to being fully embraced by operational communities. Second, sensor-and-targeting networks arose historically to provide the precise target-detection, target-location, and target-tracking information guided munitions have required, so far, to be employed effectively. And, third, not only did some military communities embrace guided munitions much earlier than others, but there are at least two significant groups in American military today—the tank communities in the US Army (USA) and US Marine Corps (USMC)—that still employ aimed-fire weapons as their primary armament.

All three of these findings demand at least some elaboration to be understood in context, and supplying that context is the main task of this chapter. Along the way, however, some other significant implications will also emerge. Perhaps the most salient finding is the suspicion that high-intensity warfare between well-equipped military forces is moving increasingly away from close combat with aimed fires and toward engagement from a distance with guided munitions. Another insight is that there are significant thresholds in the maturation of guided weapons that still lie ahead, which is to say that we have by no means reached the end of the guided-weapons story. However, these more forward-looking implications also need to be framed within an appropriate historical context. It seems best, therefore, to start at the very beginning of guided-munitions history during the Second World War. The fact that early trials of weapons conceptually recognizable as guided munitions occurred so many decades ago suggests how long, uneven, and troubled an emergence many of these weapons have had, notwithstanding some early successes in actual combat.

Guided Munitions: Origins in the 1940s

The earliest instances of combat success with recognizably modern guided munitions occurred in 1943. In March of that year the German Navy introduced the first acoustic-homing torpedo, the G7e/T4 *Falke (Falcon)*. Although the T4 was only employed by three U-boats before being replaced by the G7es/T5 *Zaunkönig (Wren)*, it reportedly sunk several merchant vessels and, if so, was the first successful *guided munition* as the term is defined in this report.[1] Two months later, an American Mark-24 acoustic-homing torpedo released from a PBY-5 patrol aircraft sank the German submarine *U-640*; by 1945 this weapon was credited with sinking 37 German and Japanese submarines and damaging 18 others.[2] And, in September 1943, four months after *U-640*'s demise, fifteen German Dornier-217 medium bombers attacked the Italian fleet with Fritz X radio-guided glide bombs.[3] Each Dornier carried a single Fritz X, two of which hit and sank the battleship *Roma*.

As would be expected, these successes spurred further wartime experimentation with guided munitions. Starting in 1944, the US Army Air Forces began employing a radio-guided, azimuth-only (AZON) glide bomb, and had "encouraging results" in both northern Italy and the China-India-Burma theater.[4] Additionally, the US Navy

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[1] "G7e Torpedo," Wikepdia at <http://en.wikipedia.org/wiki/G7e>, accessed April 18, 2006. The G7es/T5, known by the Allies as the German Naval Acoustic Torpedo (GNAT), achieved its initial combat success in September 1943—Charles M. Sternhell and Alan M. Thorndike, *Antisubmarine Warfare in World War II* (Alexandria, VA: Center for Naval Analyses, 1946), Operations Evaluation Group #51, p. 45.

[2] Frederick J. Milford, "U.S. Navy Torpedoes," Pt. 4, "WW II Development of Homing Torpedoes 1940-1946," *The Submarine Review*, April 1997, p. 75.

[3] See Francesco Cestra, "The Sinking of the Battleship *Roma*," online at <http://www.regiamarina.net/others/roma/roma_us.htm>, accessed March 2006. A second battleship, the *Italia* (after July 25, 1943 the *Littorio*), was also damaged by a Fritz X, but made it to Malta. On September 3, 1943, Italy had signed a secret surrender agreement with the Allies, one of whose clauses required the immediate transfer of the Italian fleet and Italian aircraft to the Allies. *Roma* and *Littorio* were part of a group of 14 Italian naval combatants that sailed from La Spezia to fulfill this stipulation on September 8th. The fleet was in the Gulf of Asinara when the German bombers attacked.

[4] David R. Mets, "The *Force* in US Air Force," *Aerospace Power Journal*, Fall 2000, pp. 61-62. Mets notes that during World War II the Germans experimented with virtually all the guided-munitions technologies that have since

pursued autonomous radar guidance to the point of fielding a radar-homing glide bomb with a wooden airframe, known as BAT; and in May 1945 PB4Y-2 bombers sunk several Japanese ships near Borneo with this weapon.[5]

Figure 1: World War II Guided Munitions

These early trials with small numbers of experimental guided munitions did not exert any major influence on the course or outcome of World War II. In terms of their overall contributions to Allied victory, the guided weapons of the 1940s pale in comparison with the impact of radio detection and ranging (radar) for the detection and tracking of aircraft and naval combatants, the lethality improvements that stemmed from radar-proximity fuses, or the advent of the atomic bomb in 1945. On the other hand, the successes achieved by G7es/T5 *Zaukönig*, Fritz X, the Mark-24, AZON, BAT and other guided munitions during the Second World War presaged a far greater role for guided munitions in future wars.

Arguably, the US Navy was the American military service that initially saw the greatest potential in guided munitions toward the end of the Second World War and initiated programs to exploit that potential. Even before the first suicide attacks by Kamikaze ("divine wind") pilots against American naval forces in October 1944, the US Navy had grown concerned about the future vulnerability of its surface combatants to aircraft-launched guided missiles.[6] The Germans not only de-

come into widespread use with the sole exception of laser guidance (ibid., p. 58).

[5] Mets, "The *Force* in US Air Force," pp. 58, 62.

[6] Norman Friedman, *U.S. Destroyers: An Illustrated Design History* (Annapolis, MD: Naval Institute Press, 2004 rev. ed.), p. 219.

veloped guided glide bombs during World War II but guided missiles for attacking surface targets as well. Apprehension regarding the threat such weapons posed for surface combatants led to the establishment of Project Bumblebee even before the large-scale Kamikaze attacks against the American fleet off Okinawa occurred in the spring of 1945. Bumblebee set out to develop the radars, surface-to-air missiles, and combat information centers (CICs) to defend US surface combatants against airborne missile attacks. Other projects sought to develop effective air-to-air missiles for naval interceptors. Accelerated by the damaging Kamikaze attacks off Okinawa, Bumblebee eventually produced the first generation of American naval SAMs—the medium-range Terrier, the short-range Tartar, and the long-range Talos with its distinctive ramjet design.

Figure 2: Talos RIM-8J Naval SAM[7]

American submariners were also early adopters of guided munitions—and for compelling tactical reasons. Aside from the wartime success of the Mark-24 and other homing torpedoes, they recognized that only a guided torpedo would have much chance against a submerged enemy submarine able to maneuver in three dimensions. Given this tactical imperative, the only unguided torpedo the US Navy fielded after 1945, the Mark-45, carried a nuclear warhead.

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7 The close-up photo shows the Talos RIM-8J missile at the Smithsonian's Udavy-Hazy Center near Dulles Airport in Virginia. Not shown is the missile's solid booster, which can be seen in the inset of the initial firing of two RIM-8s at White Sands in 1951. The Talos missile without the booster was over 21-feet long. At launch the missile and its booster weighed over 7,000 lbs. Talos was first deployed on the guided-missile cruiser USS *Galveston* in 1958 and is usually credited with a maximum range of 70 nautical miles (nm) or 130 kilometers.

Cold War Developments and Prospects

The early promise of guided munitions, though, was not quickly fulfilled. For the most part, the conventional guided weapons of the 1940s, 1950s, 1960s and early 1970s were too few, too inaccurate, too unreliable, or too susceptible to simple countermeasures to precipitate anything approaching a revolution in military affairs (RMA) comparable to the rise of armored warfare (*Blitzkrieg*) or carrier aviation during the interwar years 1918-1939. For example, once the US Air Force (USAF) became concerned about intercepting Soviet long-range bombers before they could deliver atomic bombs on targets in the continental United States (CONUS), its AIM-4 Falcon family of air intercept missiles was refocused from a self-defense weapon for penetrating bombers to an offensive one for fighter-interceptors assigned to the continental air defense mission. Yet, although tens of thousands of these missiles were eventually produced for the Air Defense Command, their brief combat trials during the long American involvement in Southeast Asia was so disappointing that Colonel Robin Olds, commander of the 8th Tactical Fighter Wing (TFW) in Thailand, took the Falcons off his F-4s and replaced them with the more reliable US Navy AIM-9 Sidewinders. Similarly, anti-ship missiles (ASMs) for ship-versus-ship engagements did not make an appreciable impression on the thinking of Western navies until 1967, when Soviet-supplied Styx missiles sank the Israeli destroyer *Eliat*.

On the other hand, the downing of Gary Francis Powers' U-2 by a salvo of fourteen Soviet SA-2s near Sverdlovsk on May 1, 1960, spurred the migration of American strategic reconnaissance into near-earth space.[8] Furthermore, the introduction of SA-2 surface-to-air missiles into North Vietnam in 1965 brought about changes in American operations by US Air Force and US Navy (USN) fighters and bombers. The Air Force and Navy fighter/attack communities immediately adopted low-altitude penetration tactics to reduce exposure to the SA-2 and aircrews began learning how to out-maneuver SA-2s in the air. Later, the USAF introduced specialized "Wild Weasel" aircraft to provide strike packages with warnings of SAM launches and to attack active SA-2 sites with bombs and anti-radiation missiles. Eventually, fairly effective jamming pods also appeared that interfered with SA-2 target-tracking and missile-guidance.

[8] Ben R. Rich and Leo Janos, *Skunk Works: A Personal Memoir of My Years at Lockheed* (New York: Little, Brown and Company, 1994), p. 160.

From the standpoint of offensive strike operations, these various responses to the challenge posed by early radar-guided SAMs appear, on the whole, to have sufficed. Neither the SA-2 in Southeast Asia (SEA), nor the SA-2, SA-3 and SA-6 in the Middle East, succeeded in pushing American or Israeli air forces into a defense-dominant regime. For the most part US and allied air forces were able to devise tactics and technologies to suppress, roll back, destroy, or otherwise defeat Russian-built SAMs while preserving the ability to deliver unguided or guided munitions via composite strike packages.

Figure 3: SA-2 Surface-to-Air Missile[9]

The one partial exception was the early success of the SA-6 against the Israeli Air Force (IAF) during the Yom Kippur (or Ramadan) War of October 5-24, 1973. The mobility of the SA-6 denied IAF aircrews the intelligence needed to eliminate these missiles at the outset; the visual cues the missile itself provided in flight were quite different from those American and Israeli aircrews had long counted on to see and out-maneuver SA-2s and SA-3s; and the IDF had no

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9 The main photo shows an Egyptian SA-2 "Guideline" missile and booster on its launcher during Exercise Bright Star '85. The insert shows a Fan Song-E missile-control radar. Both the missile and missile-control radar in Figure 3 are improved versions of those used in Vietnam. Unlike later Soviet SAMs, the SA-2's booster did not detach once its fuel was exhausted.

electronic countermeasures (ECM) against the SA-6 when the fighting began.[10] Because of the attrition the IAF was forced to accept in providing close air support (CAS) on the Golan Heights to prevent a decisive Syrian breakthrough, the Israelis ended up pushing ground forces across the Suez Canal to "disrupt the deep belt of Soviet-supplied surface-to-air missiles" sufficiently to regain the freedom to strike targets deep in Egypt.[11] Nevertheless, the extraordinary success that the IAF had in June 1982 in destroying the Syrians' dense, integrated defenses in Lebanon's Beqa'a Valley indicates that the prior successes of Soviet-supplied surface-to-air missiles did not portend a shift toward a SAM-dominant regime.[12]

Perhaps the earliest (albeit limited) example of guided munitions precipitating voluntary changes in American air-to-ground strike operations was the exploitation of laser-guided bombs in response to North Vietnam's all-out invasion of South Vietnam in the spring of 1972. From the beginning of what became Operation Linebacker I, LGBs began systematically dropping key bridges that the North Vietnamese needed to sustain their mechanized offensive.[13] Besides cutting highway and railroad bridges, the accuracy of these munitions enabled aircrews to take out individual anti-aircraft artillery (AAA) sites, tanks and other point targets, often with just one or two weapons. After the Paul Doumer and Thanh Hoa bridges were dropped by LGBs in May 1972, the US 7th Air Force restructured its daylight strike

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[10] "Israeli Aircraft, Arab SAMs in Key Battle," *Aviation Week & Space Technology*, October 22, 1973, pp. 14-15; and Chaim Herzog, *The Arab-Israeli Wars: War and Peace in the Middle East from the War of Independence through Lebanon* (New York: Vintage Books, January 1984), pp. 307-308.

[11] Herzog, *The Arab-Israeli Wars*, pp. 309-310; and "Mideast Cease-fire Spurs New Tensions," *Aviation Week & Space Technology*, October 29, 1973, p. 15.

[12] In a single strike during the afternoon of June 9, 1982, the IAF took out 19 SAM batteries and damaged four more without losing a single aircraft (Herzog, *The Arab-Israeli Wars*, p. 347).

[13] Operation Linebacker I began on May 10, 1972, and continued until October 23, 1972, when President Richard Nixon suspended the bombing of North Vietnam above 20° North—Wayne Thompson, *To Hanoi and Back: The U.S. Air Force and North Vietnam, 1966-1973* (Washington, DC: Smithsonian Institution Press, 2000), pp. 229, 253. Linebacker II ran the eleven days December 18-28, 1972, when B-52 heavy bombers were finally employed throughout North Vietnam to force the North Vietnamese to resume peace negotiations.

packages against targets in heavily defended areas of North Vietnam to exploit and preserve its limited LGB capabilities, which centered on the six Pave Knife laser-designator pods that permitted LGBs to be employed with reasonable safety in high-threat areas.[14]

Of course, neither laser-guided bombs alone, nor even American air power writ large, single-handedly halted Hanoi's 1972 "Easter Offensive." Heavy fighting on the ground was also needed to turn back the invasion. The most that can be said of the contribution of US precision-guided munitions (PGMs) during April-October 1972 is that, while they constituted only a small fraction of the air-to-ground ordnance expended by USAF, USN and USMC strike aircraft, they were "the key munitions" because of their unprecedented accuracy.[15] Of the more than 10,500 LGBs delivered throughout Southeast Asia from February 1972 through February 1973, 5,107 (48.1 percent) were assessed as direct hits; and another 4,000 achieved a circular error probable (CEP) of 25 feet.[16] Compared to the 500-foot CEP of F-105s using manual dive-bombing to deliver unguided bombs against heavily defended targets in North Vietnam during 1965-1968, this was a remarkable improvement.[17] Laser-guided bombs achieved an estimated CEP of 10-15 feet. Thus, although LGBs required clear air and were mostly limited to daytime operations in Vietnam, their accuracy was 33-50 times better than unguided bombs.

RAND Corporation analysts subsequently observed that the results produced by LGBs in Linebacker I were "spectacularly good," and they recommended that the Air Force press ahead to exploit their potential—particularly in missions that had not previously been consid-

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14 Thompson, *To Hanoi and Back*, p. 231.

15 Wayne Thompson, "PGM & Dumb Bomb Tonnage Dropped in SEA [Southeast Asia]," internal Gulf War Air Power Survey (GWAPS) email, November 12, 1992.

16 Major Donald K. Ockerman, "An Analysis of Laser Guided Bombs in SEA (U)," Headquarters 7th Air Force, Thailand, Tactical Analysis Division, Air Operations Report 73/4, 28 June 1973, SECRET (declassified 31 December 1981), pp. ii, 9, 34. CEP is the radius of a circle, centered on the aim-point, within which 50 percent of the weapons are expected to fall.

17 Thompson, *To Hanoi and Back*, pp. 45-6; and R. L. Blachly, P. A. CoNine and E. H. Sharkey, *Laser and Electro-Optical Guided Bomb Performance in Southeast Asia (LINEBACKER 1): A Briefing* (Santa Monica, CA: RAND Corporation, October 1973), R-1326-PR, p. v.

ered feasible due to inadequate bombing accuracy.[18] Moreover, at least some of the airmen who had participated extensively in strikes with LGBs during this period went even further, concluding that they had seen "the future" of air warfare.[19] Historically, the vast majority of unguided bombs had missed their aim-points by substantial distances—typically by hundreds of feet in the case of missions against heavily defended targets. Mass was the only way to compensate for such inaccuracy, which meant sending large numbers of sorties to deliver even larger numbers of unguided munitions against each and every target, often multiple times. During 1972-73, though, over two-thirds of the LGBs had hit within 25 feet of their aim-points. This dramatic improvement in accuracy pointed, therefore, to the possibility of a future in which air-to-ground strike operations would be built around guided munitions that could hit within 10-20 feet of their aim-points the majority of the time. This prospect, in turn, foreshadowed changes in air warfare at least as revolutionary as the emergence of carrier aviation or *Blitzkrieg* during 1918-1939.

At this juncture, however, the corporate Air Force embraced neither guided munitions nor the vision of future air warfare they implied. While the performance of LGBs in Vietnam represented a dramatic step forward in accuracy and effectiveness, nearly two more decades would pass before the Air Force would take that step. Only in the aftermath of the 1991 Persian Gulf War did the USAF finally accept guided munitions as the centerpiece of future air-to-ground strike operations. The primary reason for the long delay, as will emerge in the LGB case study, was not immature technology, but the underlying belief systems of the Air Force's tactical-fighter community.

As a result, by early 1975, when Albert Wohlstetter was drafting the summary report of the Long Range Research and Development Planning Program (LRRDPP), the center of gravity of American think-

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[18] Blachly, CoNine and Sharkey, *Laser and Electro-Optical Guided Bomb Performance in Southeast Asia (LINEBACKER 1)*, pp. v, vi.

[19] James O. Hale, telephone interview with Barry Watts, November 7, 1996. In 1972, Hale was a first lieutenant F-4 frontseater (or aircraft commander) assigned to 433rd Tactical Fighter Squadron, 8th TFW, at Ubon, Thailand. He participated in the 8th TFW's May 10, 1972, strike with laser-guided and electro-optical (EO) bombs on the Paul Doumer Bridge in Hanoi, and later flew as a Wolf "fast FAC [forward air controller]" employing the White Lightning (or "Zot") laser designator.

ing about the future of guided weapons had arguably shifted from the US Air Force to the Office of the Secretary of Defense (OSD) and its associated agencies and contractors, most notably to the Advanced Research Projects Agency (ARPA) and the Defense Nuclear Agency (DNA).[20] Among other things, the LRRDPP summary report explored the prospective utility of "near zero miss" conventional weapons to substitute for "massive nuclear destruction," emphasized the importance of developing all-weather guided munitions, and conceptualized a reconnaissance-strike capability using guided munitions and advanced sensors.[21] In pursuit of these ideas, in 1978 the Pentagon's director of research and engineering, William Perry, established the Assault Breaker program to explore the viability of such capabilities.

By the early 1980s Assault Breaker demonstrations at White Sands had confirmed the technical feasibility of missile-delivered guided submunitions targeted by wide-area sensors for destroying follow-on Soviet armored-and-mechanized units before they could be brought to bear in a conventional contest between the North Atlantic Treaty Organization (NATO) and the Warsaw Pact (WP). Nonetheless, the US Air Force remained skeptical about guided munitions.

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[20] The main contractors involved in the LRRDPP were Braddock, Dunn and McDonald (BDM), Lulejian and Associates, the General Research Corporation, and Science Applications, Inc. In 1996 ARPA, which had been established in 1958 following the Soviets' launch of the first artificial satellite, was renamed the Defense Advanced Research Projects Agency (DARPA) for the second time in its history. Science Applications, Inc. is now Science Applications International Corporation (SAIC). The LRRDPP's technology panel was chaired by Donald A. Hicks from Northrop and included individuals from Boeing, Lockheed, and TRW. Thus the LRRDPP also had involvement from the aerospace industry.

[21] Dominic A. Paolucci, *Summary Report of the Long Range Research and Development Planning Program* (Falls Church, VA: Lulejian and Associates, February 7, 1975), DNA-75-03055, SECRET (declassified December 31, 1983), pp. iii, 7, 30; and Richard H. Van Atta, Alethia Cook, Ivars Gutmanis, Michael J. Lippitz, Jasper Lupo, Rob Mahoney and Jack H. Nunn, *Transformation and Transition: DARPA's Role in Fostering an Emerging Revolution in Military Affairs*, Vol. 2, *Detailed Assessments* (Alexandria, VA: Institute for Defense Analyses, November 2003), P-3698, p. IV-1. Besides the technology panel, the LRRDPP also had strategic alternatives and munitions panels, chaired, respectively, by Wohlstetter and J. Rosengren (who had previously been DNA's deputy director).

Ironically, it appears to have been the Soviet General Staff, rather than the USAF, that did the most thinking about their implications for future war during the late 1970s and early 1980s. Even before the results of the Assault Breaker demonstrations were made public in late 1982, the Soviets began to respond to the possibility that NATO deployments of reconnaissance-and-strike complexes employing precision munitions would begin tipping the conventional balance of forces in Central Europe against the WP.[22] The recollection of the Pentagon's Director of Net Assessment, Andrew W. Marshall, is that the Soviets began discussing this emerging threat during the late 1970s in the General Staff's classified journal *Military Thought* (*Военный мысль*), and even ran some exercises in which NATO was assumed to possess Assault Breaker-like capabilities.[23] By the mid-1980s concern about such capabilities had reached the highest levels of the Soviet military. In 1984 no less than the head of the Soviet General Staff, Marshal N. V. Ogarkov, stated that "automated reconnaissance-and-strike complexes" with accurate, terminally guided conventional munitions would make it possible to achieve effects approaching those of nuclear weapons.[24]

While the center of gravity of American thinking about precision weapons—particularly about their role in strike operations—was shifting from the Air Force to OSD and ARPA in the 1970s, a far less visible threshold in the maturation of guided munitions was crossed by the growing application of solid-state electronics to military systems. The AIM-7D/E/E-2 models of the Sparrow III air-to-air missile—the medium-range, radar-guided AIM designed as an integral part of the

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[22] In November 1982, *Armed Forces Journal International* published the claim, based on Assault Breaker, that "*several* MLRS [Multiple Launch Rocket System] missiles can destroy a company of 13 armored fighting vehicles, just as one small-yield nuclear weapon can destroy a tank company" (N. F. "Fred" Wikner, " 'ET [Emerging Technology]' and the Soviet Union," *Armed Forces Journal International*, November 1984, p. 100). Figure 5 depicts Assault Breaker's operational concept and Figure 6 shows the "Skeet" guided submunition whose successful test elicited the 1982 revelation in *Armed Forces Journal*.

[23] Andrew W. Marshall, e-mail to Barry D. Watts, March 10, 2006.

[24] Marshal N. V. Ogarkov, "The Defense of Socialism: Experience of History and the Present Day," *Красная Звезда [Red Star]*, May 9, 1984; trans. Foreign Broadcast Information Service, *Daily Report: Soviet Union*, Vol. III, No. 091, Annex No. 054, May 9, 1984, p. R19.

Navy's F-4 Phantom II weapon system—had been a major disappointment in the skies of Southeast Asia. The 600-plus Sparrow IIIs US aircrews expended in anger in Southeast Asia achieved an overall kill probability of less (P_k) than 10 percent. There were a variety of reasons for this poor result. Certainly the understandable sensitivity of American aircrews to fratricide (Blue-on-Blue kills) severely constrained the missile's utility in beyond-visual-range (BVR) engagements whenever there was even the slightest chance that the target being tracked on the Phantom's radar was an American aircraft rather than an enemy fighter. Still, the hand-soldered, vacuum-tube electronics inside the missile proved so difficult to maintain—especially when operating from aircraft carriers in the Gulf of Tonkin—that US Navy F-4 crews chose, by 1972, to rely primarily on the more robust AIM-9 Sidewinder. Not until production of the AIM-7F began in 1976 did the incorporation of solid-state electronics yield a maintainable and reliable version of this missile—one that worked more or less as advertised most of the time. Thus, the rugged, solid-state electronics that started to become available for military applications in the early 1970s constituted a major step forward in the maturation of precision weapons.

Another important threshold was the emergence in the 1990s of relatively inexpensive, an all-weather PGM, the Joint Direct Attack Munition. The initial combat employment of JDAM occurred during Operation Allied Force (OAF) in 1999. B-2A bombers delivered 652 2,000-pound (lb) JDAMs and four 4,700-lb Global Positioning System (GPS)-Aided Munitions (GAMs) against Serbian targets during NATO's 78-day air campaign.[25] Like LGBs, JDAMs turned dumb bombs into smart munitions by adding guidance kits. During OAF, JDAM tail kits, which integrated inertial-navigation-system (INS) guidance with location-and-timing information from GPS satellites, were added to 2,000-lb Mark-84 and BLU-109/B bombs, and to the 4,700-lb BLU-113 warhead, for employment by B-2 bombers. After the campaign, nearly 90 percent of these munitions were assessed to have hit well within the advertised CEP of around 13 meters (42.7 feet).[26] In fact, subsequent analysis indicated that during this initial

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[25] 509th Bomb Wing, "Operation Allied Force," PowerPoint presentation, August 1999, slide 22.

[26] 509th Bomb Wing, "Operation Allied Force," slide 23. The Mark-84 JDAM was designed Guided Bomb Unit (GBU)-31V1, the JDAM with the hard-target-penetrator (BLU-109) warhead was the GBU-31V3, and GAM was the GBU-37.

trial, JDAMs delivered from the B-2, with its GPS-Aided Targeting System (GATS), achieved a CEP of around 4 meters (13.1 feet)—less than half the 9.6-meter (31.5-feet) CEP JDAM had averaged during prior testing.[27]

JDAM, of course, required the prior deployment of a constellation of satellites able to provide precise location-and-timing information anywhere on the globe, day or night, regardless of weather. Both the US Navy and Air Force had begun exploring predecessors to what became GPS during the 1960s. It was not until 1973, however, that deputy defense secretary William Clements designated the Air Force the lead agency to "consolidate the various satellite navigation concepts into a single comprehensive DoD [Department of Defense] system" for "precision weapon delivery."[28] The viability of GPS concept was proven by the launch of two NAVSTAR satellites in 1974 and 1977, and the first Block-I satellite was orbited in 1978. Whereas solid-state microelectronics had begun solving the reliability and accuracy problems of most early guided munitions, the atomic clocks at the heart of the GPS satellites enabled the United States to begin fielding inexpensive all-weather PGMs.

By the close of the 20th century, therefore, the US military had achieved the longstanding desideratum of "pickle-barrel" accuracy regardless of weather or other obscurations. Furthermore, in the case of "long-range" non-nuclear cruise missiles, accuracy had been achieved independent of range (though not independent of unit cost). Starting in 1991, CALCM and the non-nuclear TLAM began demonstrating accuracies approaching those of LGBs and JDAMs in actual combat use, and they could achieve these accuracies whether fired from ranges of 100 or 1,000 nautical miles (nm). Against fixed targets at least, the problem of pinpoint accuracy had arguably been solved,

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Of the 656 guided bombs dropped by B-2s in Allied Force, 609 were GBU-31V1s.

[27] William M. Arkin, "Belgrade Hit Earlier Than Previously Reported," *Defense Daily*, October 27, 1999, p. 3. GATS used the B-2's synthetic aperture radar to eliminate most of the target-location error in the GPS coordinates of individual aim-points during the approach to the target.

[28] Scott Pace, Gerald P. Frost, Irving Lachow, Dave Frelinger, Donna Fossum, Don Wassem, and Monica M. Pinto, *The Global Positioning System: Assessing National Policies* (Santa Monica, CA: RAND, 1995), pp. 238, 240.

even though the most widely used US guided munition, the laser-guided bomb, still required clear air to be effective.[29]

True, some substantial guided-munitions challenges remained at the dawn of the 21st century. Even fixed targets could be buried so deep or hardened enough to be beyond the reach of even highly accurate conventional PGMs. Also, moving, "relocatable," "emergent" and time-sensitive targets remained tactically challenging. In light of these outstanding problems, it seems safe to say that the guided-munitions story is by no means at an end despite six decades of intermittent progress. Substantial improvements in the "information content" of guided munitions are still possible. Nevertheless, the achievement of accuracy that is relatively independent of range, weather, or time of day against fixed targets constitutes a considerable achievement.

What are some of the major challenges that remain outstanding or unsolved? Beyond the tactical challenges just noted is the matter of achieving accuracy more or less independent of *both* cost and range.[30] The roughly 60-fold cost difference between a full-up JDAM round and a TLAM illustrates what has, so far, been a persistent problem for the American military. The unit-production cost of a JDAM with a Mark-84 warhead and fuze has averaged less than $33,000.[31] By comparison, the average unit-production price of the 4,201 TLAMs the Navy procured through fiscal year (FY) 2001 was $1.98 million per round.[32] As Chapter IV will show in more detail, "long-range" preci-

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[29] By early 2002, Air Force secretary James Roche was willing to declare the fixed-target problem "solved" (Peter Grier, "The Strength of the Force," *AIR FORCE Magazine*, April 2002, p. 24).

[30] My CSBA colleague Robert Work deserves credit for this insight. He was also the first to see its logical implication. If the cost of precision can be made as independent of range as accuracy currently is, then the attacker should generally be able to overwhelm any defense with a large enough salvo at selected points of attack. The upshot, of course, is that even if both attacker and defender emphasize guided weapons, the result will be an intensely offense-dominant regime.

[31] Department of the Air Force, *Procurement Program: Fiscal Years 2004/2005 Budget Estimates, Procurement of Ammunition*, February 2003, P-1 Item No. 7, p. 73; available online as a pdf file at <https://www.saffm.hq.af.mil/FMB/pb/2004/proc.html>, accessed February 9, 2006.

[32] Department of the Navy, *Fiscal Year (FY) 2004/2005, Biennial Budget Estimates, Justification of Estimates, Weapons Procurement, Navy*, February

sion munitions for under $100,000 per round still elude the US Defense Department's acquisition system, although Tactical Tomahawk and the Joint Air-to-Surface Standoff Missile (JASSM) are both striving for unit-production costs of around half a million dollars.

Another threshold in the evolving maturation of guided munitions that still lies in the future is the ability to deal with so-called "imprecisely located" targets—those for which a general location or broad area may be known, but not their precise coordinates. One of the deeper insights that emerged from examination of the 1991 Persian Gulf War was that precision munitions require "correspondingly precise target information."[33] The need for an exact target location or active tracking in order to achieve the required accuracy against surface or airborne targets applies to most of the guided munitions discussed so far. The Fritz X and the "Paveway I" LGBs got around this requirement by having a human "in-the-loop" to guide the munition to its aim-point visually. But once the human is no longer close enough to see the target, the need for precise target location becomes paramount. One solution has been to put sensors in the noses of guided munitions and data-link an image back to the operator. However, if the prospective targets are dispersed over a large area, or if there are large numbers of targets, then the limitation of man-in-the-loop target acquisition starts to reassert itself, and the prospect of munitions able to search significant areas for targets on their own appears to be a more attractive solution.

Munitions with enough on-board target-recognition capability to search significant areas for specific targets have yet to be fielded, although programs to develop them date at least back to the 1980s. More recently, the powered version of the Low Cost Autonomous Attack System (LOCAAS) has been under development since 1998 as a Defense Advanced Research Projects Agency (DARPA) and USAF advanced technology demonstration (ATD). The basic idea of LOCAAS is to use a laser-detection-and-ranging (ladar) sensor and automatic-target-recognition (ATR) algorithms to provide the capability to rec-

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2003, P-1 Shopping List, Item No 5, p. 1; available online at <http://navweb.secnav.navy.mil/pubbud/04pres/book_frame.htm>, accessed February 9, 2006.

33 Thomas A. Keaney and Eliot A. Cohen, *Revolution in Warfare? Air Power in the Persian Gulf War* (Annapolis, MD: Naval Institute Press, 1995), p. 211.

ognize a range of targets. Given the difficulties US forces have had in recent decades destroying "shoot-and-scoot" targets such as ballistic missile launchers and mobile SAMs, fielding munitions with the characteristics of LOCAAS might well prove a more far-reaching change in the conduct of military operations than even the fielding of LGBs or INS/GPS-aided munitions. Nevertheless, as will emerge later, there is evidence of cultural resistance to embracing truly autonomous robotic systems as part of war's future, even though LOCAAS' revolutionary ATR algorithms appear to be fairly mature.

The Origins of Battle Networks

The long-term prospect of weapons becoming autonomous or robotic enough to supply, at least in part, their own targeting information highlights another aspect of guided weapons: their historical relationship to surveillance-and-targeting networks. The first recognizably modern battle network was built around the system of Chain Home radar transmitters and receivers that the Royal Air Force (RAF) utilized to defend the British Isles against German efforts to gain daytime air superiority over southern England during the 1940 Battle of Britain. This air-defense network was used to concentrate the RAF's Spitfire and Hurricane fighters against incoming German air raids, which initially focused on destroying RAF Fighter Command and strangling British ports and shipping as preludes to a cross-Channel invasion.[34] By the end of October 1940, not only was Fighter Command's existence no longer in peril, but the Germans had abandoned their invasion plans.[35] This seminal example of an information-gathering network that affected the course of a war preceded the Pentagon's contemporary enthusiasm for "net-centricity," based on harnessing "the power of information connectivity," by over a half century.[36] It therefore reveals that, despite the growing importance enthusiasts such as the late Vice Admiral Art Cebrowski have accorded "network-centric"

[34] Air Vice Marshal Sir T. W. Elmhirst, *The Rise and Fall of the German Air Force, 1933-1945* (Poole, England: Arms and Armour Press, 1983), p. 79.

[35] Francis K. Mason, *Battle over Britain* (Bourne End, England: Aston Publications, 1990; originally McWhirter Twins, 1969), p. 381.

[36] DoD, *Quadrennial Defense Review Report*, February 6, 2006, p. 58.

approaches to warfare, networks are not exactly something new under the sun.[37]

Moreover, in the Battle of Britain the network of Chain Home radars did not just track German aircraft, but the tracking information they produced was used to facilitate the interception of German aircraft by RAF fighters. The various World War II surveillance networks not only gathered information, but were consistently employed to bring weapons to bear, albeit unguided ones. After World War II this fundamental purpose persisted, but the munitions being actively targeted themselves became, increasingly, guided ones. As the case studies in Chapters III and IV will show, since the 1950s most American surveillance networks have been developed first and foremost to provide the precision targeting information necessary to make guided munitions effective. This observation is not to deny the broader military potential of information connectivity, but to recognize that surveillance-and-targeting networks, like GPS, have been driven by the need to furnish precise targeting information to precision weapons. In fact, the US Navy's Cooperative Engagement Capability (CEC), which produces an integrated picture of the radar-tracking information from all the Aegis phased-array radars in a battle group for mutual air defense, became the exemplar of network-centric warfare during the 1990s.[38]

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37 Cebrowski and John Garska have argued that today's increasingly powerful military networks have their origins in the broad economic, societal and technological changes associated with the transformation of developed societies from the industrial to the information age (Vice Admiral Arthur K. Cebrowski and John J. Garstka, "Network-Centric Warfare: Its Origin and Future," *US Naval Institute Proceedings*, January 1998, online at <http://www.usni.org/Proceedings/Articles98/PROcebrowski.htm>, accessed February 2006; also Arthur K. Cebrowski, "An Emerging Military Response to the Information Age," speech at the 1999 Command and Control Research and Technology Symposium, June 29, 1999, at <http://www.nwc.navy.mil/pres/speeches/ccrp2%5F.htm>, accessed February 2006). They argue that one must look all the way back to the introduction of the *levée en masse* by revolutionary France, which gave rise to the modern nation in arms, to find a transformation in war's conduct as fundamental as that associated with the rise of modern battle networks. However, this somewhat revisionist view ignores a lot of guided-munitions history.

38 Cebrowski and Garstka, "Network-Centric Warfare: Its Origin and Future."

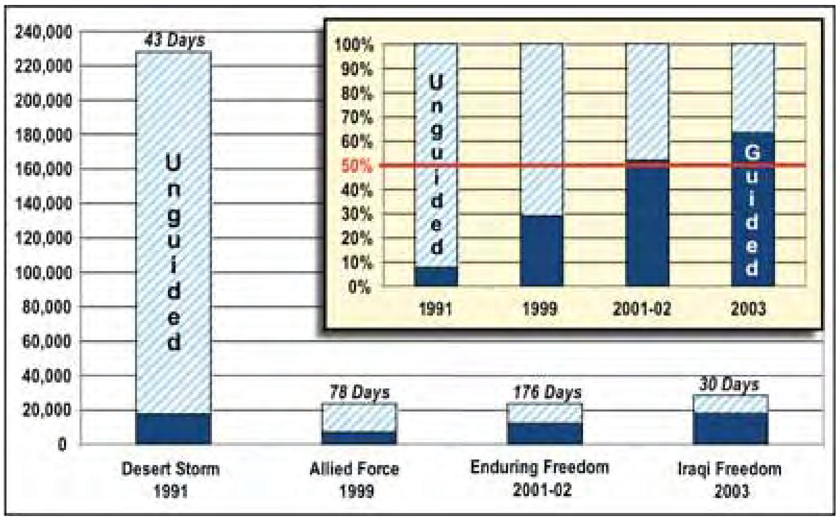
Early versus Late Adopters

Beyond documenting the long gestation periods of various guided munitions, the case studies in this report encompass examples from enough different military services and war-fighting communities to render the main historical trend since the 1940s difficult to mistake. Open battle between major, well-equipped military forces appears, on the whole, to be moving away from close combat with aimed fires toward engagement from a distance with guided munitions. With the obvious exception of counterinsurgency and anti-terrorist operations in "urban terrain," the longstanding belief—widespread among soldiers and marines—that tactical success ultimately hinges on destroying the enemy in close combat seems to be receding in terms of preferred practice by advanced militaries. Indeed, adversaries such as al Qaeda in Iraq and Islamic jihadists have had success since mid-2003 in forcing US forces to fight them in cities, but this sort of close combat is hardly the preference of the American military.

The trend toward engaging at a distance with guided munitions is especially unmistakable in the shift toward increasing reliance on them in US strike operations since Operation Desert Storm (January 17-February 28, 1991). Despite the unexpected effectiveness of LGBs and other guided weapons in Desert Storm, doubts persisted among senior airmen into the mid-1990s that the United States would ever wage mostly precision strike campaigns. Yet that is precisely what the expenditure data in Figure 4 reveal has become the dominant American practice.

Granted, even in the American military, not every war-fighting community has embraced guided weapons. In the case of engagements between main battle tanks, during the Cold War the US and Soviet armies both experimented unsuccessfully with guided missiles as alternatives to high-velocity cannons as the tank's primary armament. Spurred by improvements in armor protection, missiles like the US Army's Shillelagh were developed in the 1960s and put into operational service during the 1970s with the hope of being able to defeat enemy armor at much greater ranges than existing kinetic-energy (KE) and high-explosive anti-tank (HEAT) rounds from cannons permitted. In the end, however, the Army abandoned Shillelagh, returned to aimed-fire for tank-on-tank close combat, and there is every reason to think this was the right decision. The most compelling evidence came in 1991 during Operation Desert Storm's brief ground campaign. Not only did the M1A1 with depleted-uranium (DU) rounds demonstrate extraordinary lethality against Soviet T-72s with laminate armor at ranges of 3,000 meters or greater, but the M1 proved nearly impervious, even at close range, against the best T-72 125-millimeter (mm) KE and HEAT rounds.

Figure 4: US Guided and Unguided Munitions Expenditures in Four Campaigns[39]



When and why a given war-fighting community embraces guided munitions, then, can vary considerably. The tank communities in the US military have yet to make to the transition to guided munitions that the US Navy's submarine community made after World War II. Part of the reason stems from the viability of the unguided options accessible to a given community. In the case of tank-on-tank combat,

39 Primary sources: GWAPS, Vol. V, *A Statistical Compendium and Chronology*, Part 1, *A Statistical Compendium* (Washington, DC: US Government Printing Office, 1993), pp. 553-554; USAF, "Air War over Serbia (AWOS) Fact Sheet," Washington, DC, January 31, 2000; Headquarters USAF/XOOC (Checkmate), "ISO Joint Staff 'Quick Look' After-Action Review Panel," PowerPoint slides, December 15, 1999; William Arkin, "Weapons Total from Afghanistan Includes Large Amount of Cannon Fire," *Defense Daily*, Vol. 213, No. 42, March 5, 2002; and, Lieutenant General T. Michael Moseley, *Operation IRAQI FREEDOM—By the Numbers* (CENTAF-PSAB, Kingdom of Saudi Arabia: US Central Command Air Forces, April 30, 2003).

advances such as depleted-uranium rounds provided a gun-based alternative to missiles. Furthermore, tank-on-tank engagements are line-of-sight or direct-fire encounters at relatively short ranges with shooters and targets virtually stationary relative to the time it takes a high-velocity round from a tank's main gun to cover two or three kilometers. In other words, the time interval between firing a round and it hitting an enemy tank is too short for the target to get out of the way. Finally, tanks on both sides are pretty much confined to maneuvering in the same-two dimensional plane.[40] Thus, the imperatives that drove American submariners to embrace guided torpedoes in the 1940s were quite different from those that American armored branches face even today. Soviet nuclear submarines were free to maneuver in three dimensions, they could remain submerged for weeks at a time, and acoustic tracking was entirely different from directly seeing an enemy tank through a thermal-imaging sight. These sorts of differences in engagement dynamics appear to provide a basis for understanding when and why individual military communities either opted for guided munitions or persisted with unguided ones. Exploring these differences in specific cases will be a central focus of Chapters III and IV.

At this historical juncture, the American military appears to have an enormous lead in guided weapons along with their requisite surveillance-and-targeting networks. Nevertheless, how much of a competitive advantage this early lead confers over current and future adversaries remains to be seen. In the first place, the US military has yet to fight an opponent with comparable guided-munitions and sensor-targeting networks. In all four of the major campaigns in Figure 4, the United States enjoyed huge asymmetric advantages in both PGMs and battle networks. Second, as of 2006 at least, neither had the US military attempted to mount decisive conventional operations against a nuclear-armed adversary.[41] As Paul Bracken has pointed out, the de-

[40] I owe much to Robert Work for pointing out the relation between the inclinations of American operational communities in the 1940s and 1950s to embrace guided munitions and the number of dimensions in which attackers and defenders (or targets) can maneuver. The idea grew over time into a major theme in this report (see the discussion of drivers and causation in Chapter V).

[41] There is one marginal exception to this statement. During the Cold War, not only did American pilots encounter Soviet MiG-15s in air-to-air combat over the Korean Peninsula, but the Soviet MiG-15 regiments operated from Chinese bases in Manchuria (see Steven J. Zaloga, "The Russians in MiG Alley," *AIR FORCE Magazine*, January 1991 online at

terrence of nuclear use in such conflicts is likely to be very different and more uncertain than the deterrence of a large-scale nuclear exchange between the United States and the Soviet Union was during 1947-1991.[42] Third, there are growing questions about the utility of guided munitions and battle networks in so-called "small wars" such as the Iraqi insurgency that arose following the rapid overthrow of Saddam Hussein's Sunni-dominated regime in 2003.[43] Certainly it is difficult to see how precision engagement from afar could do much to track down key members of terrorist networks or alleviate the swelling anti-American sentiment in the Muslim world. Thus, there are serious questions about the long-term efficacy and relevance of the ongoing guided-weapons "revolution" (if this is a defensible term)—questions that warrant further thought and examination. These are issues to which the discussion will return in the concluding chapter.

<http://www.afa.org/magazine/1991/0291russian.asp>). At the time, however, neither superpower acknowledged direct Soviet involvement in the fighting, and Josef Stalin, having started the Korean War, may well have been prepared to abandon the North Koreans had the Chinese not intervened in November 1950—John Lewis Gaddis, *The Cold War: A New History* (New York: Penguin Press, 2005), p. 60. Moreover, if one relies, as Gaddis does, on the Natural Resources Defense Council's nuclear databases (at <http://www.nrdc.org/nuclear/nudb/datainx.asp>), even by 1953 the Soviet stockpile of atomic bombs was tiny compared to America's and Soviet Long Range Aviation (LRA) had not achieved an operational capability for striking targets in the continental US with atomic bombs. Of course, by 1951 or 1952, LRA might have been able to intervene in Korea with a crude atomic weapon (ibid., pp. 48-49).

[42] Paul Bracken, "The Second Nuclear Age," *Foreign Affairs*, January/February 2000, especially pp. 150-156.

[43] See, among other alternative views, H. R. McMaster, *Crack in the Foundation: Defense Transformation and the Underlying Assumption of Dominant Knowledge in Future War* (Carlisle, PA: Center for Strategic Leadership, US Army War College, November 2003), Vol. S03-03, available online at <http://www.carlisle.army.mil/usacsl/Publications/S03-03.pdf>; Frank G. Hoffman, "Small Wars Revisited: The United States and Nontraditional Wars," *The Journal of Strategic Studies*, December 2005, pp. 918-919; also Ralph Peters, "The Counterrevolution in Military Affairs," *The Weekly Standard*, February 6, 2006, Vol. 011, Issue 20, at <http://www.weeklystandard.com/Content/Public/Articles/000/000/006/649qrsob.asp>, accessed February 13, 2006.

The Rest of This Report

Between here and there, this report proceeds as follows. Chapter II covers various preliminary and contextual issues. The main question it attempts to address is: How should one think about the role and efficacy of guided munitions in early 21st-century warfare? Toward this end, Chapter II explores the difference between war's enduring nature and its actual conduct, the influence of superior technology or numbers on combat outcomes, and the problems of identifying revolutionary change in areas of human affairs as diverse as science and contemporary warfare. It also raises a number of questions about the future influence of guided munitions and advanced battle networks on the conduct of war and points out an anomaly whose resolution is deferred until Chapter V.

Chapters III and IV contain the case studies that constitute the bulk of this report. Chapter III focuses on platform-versus-platform cases such as torpedoes for submarine-versus-submarine engagements and air-to-air missiles for fighter-versus-fighter combat or shooting down enemy bombers. Chapter IV turns to a set of surface-attack case studies, which include LGBs, GPS-aided munitions, long-range cruise missiles, LOCAAS and the CEC network for the air defense of surface combatants. Whereas Chapter III concentrates on the influence of guided munitions on tactical engagements, Chapter IV's cases begin to address their higher-level effects on operations and campaigns.

Taken together, the aim of these two chapters is to examine a wide enough range of individual cases from different military services and distinct operational communities to have a firm empirical basis for understanding the influence guided weapons have exerted on the conduct of warfare to date and the influence they are likely to have in coming decades. Most discussions of guided weapons to date have focused on narrow slices of the broader story. There is, however, considerably more to the rise of guided munitions and battle networks over the last six decades than, say, the growing accuracy of air-to-ground PGMs. Chapters III and IV endeavor, therefore, to cast a wide net in terms of the breadth and diversity of case studies examined.[44]

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[44] It was Andrew W. Marshall, the Director of Net Assessment, Office of the Secretary of Defense, who originally had the idea of examining cases from a range of war-fighting communities across the US military services.

The concluding chapter draws out both the near- and longer-term implications for the future of guided munitions suggested by the cases in Chapters III and IV. In effect, Chapter V takes up where this introduction leaves off, fleshing out the implications already mentioned. In the near term, for example, the prospects of achieving accuracy regardless of range to the target without high costs-per-round appear dim in the absence of some fundamental reform to the Pentagon's acquisition practices. Nor is there much likelihood of dramatically improving our ability to cope with imprecisely located targets, although the main obstacle here appears to be less technological inadequacy than a cultural reluctance to field increasingly autonomous robotic systems. Another prospective implication of Chapters III and IV is that the evolving guided-munitions era will grow even more offense dominant than it already is and, as a result, affect both the location of main-operating bases and the dispersion of traditional land forces such as armored and mechanized ground formations. These possibilities underscore the judgment that the evolution of guided weapons and battle networks is by no means at an end.

What about the long-term future? Here the greatest uncertainty may lie in the strides made over the next decade or two in the power and mobility of high-energy lasers. While one hesitates to project how soon the underlying technologies may mature, there is a real possibility the long-anticipated maturation of directed-energy weapons could lead to even more disruptive changes in how wars are fought. Effective chemical or solid-state laser weapons for close-in defense could radically reduce the vulnerability of surface combatants or main operating bases to salvo attacks with conventional guided munitions. In that case, one can imagine the emergence of a defense-dominant regime, at least at the conventional level.

II. How To Think about Guided Munitions and Battle Networks

Based on the analysis it appears that non-nuclear weapons with near zero miss may be technically feasible and militarily effective.

— LRRDPP, 1975[1]

. . . rapid changes in the development of conventional means of destruction and the emergence in the developed countries of automated reconnaissance-and-strike complexes, long-range high-accuracy terminally guided combat systems . . . and qualitatively new electronic control systems make many types of weapons global and make it possible to sharply increase (by at least an order of magnitude) the destructive potential of conventional weapons, bringing them closer, so to speak, to weapons of mass destruction in terms of effectiveness. The sharply increased range of conventional weapons makes it possible to immediately extend active combat operations not just to the border regions, but to the whole country's territory . . . . This qualitative leap in the development of conventional means of destruction will inevitably entail a change in the nature of the preparation and conduct of operations . . .

— Marshal N. V. Ogarkov, 1984.[2]

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[1] Paolucci, *Summary Report of the Long Range Research and Development Planning Program*, p. iii.

[2] Ogarkov, "The Defense of Socialism: Experience of History and the Present Day," p. R19. Within months of this interview appearing in *Red Star*, Ogarkov

> Dramatic developments in military technology appear feasible over the next twenty years. They will be driven primarily by the further exploitation of microelectronics, in particular sensors and information processing, and the development of directed energy. . . . The much greater precision, range, and destructiveness of weapons could extend war across a much wider geographic area, make war much more rapid and intense, and require entirely new modes of operation.
>
> — *Discriminate Deterrence*, 1988[3]

> . . . it's probable that we are near the beginning of the real revolution in military affairs. The [1991] Gulf War needs to be seen as something like Cambrai. A first trial of new technology and new ways of operating was undertaken. Because we're at the beginning, perhaps in 1922 in the analogy to the [19]20s and [19]30s, we cannot fully foresee how things are going to work out. This means to me that our first challenge is an intellectual one.
>
> — A. W. Marshall, 1993[4]

Definitional Matters and Scope

As already indicated, guided munitions are defined as projectiles, bombs, missiles, torpedoes and other munitions that can actively correct for initial-aiming or subsequent errors by homing on their targets or aim-points after being fired, released, or launched. Here homing on targets or aim-point is understood to mean active guidance during the terminal phase of the engagement, if not to the moment of impact. The insistence on *terminal* guidance excludes virtually all Cold War

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was succeeded by Marshal S. F. Akhromeyev as chief of the Soviet General Staff.

[3] Fred C. Iklé, and Albert Wohlstetter (co-chairmen), *Discriminate Deterrence: Report of the Commission on Integrated Long-Term Strategy* (Washington, DC: US Government Printing Office, January 1988), p. 8. Commission members included Zbigniew Brzezinski, General Andrew J. Goodpaster (USA, Ret.), General Bernard A. Schriever (USAF, Ret.), General John W. Vessey (USA, Ret.), Samuel P. Huntington, and Henry A. Kissinger.

[4] Andrew W. Marshall, "Some Thoughts on Military Revolutions," memorandum for the record, Office of Net Assessment, Office of the Secretary of Defense (OSD/NA), August 23, 1993, p. 3. The British tank assault at Cambrai took place on November 20, 1917. It was the initial, large-scale British attempt to use massed tanks to break through German lines and restore movement to the battlefield following some three years of stalemate on the Western Front. For a firsthand account, see Brevet-Colonel J. F. C. Fuller, *Tanks in the Great War 1914-1918* (New York: E. P. Dutton, 1920), pp. 140-153.

intercontinental and submarine launched ballistic missiles (ICBMs and SLBMs) even though some, such as the MX/Peacekeeper, had exquisite guidance systems for aiming their ballistic warheads.[5]

There are a couple reasons for preferring the term *guided* to *precision* despite the fact that the latter has gained widespread acceptance within the US military as well as abroad. First, terms such as *precision strike*, *precision engagement*, and *precision munition* beg the question of how accurate a weapon must be to be judged precise. Is an average miss distance of 20 feet *precision*, *near-precision*, or neither? A 20-foot miss with a 2,000 bomb may be close enough "for government work" against most targets, whereas the same miss distance with the 20-pound shaped-charge warhead in the AGM-114F Hellfire anti-tank missile is simply a miss—particularly against a main battle tank. Second, *guided* emphasizes the central attribute of being able to correct for initial aiming errors after the munition has been fired, released, or launched by homing on aim-points or coordinates. Out to three kilometers or so, the M1A1's fire-control system makes its 120-mm main gun quite accurate and, with depleted-uranium APFSDS (armor-piercing fin-stabilized discarding-sabot) rounds, extraordinarily lethal against opposing tanks such as the T-72. But since rounds from the M1's main gun cannot correct for initial aiming errors, they fall outside the scope of this report. Nor does it appear unreasonable to extend this line of reasoning to exclude both direct-fire AAA systems such as the Russian ZSU-23-4, or indirect-fire systems such as the Navy's Phalanx Close-in Weapon System (CIWS), even though both systems use target-tracking radars to aim streams of unguided shells. Of course, the addition of an INS/GPS-aided round to a field artillery system for terminal guidance would, based on this understanding of the term *guided*, move the system from the unguided into the guided category. Again, the munitions at issue are those that can, in one way or another, correct for initial aiming errors right up to the moment of impact. It is this attribute that is central to whether a given platform or weapon system qualifies as guided or unguided.[6]

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[5] For a detailed account of Peacekeeper's Advanced Inertial Reference Sphere (AIRS), see Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge, MA: MIT Press, 1993), pp. 165-239.

[6] If the absolute accuracy of a guided weapon is secondary compared to the primary attribute of being guided, then the same can be said of the precise guidance phenomenology employed by a particular munition. Guided muni-

The munitions themselves, however, do not provide a satisfactory conceptual framework for this report. Surveillance-and-targeting networks arose historically to provide precision information on aim-points for guided munitions, and "smart" munitions are simply components, albeit necessary ones, of "sense-and-strike" systems. Borrowing from Soviet military thinking about future warfare during the 1970s and 1980s, a concept that captures this point is that of a reconnaissance-strike complex (рекогносцировк-удара комплекс). In Soviet usage, a reconnaissance-strike complex (RUK) has three main components: (1) long-range or wide-area sensors, (2) command-and-control (ideally, automated C2), and (3) guided or precision weapons delivered by missiles or strike aircraft (as opposed to tube artillery).[7]

As mentioned in Chapter I, American thinking about reconnaissance-strike complexes reaches at least back to the 1975 ARPA-DNA Long Range Research and Development Planning Program. Starting in 1978, a concept-demonstration program, Assault Breaker, began that sought to develop the LRRDPP's early thinking about guided munitions and battle networks. Similarly, the US Air Force later considered a variant, the Precision Location Strike System, which envisioned using the electronic emissions of Warsaw Pact air defense systems to attack them at the outset of a NATO-WP conflict in central Europe. While neither of these early efforts led directly to a US RUK, in the early 1980s an unclassified account of the Assault Breaker concept

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tions have utilized a wide range of phenomenologies to home on targets or aim-points. These include radar returns from a target illuminated by a fire-control radar, passive infrared emissions from the target, its own active radar emissions, electromagnetic radiation reflected off the target by a laser illuminator, the target's acoustic signature, a combination of inertial guidance and GPS location information to guide the weapon to a set of GPS coordinates, and electro-optical images of the target. This diversity of guidance methods notwithstanding, the choice of guidance phenomenology is secondary relative to the primary characteristic of homing on the aim-point or target after release, launch, or firing.

[7] Notra Trulock, III, Kerry L. Hines, and Anne D. Herr, *Soviet Military Thought in Transition: Implications for the Long-Term Military Competition* (Arlington, VA: Pacific-Sierra Research Corporation, May 1988), p. v; Timothy L. Thomas, "Information Warfare in the Second (1999-Present) Chechen War: Motivator for Military Reform?" p. 7 (in the electronic version available online at <http://fmso.leavenworth.army.mil/documents/iwchechen.htm>, accessed February 2006). Thomas' article originally appeared in *Russian Military Reform 1992-2002* (eds.) Anne C. Aldis and Roger N. McDermott (London: Frank Cass, 2003), pp. 209-233.

appeared in *Scientific American*, and the ARPA program conducted successful "tests" against stationary targets at the White Sands proving ground in New Mexico using a ground-based version of the PAVE MOVER radar and terminally guided submunitions delivered by T-16 Patriot and T-22 Lance II missiles.[8] Additionally, in late 1982, the results of at least one successful Assault Breaker test were published in *Armed Forces Journal International*, ensuring that the Soviets were aware of what the Americans had in the offing.[9]

Figure 5: The Assault Breaker Concept

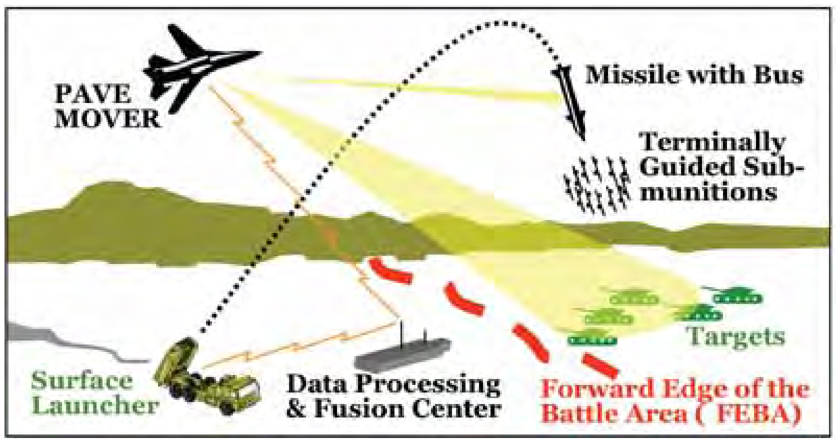

Figure 5 depicts the original Assault Breaker concept. The aim of the program, as the Soviet General Staff realized, was to exploit the US lead in advanced technologies to offset the roughly three-to-one advantage the Warsaw Pact had in "tanks, artillery [pieces], and armored personnel carriers" over NATO.[10] The PAVE MOVER aircraft in Figure 5 represents a moving-target-indicator (MTI) radar on a US F-111 fighter-bomber, and the principal targets the program had in mind are, of course, second-echelon Soviet tank units advancing to engage

[8] Paul F. Walker, "Precision-guided Weapons", *Scientific American*, August 1981, pp. 36-45; Van Atta, et al., *Transformation and Transition: DARPA's Role in Fostering and Emerging Revolution in Military Affairs*, Vol. 2, *Detailed Assessments*, pp. IV-17 to IV-19.

[9] Wikner, "'ET [Emerging Technology]' and the Soviet Union," p. 100.

[10] "Perry on Precision Strike," *AIR FORCE Magazine*, April 1997.

US/NATO along the forward edge of the battle area (FEBA).[11] The immediate tactical goal was to begin disrupting and attriting WP follow-on ground units before they could engage NATO forces.

Figure 6: The Skeet Submunition

Assault Breaker tested two "smart" munitions: the General Dynamics Terminally Guided SubMunition (an unpowered, fabric-winged missile that used a two-color infrared sensor for terminal homing); and the Avco Skeet (a self-forging warhead packaged in fours on a delivery-vehicle assembly to make the BLU-108B).[12] In the case of Skeet, once the warheads had been released from the delivery assembly, they also used a two-color infrared (IR) sensor to scan for targets within their trajectory footprint. Upon detecting a valid target, the munition would then detonate, driving a self-forging slug into the enemy tank or other vehicle.[13]

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[11] PAVE MOVER was not fielded. The first wide-area MTI radar of the sort envisioned by the Assault Breaker program did not enter active service until the E-8C Joint Surveillance Target Attack Radar (Joint STARS) achieved initial operational capability in 1997. However, two developmental Joint STARS aircraft were used with considerable success during Desert Storm in 1991.

[12] Carlo Kopp, "Precision Guided Munitions: The New Breed," *Australian Aviation*, September 1984; a 2005 version of this article with additional images is available at <http://www.ausairpower.net/TE-Assault-Breaker.html>, accessed September 26, 2006.

[13] Strictly speaking, Skeet is a "precisely aimed" submunition, not a "guided munition" as the term is used in this report. The Air Force has packaged BLU-108Bs into a 1,000-lb class munition, the Sensor Fuzed Weapon (SFW).

Viewed together, Figures 5 and 6 illustrate where precision munitions fit within the more comprehensive conception of a reconnaissance-strike complex. The guided munitions themselves are, at most, the business end of a broader system (or "system of systems," to recall a term that gained notoriety during US discussions of the emerging RMA during the 1990s[14]). After all, even in the case of LGBs, targets for these PGMs have often been initially located using space-based reconnaissance satellites such as the KEYHOLE (KH)-11s.[15] More recently, guided munitions such as JDAM and CALCM, which home on coordinates in GPS space, have required an entire satellite constellation.

While neither the United States nor the Soviet Union managed to field full-blown reconnaissance-strike complexes before the Cold War ended, the Soviets also made efforts in this direction. The stated mission of the Soviet (now Russian) Oscar II-class guided-missile nuclear submarine (SSGN) was (and remains) to attack US carrier battle groups (CVBGs). True, the supersonic (1.5-2.5 Mach), long-range (550 kilometers or more) Granit cruise missiles that constitute the Oscar II's primary armament can also be used to attack targets ashore, including American cities with nuclear warheads. But in the case of a coordinated, non-nuclear attack against an American aircraft carrier mounted by Oscar IIs in conjunction with Tu-22M Backfire bombers (carrying Kh-22 Burya ASMs), the most likely approach would be to salvo the opening wave of Granit missiles toward the American CVBG

The unguided SFW is the Cluster Bomb Unit (CBU)-97B; the version with a wind-corrected tail-kit is the CBU-105.

[14] For a classic account of the system-of-systems concept, see Admiral William A. Owens, "The Emerging U.S. System-of-Systems," *Strategic Forum*, National Defense University, No. 63, February 1996; available online at <http://www.ndu.edu/inss/strforum/SF_63/forum63.html>, accessed February 2006. At the time, Owens was vice chairman of the US Joint Chiefs of Staff (JCS).

[15] During Operation Allied Force in 1999, for example, the US military is believed to have had available three advanced KH-11 EO/IR imaging and two Lacrosse radar-imaging satellites (Craig Covault, "Recon, GPS Operations Critical to NATO Strikes," *Aviation Week & Space Technology*, April 26, 1999, p. 35). The advantage of Lacrosse over the KH-11, of course, was that it could provide synthetic aperture radar (SAR) imagery through clouds. At least one Lacrosse satellite is believed to have been on orbit during Desert Storm (Craig Covault, "Secret Relay, Lacrosse NRO Spacecraft Revealed," *Aviation Week & Space Technology*, March 23, 1998, p. 27).

while the SSGN remained submerged. In this scenario, both the Backfires and Oscars would probably rely on ocean-surveillance satellites for the initial bearing and distance to the target for their missiles, although both Granit and Burya are assessed to have active-radar and radar-homing modes.[16] Like Assault Breaker's missiles and "smart" submunitions, therefore, the Oscar SSGNs, Backfires, and their anti-ship missiles, could be viewed as constituting the strike element of a primitive RUK. To be militarily useful, though, the reconnaissance-strike *system* requires sensor-and-targeting (or battle) networks as well, and it is this overall system that delineates the proper focus and scope of this report.

War's Nature versus War's Conduct

Even with the importance of the information aspects of precision strike in mind, some readers may be tempted to suppose that an unstated premise—or an eventual conclusion—is that the emergence of a mature guided-munitions regime changes the *nature* of war. Nothing, however, could be further from this author's intention and viewpoint. Insofar as war's *nature* is about the organized use of violence to select between the incompatible ends of opposing polities, there is no persuasive evidence for supposing that war's nature has changed one whit since the time of Thucydides. As Carl von Clausewitz correctly observed, because war is a "continuation of political intercourse, with the addition of other means" [*eine Fortsetzung des politischen Verkehrs mit Einmischung anderer Mittel*], policy [*Politik*] determines its character with the consequence that "all wars are things of the *same* nature [einer *Art*]."[17]

Even in what Colin Gray has termed the "Age of Terror," the fact that al Qaeda and its affiliates are a loose confederation of transna-

[16] Lieutenant Commander William R. Bray, "Five Fleets, Part 6: Around the World with the *Nimitz*," *US Naval Institute Proceedings*, September 1998, online at <http://www.usni.org/Proceedings/articles98/PRObray.htm>, accessed February 2006.

[17] Carl von Clausewitz, ed. and trans. Michael Howard and Peter Paret, *On War* (Princeton, NJ: Princeton University Press, 1976), pp. 605, 606; Clausewitz, Werner Hahlweg (ed.), *Vom Kriege: Hinterlassenes Werk des Generals Carl von Clausewitz* (Bonn: Ferd. Dümmlers, 1980 and 1991), pp. 990, 992. The emphasis is in both Howard and Paret's translation and Hahlweg's presentation of the original German text.

tional terrorist networks rather than a nation state does not undermine Clausewitz's insight that war's nature is about use of organized violence to achieve political ends.[18] After all, al Qaeda's long-term goals are surely, by now, no mystery. As articulated by the chief counter-terrorism expert on the US National Security Council (NSC) in early 2001, Osama bin Laden and his associates seek two ends: "to drive the US out of the Muslim world, forcing the withdrawal of our military and economic presence in countries from Morocco to Indonesia; [and] to replace moderate, Western regimes[s] in Muslim countries with theocracies modeled along the lines of the Taliban."[19] Notwithstanding the religious coloration of these strategic objectives, they are every bit as political in Clausewitz's sense as those of the Continental Congress during the American Revolutionary War (1775-1783) or of Soviet political leaders during their ill-fated military incursion into Afghanistan (1979-1989).

Nor is the use of violence to achieve political ends the only aspect of war's nature that has been unchanged by the maturation of guided munitions and battle networks. Consider Clausewitz's notion of the *Gesamtbegriff einer allgemeinen Friktion*, which is best rendered into English as the "unified concept of a general friction."[20] Clausewitz had been a soldier from the age of 12 until his death at 51 in 1831. He first saw action near Mainz in early 1793 as an ensign and officer candidate; by the time he was 35, he had fought in five land campaigns against France, including taking command of a battalion in the aftermath of Prussia's defeat at Jena-Auerstädt in 1806 and service with the Russians during Napoleon Bonaparte's disastrous invasion of Rus-

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[18] Colin S. Gray, *Recognizing and Understanding Revolutionary Change in Warfare: The Sovereignty of Context* (Carlisle, PA: Strategic Studies Institute, February 2006), p. v.

[19] Richard A. Clarke, "Presidential Policy Initiative/Review—The *Al-Qida* Network," memorandum for Condoleezza Rice, NSC, January 25, 2001, p. 1. While originally classified, this memo is available online in the George Washington University's National Security Archive at <http://www2.gwu.edu/~nsarchiv/NSAEBB/NSAEBB147/index.htm>. For the 1996 fatwa in which bin Laden declared war against the United States, see "Declaration of War against the Americans Occupying the Land of the Two Holy Places," first published in the London-based paper *Al Quds Al Arabi*, at <http://www.pbs.org/newshour/terrorism/international/fatwa_1996.html>, accessed March 2006.

[20] Hahlweg, *Vom Kriege*, p. 265.

sia in 1812.[21] Clausewitz developed his overarching notion of a general friction over a period of years to explain the vast gap he had begun to perceive by 1806 between "real war" (*wirklichen Krieg*) and war "on paper."[22] Over time, Clausewitz's writings suggested that friction had numerous sources: (1) danger's effects on the ability to think clearly or act effectively in war; (2) the effects on thought and action of combat's demands for exertion; (3) the uncertainties and imperfections in the information on which action in war is based; (4) the internal resistance to effective action stemming from the interactions between the many men, organizations, weapons, and power centers within one's own forces; (5) the play of chance events, of good luck and bad, that can never be fully foreseen; (6) physical and political limits to the use of military force; (7) unpredictability arising from interaction with the enemy; and (8) disconnects between ends and means in war.[23] Altogether, these various sources of resistance to effective action combined, in Clausewitz's view, to make war's actual practice profoundly different and vastly more difficult than its pure theory.

Particularly during the RMA debate of the 1990s, some observers of military affairs argued that technological advances would greatly dissipate, if not eliminate, Clausewitzian friction. Admiral William Owens became a vocal advocate of this view during his tenure as vice chairman of the US Joint Chiefs of Staff (JCS).[24] Nonetheless, the dif-

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[21] Hugh Smith, *On Clausewitz: A Study of Military and Political Ideas* (New York and Houndsmills: Palgrave Macmillan, 2005), pp. 3-4, 6-7, 10-11.

[22] Howard and Paret, *On War*, p. 119. Clausewitz first used *Friktion* in September 1806 to refer to the Prussian Army's fragmented command structure—"three commanders-in-chief and two chiefs of staff." Although the Prussian king had put Clausewitz's mentor, Gehard von Scharnhorst, nominally charge of operations, Scharnhorst was unable to prevent, among other things, the "major calamity" of the army being divided into two forces within a single theater of operations—Carl von Clausewitz, "From *Observations on Prussia in Her Great Catastrophe* (1823-1825)" in Peter Paret and Daniel Moran (ed. and trans.), *Historical and Political Writings* (Princeton, NJ: Princeton University Press, 1992), p. 44.

[23] Barry D. Watts, *Clausewitzian Friction and Future War* (Washington, DC: National Defense University, rev. ed. 2004), McNair Paper 68, pp. 19-21.

[24] Admiral William A. Owens, "System-of-Systems: US' Emerging Dominant Battlefield Awareness Promises to Dissipate the 'Fog of War'," *Armed Forces Journal International*, January 1996, p. 47; also Admiral William A. Owens with Ed Offley, *Lifting the Fog of War* (New York: Farrar, Straus and Giroux, 2000), p. 15.

ficulties the United States has experienced since 1991 in achieving its ultimate strategic aims in Iraq argue that there is still scant, if any, empirical basis for Owens' bold claim. However much of a military triumph Operation Desert Storm may have been, it was not the end of America's struggle with Saddam Hussein's Iraq. Twelve years after the major-operations phase of the first Persian Gulf War ended, President George H. W. Bush's son, President George W. Bush, felt compelled to initiate a second Persian Gulf War to topple the country's Ba'athist regime. Yet, as successful as the major-combat-operations phase of that campaign was, the inability of US forces to find weapons of mass destruction afterwards and the ferocity of the subsequent insurgency were both major surprises—as well as testaments to general friction's persistence as a fundamental feature of war. Indeed, the difficulties the United States has encountered in Iraq and Afghanistan since 2001 prompted Antulio Echevarria to suggest that the most debilitating weakness in the American "way of war" is the tendency "to shy away from thinking about the complicated process of turning military triumphs, whether on the scale of campaigns or small-unit actions, into strategic success."[25] General friction's stubborn persistence, then, is another way in which the nature of war remains unchanged.

War's conduct, though, is another matter. Changes over time in underlying technology, weaponry, tactics and methods, operational concepts, organizational arrangements, military doctrine, and, above all, societal context have continually produced dramatic changes in actual practice. For example, although the US Army retained a few horse-cavalry units following General George Marshall's reorganization of March 1942, the only horse-mounted unit that fought mounted during World War II was the 26th Cavalry Regiment in the Philippines between the Japanese attack on Pearl Harbor the surrender of the American forces at Bataan in April 1942. In effect, the success of German *Blitzkrieg* campaigns in 1939 and 1940 led to the divestiture of horse-cavalry from the US Army despite the staunch resistance of the cavalry branch into 1942.[26] This outcome had, of course, a technological component in the maturation of tanks, but those who have taken the greatest care in assessing why mobile, armored warfare was

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[25] Antulio J. Echevarria, II, *Toward an American Way of War* (Carlisle, PA: Strategic Studies Institute, March 2004), p. 7.

[26] David E. Johnson, *Fast Tanks and Heavy Bombers: Innovation in the U.S. Army 1917-1945* (Ithaca, NY: Cornell University Press), pp. 176-181.

so successful during this period have placed even more emphasis on the role of such things as Hans von Seeckt's leadership of the German army after World War I, the 1933 doctrinal manual *Troop Leadership [Truppenführung*], the quality of the World War II German Army's commissioned and noncommissioned officers, and the fact that the panzer division was "a combined-arms force that used all of its weapons, not just tanks, with maximum effectiveness."[27] In any event, by the end of the Second World War, horse cavalry had largely been displaced by mechanized forces and it is unlikely that modern militaries will bring back horses. In this sense, the *conduct* of war by the great powers had clearly changed.

Since World War II, the societal context within which the US military wages conventional war has also evolved enough to alter American practice. As Gray has observed, during World War II the United States was "preponderantly an industrial society" and it waged industrial-age warfare on a scale that "confounded foes and astonished allies."[28] Among other things, this approach entailed a willingness to target the enemy population right along with enemy war production. The apogee of this ruthlessness was manifested on the night of March 9-10, 1945, when 285 B-29s delivered some 1,900 tons of napalm-filled incendiary munitions on an area of eastern Tokyo.[29] The primary target was an approximately four-by-three-mile zone bordering

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[27] James S. Corum, *The Roots of Blitzkrieg: Hans von Seeckt and German Military Reform* (Lawrence, KS: University of Kansas Press, 1992), pp. 199-202; Williamson Murray and Allan R. Millett, *A War To Be Won: Fighting the Second World War* (Cambridge, MA: Belknap Press of Harvard University Press, 2000), pp. 66-76; and Robert Allan Doughty, *The Breaking Point: Sedan and the Fall of France, 1940* (Hamden, CT: Archon Books, 1990), pp. 324-331.

[28] Gray, *Recognizing and Understanding Revolutionary Change in Warfare*, p. 20.

[29] Assistant Chief of Air Staff, *IMPACT*, Vol. III, No. 4, April 1945, pp. 19-23 in Air Force Historical Foundation, *IMPACT: The Army Air Forces' Confidential Picture History of World War II*, Vol. 6, *Bombing Night and Day: The Two-Edged Sword* (Harrisburg, PA: Historical Times, 1982). This attack involved three B-29 wings originating from Guam, Saipan and Tinian in the Mariana Islands. The planned force totaled 334 bombers carrying about 2,000 tons of incendiaries. All but the pathfinders carried 24 500-lb cluster bombs, each containing 38 6-lb Mark-69 napalm incendiaries. The pathfinders carried 180 70-lb Mark-47 incendiaries, also filled with gasoline gel.

"the most important industrial section of Tokyo."[30] This densely populated area of the city was chosen on the grounds that it was more vulnerable to incendiary attack than the neighboring industrial areas. Less than 30 minutes after the attack began, 28-mile-per-hour winds fanned the fires out of control, temperatures eventually approached 1,800 degrees Fahrenheit, and during the long journey back to their bases in the Marshall Islands B-29 gunners were able to see the glow from the resulting inferno 150 miles away.[31] Post-strike photos showed that 15.8 square miles of Tokyo had been utterly destroyed; Japanese records listed 83,793 dead, 40,918 wounded, over a million persons rendered homeless, and more than 260,000 buildings destroyed.[32] No subsequent urban-area attack against a Japanese city was as destructive, including the atomic bombings of Hiroshima and Nagasaki.[33]

By comparison, American planning for and execution of Operation Desert Storm in 1990-91 consciously excluded targeting the Iraqi population. During Operation Enduring Freedom in 2001-02 not only was Afghanistan's population off limits but its physical infrastructure was as well. Indeed, on occasion attacks against key Taliban leaders were stopped or delayed to avoid damage to the country's roads. What had brought about these added constraints on the use of force by the US military? The answer is American societal values: Americans and their political leaders are no longer willing to tolerate systematic attacks on enemy civilians of the sort that were enthusiastically carried out in World War II. Thus, the belief-systems of a given society can alter how a given polity conducts war as significantly as the fielding of more lethal weaponry or the emergence of novel operational concepts and organizational arrangements.

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[30] James L. Cate and James C. Olson, "The All-Out B-29 Attack" in Wesley F. Craven and James L. Cate (eds.), *The Army Air Forces in World War II*, Vol. 5, *The Pacific: Matterhorn to Nagasaki June 1944 to August 1945* (Washington, DC: US Government Printing Office, 1983 new imprint), p. 615.

[31] Victor Davis Hanson, *The Soul of Battle: From Ancient Times to the Present Day, How Three Great Liberators Vanquished Tyranny* (New York: The Free Press, 1999), p. 2. Hanson's father, who was a B-29 tail gunner on this mission, said he could smell burned flesh all the way back to Tinian (ibid.).

[32] Cate and Olson, "The All-Out B-29 Attack," pp. 616, 617.

[33] United States Strategic Bombing Survey, *Summary Report (Pacific War)* (Washington, DC: US Government Printing Office, July 1946), pp. 17, 22-24.

The Influence of Technology and Numbers

How *frequently* have superior weaponry or greater numbers decided engagement or battle outcomes? Other things being equal, it seems plausible to suppose that either the "bigger battalions" or more effective weaponry could be the key to tactical success. Here the crucial premise is that disparities in either opposing weaponry or numbers constitute the only meaningful differences between the two sides. The rub, however, is that actual military encounters tend to be riddled with differences and asymmetries that one side or the other could exploit to its advantage. And, since combat is a life-or-death struggle, both sides have powerful incentives to do so. Thus, as tempting as it may be to think that tactical outcomes are decided the majority of time by such concrete factors as superior technology or superior numbers, the assumption on which this view rests is rarely fulfilled in real war.

If, in the main, neither technological nor numerical disparities usually determine combat outcomes, then what sorts of factors do? The most straightforward way to begin answering this question is to consider some actual cases. One place to start is with the Germans' victory over the Western Allies in May 1940. This campaign began around 0545 on May 10, 1940, when the leading elements of the *Wehrmacht* began crossing the frontiers of Belgium, Luxemburg, and the Netherlands. The plan called for the main effort to be made in the center through the Ardennes Forest by Generaloberst Gerd von Rundstedt's Army Group A. There the Germans concentrated eight of their ten panzer divisions in three panzers corps under von Rundstedt (Figure 7).

The pivotal events in the campaign's outcome were the successful crossings of the Meuse River by Army Group A's panzer corps at Dinart, Mézières and Sedan, crossings that the headquarters of the French forces under by General Maurice Gamelin did not even mention in its activity summary for May 13th.[34] After an operational halt on May 15th, during which the German high command regained its "nerves," the two panzer corps under Ewald von Kleist broke "clean through the French defense west of the Meuse" on May 14th and advanced rapidly toward the British Expeditionary Force and French

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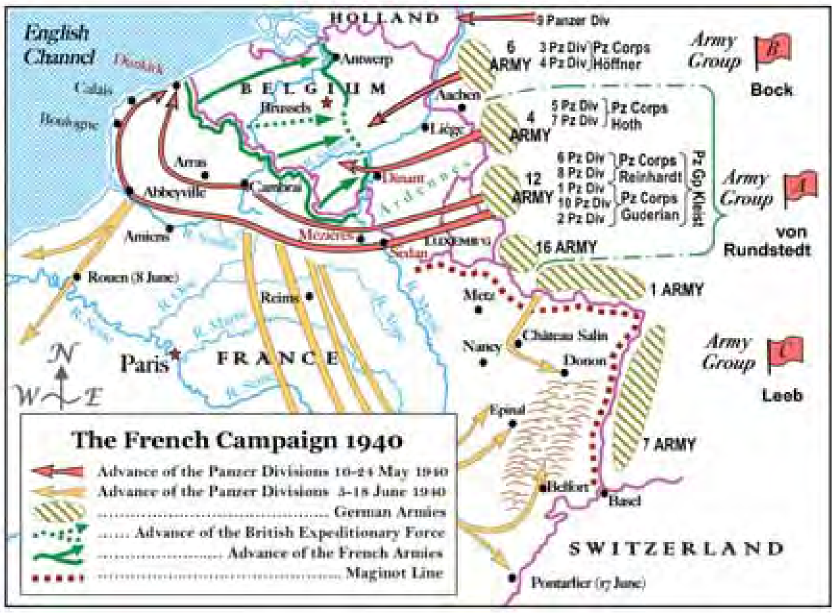
[34] Doughty, *The Breaking Point: Sedan and the Fall of France, 1940*, p. 100.

forces in Belgium.[35] By May 23rd, the leading panzer divisions were within 18 miles of Dunkirk, from which over 330,000 Allied soldiers escaped between May 26th and June 4th due, in part, to Adolf Hitler's decision on May 24th to give the Luftwaffe a chance to destroy the Allied forces trapped on the beaches around Dunkirk.[36]

Figure 7: France, May 1940[37]



The lopsided outcome of this campaign appears to have been almost as much of a surprise to most of the Germans as it was to the French and British. Heinz Guderian, who commanded one of the

35 Major General F. W. von Mellenthin, trans. H. Betzler, ed. L. C. F. Turner, *Panzer Battles: A Study of the Employment of Armor in the Second World War* (Norman, OK: University of Oklahoma Press, 1956), p. 16.

36 Charles Burdick and Hans-Adolf Jacobsen (eds.), *The Halder War Diary 1939-1942* (Novato, CA: Presidio, 1988), p. 165.

37 Murray estimates that Panzergruppe Kleist had about 40,000 trucks and armored vehicles, including 1,222 tanks—Williamson Murray, "May 1940: Contingency and Fragility of the German RMA" in MacGregor Knox and Williamson Murray, *The Dynamics of Military Revolution 1300-2050* (Cambridge, England: Cambridge University Press, 2001), p. 169.

three panzer corps in Army Group A, described his successful crossing of the Meuse at Sedan on May 13 as “almost a miracle,” and rightly so given what is now known of how narrow the margin of German success at this point was.[38] For present purposes the question at issue is the degree to which the actual outcome of the 1940 campaign can be satisfactorily explained by superior German numbers or technology.

Table 1: Allied-German Forces and Force Ratios, 1940[39]

May 10, 1940	Allies	Germans	Ratio
Manpower	3,368,000	2,758,000	1.22
Divisions	140	136	1.03
Armored Divisions	4	10	0.40
Tanks	4,098	3,227	1.27
Anti-tank Guns	8,832	12,800	0.69
Artillery	13,326	7,700	1.73
Armored Carriers	1,830	800	2.29
Mortars	11,912	14,300	0.83
Rifles	1,160,000	900,000	1.29
Machineguns	112,100	147,000	0.76
Aircraft	1,649	3,124	0.53
Anti-aircraft Artillery	4,232	8,700	0.49

Table 1 reveals that in terms of troop strength, total divisions, tanks, artillery, armored personnel carriers, and rifles, the Germans were numerically inferior. Only in armored divisions, anti-tank guns, mortars, machineguns, aircraft and AAA did the Germans enjoy numerical superiority at the theater level, and the average German advantage across these five categories was only about 1.6-to-1. Overall, therefore, the theater-level ratios do not appear to go very far in accounting for either the rapidity or the magnitude of the Allied disaster. It is simply not plausible to argue that superior German numbers ex-

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38 Robert A. Doughty, “Almost a Miracle,” *The Quarterly Journal of Military History*, Spring 1990, pp. 42-43.

39 Phillip A. Karber, Grant Whitley, Mark Herman, and Douglas Komer, *Assessing the Correlation of Forces: France 1940* (McLean, VA: BDM Corporation, June 18, 1979), BDM/W-79-560-TR, pp. 2-2 to 2-4. All ten of the German panzer divisions are identified in Figure 7.

plain the outcome. German inferiority in total tanks is especially telling in this regard.

Indeed, not only did the Allies enjoy nearly a 1.3-to-1 quantitative edge in tanks, but at least some of the Allied tanks were superior to the Germans'. The British Matilda "had stronger armor" and its 2-pounder was superior to the 37-mm gun on the German Mark III.[40] More than half of the German tanks were light Mark Is and Mark IIs, and the French had 1,800 heavy tanks, including the "Souma with the 47-mm gun and the Char B with heavy armor, a 75-mm hull gun, and a 47-mm turret gun," making the Char B possibly the best tank on any battlefield in 1940.[41] Thus, superior weaponry, like superior numbers, does not explain the catastrophic Allied collapse in the spring of 1940.

Again, the decisive period in this campaign was May 13-15, when the Germans got three panzer corps across the Meuse River and thereafter succeeded in breaking two of those corps into the open behind the defensive lines of the French. Of these critical few days Williamson Murray and Allan Millett have written:

> The real explanation for the catastrophe along the Meuse lies in the quality of German leadership, from generals to NCOs. . . . A relatively few individuals wearing field-gray uniforms, in a blood-stained, smashed-up, obscure provincial town, diverted the flow of history into darker channels. The tired, weary German infantry who seized the heights behind the Meuse and who opened the way for the armored thrust to the coast made inevitable the fall of France, the subsequent invasion of Russia, the Final Solution, and the collapse of Europe's position in the world.[42]

Murray and Millett also underscore "how slim the German margin of success actually was," and assess General Erwin Rommel's "performance on the banks of the Meuse as engineer, company commander, and division commander [of 7th Panzer] all rolled into one" as "one of

[40] F. W. von Mellenthin, *Panzer Battles*, p. 12.

[41] Corum, *The Roots of Blitzkrieg*, p. 203. Corum puts the tank balance in 1940 as approximately 3,000 Allied tanks opposing 2,200-2,800 German tanks (ibid.). These figures put the theater-level tank ratio at 1.07- to 1.36-to-1 in favor of the Allies as compared with the 1.27-to-1 in Table 1.

[42] Murray and Millett, *A War To Be Won*, p. 75.

the most inspired pieces of generalship of the whole war."[43] Nor should one ignore the extraordinary fact that in the initial crossings of the Meuse, German infantry continued fighting despite casualties "upward of 70 percent" in some companies.[44] At the same time, on the French side, there was also a fair degree of incompetence. For example, on May 13th, 1940, the commander of the French 2nd Army stated that "There are no urgent measures to take for reinforcement of the Sedan sector."[45] In hindsight, the "French would not have needed large forces to block the initial thrust across the Meuse, and change the entire course of the campaign." But, being *unaware* of their peril, they did not do so.[46]

The fall of France in 1940 is one of the most thoroughly documented and meticulously studied campaigns in military history. True, it is but one campaign out of many in recent centuries. Nevertheless, it offers scant encouragement, to put it mildly, for thinking that either superior numbers or superior weaponry drive combat outcomes most of the time—especially outcomes as unexpected and lopsided as the results of this campaign proved to be. In this instance at least, explanations of the outcome based on aggregate disparities in numbers or weapons at the theater level are simply not persuasive.

Might things look different if the level of analysis moves from the theater level to that of the German army groups? Again, the German plan was to focus the main effort in the center, through the Ardennes. The Germans concentrated 45 divisions there under General von Rundstedt, including seven of their ten panzer divisions, giving them a 3-to-1 advantage over the 15 divisions of the French 2nd and 9th Armies.[47] Given this numerical disparity, it is far more tempting to suggest that force ratios explain what happened. There are, however, two reasons for resisting this explanation.

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43 Murray and Millett, *A War To Be Won*, pp. 71, 73.

44 Knox and Murray, "Thinking about Revolutions in Warfare" in *The Dynamics of Military Revolution 1300-2050*, p. 12; see, also, pp. 169-173.

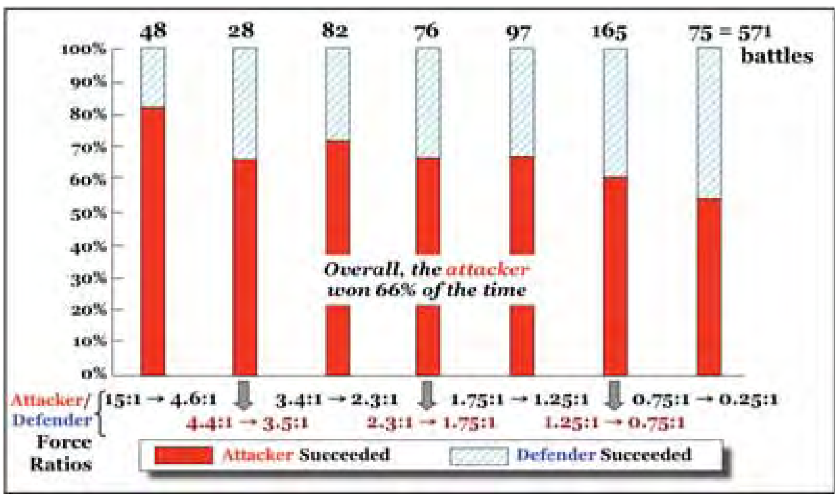
45 Cited in Richard O. Hundley, *Past Revolutions, Future Transformations* (Santa Monica, CA: RAND Corporation, 1999), p. 44.

46 Murray, "May 1940: Contingency and Fragility of the German RMA," p. 173.

47 Karber, et al., *Assessing the Correlation of Forces: France 1940*, p. 4-7.

First, when the von Rundstedt's panzers got to the Meuse, three of the six initial attempts to get across the river failed. In effect, at all six locations on the Meuse the "Germans faced a straightforward infantry river-crossing operation in which infantry and artillery (with air support when available) assaulted well-dug-in and well-sited enemy positions."[48] The Germans did get across, but the leadership of individuals such as Rommel and the willingness of German infantry companies to continue advancing despite heavy casualties was pivotal, and the Germans' 3-to-1 force-ratio advantage in the center does not provide any obvious explanation for these crucial facts. Suffice it to say that if von Kleist's panzer corps had taken a week to get across the Meuse, even the French commander, General Gamelin, might have managed to contain a German breakthrough in the center.

Figure 8: Force Ratios versus Battle Outcomes[49]



Second, there is a broader problem with force ratios as either a predictor or an explanation of battle outcomes. In 1993 Robert McQuie examined the relationship between force ratios and tactical success in 571 historical battles from 1600 through the early 1980s

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48 Murray, "May 1940: Contingency and Fragility of the German RMA," pp. 169-170.

49 Robert McQuie, "Force Ratios," *Phalanx*, June 1993, p. 27. Note that the force ratios for these battles were based on opposing troop counts. *Phalanx* is the journal of the Military Operations Research Society.

using a land-warfare database developed by Trevor Dupuy. The database spanned force ratios from 15-to-1 favoring the attacker to 4-to-1 favoring the defender. As Figure 8 indicates, however, the correlation between force ratios and attacker success was, at best, very, very weak:

> . . . no matter what the ratio, the percentage of successful attacks has been about the same. . . . Moreover, an overwhelming advantage, as measured by force ratios, had not always ensured a victory. At times an attacker has deployed a superiority of more than four times that of the defender and lost. At other times, he has deployed almost as high an advantage, but has won. There have even been times when, despite a huge preponderance of troops, 17 times the strength of the defender, an attacker has still lost. The basic pattern in the historical evidence shows almost no difference between the distribution force ratios in a successful attack and in a failure.[50]

What McQuie's analysis suggests is that having the bigger battalions at the start of the encounter does not generally provide the margin of victory when all is said and done. Put somewhat differently, quantitative input metrics such as force ratios do not provide much insight into how the engagement or battle will actually turn out in the real world. Nor do output metrics such as casualties fare any better than initial force ratios. In 1987 McQuie explored the relation between casualties and defeat in 80 battles from World War II during 1941-45 and the Arab-Israeli conflicts in 1967 and 1973.[51] Within these 80 battles, some "forces gave up with casualties less than 1/20 those of their opponent" while others "took more than ten times the casualties of the opponent before admitting defeat."[52] The variability of casualty ratios between the two sides in relation to defeat, then, was astonishingly wide across the 80 cases McQuie examined, and his bottom line was that "there seems to be no pattern of influence" between casualties, no matter how measured, and defeat: "battles have been

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50 McQuie, "Force Ratios," p. 27.

51 Robert McQuie, "Battle Outcomes: Casualty Rates as a Measure of Defeat," *Army*, November 1987, p. 32. As in his later analysis of force ratios, McQuie relied upon a historical database developed by Trevor Dupuy's Historical Evaluation and Research Organization.

52 McQuie, "Battle Outcomes: Casualty Rates as a Measure of Defeat," p. 32.

given up when casualties ranged from "insignificant to overwhelming."[53] Thus, even obvious output measures of the results of combat do not correlate well with winning or losing.

Consequently, it appears that the outcome of the German campaign in May 1940 is not a rare, isolated exception to the oft-presumed supposition that superior numbers usually prevail. But what about superior weaponry? Could one still argue that France in 1940 does not necessarily undercut the view that the better-armed side usually wins? Evidently not since the winning side in this instance was not technologically superior. Still, the question posed at the beginning of this section was about the *frequency* with which either numerical advantage or technological superiority decide combat outcomes at the tactical level. Addressing this residual question about how often more lethal or effective weaponry determines tactical outcomes requires the examination of additional data.

The best evidence comes from the realm of air-to-air combat between opposing fighters. First, there is a lot of comparable data from both actual and simulated air combat. Second, this is a category of modern combat that is highly dependent on technology, starting with the airplane itself. In fact, one is hard-pressed to suggest a *more* technologically dependent mission area. The outcomes of submarine-on-submarine encounters, for instance, appear comparably dependent on technology, but not substantially more so in any obvious respect. Fighter-against-fighter encounters, then, are as likely an area of combat as any in which one might expect technologically superior weaponry to dominate outcomes.

The available data, however, do not support the supposition that technological superiority drives outcomes in air-to-air encounters the majority of the time. To start with, consider the decisive engagements that occurred between US and opposing MiG fighters in Southeast Asia from December 1971 through January 1973, where a "decisive" engagement is one in which at least one American or enemy fighter was destroyed.[54] During December 1971-January 1973, there were 112 such engagements, all of which were carefully reconstructed and ana-

53 McQuie, "Battle Outcomes: Casualty Rates as a Measure of Defeat," p. 33.

54 MiG is the acronym for Mikoyan-Gurevich. Artiom Mikoyan and Mikhail Gurevich's famous aircraft design bureau was established in 1939.

lyzed by Project Red Baron III to determine why each loss occurred. The 112 decisive encounters resulted in the loss of 75 MiGs and 37 US aircraft.[55] What factor, or set of factors, might explain the majority of these losses? Red Baron III's evaluation was as follows:

> About 60 percent (67 of 112) of all US and enemy aircraft lost in combat were apparently unaware of the attack. An additional 21 percent (24 of 112) became aware of the attack too late to initiate adequate defensive action.[56]

In other words, in 91 of 112 decisive engagements (81.25 percent), the airmen shot down were either unaware of the attack prior to enemy ordnance hitting their aircraft, or else they only became aware when it was too late to avoid being hit by enemy gun fire or missiles. In only 21 of the 112 decisive engagements (18.75 percent) did Red Baron III event reconstructions offer any other immediate cause of being shot down than a breakdown of what the American fighter community later came to term "situation awareness" (or SA). What is SA? As articulated in the late-1970s and early 1980s within the USAF and USN fighter communities, it is the capability of opposing aircrews to develop and sustain accurate representations of where all the friendly and enemy aircraft in or near the combat arena are, what they are doing, and where they are likely to be in the immediate future.[57]

To be stressed is that an SA advantage is fundamentally a human factor. It is not driven by how well one's fighter can maneuver in the air-combat area, the lethality of one's air-to-air weapons, or, for that

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[55] *Project Red Baron III: Air-to-Air Encounters in Southeast Asia (U)*, Vol. III, Part 1, *Tactics, Command and Control, and Training* (Nellis Air Force Base, NV: US Air Force Tactical Fighter Weapons Center, June 1974), p. 49.

[56] *Project Red Baron III*, Vol. III, Part 1, *Tactics, Command and Control, and Training*, p. 61.

[57] S. R. "Shad" Dvorchak, "On the Measurement of Fog," slide presentation to the Military Operations Research Society, Washington, DC, June 1986, slide 9. By the time Dvorchak articulated this understanding of SA, he had been involved in the analysis of data from two major air-combat tests: the Air Combat Evaluation (ACEVAL), which had been flown with actual aircraft on an instrumented range at Nellis Air Force Base (AFB), NV, in the late 1970s, and the Advanced Medium-Range Air-to-Air Missile (AMRAAM) Operational Utility Evaluation (OUE), which was "flown" in simulators at the McDonnell-Douglas plant in St. Louis during the early 1980s.

matter, the numerical force ratio between the opposing sides. Instead, it appears to be fundamentally a cognitive function of the human participants inside the opposing fighters—specifically of their ability to synthesize fragmentary snippets of information into a coherent picture of what is taking place around them in a highly dynamic situation in which even momentary lapses or confusion can result in being shot down or killed. The fundamentally cognitive basis of SA does not, as will emerge later in this discussion, preclude exploiting advanced technology to facilitate being able to sustain an SA advantage over adversaries. But it is clearly not a direct function of platform performance, weapon lethality, or force ratios, as these technological and quantitative factors are generally understood.

The question that remain is whether this combat data from the final 13 months of major operations by US forces in Southeast Asia is reflective of air combat either before or since 1971-73. With regard to earlier air-combat experience, the available information is fragmentary at best, and does not approach the quality or comprehensiveness of the data cited from Red Baron III event reconstructions.[58] In fact, the few insights on how often a breakdown of SA was the immediate cause of being shot down by another fighter in World War II or Korea

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[58] Events 69 and 70 in Red Baron III, which both occurred on the afternoon of July 29, 1972, encompass three decisive engagements: two North Vietnamese MiG-21s were downed by USAF F-4s and one F-4 was lost to a MiG-21 (*Project Red Baron III: Air-to-Air Encounters in Southeast Asia*, Vol. I, *Executive Summary*, p. D-2). For a meticulous reconstruction of these events, see Todd P. Harmer and C. R. Anderegg, *The Shootdown of Trigger 4: Report of the Project Trigger Study Team* (Washington, DC: HQ USAF, April 2001). The Trigger study team was set up to resolve once and for all whether the F-4 loss in these events was to a MiG or to one of the F-4s involved. Its report reveals just how much information was available to reconstruct decisive encounters in the *Project Red Baron III* report. In this instance, aircrew tape recordings of intercom voice chatter inside individual F-4 cockpits, radio transmissions made and received, and cockpit warning tones were available from five of the F-4s involved. These recordings permitted the Trigger study team to reconstruct a timeline of events that synchronized actions taken by members of three different flights of F-4s (radio call-signs Cadillac, Pistol and Trigger) as well as transmission of information on MiG activity from Red Crown (the radio call-sign of the Navy Air Weapons Control in the Gulf of Tonkin). The point of this digression is that the underlying data on air-to-air engagements in Southeast Asia during this period is about as good as data from actual combat gets. Also worth noting is that the Trigger study team eventually confirmed Project Red Baron III's 1974 judgment that Trigger 4 was downed by a MiG-21, not by Cadillac 1.

are frankly anecdotal. Nevertheless, one can point to observations from combat pilots that certainly suggest losing SA was the most frequent cause of being shot down over Western Europe and on the Eastern Front during 1939-45.

In the spring of 1944, the US 8th Fighter Command in England published a (then) classified account of what its pilots had learned in the course of flying long-range escort missions for the 8th Air Force's heavy bombers. Starting in February, the 8th Army Air Force had been mounting increasingly heavy raids against targets in Germany as the Allies struggled, above all else, to achieve daylight air superiority prior to the planned Normandy landings. The document contains tactical observations from 25 of 8th Fighter Command's most successful fighter pilots. The eight highest-scoring individuals in this group were credited with a combined total of over 175 air-to-air kills. Hubert Zemke, who was, at the time, commander of the 56th Fighter Group, emphasized that ". . . few pilots are shot down by enemies they see [emphasis in original]."[59] Similarly, Mark Hubbard, commanding the 20th Fighter Group, noted that "90% of all fighters shot down never saw the guy who hit them [emphasis in original]."[60] Turning to the Eastern Front, the highest-scoring fighter ace of not only World War II but, with 352 kills, of all time was the German Me-109 pilot Erich Hartmann. After his return to West Germany following a decade as a Soviet prisoner of war, he stated that he was "sure that eighty percent" of the pilots he shot down never knew he was there before he opened fire.[61]

Again, these observations from the Second World War, while based on more total kills than Red Baron III's 112 decisive encounters, are less comprehensive and more anecdotal than the 1971-73 data

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[59] Major General W. E. Kepner, *The Long Reach: Deep Fighter Escort* (England: 8th Fighter Command, May 29, 1944), p. 33. Zemke is credited with 17.75 air-to-air kills.

[60] Kepner, *The Long Reach*, p. 11. Hubbard is credited with five air-to-air kills, but was missing-in-action when *The Long Reach* appeared.

[61] Raymond F. Toliver and Trevor J. Constable, *The Blond Knight of Germany* (New York: Ballantine Books, 1970), p. 173. In a later interview for the Navy Fighter Weapons School's journal, Hartmann stated that the percentage of his victims taken by surprise was 90 percent (*TOPGUN Journal*, Fall/Winter 1977, p. 8). Hartmann, like Chuck Yeager, had exceptional vision that usually enabled him to spot enemy planes long before his comrades (ibid.).

from Southeast Asia. Zemke, Hubbard and Hartmann were also talking about the era of propeller-driven fighters in which air-to-air kills were scored at close range with machineguns or cannons. Beyond-visual-range missile shots employing air-to-air radars were not then part of the fighter pilot's kit. Still their observations about the percentage of the time—80-90 percent—in which a breakdown of situation awareness was the immediate cause of fighter pilots being shot down by enemy fighters brackets the 81.3 percent reported by Red Baron III.

What about post-Vietnam evidence for this pattern? Some of the best data come from later simulations of air combat on either instrumented ranges or in flight simulators rather than actual combat. Nevertheless, tests such as the Air Combat Evaluation (ACEVAL) and the Advanced Medium-Range Air-to-Air Missile (AMRAAM) Operational Utility Evaluation (OUE) were carefully designed to yield statistically meaningful data on engagement outcomes.

ACEVAL was flown in 1977 using the Air Combat Maneuvering Instrumentation (ACMI) on the Nellis Air Force Base (AFB) range complex in Nevada, which data linked real-time information from all the aircraft involved to a ground station. The Blue Force consisted of either F-15s or F-14s armed with 20-mm guns, AIM-9L Sidewinders, and AIM-7F Sparrows; the opposing Red Force flew F-5Es, which simulated the Soviet MiG-21 in performance and size, with AIM-9Ls and a 23-mm gun.[62] The aim of the test was to evaluate the effects on engagement outcomes of different initial conditions and force-ratios.[63] The test matrix went from 1-versus-1 engagements (one Blue fighter against one Red fighter) to 4-versus-4, and included trials in which either Blue or Red had a 2-to-1 force-ratio advantage. Differences in

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[62] The radars and missiles used in ACEVAL were substantial improvements over those used during the final 13 months of major US operations in Southeast Asia. The AIM-7F was the first version of the Sparrow with reliable, solid-state electronics. The AIM-9L was the first all-aspect Sidewinder, meaning that its seeker was sensitive enough to permit nose-to-nose shots. And the F-15's look-down/shoot-down radar was a huge improvement over F-4 radars, which had severe clutter problems when trying to look down at a lower-altitude target. Indeed, the MiG-17 wagon-wheel tactic arose in SEA to exploit this vulnerability of the F-4.

[63] Colonel E. J. Griffith, Jr., "ACEVAL: Origin, Description, Results, Applicability," undated, Slide 2. Griffith was the Blue Force commander.

initial conditions had to do with whether one side or the other, or both, had ground controlled intercept (GCI) assistance. When all was said and done, the test matrix required 360 valid engagements involving 1,488 sorties. However, because both sides were required to visually identify their targets before "shooting," the rules-of-engagement (ROE) precluded BVR engagements.[64]

At the time, there was considerable controversy over ACEVAL's implications. The Blue Force commander, for example, insisted that the test covered no more than a tiny fraction of the broader domain of real-world aerial combat and even cautioned that the test objective of quantifying the influence of "numbers" on engagement outcomes had not only not been achieved, but was "probably an impossible task."[65] Nonetheless, when S. R. "Shad" Dvorchak reviewed the test in 1979, he observed that in the short term quantifiable variables such as numbers only accounted for about 10-20 percent of the variation in outcomes, whereas human factors had "more than five times the effect on results" compared to variables such as "force ratio or whether somebody does or doesn't have GCI."[66] Thus, tactical interplay between opposing pilots appeared to drive engagement outcomes five times as often as variables such as force ratios or GCI state, which mean that human factors dominated results 83-84 percent of the time. The correlation with earlier results in World War II and Southeast Asia results regarding SA is striking.

The AMRAAM OUE, which was "flown" in simulators at the McDonnell Douglas plant in St. Louis, Missouri, by operational aircrews from the Tactical Air Command (TAC) during the early 1980s only served to add additional support to Dvorchak's interpretation of the ACEVAL results. ACEVAL had been pretty much a within-visual-range (WVR) test because of the ROE that required visual identification of the target prior to shooting. But since the whole point of the ARMAAM OUE was to assess the utility of a medium-range air-to-air missile that could be shot BVR, half the test matrix permitted beyond-

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[64] Griffith, "ACEVAL: Origin, Description, Results, Applicability," Slide 3.

[65] Griffith, "ACEVAL: Origin, Description, Results, Applicability," Slides 12, 13.

[66] Lieutenant Colonel Dvorchak, "Getting It On in the All-Aspect Arena (U)," *Tactical Analysis Bulletin*, Vol. 79-2 (Special), July 25, 1979, pp. 3, 4. At the time Dvorchak was still on active duty and assigned to TFWC/OAA at Nellis AFB in the Tactical Fighter Weapons Center.

visual-range shots by the Blue force. Table 2 shows the complete test matrix for this test.

Table 2: AMRAAM OUE Test Matrix[67]

AIRCRAFT		F-15 & F-16 SEPARATELY															
WEAPON		AMRAAM								BASELINE							
GCI State		BENIGN				ADVERSE				BENIGN				ADVERSE			
ROE		WVR		BVR		WVR		BVR		WVR		BVR		WVR		BVR	
AVIONICS		SST	MTT	SST	MTT	SST	MTT	SST	MTT	SST	MTT	SST	MTT	SST	MTT	SST	MTT
CAP	2v2+4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	2v2+6	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	4v4+4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
SWEEP	2v2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	2v4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
EXCURSIONS		SCENARIO & NUMBER FLOWN VARIED, BUT APPROXIMATELY DOUBLED THE SIZE OF THE TEST															

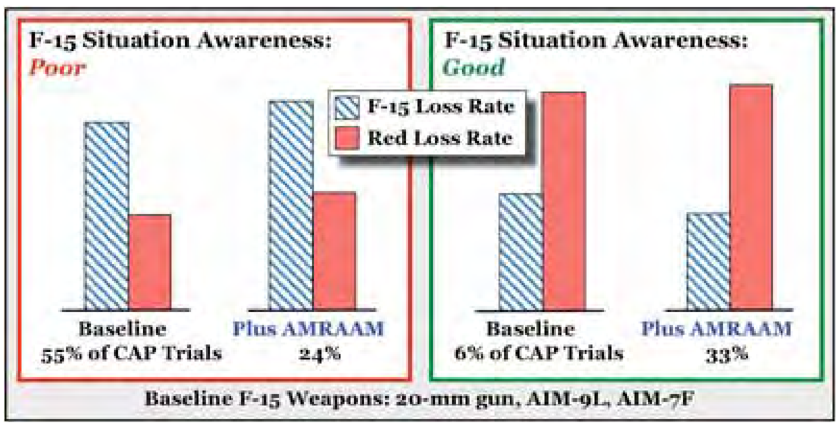
"Flying" the combat air patrol (CAP) and sweep portions of the test matrix with the F-15 required 5 x 64 = 320 valid trials involving 2,688 sorties. Repeating those parts of the matrix with the F-16 added another 320 trials and 2,688 sorties for a total of 640 trials and 5,376 sorties. Assuming the excursions in the bottom of matrix roughly doubled the actual test, then the AMRAAM OUE required around 1,200 valid trials and more than 10,000 sorties.

The expectation, of course, was that the AMRAAM, because of its advanced features and greater range relative to the AIM-7, would enable the Blue fighters to dominate outcomes in the BVR portions of the test, especially if they had multiple-target track (MTT) as opposed to single-target track (STT). Stated more bluntly, most of those involved in this test expected advanced technology—specifically the medium-range AMRAAM—to dominate outcomes. The results, though, turned out quite differently. Granted, when the "Blue Force" F-15s had AMRAAM on CAP missions as well as good situation awareness, they were able to achieve loss rates roughly half the Red side's in more than five times as many of the valid trials as in the baseline F-15 case

[67] Veda Corporation, "AMRAAM OUE Lessons Learned Briefing (U)," April 11, 1984, Slide 9. SST: single-target track; MTT: multiple-target track; CAP: combat air patrol; 2v2+4 means two Blue F-15s or F-16s versus two Red fighters escorting four Red strike aircraft.

without AMRAAM (compare the loss-rate bars in the right half of Figure 9). But when the F-15 pilots had poor SA, the Red side's loss rate was half that of the F-15s in the baseline case across 55 percent of the trials; adding AMRAAM was only able to reduce to 24 percent the portion of valid CAP trials in which Red enjoyed a similar advantage in lower loss rates (see the left half of Figure 9). In neither the "poor" nor "good" SA cases in Figure 9 did possession of AMRAAM appear to have a large influence on Blue-versus-Red loss rates.

Figure 9: F-15 versus Red Loss Rates (CAP Mission) by SA and Weapons[68]



What these data highlight, then, is that, even in the AMRAAM OUE, situation awareness, rather than hardware differences such as having AMRAAM, dominated outcomes just as it had in ACEVAL and Southeast Asia during 1971-73. To recall perhaps the overriding "lesson" of this test:

> SITUATION AWARENESS IS THE SINGLE MOST IMPORTANT FACTOR IN DETERMINING OUTCOME—REGARDLESS OF

[68] S. R. "Shad" Dvorchak, "On the Measurement of Fog," presentation to the Military Operations Research Society, Washington, DC, June 1986, Slide 10. At the time, the actual loss rates were classified, which is why they are not quantified except relative to one another in the figure.

AIRCRAFT, AVIONICS, WEAPON ENVIRONMENT, OR OTHER TEST VARIABLE.[69]

There is another piece of evidence from air-to-air combat to consider before concluding that engagement outcomes have rarely been the result of superior hardware (or numbers), and that these factors are unlikely to dominate outcomes in the future. In 2005 the Air Force's latest air-superiority fighter, the F-22 Raptor, completed its initial operational test and evaluation (IOT&E). The IOT&E included engagements flown on an instrumented range at Nellis AFB as well as more complex scenarios "flown" in simulators at the Lockheed Martin plant in Marietta, Georgia. While the details of this evaluation have not yet been made public, all indications are that the Raptor was able to dominate opposing fighters the vast majority of the time, even when outnumbered. By and large, the F-22 pilots were usually able locate, target and "kill" opposing F-15s and F-16s BVR before the pilots of the older fighters were able detect them. By the end of the IOT&E, participating pilots "raved" about the Raptor being "a huge leap over the time-tested" F-15.[70] The question is: do these impressive results constitute a case in which a new fighter is so overwhelming that hardware alone, rather than human factors such as SA, determined most engagement outcomes? Has the F-22 provided a counterexample to the evidence from prior air-to-air experience—from World War II to the AMRAAM OUE and even Desert Storm—that SA most often drives results?[71]

Upon close examination, the answer is "No." On the one hand, the Raptor's low observability (which, when coupled with sound tactics, resulted in stealth), ability to cruise at Mach 1.5 or above without afterburners ("supercruise"), and advanced avionics (including an active electronically scanned array [AESA] radar and advanced sensor fusion) generally allowed the Raptor pilots to kill their opponents from a distance without being detected. On the other hand, these ad-

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[69] Veda, "Man in the Loop Lessons Learned," March 1985, Slide 1.

[70] John A. Tirpak, "The F/A-22, in Fire and Flak," *AIR FORCE Magazine*, February 2005, p. 33.

[71] No systematic effort to assess the role of SA during Desert Storm was made, in no small part because the USAF F-15C community, which scored 30 of the Coalition's 38 kills, was absolutely convinced that SA was king. However, even a casual review of the decisive engagements tends to reinforce this view.

vanced platform features can—and should—be viewed as explicitly exploiting technology to give Raptor pilots the wherewithal to achieve huge margins of SA advantage most of the time. In this regard, Dvorchak has noted that, in the wake of the AMRAAM OUE and one later test on multi-sensor integration, achieving superior SA was one of the overriding objectives underlying the design of the F-22 from the outset.[72] Seen in this light, the F-22's overwhelming superiority in the IOT&E does not argue that aircraft technology as traditionally understood—thrust-to-weight ratio, turn rates, specific excess power, avionics performance, weapons, etc.—generally determine tactical outcomes. Instead the F-22's success reaffirms that human factors, notably SA, most often determine who wins and who loses in aerial combat—especially when technology is harnessed to enhance SA.

The case of F-22 IOT&E is especially revealing with respect to another question: Is there evidence that SA is as important in ground combat as it remains in air-to-air engagements? Two data points should suffice to provide a positive answer to this question. The first is anecdotal and concerns the situation awareness needed to sense the likelihood of insurgent ambushes or attacks in urban settings in occupied Iraq after the summer of 2003. By 2005 American commanders had come to realize that "an Iraqi soldier—even one who was overweight and undertrained—was more effective standing on an Iraqi street corner than the most disciplined U.S. Army Ranger."[73] As General John Abizaid, then commander of U.S. Central Command, put it: "They sense the environment in a way that we never could."[74]

The second data point is more comparable to a formal test such as the F-22 IOT&E and stems from evaluation of the US Army's Stryker Brigade Combat Team (BCT). The basic idea behind this medium-weight unit was to integrate digital communications networks and command systems with a wheeled infantry-carrier vehicle (Stryker) and a new organizational structure in order to "gain and exploit an information advantage" through a network-centric ap-

[72] S. R. Dvorchak, telephone conversation with the author, March 9, 2006.

[73] Thomas E. Ricks, *Fiasco: The American Military Adventure in Iraq* (New York: Penguin Press, 2006), p. 416.

[74] Ricks, *Fiasco*, p. 416.

proach.[75] Organizationally, the Stryker BCT included a reconnaissance, surveillance, and target-acquisition (RSTA) squadron, a military intelligence company, and other features that made it capable of generating its own situational awareness and quickly fusing this data so as to be able "to act decisively" against enemy weapons before they could close to ranges at which the Stryker's light armor would be vulnerable.[76] The Army hoped that networking would enhance both lethality and survivability.

The first empirical test of the Stryker concept came in a certification exercise (CERTEX) and Operational Evaluation (OPEVAL) that took place at the Joint Readiness Training Center (JRTC) in May 2003.[77] Because no predecessor medium-weight unit existed in the Army force structure, RAND's analysis of the CERTEX elected to compare the Stryker BCT's performance at the JRTC in a small-scale contingency scenario with that of a nondigitized light-infantry brigade.[78] Based on this comparison, RAND researchers concluded that the Stryker brigade was an order-of-magnitude more effective than the predecessor light infantry brigade as measured by Blue-Red casualty ratios.[79] This outcome provides further empirical support for the view that SA is just as dominant a factor in ground engagements as it is in air-to-air combat.

Before turning to one final historical case in which neither larger numbers nor more effective weaponry explains the results of combat, some clarifications may help to avoid misunderstanding. The claim for which this discussion has been marshalling evidence is *not* that neither bigger battalions nor better weapons *ever* drive outcomes. In the case of Red Baron III's 112 decisive engagements, for instance, the possibility remains open that either or both of these traditional factors provided the margin of victory in as many as 21 (18.75 percent) of the

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75 Daniel Gonzales, Michael Johnson, Jimmie McEver, Dennis Leedom, Gina Kingston, and Michael Tseng, *Network-Centric Operations Case Study: The Stryker Brigade Combat Team* (Santa Monica, CA: RAND, 2005), p. xiii.

76 Gonzales, et al., *Network-Centric Operations Case Study*, pp. xiii-xiv, xvii-xviii.

77 Gonzales, et al., *Network-Centric Operations Case Study*, p. 57.

78 Gonzales, et al., *Network-Centric Operations Case Study*, p. xviii.

79 Gonzales, et al., *Network-Centric Operations Case Study*, pp. 104-106.

encounters. Again, if all other things are equal—or if the opposing combatants are too dull, too exhausted, too stunned, too distracted, too confused, too ill-trained, or just too unimaginative to exploit the asymmetries that do exist—then it is entirely plausible that greater numbers or better hardware will prevail. The question at the beginning of this section, however, was about the *frequency* with which superior numbers or superior hardware do so. The answer that emerges from reviewing modern battles such as France in 1940, older historical battles going back centuries, and a fair amount of data from the air-combat area is clear: not very often.

With these clarifications in mind, the argument of this section will conclude with a brief examination of how and why a relatively tiny band of Spanish soldiers under Francisco Pizarro were able to overthrow the Inca empire during the 1530s. This last historical example of neither vastly greater numbers nor superior technology adequately explaining tactical combat outcomes has been deferred to this point in the discussion due to the character of the historical evidence. The conquest of the Incas is distant in time and our understanding of why the Spaniards proved so superior in battle to native American fighters relies mainly on anecdotal accounts written long after the pivotal battles.

The first major test of arms between the two sides came at Cajamarca on November 16, 1532. Some first-hand reports of this encounter and subsequent events during the conquest were written by Spanish participants, including Pizarro's half brother Hernando and his secretary Francisco de Xerez, before the total subjugation of Peru was completed in 1539; the more comprehensive histories of the Inca empire and its conquest, though, were not written until the 1550s.[80] If these various sources are taken more or less at face value, then the basic facts regarding what happened at Cajamarca are as follows.

[80] Francisco Pizarro could not write. One of the earliest accounts of the encounter at Cajamarca is a letter Hernando Pizarro wrote to the Royal Audience of Santo Domingo on November 23, 1533. Francisco de Xerez's account of the conquest was published in 1534. The early chroniclers of the Incan empire and its subjugation by the Spanish include Pedro de Cieza de León's *The Discovery and Conquest of Peru* and Juan de Betanzos' *Narrative of the Incas*, both of which were written in the 1550s.

The conquest began with an ambush of the Inca ruler, Atahualpa, and his bodyguard in a square some 200 yards on a side, enclosed by long, low buildings on three sides and an earthen wall on the fourth.[81] Within this square, Pizarro's conquistadors numbered only some 60 on horses and just over 100 on foot; opposing them were an estimated 5,000-6,000 natives of the Inca's bodyguard, which meant that the Incas outnumbered Pizarro's small force within the square by at least 30-to-1.[82] On the surrounding plain, beyond the square, lay Atahualpa's army of at least 40,000 effectives (and possibly twice that number), fresh from a series of crushing victories over Atahualpa's brother Husacar to determine which of them would succeed their father, Huayna-Capac, as the absolute ruler of the Inca empire.[83] Overall, then, the Spaniards were outnumbered more than 200-to-1 at Cajamarca.

The Europeans, of course, were better armed. They had steel swords, steel-tipped lances, and gunpowder weapons (arquebuses and four small cannons); they also had steel armor, which made them almost invulnerable to the Incas' weapons, and horses, which the Incas at Cajamarca had not previously encountered in battle. By contrast, Atahualpa's men marched into the ambush unarmed except for small battleaxes, slings and pouches of stones.[84] Further disadvantaging the

[81] John Hemming, *The Conquest of the Incas* (New York: Harcourt Brace & Company, 1970), pp. 37-38. Hemming's book is perhaps the most detailed and comprehensive single work on the Incan conquest available in English. *The Conquest of the Incas* improves upon W. H. Prescott's 1847 *History of the Conquest of Peru*. Hemmings' research, which included sources not available to Prescott, was also informed by a year of traveling to all parts of Peru, visiting most of the known Incan sites. He also did his own translations from original Spanish sources (ibid., p. 547).

[82] John F. Guilmartin, Jr., "The Cutting Edge: An Analysis of the Spanish Invasion and Overthrow of the Inca Empire, 1532-1539," in Kenneth J. Andrien and Rolena Adorno, *Transatlantic Encounters: Europeans and Andeans in the Sixteenth Century* (Berkeley, CA: University of California Press, 1991), p. 46.

[83] Hemming, *The Conquest of the Incas*, pp. 28-29, 36.

[84] Hemming, *The Conquest of the Incas*, p. 39. While sling stones may not sound like an impressive weapon today, "they were capable of shattering a horse's thigh or snapping a sword blade in two with a square hit at short range," and the Spanish in Peru feared these missiles as they feared no other indigenous weapon, probably because of their randomness (Guilmartin, "The Cutting Edge," p. 52).

Amerindians, the Inca Atahualpa had mistakenly concluded that this handful of Spaniards, whom he understood to be men rather than gods, posed no serious threat, and he eventually chose, based primarily on information from his emissary Ciquinchara, to approach the face-to-face encounter with Pizarro as a ceremonial parade on the assumption that the foreigners were fully within his power to kill or enslave.[85]

By the time the Incas began entering the square at Cajamarca, Pizarro had concealed his entire force, including the horses, in the surrounding buildings with strict orders not to attack until Pizarro gave the signal. As Hernando Pizarro wrote of the ensuing encounter a year later:

> When Atahualpa had advanced to the centre of an open space, he stopped, and a Dominican friar, who was with the Governor [Francisco Pizarro], came forward to tell him . . . that he was sent to speak with him. The friar then told Atahualpa that he was a priest, and that he was sent there to teach the things of the faith if they should desire to be Christians. He showed Atahualpa a book . . . and told him that that book contained the things of God. Atahualpa asked for the book, and threw it on the ground, saying: "I will not leave this place until you have restored all that you have taken in my land. I know well who you are and what you have come for." Then he rose up in his litter and addressed his men, and there were murmurs among them and calls to those who were armed. The friar went to the Governor and reported what was being done and that no time was to be lost. The Governor sent to me; and I had arranged with the captain of the artillery that, when a sign was given, he should discharge his pieces, and at that, on hearing the reports, all the troops should come forth at once. This was done, and as the Indians were unarmed they were defeated without danger to any Christian. Those who carried the litter and

[85] Pedro de Cieza de León, ed. & trans. Alexandra Parma Cook and Noble David Cook, *The Discovery and Conquest of Peru: Chronicles of the New World Encounter* (Durham, NC: Duke University Press, 1998), pp. 197-98, 209; Juan de Betanzos, trans. & ed. Roland Hamilton and Dana Buchanan, *Narrative of the Incas* (Austin, TX: University of Texas Press, 1996), pp. 247-50, 258-60.

> the chiefs who surrounded Atahualpa were all killed, falling round him.[86]

Atahualpa himself was captured by Francisco Pizarro, and the various first-hand accounts indicate that, in the square at least, "no Indian raised a weapon against a Spaniard."[87] Instead, a portion of Atahualpa's bodyguard broke out of the square through a six-foot-thick earthen wall with the Spaniards in hot pursuit. The slaughter evidently continued into the darkness of early evening, and at least one participant reported that horsemen under Hernando de Soto rode out in the aftermath of the ambush more than once and continued the slaughter until midnight.[88] While not a single Spaniard was killed, estimates of the Incas' losses made at the time start at about 2,000 dead in the square, ignoring wounded, and in later accounts run as high as 8,000.[89]

How was such a one-sided outcome possible? In his highly regarded *Guns, Germs, and Steel*, Jared Diamond concluded in 1997 that the Spanish victory in the face of "enormous numerical" inferiority is explained by the conquistadors' superior "military equipment," including their horses as well as steel swords, armor and guns.[90] His assessment, however, seems to be based on little more than the bare force ratio, which he presents as 168 Spaniards versus 80,000 Incas. Diamond's account mentions virtually none of the contextual factors affecting the outcome, such as the fact that at Cajamarca the Amerindians in the square did not, according to Spanish witnesses, fight back, but only tried to escape their foes. Surely Atahualpa's wildly mistaken estimate of the threat the Spanish posed, his ongoing con-

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[86] Hernando Pizarro, "Letter to the Royal Audience [Oidores] of Santo Domingo," Panama, November 23, 1553, in Clements R. Markham (trans. & ed.), *Reports on the Discovery of Peru* (London: Hakluyt Society, 1872), pp. 113-127 (available online at <http://www.shsu.edu/~his_ncp/Pizarro.html>).

[87] Hemming, *The Conquest of the Incas*, p. 43. Hemming cites Xerez on the lack of resistance from Atahualpa's body-guard (ibid., p. 551).

[88] Hemming (citing Pedro Cataño), *The Conquest of the Incas*, p. 551.

[89] Reportedly only three Spanish eyewitnesses attempted an estimate of the Inca dead at Cajamarca, and those estimates tended to climb with the passage of time (Hemming, *The Conquest of the Incas*, p. 551).

[90] Jared Diamond, *Guns, Germs, and Steel: The Fates of Human Societies* (New York: W. W. Norton, 1997), pp. 74-75.

cerns over the political ramifications of the civil war with his brother, the shock of seeing gunfire and horsemen in action for the first time, and the surprise of being suddenly caught by Pizarro's ambush go much further in explaining the slaughter that occurred inside the square than the superiority of steel weapons over maces and bronze or stone clubs. Similarly Atahualpa's abrupt capture offers a more convincing explanation for the lack of coherent resistance outside the square than the inferiority of Inca weaponry.[91]

Up to a point, even Diamond appears to agree with these objections to his explanation of why the Spanish prevailed so overwhelmingly in this encounter. The "novelty," he concedes, "of horses, steel weapons, and guns undoubtedly paralyzed the Incas at Cajamarca."[92] Nevertheless, he goes on to argue that in the four main battles during Pizarro's drive to the Inca capital of Cuzco in 1533, during which the Incas did fight back, small numbers of Spanish horsemen ranging from as few as 30 to as many as 110 were still able to defeat "thousands or tens of thousands of Indians"; moreover, the two later rebellions by the natives, though well-prepared and large-scale, also "failed because of the Spaniards' far superior armament."[93]

The fighting at Vilcaconga on the afternoon of November 8, 1533, is particularly instructive. This encounter took place almost a year after Cajamarca. Instead of the Spanish surprising the Incas, some 3,000-4,000 natives ambushed 70 mounted Spaniards under Hernando de Soto. The Spanish and their horses were exhausted when the Incas suddenly began hurling stones on them from above, and the fighting took place on the western slope of the Vilcaconga pass, which

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[91] Toward the end of July 1533, before setting off for Cuzco in search of more gold and silver, the Spaniards strangled Atahualpa in the ill-fated plaza at Cajamarca.

[92] Diamond, *Guns, Germs, and Steel*, p. 75.

[93] Diamond, *Guns, Germs, and Steel*, pp. 75-76. "When Manco Inca's armies attacked Cusco [Cuzco] in early May of 1536, his generals commanded a host variously estimated at from 100,000 to 400,000 by contemporary observers; the Spanish defenders of the city at that point numbered 190, only 80 of them mounted, yet they successfully held the city for almost a year; they did have the help of Indian allies, but these seem to have been considerably less numerous than the besiegers" (Guilmartin, "The Cutting Edge," pp. 46-47).

climbs to an altitude of some 12,000 feet above sea level.[94] During this engagement, the Incas for once "caught the Spaniards in hand-to-hand fighting"—the only form of battle the Amerindians knew well—and managed to kill five or six of the Spaniards by splitting their heads open with clubs, maces or battle axes as well as kill two horses.[95] By the time the fighting ended with an attempt by de Soto to lure the Indians off the slopes onto level ground, the Spanish had suffered eleven other men wounded along with fourteen wounded horses in addition to the men and horses killed.[96] Both sides then bedded down for the night, but the arrival of an additional 40 horsemen around one o'clock the next morning restored the morale of de Soto's force, and, at dawn, the "jubilant Spaniards formed a battle line and advanced up the hillside," causing most of the Incas to flee and killing any who remained on the slope.[97]

This battle, along with the two Spanish victories that preceded it at Jauja and Vicashuaman and the subsequent Inca defeat at the pass above Cuzco, "demonstrated the immense superiority of mounted, armoured Spaniards" over Inca warriors.[98] In light of the Spaniards; tactical superiority, John Guilmartin has concluded that "the estimate by John Elliott that a combined Spanish force of as few as fifty infantry and cavalry could hold out against any number of Amerindians on level terrain unless overcome by sheer fatigue seems entirely reasonable."[99] If nothing else, this judgment offers a strong counterexample to the view that the bigger battalions prevail most of the time. In Mexico and the Andes, native numerical superiority almost never provided the margin of victory. Guilmartin, however, does not believe for

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94 Hemming, *The Conquest of the Incas*, pp. 562-63. Hemming notes that there were "various good descriptions" of this important battle, the earliest of which was a May 1534 dispatch (ibid., p. 562).

95 Hemming, *The Conquest of the Incas*, p. 107; Cieza de León, *The Discovery and Conquest of Peru*, p. 290.

96 Hemming, *The Conquest of the Incas*, pp. 107-108.

97 Hemming, *The Conquest of the Incas*, p. 108.

98 Hemming, *The Conquest of the Incas*, p. 110.

99 John F. Guilmartin, Jr., "The Military Revolution: Origins and First Tests Abroad," in Clifford J. Rogers (ed.), *The Military Revolution Debate: Readings on the Military Transformation of Early Modern Europe* (Boulder, CO: Westview Press, 1995), p. 310.

a second that European tactical superiority can be explained, as Diamond would have it, strictly by the possession of better weaponry. Horses, for example, certainly helped the conquistadors in the Andes, but, regarding firearms, Guilmartin argues that "the Spanish could probably have overthrown the Incas without gunpowder."[100]

There can be no doubt of the crushing tactical superiority of Spanish infantry and cavalry in the 1500s relative to the indigenous armies of the Amerindians, both in Mexico and Peru. But if technology cannot adequately explain this superiority, what might provide a fuller understanding of the basis of the Europeans' tactical dominance? One part of the answer surely lies in the developments that took place in European military affairs during the decades preceding the New World conquests. Even if the conquistadors were not professional soldiers in a modern sense, they "surely knew of the dramatic changes in the art of war forged by Gonsalvo de Córdova and his successors; by the time of the battle of Ravenna in 1512, Spanish infantry were fighting in balanced formations of shock and shot."[101] Moreover, Pizarro's men, like those who served under Hernán Córtes in Mexico,

> were the products of a society which had internalized military skills and values to a remarkable degree. Individualist to a fault, they understood the value of proper subordination and coordination in battle; factious in victory, they hung together in combat with instinctive cohesion. Though they were not organized in any formal military structure, in combat they were soldiers rather than warriors. An observation concerning the division of booty makes the point: the owners of the horses received a larger share than footmen, but rider and owner were not necessarily one and the same. That the owner of a horse would yield his place in the saddle at the moment of combat to a better horseman who fought to receive a footman's share of the booty speaks volumes for Spanish priorities and competence.[102]

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[100] Guilmartin, "The Military Revolution: Origins and First Tests Abroad," p. 312. However, Guilmartin doubts that the conquistadors under Hernán Córtes could have survived in Mexico without firearms.

[101] Guilmartin, "The Military Revolution," p. 312.

[102] Guilmartin, "The Military Revolution," p. 312.

Again, this discussion has sought to reach an understanding of how frequently or infrequently the bigger battalions or better weapons determine tactical outcomes. The evidence from the Andes in the 1530s, while not nearly as unimpeachable as the carefully analyzed data from Vietnam during 1971-73 or the AMRAAM OUE, provides further support for the conclusion that numerical and technological advantages do not generally provide the margin of success in tactical outcomes. Greater numbers and better weaponry can help, but they are *rarely* as important as the sorts of human factors reflected in situation awareness and small-unit cohesion. This conclusion appears to hold even when the force-ratio disparities or the technological gradients are huge as they were during the conquest of the Incas.

The case of the Spanish in Peru suggests a further conclusion: that some societies may be better than others at waging war due to underlying cultural traditions and experiences. This view is the principal claim of Victor Hanson's insightful (but politically incorrect) *Carnage and Culture*, which appeared in 2001. His central argument is that the "Western military tradition of freedom, decisive battle, civic militarism, rationalism, vibrant markets, discipline, dissent, and free critique," which began with the Greek city states but was not lost after the fall of Rome, lies at the heart of understanding the emergence of European military preeminence in the 16th century.[103] On this analysis, the steepest gradient the Incas faced in the 1530s was developing balanced formations with enough tactical cohesion to withstand the shocks and stresses of close combat against determined, cohesive adversaries. The small-unit cohesion and group coherence in adverse circumstances that the Spaniards exhibited routinely and instinctively does not appear to have been present in Inca society. As a result, Pizzaro's men in the Andes, like Cortés' in Mexico, slaughtered the Amerindians in a form of "decisive battle that was largely outside their cultural experience."[104] In the Andes during the 1530s, valuing the "group over the single warrior" and being able "to march in order, to stab, thrust, or shoot en masse and on command, and to advance and retreat in unison," were beyond even the bravest of Inca warriors.[105]

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[103] Victor Davis Hanson, *Carnage and Culture: Landmark Battles in the Rise of Western Power* (New York: Doubleday, 2001), pp. 18, 168.

[104] Hanson, *Carnage and Culture*, p. 83.

[105] Hanson, *Carnage and Culture*, p. 446.

There is an important caveat that needs to be appended to the analysis presented in this section. The perceptive reader will have noticed that the data and examples offered to dispute the popular belief that bigger battalions, better weapons, or some combination of the two drive engagement outcomes have focused mostly on *tactical* interactions. What about *operational* or *strategic* outcomes? In particular, does superior situation awareness dominate operational outcomes in the same direct way as tactical interactions? The answer appears to be "No" for two reasons. First, tactical responses are tightly constrained by the laws of physics, spatial and temporal relationships, platform and weapon characteristics, and other related factors. These constraints greatly limit viable responses. In the case of air-to-air combat between opposing fighters, for example, the entire list of basic maneuvers is short and finite.[106] By contrast, viable military responses to operational-strategic problems—especially solutions that are likely to harmonize ends and means—must take into account the broader political and strategic contextual aspects of each individual situation. In other words, operational-strategic "architects" must consider a vastly larger, if not unbounded, solution space of much greater dimensionality than tactical "craftsmen."

Second, there is growing evidence that the cognitive requirements for designing and executing successful operations are qualitatively different from those underlying tactical success. Shimon Naveh, a former brigade and division commander in the Israeli Defense Forces (IDF), laid out the theoretical case for these differences in the mid-1990s.[107] Since then, the development and application of techniques based on recognition of a "distinctive operational cognition" have been credited with enough success in IDF operations to provide empirical support for Naveh's theory.[108] Not only does it explain why

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[106] Few, if any, fundamentally new basic fighter maneuvers have been discovered since John R. Boyd provided an exhaustive survey in his *Aerial Attack Study*, which was first published by the USAF Fighter Weapons School in early 1960 and revised in 1963.

[107] Shimon Naveh, *In Pursuit of Military Excellence: The Evolution of Operational Theory* (London & New York: Frank Cass, 1997), pp. 2, 8-14. While this book did not appear until 1997, Naveh had completed the dissertation on which it is based in 1994.

[108] During a May 2006 visit to Naveh's Operational Theory Research Institute, which is part of the IDF, the author was able to discuss specific instances of successful operations with three current Israeli commanders who had been

even a high degree of tactical virtuosity does not guarantee operational success (as the Germans discovered in World War II), but it suggests why "attrition, in the operational context, will not defeat the opponent, even if overwhelming quantities of force are concentrated and wasted at a rate lower than that suffered by the opposing force."[109] Thus, there are substantial reasons for thinking bigger battalions, better weapons, or combinations of both, may be even less dominant at the operational level than they have been in tactical interactions.

The Problems of Recognizing Revolutionary Change

Chapter I clearly implied the judgment that the growing maturity of guided munitions either already have brought about, or are on the brink of bringing about, revolutionary change in the conduct of war. The Ogarkov quote at the beginning of this chapter even suggests a criterion—reconnaissance-strike complexes (RUKs) approaching the effectiveness of nuclear weapons—by which such change could be recognized. Nevertheless, the fact that guided munitions have been "emerging" since the 1940s also suggests a serious categorization problem. If it has already taken five or six decades for these weapons and their associated sensor-and-targeting networks to begin exerting unmistakable changes in how wars are fought by technologically advanced militaries—notably those of the United States—then perhaps it would be more sensible to categorize what has occurred so far as *evolutionary* rather than *revolutionary* change.

As it turns outs, the difficulties of reaching anything approaching an unimpeachable judgment as to whether the emergence of guided munitions over a time-span of at least a half century constitutes a revolutionary change in military affairs—to use the term Andrew Marshall introduced to such debates in the summer of 1993—is just the tip of the iceberg.[110] There is virtually no field of human endeavor in

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trained in OTRI's *systemic operational design* practices and then applied them in the actual operations.

[109] Naveh, *In Pursuit of Military Excellence*, pp. 23, 128-150.

[110] Andrew W. Marshall, "Some Thoughts on Military Revolutions," memorandum for the record, OSD/NA, July 27, 1993, p. 2. This document is the initial version of the August 23, 1993, memorandum of the same title quoted at the beginning of this chapter.

which we possess precise, unambiguous, cut-and-dry criteria for distinguishing evolutionary from revolutionary change. The term *revolution* has increasingly come to be applied to seemingly dramatic, discontinuous changes in almost every major field of human endeavor. Today one regularly encounters references to and discussions of economic, political, cultural and scientific revolutions, among others. Quantum electrodynamics (the strange theory of light and matter),[111] the industrial revolution of 1750-1880, the American political revolutions of 1776 and 1787,[112] and the advent of atomic weapons in 1945 are frequently cited examples. Consider, for example, the most profound difference between the physics Isaac Newton advanced in his 1687 *Philosophiæ Naturalis Principia Mathematica [Mathematical Principles of Natural Philosophy]* and quantum electrodynamics or QED. Newton's physics was strictly deterministic whereas QED is not. The "laws of quantum mechanics are basically statistical" whereas those of classical physics are not.[113] Given a difference this fundamental, it is easy to appreciate why, during the 1920s, physicists came to see quantum mechanics as a revolutionary departure from classic Newtonian theory. The same, of course, came to be said of Albert Einstein's insight in 1905 that, because the speed of light in a vacuum is the same for all observers (299,792,458 meters/second),

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[111] Quantum electrodynamics (QED) describes the interaction of light and matter. QED is an extraordinarily well-confirmed theory. As Richard Feynman observed in 1985, during the first fifty years after its development "*no significant difference* between experiment" and QED had emerged—Richard P. Feynman, *QED: The Strange Theory of Light and Matter* (Princeton, NJ: Princeton University Press, 1985), p. 7. Yet, as Feynman himself has also observed, QED is so strange, so contrary to our everyday experience, that even *he* would not claim to understand why nature behaves in the way implied by quantum theory (ibid., pp. 9-10).

[112] The first American revolution began with a declaration of independence from Britain in 1776, and it became both a political and military revolution. Realization of the declaration of independence by the American colonies came seven years later, when England recognized the independence of its former colonies in the 1783 Treaty of Paris. The second American revolution, which was entirely political, was embodied in the constitutional convention of 1787 and the US Constitution's subsequent ratification. This revolution produced a strong federal government by early 1789 even though the thirteenth state to ratify the new arrangement, Rhode Island, did not do so until 1790.

[113] Werner Heisenberg, "The Development of Quantum Mechanics," Nobel Lecture, December 11, 1933, *Nobel Lectures, Physics 1922-1941* (Amsterdam: Elsevier Publishing Company, 1965), p. 299; available online at <http://nobelprize.org/physics/laureates/1932/>.

observations of length and time by different observers depend upon, or vary with, their relative motion.[114] Einstein's special theory "relativized" the absolute space and time of Newtonian mechanics and, as early as 1912, was described by a recent Nobel laureate in physics, as "one of the most significant accomplishments ever achieved in theoretical physics."[115]

As used in the preceding paragraph, the term *revolution* refers to leaps or giant steps forward that imply "a break in continuity, the establishment of a new order that has severed its links with the past, a sharply defined cleavage between what is old and familiar and what is new and different."[116] Especially since the appearance in 1962 of Thomas Kuhn's influential but controversial book, *The Structure of Scientific Revolutions*, this meaning has become the widely accepted, contemporary interpretation of the term.[117] It is also the core meaning that will be presumed throughout this report as a working definition.

Kuhn's basic argument was that while scientific research *normally* takes place within the framework of a scientific community's shared set of (largely tacit) beliefs and assumptions about the world and how to practice science within it, there are also *revolutionary* pe-

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[114] Brian Greene, *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory* (New York: W. W. Norton, 1999), pp. 31-51; Abraham Pais, *'Subtle is the Lord . . .' The Science and Life of Albert Einstein* (Oxford: Oxford University Press, 1982), pp. 138-46; and Albert Einstein, "On the Electrodynamics of Moving Bodies" in W. Perrett and G. B. Jeffery (trans.) *The Principle of Relativity: A Collection of Original Papers on the Special and General Theory of Relativity* (New York: Dover, first published 1923), pp. 37-65.

[115] Pais, *'Subtle is the Lord . . .' The Science and Life of Albert Einstein*, p. 153.

[116] I. Bernard Cohen, *Revolution in Science* (Cambridge, MA: Belnap Press of Harvard University Press, 1985), pp. 3, 6.

[117] "Few books in the history of science have stimulated so much interest and so continuing a dialogue" (Cohen, *Revolution in Science*, p. 23). By the early 1970s, the two most influential books in the philosophy of science were Karl Popper's 1934 *The Logic of Scientific Discovery*, which did not appear in English until 1959, and Kuhn's 1962 *The Structure of Scientific Revolutions*. Popper rejected Kuhn's notion of normal science, insisting that it was not normal, and dismissed paradigms as a "logical and philosophical mistake"—Karl Popper, "Normal Science and Its Dangers" in Imre Lakatos and Alan Musgrave (eds.), *Criticism and the Growth of Knowledge* (Cambridge, England: Cambridge University Press, 1970), pp. 53, 56.

riods in which this original worldview is supplanted by an incommensurable one in response to one or more anomalies that cannot, despite repeated efforts, be aligned with the community's expectations based on the earlier *paradigm*.[118] While Kuhn was initially vague as to what he meant by a paradigm, he eventually embraced Margaret Masterman's insight that scientific paradigms are prior to, and more fundamental than, the full-blown theories a scientific community elaborate within a given paradigm during periods of normal science.[119] On this reading of Kuhn's text, Masterman took paradigms to be concrete, but crude analogies that constituted a way of seeing reality as well as an artifact for doing science.[120] Paradigms, in other words, were the pre-theory commitments of a scientific community about the way the world worked and the proper practice of science. To recall one of Kuhn's own examples of incommensurable paradigms: "Newtonian mass is conserved; Einsteinian is convertible with energy. Only at low velocities may the two be measured in the same way, and even then they must not be considered to be the same."[121] Later, in 1990, Kuhn associated paradigms with "taxomonic modules" that he took to be "prelinguistic and possessed by animals."[122] Yet, despite Kuhn's vari-

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[118] Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago, IL: University of Chicago Press, 1962 and 1970 2nd ed.), pp. x, 4, 6, 10.

[119] Thomas S. Kuhn, James Conant and John Haugeland (eds.), *The Road Since Structure: Philosophical Essays, 1970-1993, with an Autobiographical Note* (Chicago, IL: University of Chicago Press, 2000), pp. 298-300; Margaret Masterman "The Nature of a Paradigm" in Lakatos and Musgrave, *Criticism and the Growth of Knowledge*, pp. 66-68, 79-80. After Masterman's criticism of the multiple meanings Kuhn gave to paradigm, he added a postscript in which he advanced two core meanings: (1) "the entire constellation of beliefs, values, techniques, and so on shared by members of a community"; and, (2) "the concrete puzzle solutions" or exemplars that, "employed as models or examples, can replace explicit rules as a basis for the solution of the remaining puzzles of normal science" (*The Structure of Scientific Revolutions*, p. 175). The latter, Kuhn said, was the deeper of two meanings and the source of the misunderstanding that he had made science "a subjective and irrational enterprise" (ibid.).

[120] Masterman "The Nature of a Paradigm," pp. 76-80.

[121] Kuhn, *The Structure of Scientific Revolutions*, p. 102. Even though both Newtonian and relativistic physics use the word 'mass,' Kuhn's position is that the word has different, incommensurable meanings depending on the paradigm within which the word is used.

[122] Kuhn, "The Road Since Structure" in *The Road Since* Structure*: Philosophical Essays, 1970-1993, with an Autobiographical Note*, p.94. Gerald

ous efforts to clarify what he meant by a paradigm, the concept remains controversial to this day. And notwithstanding the difficulties, the idea of a paradigm has also come to be widely used in modern discussions of change in virtually any and every area of human affairs.

The more relevant question for present purposes is whether revolutions in the modern sense of discontinuous leaps forward have occurred. George Sarton, one of the founders of the academic history of science, argues that the impression of science advancing by discontinuous giant steps is a superficial one that would vanish altogether in the face of sufficiently detailed analysis, and many scientists and historians have agreed with Sarton.[123] The situation is no less unsettled in that most mathematical of the social sciences, economics. In the judgment of the Nobel laureate Douglass North, because of the ubiquitous uncertainty of a non-ergodic world—meaning one in which average outcomes calculated from past observations *can* "be persistently different from the time average of future outcomes"—we not only lack a "dynamic theory of economic change," but, in North's view, such a general theory "is unlikely" to emerge.[124]

These various difficulties regarding changes in human affairs appear to have some important, if confounding, implications for those who hope for some way of unambiguously delineating periods of revolutionary change from evolutionary periods, whether in military matters, the physical sciences, economics, or virtually any other field. At the present time, the fact seems to be that there is virtually no area of human social endeavor in which we possess precise, cut-and-dry, unimpeachable criteria for separating these two seemingly disjointed

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Edelman's view of how, even in animals, the interaction of value-category memory in the limbic-brain stem system and perceptual categorization in the cortex has given rise to the correlated "scenes" that constitute primary consciousness certainly suggests that Kuhn's notion of paradigms has correlates in the brain processes underlying consciousness. See Gerald M. Edelman, *Bright Air, Brilliant Fire: On the Matter of Mind* (New York: BasicBooks, 1992), pp. 117-120; also, *Wider Than the Sky: The Phenomenal Gift of Consciousness* (New Haven, CT: Yale University Press, 2004), pp. 8-9, 55-59.

[123] Cohen, *Revolution in Science*, p. 22. It is doubtful, however, whether even detailed analysis can recover enough information about causal linkages to turn seemingly discontinuous change into incremental progress.

[124] Douglass C. North, *Understanding the Process of Economic Change* (Princeton and Oxford: Princeton University Press, 2005), pp. 8, 19, 125-126.

categories. Disputes over whether a given historical period is best categorized as one or the other are inherently impossible to resolve to everyone's satisfaction, much less to do so once and for all.

A brief review of the debate among Anglo-American military historians regarding the various military revolutions in Europe since the late 15th century should suffice to highlight one important reason for this lack of consensus. As Andrew Ayton and J. L. Price wrote in 1995:

> The idea of a military revolution was introduced by Michael Roberts, who argued [in 1955] that the tactical reforms pioneered by the Dutch army at the end of the sixteenth century and perfected by the Swedish army under Gustavus Adolphus, together with the accompanying rise in the size and cost of these new armies, constituted a radical break with the immediate past. Subsequently, the concept of such a revolution has been very generally accepted by historians of the period, but only with considerable disagreement over both its content and its timing. Geoffrey Parker criticized Roberts [in 1984] for overlooking the developments, especially in the Spanish armed forces, of the earlier years of the sixteenth century, and it has since become conventional to stretch out the military revolution to cover the period from the beginning of the sixteenth century to the middle of the seventeenth, although Jeremy Black has recently suggested [in 1995] that more importance should be given to the century after 1660.[125]

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[125] Andrew Ayton and J. L. Price (eds.), *The Medieval Military Revolution: State, Society and Military Change in Medieval and Early Modern Europe* (London: Tauris Academic Studies, 1995), p. 1. For the lecture, given in 1955 at Queens University Belfast, that initially postulated a military revolution in early modern Europe, see Michael Roberts, "The Military Revolution 1560-1660" in Rogers, *The Military Revolution Debate*, pp. 13-35. For the 1984 Lee Knowles lectures at Cambridge University's Trinity College that linked military innovation to the rise of the West, see Geoffrey Parker, *The Military Revolution: Military Innovation and the Rise of the West 1500-1800* (Cambridge: Cambridge University Press, 1988). For the view that "Roberts' century was in relative terms one of limited change between two periods of greater importance," see Jeremy Black, "A Military Revolution? A 1660-1792 Perspective" in Rogers, *The Military Revolution Debate*, pp. 96-97. "On sea as on land," Black wrote, "the military capability of the European powers was far from static" during 1660-1792, and the importance of these changes, he

The implication that emerges from Ayton and Price's review is, of course, that there is a certain arbitrariness to the identification of precise periods of revolutionary change in military and other affairs, the presumed precision having to do with the specification of the exact beginning and end points for the transformational period.

Confirmation of this suspicion emerged in subsequent efforts by social scientists and historians to delineate the various revolutionary periods in European military affairs since the late Middle Ages. In 1993 Clifford Rogers argued that, during the Hundred Years' War (1337-1453), there had been two distinct military revolutions: an "Infantry Revolution" that reached fruition in the 1340s and 1350s, and a gunpowder "Artillery Revolution," which matured during the decades 1420-1440.[126] He added, moreover, that these changes were followed by two other revolutions in fortifications and the administration of war, only the last of which corresponded to Roberts' original "Military Revolution" of 1560-1660. A year later, Andrew Krepinevich, in an influential article published after he had written the 1992 assessment of the military-technical revolution (MTR) for Andrew Marshall's Office of Net Assessment, suggested that there "appear to have been as many as ten military revolutions since the fourteenth century"—not counting the current one that he and Marshall hypothesized might be underway as a result of advances in PGMs, wide-area sensors, command-and-control systems, and related conceptual and organizational changes in the conduct of war.[127] And in 1997, Williamson Murray identified no less than 21 "possible RMAs" since the 13th century.[128] In short, as historians and others built on Roberts' original hypothesis of a military revolution in early modern Europe during 1560-1660, the list of distinct periods of significant, discontinuous change in military affairs gave every indication of undergoing cancerous growth. Thus, by the mid-1990s, there was growing uneasiness about the seeming

concluded, needs to be fully understood relative to both "Roberts' century" and the subsequent "Revolutionary/Napoleonic period" (ibid., p. 111).

126 Clifford J. Rogers, "The Military Revolutions of the Hundred Years' War," *The Journal of Military History*, April 1993, pp. 244, 252, 258.

127 Andrew F. Krepinevich, Jr., "Cavalry to Computer: The Pattern of Military Revolutions," *The National Interest*, Fall 1994, pp. 31, 40-41.

128 Williamson Murray, "Thinking about Revolutions in Military Affairs," *Joint Force Quarterly*, Summer 1997, p. 70.

tendency of researchers to be able to discern revolutions in military affairs wherever they looked.

In reaction to this growing concern Jeremy Black, while emphasizing that Roberts' notion of a European military revolution during 1560-1660 "had been useful in offering a conceptual framework within which early-modern warfare" could be discussed, went on to note that the identification of revolutionary periods was "subjective": there were "no agreed-upon criteria by which military change . . . can be measured or, significantly, revolution discerned."[129] In 2002 Colin Gray went even further, arguing that because the identification of revolutionary change is contingent on "clear periodization"—meaning the "preceding and postdating periods of contrasting relative stasis"—RMAs are "intellectual constructs," the "inventions of scholars and other thinkers."[130] Based on this line of reasoning, he rejected RMA arguments "of an existential kind," his point being that "RMAs do not exist 'out there' . . . waiting to be discovered by the intrepid explorer-theorist."[131] He is largely right in insisting that periodization is always, to some degree, arbitrary. But insofar as this view was intended to deny the existence of change in the world, he appears to have pushed his argument a bit too far. The fact that we can quibble endlessly about the precise start date for, say, the Russian revolution in no way argues that the discontinuous political changes that rocked Russia during 1917-23 did not occur. The arbitrariness inherent in any periodization reflects, instead, the large gaps and shortcomings in our knowledge of the full panoply of causal linkages underlying what occurred. In this regard the historical record is best envisioned as being fundamentally incomplete—riddled with holes and missing pieces even in the case of recent events.[132]

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[129] Black, "A Military Revolution? A 1660-1792 Perspective," pp. 95, 98.

[130] Colin S. Gray, *Strategy for Chaos: Revolutions in Military Affairs and the Evidence of History* (London: Frank Cass, 2002), pp. 10, 14, 15.

[131] Gray, *Strategy for Chaos*, p. 12.

[132] Historians have been spectacularly reticent about admitting how fragmentary the so-called historical record generally is, much less in openly discussing the implications of this situation for their discipline. My own guess is that, even in the case of events still within living memory, historians are hard-pressed to recover even 5-10 percent of the detailed causal linkages required for a complete or unimpeachable understanding of what happened.

In an early 2006 discussion of change in warfare, Gray seems to have moderated his earlier misgivings regarding the reality of revolutionary periods in military affairs, however arbitrary our periodizations of such transformations may be. In discussing the possibility of all change being evolutionary, he gave every indication of believing that changes do occur in some objective sense.[133] Indeed, as he explained in an endnote, Gray was not at all inclined to embrace the post-modern insistence that historical truth is, at best, a fable, which, like beauty, is entirely in the eye of the beholder; instead he professed to persist "in regarding historical study as a practicable search for truth."[134]

Moreover, although the categorization of some span of years or decades in any field of human endeavor as having been one of revolutionary change is, in part, a matter of convention, it does not follow that such periodizations are wholly arbitrary or wholly subjective. Two observations should suffice to block this inference. First, consider the role of observers and observations in quantum mechanics. As Werner Heisenberg stated in 1933, "Whereas in the classical theory the kind of observation has no bearing on the event [observed], in quantum theory the disturbance associated with each observation of the atomic phenomenon has a decisive role [in the physical measurements resulting from the experiment]."[135] The unrestricted objectivity of Newtonian physics does not carry over into quantum mechanics, which incorporates an element of, if you will, subjectivity. Second, much the same is true of our perceptions of color; they, too, have a subjective or arbitrary component. As neurobiology has only come to fully appreciate in recent decades, the "sense of color" enjoyed by any normal human is "a construct" of the individual's "nervous system."[136] The colors that we "see" are "false" in the sense of being "arbitrary conventions" used by our brains "as convenient labels" for the signals the rods and cones of our retinas send to the brain when visible light

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[133] Gray, *Recognizing and Understanding Revolutionary Change in Warfare*, pp. 11-12.

[134] Gray, *Recognizing and Understanding Revolutionary Change in Warfare*, pp. 49-50.

[135] Heisenberg, "The Development of Quantum Mechanics," p. 297.

[136] Christof Koch, *The Quest for Consciousness: A Neurobiological Approach* (Englewood, CO: Roberts and Company, 2004), p. 52.

of different wavelengths falls on them.[137] Indeed, since color precepts remain stable over a wide variation in light sources, cognitive science reveals that "our bodies and brains have evolved to create color."[138] And to generalize these facts, Richard Dawkins has hypothesized that every species "that has a nervous system uses it to construct a model of its own particular world, constrained by continuous updating through the sense organs."[139] Thus, the charge that any classification of a historical period as having been revolutionary, as opposed to evolutionary, is to some degree a matter of arbitrary convention is far less damning than has usually been supposed.[140] The elements of arbitrariness and subjectivity that infect perceptions of color and quantum mechanics do not fatally undermine either color vision or physics on the scale of atomic and subatomic particles.

What follows, then, from the concerns of Black, Gray, and others about the objectivity of identifying periods of revolutionary change in military affairs? The implication is not to reject such classifications altogether. Rather, the more sensible conclusion is just that such classifications will always be conditional—subject to challenge, debate, and revision—although one could make the same observations about special relativity, Darwinian evolution, and quantum mechanics.

However, because the classifications underlying the view that the interwar years 1918-1939 witnessed several distinct revolutions in military affairs are conceptual, there is a further implication. Simply put, the boundary between our concepts of revolutionary and evolutionary change is not a sharp line. Rather, both concepts are distinctly fuzzy toward their edges, and the area of transition between them is inherently murky: there is, if you will, a fair amount of middle ground

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137 Richard Dawkins, *Unweaving the Rainbow: Science, Delusion and the Appetite for Wonder* (New York and Boston: Houghton Mifflin, 1998), p. 57.

138 George Lakoff and Mark Johnson, *Philosophy in the Flesh: The Embodied Mind and Its Challenge to Western Thought* (New York: Basic Books, 1999), p. 23.

139 Dawkins, *Unweaving the Rainbow*, p. 274.

140 Rapid, reasonably accurate classification is one of the most fundamental functions of animal brains. Indeed, classification is a matter of survival. Consider, for example, the importance to individual survival of the following categories: food, sexual partner, offspring, danger, and predator.

within which it is very difficult to decide whether one is looking at an evolutionary or revolutionary period.

With that realization firmly in mind, what sorts of criteria for recognizing revolutionary periods in military affairs have participants in the RMA debate put forward since 1992? It seems appropriate to start with Krepinevich's framework on the grounds that he wrote the MTR assessment that precipitated the RMA debate of the 1990s. His most complete formulation appeared in 1994:

> What is a military revolution? It is what occurs when the application of new technologies into a significant number of military systems combines with innovative operational concepts and organizational adaptation in a way that fundamentally alters the character and conduct of conflict. It does so by producing a dramatic increase—often an order of magnitude or greater—in the combat potential and military effectiveness of armed forces.
>
> Military revolutions comprise four elements: Technological change, systems development, operational innovation, and organizational adaptation. Each of these elements is in itself a necessary, but not a sufficient condition, for realizing the large gains in military effectiveness that characterize military revolutions. In particular, while advances in technology typically underwrite a military revolution, they alone do not constitute the revolution. The phenomenon is much broader in scope and consequence than technological change, however dramatic.[141]

While Krepinevich's account has been widely cited, it is by no means the only effort to nail down what is meant by a revolution in military affairs. In 1999, RAND's Richard Hundley offered an alternative characterization, one that seems thoughtful enough to warrant citing alongside Krepinevich's. An RMA, he wrote,

> involves a paradigm shift in the nature and conduct of military operations
>
> - which either renders *obsolete or irrelevant* one of more *core competencies* of a dominant player,

[141] Krepinevich, "Cavalry to Computer," p. 30.

- or creates one or more new core competencies, in some new dimension of warfare,
- or both.[142]

For the reasons already elaborated, neither definition provides a final resolution to the various controversies surrounding the existence of scientific, military, or other kinds of revolutions in human affairs, the precise location of allegedly revolutionary periods in time, or the exact meaning of key terms such as *revolution* or *paradigm*. Nonetheless, this situation need not preclude the conditional use of these definitions in considering the changes in the conduct of war brought about by guided weapons since the early 1940s. As P. B. Medawar and J. S. Medawar observed in 1983, in sciences such as biology it "is simply not true that no discourse is possible unless all technical terms are precisely defined."[143] The extension of this sentiment to understanding change in virtually any area of human social interactions argues that definitions such as those given for RMAs by Krepinevich and

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142 Richard O. Hundley, *Past Revolutions, Future Transformations* (Santa Monica, CA: RAND Corporation, 1999), p. 9. Hundley based his notion of a paradigm on Kuhn's *The Structure of Scientific Revolutions*, although he also offered some military examples. "Opposing warships arranged in line-of-battle on parallel courses and engaging with gunfire was the operational paradigm for naval fleet engagements" during the Napoleonic Wars as well as during World War I (ibid.). His notion of core competencies was drawn from business strategy in which a firm's core competencies are understood as things a firm can do well to develop and maintain advantages over its competitors—see C. K. Prahalad and Gary Hamel, "The Core Competence of the Corporation," *Harvard Business Review*, May-June 1990, especially pp. 80-85.

143 P. B. Medawar and J. S. Medawar, *Aristotle to Zoos: A Philosophical Dictionary of Biology* (Cambridge, MA: Harvard University Press, 1983), p. 66. In the early 1930s (independent of Kurt Gödel's proofs that the first-order predicate logic is deductively complete while any axiom system strong enough for the natural numbers is not), Thoraf Skolem showed that "there is no known formal system that will categorically define the natural numbers," meaning one whose "models are isomorphic"—Howard DeLong, *A Profile of Mathematical Logic* (Menlo Park, CA: Addison-Wesley, 1970), pp. 131, 146, 185. Skolem's result extends the Medawars' point to mathematics because, even with the precision of a mathematical language, there is no way to avoid an infinite number of "nonintended," non-isomporhic models for both the natural and real numbers (ibid., p. 185). Yet, while we cannot precisely define either the natural or the real numbers in Skolem's sense of providing a categorical formalization, we are still able to use them for an immense variety of productive purposes day in and day out.

Hundley can be safely used *only if* they are employed with appropriate restraint—especially regarding existence claims—and that is how they will be used in the remainder of this report.

Among other things, this stricture means that one should be especially cautious about drawing unwarranted conclusions from such definitions. A case in point that has adversely affected much of the post-1992 RMA debate has been the tendency to assume that revolutions in military affairs are first and foremost about technology. As Gray has noted, "despite the sophisticated and originally fairly tentative, essentially speculative view of Andrew Marshall and OSD Net Assessment, once the RMA ideas became general property it was captured by a profoundly technological view of the revolution that seems to beckon the Armed Forces into a new golden age of enhanced effectiveness" predicated on advanced technology.[144] From the outset, though, Marshall and Krepinevich were clear in their own minds that operational concepts and organizational adaptations were, if anything, more important than either new technology or getting it fielded in a significant number of systems. Indeed, it was the unfortunate tendency of many to fixate on the technological component of RMAs that prompted Marshall, in the summer of 1993, to begin substituting *revolution in military affairs* for the initial term *military-technical revolution*, which Krepinevich had taken from the Soviet literature and used in OSD/NA's 1992 MTR assessment. The motivation behind this shift in terminology was probably best captured in 1999 by Hundley: "Without an operational concept, the best weapon system in the world will never revolutionize anything."[145] Worth adding is that this view is well supported by the earlier discussion of technology's role in combat outcomes. The point is not to dismiss technology, because it does matter. Rather, it is to emphasize that technology "does not matter most," especially from the viewpoint of fundamental or revolutionary changes in how wars are fought.[146]

There is one last distinction regarding RMAs that warrants mention. Starting in 1997, Williamson Murray began distinguishing what

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[144] Gray, *Recognizing and Understanding Revolutionary Change in Warfare*, p. 8.

[145] Hundley, *Past Revolutions, Future Transformations*, p. 27.

[146] Gray, *Recognizing and Understanding Revolutionary Change in Warfare*, p. 9.

he termed *military revolutions* ("systemic changes in the political, social and cultural" aspects of particular nations or societies) from *revolutions in military affairs* (what occurs when military organizations integrate "the complex pieces of tactical, societal, political, organizational, or even technological changes" generated by military revolutions to develop a "new conceptual approach to warfare" or "a specialized sub-branch of warfare).[147] As Murray and MacGregor Knox reiterated in 2001, military revolutions such as the French Revolution of the late 18th century and the advent of nuclear weapons are the "earthquakes" that establish the context within which the "pre- and aftershocks" (or "lesser transformations") of RMAs such as *Blitzkrieg*[148] or, presumably, the rise of guided munitions and battle networks occur.[149]

This distinction between military revolutions and RMAs does appear to illuminate *some* instances of change in military affairs. Table 3 shows the causal relations between three of the five military revolutions Murray and Knox identified in 2001 and their "associated and resultant" RMAs. In the case of the wars of the Napoleonic period, the French Revolution does furnish a plausible context for the subsequent political and economic changes in various European nations, starting with France's *levée en masse*, the mass conscription that enabled revolutionary France to begin raising armies large enough to threaten most of Europe. The entry under the post-World War II nuclear revolution, however, is more problematic. It implies that the rise of guided weapons and battle networks were either asso-

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147 Murray, "Thinking about Revolutions in Military Affairs," pp. 70-71, 73; Knox and Murray, "Thinking about Revolutions in Warfare," in *The Dynamics of Military Revolution 1300-2050*, p. 12.

148 The understanding of *Blitzkrieg* that has dominated much discussion of this presumed "RMA" in the English-speaking world tends to be simplistic and ignore Adolph Hitler's extraction from "military control," and transfer to "amateurish and ambitious hands," any awareness or coherent pursuit of operational art (Naveh, *In Pursuit of Military Excellence*, p. 120). Naveh's critical analysis of the *Blitzkrieg* concept can be found in the fourth chapter of *In Pursuit of Military Excellence*. Perhaps his most provocative insight is that, because of the operational coherence underlying Erich von Manstein's plan for the Germans' 1940 campaign against France and the Low Countries, it should be *excluded* as an example of *Blitzkrieg* as understood and implemented by Heinz Guderian or Erwin Rommel (ibid., p. 126).

149 Murray, "Thinking about Revolutions in Military Affairs," p. 73; Knox and Murray, "Thinking about Revolutions in Warfare," pp. 12-13.

ciated with or resulted from the marriage of nuclear weapons and ballistic missiles. But since the earliest battle network using long-range sensors was employed in the summer of 1940, and as guided weapons were first employed in 1943, portraying their emergence as being caused by the appearance nuclear-tipped ICBMs and SLBMs in the late 1950s and early 1960s appears to require later events to influence earlier ones. Granted, on the American side of the Cold War, the LRRDPP did begin thinking about reconnaissance-strike complexes with near-zero-miss conventional munitions as an alternative to nuclear use in the early 1970s. Nevertheless, the tens of thousands of Paveway I LGBs that the US Air Force employed in Southeast Asia during the last couple years of major US combat operations there were developed for the Tactical Air Command to solve accuracy problems against point targets that had nothing to do with either the atomic RMA of the late 1940s or the thermonuclear-missile RMA of the 1950s.[150] Thus, the causal linkages implicit in Table 3's "associated and resultant RMAs" is surely mistaken in the case of Murray and Knox's nuclear military revolution and the guided-munitions RMA.

That said, this criticism should not be taken to undermine entirely Murray and Knox's distinction between military revolutions and RMAs. It does have the merit of highlighting the broader technological, political, economic, social, and cultural contexts within which revolutions in military affairs occur. Of course, one could also argue that recognition of the influence these broader contextual factors can exert on the conduct of war does not require the Murray-Knox distinction. A reasonably clear example is the crushing tactical superiority of Pizarro's conquistadors in Peru over Inca warriors during 1532-39. Nor does Murray and Knox's distinction eliminate the element of subjectivity inherent in the identification of periods of non-evolutionary change in military affairs, whether military revolutions or RMAs. Perhaps the most that can be said of the distinction is that it underscores the fact that RMAs of the sort Marshall, Krepinevich, and Soviet military theorists were thinking about during the 1980s and 1990s do not occur in vacuums. The point, while seemingly obvious, is one that is often forgotten, but should be constantly kept in mind.

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[150] The atomic revolution of the late 1940s was a period of US nuclear monopoly and relative scarcity in the numbers of weapons available to the United States. The thermonuclear revolution of the 1950s and early 1960s rapidly brought about nuclear plenty for both the United States and the Soviet Union.

Table 3: Military Revolutions versus RMAs[151]

Military Revolutions 2 and 3: *the French and Industrial Revolutions*
Associated and Resultant RMAs: • National political and economic mobilization; Napoleonic warfare (battlefield annihilation of the enemy's armies) • Financial and economic power based on industrialization (Britain) • Technological revolution in land warfare and transport (telegraph communications, railroads, steamships, quick-firing smokeless small-arms and artillery, and automatic weapons) • Jackie Fisher's revolution in naval warfare: the all big-gun dreadnought and battle-fleet (1905-1914)
Military Revolution 5: *Nuclear Weapons and Ballistic Missile Delivery Systems*
Associated and Resultant RMAs: • Precision reconnaissance and strike; stealth; computerization and computer networking of command and control; massively increased lethality of "conventional" munitions

This discussion has sought to illuminate the problems and pitfalls that beset discussions of non-evolutionary change in any area human affairs—scientific, political, economic, social, cultural or military. Assertions that a particular historical period was revolutionary, rather than merely evolutionary, is to some degree subjective and arbitrary. Nonetheless, rough criteria for distinguishing revolutionary from evolutionary change in military affairs have been suggested, and with proper care they can be used—and will be used in Chapter V—to reach conditional judgments about how best to view the emergence of guided weapons and battle networks over the last six decades. Our inability to provide absolutely precise definitions of RMAs, or to specify the exact moments revolutionary periods of change began or ended, arise from the inadequacies of the historical record and the inherent fuzziness of our conceptual categories. It does not follow from these limitations, however, that no useful discourse is possible about change in military affairs until these literally unsolvable prob-

[151] Knox and Murray, "Thinking about Revolutions in Warfare," p. 13. The other two military revolutions in Murray and Knox's table were: Military Revolution 1: *the 17th-century creation of the modern state and of modern military institutions*; and, Military Revolution 4: *the First World War irrevocably combines its three predecessors* (ibid.).

lems are solved. Rather they merely reveal how much care is needed in discussing them.

Questions about Future War and an Anomaly

As mentioned at the end of Chapter I, the overall aim of this chapter has been to address the question: How ought one think about the emergence of guided weapons? By the mid-1980s both Soviet military theorists and Western observers were actively trying to think through how guided munitions and battle networks might eventually affect the conduct of war by military forces able to exploit them. This final section of Chapter II reviews the main questions about guided munitions raised in the late 1980s by Andrew Marshall and Charles Wolf during their deliberations on the future security environment as co-chairmen of a working group for the Commission on Integrated Long-Term Strategy (CILTS). Additionally, the discussion also highlights one anomaly regarding reconnaissance-strike systems that has become increasingly apparent during the last decade.

The Commission on Integrated Long-Term Strategy was begun in the fall of 1986 at the direction of President Ronald Reagan's defense secretary, Caspar Weinberger, and his assistant for national security affairs, John Poindexter. The commission's initial mandate was to propose "adjustments to U.S. military strategy in view of a changing security environment in the decades ahead."[152] Co-chaired by Fred C. Iklé (then undersecretary of defense for policy) and Albert Wohlstetter, CILTS had eleven other commissioners, including Zbigniew Brzezinski, Henry Kissinger, former NATO supreme commander General Andrew Goodpaster, Samuel Huntington and former JCS chairman General John Vessey.[153]

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[152] Iklé and Wohlstetter, *Discriminate Deterrence: Report of the Commission on Integrated Long-Term Strategy*, p. i. By the time this report was published in January 1988, Frank Carlucci had replaced Weinberger as defense secretary and Colin Powell had become the assistant for national security affairs, having replaced Carlucci who had held the job from December 2, 1986, until November 23, 1987.

[153] The other CILTS members were Anne L. Armstrong, William P. Clark, W. Graham Claytor, Jr., Admiral (USN, retired) James L. Holloway III, Joshua Lederberg, and General (USAF, retired) Bernard A. Schriever.

The CILTS effort was supported by a number of working groups, whose studies were not published until after the commission's overall report, *Discriminate Deterrence*, appeared in January 1988.[154] *Discriminate Deterrence* did mention the possibility of an emerging RMA driven by the exploitation of microelectronics, information processing, and other technologies. In fact, it observed that the Soviet military was already "engaged in a major effort to understand the implications" of being able to employ precision munitions across wider geographical areas with greater rapidity and intensity than had been previously possible.[155]

However, detailed examination of these prospects and possibilities did not emerge until the report of Marshall and Wolf's CILTS working group on the future security environment was published in October 1988.[156] This group took seriously the possibility that Soviet military theorists might be right in anticipating that the conduct of war was entering a period of major or discontinuous change:

> The Working Group believes that the Soviets are correct in their assessment that the advent of new technologies will revolutionize war, and not merely make current forces marginally better at what they do. In the same way that long-range rifles and railroads transformed combat in the mid-19th century (and tanks and aircraft did in the mid-20th century), the new technologies will profoundly alter tactical requirements, operational possibilities, and even, in some cases, strategic choice in the early 21st century. New theaters of strategic concern—space, most notably—will open up, and previously discarded options (ballistic missile defense, for

[154] The topics assigned to the working groups were "the security environment for the next twenty years, the role of advanced technology in military systems, interactions between offensive and defensive systems on the periphery of the Soviet Union, and the U.S. posture in regional conflicts around the world" (Iklé and Wohlstetter, *Discriminate Deterrence*, p. i).

[155] Iklé and Wohlstetter, *Discriminate Deterrence*, p. 8.

[156] Members of the CILTS working group on the future security environment included Eliot A. Cohen, David F. Epstein, Fritz Ermarth, Lawrence Gershwin, James G. Roche, Thomas Rona, Stephen P. Rosen, Notra Trulock, III, and Dov Zakheim.

example) will appear as feasible choices. This has, in fact, already begun to occur.[157]

The group's report went on to note that the response of the American military to what Marshall would later characterize as the RMA "hypothesis" was, at this juncture, quite different:[158]

> While the U.S. is in the process of fielding many of the new technologies, and is undoubtedly ahead in a number of yet more advanced areas, the Soviets may be more fully engaged in thinking through the implications of the new technologies in war. U.S. thinking appears to center more on how new technologies can be used to enhance performance of existing military missions, whereas Soviet writings foresee a broad revolution in military affairs, requiring new forms of military organization and concepts of operations . . .[159]

What were some of the broader, or more revolutionary possibilities foreseen by Soviet military thinkers in the late 1980s?[160] Among other things, they seemed to believe that:

- conventional operations would benefit the most in the near term from ongoing advances in sensors, guided munitions, and C^2;
- reconnaissance-strike complexes would emerge as a new organizational form;
- RUKs would be able to detect and attack targets at depths 5-6 times what had been previously possible, achieve single-shot

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[157] Andrew W. Marshall and Charles Wolf, Jr., (chairmen), *The Future Security Environment* (Washington, DC: The Pentagon, October 1988), pp. 26-27.

[158] A. W. Marshall, "Revolutions in Military Affairs," statement prepared for the Subcommittee on Acquisition and Technology, Senate Armed Services Committee, May 5, 1995, p. 1.

[159] Marshall and Wolf, *The Future Security Environment*, p. 26.

[160] For an in-depth discussion of Soviet views in the late 1980s of what the Soviets perceived as an emerging MTR, see Notra Trulock, III, "Appendix B: Emerging Technologies and Future War: A Soviet View" in Marshall and Wolf, *The Future Security Environment*, pp. 97-163.

kill probabilities of 0.6-0.9 against both fixed and mobile targets, and carry out detection-to-destruction cycles in near-real time;

- more powerful conventional munitions, perhaps based on fuel-air explosives, might increase achievable zones of destruction from hectares to square kilometers (that is, one-hundred fold[161]); and,

- these various developments would enable conventional weapons to "achieve results formerly possible only by means of nuclear weapons."[162]

These various Soviet speculations about changes in the conduct of military operations raise a number of questions about future war. Some of them have already been mentioned, particularly in Chapter I. From the standpoint of rounding out this chapter's discussion of how to think about guided munitions and their associated battle networks, though, it seems appropriate to enumerate them in one place. The main questions the case studies in Chapters III and IV will attempt to illuminate are:

1. To what extent is it defensible to claim that the maturation of guided munitions and battle networks in the early 21st century constitute enough of a leap forward, or a break in continuity with the past, to be judged a revolution in military affairs as understood in the previous section?

2. Have guided munitions already given rise—or are they likely to give rise in the future—to new operational concepts or organizational arrangements?

3. Have guided munitions begun changing the planning of military operations or affected the kinds of operations being conducted?

4. Are guided munitions and battle networks altering the allocation of missions between or within military services, thereby

[161] One square kilometer equals 100 hectares.

[162] Marshall and Wolf, *The Future Security Environment*, pp. 35-36.

giving a greater role to some capabilities, force elements, or services while diminishing others? If not, will they do so one day?

5. Does growing reliance on guided munitions mean that militaries able to employ them in significant quantities will increasingly move away from close combat whenever and wherever possible?

6. Might one long-term impact of guided munitions be to bring about new levels of coordination and integration between diverse force elements, even if widely separated?

7. Might another impact of guided munitions on the conduct of future war be to reinvigorate offensive strategic warfare in the sense of rendering exchanges with long-range weapons against vital target systems between major powers once again "thinkable"?[163]

Most of these questions about how guided munitions might alter the conduct of future wars were, to one degree or another, fairly evident by the 1980s, particularly among those who had been following Soviet discussions of a third 20th-century military-technical revolution.[164] Insofar as they are the more important questions to ask

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[163] The reference is, of course, to Herman Kahn's 1962 book *Thinking about the Unthinkable*. By the early 1960s, the prevailing view in the West was that any large-scale nuclear exchange between the United States and the Soviet Union would be too destructive to both societies to serve any rational purpose, a viewpoint that Bernard Brodie had famously emphasized in 1946 and reiterated in 1978 (see Bernard Brodie, "The Development of Nuclear Strategy," *International Security*, Spring 1978, p. 65). While Kahn accepted Brodie's point that every effort should be made to deter nuclear war, he disagreed with the implication that there could be neither meaningful damage limitation during a US-Soviet nuclear exchange nor a "victor" in its aftermath—Herman Kahn, *Thinking about the Unthinkable in the 1980s* (New York: Simon & Schuster, 1984), pp. 28-29, 37. Nevertheless, nuclear weapons did largely take offensive strategic warfare "off the table" for the United States and the USSR by the 1970s, whereas a potential result of guided weapons may be to once more make it thinkable.

[164] According to William Odom, Soviet theorists identified two prior cycles of technology-enabled MTRs during the 20th century. The first arose from aviation, chemical weapons, and motorization during World War I; the second, which followed World War II, was triggered by nuclear weapons, rocketry, and cybernetics or early computers (William E. Odom, "Soviet Military Doctrine," *Foreign Affairs*, Winter 1988/89, p. 120). Starting in the late 1970s, Soviet theorists saw the beginnings of a third cycle stemming from the impact of

about the emerging era of guided munitions and battle networks, they provide an analytic framework for thinking about the case studies in Chapters III and IV. Answers to some of them have already been suggested in Chapter I. However, Chapter V will return to these questions in an effort to formulate more complete answers—responses that reflect both the historical cases as well as the various pieces of context in this chapter regarding how to think about guided munitions.

Before turning to the case studies, there is one oddity about the current American position in guided munitions and battle networks that bears mention. Colin Gray has repeatedly argued—with good reason—that prospective adversaries, too, have a say in the pace, character, and ultimate success of RMAs:

> *Revolutionary change in warfare always triggers a search for antidotes. Eventually, the antidotes triumph. They can take any or all of tactical, operational, strategic, or political forms.*[165]

An often-cited illustration can be found in the responses of the Soviets and the Western Allies to the early triumphs of Germans in their *Blitzkrieg* campaigns of 1939-41. The British, American, and Red armies were eventually able to develop their own versions of *Blitzkrieg* and ultimately defeated Hitler's Third Reich despite the initial successes of the Germans' new way of fighting in Poland, France and the Low Countries, and Russia. In their responses to the German challenge, the Allied antidotes were largely based on emulation rather than evasion or asymmetric countermeasures, which is to say that the British, American, and Soviet adaptations were basically symmetric.

By comparison, American capabilities for reconnaissance-and-precision strike, first demonstrated in the 1991 Persian Gulf War, have not yet generated obviously symmetric responses by potential adversaries. Not only has the United States maintained a substantial lead over any other nation in the variety, quantities, and sophistication of

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solid-state electronics on sensors, avionics, computation, the accuracy of conventional munitions, and communications (ibid., p. 124).

[165] Gray, *Recognizing and Understanding Revolutionary Change in Warfare*, p. 45 (emphasis in original).

the guided weapons and wide-area sensors in its military arsenal for the last decade and a half but, if anything, the American margin of advantage appears to have grown over time. This situation appears fundamentally at odds with the pattern of symmetric responses to *Blitzkrieg* operations during 1942-45.

Part of the reason for the persistence—so far—of American dominance in reconnaissance-and-precision strike undoubtedly lies in the enormous costs of these capabilities. Consider the NAVSTAR Global Positioning System, which uses a constellation of 21 operational satellites (plus three on-orbit spares) at an altitude of some 11,000 nautical miles to provide precise location information to users around the globe. GPS first demonstrated its utility in military operations during the 1991 Persian Gulf War. Although only sixteen NAVSTAR satellites were available on 17 January 1991—five of which were developmental Block-1 systems—the procurement of thousands of handheld GPS receivers enabled American ground units to grid maps with highly accurate latitude and longitude markings, navigate across trackless desert terrain without getting lost, pinpoint key Iraqi positions in GPS space, and reduce fratricide by keeping out of each other's fields of fire; also, the Air Force used GPS to guide strike aircraft to their targets through adverse weather, and the Navy exploited it to clear mines in the Persian Gulf and provide more precise launch coordinates for TLAMs.[166] And, to highlight a guided-munitions first from Desert Storm, the 35 AGM-86C CALCMs expended by B-52Gs on the opening night of the conflict constituted the initial wartime employment of a guided munition utilizing GPS location information for both en-route navigation and terminal guidance.[167]

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[166] US Space Command, *Operations Desert Shield and Desert Storm Assessment*, January 1992, SERCET/NOFORN (redacted version) pp. 26-28; <http://www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB39/#doc>, accessed August 24, 2006. During Desert Storm, the NAVSTAR GPS constellation provided two-dimensional positioning (three satellites in view) "almost the entire day" during the ground campaign, and three-dimensional coverage (four satellites in view) about 18 hours a day (ibid., p. 28).

[167] Major Stephen R. Hess, "Conventional Air Launched Cruise Missile Development—Employment and the Cost of Global Presence," Marine Corps University, Command and Staff College, April 18, 1995, p. 19; Michael Rip and James M. Hasik, *The Precision Revolution: GPS and the Future of Aerial Warfare* (Annapolis, MD: Naval Institute Press, 2002), pp. 156-161. The AGM-86C is a modified version of the AGM-86B nuclear-armed cruise mis-

The costs of maintaining worldwide GPS coverage, like those of operating a fleet of electro-optical and radar reconnaissance satellites, go far to explain why no other nation is presently even close to replicating the full range of US capabilities for reconnaissance-and-precision strike. An additional question to consider, therefore, is how readily potential opponents could develop comparable capabilities. From a hardware perspective, it was not that difficult for industrial powers such as the United States, Great Britain, and the USSR to field symmetric responses to the German *Blitzkrieg* during World War II. The resource and technical barriers to matching American capabilities for global precision strike, however, appear considerably steeper, even for the Russians, Chinese, and Europeans.

For example, late in the Cold War, the Soviets deployed their own version of GPS, called the Global Navigation Satellite System (GLONASS). However, 1995 was the only year since 1987—when GLONASS began operations—in which the Soviets managed to have on orbit a full constellation of 24 satellites.[168] The Chinese have orbited three first-generation, BeiDou-1 geosynchronous navigation satellites (two operational and one back-up), but the system only covers East Asia and has been reported to require integration with GPS for high-accuracy geo-location.[169] As for America's European allies, the European Union remains committed to fielding its own satellite-navigation constellation, Galileo, by 2008, and the first Giove-A payload was placed in a Galileo orbit at the end of December 2005.[170] So there are indications that, in the long term, alternatives to

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sile. The modification program replaced the W-80 nuclear warhead and terrain contour matching (TERCOM) system with a conventional warhead and a GPS-receiver. The result was the first non-nuclear cruise missile employing INS/GPS guidance.

168 Sergey Revnivykh, "GLONASS: Status and Perspectives," Federal Space Agency of the Russian Federation, March 14-15, 2005, PowerPoint presentation, Slide 9.

169 "BeiDou-1 Satellite Navigation System," *Chinese Defence Today*, page last updated March 12, 2006, accessed August 24, 2006, online at <http://www.sinodefence.com/strategic/spacecraft/beidou1.asp>.

170 Keith D. McDonald, "Galileo's First Launch," *Geospatial Solutions*, February 2006, online at <http://www.geospatial-online.com/geospatialsolutions/article/articleDetail.jsp?id=303342>, accessed April 11, 2006.

GPS may emerge. But the costs of such systems are high, and satellite-navigation constellations are just one element of existing US capabilities for global reconnaissance-and-precision strike.

All of this raises the question of the reproducibility of the current American advantage in guided munitions and battle networks. It is an issue to which the discussion will return in Chapter V. For now it should suffice to crystallize the issue by observing that emulation of the sort that occurred during 1942-45 in the case of *Blitzkrieg* is not the only historical precedent. The United States Navy developed a formidable fleet of aircraft carriers during World War II. By August 1945, the USN had over 30 fast carriers in service and Japan's initially competitive carrier force had been eliminated. However, as the costs of maintaining aircraft carriers and their associated air wings grew in succeeding decades, only the United States was able to retain a major position in this "business"—an enterprise in which the Royal Navy had been the original innovator and early leader during 1914-18. In terms of these two contrasting examples, the issue about the reproducibility by other allies or adversaries of guided-munition and battle-network capabilities approaching those of the United States boils down to this question: Is this emerging guided-munitions regime more akin to large-deck aircraft carriers following World War II, or to the *Blitzkrieg* after the fall of France in 1940?

III. Platform-versus-Platform Cases

This chapter examines four post-World War II cases of guided munitions for platform-versus-platform combat. The cases selected are: submarine-versus-submarine during the US-Soviet Cold War; air-to-air combat between jet fighters since the first engagements by US aircrews with North Vietnamese MiGs in 1965; naval surface engagements starting with the sinking of the Israeli destroyer *Eilat* by Soviet-built Styx anti-ship missiles in October 1967; and tank-on-tank close combat in 1991 and 2003. In addition, a brief discussion of the shift from vacuum-tube to solid-state electronics has been included prior to the air-to-air case.

These four historical episodes reveal a wide variation in the responses of the war-fighting communities involved to guided munitions. As mentioned in Chapter I, the US Navy began embracing guided torpedoes during World War II and, during the Cold War that followed, the only unguided torpedo the USN's submarine community accepted into operational service had a nuclear warhead. The US Army's tank community, on the other hand, relies to this day primarily on aimed fire from a high-velocity main gun for tank-on-tank engagements. The fundamental reason for the wide variation in when individual war-fighting communities embraced guided munitions appears to lie in the complexity of engagement dynamics. The more dimensions in which the delivery platform, the target platform, or both, can maneuver, the stronger the tactical imperative to move to guided munitions.

US Navy Torpedoes after World War II

From the late 1860s until the 1940s, torpedoes were essentially unguided munitions that, initially, were controlled after being fired only in the limited sense of being able to run at a constant depth. Later, in the 1890s, their accuracy as aimed-fire munitions was improved by the addition of gyroscopic devices that enabled torpedoes to maintain a constant azimuth once in the water. Until the advent of guided torpedoes in World War II, these munitions were primarily used by submarines or surface combatants to sink ships on the ocean's two-dimensional surface. Only with the emergence of submarines designed for sustained submerged maneuvering and the onset of the US-Soviet Cold War did it become vital for American submarines to be able to hunt down and destroy enemy submarines beneath the seas. For this problem aimed-fire torpedoes would not suffice.

The first self-propelled or "automotive" torpedoes that entered operational service with the various European and other navies were developed in the 1860s by the Englishman Robert Whitehead.[1] In 1864, an Austrian naval captain, Giovanni Luppis, approached Whitehead with the papers of an unknown Austrian marine-artillery officer who had "conceived the idea of employing a small boat carrying a large charge of explosives, powered by a steam or an air engine and remotely steered by cables to be used against enemy ships."[2] Whitehead, then the manager of the Austrian *Stabilimento Tecnico Fiumano* factory in Fiume on the Adriatic Sea, was sufficiently impressed that he "determined to build an automatic torpedo that could run at a given depth below the surface for a reasonable distance."[3] By 1880 nearly

[1] Russian documents from this period indicate that I. F. Aleksandrovskiy developed the first successful self-propelled torpedo in 1865, a year prior to the first Whitehead torpedo, but the Russian naval ministry preferred Whitehead's design—E. W. Jolie, *A Brief History of U.S. Navy Torpedo Development* (Newport, RI: Naval Underwater Systems Center, September 1978), NUSC Technical Document 5436, p. 7.

[2] Jolie, *A Brief History of U.S. Navy Torpedo Development*, p. 7.

[3] Jolie, *A Brief History of U.S. Navy Torpedo Development*, p. 7. Whitehead's first automotive torpedo exhibited very erratic depth keeping. Within two

1500 Whitehead torpedoes had been sold to the navies of Great Britain (254), Russia (250), France (218), Germany (203), Austria (100), Italy (70) and eight other countries (which did not include the United States).[4]

The use of the term 'torpedo' to refer to these weapons, whether able to home on their targets or not, recalls the fact that they are the descendants of various classes of mines designed to attack surface ships. During the American revolutionary war, David Bushnell's discovery that gunpowder could be detonated underwater led to an unsuccessful attempt to use two small submersible vessels to fasten a 150-lb mine underneath the hull of the British flagship HMS *Eagle* in New York harbor in 1776.[5] Subsequently, the inventor Robert Fulton improved upon Busnell's primitive submersible and, in 1801, used what he termed a 'submarine torpedo' to sink a small French ship at Brest.[6]

In contrast to Whitehead's automotive torpedoes, Fulton's were neither mobile nor self-propelled. Instead, they were mines that had to be positioned under an enemy ship either by a submersible or a small boat. Fulton, however, had no luck selling his submersible to any navies, including that of the United States, and he turned to the use of explosive mines or "spar torpedoes" positioned by "torpedo" boats. During the American civil war both the Confederate and Union navies engaged in mine warfare using spar torpedoes.[7] Fulton also

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years, however, he invented a hydrostat-pendulum combination that largely solved this critical problem.

[4] Jolie, *A Brief History of U.S. Navy Torpedo Development*, p. 7. The US Navy, seeing various problems with the Whitehead torpedo, chose to develop its own designs, the first successful American example of the weapon being the Howell torpedo of 1889 (ibid., pp. 13-17). However, in the 1890s the US Navy negotiated an arrangement with the Whitehead Company for E. B. Bliss in Brooklyn to manufacture Whitehead torpedoes (ibid., p. 19).

[5] Russell Thomas, "The History of the Torpedo and the Relevance to Today's U.S. Navy," p. 1; online at the website of the U. S. Navy's Naval Undersea Museum in Keyport, WA, at <www.keyportmuseum.cnrnw.navy.mil/History_of_the_Torpedo_and_the_Relevance_to_Todays_Navy.pdf >.

[6] Jolie, *A Brief History of U.S. Navy Torpedo Development*, p. 5.

[7] Jolie, *A Brief History of U.S. Navy Torpedo Development*, p. 5. Twenty-two Union ships were sunk and twelve damaged by Confederate "torpedoes"; the Confederates lost six ships to Union "torpedoes" (ibid.).

developed a floating mine for the American navy in 1810, and eventually sold his concept to the English to use against the French, who considered the devices "immoral and indefensible."[8]

Starting in the late 1860s, however, mine and torpedo development began diverging with the advent of self-propelled torpedoes. During 1869-70, the Royal Navy conducted a series of largely successful experiments with 14-inch- and 16-inch-diameter versions of Whitehead's automotive torpedo. These trials led to an initial order for a batch of Whitehead's torpedoes followed, in 1871, by the Royal Navy's purchase of manufacturing rights for production by the Royal Laboratories at Woolwich.[9] Many other navies around the world followed the British example and began acquiring or developing their own automotive torpedoes. The attraction was the potential of the new weapon to sink capital ships by attacking them where they were most vulnerable—below the waterline.

The rapid spread of this new weapon led to the development of small, fast torpedo boats whose mission was to get close enough to ships of the line to deliver a fatal blow with what were initially short-range weapons. The Royal Navy built the first modern torpedo boat, HMS *Defender*, in 1877, and similar vessels spread quickly to other navies around the world. However, early torpedo boats had to get very close to their targets to be effective even after Whitehead's new weapon displaced spar torpedoes. Early Whitehead torpedoes had maximum ranges of only 500-600 yards. Indeed, until the introduction of gyroscopes in the early 1890s to enable free-running torpedoes to steer a constant course or azimuth, there was little tactical incentive to increase torpedo ranges and range was not considered an important performance parameter.[10] The May 1905 Battle of Tsushima, in which the Japanese fleet massacred a reinforced Russian Baltic fleet, was

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8 Thomas, "The History of the Torpedo and the Relevance to Today's U.S. Navy," p. 1.

9 Geoff Kirby, "A History of the Torpedo: The Early Days," *Journal of the Royal Navy Scientific Service*, Vol. 27, No. 1; available online at <http://www.btinternet.com/~philipr/torps.htm>, p. 6 of Microsoft Word file (no pagination in the online version).

10 Kirby, "A History of the Torpedo: The Early Days," pp. 6, 8 (Word pagination). The USN's Howell torpedo, fielded in 1892, stored energy with a large fly-wheel whose gyroscopic effects enabled the weapon to maintain a stable course (ibid., p. 17). The first gyroscopic torpedoes appeared in 1895.

decided by naval gunfire at ranges of 4,000-6,000 yards, whereas the maximum ranges of pre-gyroscope torpedoes was, at most, 4,000 yards, and the majority of these earlier weapons had ranges of 1,000 yards or less.[11]

Predictably, the threat of the torpedo boat generated a response: the development of the torpedo-boat destroyer (now known simply as destroyers). The earliest combat success by a torpedo boat appears to have been the sinking of the *Blanco Encalda* with Whitehead torpedoes on the night of April 23rd, 1891, during the Chilean civil war.[12] Four years later, in 1895, Japanese torpedo boats successfully attacked the Chinese fleet at anchor. It was this naval action that appears to have triggered the development of torpedo-boat destroyers.[13] This new class of ships, whose role by the eve of World War I was to screen the fleet battle-line of dreadnoughts and cruisers from enemy torpedo-boat attacks, was armed with torpedoes as well as guns.[14]

By the eve of World War I, torpedoes had evolved into fairly formidable weapons. The 21-inch diameter Weymouth Mark II offered a range of 10,000 yards at 29 knots and torpedo speeds up to 45 knots had been demonstrated. Furthermore, the first "pattern runners"—torpedoes that could track a heading for a preset distance and then zig-zag back and forth across that heading—had been developed, the

[11] Wayne P. Hughes, Jr., *Fleet Tactics and Coastal Combat* (Annapolis, MD: Naval Institute Press, 2000), p. 69; Kirby, "A History of the Torpedo: The Early Days," pp. 17-18 (Word pagination). "The Japanese ships were superior in speed and armament, and, in the course of the two-day battle, two-thirds of the Russian Fleet was sunk, six ships were captured, four reached Vladivostok, and six took refuge in neutral ports" ("Tsushima, Battle of," *Encyclopædia Britannica*, accessed April 16, 2006, at <http://wwwa.britannica.com/eb/article-9073639>).

[12] Kirby, "A History of the Torpedo: The Early Days," p. 18 (Word pagination). Built in England in 1875, the *Blanco Encalda* had a displacement of 3,560 tons and a main battery of 8-inch guns. The torpedoes sent the *Blanco Encalda* quickly to the bottom with 180 officers and men. However, the *Blanco Encalda* was without torpedo nets that night and none of her watertight doors were closed when she was torpedoed (ibid.).

[13] Jolie, *A Brief History of U.S. Navy Torpedo Development*, p. 28.

[14] The US Navy's first torpedo-boat destroyer, the USS *Bainbridge*, was launched in 1901, displaced 420 tons, had a maximum speed of 29 knots, and was armed with 3-inch guns and two 18-inch torpedo tubes (Jolie, *A Brief History of U.S. Navy Torpedo Development*, p. 28).

Royal Navy was conducting some 8,000 test shots a year and achieving a 98 percent hit rate, and, finally, torpedoes had become the primary offensive armament of submarines.[15] Yet, despite all that had been achieved by the British and other navies, torpedoes were fundamentally aimed projectiles. They remained so until World War II, when the Germans introduced the first homing torpedo, the G7e/T4 *Falke*, which homed on the sound generated by cavitation from the target's propellers.[16] Nevertheless, even with aimed weapons, the German submarine or *Unterseeisch-Boot* (U-boat) proved a formidable threat to Great Britain during the First World War. The German effort to blockade England with unrestricted submarine warfare on merchant shipping, belatedly resumed in February 1917, came perilously close to success, and might well have succeeded had the British not finally embraced the convoy system.[17]

During World War II, the vast majority of the torpedoes expended by submarines were also free-running munitions, meaning that they did not home on their targets but were aimed. Whitehead's development of a hydrostat-pendulum combination enabled torpedoes to run at a constant, set depth under the water, thus reducing the targeting problem against a surface vessel to accurate aiming against a target moving in a two dimensional plane.[18] Once gyroscopic devices had been introduced to enable free-running torpedoes to hold a steady

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[15] Kirby, "A History of the Torpedo: The Early Days," pp. 22-23 (Microsoft Word pagination).

[16] Cavitation is the formation and collapse of vapor bubbles on propeller blades. The collapse of the bubbles generates noise. Cavitation occurs on propellers that are heavily loaded in order to propel a vessel through the water. The German 21-inch (53.3 centimeter) T5 *Zaunkönig* acoustic-homing torpedo was launched on a collision-course bearing toward the target and then began homing when it got close enough to detect cavitation noise around 24,500 Hertz (Sternhell and Thorndike, *Antisubmarine Warfare in World War II*, p. 161; "German Torpedoes of World War II," February 19, 2006, at <http://www.navweaps.com/Weapons/WTGER_WWII.htm>, accessed April 18, 2006).

[17] Sternhell and Thorndike, *Antisubmarine Warfare in World War II*, p. 1. Of course, the biggest downside of the U-boat campaign had been the sinking of ocean liners with American citizens on board, which had eventually drawn the United States into the War on Britain's side.

[18] Kirby, "A History of the Torpedo: The Early Days," pp. 4-5 (Word pagination).

course, the targeting problem for a submarine against a surface ship boiled down to selecting the correct azimuth or direction in which to fire the torpedo so that it would intercept the target vessel. Calculating the "gyro angle" for a collision course with a surface target involved a number of variables: the torpedo's speed; the submarine's course and speed; and the target's length (stem to stern), course, speed, aspect angle relative to the submarine, and range and bearing from the submarine. The ideal geometry for the submarine was a "beam" shot from the target's side (a 90 degree aspect angle), and straight-running torpedoes had a reasonable hit probability at ranges as great as 7,000 yards.[19] During World War I, the attacking submarine typically had to meet a precise release time and position for an accurate shot, and manual means of computation, such as circular slide rules, were developed to make the required targeting calculations. In World War II, more automated methods were developed, the most sophisticated being the American Mark III TDC (target data computer), whose position keeper enabled US fleet submarines to fire accurately without first estimating a future firing position and steering to that position.[20] However, because the German U-boats running on the surface could also detect Allied radars, they could usually escape by submerging, at which point they were no longer vulnerable to unguided torpedoes.

The two-dimensional, flat-plane targeting problem faced by submarines (or surface ships) employing torpedoes was sufficiently constrained for aimed fire. The challenge that prompted the US Navy to engage Bell Telephone Laboratories in December 1941 to develop a homing torpedo was a different problem: attacking a submerged submarine from the air. By the summer of 1941, the struggle between the German U-boats and the Royal Navy was already in its third phase, and the US Navy had not yet joined the British in conducting convoy operations.[21] During the first phase, September 1939-June 1940, the U-boats, largely operating individually and attacking submerged, had rapidly escalated to unrestricted submarine warfare, which included

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[19] Kirby, "A History of the Torpedo: The Early Days," p. 11 (Word pagination).

[20] The Mark III TDC was linked to the targeting systems in the torpedo rooms, which enabled the gyro angles to be continuously updated to the moment of firing.

[21] The USN joined the British convoy effort in mid-1942 (Sternhell and Thorndike, *Antisubmarine Warfare in World War II*, p. 81).

attacks on neutral merchant ships. In response, the British had introduced the convoy system. During the second phase, July 1940-March 1941, the U-boats had abandoned daytime attacks by individual submarines running submerged in favor of surface attacks at night. The U-boats had also turned increasingly to attacking in groups or "wolf packs" due to the higher losses experienced by U-boat commanders attacking convoys individually.[22] In the third phase, April-December 1941, the German submarines managed to lower their monthly losses compared to the second phase while tripling the number of U-boats at sea in the Atlantic from an average of 10 to 30, but the growing effectiveness of Allied convoys offset the increased U-boat strength, reducing the gross tonnage lost to them from about 224,000 to 175,000 tons a month.[23] Part of the reason for these trends appears to have been the increasing success of patrol aircraft in "harassing and damaging U-boats" after locating them with radar.[24] However, U-boats running on the surface could detect Allied surveillance radars and submerge, at which point the weapons carried by the aircraft were useless.[25] This tactical problem was the impetus that led to the development of the first American guided munition of World War II, the Mark-24 FIDO "mine," which was the first of three passive acoustic-homing torpedoes that saw operational service with the US Navy during the war (the other two being the Mark-27 and Mark-28 torpedoes).[26]

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[22] Sternhell and Thorndike, *Antisubmarine Warfare in World War II*, p. 8.

[23] Sternhell and Thorndike, *Antisubmarine Warfare in World War II*, pp. 15, 22-23. During both July 1940-March 1941 and April-December 1941, U-boats accounted for just over half of the gross Allied tonnage lost to enemy action (ibid.).

[24] Sternhell and Thorndike, *Antisubmarine Warfare in World War II*, p. 24.

[25] A. C. Dickieson, "Early 'Smart Bombs' at Bell Labs," *Vintage Electrics*, Southwest Museum of Engineering, Communications and Computation, Vol. 3, No. 1; accessed April 18, 2006, available online at <http://www.smecc.org/early_'smart_bombs'_at_bell_labs.htm>.

[26] Milford, "U.S. Navy Torpedoes," Pt. 4, "WW II Development of Homing Torpedoes 1940-1946," p. 69. The Mark-24 was designated a mine for security reasons. The other two homing torpedoes used by the USN during World War II were the Mark-27 CUTIE and the Mark-28 (ibid., p. 68). In addition, the US Navy developed two active acoustic-homing torpedoes during 1941-45, the Mark-22 and Mark-32 (ibid., pp. 69-70, 77-79).

Figure 10: Mark-24 FIDO "Mine"[27]

Creation of the organizational and scientific foundation for the development of FIDO was begun in July 1940, in the aftermath of the fall of France, with the establishment of the National Defense Research Committee (NDRC). The NDRC was created, at the urging of Vannevar Bush, "to correlate and support scientific research on the mechanisms and devices of warfare."[28] Bush became the NDRC chairman, reporting only to President Franklin D. Roosevelt. In May 1941, the NDRC was superceded by the Office of Scientific Research and Development (OSRD). The new OSRD was also run by Bush, again reporting directly to the president, and enjoyed unrivaled authority for access to funding, resources, and people during the Sec-

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27 The US Naval Undersea Museum is located in Silverdale, WA. The Mark-24 was 19 inches in diameter, 84 inches long, weighed 680 lbs, contained a 92-lb HBX-1 warhead, had a speed of 12 knots and ten minutes duration (~4,000 yards), and used contact fuzing.

28 The White House, "Order Establishing the National Defense Research Committee," approved by Roosevelt June 27, 1940, p. 1; available online at <http://en.wikipedia.org/wiki/National_Defense_Research_Committee>. Bush, then director of the Carnegie Institution, had seen the lack of cooperation between civilian scientists and the military during World War I. He met with Roosevelt on June 12, 1940, to urge the creation of a group with the authority and money to develop new weapons using the best talent in the country. Roosevelt approved the recommendation within ten minutes, and the eight-member NDRC held its first official meeting on July 2, 1940 (ibid). The only area of wartime research and development exempted from NDRC control was aeronautics, which remained with the National Advisory Committee for Aeronautics.

ond World War.[29] Among the OSRD's wartime projects were the development of radar, proximity fuzes, the atomic bomb, and acoustic-homing torpedoes.[30]

While the NDRC and OSRD clearly circumvented the prior bureaucratic arrangements of the War and Navy Departments, it opened the door to the rapid development of innovative weaponry. In the case of the Mark-24, the project began with an NDRC-requested meeting at Harvard University on December 10, 1941, to explore the possibility of a homing torpedo; in May 1943, only 17 months later, the Mark-24, which had been developed by a consortium largely outside auspices of the US Navy's ordnance bureau or the Newport torpedo station, scored its first combat kill against a German U-boat.[31] In hindsight, it is likely that a much longer gestation period would have been required if development of the first US homing torpedo had been left entirely to the US Naval Torpedo Station (USNTS) at Newport.[32] Indeed, given the USNTS' longstanding focus on non-homing torpedoes and the serious problems that emerged after the United States entered World War II in the Pacific with Newport's Mark-14 torpedo, it is possible that, without the NDRC's involvement, the US Navy might well have failed to field an operational homing torpedo before the end of the war.

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[29] "Office of Scientific Research and Development," online at <http://en.wikipedia.org/wiki/Office_of_Scientific_Research_and_Development>. The OSRD was not formally put into law until June 28, 1941.

[30] As Westrum wrote in 1999, "*The most important invention of the war was OSRD itself [italics in original]*"—Ron Westrum, *Sidewinder: Creative Missile Development at China Lake* (Annapolis, MD: Naval Institute Press, 1999), p. 17. It is fair to say that OSRD produced "an effective partnership of scientists, engineers, industrialists, and military men, such as was never seen before"—Vannevar Bush in James Phinney Baxter, 3rd, *Scientists against Time* (Cambridge, MA: MIT Press, 1946), p. xvi.

[31] Milford, Pt. 4, "WW II Development of Homing Torpedoes 1940-1946," pp. 72-73. The Mark-24 was developed by a group that included Western Electric, Bell Telephone Laboratories (Murray Hill), Harvard University Underwater Sound Laboratory, and General Electric. Western Electric and General Electric produced the torpedo.

[32] Jolie, *A Brief History of U.S. Navy Torpedo Development*, p. 9. The Newport torpedo station was established in 1869 on Goat Island in Newport, Rhode Island.

The Mark-14 was the principal torpedo used by US Navy submarines during World War II. It had been developed during the 1930s by the Newport Torpedo Station.[33] However, operational experience by US submarines in the Pacific eventually revealed three major deficiencies in the Mark-14.[34] Tests conduced by operational submarines based in Australia in mid-1942 confirmed what many submarine skippers had begun to suspect: that the Mark-14 ran deeper than its set depth—an average of some 10-11 feet deeper, in fact.[35] Further tests and combat experience revealed, by April 1943, that the Mark-14's magnetic-influence exploder was defective and, in mid-1943, that its contact exploder was also prone to fail when the impact angle approached 90 degrees, a perfect shot.[36]

Due to an unfortunate confluence of personalities and bureaucratic inertia, it took 21 months of war to isolate and correct all of the Mark-14's defects—four months longer than it took the OSRD to develop and field the Mark-24 from scratch.[37] Part of the reason it took the Newport Torpedo Station so long was that each problem masked the remaining ones. Running deeper than set, for example, was sufficient to explain early wartime lack of success and gave no hint that both exploders were defective as well. Nor was it surprising that the Mark-14 went into service with major defects. The German experienced similar problems early in World War II. Furthermore, prior to December 1941, the US Navy's total wartime experience with 20th century torpedoes apparently consisted of a mere eleven firings against

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33 Frederick J. Milford, "U.S. Navy Torpedoes," Pt. 2, "The Great Torpedo Scandal, 1941-43," *The Submarine Review*, October 1996, pp. 81, 82. While the Mark-14, like the Mark-13 and Mark-15 torpedoes, had "significant problems," once the defects were identified and fixed, they remained in service long after World War II. The Mark-14 remained in the active inventory until 1980 (ibid., p. 82).

34 The older Mark-10 torpedoes proved a "nightmare" in combat during World War II—Clay Blair, Jr., *Silent Victory: The U.S. Submarine War against Japan* (New York: Bantam Books, 1975), p. 345. Their warheads detonated prematurely, they ran erratically, and exhibited other problems.

35 Blair, *Silent Victory*, pp. 20, 160, 274-278, 292; also, Milford, Pt. 2, "The Great Torpedo Scandal, 1941-43," pp. 83-87.

36 Blair, *Silent Victory*, pp, 413-15, 437-38; also, Milford, Pt. 2, "The Great Torpedo Scandal, 1941-43," pp. 87-90.

37 Blair, *Silent Victory*, pp. 136, 140-41, 170-71, 206, 216, 225-227, 280-281, 348, 367, 401-04, 414-415.

German U-boats during the First World War, and, even after operational units began experiencing problems with the Mark-14 on combat patrols, the USNTS resisted realistic testing.[38] "The scandal," as Frederick Milford has written, "was not that there were problems in what was then a relatively new weapon, but rather the refusal by the ordnance establishment [ashore] to verify the problems quickly and make appropriate alterations."[39] As Clay Blair observed in 1975, each of the Mark-14's major defects was largely "discovered and fixed in the field—always over the stubborn opposition of the [Navy's] Bureau of Ordnance."[40]

By comparison, Bell Telephone Laboratories and its partners were able to get an effective homing torpedo into operational service before Newport managed to fix the Mark-14. Moreover, in doing so the civilians scientists had to overcome greater engineering challenges than those the USNTS faced with the Mark-14's defects. The electronics connected to the four hydrophones the Mark-24 used to home on propeller cavitation contained 21 vacuum tubes, but in early 1942 no one knew whether you could drop a vacuum-tube system into the water at 300 knots and have it work.[41]

Not only did the civilians get the first US homing torpedo to work, but both the Mark-24 and the follow-on Mark-27 CUTIE, whose wartime versions were designed to go against escort vessels rather than submerged submarines, achieved decent combat results. In American hands, the Mark-24 was credited with sinking 31 U-boats and damaging 15 more in the course of 142 attacks (for a 32 percent hit rate).[42] By the end of World War II, 106 Mark-27s had been fired against enemy escorts, achieving 33 hits (24 enemy escorts sunk and

[38] Milford, Pt. 2, "The Great Torpedo Scandal, 1941-43," p. 82.

[39] Milford, Pt. 2, "The Great Torpedo Scandal, 1941-43," p. 83.

[40] Blair, *Silent Victory*, p. 439; Milford, Pt. 2, "The Great Torpedo Scandal, 1941-43," p. 92.

[41] Dickieson, "Early 'Smart Bombs' at Bell Labs."

[42] Milford, Pt. 4, "WW II Development of Homing Torpedoes 1940-1946," footnote 10, p. 75. As will be seen later in this chapter, the Mark-24's hit rate in World War II was roughly triple that achieved by the AIM-7 against North Vietnamese fighters during 1965-73.

nine others damaged) for a 31 percent hit rate.[43] Given the technical challenges, especially with the first of these new weapons, Milford appears justified in judging FIDO in particular to have been "a major success whose achievements have long gone unheralded."[44]

Through the end of World War II, then, torpedoes were used primarily to sink surface ships. The Mark-24, an air-delivered torpedo, was credited with only 31 (4.2 percent) of the estimated 733 German U-boats sunk during 1939-45.[45] So as innovative as FIDO was, it by no means won the battle against the U-boat. Moreover, the submarine-on-submarine use of torpedoes that was advanced as the focus of this discussion did not occur during the Second World War. The shift in the primary targets for torpedoes from surface vessels to submerged submarines maneuvering in three dimensions came with the emergence of the US-Soviet Cold War, although this change was triggered by German advances in submarine design late in the war (after the Allies had won Battle of the Atlantic).

The initial impetus in this shift was the development of German Type XXI diesel-electric submarine. At the culminating point of the Battle of the Atlantic in mid-1943, the workhorse of the German submarine fleet was the Type VIIC U-boat.[46] The Type VIIC, however, was more of a temporarily submersible boat than a true submarine. Its submerged speed was only some 7 knots, whereas it could make 17-18 knots on the surface, and its crush depth was about 200 meters. These characteristics forced the Type VII to operate close to the surface. By comparison, the Type XXI incorporated three design changes that "radically" improved its capacity for submerged operations: greater battery capacity, a hydrodynamic hull form that enabled the submarine to go about two knots faster submerged than its 15-knot

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43 Milford, Pt. 4, "WW II Development of Homing Torpedoes 1940-1946," pp. 75-76.

44 Milford, Pt. 4, "WW II Development of Homing Torpedoes 1940-1946," p. 75.

45 Sternhell and Thorndike, *Antisubmarine Warfare in World War II*, p. 80.

46 The Type VII constituted nearly half of the some 1,500 U-boats the Germans produced before and during World War II (Sternhell and Thorndike, *Antisubmarine Warfare in World War II*, p. 80; "Type VII U-Boat," online at <http://www.uboataces.com/uboat-type-vii.shtml>, accessed April 19, 2006).

speed on the surface, and a snorkel that allowed the main diesel engine to breath from periscope depth.[47]

These features negated key antisubmarine warfare (ASW) capabilities the British and Americans had employed to defeat the U-boat threat in 1943. The wolf-pack tactics that the Germans had initiated against Atlantic convoys in 1941 were predicated on the U-boat's ability to operate in groups on the surface in close proximity to the convoys at night. An important element of the Allied response to these tactics was to integrate microwave radar and homing torpedoes on long-range aircraft, primarily B-24s flying out of Newfoundland, Iceland, and Northern Ireland.[48] The Type XXI's snorkel took away the large radar cross section upon which Allied long-range ASW aircraft had depended for target acquisition. This ability to run at periscope depth, when coupled with a hull form optimized for submerged speed, restored the submarine's tactical mobility.

When the fighting in Europe ended in May 1945, over 110 German Type XXI diesel-electric submarines had been commissioned, although no more than a couple are thought to have begun combat patrols before the war ended. Examples of the Type XXI fell into American, British, and Soviet hands, and the US Navy soon "discovered that it would face a major ASW challenge if the Soviet Navy built large numbers of ocean-going Type XXIs."[49] During 1945-50 the US Navy "expected that the Soviets, a continental power like Germany with both limited access to and dependence upon the sea, would focus their maritime efforts on interdicting Allied sea lines of communications by deploying a large force of modern submarines."[50] Thus, the US Navy anticipated that the Soviet Navy would field substantial numbers of new submarines incorporating the advanced features of the Type XXI U-boat. In 1946, US naval intelligence forecast a Soviet force of 300 Type XXI equivalents by 1950.[51]

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[47] Owen R. Cote, Jr., *The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines* (Newport, RI: Naval War College, 2003), Newport Papers No. 16, p. 13.

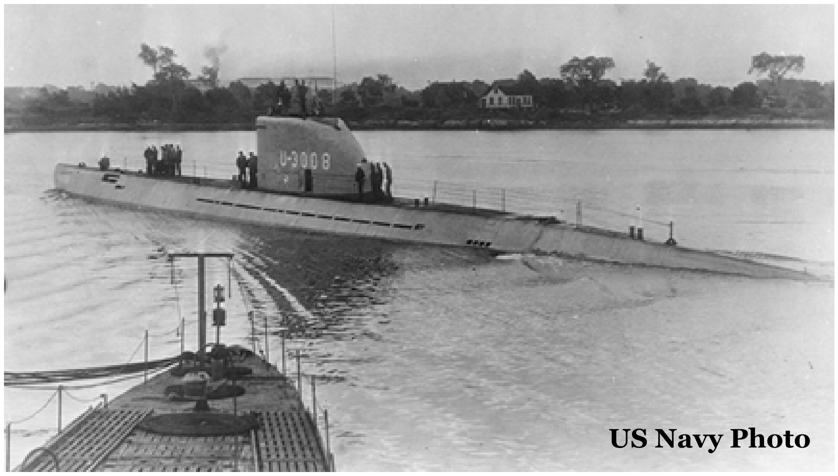
[48] Cote, *The Third Battle*, pp. 10-11.

[49] Cote, *The Third Battle*, p. 14.

[50] Cote, *The Third Battle*, p. 15.

[51] Cote, *The Third Battle*, p. 18.

Figure 11: USS *U-3008* Off the Portsmouth Naval Shipyard, ME, August 1946[52]



This Soviet threat did not materialize as anticipated. The two new diesel submarine classes the Soviets began deploying after World War II were the Whiskeys and Zulus (their NATO code names). The USSR built over 230 Whiskey-class submarines between 1949 and 1958, but they were fundamentally coastal-patrol designs that, even when equipped with cruise missiles, did not realize the potential of the German Type XXI. The Zulu, on the other hand, "was a true Type XXI, equipped with a snorkel, capable of 16 knots submerged, and possessing the size, habitability, and range necessary for long-range, blue-water interdiction operations."[53] While sources vary on the number of these attack submarines built between 1949 and 1958, the total was no more than 28, a half dozen of which were converted to carry R-11FM (SS-1b Scud) missiles, making the Zulu the USSR's first ballistic missile submarines.[54] Subsequently, nuclear propulsion en-

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[52] Completed at Bremen during the final weeks of World War II in Europe, *U-3008* was surrendered at Kiel in May 1945, sailed to the United States, and placed in service with the USN as a test vehicle.

[53] Cote, *The Third Battle*, p. 18.

[54] Pavel Podvig (ed.), Oleg Bukharin, Timur Kadyshev, Eugene Miasnikov, Igor Sutyagin, Maxim Tarasenko, and Boris Zhelezov, *Soviet Strategic Nuclear Forces* (Cambridge, MA: The MIT Press, 2001), pp. 283-286, 309-31; "Project 611 Zulu Class," accessed April 19, 2006, at <http://www.globalsecurity.org/military/world/russia/611.htm>. The ballis-

abled submarines to remain submerged for weeks or months, thereby intensifying the potential of Soviet submarines to threaten the sea lines of communications between North American and Western Europe as well as posing the threat of a nuclear strike on the continental United States.

Even before the first nuclear submarines, however, the US Navy's overall response to the perceived threat posed by advanced Soviet submarines set the stage for the development, by the late 1950s, of an innovative approach to antisubmarine warfare that would give US submarines and ASW forces large margins of acoustic advantage over the Soviets—margins of advantage that the US Navy was able to sustain throughout what Owen Cote has termed the "happy time" of 1960-80.[55] The main components of this asymmetric advantage were: (1) passive-acoustic, long-range SOSUS (Sound Surveillance System) arrays, consisting of hydrophones spaced along undersea cables, which were eventually deployed worldwide as part of a forward-barrier strategy; (2) quiet, ASW-optimized nuclear-powered attack submarines (SSNs), of which the nuclear-powered *Thresher* (SSN-593), with its tear-drop hull of high-yield (HY80) steel and single screw, was the first example; and (3) signal-processing techniques such as Jezebel/Codar/Julie, which gave land-based patrol aircraft the ability to search areas SOSUS identified as probably containing Soviet submarines quickly enough to localize them using low-frequency sonobuoys and then prosecute attacks against them.[56] In light of this overall approach, the quiet American nuclear submarine emerged not only as the "near-optimum" sonar and ASW platform against Soviet submarines transiting into the open ocean past SOSUS barriers, but as an

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tic missiles on the converted Zulus were one-stage Scuds with a maximum range of only 150 kilometers.

[55] Cote, *The Third Battle*, pp. 41, 44-45.

[56] Cote, *The Third Battle*, pp. 25, 26-28, 32, 41. Cold War SOSUS focused on low-frequency, narrowband tonals propagating outward horizontally along the deep-sound channel from Soviet submarines (ibid., 81). During the "happy time" of 1960-80, LOFAR (low-frequency analysis and ranging) signal processing and the use of towed arrays also enabled the US Navy to create and maintain a signature library of Soviet submarines (ibid., p. 49).

effective response to the USSR's attack and ballistic-missile submarines.[57]

The emergence, starting in the late 1950s, of the first Soviet submarines armed with nuclear ballistic missiles gave even greater urgency to being able to target submerged Soviet submarines. Whether the attack was to be prosecuted by a patrol aircraft or a submarine, the ability of enemy submarines to maneuver underwater in three dimensions to depths of 2,000 feet or more clearly required guided solutions–torpedoes capable of actively homing on the target. Constant-depth, straight-running torpedoes were virtually useless in the face of this new threat. Against a fast, deep-running submarine such as the Soviet Alpha SSN, the torpedo either needed to be able to home in three dimensions, or else carry a nuclear warhead large enough to compensate for initial aiming errors.[58]

These realities were not lost on the American submarine community during the late 1940s and early 1950s as submariners and intelligence analysts contemplated the likely threats stemming from Soviet access to the German Type XXI as well as the potential of nuclear-power to produce true submarines, as opposed to submersibles confined to operating on or near the ocean surface except when forced deeper to escape enemy ASW forces.[59] As Frederick Milford observed in 1997, the homing concept was "so attractive" that "only one new non-homing torpedo has entered service with the US Navy since 1944," and that sole exception was the unguided Mark-45, which featured a low-yield nuclear warhead (probably less than 20 kilotons).[60]

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[57] Cote, *The Third Battle*, p. 43. For a declassified account of a mission in 1978 during which the USS *Batfish* (SSN-681) managed to shadow a Soviet *Leninets*-class SSBN (NATO code named Yankee) for 50 days undetected while the Soviet "boomer" patrolled off the east coast of the United States, see Thomas B. Allen, "Run Silent, Run Deep," *Smithsonian*, March 2001, pp. 50-58, 60-61.

[58] The Soviet Alpha SSN, which appeared in 1970, was estimated to have a top submerged speed of 45 knots and, due to its titanium pressure hull, the ability to operate as deep as 2,000-2,500 feet (Cote, *The Third Battle*, p. 59).

[59] The US Navy made the decision to develop what became the first nuclear submarine, *Nautilus*, in 1949 (Cote, *The Third Battle*, p. 19).

[60] Milford, Pt. 4, "WW II Development of Homing Torpedoes 1940-1946," p. 1. The Mark-45 Anti-Submarine Torpedo Ordnance Rocket (ASTOR) was wired-

What emerges in the case of the US Navy torpedoes following World War II is that American submariners, along with their ASW counterparts flying maritime patrol aircraft, were confronted with a challenge from Soviet submarines that could not be solved with aimed-fire munitions. Consequently, they embraced guided weapons as early as they could and never looked back. The challenge of a stealthy platform operating in three dimensions down to depths of 1,000 feet or more in the relatively opaque medium of the world's seas and oceans left the US Navy with little choice, especially for submarine-on-submarine engagements. Short of resorting to nuclear weapons, guided munitions were the only viable solution for American attack submarines hunting Soviet submarines that could operate submerged for extended periods of time. By assigning individual American SSNs large operating areas to ensure procedurally that no other US submarines operated in those areas, the US Navy minimized the chances of inadvertent "Blue-on-Blue" engagements. However, if the United States and the USSR had gone to war after the 1950s, any chance of early success against Soviet submarines—particularly sinking Soviet nuclear-powered ballistic-missile submarines (SSBNs or "boomers") before they could fire their nuclear missiles at targets in the United States—would have required guided torpedoes.[61] The post-World War II shift of the critical targets for torpedoes from surface ships confined to the two-dimensional plane of the ocean's surface to submarines able to maneuver freely throughout the three-dimensional undersea medium dictated the early adoption of guided munitions. Today's Mark-48 ADCAP enjoys a speed advantage over the fastest nuclear submarines and can reach to depths greater than 2,000 feet.

Solid-State Microelectronics

Part of the motivation for the extensive exploration of early torpedo history was to highlight some of the key technological developments that eventually produced the Mark-24 and provided the proof-of-concept for subsequent American guided torpedoes. Whitehead's hy-

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guided and command-detonated when within range of its target—Chuck Hansen, *U.S. Nuclear Weapons: The Secret Story* (Arlington, TX: Aerofax, 1988), p. 207. According to Hansen, the Mark-45 ASTOR was the only nuclear torpedo ever deployed by the US Navy and he gives the yield as 10-15 kilotons (ibid., p. 208).

[61] Allen, "Run Silent, Run Deep," p. 53.

drostat-pendulum, which enabled his torpedoes to run at a set depth, and the introduction of gyroscopic devices to keep them on a set azimuth, were important technical achievements that led to the emergence of modern ASW torpedoes such as the Mark-48 and Mark-48 ADCAP.[62] Before turning to air-intercept missiles for fighter-versus-fighter combat, there are several developments in solid-state electronics and computers worth recalling because of their importance to virtually all modern sensors, guided munitions, and battle networks. At the heart of these developments are three post-World War II inventions:

(1) the transistor,

(2) the integrated circuit, and

(3) the microprocessor or microchip.

During late 1947 and early 1948 William Shockley, Walter Brattain, and John Bardeen developed the first germanium transistors at Bell Telephone Laboratories in Murray Hill, New Jersey. Shockley was the team leader of Bell Labs' effort to develop a solid-state amplifier. His team's invention of the point-contact transistor during the "miracle month" November 17-December 23, 1947, followed by Shockley's invention of the junction transistor during January-February 1948, constituted a triumph of post-World War II solid-state physics based on "a firm foundation of quantum mechanics and a broad understanding of atomic and crystalline structure."[63] By late June 1948

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[62] Since its introduction in 1972, the Mark-48 has become the standard torpedo for all US attack and ballistic-missile submarines. The Mark-48 is a 21-inch weapon, weighs 3,400-3,700 lbs, carries a 650-lb warhead, and offers three guidance modes (wire, passive acoustic, and active acoustic). It replaced both the unguided Mark-14 as well as the guided Mark-37, which is frequently described as the "first modern ASW torpedo" (Frederick J. Milford, "U.S. Navy Torpedoes," Pt. 5, "Post-WW-II Submarine Launched/Heavyweight Torpedoes," *The Submarine Review*, July 1977, p. 75. The Mark-48 ADCAP was fielded in 1988. For pictures of a 1999 Mark-48 war-shot from the Australian submarine HMAS *Farncomb* against a 28-year-old destroyer escort, see <http://www.dcfp.navy.mil/mc/presentations/Mark-48/Mark-481.htm>, accessed August 24, 2006.

[63] Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Invention of the Transistor and the Birth of the Information Age* (New York: W. W. Norton, 1997), pp. 109-114, 120-141, 148-161, 192-194, 282; and Robert Buderi, *The Invention That Changed the World: How a Small Group of Radar Pioneers*

two classic papers by Bardeen and Brattain describing these inventions had been accepted for publication in the July 15 issue of *Physical Review*, and on June 30 Bell Labs held a press conference announcing the transistor's invention.[64]

By the early 1950s germanium transistors were starting to supplement or replace vacuum tubes in military systems. The engineering incentives behind these changes were not, initially at least, cost or switching speed—areas in which the early transistors were inferior to vacuum tubes—but the transistor's smaller size, lower power consumption and heat production, and greater reliability.[65] One of the earliest military applications of the transistor was in the AN/TSQ data transmitters used to control the US Army's Nike-Ajax surface-to-air missiles deployed to defend the United States against Soviet long-range bombers carrying atomic bombs.[66] While these data transmitters used both vacuum tubes and transistors, the incorporation of large numbers of transistors made them five times smaller and cut their power requirements to one-eighth that of wholly vacuum-tube devices.[67] Given advantages this dramatic, there was every incentive to move rapidly toward solid-state computers and in 1954 engineers from Bell Telephone's Whippany laboratory built the first fully transistorized computer for the US Air Force.[68]

In the long run, however, germanium was not the element on which computers in the second half of the 20th century would be

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Won the Second World War and Launched a Technical Revolution (New York: Touchstone, 1997), pp. 308-333.

64 Riordan and Hoddeson, *Crystal Fire*, pp. 163-167. Shockley, Bardeen and Brattain shared the 1956 Nobel Prize in physics "for their researches on semiconductors and their discovery of the transistor effect." By then only Brattain was still working at Bell Labs. Shockley had moved to what would become California's Silicon Valley, where he founded Shockley Semiconductor. Bardeen was at the University of Illinois.

65 Riordan and Hoddeson, *Crystal Fire*, p. 202.

66 For purposes of North America air defense in the 1950s, Nike-Ajax batteries were integrated with interceptors through MITRE's Semi-Automatic Ground Environment (SAGE) system, which was the first major, real-time, computer-based command-and-control system.

67 Riordan and Hoddeson, *Crystal Fire*, p. 203.

68 Riordan and Hoddeson, *Crystal Fire*, p. 204.

based. Silicon is more reactive and much more difficult to work with than germanium; however, silicon is more plentiful and, most crucially, retains its electrical properties at temperatures above 75°C (167°F), the point at which germanium transistors quit working altogether.[69] Because the armed services were the biggest users of the early transistors and needed reliable performance even in high temperatures or humidity, there were strong incentives to develop methods for the growing and doping of large silicon crystals. Gordon Teal had worked on this problem during his last two years at Bell Labs, but it was only after he joined Texas Instruments in 1952 that he was able to put together the team that produced the first grown-junction silicon transistors.[70] By October 1954, Texas Instruments had used Teal's breakthrough to market the first commercial transistor radio.

The next major step forward in solid-state electronics was the independent invention of the integrated circuit by Jack Kilby at Texas Instruments in 1958, and by Robert Noyce at Fairchild Semiconductor in 1959. The underlying problem was that the digital computers and switching networks being developed by this time required thousands of transistors, each with two or three leads that had to be attached to the circuitry (a tedious task done largely by assembly lines of women because of their greater manual dexterity).[71] Printed circuit boards, which became commonplace during the 1950s, attempted to address the explosion of interconnections, but eventually a few visionary engineers began looking for way to eliminate individual components and wire leads altogether. In realizing what became known as the "monolithic integrated circuit," Kilby and Noyce showed that integrated circuits could be built from a single slice of semiconductor material.[72] Noyce's use of diffusion and photolithography processes not only promised to eliminate a tremendous amount of labor and production cost, but led to the realization that it was "possible to make hundreds of transistors on a single silicon wafer."[73] By the mid-1960s, the light

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[69] Riordan and Hoddeson, *Crystal Fire*, pp. 207-208.

[70] Riordan and Hoddeson, *Crystal Fire*, pp. 206, 208-209.

[71] Riordan and Hoddeson, *Crystal Fire*, pp. 254-255.

[72] Riordan and Hoddeson, *Crystal Fire*, pp. 255, 259, 262-263, 265. Kilby's flip-flop integrated circuit used crystalline germanium and incorporated two transistors; Noyce's used silicon.

[73] Riordan and Hoddeson, *Crystal Fire*, p. 264.

weight, small size, and high reliability of integrated circuits had made them very important in the National Aeronautics and Space Administration's Apollo program and in military systems like the Minuteman ICBM and the Polaris SLBM.[74]

The final breakthrough in the development of the hardware underlying solid-state electronics and modern computers was, of course, was the invention of the planar microprocessor. In the summer of 1968 Noyce and Gordon Moore, who had grown unhappy with the situation at Fairchild Semiconductor, left the company to found the Intel Corporation in Mountain View, California. Noyce and Moore described Intel (the name shortened from **Int**egrated **El**ectronics) as a "community of common interests," and in 1969 the company marketed its first money-making product, the 3101 Schottky bipolar, 64-bit random access memory (RAM) chip. The following year, 1970, Intel produced the 1103 dynamic random access memory chip, which was the first of the commercial memory chips that subsequently enabled the explosive growth of personal computers. Then, in 1971, Federico Faggin, Marcian E. (Ted) Hoff, and Stan Mazor developed the first microprocessor, the Intel 4004, which contained over 2,300 transistors. The Intel 4004 provided roughly the same computational capacity as the massive (over 30 tons) World War II ENIAC (Electronic Numerical Integrator and Computer), but in a package that measured only 1/8th by 1/6th inches.[75] Whereas integrated circuits could neither change programs nor remember anything, the 4004 chip could do both.

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74 Riordan and Hoddeson, *Crystal Fire*, p. 283.

75 Mary Bells, "Intel 4004: The World's First Single Chip Microprocessor," available at <http://inventors.about.com/library/weekly/aa092998.htm>, accessed April 21, 2006. ENIAC was one of the earliest all-electronic computers. Designed to compute ballistic firing and bombing tables for the Army in World War II, it began partial operations in June 1944 (Martin H. Weik, "The ENIAC Story," *Ordnance*, January-February 1961, online at <http://ftp.arl.mil/~mike/comphist/eniac-story.html>, accessed August 24, 2006). ENIAC employed 19,000 vacuum tubes, 1,500 relays, hundreds of resistors, capacitors, and inductors and consumed almost 200 kilowatts of electricity when operating at full blast (ibid.). It required bushel baskets of spare vacuum tubes to be kept on hand to replace the ones that were constantly burning out and, because it could not store a program, had to be rewired for each new computational problem (Riordan and Hoddeson, *Crystal Fire*, p. 200).

Even before Intel was founded, Gordon Moore had made the empirical observation that the number of transistors on in an integrated circuit had doubled every twelve months from 1959 to 1965, and he speculated that this periodic doubling would persist at least through 1975.[76] While Moore later adjusted the period for this doubling to 18 months, the trend he identified, now known as "Moore's law," has continued down to the present, and no end to this exponential increase in computational capacity is yet in sight.[77] As Michael Riordan and Lillian Hoddeson noted in 1997, this "sustained explosion" in microchip complexity and capacity "has no convenient analogue in normal human experience," and while the term 'revolution' is often misused in contemporary discourse, "it does apply to the careening social, cultural, and political dislocations that are occurring today as a result of the crystal fire ignited by the transistor."[78]

This account of the post-World War II development of solid-state electronics and digital computers has focused so far on hardware. The equally vital parallel development that provides the other half of this complex story is, of course, software. John von Neumann has been somewhat unfairly credited with inventing the stored-program architecture that has been used in virtually all computers since the late 1940s. In three 1945 papers (one written with Arthur W. Burks and Hermann H. Goldstine), von Neumann laid out the requirements of a general-purpose computer that could, without hardware modification or rewiring, execute any kind of computation by following a properly written set of instructions (or program).[79] However, there is evidence of the stored-program idea at the University of Pennsylvania's Moore School of Electrical Engineering as early as December 1943 during the development of ENIAC, even though this early digital computer ended up with a hard-wired program structure and it is not known who at the

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[76] Gordon E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics*, Vol. 38, No. 8, April 19, 1965, pp. 115-116.

[77] "Happy Birthday: The Tale of a Frivolous Rule of Thumb," *The Economist*, March 26, 2005, accessed April 22, 2006, online at <http://www.economist.com/displaystory.cfm?story_id=3798505>.

[78] Riordan and Hoddeson, *Crystal Fire*, pp. 284, 285.

[79] H. Norton Riley, California State Polytechnic University, "The von Neumann Architecture of Computer Systems," September 1987, p. 1; online at <http://www.csupomona.edu/~hnriley/www/VonN.html>, downloaded April 22, 2006.

Moore School originated the idea of a stored program.[80] In any event, von Neumann's June 1945 paper "First Draft of a Report on the EDVAC [**E**lectronic **D**iscrete **V**ariable **A**utomatic **C**omputer]" describes the main components of a general-purpose, stored-program computer: a control unit, memory, an arithmetic-logic unit, and input-output.[81]

While software development in the 1950s concentrated primarily on large, expensive mainframe computers, progress in hardware and software during the 1960s laid the foundations for both the Internet and the personal computer. The emergence of Internet in the 1990s can be traced back to a series of technology teams J. R. C. Licklider began putting together at DARPA in the early 1960s to work on the "man-machine interface" and what he called the "Intergalactic Computer Network."[82] Together with the contributions of Paul Baran and his RAND colleagues on "packet switching" for distributed communications, the ARPANET developed the software protocols and standards underlying today's ubiquitous Internet.[83] Personal computers, of course, emerged earlier than Internet. The 1975 Altair 8800, with its Intel 8800 microprocessor, is generally considered the first general-purpose, personal computer. The market for the Altair 8800 was hobbyists, and the machine was of little practical use until Paul Allen and Bill Gates, the co-founders of Microsoft, supplied their

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[80] "Von Neumann Architecture," Wikepedia online encyclopedia at <http://en.wikipedia.org/wiki/Von_Neumann_architecture#endnote_edvacreport>, accessed April 22, 2006.

[81] John von Neumann, typographical corrections by Michael F. Godfrey, "The First Draft Report on the EDVAC," June 30, 1945, pp. 1-4; as published in *IEEE Annals of the History of Computing*, Vol. 15, No. 4, 1993, pp. 27-75.

[82] William B. Bonvillian, "Power Play: The DARPA Model and U.S. Energy Policy," *The American Interest*, November/December 2006, pp. 44-45; and the Robert W. Taylor's preface to "In Memoriam: J. C. R. Licklider 1915-1990," Digital Systems Research Center, No. 61, August 7, 1990, online at <http://sloan.stanford.edu/mousesite/Secondary/Licklider.pdf>, accessed October 20, 2006.

[83] The problem that motivated RAND's work in the 1960s on distributed communications was that of designing a network that could survive the destruction of many of its nodes and linkages in the event of a Soviet nuclear attack on the United States (Paul Baran, "On Distributed Communications: I. Introduction to Distributed Communications Networks," RAND memorandum RM-3420-PR, August 1964, pp. 1-3, 9-12).

BASIC programming language. The first personal computer with mass-market appeal was the Apple II, which debuted in April 1977. The first "killer application" for the Apple II was VisiCalc, the earliest computer spreadsheet. In the 1970s, Bell Laboratories at Murray Hill, besides being the birthplace of the transistor, also made major contributions to modern software, notably the C programming language and the Unix operating system.[84]

The various advances in solid-state electronics and computer software exerted far-reaching effects on guided munitions. One of the earliest examples of these developments turning a guided munition from a disappointment into an effective weapon was the maturation of the Sparrow III after the Vietnam War. The underlying issues with the missile were maintainability and reliability in combat environments, and the incorporation of solid-state electronics in the mid-1970s solved these problems.

The AIM-7 Sparrow III

This case study focuses on the semi-active, radar-guided, AIM-7 series of air-to-air missiles. The Sparrow III was the first all-weather, beyond-visual-range air-to-air missile used extensively in combat by American and allied aircrews. Over 600 were fired in combat during 1965-1973 by US Navy, Air Force and Marine F-4 crews. The AIM-7Ds, -7Es, and -7E-2s employed in Southeast Asia proved disappointingly unreliable and ineffective, especially in the dynamic tactical environments in which they were employed. As suggested above, however, the improvements made to the missile after the Vietnam War based on solid-state electronics turned a disappointing muntion into a lethal one, as combat results from Operation Desert Storm in 1991 later showed. To be able to eliminate such important variables as the realistic training underpinning superior situation awareness, this case will need to be explored in some detail. In addition, some understanding of the history and demands of air-to-air combat will be necessary to appreciate why the Navy and Air Force

[84] "Unix's Founding Fathers," *The Economist*, Technology Quarterly, June 12, 2004, p. 37. For an account of how, by the mid-1990s, 85 percent of the personal computers in the world ended up using Microsoft operating systems, see Robert X. Cringely, *Accidental Empires: How the Boys of Silicon Valley Make Their Millions, Battle Foreign Competition, and Still Can't Get a Date* (New York: Harper Business, 1996 rev. ed.).

stuck with the Sparrow III as long as they did despite its poor performance in Southeast Asia.

To begin at the beginning, in 1903 Wilbur and Orville Wright demonstrated the feasibility of heavier-than-air flight at Kill Devil Hills on the outer banks of North Carolina. Only six years later, in 1909, French achievements such as Louis Blériot's crossing of the English Channel in July and the Reims aviation week in August, "stimulated aviation development and military interest everywhere," but especially in France, Germany and Great Britain.[85] The year 1909, therefore, is a reasonable beginning for both military aviation and national aviation industries in these countries as well as in others.[86]

During the initial five months of World War I in 1914, aviation established itself as "a primary reconnaissance tool in all armies," and demonstrated its potential for bombing and aerial combat.[87] Among other things, 1914 witnessed the first aerial victory by a French Voisin over a German Aviatik as well as initial experiments with aerial photography and wireless communications. 1915 saw the development of fighter (pursuit) aviation, including the appearance of mechanical interrupter gears to enable fixed, forward-pointing guns to fire through the arc of spinning propellers.[88] In 1916 control of the air emerged as the "crucial issue" in the Germans' Verdun offensive and the British Somme counteroffensive due to the large numbers of

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[85] John H. Morrow, Jr., *The Great War in the Air: Military Aviation from 1909 to 1921* (Washington, DC: Smithsonian Institution Press, 1993), p. 11. The great merits of Morrow's book are the comparisons of all the major air services during this period and the attention given to the industrial and technological underpinnings of early air power, especially to engines such as the Hispano-Suiza (ibid., p. 97).

[86] Morrow, *The Great War in the Air*, p. xiii.

[87] Morrow, *The Great War in the Air*, p. 85.

[88] Morrow, *The Great War in the Air*, pp. 104-106, 130. Roland Garros, a famed French prewar flier and test pilot, developed the first synchronizing gear for a machine gun to fire through the propeller arc in late 1914, and April 1915 he shot down three German aircraft in a Morane monoplane fitted with this innovation (ibid., pp. 91-92). When Garros was shot down by AAA in the spring of 1915, he and his plane were captured by the Germans, and the first Fokker monoplanes with synchronizing gears to fire through the propeller arc entered operational service in July 1915 (ibid., pp. 104-105).

aircraft both sides put into the air over these battlefields.[89] During 1917 aerial combat became a brutal, cold-blooded business, even for the English, whose domestic press persisted in portraying air-to-air contests between pursuit pilots as a "gloriously exhilarating sport" right to the war's end.[90] As early as 1916, however, air superiority was increasingly viewed by air and ground commanders as a means to other ends such as the observation and air-to-ground attack of enemy ground forces. By 1917 it was becoming evident, for instance, that poor reconnaissance of enemy attack preparations could cost all the gains of a successful previous attack.[91] By 1918, the airplane "had become the instrument to be used en masse over the battlefield," even though efforts to use airships and bombers for "strategic" attacks on an enemy's war industry and morale had been largely disappointing.[92] 1918 also saw the formation of a unified British air ministry and, on April 1st, the establishment of the Royal Air Force by amalgamating the Royal Air Service and the Royal Naval Air Service.[93]

From its earliest days, war in the air permitted both attackers and defenders to maneuver in a three-dimensional medium extending from the surface of the earth to the maximum operational altitudes of the aircraft involved, which by 1917 were already approaching 20,000 feet in the case of a modified version of the British SE5A and the Germans' "V"-class Zeppelin.[94] Prior to the advent of air-to-air guided

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[89] Morrow, *The Great War in the Air*, pp. 131, 195.

[90] Morrow, *The Great War in the Air*, pp. 239-242. 1917 also saw the entry of the United States into the Great War on April 6th.

[91] For example, the first large-scale use of tanks by the British at Cambrai on November 20, 1918, not only broke through the supposedly impenetrable Hindenburg Line but initially achieved penetrations as deep as eight kilometers. Ten days later, however the German counterattack apparently came as a surprise to the British and, by December 7th, most of the British territorial gains had been abandoned. Morrow argues that British surprise on November 30th stemmed largely from inadequate aerial reconnaissance (Morrow, *The Great War in the Air*, pp. 218, 236-237).

[92] Morrow, *The Great War in the Air*, pp. 221-222, 244, 257, 281.

[93] These organizational changes were taken in response to J. C. Smuts' second report on home defense, air organization and operations (Morrow, *The Great War in the Air*, pp. 239-249, 256-258). Parliament's Air Force Bill, which legislated these changes, was passed on November 29, 1917.

[94] Morrow, *The Great War in the Air*, pp. 220-221.

missiles, fighters were generally armed with machine guns or cannons that fired forward along the plane's longitudinal axis. Since the weapons were fixed, the attacking fighter pilot had to maneuver his airplane into a position relative to his opponent that would enable him to bring the stream of bullets from his guns to bear. Ignoring high-angle-off deflection shots, the ideal firing position was behind the defending aircraft (at "six o'clock"). Thus, pilots in aerial dogfights during World War I, World II, and the Korean War generally sought to reach a "guns tracking" position behind the target, close enough for aimed fire to be effective. While exceptional marksmen such as the Germans Hans-Joachim Marseille and Erich Hartmann were capable of hitting a maneuvering opponent at 1,000 or even 1,500 feet, the more successful fighter aces during both world wars and the Korean conflict generally preferred to open fire from much shorter ranges.[95] In 1917 the French ace Albert Deullin engaged one of his twenty victims from so close a range that he returned with blood on his aircraft, face and clothing, and the 21-victory ace Alfred Heurtaux liked to close to 100 feet before shooting, often enabling him to down German planes with less than ten rounds of ammunition.[96] On the Russian front during World War II, Erich Hartmann—the highest scoring fighter pilot of all time with 352 kills—often closed to within 150 feet of his prey before pulling the trigger, thereby maximizing the impact of his rounds on the enemy's aircraft and conserving ammunition.[97]

From 1914 to 1953, then, air-to-air combat was dominated by aimed fire even though both attacker and defender could maneuver in three dimensions. Nations continually sought to improve aircraft maneuverability and engine performance to give their pilots maneuver advantages they could exploit to achieve effective firing positions. During the Vietnam War, the dominant role of situation awareness in

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95 When Marseille finally got his shooting eye in North Africa, he became so accurate that he expended only 15 rounds per kill flying the Messerschmitt Bf-109—Raymond F. Toliver and Trevor J. Constable, *Horrido!* (New York: Bantam, 1968), pp. 103-104. Prior to being killed while attempting to bail out of his fighter due to an engine fire, Marseille amassed 158 victories, including the impressive feat of scoring 17 in a single day.

96 Morrow, *The Great War in the Air*, pp. 201-202.

97 Toliver and Constable, *The Blond Knight of Germany*, pp. 85-86. Hartmann was originally encouraged to shoot at close range while flying with Walter Krupinski (197 victories). Both pilots survived the Second World War.

engagement outcomes was not widely appreciated until midway through the conflict. And without missiles that could reliably home on the target from appreciably greater ranges than those at which fixed cannons and machine guns were effective, there was little alternative, whenever the target could not be taken unawares, but to fall back on dogfighting skills and aircraft performance to reach relatively close-in firing positions.[98]

The technical basis for changing this situation did not materialize until the appearance of the first air-to-air guided missiles in the mid-1950s. The Air Force declared its first air-intercept missile, the AIM-4 Falcon, operational in 1955 and the missile entered service with Air Defense Command F-89H and F-102A interceptors in 1956.[99] That same year, the first production model of the infrared (heat-seeking) Sidewinder missile, developed by the Naval Ordnance Test Station (NOTS) at China Lake in California's Mojave Desert, became operational on the F9F-8 Cougar, and the Sparrow I, which was a beam-riding missile slaved to an optical sight, entered fleet service on the F-3H-2M Demon and F-7U Cutlass.[100] Of these three early American air-to-air missiles, only the infrared or heat-seeking

[98] In 1917, the speed advantage of the British SE5A over German fighters gave SE5A pilots the advantage of being able "break off combat at will" (Morrow, *The Great War in the Air*, p. 243). The USAF's "fifith-generation"F-22, which can cruise at speeds above Mach 1.5 without requiring afterburners, has much the same advantage over Russian fighters such as the MiG-29 and SU-27.

[99] "Hughes AIM-4 'Falcon' Air-to-Air Missile," Hill Aerospace Museum, Hill AB, Utah, accessed May 2, 2006, available online at <http://www.hill.af.mil/museum/photos/coldwar/falcon.htm>. The AIM-4 was the result of Project Dragonfly, which the US Army Air Forces began in 1947 to develop both viable fire-control radar and a radar-guided missile.

[100] Roy A. Grossnick, *Dictionary of American Naval Aviation Squadrons*, Vol. I, *The History of VA, VAH, VAK, VAL, VAP and VFA Squadrons* (Washington, DC: US Government Printing Office, 1995), pp. 75, 471-72, 481. The NOTS was established in 1943, and had a long, close cooperative relationship with the California Institute of Technology. In 1967 the NOTS China Lake and the Naval Ordnance Laboratory were joined to form the Naval Weapons Center (NWC). In 1992 the NWC was disestablished, and the NWC facilities, military administration, and airfield functions were consolidated into the Naval Air Weapons Station China Lake ("From the Desert to the Sea: A Brief Overview of the History of China Lake," online at <http://www.nawcwpn.navy.mil/clmf/hist.html>; originally published in *The Rocketeer*, China Lake's in-house newspaper, November 4, 1993).

Sidewinder had much success in combat. The initial model of the Falcon, the AIM-4 (originally designated the Guided Aircraft Rocket-1 or GAR-1) was a short-range, semi-active, radar-homing missile with a tiny warhead and had to hit the target to detonate since it lacked a proximity fuze.[101] The Sparrow I was apparently not capable of all-weather attack, and the Navy's efforts to add active radar guidance in the follow-on Sparrow II failed.[102]

Despite the limitations and frustrations encountered with these early air-to-air missiles, there were powerful motivations for both the Navy and the Air Force to continue investing in air-intercept missiles. In the first place, there was the fact that the Germans had developed prototype air-to-air missiles before the fighting ended in Europe. They designed the Ruhrstahl X-4 to provide German fighters with a standoff weapon that could be used to attack Allied heavy bombers from outside the reach of the bombers' defensive armament (thirteen .50-calbiber machine guns in the case of the B-17G). The X-4 was a rocket-powered, wire-controlled missile that the operator guided with a joystick; it had a maximum range of over three miles and an acoustic fuze designed to detonate the missile's 44-lb warhead within about 23 feet of a B-17.[103] After a successful test from a Focke Wulf-190 in August 1944, the Germans produced some 1,300 X-4 airframes. However, after Allied bombers attacked the BMW Stargard factory where the X-4's rocket motors were being built in February 1945, the Germans were unable to field the weapon. Although the X-4 was not used in combat, its acquisition by American technical-exploitation teams gave both the US Army Air Forces and Navy glimpses of where munitions technology might be headed in the future.[104] Because the

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[101] Westrum, *Sidewinder*, p. 28. The original Falcon warhead was only five pounds of explosive (ibid.).

[102] "AIM-7 Sparrow," Wikepedia online encyclopedia at <http://en.wikipedia.org/wiki/AIM-7_Sparrow>, last modified April 14, 2006, accessed May 2, 2006.

[103] "Ruhrstahl X-4 Air-to-Air Missile," online at the National Museum of the United States Air Force, Wright Patterson Air Force Base, Ohio, at <http://www.wpafb.af.mil/museum/arm/arm29.htm>, accessed May 2, 2006.

[104] Wolfgang W. E. Samuel, *American Raiders: The Race to Capture the Luftwaffe's Secrets* (Jackson, MS: University of Mississippi Press, 2004), pp. 4-7, 139-140.

Soviets had also gotten access to German technology and scientists in 1945, with the onset of the Cold War there was an obvious incentive for both the Navy and the Army Air Forces to develop effective air-to-air missiles before the Russians did.

Beyond the desire to stay ahead of the Russians in aircraft and conventional weaponry, though, the US Navy and, after September 1947, the US Air Force had other, more immediate reasons for pushing ahead with tactical-missile technology. In the Navy's case, the carrier's attack aircraft had emerged from World War II as the fleet's primary offensive striking arm for attacking enemy ships at sea or targets ashore, as well as for providing fleet defense against enemy air attack. Indeed, in the Pacific Theater during World War II, fleet and attack carriers had proven to be "the preeminent Naval instrument for projecting power" against the Japanese empire.[105]

During 1941-45, however, the "center of concern" for the American surface navy was the "vulnerability to naval aircraft of warships of every description," starting with the carrier of aircraft itself.[106] Recall that on December 10th, just three days after the Japanese attack on the US fleet at Pearl Harbor, Japanese high-altitude bombers and torpedo planes had intercepted the Royal Navy's Force Z, which was operating in the South China Sea without air cover, and had sent the battle-cruiser HMS *Repulse* and the new battleship HMS *Prince of Wales* to the bottom.[107] While concern within the US Navy over the vulnerability of warships to air attack dates at least back to the fleet exercises of 1929 and 1930, it was strongly reinforced during World War II by such events as the sinking of the *Repulse* and *Prince of Wales*, German success with the Fritz X against the *Roma*, and the attrition inflicted by

[105] Michael M. McCrea, Karen N. Domabyl, and Alexander F. Parker, "The Offensive Navy Since World War II: How Big and Why: A Brief Summary," Center for Naval Analyses, Arlington, VA, CRM 89-201, July 1989, p. 11.

[106] Hughes, *Fleet Tactics and Coastal Combat*, p. 95. In the fleet exercises of 1929, which have been celebrated as marking the arrival of carrier aviation, the *Saratoga* got off a successful air strike against the Panama Canal, but was then found and "sunk" three times—by surface ships, a submarine, and aircraft from the *Lexington* (ibid.).

[107] Force Z also included four destroyers. The Japanese high-altitude bombers were ineffective, but their torpedo planes scored eleven hits against the two capital ships.

Japanese Kamikazes, particularly off Okinawa in 1945.[108] In the latter instance, the Anglo-American task force that converged on Okinawa on April 1, 1945, consisted of over 1,200 ships, including more than 40 large-deck and smaller "jeep" aircraft carriers, 19 battleships, and more than 180,000 marines and soldiers.[109] Between April 6th and June 22nd, the Japanese mounted a total of ten mass attacks, each with 50 to 300 aircraft including Kamikazes, against the Allied fleet and hit some 290 surface ships.[110] The radar-picket destroyers bore the brunt of these attacks, but carriers and other large warships also suffered. As the struggle between the attacking aircraft and the Allied fleet unfolded, fighters from the carriers were used to try to break up the Japanese attacks, but there were usually too many Japanese aircraft for the available Allied fighters even though picket ships were able to detect "almost all approaching enemy aircraft."[111] In light of such experiences, the capacity of anti-air warfare (AAW) systems to defend carrier battle groups against attacking enemy aircraft and, later, guided munitions, became an overriding priority for the surface component of the American navy after 1945.

After World War II, the US Navy's basic approach to the AAW challenge was to develop guided missiles. As mentioned in Chapter 1, Project Bumblebee sought to develop not only naval surface-to-air missiles but the radars and CICs needed for effective AAW. In parallel with Bumblebee, Project Hotshot, which began in 1946 and produced the inadequate Sparrow I, sought to develop all-weather missiles for naval fighters. Thus, radar-guided SAMs and air-to-air missiles were key components of the US Navy's post-World War II approach to anti-air warfare.

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108 Thomas C. Hone, Norman Friedman and Mark D. Mandeles, *American and British Aircraft Carrier Development 1919-1941* (Annapolis, MD: Naval Institute Press, 1999), p. 135.

109 Ronald H. Spector, *Eagle against the Sun* (New York: The Free Press, 1985), p. 532. The aim of these massed attacks from Kyushu was to deny the American marines and soldiers on Okinawa the naval gun fire and air support that had proven critical in prior amphibious operations.

110 Spector, *Eagle against the Sun*, p. 537; Hughes, *Fleet Tactics and Coastal Combat*, p. 156. Hughes notes, however, that because the Allied fleet off Okinawa was so massive, the hit rate per hundred ship days of operations was actually lower than during the Guadalcanal-Tulagi landing operations (ibid.).

111 Friedman, *U.S. Destroyers*, p. 176.

Figure 12: "Joe 1"[112]

With the advent of the US-Soviet Cold War, the newly established US Air Force found itself facing a different challenge. The detonation of the first Soviet atomic bomb at Semipalatinsk in Kazakhstan on August 29, 1949, brought home to both US and Canadian leaders the prospect that, in the foreseeable future, long-range Soviet bombers carrying fission weapons would be able to threaten cities and military facilities in North America. In the early 1950s, this threat led the Canadian and US governments to agree to construct a series of radar stations across North America to detect a Soviet bomber attack over the North Pole. Sensor arrays such as the Pinetree and, later, the Distant Early Warning lines were to be linked to fighter-interceptors, as well as BOMARC IM-99A and Nike SAMs, to shoot down incoming Soviet bombers. To provide the command-and-control for this air-defense network to be effective, the Air Force contracted with the Massachusetts Institute of Technology's (MIT's) Lincoln Laboratory to develop the Semi-Automatic Ground Environment (SAGE) system.[113]

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[112] Source: Cary Sublette's "The Nuclear Weapon Archive: A Guide to Nuclear Weapons," <http://nuclearweaponarchive.org/Russia/Joe1big.jpg>. Sublette got the image from Peter Kuran, maker of the film "Trinity and Beyond."

[113] Lincoln Laboratory was established in 1951 as a federally funded research center at MIT. During World War II, the NDRC's main effort to develop microwave radar systems for aircraft, ships, and AAA guns was located at MIT's

The SAGE system sent information from its geographically dispersed radars over telephone lines and gathered it at central locations for processing by digital computers. MIT's Servomechanisms Laboratory developed the prototype for SAGE's computers, called Whirlwind, under a contract from the US Navy.[114] At the heart of SAGE was the production version of the Whirlwind prototype, Whirlwind II. A then little-known company called IBM (International Business Machines) won the contract to design and build Whirlwind II, otherwise known as the FSQ-7, and, when SAGE became fully operational, pairs of these computers were deployed at each of the 24 SAGE direction centers.[115] These centers constituted the core of a battle network designed to provide air defense against air-breathing threats such as Soviet long-range bombers over the entire North American continent.

By the late 1950s, SAGE combat-direction centers commanded 41 interceptor squadrons numbering some 800 aircraft, seven BOMARC missile squadrons, and scores of Army Nike missile battalions.[116] Insofar as the interceptors needed to be able to shoot down Soviet bombers at night or even in poor weather, air-to-air missiles were needed, particularly radar-guided ones. The Air Force's Falcon series

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Rad Lab (radiation laboratory). While the Rad Lab was dismantled after the war, through the 1960s MIT continued to conduct classified research at the Research Laboratory for Electronics, the Instrumentation Laboratory, and Lincoln Laboratory—*In the Public Interest: Report of the Ad Hoc Committee on Access to and Disclosure of Scientific Information* (Cambridge, MA: MIT, 2002), p. 2. Lincoln Laboratory grew out of a 1950 study, Project Charles, and construction of the facility at Hanscom Field in Bedford, Massachusetts, began in 1953 once continued funding was assured by the Air Force (ibid., p. 4).

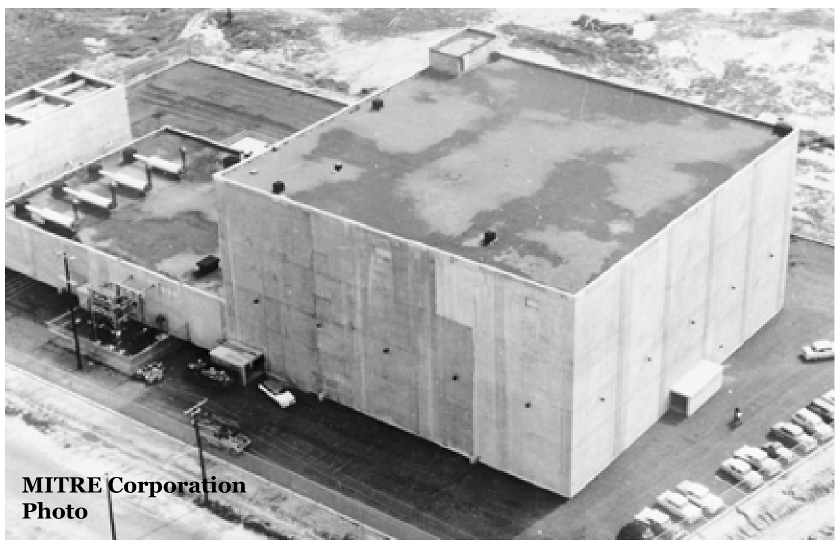
114 "Whirlwind Computer (1949)," online at <http://www.computermuseum.li/Testpage/Whirlwind-1949.htm>, accessed May 6, 2006.

115 "Semi-Automatic Ground Environment (SAGE)," online at <http://www.mitre.org/about/sage.html>, accessed May 6, 2006. Each Whirlwind II weighed about 250 tons, required a 3,000-kilowatt power supply, and contained over 49,000 vacuum tubes (ibid.). The MITRE Corporation was formed out of the Computer System Division of MIT's Lincoln Laboratory in 1958, and much of MITRE's initial work focused on the software development of SAGE's digital computer system, radar surveillance, communications, and weapons integration.

116 David F. Winkler, *Searching the Skies: The Legacy of the United States Cold War Defense Radar Program* (Langley, VA: Air Combat Command, June 1997), p. 37.

of air-intercept missiles, whose development began in 1947 as Project Dragonfly, provided the principal armament for the Air (later Aerospace) Defense Command's interceptors. While the initial models of the Falcon, the AIM-4/GAR-1 and AIM-4A/GAR-1D, were radar guided, the AIM-4B/GAR-2 and AIM-4G/GAR-4A used infrared homing.[117] The Air Force also fielded a nuclear-tipped version of the Falcon, the AIM-26A/GAR-11, which had radar-proximity fuzing and used a similar warhead to the 1.5-kiloton W-25 in the unguided AIR-2A Genie.[118]

Figure 13: SAGE Air Defense Center, McGuire AFB, NJ, Circa 1958[119]



The eventual scale of some of the post-World War II air-to-air missile programs was massive. Approximately 48,000 Falcons were produced for the USAF, and another 12,000 were sold to overseas

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117 "Hughes AIM-4 'Falcon' Air-to-Air Missile," Hill Aerospace Museum. The Super Falcon AIM-4Fs and AIM-4Gs were radar and infrared guided, respectively, and were usually carried in mixed loads on the F-106.

118 Hansen, *U.S. Nuclear Weapons*, pp. 177-178.

119 According to MITRE, the McGuire AFB SAGE center was the first to become operational. The second floor of this four-story center housed the duplex FSQ-7 computers. (Photo copyrighted by the MITRE Corporation.)

customers.[120] From 1956 through 1980, perhaps 40,000 Sparrow IIIs were produced, of which around 25,000 were the AIM-7D, -7E and -7E-2 models used by American F-4 crews in Southeast Asia during 1965-73.[121] Moreover, in terms of point air defense against jet-propelled aircraft, the US Army also invested extensively in radar-guided SAMs. Prompted by awareness of the German wartime research on guided rockets with ranges as great as 100 miles and the prospective threat of jet-powered aircraft, the Army completed a formal report on the feasibility of surface-to-air guided missiles in July 1945.[122] Initial component tests began in 1946, the first successful intercept of an airborne target (a B-17) took place in November 1951, the first Ajax firing unit was activated in March 1954, and by mid-1958 the original Ajax missiles started being replaced by the improved Nike Hercules.[123] At the program's peak, the US Army had 265 Nike batteries deployed in the United States, Alaska, and Hawaii.[124]

Given the state of the underlying technology, the majority of the guided missile systems pursued by the Army, Navy, and Air Force through the 1950s were expensive and complex. One of the few exceptions was the AIM-9 Sidewinder developed at NOTS China Lake by an unorthodox team under the leadership of the physicist William B. McLean.[125] Indeed, China Lake not only developed the Sidewinder

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120 "AIM-4 Falcon," at <http://www.afa.org/magazine/gallery/missiles/aim-4.asp>, accessed May 7, 2006.

121 Congressional Budget Office, "Past Trends in Procurement of Air Intercept Missiles and Implications for the Advanced Medium-Range Air-to-Air Missile Program (AMRAAM)," staff working paper, October 1982, p. 17. The total of 40,000 Sparrow IIIs produced through 1980 includes the AIM-7C through AIM-7F, but not the subsequent AIM-7M used in Operation Desert Storm in early 1991.

122 Mary T. Cagle, *Development, Production, and Deployment of the NIKE Ajax Guided Missile System: 1945-1959* (Redstone Arsenal, AL: US Army Ordnance Missile Command, 1959), declassified July 1962, pp. 1, 2, 4.

123 Cagle, *Development, Production, and Deployment of the NIKE Ajax Guided Missile System*, pp. 112-114, 183, 200.

124 John C. Lonnquest and David F. Winkler, *To Defend and Deter: The Legacy of the United States Cold War Missile Program (*Rock Island, IL: Defense Publishing Service, November 1996), pp. 570-572. Nike batteries often had sixteen launchers (ibid., p. 56).

125 Westrum, *Sidewinder*, pp. 5, 7, 12-13, 38-39, 75.

even after being told to restrict its research efforts to unguided ordnance, but got the missile into production despite several attempts by the Navy's bureaucracy to kill the project.[126] McLean insisted on simplicity in the Sidewinder's design, believing that this emphasis would lead to lower costs, larger inventories, and more opportunities for aviators to fire training rounds; as a result, the original Sidewinder's electronics had only fourteen vacuum tubes compared to 72 in the AIM-4.[127]

By 1958 the second model of the Sidewinder (the Sidewinder-1A later redesignated the AIM-9B) had been provided to the Chinese Nationalists on Taiwan. On September 22nd, 1958, ten Nationalist F-86F Sabres encountered perhaps twice that number of Chinese Communist-piloted MiG-17s. The Taiwanese pilots promptly downed four MiGs for an expenditure of only six Sidewinders.[128] This first combat success involving a US air-to-air guided missile was a visual engagement in which the Taiwanese pilot used the Sidewinder to negate the MiGs' higher combat ceiling. Once they had spotted the MiGs and closed on them, the Taiwanese pilots, following American advice, pitched up the noses of their F-86 Sabres to put the tailpipes of the MiG-17s flying above them within the field of view of the infrared seekers on their AIM-9Bs and fired. The early Sidewinder's range, though limited, enabled the Taiwanese pilots to achieve kills from distances well beyond the reach of the F-86's 50-caliber machine guns.[129]

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[126] Westrum, *Sidewinder*, pp. 42, 112-114, 118-119.

[127] Westrum, *Sidewinder*, pp. 28, 90.

[128] Elizabeth Babcock, *Sidewinder: Invention and Early Years* (Ridgecrest, CA: China Lake Museum Foundation, September 1999), p. 25; General Laurence S. Kuter, "The Meaning of the Taiwan Straits Crisis," *Air Force Magazine*, March 1959, p. 105.

[129] At 30,000 feet against a co-speed, non-maneuvering target, the early Sidewinder's range was 15,000-20,000 feet (2.5-3.3 nm), and it might be only half of that at low altitude (Westrum, *Sidewinder*, p. 156). If the defender turned into an attack pulling 5 Gs (five times the force of gravity), the Sidewinder's firing envelope virtually disappeared—Marshall L. Michel, III, *Clashes: Air Combat over North Vietnam 1965-1972* (Annapolis, MD: Naval Institute Press, 1997), p. 154. All that said, the missile did solve the problem of the MiG-15's superior combat ceiling that had frustrated American F-86 pilots during the Korean War. Typically the MiG-15s would climb to around 50,000 feet north of the Yalu River before heading south into the area of northwest North Korea known as MiG Alley, giving them an altitude advantage of 5,000-

Despite the Sidewinder's simplicity and maintainability, the missile had limited range. Pilots employing it still had to maneuver their planes into a rearward-projecting cone behind the enemy aircraft within which the Sidewinder's passive IR seeker could "see" the heat radiation produced by target's jet engine.[130] While a substantial advance over machine guns and cannons for aerial combat, the Sidewinder was still fundamentally a close-in or "dogfight" weapon, its effectiveness limited to within-visual-range engagements during the daytime and in clear air outside of clouds. For night or all-weather engagements, particularly at distances beyond visual range, the Sidewinder offered little capability.

By the mid-1950s, therefore, the growing air-defense challenge for US fighters and interceptors was to be able to destroy Soviet long-range bombers day or night, regardless of weather, ideally from beyond visual ranges. This challenge was especially acute for Air Defense Command's (ADC's) "Century-series" interceptors—F-101Bs, F-102s, and F-106s—whose primary mission was to shoot down Soviet bombers carrying nuclear weapons before they could reach targets in North America.[131] The most advanced of these interceptors, the F-106,

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10,000 feet over the F-86s. Armed with only machine guns, the Sabres could not bring ordnance to bear unless the MiG pilots elected to come down and fight (Lieutenant Colonel James Jabara, "A Fighter Pilot's Airplane," *Air Force Magazine*, August 1960, p. 61). The Sidewinder solved this problem.

[130] The early Sidewinder used filters to limit the seeker to radiation in the 2.05-3.0 micron range in order to maximize the missile's ability to discriminate targets from clouds (Westrum, *Sidewinder*, p. 54). In the early Falcon, Hughes used a lower, 1.85-micron cutoff, which appears to have been one reason why the missile had trouble with clouds (ibid.). As would be expected, infrared sensors evolved over time. The AIM-9B tended to home on the hottest piece of metal on the target aircraft, whereas the Navy's later AIM-9D, which could not be fired from Air Force fighters during the Vietnam War, was designed to go after the engine's exhaust plume (Captain Barry D. Watts, "Sidewinder," personal lecture notes, Top Gun Class 04-75, June 11, 1975, p. 1). Far more importantly, the advanced seeker on the AIM-9L transformed the Sidewinder into an extraordinarily lethal, all-aspect missile (Westrum, *Sidewinder*, pp. 194-196). The AIM-9L could pull 35 Gs, whereas the AIM-9A and -9B were only 10-G missiles.

[131] McDonnell built over 475 F-101Bs—the two-seat interceptor variant of the aircraft—for ADC ("McDonnell F-101B 'Voodoo'," at <http://www.wpafb.af.mil/museum/research/fighter/f101b.htm>, accessed May 6, 2006). Including 111 two-seat versions, 986 F-102As were procured in the late 1950s, and another 330 F-106s, originally designated F-102Bs, were

was usually armed with one unguided AIR-2A Genie containing a small fission warhead, and four "Super Falcons" (two radar-guided AIM-4Fs, and two IR AIM-4G)s.

USAF pilots who flew the F-101B and F-106 during the late 1960s and early 1970s recall that ADC's employment doctrine against Soviet bombers called for the lead interceptor to open the engagement with a front-aspect shot using the nuclear Genie.[132] This preference arose from the imperative to achieve the highest possible P_k (probability of kill).[133] After firing the Genie, the interceptor pilots could either follow up by attempting a front-aspect shot with the radar-guided AIM-4 or convert to the stern and reattack with both Falcon variants from the target's six o'clock. The foremost difficulty with these tactics stemmed from the likely effects of using a nuclear weapon. While the Genie's W-54 fission warhead was only supposed to yield 1.5 kilotons, it was still capable of producing a blinding radiation flash, electromagnetic pulses, and an intense shock wave. ADC interceptor pilots, who normally flew in pairs, faced a good possibility of being at least momentarily blinded by the detonation of Genie's warhead. They also expected the detonation to disrupt their radars, forcing them to re-establish radar lock-on to have any chance of a front-aspect AIM-4 shot prior to the interceptor and target passing one another. A further problem was the limited time available for a front-aspect AIM shot due to the closure rate between the interceptors and the target. Even

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delivered to ADC by 1960 ("Convair F-102 'Delta Dagger'," at <http://www.wpafb.af.mil/museum/research/fighter/f102.htm>; and ("Convair F-106A 'Delta Dart'," at <http://www.wpafb.af.mil/museum/research/fighter/f106a.htm>).

132 Patrick K. Gamble, telephone interview, January 6, 2004; Robin deTurk, telephone interviews, December 18, 2003, and January 5-6, 2004. During his time in ADC, deTurk took his lead-in course in the F-102, and later pulled ADC alert in both the F-101B and F-106. Gamble flew ADC F-106s during the 1970s.

133 "The Genie had a significantly higher P_k than any version of the Falcon, from any aspect, at any altitude. . . . provided it was launched with a full radar lock (track) with the [steering] dot centered and in a relatively stable flight condition" (Robin deTurk, e-mail, January 11, 2004). In the case of the F-101B, the Genie had to be fired at a precise distance from the target. Since this distance varied as a function of engagement geometry (altitudes, airspeeds, aspect angle, etc.), it had to be computed by the plane's fire-control system, thereby requiring a full-system radar lock-on for an automated release (deTurk interviews).

assuming quick reacquisition of a radar lock-on, the AIM-4F still had to be "prepped" by the interceptor's fire-control system and, more often than not, F-106 pilots trying to get in a front-quarter Falcon shot inside the Genie's release range would get a "time-compression abort" indication before they could fire their AIM-4s.[134] Consequently, the more likely follow-up attack after employing the Genie tended to be a stern conversion to the target's rear quarter, at which point the interceptor could fire both radar-guided and IR AIM-4s.[135] In any case, for continental air defense against Soviet bombers, the Air Force considered the AIM-4 a secondary or back-up weapon in case the Genie's warhead failed to detonate or down all the intruders.

Even without the complications of a nuclear-tipped missile, Navy fighter-interceptors faced similar problems in their AAW role. By the mid-1950s advances in aircraft performance (better thrust-to-weight ratios, higher top speeds, etc.), fighter radars, and air-to-air missiles argued that this part of the fleet-defense mission could best be done by a high-performance interceptor armed with radar-guided, all-weather, air-to-air missiles. The primary objective that drove the design of the F-4B—the initial production model of the McDonnell Douglas Phantom II for the Navy—was "to engage aircraft attacking the Navy's carriers at a distance and protect the carrier battle groups from attack." [136] For armament, the Navy chose the semi-active AIM-7C Sparrow III, guided by the Westinghouse APG-72 radar.[137] Enthusiastic about the

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[134] Gamble interview.

[135] The usual procedure was to fire the radar-guided Falcons first and IR Falcons second to avoid confusing the radar missiles. From the stern, illustrative firing parameters for the semi-active AIM-4F was a maximum angle off the target's dead six o'clock of 40 degrees, firing the missile around one nautical mile slant range with 50-100 knots of overtake on the target.

[136] Jon Lake (ed.), *McDonnell F-4 Phantom: Spirit in the Skies* (London: Aerospace Publishing, 1992), p. 21.

[137] "Semi-active" means that the Sparrow III did not itself contain a radar illuminator, but depended on the F-4's radar to guide it towards the target until the missile's small radar receiver was close enough to detect reflected radar energy from the APG-72's continuous-wave target illuminator. The APG-72 was an upgrade of the APG-50, which had accumulated some eight years of successful performance on the Douglas F4D-1 (F6-F) Skyray. As a result, the APG-72, with its 81-centimeter/32-inch radar dish, had "almost no teething problems" on the F-4B and became "legendary as the farthest-reaching and most accurate" fighter radar of its era (Lake, *McDonnell F-4 Phantom*, pp. 22-

marriage of the APG-72 with the AIM-7, the Navy also elected to eliminate an internal gun, just as the Air Force had done with its F-101B, F-102, and F-106 interceptors.[138] Indeed, as the F-4B began to replace older aircraft in Navy fighter squadrons in the early 1960s, the Sparrow III was the Phantom II's "only armament," the Sidewinder being added later.[139]

Figure 14: AIM-7 Sparrow III[140]

23). The F-4C's APG-100 added some ground-mapping capability to the APG-72, including a 5-nm range strobe for radar bombing (ibid., p. 128).

138 Ignoring reconnaissance versions of the Phantom II, the Navy procured 1,171 "gunless" F-4B/Js; the Air Force accepted over 1,375 F-4C/Ds before adding an internal 20mm Gatling gun in the F-4E, of which the USAF acquired 945 (Lake, *McDonnell F-4 Phantom*, pp. 224-225). Both services fielded external 20-mm gun pods for their F-4s during the Vietnam War, but the original design intent behind the F-4 was to rely exclusively on the Sparrow III for air-to-air armament. The USAF ended up buying the Navy's fighter because defense secretary Robert McNamara decided, in 1962, to terminate F-105 production and direct the Air Force to procure the F-4 instead—Alain C. Enthoven and K. Wayne Smith, *How Much Is Enough? Shaping the Defense Program, 1961-1969* (New York: Harper and Row, 1971), p. 263.

139 Lake, *McDonnell F-4 Phantom*, pp. 17, 22-23. VF-74, which completed carrier qualifications in the F-4 in October 1961, was the first fleet squadron to receive F-4s, and began its initial operational cruise with Phantom IIs aboard the USS *Saratoga* in August 1962 (ibid., pp. 20-21).

140 The Sparrow III was 12-feet long, 8-inches in diameter, had a 3-foot wingspan, and weighed around 500 lbs. On the F-4, four of the missiles could be carried in semi-submerged missile wells on the underside of the fuselage (see Figure 15).

Figure 15: F-4 with AIM-7s and AIM-4s[141]

The Sparrow III, when integrated with the Westinghouse APG-72 and APG-100 radars on, respectively, the US Navy's F-4B and the Air Force's F-4C, was the first air-to-air weapon system to offer tactical-fighter crews a capability to fire on enemy aircraft from medium, as opposed to short, ranges and from all target aspects (head-on, from the side or beam, or from behind).[142] In a nose-to-nose encounter, with an F-4B (or F-4C) closing with the target at 1,000 knots or more, the early models of the Sparrow III could be fired at distances greater than 20 nm if the fighter had a radar lock-on, a distance that was well beyond visual range.[143] And although the main concern during development of the F-4 was downing Soviet bombers before they could threaten an aircraft carrier, the Sparrow III's BVR capability also of-

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[141] This photo was taken by the author at the end of an uneventful MIG CAP mission over North Vietnam in late 1967. The F-4 belonged to the 497th Tactical Fighter Squadron (TFS), and the plane is shown pitching out to land at Ubon in Thailand. The plane is armed with four Sparrow IIIs in the plane's missile wells and two IR Falcons on the inboard pylons.

[142] F-4 fire-control radars operated in X-band (wavelengths of 3.75-2.4 centimeters, or frequencies of 8-12 gigahertz), where the absorption of radar waves due to water vapor is low enough for the atmosphere to be more or less transparent. However, even the F-4's powerful radar could not see through heavy rain or thunderstorms.

[143] Lake, *McDonnell F-4 Phantom*, p. 37. Lake gives the maximum AIM-7D range as 28 nm, but in SEA it was unusual for the F-4 to achieve a full-system radar lock-on against fighters as small as the MiG-17 or MiG-21 outside 20 nm.

fered the promise of being able to shoot down enemy fighters "before a dogfight could take place."[144]

Nevertheless, during the Second Indochina War (1965-73), this capability was rarely employed in combat against Vietnamese People's Air Force (VPAF) MiGs, and the same was true of Israeli air-combat experience with the Sparrow in the October 1973 Yom Kippur War and Operation Peace for Galilee in 1982.[145] A 1985 OSD review of air combat data was able to identify a total of only four BVR kills during 1958-1982.[146] In the case of Southeast Asia, the AIM-7D, -7E, and -7E-2 was credited with 56 kills during 612 launch attempts, but only two of these kills were BVR.[147] The other two BVR kills uncovered in the

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144 Westrum, *Sidewinder*, p. 31. As early as 1949, Vannevar Bush had speculated that the high speeds made possible by jet engines, along with the large turning radii of jet aircraft, would make dogfights "almost impossible"—Vannevar Bush, *Modern Arms and Free Men* (New York: Simon and Schuster, 1949), pp. 49-50. The Korean War proved otherwise. After Korea, however, the same prediction was repeated as missiles began to supplant guns on fighter aircraft; again, it was premature—Jeff Ethell, *F-15 Eagle* (London: Ian Allan, 1981), pp. 11-12.

145 The First Indochina War of the 20th century was waged by the French against the Vietnamese communists during 1946-54 in France's futile effort to regain its pre-World War II colonies in Southeast Asia. The French effort ended with their defeat at Dien Bien Phu by Vo Nguyên Giap.

146 Colonel James Burton, "Letting Combat Results Shape the Next Air-to-Air Missile," January 1985, slide 3. The research behind these slides was done by Burton, then an Air Force officer assigned to OSD/OT&E (Operational Test and Evaluation), and Gordon Smith at the Institute for Defense Analyses.

147 *Project Red Baron III*, Vol. I, *Executive Summary*, p. 18. *Project Red Baron* reports were the primary source for Burton and Smith's 1985 analysis of US air combat against VPAF MiGs during 1965-73. The total of 56 Sparrow III kills omits an F-4D believed to have been downed by a Sparrow from another F-4 on May 11, 1972. After the F-4 lost on this occasion had accelerated out in front of the flight to visually identify the bogey at which the Sparrow was fired, the shooter's radar transferred lock-on from the MiG to the F-4 (J. J. Davis, September 1998 interviews and e-mails—Davis was one of the 432nd TRW weapons officers and reviewed the radar tape from the engagement). Nor was this the only Blue-on-Blue incident during the Second Indochina War. In August 1968 a Navy F-4B crew downed their wingman with AIM-9Ds, all four of which apparently hit, during a vertical fight with "several MiG-21s"—Michael M. McCrea, *U.S. Navy, Marine Corps, and Air Force Fixed-Wing Aircraft Losses and Damage in Southeast Asia (1962-1973) (U)*, (Arlington, VA: Center for Naval Analyses, Operations Evaluation Group, August

1985 review were credited to Sparrow-equipped Israeli fighters, one in 1973 and one in 1982.[148]

Why was the Sparrow III's BVR capability so rarely utilized during 1965-82? The primary reason was the reluctance of American aircrews and commanders to risk fratricide or friendly-fire incidents between US fighters (Blue-on-Blue kills). Without equipment aboard the vast majority of American F-4s for *positively* identifying a radar return from another aircraft as a VPAF MiG, firing a Sparrow BVR inevitably entailed at least some risk of fratricide in the skies over North Vietnam.[149] The accumulation over time of incidents in which Blue-on-Blue kills were barely avoided tended to reinforce the instinctive reluctance of most F-4 crews to take the risk of shooting first and positively identifying the target later. For example, during late 1967 and early 1968, 497th Tactical Fighter Squadron (TFS) F-4s flying MIG CAP over North Vietnam experienced two incidents in which they came close to firing BVR at other US aircraft. In one case, the lead 497th F-4D had a full-system lock-on and one of the control agencies had declared the target hostile.[150] The F-4 frontseat pilot, however, insisted on with-

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1976), CRC 305, August 1976, microfiche A11 (U.S. Navy Fixed-Wing In-Flight Combat Loses in S.E. Asia).

[148] Burton, "Letting Combat Results Shape the Next Air-to-Air Missile," slide 3.

[149] Attempts to incorporate a non-cooperative target recognition capability into early F-4 radars did not yield anything useful. However, by the time bombing resumed over North Vietnam in 1972, the 432nd Tactical Reconnaissance Wing at Udorn, Thailand, had acquired about eight F-4Ds equipped with the AN/APX-76/80A gear, nicknamed Combat Tree. In the APX-76 mode, Combat Tree allowed the weapon system operator in the backseat of these F-4Ds to interrogate IFF (identification friend or foe) transponders on friendly aircraft; in the APX-80A mode, the backseater could detect, track and trigger responses from MiG transponders (Harmer and Andregg, *The Shootdown of Trigger 4*, p. 11). The APX-80A could track VPAF MiGs at ranges as great as 60 nautical miles (ibid., p. 29). As early as mid-1967, the QRC-248 on College Eye EC-121Ds and Rivet Top EC-121Ks could track various MiG transponders to distances greater than 175 nm (Michel, *Clashes*, pp. 100, 114).

[150] This episode occurred during the author's tour in the 497th TFS. The control agency could have been College Eye or Rivet Top EC-121s, or the Navy's Red Crown, a Navy guided-missile cruiser in the Gulf of Tonkin that operated a Positive Identification Radar Advisory Zone (PIRAZ). Even in 1968, the ability of US radar surveillance agencies to track MiG transponders was not shared with fighter aircrews flying MiG CAP over North Vietnam.

holding fire until he could visually identify the target, which turned out to be Navy F-4s. Thus, experience over time tended to make individual F-4 aircrews chary about BVR missile shots.

At the command level this wariness was reinforced by formal rules of engagement. For much of the Vietnam conflict, Navy F-4 crews flying missions over North Vietnam from Yankee Station carriers in the Gulf of Tonkin were under relatively unambiguous orders from 7th Air Force prohibiting BVR shots unless the target had been confirmed hostile by two independent sources or, alternatively, the F-4 had been directed to shoot BVR by a control agency such as the Positive Identification Radar Advisory Zone (PIRAZ) ship that operated under the radio callsign Red Crown.[151] Even during the Operation Rolling Thunder portion of the air war over North Vietnam (1965-1968), though, Air Force ROE were not quite as restrictive as those under which Navy fighter crews operated. From mid-1966 through the summer of 1968, the relevant 7th Air Force operational order read as follows:

> There is reasonable certainty that enemy fighter aircraft over NVN [North Vietnam], during U.S. air operations, intend to attack our forces, therefore aircraft need be visually identified only when possibility exists that the aircraft is either friendly or non-military, i.e., civilian carriers or ICC [International Control Commission] aircraft.[152]

And during Operation Linebacker I in 1972, the availability of Combat Tree on some eight F-4Ds assigned to the 432nd Tactical Reconnaissance Wing (TRW) at Udorn, Thailand, enabled further (albeit selective) relaxation of the Air Force's Rolling Thunder ROE for BVR shots because aircrews flying these planes could positively identify both

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[151] Commander John B. Nichols (USN, ret.) and Barrett Tillman, *On Yankee Station: The Naval Air War over Vietnam* (Annapolis, MD: Naval Institute Press, 1987), p. 76; Thomas C. Hone, "Southeast Asia," in Benjamin F. Cooling (ed.), *Case Studies in the Achievement of Air Superiority*, (Washington, DC: Center for Air Force History, 1994), pp. 518, 528; General (USAF, ret.) William W. Momyer with Lt. Col. A. J. C. Lavalle and Major James C. Gaston (eds.), *Air Power in Three Wars (WWII, Korea, Vietnam)* (Washington, DC: Office of Air Force History, 1978), pp. 147, 158.

[152] "7th Air Force Operations Order 100-67, Rolling Thunder," Annex B (Concept of Operations), Appendix 3 (Rules of Engagement), provided by Wayne Thompson, e-mail, November 12, 1997. The ICC was created after the First Indochina War to monitor the Geneva accords that ended it.

friendly and enemy aircraft.[153] Thus, while USAF F-4 crews had a bit more leeway in contemplating BVR shots during Rolling Thunder than did their Navy and Marine counterparts, even the Air Force did not make a concerted effort to exploit the Sparrow III's BVR potential until 1972—and even at that late date the effort was confined to a handful of experienced crews within the 432nd TRW.

Why did the Navy, which had originally chosen the Sparrow III as the F-4's primary armament for fleet air defense, not even try to exploit the AIM-7s BVR potential in 1972? The answer is that the Navy's fighter community had concluded, even before Hanoi's overt conventional invasion of South Vietnam in the spring of 1972, that the hand-soldered, vacuum-tube electronics inside the Sparrow III were too fragile to be maintained at sea in the harsh environment of carrier operations on Yankee Station.[154]

This conclusion stemmed in large part from Captain Frank W. Ault's investigation of the reasons for the US Navy's declining air-to-air performance against VPAF MiGs in late 1967 and early 1968. To summarize the situation that precipitated Ault's investigation of the Navy's air-to-air "business practices" during the final 13 months of Rolling Thunder (October 1967-October 1968), Navy F-8s and F-4s only managed to shoot down nine MiGs against six losses while expending large numbers of Sidewinder and Sparrow missiles.[155] Focus-

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[153] For details on Combat Tree, see footnote 149 in this chapter. A distinction has been made between aircrew attitudes in operational units and ROE promulgated by higher authorities for the obvious reason that individual aircrews did not always obey the ROE. For example, Rasimus has described a mission on which his flight lead took a four-ship formation of F-105s 90 nm into China trolling for MiGs—Ed Rasimus, *When Thunder Rolled: An F-105 Pilot over North Vietnam* (Washington, DC: Smithsonian Books, 2003), pp. 181-183.

[154] Nichols and Tillman, *On Yankee Station*, p. 77. On a cruise, both the missiles and the F-4's radar were constantly subjected to the stresses of high-G catapult launches and "traps" when the F-4 recovered using its arresting hook.

[155] R. Frank Futrell, et al., *Aces and Aerial Victories: The United States Air Force in Southeast Asia 1965-1973* (Washington, DC: Albert F. Simpson Historical Research Center and the Office of Air Force History, 1976), pp. 118-122; Robert L. Young, "USAF/USN Air-to-Air Loss Chronology: Southeast Asia (1965-1972)," undated, US Air Force History Office; Roy A. Grossnick, et al., *United States Naval Aviation, 1910-1995* (Washington, DC: US Government Printing Office, 1997), pp. 769-770; and Michael M. McCrea, *U.S. Navy, Marine Corps, and Air Force Fixed-Wing Aircraft Losses and Damage in Southeast Asia (1962-1973) (U)*, microfiche E09-F11 (U.S. Navy Fixed-Wing In-

ing on the Navy's premier fighter-interceptor at the time, the Sparrow III-equipped F-4, the box score during these 13 months was a depressing three kills against six losses—an adverse exchange ratio of 1-to-2 in favor of the North Vietnamese.

In March 1968, midway through this period of deteriorating performance by the Navy's fighter community, Admiral Thomas Moorer, the Chief of Naval Operations (CNO), became sufficiently alarmed about the situation to direct Rear Admiral Bob Townsend and Vice Admiral Tom Connolly to task Captain Ault to find out why Navy fighters were firing so many missiles in anger while scoring so few kills.[156] In fact, Ault's mandate was not just to uncover the reasons for the poor performance but to produce remedies that would boost the Navy's performance by at least a factor of three.[157]

Ault was given *carte blanche* to run his study. He formed five teams to examine the quality of the weapon-system components supplied by industry, the handling of various components (especially missiles) by the Navy's shore establishment en route to the fleet, the handling and readying of the F-4 and munitions at sea, the principle factors influencing air-to-air performance over North Vietnam, and the Navy's system for overhaul and repair of weapon-system components. What Ault and his study teams eventually concluded, after conducting a "womb-to-tomb" investigation, was that nearly everything that could have gone wrong had. The dismal air-to-air performance that started in the fall of 1967 was the "the byproduct of an insidious conglomeration of small items, many relatively insignificant, which, in combination with others, seriously vitiated combat performance."[158] The following list of the more prominent "small items" confirms this judgment.

Flight Combat Loses in S.E. Asia), H14-B15 (U.S. Marine Corps Fixed-Wing In-Flight Combat Loses in S.E. Asia). The box score of nine MiGs downed against three US Navy losses omits one A-1H from VA-25 lost to a Chinese J-6 (a copy of the MiG-19) in February 1968.

[156] Frank. W. Ault, "The Ault Report Revisited," *The Hook*, Spring 1989, p. 36. Townsend was the commander of Naval Aviation and Connelly the deputy CNO for air.

[157] Ault, "The Ault Report Revisited," p. 36.

[158] Ault, "The Ault Report Revisited," p. 38.

- To begin with, the Navy had not been paying sufficient attention to ensuring that industry contractors fully met specifications rather than just doing the minimum, resulting in quality problems.
- The missiles themselves were being handled ashore like dumb bombs rather than the complex devices they were. The AIM-7 needed an aircraft-like maintenance system rather than a traditional ordnance maintenance system.
- Aboard the carriers in the Gulf of Tonkin, preflight testing and environmental protection of missiles were inadequate, and physical damage (dents, cuts and scrapes) was a recurrent problem.
- In the air, it was not uncommon for crews (and their planes) to be suddenly confronted with firing their very first missile in actual combat.
- Missile envelopes had not been verified, or tactics developed, for the high-G dogfights encountered over North Vietnam (in which the difference between the minimum and maximum ranges of the Sparrow III could be a little as 500 feet).
- There were shortcomings with the dynamic response characteristics of the missiles and the dead-time of the fire-control system.
- The absence of an internal gun on the F-4 was a serious limitation inside the minimum ranges of its missiles, and resulted in kill opportunities being missed.
- Finally, the Navy's aviation community had implicitly assumed that missiles such as the AIM-7 would never need to be overhauled and inadequate attention had been paid to verifying the end-to-end performance of aircraft, fire-control systems, and the missiles themselves.[159]

Ault's final report in early 1969 contained 242 recommendations for changes or improvements involving a fiscal outlay estimated at the time to be as much as half a billion dollars.[160] The two most well-

[159] Ault, "The Ault Report Revisited," p. 38.

[160] Ault, "The Ault Report Revisited," p. 37.

known recommendations focused on improving aircrew training by establishing what became “the Navy Fighter Weapons School (*Topgun*)” and developing an instrumented air combat maneuvering range (ACMR).[161] While the first ACMR was not available prior to the beginning of Linebacker I, Topgun graduated its first class in April of 1969 and, by mid-1972, had sent more than 200 graduates from 25 classes back to every Pacific F-4 squadron and to many in the Atlantic fleet as well.[162]

Topgun training, which included flying against adversary aircraft similar in size and appearance to MiG-17s and MiG-21s, is rightly given the lion’s share of the credit for the improved air-to-air performance of Navy fighter (VF) squadrons in 1972.[163] During January 1972-January 1973, Navy VF crews achieved 24 kills for 2 losses against North Vietnamese MiGs, a dramatic improvement over the three kills for six losses during October 1967-October 1968. However, only one of these 24 kills was with the Sparrow; the other 23 were with the AIM-9G.[164] In the wake of the Ault report, the Navy’s F-4 community largely lost faith in the Sparrow. The Air Force, operating from well-established airfields in Thailand during 1971-73, was better able to keep their AIM-7s operational. Yet, as the Topgun staff had forecast,

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[161] Ault, “The Ault Report Revisited,” p. 38.

[162] Lt. Joseph H. Weisberger, “MIG Killers All,” *Naval Aviation News*, September 1972, p. 15; also, Michel, *Clashes*, pp. 186-188.

[163] To provide a sense how dissimilar the F-4 and MiG-17, for example, were during a close-in dogfight, the smaller MiG had a takeoff weight of around 13,000 pounds and a fuselage length of 31 feet. The F-4 was 58 feet long and, in an air-to-air configuration (missiles, empty drop tanks and internal fuel), had a gross weight around 42,000 pounds. At this weight, the F-4’s wing loading was nearly 80 pounds per square foot (lbs/ft^2) whereas the MiG-17’s would be under 50 lbs/ft^2, depending on the amount of fuel remaining. These differences gave the MiG-17 horizontal turning performance that was simply eye-watering the first time an F-4 crew, whose air-to-air training had been exclusively against other F-4s, encountered the smaller jet. Moreover, the two J-79 engines in Vietnam-era F-4s left highly visible smoke trails, whereas the single engine in MiG-17 did not. The smoke from F-4 engines gave VPAF pilots a distinct edge in visually acquiring the larger Phantom IIs.

[164] This box score ignores the kill credited to the Marine squadron VFMA-333 on September 11, 1972, which was also made with AIM-9Gs.

during 1971-1973 AIM-7 reliability "was terrible—about 66 percent of the AIM-7s fired by both services malfunctioned."[165]

Table 4: AIM-7 Performance in SEA[166]

	Firing Attempts	Kills	P_k
June 1965-October 1968	331	26	**7.9%**
December 1971-January 1973	281	30	**10.7%**
Overall 1965-1973	612	56	**9.2%**

Table 4 summarizes combat results with the AIM-7D/E/E-2 in Southeast Asia. The overall P_k, of just over 9 percent, was disappointing. The data indicate that a slight improvement in effectiveness was achieved during the Linebacker operations as compared with Rolling Thunder. But the 2.8 percent increase in P_k still meant that almost nine of every ten Sparrows fired failed to kill any MiGs. These statistics, therefore, certainly support the judgment that the AIM-7 was not a very effective munition in the skies of North Vietnam, especially when compared to the AIM-9. The various models of the less sophisticated, but more reliable Sidewinder expended in SEA achieved a 17.8 percent P_k, and in 1972 Navy VF squadrons posted an impressive 46 percent P_k with the AIM-9G (23 kills for some 50 missiles).[167]

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[165] Michel, *Clashes*, p. 279. Only one of the 24 kills credited to Navy VF squadrons during January 1972-January 1973 was made with the AIM-7. This kill occurred on the night of August 10, 1972—Brad Elward and Peter Davies, *US Navy F-4 Phantom II MiG Killers 1972-73* (Oxford, Great Britain: Osprey, 2002), pp. 79-80. The rest of the kills credited to VF squadrons during this period, as well as the one kill credited to the Marine squadron VFMA-333 on September 11, 1972, were made with AIM-9Gs.

[166] *Project Red Baron II: Air-to-Air Encounters in Southeast Asia (U)*, Vol. I, *Overview of the Report Summary* (Nellis Air Force Base, NV: US Air Force Tactical Fighter Weapons Center, January 1973), p. 13; *Project Red Baron III*, Vol. I, *Executive Summary*, p. 18.

[167] Michel, *Clashes*, p. 279. The IR AIM-4D's 8.2 percent P_k (5 kills for 61 missiles) is best compared with the AIM-9's. For a variety of reasons—including its small warhead, lack of an influence fuze, and the greater complexity of employing the missile in a swirling dogfight—the AIM-4D was less effective than the AIM-9 during the period in late 1967 and early 1968 in which the Falcon was carried on USAF F-4Ds.

In light of the AIM-7's greater complexity and higher cost-per-round than the more successful Sidewinder, the natural conclusion to draw from the data in Table 4 is that the Sparrow III turned out to be something of a failure in the skies over North Vietnam.[168] Granted, there were a number of mitigating circumstances. As F-4 crews grew aware of the missile's reliability problems, they were increasingly inclined to fire two or even four AIM-7s at an individual MiG in hopes that at least one of the missiles would work. Also, inadequate aircrew training not only meant that aircrews had difficulty visually recognizing AIM-7 envelopes in maneuvering dogfights, but a substantial percentage of the time F-4 crews did not even manage to fire the missile inside its actual maneuver envelope. During 1965-68, "over one-third" of the 331 AIM-7 shots attempted were taken "out of parameters."[169] Finally, because the F-4's radar had been initially designed against a bomber-size target penetrating at 40,000 feet, it had little capability to detect or track fighter-size targets when looking down into ground clutter.[170] VPAF MiG pilots quickly learned to exploit this limitation. By simply staying at very low altitude where ground clutter greatly complicated detection, much less a radar lock-on, they could defeat an effective Sparrow shot from an F-4. Thus, there was no shortage of factors that undermined the AIM-7's performance in the skies of North Vietnam.

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[168] Both USAF and Navy sources put the unit cost of Vietnam-era AIM-7s at around $125,000. This price is probably in 1970s or earlier then-year dollars. (The current price of the AIM-7's successor, the AIM-120 AMRAAM, is over $750,000 and the AIM-9 costs more than $230,000 each.) AIM-9 prices comparable to the $125,000 currently cited for the AIM-7 vary significantly, with the USAF putting one of these missiles at $84,000 while the USN offers $41,300. Using these prices, the Vietnam-era Sparrow III was at least half again more expensive than the AIM-9s of that period, and may have been three times costly.

[169] *Project Red Baron II*, Vol. I, *Executive Summary*, pp. 13, 18. Sidewinder out-of-parameters shots during 1965-68 were an even higher percentage of total launch attempts than the Sparrow's: "almost one-half" of 286 Sidewinder launch attempts were outside the AIM-9's envelope (ibid., pp. 14, 18).

[170] The first coherent, pulse-Doppler fighter radars offering a robust look-down/shoot-down capability were the F-15A's APG-63 and the F-14A's AWG-9. Both radars, however, required digital signal control and digital processing that could not be implemented in a fighter when the F-4 was being designed. Neither the F-14 nor the F-15 entered service in time for the Linebacker operations.

Still, even taking these mitigating circumstances into account, it is difficult to escape the conclusion that the F-4/Sparrow weapon system was not very effective during 1965-73. The weapon system's BVR potential was rarely exploited due to ROE and understandable aircrew aversion to fratricide. The AIM-7s and their associated radars were temperamental and complex to employ in dynamic tactical engagements; the missiles themselves were unreliable; and the F-4's radar had vulnerabilities such as no look-down/shoot-down capability that the MiGs exploited. Last but not least, the AIM-7D/E/E-2 certainly did not eliminate within-visual-range dogfights, either in Southeast Asia or in later Arab-Israeli conflicts. In 1973 and 1982, Israeli Air Force F-4s and F-15s, both of which carried Sparrows, are only believed to have fired a total of 35 AIM-7s, suggesting that the Israelis were as unenthusiastic about the Sparrow as Navy VF squadrons had been in 1972-1973.[171] For example, during June-September 1982, nearly half of the 85 Syrian MiG kills claimed by Israeli fighters were scored by Sparrow-equipped F-15s, but the Israeli Air Force insisted that its pilots "took no shots . . . from beyond visual range."[172]

Despite the AIM-7's disappointing performance in Southeast Asia, neither the Navy nor the Air Force gave up on the Sparrow III. True, the Navy's successor to the F-4, the F-14 Tomcat, was designed around the long-range AIM-54 Phoenix missile and the AWG-9 radar, which could simultaneously track up to 24 targets and guide as many six Phoenix missiles. While the F-14, like the F-15, also incorporated an internal 20-mm Gatling gun, the AAW mission of defending carrier battle groups from attacks by Soviet naval aviation bombers armed with cruise missiles clearly drove the Tomcat's design as a weapon system: the Phoenix missile is generally credited with a maximum range beyond 100 nm.

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[171] Burton, "Letting Combat Results Shape the Next Air-to-Air Missile," slide 5.

[172] Benjamin S. Lambeth, *Moscow's Lessons from the 1982 Lebanon Air War* (Santa Monica, California: RAND, September 1984), R-3000-AF, pp. 9-11; also, Shlomo Aloni, "Syrian Shootdown," *AirForces Monthly*, February 2000, pp. 32-35. A review of recent journal articles on the Israeli Air Force by Aloni and others suggests that the F-15 "Baz" downed at least 35 and perhaps as many as 40 Syrian MiG-21s and MiG-23s in June 1982—Lon O. Nordeen, *Air Warfare in the Missile Age* (Washington: Smithsonian Institution, 2nd ed. 2002), p. 162.

In the case of the F-15, however, the Air Force was content with a redesign of the AIM-7 that included solid-state electronics, a dual-stage rocket motor for longer range, and a larger warhead. Combined with a 20-mm Gatling gun, improved Sidewinders, and the pulse-Doppler APG-63 radar that provided a robust look-down/shoot-down capability, the agile F-15 corrected most of the air-to-air shortcomings US airmen had experienced with the F-4 during the Second Indochina War. These various post-Vietnam improvements yielded the far more reliable AIM-7F. During this same period, appearance of the all-aspect AIM-9L model of the Sidewinder made it far more difficult than before for fighter crews to stay safely outside the envelopes of these new IR missiles. Together, these improved air-intercept missiles made the post-Vietnam air-to-air arena considerably more lethal than it had previously been, particularly when employed on the more agile generation of US fighters that succeeded the F-4.

Table 5: AIM-7M Performance in Desert Storm[173]

		Attempts	Hits	Hit Rate	Kills	P_k
		612	97	**15.8%**	56	**9.2%**
AIM-7M	**Coalition**	88	32	**36.4%**	26	**29.5%**
1991	**F-15C**	67	30	**44.8%**	24	**35.8%**

By the time of Operation Desert Storm took place in January-February 1991, the AIM-7F had been succeeded by the AIM-7M. This model of the Sparrow III added an inverse monopulse seeker for better look-down/shoot-down performance, an active radar fuze, digital controls, improved resistance to electronic countermeasures, and better low-altitude performance.[174] How did this descendant of the AIM-7D/E/E-2 perform in the skies of Iraq? The data in Tables 5 and 6 endeavor to answer this question. When the data in these tables is examined in detail, the basic answer is that solid-state electronics and digital processing produced a medium-range, radar-guided air-to-air

[173] *Project Red Baron III*, Vol. I, *Executive Summary*, p. 18; and Major Lewis D. Hill, Doris Cook, and Aron Pinker, Gulf War Air Power Survey, Vol. V, *A Statistical Compendium and Chronology* (Washington, DC: Government Printing Office, 1993), Part 1, *A Statistical Compendium*, pp. 550-552, 653-654.

[174] "AIM-7 Sparrow," Wikepedia online encyclopedia.

missile whose performance—particularly in the hands of well-trained Air Force F-15C pilots—exceeded the expectations and promises made by forward-looking aerospace engineers in the late 1950s.

To begin with, the AIM-7's share of the air-to-air kills credited to friendly fighters more than doubled from Southeast Asia to Desert Storm. During 1965-1973, US fighters scored a total of 195 kills, of which 56 are credited to AIM-7s (28.7 percent). During Operation Desert Storm (January 17-February 28, 1991), Coalition fighters recorded 38 air-to-air kills, of which 26 were made by AIM-7Ms (68.4 percent).[175] In 1991, therefore, the AIM-7 was the dominant weapon used to shoot down enemy aircraft, even though the F-15s that scored the majority of the kills (33 of 38) were also armed with Sidewinders and an internal 20-mm Gatling gun.

Next, both the AIM-7M's hit rate and P_k also showed substantial improvement when compared with AIM-7D/E/E-2 performance during 1965-1973. The F-15C hit rate is nearly triple the average from Southeast Asia, and the corresponding kill probability is almost four times better (Table 5). Granted, compared to typical USAF F-4 crews during 1965-1973, the air-to-air proficiency of the Air Force's F-15 community in 1991 had benefited enormously from the post-Vietnam commitment of Tactical Air Command, following the example of the Navy's Topgun program, to realistic training. Dedicated F-5 Aggressor squadrons employing tactics and aircraft that closely mimicked those of Soviet pilots and fighters, regular Red Flag composite-force training exercises on the Nellis AFB ranges, the debriefing objectivity enforced by instrumented air-to-air training using the ACMRs that emerged from the Ault's report, and the availability of Airborne Warning and Control System (AWACS) E-3s all contributed to proficiency and SA levels among line F-15C pilots in 1991 that, in hindsight, made air-to-air training for most Air Force F-4 crews who flew in Southeast Asia appear criminally negligent by comparison. Moreover, the USAF F-15 community was strictly dedicated to the air superiority mission, the informal motto under which TAC developed the Eagle having been "Not a pound for air-to-ground." As a result, in 1991 F-15 pilots were much better prepared than their predecessors in Southeast Asia had

[175] The 38 Coalition kills consisted of 19 MiGs (including five MiG-29s), eight F-1s, three Su-7/17s, two Su-25s, one IL-76, and five helicopters. Not included is the Mi-24 helicopter downed by an F-15E using a GBU-10 laser-guided bomb on February 14, 1991.

been to fire AIM-7s with the cockpit switches correctly set, to employ the missile inside its actual envelope, and resist firing several Sparrows when one would suffice. Still, the overall performance data in Table 5 suggest that the AIM-7M was a considerably more reliable and effective missile than the AIM-7D, AIM-7E, or even the "dogfight" AIM-7E-2 had been.

This conclusion is strongly supported by the data in Table 6, which concentrates on AIM-7M performance in decisive engagements during Desert Storm. Part of the reason for focusing on this narrower slice of the air-to-air data summarized in Table 5 is the availability of fine-grain information about those encounters that resulted in an Iraqi aircraft being shot down. The deeper reason, though, is uncertainty about the Desert Storm expenditure totals in the third column of Table 5. These numbers, which are surprisingly larger than those in Table 6, are based on logistics reporting, and provide no information regarding how many of the 46 AIM-7Ms not expended in decisive engagements were actually fired by Coalition fighters in air combat without effect through February 28, 1991, as opposed to being "expended" later or lost to non-operational causes such as damage from improper handling, exposure to sand, or other reasons.[176] Additionally, US Central Command Air Forces' reports of daily munitions expenditures, which would have included all those fired by F-15Cs, show only 43 AIM-7Ms having been expended on combat sorties as of February 28, 1991.[177] Thus, there are ample reasons for thinking that even if the decisive-engagement data overlook a few Sparrows that were expended without result by February 28th, Table 6 provides a better indication of the lethality and effectiveness of the AIM-7M than Table 5.

[176] One F-15C pilot who downed a MiG-23 on January 30, 1991, reported seeing a pair of Bitburg F-15s firing missiles at some MiG-23s—John M. Deur, *Wall of Eagles: Aerial Engagements and Victories in Operation Desert Storm* (Cleveland, OH: Intercept Publications, 1994), p. 28. Since these aircraft did not record a kill that day, whatever they expended—whether AIM-7Ms or AIM-9Ms—have not been included in Table 6. USAF F-15Cs shot down three additional Iraqi aircraft during 21-23 March 1991, although none of these kills were with AIM-7s.

[177] Hill, Cook, and Pinker, GWAPS, *A Statistical Compendium*, p. 606.

What Table 6 clearly shows are hit rates in the vicinity of 75 percent and P_ks around 60 percent.[178] The Desert Storm kill-rate is roughly a six-fold improvement over the AIM-7's P_k in Southeast Asia, and AIM-7M performance in the decisive engagements in 1991 is certainly indicative of a lethal and effective munition. Moreover, not only was the Sparrow lethal and effective but, due to long training with the AWACS and the availability of non-cooperative target recognition (NCTR) capabilities that enabled the stringent ROE for BVR shots imposed by Lieutenant General Charles Horner to be satisfied, 29 of the 42 Sparrows expended in decisive engagements by Coalition fighters during Desert Storm (69 percent) were fired beyond visual range.[179] Not only was the AIM-7M lethal and effective, but pilots, aided by the battle-network capabilities of the AWACS, were able to exploit its BVR capability with minimal risk of fratricide.

Table 6: AIM-7M Performance in Decisive Engagements[180]

		Attempts	Hits	Hit Rate	Kills	P_k
AIM-7M	**Coalition**	42	32	**76.2%**	26	**61.9%**
1991	**F-15C**	40	30	**75.0%**	24	**60.0%**

In the late 1950s, many involved in the development of the AIM-7 predicted that the missile, with its all-aspect and BVR capabilities, would dramatically change air-to-air combat. The presumption was that the missile could do the hard maneuvering and kills could be achieved before opposing pilots could even see one another visually.

178 The hit rate is higher than the kill rate because on occasion a second AIM-7M guided to and detonated at the fireball left by the impact of a prior missile.

179 NCTR based on other techniques than exploiting enemy IFF was attempted using the F-4's radar in the late 1960s with little success. The technology finally matured on the Multi-Stage Improvement Program (MSIP) F-15Cs in time for Operation Desert Storm. Horner was the Joint Force Air Component Commander during Desert Storm.

180 Deur, *Wall of Eagles*, pp. 5-36. A pre-publication version of Deur's *Wall of Eagles* acquired by GWAPS researchers in 1992, rather than the published book, was used for the engagement details during Operation Desert Storm (January 17-February 28, 1991). Deur's engagement reconstructions are based on interviews with the pilots involved.

The need for hard maneuvering by opposing fighters has not been eliminated—at least not yet. Hard maneuvering on the edges of the lethal envelopes of contemporary air-to-air missiles can enable the targeted aircraft to reduce or distort the missile's effective envelope just enough to escape a lethal shot, a lesson that was underscored in the AMRAAM OUE. The pattern that emerged from the AMRAAM OUE was that the AIM-120 AMRAAM forced adversaries facing the new missile to begin hard maneuvering at even greater ranges than had been observed in ACEVAL, which had witnessed an expansion of the distances at which hard maneuvering began due to the inclusion of the all-aspect AIM-9L. Nevertheless, it is difficult to escape the conclusion that high-G, reliable missiles such as the AIM-120 and AIM-9X have substantially transformed what it takes to survive in today's air combat arena. As one author has noted, "Even early generation F-4s of the German Luftwaffe have shown that with the AIM-120 and proper tactics they can counter all adversaries, even the highly maneuvrable MiG-29 with its eye-watering AA-11 (R-73) missile and helmet-mounted sight which provides excellent close in attack capability."[181] Similarly, the defense reporter George Wilson, after "auditing" the Navy's 11-month test-pilot course at Patuxent River Naval Air Station, observed that aerial engagements were becoming so dominated by "systems"—radars, communications and missiles—and the fighter platforms themselves "so secondary," that the pilots were complaining "they had been reduced to office managers running the systems."[182] The late-1950s' vision of guided missiles changing the dynamics of fighter-versus-fighter combat, then, may finally be upon us (albeit nearly a half century later than originally envisioned).[183] Equally clear, though, is that these changes would not have been possible without solid-state electronics, including microprocessors, and digital signal processing.

[181] Nordeen, "Air Combat: The Sharp End," *AirForces Monthly*, October 1999, p. 61.

[182] George C. Wilson, "Planes the Air Force Doesn't Need," *The Washington Post*, April 5, 2004, p. 17. Ben Lambeth, long a keen student of fighter tactics, drew similar conclusions in the year following the 1991 Gulf War.

[183] Nordeen's observations about the ability of the F-4F/AMRAAM to hold its own even with the MiG-29/A-11 also argue that the inclusion of a 20-mm Gatling gun internally mounted on the F-22, far from being necessary, is an anachronistic holdover from American air-to-air experience with gunless F-4s in Southeast Asia. The same can be said of the desire to retain an internal cannon on some models of the F-35 Joint Strike Fighter.

In this regard, Wayne Hughes has argued that the generation-by-generation developmental pattern evident in successive classes of US heavy cruisers, from the beginning of the naval treaty period in 1921 to the end of World War II, offer "the perfect example of a successful evolutionary approach" to the maturation of complex weaponry.[184]

> New weapons often require the development of new tactics by men of great vision. Both weapons and tactics will be perfected more quickly if a series of similar fighting machines are built, each model following rapidly on the heels of its predecessor. It is impossible to design the perfect weapon for large-scale production and employment without practicing with it; even then, it takes three of four generations of hardware before a weapon realizes its full potential.[185]

The AIM-7 illustrates this pattern. The Sparrow I and II were more or less failures while the Sparrow III was a marginal weapon at least until the mid-1970s. Arguably the AIM-7 did not live up to its promise in combat until 1991, and there were at least four Sparrow III models between the marginal AIM-7C and the deadly AIM-7M.

Given the degrees of freedom available to both attacker and target in aerial combat, the US Navy and US Air Force embraced radar-guided air-to-air missiles long before they were either highly reliable or moderately lethal—and rightly so given the threats and problems the early Falcons and Sparrows were intended to address. In the early days, the vacuum-tube electronics and hand-soldered circuits of the AIM-7 were simply not up to the demands of fighter-versus-fighter combat. Nonetheless, the Navy and Air Force persisted, and the emergence of solid-state electronics and digital processing after the American involvement in the Second Indochina War eventually turned engineering promise into combat reality.

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184 Hughes, *Fleet Tactics and Coastal Combat*, pp. 233-34.

185 Hughes, *Fleet Tactics and Coastal Combat*, p. 242.

Styx and Harpoon Anti-Ship Missiles

The first two cases in this chapter—torpedoes after World War II and the Sparrow III—examined instances of the early adoption of guided munitions by war-fighting communities in the US Navy and US Air Force. Looking back, it seems fair to say that the submariners, the surface-combatant portion of the Navy charged with defending carriers against air attack, and the US Army all began embracing guided munitions before the end of World War II. In the case of the Army, the German *Wasserfall* (waterfall) surface-to-air missile, of which three variants were developed, provided the impetus in 1944 for what became the Nike series of SAMs as well as the Air Force's BOMARC. If anything, the adoption of air-to-air missiles for Navy and Air Force fighter-interceptors came a few years after the commitment of these other communities to guided munitions. In all these cases, however, the war-fighting communities involved were not only early developers and adopters, but embraced the underlying technologies before they were very reliable or mature.

By comparison, ASMs for ship-versus-ship engagements constitute a case in which the US Navy's surface-warfare community appears to have been a late and somewhat reluctant adopter. The burden of this discussion is to explore why it took the US Navy a decade after the Israeli destroyer *Eliat* was sunk in 1967 by Soviet-supplied Styx anti-ship missiles to field the AGM/UGM/RGM-84 Harpoon, which was developed as the service's "basic anti-ship missile for fleet-wide use."[186] The seemingly tardy fielding of Harpoon is especially puzzling in light of the US Navy's earlier commitment to Project Bumblebee, which produced the first-generation of US naval SAMs (Tartar, Talos, and Terrier).

The Harpoon, which entered operational service in 1977, was the first US Navy "missile designed for shipboard launch against surface targets since the Regulus I," which had been "deployed in the 1950s . . . primarily for the strategic [that is, nuclear], land-attack role."[187]

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[186] "Harpoon Missile," United States Navy Fact File, online at <http://www.navy.mil/navydata/fact_display.asp?cid=2200&tid=200&ct=>, accessed May 23, 2006.

[187] Norman Polmar, *The Naval Institute Guide to the Ships and Aircraft of the U.S. Fleet* (Annapolis, MD: Naval Institute Press, 17th ed. 2001), p. 508. One could argue that Tomahawk, rather than Harpoon, is better seen as successor to Regulus on the grounds that Tomahawk has come to be used exclusively in

The Chance Vought Regulus I was an early cruise missile the US Navy fielded on a few cruisers, diesel submarines, and aircraft carriers to give it a sea-based alternative to the deterrent capability of Air Force bombers. Regulus was designed to deliver an atomic (and, later, thermonuclear) warhead, weighing as much as 3,000 pounds, to distances up to 500 nautical miles (929 km). While the targets envisioned for Regulus were surface targets, they were enemy fixed facilities ashore not, as in the case of Harpoon, other ships on the ocean's surface.[188] Regulus I was also a large vehicle—over 14,500 pounds at launch—and, like other 1950s cruise missiles, unreliable and inaccurate.[189] In the end, Regulus I only remained in service a few years beyond the first deterrent patrols by American nuclear-powered ballistic-missile submarines, which began in late 1960, and Regulus II, a proposed successor, was cancelled in favor of the Polaris submarine-launched ballistic missile.[190]

In the early 1950s, both the Navy and the Air Force had initially favored cruise over ballistic missiles for the delivery of atomic weapons at longer ranges. The early resistance to wingless ballistic missiles seems to have been emotional and cultural, since quantitative studies indicated that cruise missiles would be less accurate, less dependable, and more costly.[191] Ultimately, biases favoring cruise missiles were

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a land-attack role, although there was an anti-ship variant early in the program.

188 Kenneth P. Werrell, *The Evolution of the Cruise Missile* (Maxwell AFB, AL: Air University Press, September 1985), p. 114. Regulus initially carried a W-5 warhead with a yield of 40-50 kilotons; a 1-2 megaton W-27 warhead was later used. Apparently only 55 W-5 and W-27 warheads were produced for Regulus (Hansen, *U.S. Nuclear Weapons*, pp. 190-91, 193).

189 Werrell, *The Evolution of the Cruise Missile*, pp. 135, 236. Five submarines made 40 strategic-deterrent patrols with Regulus between October 1959 and July 1964; four cruisers went on operational patrols with Regulus during 1955-61; and two carriers deployed with the missile (David K. Stumpf, "Regulus Guided Cruise Missile," at <http://www.wa3key.com/regulus.html>, accessed August 24, 2006).

190 The USS *George Washington* (SSBN-598) and *Patrick Henry* (SSBN-599) began their first patrols with 16 Polaris A-1 ballistic missiles in November and December 1960, respectively.

191 Werrell, *The Evolution of the Cruise Missile*, p. 104. As would be expected, reliability was a major problem with early cruise missiles like Regulus and the US Air Force's Snark. To recall one of the worst episodes, in December 1956 a

overcome, but it took a confluence of bureaucratic developments and personalities in both services to give priority to ballistic missiles, enabling them to surpass and displace the post-World War II generation of land-attack cruise missiles in the early 1960s for the nuclear deterrent mission.[192]

Figure 16: Styx and Harpoon ASMs[193]

Harpoon, then, was in many respects a return by the US Navy to cruise missiles after a long hiatus. By contrast with Regulus I, Har-

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Snark launched from Cape Canaveral stopped responding to control inputs and ended up crashing in the jungles of Brazil (ibid., p. 92).

[192] MacKenzie, *Inventing Accuracy*, pp. 98-113, 134-39; Werrell, *The Evolution of the Cruise Missile*, p. 106.

[193] The photo of the Harpoon launch on the right is courtesy of Boeing.

poon weighs some 1,520 pounds (lbs), including a booster for surface or submarine launch, and contains a 488-lb high-explosive warhead designed to penetrate naval combatants. As the AGM/RGM/UGM-84 nomenclature indicates, the weapon can be launched from aircraft, ships, and submarines. The Harpoon is a high-subsonic, sea-skimming missile with active radar terminal guidance. It has also been adapted for use by land-based coastal batteries. The Block-II version of the missile incorporated GPS-assisted inertial navigation, thereby giving Harpoon a land-attack capability in addition to its anti-ship role.

Again, the basic question is why the American surface navy did not field an anti-ship cruise missile until the late 1970s. The answer appears to be that Harpoon was a somewhat belated response to a series of mostly external events. First, in the late 1950s the Soviets began developing what NATO designated Komar-class fast attack craft (FACs). These missile boats were initially armed with a pair of SS-N-2a Styx anti-ship missiles, each weighing some 5,070 lbs (without a booster), armed with a 1,000-lb high-explosive warhead, having a maximum range of 45 km (24.3 nm), and employing an active radar sensor in the missile's nose for terminal guidance.[194] The promise—or threat—of the Komar/Styx FAC was that its "combination of high speed [39 knots] and powerful anti-ship missiles would render all frigates, destroyers and major warships obsolete."[195]

Similar claims had been advanced by the French, starting in the 1870s, about the potential of the torpedo boat to sweep the battleship from the seas. The Royal Navy began to counter this threat with the introduction of the torpedo-boat destroyer in 1893 as an effective defense against torpedo boats.[196] While the range of torpedoes steadily

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[194] The Soviet SS-N-2a had a maximum range of 24-25 nm, which was a few miles beyond a nominal radar horizon of around 19 nm for FACs. Soviet designers solved the problem of shooting beyond the radar horizon by giving the missile an autopilot that would allow it to be launched on a bearing to the target—presumably supplied by an off-board sensor or an observer. Then, once the missile got close enough to the target to be within the SS-N-2's radar field of view, the radar sensor in the nose would go active, and the missile would begin guiding itself to the target.

[195] Anthony Preston, *The World's Worst Warships* (London: Conway Maritime Press, 2002), p. 177.

[196] Preston, *The World's Worst Warships*, p. 181.

grew over the next fifteen years, destroyers also grew in size and capability, and torpedo boats decreased in importance as a threat to capital ships after the Russo-Japanese war of 1904-05. In the 1960s, the prospect that fast patrol boats (FPBs) could render surface combatants obsolescent by outranging them with anti-ship missiles posed a similar problem. The main difference was that Styx missiles, unlike torpedoes prior to the German G7e/T4 *Falke* and G7es/T5 *Zaunkönig*, could guide on their target rather than being only aimed. In hindsight, the concern that FPBs would obviate larger surface combatants appears to have been exaggerated. Guided-missile boats have had no more success in eliminating large surface combatants than early air-to-air missiles had in eliminating dogfights.

In the case of the Komar/Styx, however, a dramatic early combat success against the Israeli destroyer *Eilat* led many observers of naval affairs to take this emerging threat to heart. On October 21, 1967, the *Eilat* was patrolling alone some 14 miles off Egypt's Port Said naval base. At 1716 hours, a signalman on the *Eilat* reported bright bursts and curls of smoke in the direction of Port Said, and the *Eilat* resumed zigzag maneuvers to guard against enemy submarines.[197] Shortly thereafter a Styx missile hit the *Eliat*'s stern, followed minutes later by a second Styx, which hit amidships. The *Eilat*'s crew struggled for about two hours to save the ship, which had begun to sink with a noticeable list, when a third Styx detonated the *Eilat*'s ammunition magazine, forcing the captain to abandon his ship.[198] A fourth and last Styx was fired, but apparently fell on a derelict *Eilat*, spilling fuel and oxidizer, and the ship soon sank.

In the wake of this encounter, a near panic ensued among at least some observers over the perceived vulnerability of surface combatants to ASMs. Initially at least, the *Eilat*'s lack of either passive or active defenses against cruise missiles, as well as its skipper's recklessness in loitering during daylight near a hostile port, were largely ignored. Instead, the *Eliat*'s sinking spurred several nations, including the French, to begin developing their own sea-skimming cruise missiles and fast missile boats.[199] The Israeli navy also accelerated efforts to

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197 Lieutenant Commander Asen N. Kojukharov, "In Retrospect: The Employment of Antiship Missiles," *Naval War College Review*, Autumn 1997, p. 122.

198 Kojukharov, "In Retrospect: The Employment of Antiship Missiles," p. 122.

199 Preston, *The World's Worst Warships*, pp. 178-80.

field its sea-skimming Gabriel anti-ship missile, which had been in development since 1962, and to begin fitting them on Sa'ar 2 and Sa'ar 3 FPBs, five of which had been spirited from Cherbourg without official French approval in December 1969.[200] These Israeli initiatives obviously sought to counter the perceived, post-*Eilat* threat of Styx anti-ship missiles on the Soviet-made "Komar" and "Osa" class FPBs (or FACs) operated by the Egyptian and Syrian navies.[201]

The dénouement to the world's first sinking of a sizeable naval combatant by an anti-ship cruise missile came during the October 1973 Arab-Israeli War. In that conflict, Israeli missile boats claimed to have sunk three Syrian and five Egyptian FACs in a series of naval battles without losing any of their own.[202] The Israelis achieved this 8-to-0 box score even though the SS-N-2a outranged Gabriel by at least a factor of two and Arab FACs fired some 52 Styx missiles at them.[203] Given the Styx's range advantage, the explanation for this one-sided outcome has been that the Israelis induced their opponents "to fire all their missiles ineffectually, then closed in for a devastating finale."[204] For example, during the night battle off the Syrian port of Latakia on the second day of the war (October 7, 1973), the Israelis employed tactics that took advantage of the SS-N-2a's dependence on terminal radar guidance until target impact. The five Israeli missile boats approached at high speed in two columns and induced the Syrians to fire first at long ranges outside Gabriel's reach. They then utilized chaff and electronic countermeasures ("false radar signals") to

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200 The five ships spirited out of Cherbourg by their Israeli crews were Combattante III fast patrol boats, with displacements under 500 tons.

201 "Saar," Israeli-Weapons.com, online at <http://www.israeli-weapons.com/weapons/naval/saar/Saar.html>, accessed August 26, 2006.

202 "The Israeli Navy Throughout Israel's Wars," Jewish Virtual Library, at <http://www.jewishvirtuallibrary.org/jsource/Society_&_Culture/navywar.html>, accessed August 28, 2006.

203 "SS-N-2 Styx," Global Security, online at <http://www.globalsecurity.org/military/world/russia/ss-n-2.htm>, accessed August 28, 2006. The maximum range of the initial model of the Gabriel missile was 20 kilometers (10.8 nm). During the Battle of Latakia, one Israeli Sa'ar reported a radar contact against a Syrian ship running for shore at 25 kilometers (13.5 nm).

204 Hughes, *Fleet Tactics and Coastal Combat*, p. 84. The maximum range generally given for the SS-N-2a is 45 kilometers, whereas the maximum range for the initial version of Gabriel was only 20 kilometers.

defeat the Syrians' initial SS-N-2a salvos. Finally, the Israeli missile boats closed to inside Gabriel's range and fired, sinking two Syrian FACs with missiles and finishing off a third with gunfire after it became stuck in shallow waters while trying to escape.[205] By the end of this engagement the Syrians had lost a torpedo boat, a minesweeper, and three missile boats (one Osa and two Komars). As a result, the Syrian navy was bottled up in port for the remainder of the war. The Egyptian navy suffered a similar fate.[206]

In the wake of Israeli success with fast missile boats in October 1973, it was not unreasonable for students of naval warfare to conclude that the world's navies had entered "a new age" in which anti-ship missiles were "the most influential weapons shaping tactics."[207] As Wayne Hughes observed, in the 1971 Indo-Pakistan War nine Styx missiles were "employed with much success by India against Pakistani warships and merchants," and in October 1973 a "total of 101 Styx and Gabriel missiles were exchanged in five separate battles with devastating effects on the Syrian and Egyptian flotillas and no harm whatsoever to the Israelis."[208] These events argued that mastery of missile warfare would increasingly dominate future engagements between surface combatants at sea.

The US Navy did not get a modern anti-ship cruise missile into operational service until 1977. Harpoon was not even established as an acquisition program until 1969, two years after the *Eliat*'s sinking.[209] Why did it take the American navy another eight years to deploy an anti-ship missile on a par with the Israelis' Gabriel or the Soviets' Styx? Was the US Navy slow to appreciate the advent of the missile age at sea, or were there mitigating circumstances behind this seeming tardiness?

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[205] Captain Opher Doron, "The Israelis Know Littoral Warfare," *US Naval Institute Proceedings*, March 2003, p. 67; also, "The Battle of Latakia (October 7, 1973)," at <http://www.us-israel.org/jsource/History/latakia.html>, accessed August 28, 2006.

[206] Doron, "The Israelis Know Littoral Warfare," p. 66.

[207] Hughes, *Fleet Tactics and Coastal Combat*, p. 149.

[208] Hughes, *Fleet Tactics and Coastal Combat*, p. 152.

[209] Werrell, *The Evolution of the Cruise Missile*, p. 150.

If there were mitigating circumstances, they did not lie in the US Navy's lack of state-of-the-art missile technology or well-funded missile programs. Project Bumblebee began December 1944 under the leadership of Merle Tuve, director of the Applied Physics Laboratory (APL) at the Johns Hopkins University. Tuve, whose Section T of the World War II NDRC is credited with developing radio proximity fuzes capable of being mass produced for artillery and anti-aircraft shells, was tasked by the Navy to find the best way to defend large surface ships against air attack.[210] Talos, with a range of over 60 nm, and the shorter-range Terrier and Tartar, all emerged from Bumblebee.[211]

Again, the US Navy's push for naval SAMs had its initial impetus in the vulnerability to air attack that surface combatants had exhibited early in World War II, especially in the Pacific. By 1942, carrier-based air wings had conclusively demonstrated their ability to sink opposing surface combatants, including battleships, out to distances of 200-250 nautical miles during daylight.[212] Furthermore, the aircraft carriers were themselves vulnerable to the air attack—at least in the daytime—and this vulnerability led the Navy to begin assigning battleships and other surface combatants to the AAW role.

> By 1942 a flood of AAW weapons was being installed, with radar sensors, deadly proximity fuzes, and new, capable

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[210] Buderi, *The Invention That Changed the World*, p. 221. The radar-proximity or VT fuze, combined with the M9 gun director and the SCR-584 radar, proved particularly effective in defending England against German V-1 cruise missiles. The first V-1s were fired at London in mid-June 1944. During the last two weeks of the 80 days during which these weapons were launched from northwestern France, antiaircraft artillery using the VT-fuze/M9/SCR-584 combination destroyed over two-thirds of all targets engaged—Ralph B. Baldwin, *Deadly Fuze: The Secret Weapon of World War II* (San Rafael, CA: Presidio Press, 1980), p. 266.

[211] Talos, with a slant range of over 60 nm, could reach as high as 87,000 feet; Terrier and Tartar had slant ranges of about 10 nm and maximum altitudes around 40,000 feet—Kenneth P. Werrell, *Archie, Flak, AAA, and SAM: A Short Operational History of Ground-Based Air Defense* (Maxwell Air Force Base, AL: Air University Press, December 1988), p. 87. By comparison, the Soviet V-75 Dvina (SA-2 Guideline in NATO terminology) had a slant range around 25 nm, and could reach at least 70,000 feet.

[212] After dark, guns, not carrier aircraft, dominated naval warfare in the Pacific through the end of World War II, as is "clearly seen in the climatic action in the Battle for Leyte Gulf" (Hughes, *Fleet Tactics and Coastal Combat*, p. 111).

> fire-control systems to lead and hit fast-moving targets. By 1944 attacking [Japanese] aircraft faced a veritable curtain of fire. In the last year of the war [in the Pacific], modern surface combatants had redressed the balance of power they had lost to naval aircraft.[213]

However, two other events suggested that the AAW solutions of 1944 would not suffice in the future. The first was the success of German guided bombs against the Italian battleship *Roma* in 1943. The second was Japan's success with Kamikazes, especially against the Anglo-American fleet during the battle of Okinawa (April 1 to July 2, 1945). The toll from the ten mass Kamikaze attacks against Task Force 58 was substantial. Ill-trained, third-rate Japanese suicide pilots, who effectively converted their second-rate aircraft into "first-rate guided missiles," cost Task Force 58 "a staggering 36 ships sunk and 368 hit" as well as nearly 5,000 dead, making it the "most costly of any single battle in the history of the United States Navy."[214] These events led, understandably, to an institutional commitment by the American navy to begin developing guided missiles for the defense of its surface combatants against air attack even before the war in the Pacific ended.

Two post-war events gave even greater urgency to this commitment. One was the advent of the atomic bomb. When this weapon was first used against Hiroshima and Nagasaki in August 1945, the United States had a monopoly on nuclear weapons. The explosion of the first Soviet fission weapon in August 1949 (Figure 12) not only broke this monopoly, but compounded the US Navy's AAW problem by adding the threat of atomic bombs. The other event that underscored Bumblebee's urgency was advent of jet aircraft during the Korean War. The faster speeds of jet fighters and bombers reduced the reaction times available to surface combatants trying to defend themselves against air attack.

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[213] Hughes, *Fleet Tactics and Coastal Combat*, p. 189.

[214] Victor Davis Hanson, *Ripples of Battle* (New York: Doubleday, 2003), pp. 27, 29, 37. Hughes argues that the lethality of the Kamikaze attacks against Task Force 58 off Okinawa "marked a turning point in operations at sea and metaphorically represent the start of the missile era" (*Fleet Tactics and Coastal Combat*, p. 168). Hanson, who likens Kamikaze suicide craft to both a first-rate guided missile and a "smart" shell, agrees (*Ripples of Battle*, pp. 37, 48).

Given the US Navy's early commitment to guided missiles for fleet air defense, it seems all the more puzzling that the Harpoon anti-ship guided missile was not introduced until 1977, over three decades after Bumblebee began. After all, Bumblebee produced missiles that had some success in combat. While the North Vietnamese never mounted major attacks against American carrier battle groups operating in the Gulf of Tonkin, during both 1968 and 1972 US guided-missile cruisers downed North Vietnamese MiGs using Talos and, on one occasion, Terrier SAMs.[215]

Why was this missile technology not applied to the anti-ship mission by the US Navy prior to the beginning of the Harpoon program? Part of the reason is that for the USN's surface community, the primary problem, even as late as the early 1970s, was defending the carrier against air attack. The urgency of this problem appears to have kept the surface fleet focused on naval SAMs as opposed to anti-ship missiles. Arguably, in a "blue-water" context the Soviet Navy had the same focus. The first Soviet guided-missile combatants, the *Kashin*-class destroyers, were originally armed with SA-N-1 surface-to-air missiles. It was only in the 1970s that six *Kashins* were modified to carry Styx missiles on their sterns. On the open ocean, however, the chances of *Kashins* getting close enough to hit a carrier with Styx missiles was probably low.

Another part of the answer lies in the very different circumstances of the Israeli and American navies during the late-1960s and 1970s together with the USN's dominance by naval aviators who "saw little need for cruise missiles."[216] The Israeli Navy has always been "a littoral navy" operating within seas adjacent to enemy coasts—coastlines that were "protected by detection and weapon systems based on land, ships, and aircraft."[217] It has never had a naval air arm, much less an aircraft carrier. The engagements Israel's navy fought in 1967 and 1973 were fundamentally ship-against-ship encounters be-

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[215] Werrell, *Archie, Flak, AAA, and SAM*, p. 136. The cruiser *Long Beach* (CG-9) is believed to have downed two MiG in 1968; the cruisers *Chicago* (CG-11) and *Sterett* (CG-31) are thought to have scored additional MiG kills in early 1972. There is some evidence that an anti-radiation version of Talos was used against North Vietnamese mobile radar vans in 1972.

[216] Werrell, *The Evolution of the Cruise Missile*, p. 150.

[217] Doron, "The Israelis Know Littoral Warfare," pp. 66, 67.

tween combatants with comparable armament and capabilities. The 1973 Battle of Latakia illustrates the kind of relatively symmetric, fleet-on-fleet engagements between opposing surface combatants that have characterized Arab-Israeli naval actions.

Table 7: US and Soviet Conventional Naval Inventories, FY 1990[218]

Combatant Category	USN	Soviet Navy
Aircraft Carriers	14	0
VSTOL/Helicopter Carriers	0/12	4/0
Battleships	3	0
Cruisers	36	36
Destroyers	68	51
Frigates	119	36
Corvettes	0	147
Submarines	100	299
Total	**352**	**573**

By comparison, the US Navy was fundamentally a blue-water navy throughout the US-Soviet Cold War, whereas its principal opponent, the Soviet Navy, had a more coastal orientation right to the end of their long-term rivalry (Table 7). On the high seas, the US Navy was the world's most capable and dominant naval force. During 1946-91, its unmatched capabilities for conventional power-projection were based on an average inventory of between 13 and 14 multipurpose aircraft carriers.[219] The Soviet Navy never fielded comparable multipur-

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[218] Frank C. Carlucci, *Annual Report to Congress on the FY 1990/FY 1991 Biennial Budget and FY 1990-94 Defense Programs* (Washington, DC: US Government Printing Office, January 9, 1989), p. 29. Frigates were defined as ships of 2,000 tons displacement and larger. Corvettes included frigates under 2,000 tons. Because the comparison focused on conventional naval forces, the submarine totals excluded SSBNs on both sides. During 1989-90, the US possessed 33 deployable SSBNs and the Soviet Navy 60-68 (Natural Resources Defense Council historical databases on nuclear forces at <http://www.nrdc.org/nuclear/nudb/datainx.asp>, accessed August 2006).

[219] McCrea, et al., "The Offensive Navy Since World War II," p. 12. As of October 2006, the USN had a total of 12 multipurpose carriers (10 nuclear-powered CVNs and two conventionally powered carriers, the USS *Kitty Hawk* and the USS *John F. Kennedy*—Naval Vessel Register at <http://www.nvr.navy.mil/>). Since at least one carrier is normally undergoing major maintenance (e.g., the Service Life Extension Program), the number

pose aircraft carriers. Until the appearance of the Tomahawk cruise missile in the 1980s, the long-range offensive striking power of American carrier battle groups resided almost entirely in carrier air wings, whose fighter and attack aircraft could deliver intense pulses of combat power hundreds of miles from the carrier and its protective battle group. Naval aviators had dominated the US Navy since their glory days during World War II, and they saw little reason to undermine the primacy of fighters and fighter-bombers by embracing cruise missiles.[220] Given the long reach and striking power of the carrier air wing, to say nothing of the sensor reach of the carrier battle group, opposing surface combatants with Styx ASMs did not pose much of a threat.

Again, the defensive problem that drove the evolution of US carrier battle groups after World War II was that of defending surface combatants, especially the carrier itself, against air attack. The dominant threat for the carrier-centric American surface navy during the late 1970s and 1980s was not the small missile boat with short-range weapons like the Styx, but long-range Soviet naval systems such as Tu-95 Bear and T-22M Backfire bombers, and Oscar II missile submarines, all of which carried long-range cruise missiles.[221] In fact, the few times American or British naval forces have had encountered FACs, the missile boats have been destroyed long before they could close to firing range. For example, on January 29, 1991, Lynx helicopters from HMS *Gloucester*, *Cariff* and *Brazen* located and engaged fifteen Iraqi FPBs trying to escape to Iran. Using Sea Skua missiles, the helicopters

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of active carriers, meaning the number available for operational deployments in late 2006, was eleven.

[220] While Werrell portrays Harpoon's development as a response by the US Navy to the *Eliat*'s sinking, he gives no indication that the naval aviators saw much value in the weapon except when fired from naval aircraft (*The Evolution of the Cruise Missile*, pp. 150, 226).

[221] The Bear G and Backfire both were eventually capable of carrying the anti-ship model of the Kh-22/AS-4, a beam-riding missile that used radar on the launching aircraft for guidance. The Kh-22/AS-4 had a range of about 400 kilometers (216 nm) and a speed of Mach 3.5. The Oscar IIs were explicitly designed to attack American carrier battle groups and carried 24 SS-N-19 (P-700) "Shipwreck" cruise missiles. The SS-N-19 could deliver conventional or nuclear warheads to a range of 650 kilometers (351 nm), was credited with a speed of Mach 2.5, and utilized a variety of methods for acquisition of over-the-horizon targets.

sank or severely damaged at least a dozen of the Iraqi ships. That night an A-6 and some F/A-18s under the control of an E-2C also destroyed another half dozen, and the following day, 21 engagements between Coalition aircraft and fleeing Iraqi naval vessels over the course of thirteen hours (the Battle of Bubiyan) pretty well finished off the Iraqi navy, including its thirteen missile boats.[222] In the face of Coalition control of the air, the Iraqi missile boats did not even attempt to engage American or British surface combatants in the Persian Gulf.

What these engagements demonstrate is the robust, asymmetrical capacity of carrier battle groups to locate fast missile boats—or modified *Kashins*, for that matter—with sea-based air power and destroy them far from the fleet. The symmetrical challenge faced by Israeli missile boats against Arab FACs after 1967 is quite different from that faced by the US Navy during the Cold War. Indeed, the American navy, in contrast to the Israeli navy in 1967 and 1973, has not fought a classic fleet-versus-fleet surface battle since 1945 due to the large margin of asymmetric offensive striking power inherent in its carrier-based air wings.

In all likelihood, the US Navy could have fielded Harpoon or a comparable ASM well before 1977. The need to do so, however, does not appear to have been very compelling, and both carrier-based air power and attack submarines provided alternative ways of dealing with early ASMs such as Styx. While the symmetric challenge that squarely confronted the Israeli navy after the *Eilat*'s sinking demanded a symmetric response given Israel's limited naval resources, adding Harpoon earlier to the highly asymmetric striking power of US carrier battle groups would have been, at best, a marginal improvement to their offensive capabilities. True, in 1988 an American guided-missile cruiser, USS *Wainwright* (CG-28), did sink an Iranian patrol boat with Harpoon missiles.[223] Also, Harpoon's introduction can be seen in hindsight as a first step toward restoring some offensive striking power to other elements of American carrier battle groups

[222] Department of Defense, *Conduct of the Persian Gulf War: Pursuant to Title V of the Persian Gulf Supplemental Authorization and Personnel Benefits Act of 1991 (Public Law 102-25): Final Report to Congress* (Washington, DC: GPO, April 1992), pp. 190, 195.

[223] Nordeen, *Air Warfare in the Missile Age*, p. 198. Two years before the *Wainwright*'s success with Harpoon, in March 1986, a US Navy A-6E sank a Libyan corvette with Harpoon (ibid., p. 164).

besides the carrier air wings. Nevertheless, the box score to date from engagements between American and British naval combatants and corvette-size ships or fast attack craft (including missile boats) is around 40-to-0.[224] Missiles may in fact "dominate modern warfare at sea," but against first-rate navies, most of the damage to combatants has been inflicted by sea-based aircraft firing air-to-surface cruise missiles such as the French Exocet or the American Harpoon.[225] Granted, anti-ship cruise missiles fired from shore seem likely to pose a growing threat for US surface combatants operating in littoral waters in the future. But, as Israeli experience in 1973 shows, countermeasures are possible and, for the US Navy, the future threat of shore-based cruise missiles provides no basis for arguing that Harpoon should have been fielded earlier than it was. That the Israelis did have a tactical imperative to bring Gabriel on line before 1973 in no way undermines this conclusion. When placed in the broader context of overall US naval dominance on the high seas during the Cold War, the "tardiness" of the American navy in fielding Harpoon appears both explicable and defensible, even though the requisite missile technology was available.

The Shillelagh Anti-Tank Missile

The final platform-on-platform case explores an instance in which the underlying technology proved inadequate for its intended tactical application in land warfare. Substituting guided missiles for cannons as the primary armament of US tanks and armored fighting vehicles (AFVs) in engagements with enemy main battle tanks turned out to be beyond the missile-and-guidance technologies of the 1960s. As the case study reveals, however, when the experiment with Shillelagh failed the US Army had a viable aimed-fire alternative in the M1 Abrams main battle tank armed with cannon-fired depleted uranium anti-tank rounds and protected by advanced armors. This alternative mitigated any strong incentive to persist with guided missiles as the main armament for American tanks.

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[224] Preston, *The World's Worst Warships*, pp. 182.

[225] Hughes, *Fleet Tactics and Coastal Combat*, pp. 153, 275-76.

Figure 17: Shillelagh Missile Fired by a Sheridan

Credit: Redstone Arsenal

Starting in the late 1940s and continuing into the 1960s, the US Army became convinced that steady improvements in "armored vehicle design, particularly the thickness and obliquities of armor in hulls and turrets, dictated the creation of better and more powerful weapon-ammunition combinations."[226] Before the Korean War had ended, the US Army was contemplating an anti-tank missile with a 90 percent P_k against the heaviest known tank at 6,000-8,000 yards, ranges which were well beyond the 1,500-yard reach of both the rifled and smoothbore cannons of the day.[227] Such requirements led eventually to the development of both the Shillelagh and the Tube-launched, Optically tracked, Wire-guided (TOW) missiles. The TOW missile was a great success. It provided infantrymen with a viable weapon with which to engage enemy armor at "standoff" ranges of three kilometers or greater.[228] Shillelagh, however, was a great disappointment.

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[226] Elizabeth J. DeLong, James C. Barnhart, and Mary T. Cagle, *History of the Shillelagh Missile System 1958-1982* (Redstone Arsenal, AL: US Army Missile Command, August 17, 1984), p. 3.

[227] DeLong, et al., *History of the Shillelagh Missile System*, pp. 5, 6.

[228] While anti-tank guided missiles such as the TOW and the Soviet Sagger were not chosen as a case study for this report, their main contribution has been to increase the killing power of infantry and attack helicopters, thereby making survival on the modern battlefield more difficult for armored vehicles.

The MGM-51 Shillelagh became part of a formal development program in mid-1959. For a time, Shillelagh suffered from fragmented management because the Army's acquisition managers viewed the missile "sub-system" as only having value when placed on AFVs. This problem was corrected in 1964 when a separate Shillelagh project office was established and remained active through 1971, when the missile transitioned to a commodity-management arrangement.[229] While hit and kill probabilities for Shillelagh were not specified, the initially desired level of performance was to be able to defeat "150mm of rolled homogeneous armor at 60° obliquity" at the maximum range of 2,000 meters.[230] The project concept was for a 45-pound, direct-fire, line-of-sight missile that would be tracked optically, guided through an infrared command link (similar to a television remote control), and could be fired from a closed-breech, low-pressure gun, which ended up being 152-mm gun/missile-launcher.[231] Although the fielded Shillelagh grew to over 60 pounds, the basic concept was retained. The missile was first fired in August 1961, entered production in 1964, reached field units in 1967 on the 17-ton, aluminum-armor M551 Sheridan armored reconnaissance vehicle, and, by the time production ended in 1971, over 88,100 Shillelaghs had been produced.[232]

Again, the concern that motivated Shillelagh was the steadily growing capacity of armor to defeat traditional ballistic rounds that depended on kinetic energy for penetration. On the one hand, the British L7 series of rifled, 105-mm guns offered a near-to-mid-term solution to maintaining the killing power of Western main-battle tanks against the improving armor of Soviet tanks. The L7 series became the standard tank gun for NATO, equipping both the US M60A1s produced during 1963-80 as well as the initial model of M1 Abrams, which used a derivative of the L7, the M68A1 gun. On the other hand,

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For example, along the Suez Canal in October 1973, Saggers in the hands of the Egyptian Army quickly reminded the Israeli armored forces that, despite their successes in 1967, tanks still needed to be employed in a combined-arms context.

[229] DeLong, et al., *History of the Shillelagh Missile System*, pp. 15-16, 31-33.

[230] DeLong, et al., *History of the Shillelagh Missile System*, p. 35. The MGM-51A's range was extended to 3,000 meters with the "B" model (ibid., pp. 86-88).

[231] DeLong, et al., *History of the Shillelagh Missile System*, p. 38.

[232] DeLong, et al., *History of the Shillelagh Missile System*, pp. 76, 79, 99.

during the 1960s there was concern within the US Army that the size and weight of ever-larger caliber guns with higher muzzle velocities might grow too great to be accommodated even by heavy tanks. Hence, the US Army began exploring shaped-charged solutions.[233] Shaped-charge rounds use a jet of molten metal to penetrate armor, allowing the round to be fired at much lower velocities from lighter guns than those required by KE rounds. However, because the lower velocities of shaped-charge or HEAT rounds make them increasingly difficult to aim accurately over distances beyond a few hundred yards, the Army also began exploring guided missiles to address the need to kill even the heaviest enemy tanks at longer ranges.[234]

The MGM-51 Shillelagh was eventually fielded on the M60A2 main battle tank as well as on the M551 Sheridan. In contrast to the Air Force's and Navy's leap to gunless fighters and interceptors in the late 1950s, the Shillelagh was designed from the outset to be launched from a gun that could also fire HEAT rounds through its barrel, even though Shillelagh was intended to be the "primary armament on the M60 series tank."[235] Nevertheless, the Shillelagh missile is generally viewed as having been a failure, especially on the M60A2.

The degree to which both the M60A2/Shillelagh and M551/Shillelagh disappointed can be seen in the short time these systems were in frontline service with the US Army. As the official history of Shillelagh later recalled:

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[233] "A shaped charge is a concave metal hemisphere or cone (known as a liner) backed by a high explosive, all in a steel or aluminum casing. When the high explosive is detonated, the metal liner is compressed and squeezed forward, forming a jet whose tip may travel as fast as 10 kilometers per second." (Katie Walter, "Shaped Charges Pierce the Toughest Targets," June 1998, Lawrence Livermore National Laboratory, <http://www.llnl.gov/str/Baum.html>, accessed August 28, 2006). This article reported on Lawrence Livermore successfully testing "a shaped charge that penetrated 3.4 meters of high-strength armor steel" with a jet of molybdenum. Physicist Dennis Baum was the lead researcher. A modern shaped charge can typically penetrate steel armor to a depth of about seven times its diameter.

[234] "Shillelagh Missile," Fact Index, online at <www.fact-index.com/s/sh/shillelagh_missile.html>, accessed August 28, 2006.

[235] DeLong, et al., *History of the Shillelagh Missile System*, pp. 93-94.

> Following the initial issue of M551 SHERIDAN/SHILLELAGH systems to CONUS units in mid-1967, deployments were extended worldwide in early 1969. Early in 1975 SHILLELAGH missile systems mounted on M60A2 tanks were fielded to armor units in Europe and the Continental United States (CONUS). . . . Inventory phasedown of both SHERIDAN vehicles and M60A2 tanks during the late 1970's was accompanied by parallel reductions in deployed SHILLELAGH missile assets. By FY 1981, only 140 SHILLELAGH-equipped SHERIDAN vehicles, designated a residual fleet, remained in the Army inventory, while conventional guns replaced the SHILLELAGH's mounted on M60A2 tanks.[236]

In early 1978, when worldwide deployment of Shillelagh-equipped AFVs peaked, the Army had some 1,570 Sheridan/Shillelagh systems in service, over half of which were assigned to armored cavalry units in West Germany, and the bulk of the 540 M60A2s in service were also in Europe.[237] However, in February 1978 the Army decided to replace the Sheridan in nearly all armored cavalry units "with improved M60 series main battle tanks armed only with conventional guns"; two years later, in February 1980, the Army opted to phase out the M60A2 as well.[238]

The M60A2 quickly disappeared. While over 15,000 M60 (Patton series) main battle tanks were produced, no more than 570 were M60A2s.[239] The other models of the M60, particularly the M60A1 and M60A3, were regarded as capable tanks in their day. Gun-equipped M60s remained in frontline service with the US Marine Corps as late as the 1991 Persian Gulf War, when the 1st Marine Expeditionary Force employed over 200 M60A1s in its drive to Kuwait City.

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236 DeLong, et al., *History of the Shillelagh Missile System*, p. 99. While 240 Sheridans saw service in South Vietnam, those sent to Southeast Asia did not carry the Shillelagh (ibid., p. 101).

237 DeLong, et al., *History of the Shillelagh Missile System*, p. 116.

238 DeLong, et al., *History of the Shillelagh Missile System*, p. 116.

239 "M60A3 Main Battle Tank, USA," <http://www.army-technology.com/projects/m60/>, accessed August 29, 2006. M60s armed with 105mm main guns eventually saw frontline service in the armies of 22 nations.

Sheridan persisted longer. Some 50-60 M551s remained in operational service through the mid-1990s with the 73rd Tank Battalion of the 82nd Airborne Division, largely because it was the US Army's only air-droppable AFV. In addition, the Opposing Force (the 11th Armored Cavalry Regiment) at the Army's National Training Center in California visually modified around 300 M551s for use as threat tanks and armored vehicles, although the last of these were retired in early 2004.[240]

Still, there seems little doubt that Shillelagh—in contrast to the TOW missile developed more or less in parallel with the MGM-51A/B/C—was not favorably received by M60 and Sheridan crews. Why? The preface to the US Army Missile Command's (MICOM's) 1984 history of the Shillelagh program observes that overseas deployment "was relatively short-lived, chiefly because of user dissatisfaction and problems with both the carrier vehicles and the missile."[241] In the case of the M60A2/Shillelagh, the weapon system was originally recommended on the grounds that it would have "almost twice the armor penetration of the M60A1," and in 338 test firings from the M60 during 1970-71 Shillelagh recorded a hit probability of 80 percent at ranges under 2,000 meters, and a 70 percent hit probability at 2,000-3,000 meters.[242] However, during 1978-1979 significant problems emerged with the Shillelagh missile and the M60A2's turret, which had been specially developed to accommodate Shillelagh. These problems included: recurring missile failures; a "catastrophic" block-assembly problem involving the 152-mm gun/missile-launcher while firing conventional rounds in Germany in mid-1979; frequent failures of the fire-control system to hold a "ready" or "go" status from checkout to firing, thereby preventing crews from developing "confidence in and proficiency with" Shillelagh; high failure rates with the missile's optical tracker; the difficulties of maintaining pre-solid-state electronics in the harsh environment faced by ground combat systems (shock, vibration, dirt, etc.); and, "overall system reliability and maintainability" in the field.[243] In the face of these accumulating difficul-

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[240] Lieutenant Colonel Burton S. Boundinot, "A Sherdian Memoir: The Early Days," *Armor*, January-February 1997, p. 14.

[241] DeLong, et al., *History of the Shillelagh Missile System*, p. vii.

[242] DeLong, et al., *History of the Shillelagh Missile System*, pp. 94-5.

[243] DeLong, et al., *History of the Shillelagh Missile System*, pp. 104-105, 107-108, 110.

ties, US Army in Europe elected to resolve them by replacing the M60A2.

The Sheridan/Shillelagh system faced similar troubles. Granted, the MICOM history argues that the perception of many tactical users that the "heavy recoil of the main gun could render the missile system inoperative" was due to unfamiliarity with the Shillelagh system and that much of the "excessive maintenance" generated by this perceived problem was unnecessary.[244] Regardless, it is clear that realigning the fire-control system was a lengthy process and user concerns about having to do so in the heat of battle undermined confidence in the system, especially among units deployed in West Germany in the late 1970s facing Soviet tank armies across the Inner German Border.[245] In addition, while the M551's aluminum hull made the vehicle light enough to be air dropped, aluminum armor offered little protection for the crew inside: the hull could be penetrated by heavy machine-gun rounds.

The other factor that argued against retaining either the M60A2/Shillelagh or M551/Shillelagh systems beyond 1981 in front-line armored or mechanized-infantry units was the considerable room for growth in the lethality of kinetic-energy rounds fired by conventional tank guns. The following account of an encounter in 1991 between three Iraqi T-72s and a 24th Infantry Division M1A1, which had been left behind to await recovery after becoming mired in mud, demonstrates the killing power of the M1A1's gun system as well as the level of protection provided by its advanced armor. The US tank in question was an M1A1 (HA) variant of the M1A1 and its "heavy armor" employed layered DU for increased protection.[246]

> Three T-72's appeared and attacked [the American tank mired in the mud]. The first fired from under 1,000 meters,

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244 DeLong, et al., *History of the Shillelagh Missile System*, p. 101.

245 There are firsthand accounts that at Fort Hood, Texas, in the mid-1970s, Sheridan crews were instructed to realign the missile tracker after every Shillelagh firing (see "Armored Cavalry Scout Part II (Ver. 2) on Douglas Greville's website at <http://www.users.zetnet.co.uk/lsm/dhmg/crew015.html>, accessed August 29, 2006).

246 Over 1,800 M1A1s and M1A1 HAs were deployed to Kuwait for Operation Desert Storm.

> scoring a hit with a shaped-charge (high explosive) round on the M1A1's frontal armor. The hit did no damage. The M1A1 fired a 120mm armor-piercing round that penetrated the T-72 turret, causing an explosion that blew the turret into the air. The second T-72 fired another shaped-charge round, hit the frontal armor, and did no damage. This T-72 turned to run, and took a 120mm round in the engine compartment . . . [that] blew the engine into the air. The last T-72 fired a solid shot (sabot) round from 400 meters. This left a groove in the M1A1's frontal armor and bounced off. The T-72 then backed up behind a sand berm and was completely concealed from view. The M1A1 depressed its gun and put a sabot round through the berm, into the T-72, causing an explosion.[247]

During Operation Desert Storm, depleted-uranium, long-rod, kinetic-energy penetrator rounds were the primary ammunition of US tank crews against Iraqi tanks such as the Soviet-supplied T-72. Over 9,500 105-mm and 120-mm depleted-uranium, fin-stabilized, discarding-sabot (APFSDS) rounds were expended by American tank crews during the ground campaign, and British tank crews fired another 100 or so. The US Army's concern that advances in armor would negate the killing power of late-1950s and 1960s anti-tank rounds was well founded. As the encounter just cited makes amply clear, the heavy armor of the M1A1 was as invulnerable to T-72 main guns as the T-72 was vulnerable to DU sabot rounds, even at the 3-km ranges that turned out to be the outer limit of improved models of Shillelagh.[248]

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[247] Department of Defense, *Environmental Exposure Report: Depleted Uranium in the Gulf (II)*, December 13, 2000, Tab F—DU Use in the Gulf War, <http://www.deploymentlink.osd.mil/du_library/du_ii/du_ii_tabf.htm#tabf>, accessed 2003.

[248] DoD, *Environmental Exposure Report: Depleted Uranium in the Gulf (II)*, December 13, 2000, Tab E—Development of DU Munitions, at <http://www.deploymentlink.osd.mil/du_library/du_ii/du_ii_tabe.htm>, accessed 2003. Tungsten carbide was the primary material for kinetic-energy rounds in the late 1950s and gave a "quantum improvement" over its nearest rival, high-carbon steel. The advent of double- and triple-plated tank armors in the 1960s, however, promised to defeat the best tungsten-carbide kinetic-energy penetrators, prompting a search for alternatives, of which Shillelagh was one candidate. In the mid-1970s, the Army began exploring another al-

Figure 18: Iraqi T-72 Hit by a DU Antitank Round

In the 1970s and early 1980s, then, Shillelagh simply did not provide a robust alternative to unguided kinetic-energy rounds as the primary armament of main battle tanks. In the first place, tank-on-tank engagements were basically confined to a two-dimensional plane on the earth's surface. Second, there was an alternative to guided missiles. While the US Army had a legitimate need for increased penetration capability against advanced armors, the cheapest and most effective solution turned out to lie in fin-stabilized, discarding-sabot, KE penetrators, particularly those that exploited depleted uranium to increase the round's penetrating power.[249]

Ironically, the US Army was not alone during this period in seeing merit to missiles as the main armament of tanks and AFVs. In the late 1970s the Soviet General Staff gave the M60A2/Shillelagh a substantially higher combat-potential score than any other Soviet or US

ternative, depleted uranium alloyed with titanium, which in the 1970s ushered in "a new generation of kinetic-energy penetrators for the Army" (ibid.).

[249] The long-rod penetrators in these rounds were made of a DU-titanium mixture, of which only 25 percent was depleted uranium.

main battle tank.[250] Looking back, though, this evaluation appears to have seriously exaggerated the value of the M60A2/Shillelagh in tank-on-tank combat.

In any event, the situation confronting armored forces against enemy main battle tanks in the 1960s differed fundamentally from the tactical challenges facing submariners after World War II or fighter crews after the Korean War. In the case of engagements between submarines able to maneuver submerged in three dimensions for extended periods of time, unguided torpedoes running at constant depths and azimuths were clearly insufficient; for this particular tactical problem, guided torpedoes offered the only viable solution absent the use of nuclear warheads. In the cases of fighter-versus-fighter engagements or intercepting enemy bombers with long-range cruise missiles or nuclear weapons, guns and short-range missiles such as the AIM-9 did not lose their effectiveness at close ranges as did pre-DU penetrators against laminated armors. But confronted with nuclear-armed attackers, whether against American cities or carrier battle groups, the incentives for fighters and interceptors to be able to fire on radar contacts from BVR ranges grew steadily during the 1950s and 1960s. For the most pressing air-intercept problems confronting the USAF and USN during the early decades of the Cold War, a guided missile along the lines of the AIM-7 was the only available solution, and the Navy and Air Force fighter communities were right to continue investing in the Sparrow III until they fielded a viable model, of which the AIM-7F was the first.

Presumably, the US Army could have shown similar persistence with Shillelagh, but depleted-uranium KE penetrators, combined with

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[250] Soviet "combat-potential" scores (or commensurability coefficients) for various weapons and units attempted to quantify the relative contributions of different weapons and units to the outcomes of combat, recognizing that beyond a certain point a fighter-bomber, for example, cannot be substituted for a main battle tank—John G. Hines, "Calculating War, Calculating Peace: Soviet Military Determinants of Sufficiency in Europe," R. K. Huber, H. L. Linnenkamp, and I. Scholch, eds., *Military Stability—Prerequisites and Analysis Requirements for Conventional Stability in Europe* (Baden-Baden, Germany: NOMOS-Verlagsgesselschaft, 1990), pp. 186-93. During the negotiations on conventional forces in Europe that occurred at the end of the Cold War, the Soviet General Staff provided combat-potential scores for most NATO and Warsaw Pact tanks, AFVs, artillery, anti-tank missiles, SAMs, and combat aircraft.

gun-stabilization, thermal-imaging sights, laser rangefinders and digital ballistic computers, provided a robust alternative that neither the submariners nor the fighter pilots had. The same point appears to apply to the US Navy's tardiness in fielding Harpoon. Carrier air wings provided a time-tested alternative in which the naval aviators had an enormous vested interest, which meant that incentives to field Harpoon even after the *Eliat* was sunk were, at best, marginal. Finally, while Shillelagh failed, the US Army by no means abandoned antitank missiles entirely. Starting in 1970 the TOW missile began displacing 106-mm recoilless rifles and other infantry anti-tank weapons whose role was to give dismounted Army soldiers a capability to defeat enemy tanks.[251] Additionally, guided missiles (TOW and Hellfire) were fielded on US Army attack helicopters and AFVs (the M-2 Bradley Infantry Fighting Vehicle and the M-901 Improved TOW vehicle). For dismounted troops, attack helicopters, or AFVs other than main battle tanks, missiles offered more or less the only solution when confronting masses of heavily armored enemy tanks. Therefore, these missiles, unlike Shillelagh, were retained in service and the US Army fielded follow-on variants and new anti-tank missile systems.

The four platform-versus-platform case studies in this chapter shed light on the deeper motivations, tactical imperatives, and logic underlying the decisions of particular war-fighting communities either to pursue, or to ignore, guided munitions since 1943. Unguided torpedoes worked reasonably well against the two-dimensional problem of sinking surface combatants or enemy shipping. Against nuclear-powered submarines able to operate at great depths, they were all but useless. By comparison, fighter and interceptor crews seeking to shoot down enemy aircraft at night, in weather, or at BVR distances had little choice but to persist with radar-guided air-to-air missiles. To reiterate the notion advanced in Chapter I, the number of dimensions in which both the attacking platform and the prospective target are free to maneuver can have a profound influence on how willing or reluctant a given war-fighting community may be to embrace guided munitions.

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[251] Mary T. Cagle, *History of the TOW Missile System* (Redstone Arsenal, AL: US Army Missile Command, October 20, 1977), p. v. "The TOW was successfully deployed on an unprogrammed, urgent basis to the 82d Airborne Division in December 1970, to South Vietnam in both the ground and helicopter applications in May 1972, and to Israel in October 1973" (ibid., p. 158).

The Shillelagh's failure surfaces one other observation regarding the time interval between firing a round or projectile and it reaching the target.[252] The armor communities in the US military have unquestionably been successful staying with aimed fires for tank-on-tank engagements right down to the present. The muzzle velocity of the M1A1's 120-mm main gun is over 1,600 meters/second (roughly 5,250 feet/second). At a range of 3,000 meters, the interval between trigger squeeze and round impact for a discarding-sabot DU round is perhaps two seconds, and an opposing tank or other target is unlikely to avoid being hit. For ranges this short and projectile speeds this fast, aimed fire with kinetic rounds remains lethal and effective (as Desert Storm engagements between M1A1s and T-72s showed). But as the interval between "trigger squeeze" and impact grows to minutes or longer, terminal homing becomes more and more attractive. Lasers, which offer the prospect of speed-of-light weapons, would obviously increase the ranges out to which aimed fire could be effective (albeit with photons rather than projectiles). This possibility is one to which the discussion will return in Chapter V.

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[252] Patrick Towell deserves credit for raising this issue, which he characterized as "click-to-bang" time.

IV. Surface-Attack Cases

> It is fair to say that the airmen have perennially neglected munitions. Over the first six decades of flight, aircraft steadily improved, while airmen continued to use the same basic means of attack, overflying and dropping unguided ("dumb") bombs on their targets. Obtaining accuracy with this method was difficult as the attitude, altitude, and speed of the aircraft and winds are critical factors. In addition, such tactics exposed the attacker to hostile fire, endangering the aviators and detracting from accuracy. Nevertheless, American airmen entered the Vietnam War still using such bombs as its principal means of attack, just as they had fifty years earlier in World War I.
>
> — Kenneth Werrell, 2003[1]

This chapter focuses on guided weapons that have either been designed or primarily used to attack surface targets, especially on land. The previous chapter's platform-versus-platform cases emphasized the effects guided munitions have exerted on tactical engagements in specific mission areas. The surface-attack cases in this chapter, by contrast, are more concerned with the higher-level effects guided munitions have increasingly exerted at the operational and strategic levels

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[1] Kenneth P. Werrell, *Chasing the Silver Bullet: U.S. Air Force Weapons Development from Vietnam to Desert Storm* (Washington, DC: Smithsonian Books, 2003), pp. 137-38.

of entire campaigns. For example, growing use of munitions "smart" enough to hit what they are targeted against most of the time, rather than missing, have not eliminated the use of massed fires in modern warfare, but they have substantially transformed its application.

Two of the munitions discussed—the laser-guided bomb and the Joint Direct Attack Munition—are arguably among the most successful guided weapons ever developed. Both munitions worked more or less as advertised during their initial combat trials and have been improved since. Compared to TLAM and CALCM, which are complex long-range cruise missiles, LGBs and JDAMs are relatively cheap because they consist of inexpensive guidance kits added to freefall bombs. This fact goes far to explain why unpowered LGBs and JDAMs have constituted over three-quarters of the guided weapons expended by US air and naval forces in major campaigns such as Operation Desert Storm (ODS), Operation Allied Force, Operation Enduring Freedom (OEF), and Operation Iraqi Freedom (OIF).

Figure 19 unpacks the guided-weapon expenditures in Figure 4 using five categories:

(1) Paveway II and III LGBs (GBU-10, GBU-12, GBU-16, GBU-24, GBU-27, and GBU-28);

(2) munitions that home on GPS coordinates, which are mainly JDAMs (GBU-31, GBU-32, and GBU-38) but also include the AGM-86C/D CALCM;

(3) the BGM-109 Tomahawk Land Attack Missile (TLAM);

(4) anti-radiation missiles or ARMs (mainly the AGM-45 Shrike and the AGM-88 High-Speed Anti-radiation Missile or HARM); and

(5) other air-to-ground guided weapons (various models of the AGM-65 Maverick, GBU-15, AGM-84 Stand-Off Land Attack Missile, etc.).

It is important to keep in mind, though, that Figure 19 depicts changes over time in guided-munitions usage as *inputs* to four campaigns, not the tactical, operational, or strategic outputs or effects to which they may have given rise.

Figure 19: US Guided Expenditures in Four Campaigns[2]

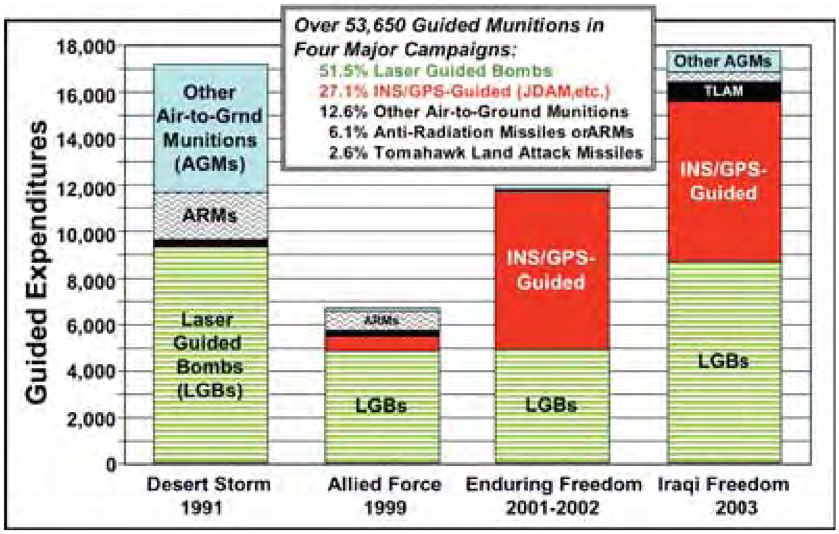

Figure 19's data show that just over half the guided munitions expended by American forces in the four major US campaigns of 1991-2003 were LGBs, and there is no indication of declining reliance on laser-guided bombs. The data also show that in the two most recent campaigns in Afghanistan and Iraq, expenditures of munitions employing INS/GPS guidance—primarily JDAM—have been comparable to those of LGBs. Quantitatively, JDAMs and LGBs have emerged as the guided munitions of choice against point targets over older guided munitions such as Maverick, just as guided munitions have increasingly displaced unguided or "dumb" munitions since 1991 (see Figure 4).

Note, too, that CALCM is included in Figure 19's INS/GPS-guided category. While CALCM is discussed later in the chapter in conjunction with TLAM, it is interesting to note that during ODS,

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[2] The sources are the same cited for Figure 4, and the same cautions apply concerning the quality of data from these four campaigns. The ODS expenditures are the most accurate of the four data sets displayed and the Allied Force expenditures are the least accurate. Also, by OIF all the TLAMs expended were probably Block-IIIs, which meant that INS/GPS guidance had been added to the prior TERCOM (Terrain Contour Matching) navigation and DSMAC (Digital Scene Matching Area Correlation) terminal guidance.

OAF, OEF, and OIF only some 1,370 TLAMs and 260 CALCMs were expended (see Table 8). These 1,630 long-range cruise missiles represent some 70 percent of the roughly 1,880 TLAMs and 360 CALCMs US forces have expended since mid-January 1991, but are only 3.1 percent of the total guided-munition expenditures in Figure 19. Quantitatively, then, if LGBs and JDAMs have been the mainstay of large-scale American precision-strike campaigns in recent decades, TLAM and CALCM have been bit players. Only in comparatively small operations such as Operation Desert Fox in December 1998, when some 415 TLAMs and CALCMs were expended, have these missiles constituted a large share of the guided munitions employed, and even in the four days of Desert Fox they only amounted to around 41 percent of the PGMs delivered.

In large campaigns, TLAM and CALCM have primarily appealed to operational planners for attacking well-defended, high-value targets—especially in the opening days before enemy air defenses have been suppressed. Much of the reason for this narrow use is that TLAM and CALCM are very expensive rounds and their inventories have been limited. Furthermore, in TLAM's case there were other costs associated with early models of the missile: namely, the infrastructure required to get it to the target using terrain contour mapping (TERCOM) for en-route navigation. Consequently, in major campaigns like Desert Storm in which operational planners were confronted with tens of thousands of aim-points, it is not at all surprising that TLAM and CALCM only accounted for a small percentage of the guided munitions ultimately expended.

The other aspect of Figure 19 warranting mention is that it omits expenditures of guided munitions employed directly by US ground forces. During ODS in 1991, for example, US forces expended just over 3,000 AGM-114 Hellfire anti-armor guided missiles and nearly 3,000 BGM-71 TOWs; during OIF in 2003, comparable expenditures were some 560 Hellfires and TOWs. Nor have US expenditures of air-to-air missiles or Patriot SAMs during these two campaigns been included. Figure 19, therefore, is best understood as a depiction of trends in guided-munition expenditures for precision-strike campaigns by air and naval forces rather than as a complete picture of their use in recent conflicts by the US military as a whole. Still, US expenditures of air-intercept missiles, ground-combat missiles such as Hellfire and TOW, and Patriot SAMs since January 1991 have been quantitatively modest compared to the ordnance expenditures in Figure 19. True, a major reason for this overall pattern is undoubtedly the limited military capabilities of US opponents in Iraq, Kosovo, and Afghanistan. Nevertheless, to date American employment of guided munitions has been dominated by air-to-surface strike operations. Indeed, the LGB case study indicates, this pattern extends as far back as the Second Indochina War of 1965-1973. Despite this pattern, Chapter IV will explore one US Army guided munition, the laser-guided, M712 Copperhead 155mm artillery shell, because it was a logical extension to field artillery of the LGB technology proven in Southeast Asia. As will emerge, however, Copperhead, like the USAF's AIM-4 Falcon discussed in Chapter III, proved to be too complicated and unreliable a weapon to be practical in the combat role for which it was intended.

Laser-Guided Bombs

The alacrity with which early lasers were applied to the longstanding problem of bombing accuracy is an impressive example of getting new technology into the field in response to the needs of combat. While the concept of stimulated emission dates back to Albert Einstein in 1917, the first papers on microwave amplification by stimulated emission of radiation ("maser") were published in the mid-1950s as a result of investigations by Charles Townes and co-workers at Columbia University in New York and by Nicolay Basov and Alexsandr Prochorov at the Lebedev Institute in Moscow.[3] The first laboratory test article of light amplification by stimulated emission of radiation (laser) was operating in 1960.[4] These devices emitted coherent light, meaning visi-

[3] B. Edlén, "Presentation Speech" for the Nobel Prize in physics 1964, available online at <http://www.nobel.se/physics/laureates/1964/>, accessed August 29, 2006. Townes, Basov and Prokhorov split the 1964 Nobel Prize in physics 1/2, 1/4 and 1/4, respectively, "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle" (ibid.).

[4] Because the step from microwave to visible light meant a 100,000-fold increase in frequency, the Nobel Prize committee considered the laser essentially new invention (Edlén, "Presentation Speech"). Amplification of stimulated radiation can occur "only if the stimulated emission is larger than the absorption, and this in turn requires that there should be more atoms in a high energy state than in a lower one," such an unstable energy condition in matter being "called an inverted population"; an essential step "in the invention of the maser and the laser was, therefore, to create an inverted population under such circumstances that the stimulated emission could be used for amplification" (ibid.).

ble electromagnetic radiation having exactly the same phase and frequency, which meant that it could be focused into very narrow beams with little or no convergence or divergence.

The possibility of using laser beams to guide air-to-ground munitions had been raised by the Limited War Panel of the US Air Force's Woods Hole Summer Study Group in 1958, two years before the first working laser had been demonstrated by Theodore H. Maiman.[5] Air Force interest in laser guidance arose during 1961-1965 at Eglin AFB, Florida, specifically within Eglin's Detachment 4, which soon became the Air Force Armament Laboratory.[6] The impetus for this initiative was the belief that ongoing developments in ground-based air defenses would increase the likely losses of aircrews and planes from repeated attacks with unguided weapons—particularly at low level.[7] The main concern at the time was not enemy anti-aircraft and small-arms/automatic-weapons fire, which had accounted for 88 percent of US fixed-wing aircraft losses during the Korean War and claimed 76 percent in Southeast Asia.[8] Instead, it was the emerging threat posed by radar-guided surface-to-air missiles, most notably the Soviet V-75 Dvina (Двина), which NATO designated the SA-2.

Design of the SA-2 began in 1953, and widespread operational deployment with PVO-Strany, the territorial air defense troops of the USSR, began in 1958. The SA-2's first success came on May 1, 1960, when an improved version of the SA-2's Guideline missile (probably the SA-2C) brought down Francis Gary Powers' U-2 as he approached

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[5] David R. Mets, *The Quest for a Surgical Strike: The United States Air Force and Laser Guided Bombs* (Eglin AFB, FL: Office of History, Armament Division, Air Force Systems Command, 1987), pp. 50-51.

[6] Mets, *The Quest for a Surgical Strike*, pp. 52-53.

[7] Mets, *The Quest for a Surgical Strike*, p. 53.

[8] During the Korean War, enemy gunfire claimed all but 143 of the 1,230 Air Force, Navy, and Marine aircraft lost to enemy action (Werrell, *Archie, Flak, AAA, and SAM*, p. 74). Of the 2,317 fixed-wing aircraft combat losses sustained by the United States in Southeast Asia from February 1962 to June 1973, 1,769 were attributed to either anti-aircraft artillery (AAA) or small-arms/automatic-weapons fire—McCrea, *U.S. Navy, Marine Corps, and Air Force Fixed-Wing Aircraft Losses and Damage in Southeast Asia (1962-1973) (U)*, pp. 6-37, 6-46, and 6-55. The same pattern persisted in Desert Storm: low-altitude air defenses—AAA and man-portable infrared surface-to-air missiles accounted for 71 percent of the Coalition's fixed-wing aircraft losses.

an airfield southeast of Sverdlovsk at an altitude of about 70,000 feet.[9] Next, in September 1962 a Taiwanese-flown U-2 was apparently lost over western China to the SA-2.[10] Finally, a second American-flown U-2 was downed over Cuba on October 27, 1962, during the Cuban missile crisis.[11] Admittedly, these early successes of the SA-2 came against fragile, non-maneuvering U-2s operating at high altitudes. Still, it is easy to see why these successes would have spurred Air Force interest in guided munitions for air-to-ground attack. If so, then the early successes of a Soviet guided air-defense weapon played a role in stimulating the development of a new category of American guided munition, the laser-guided bomb.

However, the initial steps toward practical laser guidance were taken not by the Air Force but by the Army's Missile Command (MICOM) in Huntsville, Alabama. Between 1962 and 1965, work on laser guidance at the Redstone Arsenal led to "the production of a pulsed LASER generator and a detector that could identify a spot of LASER light projected by that generator from some distance."[12] Toward the end of this period of pioneering development, MICOM engineers, notably David J. Salonimer and Norman L. Bell, began sharing their results with USAF Colonel Joe Davis, who was almost alone at

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[9] Dino A. Brugioni, *Eyeball to Eyeball: The Inside Story of the Cuban Missile Crisis* (New York: Random House, 1990 and 1991), pp. 43-44; Francis Gary Powers with Curt Gentry, *Operation Overflight* (New York: Holt, Rinehart and Winston, 1970), p. 82. Lockheed's Skunk Works, which built the U-2, was told that as many as 14 SA-2s were shot-gunned at Powers' plane and one is believed to have destroyed a MiG-19 interceptor—Ben R. Rich with Leo Janos, *Skunk Works: A Personal Memoir of My Years at Lockheed* (New York: Little, Brown and Company, 1994), pp 159-160.

[10] Brugioni, *Eyeball to Eyeball*, p. 132. Eventually the Taiwanese lost four U-2s (Rich, *Skunk Works*, p. 181).

[11] Brugioni, *Eyeball to Eyeball*, pp. 43-44; Rich, *Skunk Works*, p. 186.

[12] Mets, *The Quest for a Surgical Strike*, p. 55. See also "The Evolution of the Smart Bomb . . . A Story of Technology Transfer," available at <http://www.redstone.army.mil/history/chron4/LASER2.html>, accessed August 30, 2006; this story originally appeared in *The Redstone Rocket*, August 16, 1972, pp. 1, 10-11. David J. Salonimer is credited with coming up with the idea of a pulsed laser in order to reduce the size and weight of the illuminator by reducing its power requirements.

Eglin AFB in having confidence that laser guidance would work.[13] The upshot was that, in the spring of 1965, the Air Force began a program to demonstrate the feasibility of laser-guided bombs using MICOM's illuminator. Two competing contractors, Texas Instruments (TI) and North American Autonetics, were selected to demonstrate laser-guidance kits for the M117 750-pound general-purpose bomb (a post-World War II munition whose shape had been streamlined for external carriage).[14]

The Air Force awarded contracts for LGB prototypes to Autonetics and TI in late 1965, and both companies successfully demonstrated their competing designs between mid-1966 and early 1967. The salient point about this competition is not that Texas Instruments won, but why.

> At first Autonetics had better results than its rival, achieving 24- and 52-foot accuracy during the best two of its four drops. But TI's cheaper system allowed more tests, during which its accuracy improved: it achieved accuracies between 10 to 27 feet during four of its eight tests. In addition to better accuracy, TI's system was simpler in both design and operation and looked as if it would be more reliable and less expensive.[15]

Lower cost, which permitted more test drops and incremental improvements, plus the likelihood of greater reliability prevailed.[16] As the later discussion of TLAM and CALCM reveals, though, low cost-

[13] Vernon Loeb, "Bursts of Brilliance: How a String of Discoveries by Unheralded Engineers and Airmen Helped Bring America to the Pinnacle of Modern Military Power," *The Washington Post Magazine*, December 15, 2002, p. 10.

[14] Mets, *The Quest for a Surgical Strike*, pp. 56-57. Autonetics was one of the two major American teams involved in the post-World War II development of inertial guidance for long-range ballistic missiles, the other American team being MIT's Instrumentation Laboratory, which was renamed the Charles Stark Draper Laboratory, Inc. after its early-1970s divestiture by MIT (MacKenzie, *Inventing Accuracy*, p. 22).

[15] Werrell, *Chasing the Silver Bullet*, p. 148.

[16] In the cases of both early LGBs and JDAMs, low cost was an important programmatic concern. TLAM and CALCM, by contrast, illustrate complex munitions in which cost-per-round was not a major constraint.

per-round has not always been a driving concern in the development of American guided weapons.

In May 1967 Texas Instruments won a $1.35 million contract to produce 50 laser kits for developmental engineering and testing at Eglin AFB. By April 1968 the TI weapon had been made to spin to increase accuracy; a new seeker had been added; and a way had been found to illuminate the target by having a second F-4, accompanying the one dropping the LGB, use a pylon turn (a left bank of about 30 degrees) around the target to keep a laser beam, projected sideways out a hole in the rear cockpit canopy, on the aim-point throughout the roughly 30 seconds from bomb release to impact. Once the target was illuminated by one F-4, the one delivering the LGB would roll in from 20,000-24,000 feet and release the weapon using a dive-bomb delivery calculated to place the LGB inside the cone emanating from the target within which the seeker on the LGB could sense the laser spot and guide on it. At 12,000 feet above the target, this cone or basket was about 6,000 feet (or nearly a nautical mile) across, but its diameter grew smaller and smaller as the altitude above the target decreased.[17]

The initial combat trial of "Paveway I" LGBs in Southeast Asia occurred during May-August 1968. The trial used both M117 750-pound and Mark-84 2,000-pound general-purpose bombs as warheads for, respectively, the BOLT-117 and Mark-84L LGBs (see Figure 20). Of the 76 Paveways delivered during this period against targets in

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[17] Mets, *The Quest for a Surgical Strike*, pp. 66-67. In manual dive bombing, getting steep or fast generally resulted in a more accurate bomb, and releasing steep *and* fast was the instinct of most pilots who grew up in the manual-dive-bombing era. With Paveway I laser-guided bombs, getting steep and fast tended to place the bomb outside the envelope within which it had the aerodynamic capability to hit the laser spot—James O. Hale, "Laser-guided Bombs (LGBs) in Southeast Asia (SEA)," December 14, 1996. Hale flew as a laser bomber on the May 10, 1972, strike against the Paul Doumer Bridge across the Red River in Hanoi; he later became a Wolf FAC (forward air controller) and had extensive experience employing Paveway I LGBs ("Zot" to the aircrews) in the lower route packages of North Vietnam during Operation Linebacker I. For a detailed account of the 8th Tactical Fighter Wing's May 10 attack on the Paul Doumer Bridge, see Jeffrey Ethel and Alfred Price, *One Day in a Long War: May 10, 1972, Air War, North Vietnam* (New York: Random House, 1989), pp. 78-101, 199-201. Colonel Carl Miller, the 8th TFW commander, led the strike force on this mission, and Hale was the frontseater (aircraft commander) in Jingle 2.

southernmost North Vietnam (Route Package I, which ran from the demilitarized zone dividing North and South Vietnam at the 17th parallel to just above the 18th parallel), "more than half scored direct hits."[18] To offer a benchmark for comparison, contrast the 50 percent hit rate recorded during the initial Paveway trials with the manual dive-bombing CEP of 500 feet for F-105s attacking heavily defended targets in North Vietnam's Red River Valley with unguided M117 750-pound "dumb" bombs during 1965-1968.[19] Moreover, LGB results the following year, after bombing of North Vietnam had been halted by President Lyndon Johnson, were even better:

> During 1969 the Air Force released 1,601 2,000-pound LGBs, 61 percent of which scored direct hits; and the 85 percent that guided had an average error of 9.6 feet. Since this error was less than the lethal radius of the bomb, bombing results were impressive.[20]

These statistics should not be taken to suggest that first-generation LGBs did not have any operational limitations. Clouds, smoke, atmospheric haze and darkness could hinder or even nullify successful employment of these munitions; initially two aircraft were

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[18] Werrell, *Chasing the Silver Bullet*, p. 149. The 433rd Tactical Fighter Squadron at Ubon Air Base, Thailand, was given the LGB mission in 1968. The Paveway I seeker had a 24-degree field of view, with the detector divided into quadrants to generate guidance signals; the illuminators employed a neodymium doped glass rod excited by a Xenon flash lamp; since the laser energy passed through a narrow bandpass filter (bandwidth 0.015 microns) centered at 1.06 microns, the illumination was in the near-infrared region rather than the visible light spectrum—Colonel Breitling, *Guided Bomb Operations in SEA: The Weather Dimension, 1 Feb-31 Dec 1972* (7th Air Force, CHECO/CORONA HARVEST Division, Headquarters Pacific Air Forces, October 1, 1973), pp. 1-2.

[19] Thompson, *To Hanoi and Back*, pp. 45-6. Manual diving bombing involved the pilot setting his gun-sight to a fixed depression angle ("MIL setting") for the desired release conditions, and then trying to have the pipper over the target and the aircraft unloaded simultaneously with achieving the proper dive angle, airspeed, and release altitude. As another point of comparison, in 1948 the US Air Force specified a CEP of 3,000 feet for radar bombing—Steven T. Ross and David Alan Rosenberg (eds.), *America's Plans for War against the Soviet Union, 1945-1950*, Vol. 9, *The Atomic Bomb and War Planning: Concepts and Capabilities* (NY: Garland, 1989), JCS 1823/11, p. 58.

[20] Werrell, *Chasing the Silver Bullet*, p. 149. The lethal radius of a 2,000-lb Mk-84 bomb against most targets is 15-20 feet.

required to employ LGBs and both planes had to be within line-of-sight of the target; the plane doing the laser designation had to loiter over the target flying a predictable flight path, thereby exposing it to air defenses; and the seeker heads proved susceptible to damage if flown through Southeast Asian rainstorms.[21] Nevertheless, compared to manual dive bombing, LGB accuracy and overall reliability constituted a major step forward for American air-to-ground strike operations. Also breaking with most prior experience, Paveway I guided bombs performed as they had been designed to perform from the outset. Initial reliability estimates were that about 30 percent of the weapons would not work, but in 1969 only about 15 percent failed.[22] In short, the increase in lethality per pass, sortie or mission that the Air Force sought from LGBs was achieved.

Figure 20: Early ("Paveway I") LGBs

The classic illustration of this leap forward in tactical efficiency and lethality is provided by the cutting of the Thanh Hoa Bridge during the Second Indochina War. In April 1964, JCS contingency planners for an air campaign against North Vietnam identified 94 of the most important targets in the country. Fourteenth on the list was the Thanh Hoa Rail and Highway Bridge over the Song Ma River north of

[21] Werrell, *Chasing the Silver Bullet*, p. 149.

[22] Mets, *The Quest for a Surgical Strike*, p. 68.

the provincial capital of Thanh Hoa, about 70 miles south of Hanoi.[23] This bridge was vital to Hanoi's ability to supply its insurgent and, later, regular forces in South Vietnam. Most supplies moving south from Hanoi into the panhandle of North Vietnam crossed the Song Ma River at Thanh Hoa.[24]

The Thanh Hoa Bridge had a colorful history. The Viet Minh had destroyed it in 1945 by running two locomotives filled with explosives together in the middle of the bridge. After the French lost the First Indochina War (1945-1954), the victorious communists began reconstruction in 1957 with Chinese assistance. When reconstruction was completed in 1964, Ho Chi Minh himself presided at the dedication of the bridge, which was called the Ham Rung (or Dragon's Jaw) by the Vietnamese.[25] The Ham Rung Bridge was 540 feet long, 56 feet wide, about 50 feet above the Song Ma River, and its two steel thru-thrust spans rested in the center on a massive concrete pier in the middle of the river.

Once Rolling Thunder got underway, the first concerted effort to knock out this bridge occurred shortly after noon on April 3, 1965, but neither 750-pound bombs nor Bullpup missiles managed to inflict significant damage, much less take down the Dragon's Jaw.[26] Including this initial attack, some 870 sorties were flown against the Thanh Hoa Bridge by Air Force and Navy strike aircraft over the next three years. Eleven planes were lost in these attacks, including a C-130 and its crew. Despite all these sorties and the losses, when President Lyndon Johnson suspended bombing of North Vietnam above the 20th parallel at the end of March 1968, the "Thanh Hoa Bridge still stood, no span

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[23] Major A. J. C. Lavalle (ed.), *The Tale of Two Bridges and the Battle for the Skies over North Vietnam* (Washington, DC: US Government Printing Office, 1976), USAF Southeast Asia Monograph Series, Vol. 1, p. 3. The other bridge in this study was the Paul Doumer Rail and Highway Bridge over the Red River on the northern outskirts of Hanoi. It was twelfth on the JCS list.

[24] Lavalle, *The Tale of Two Bridges and the Battle for the Skies over North Vietnam*, pp. 6-7. All supplies shipped to Hanoi from China via rail had to pass over the Doumer Bridge.

[25] Lavalle, *The Tale of Two Bridges and the Battle for the Skies over North Vietnam*, p. 9.

[26] Lavalle, *The Tale of Two Bridges and the Battle for the Skies over North Vietnam*, pp. 31-8.

had ever fallen, and none of the damage done had made this bridge unusable for very long."[27]

Starting on March 30, 1972, the North Vietnamese launched a multi-pronged, conventional invasion of South Vietnam with five divisions, more than 100,000 men, and hundreds of tanks. This so-called "Easter" offensive provoked President Richard Nixon to resume bombing North Vietnam. When US fighter-bombers returned to the Thanh Hoa Bridge on April 27, cloud cover precluded using LGBs and the strike package was limited to delivering five television-guided bombs, which "closed the bridge to traffic but did not down a span."[28] The 8th Tactical Fighter Wing (TFW) returned to the Dragon's Jaw on May 13, 1972. This time the weather cooperated, and 14 F-4s delivered nine 3,000-lb and fifteen 2,000-lb LGBs along with 48 500-lb unguided Mark-82s.[29] As the post-strike image in Figure 21 clearly shows, the southwestern span of the bridge was knocked completely off its abutment, closing the bridge to railroad traffic for the rest of the year. However, in typical fashion the North Vietnamese were soon able to restore truck traffic, and additional strikes by Air Force and Navy strike aircraft were required later in Linebacker I to keep the bridge completely impassable. Nonetheless, LGBs had finally succeeded where "dumb" bombs had failed during 1965-1968, as had Bullpup missiles (due to their tiny warheads) as well as the US Navy's television-guided Walleyes (due to both warhead size and accuracy problems).[30]

At the campaign level, LGBs were used during May-October 1972 to mount a more effective interdiction effort against the flow of North Vietnamese forces and supplies into South Vietnam than had been previously feasible. Altogether the Air Force "destroyed more than a hundred bridges, some of them several times," and in the northernmost parts of North Vietnam assigned to the Air Force, interdiction

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[27] Thompson, *To Hanoi and Back*, pp. 234-5; Mets, *The Quest for a Surgical Strike*, p. 85-6.

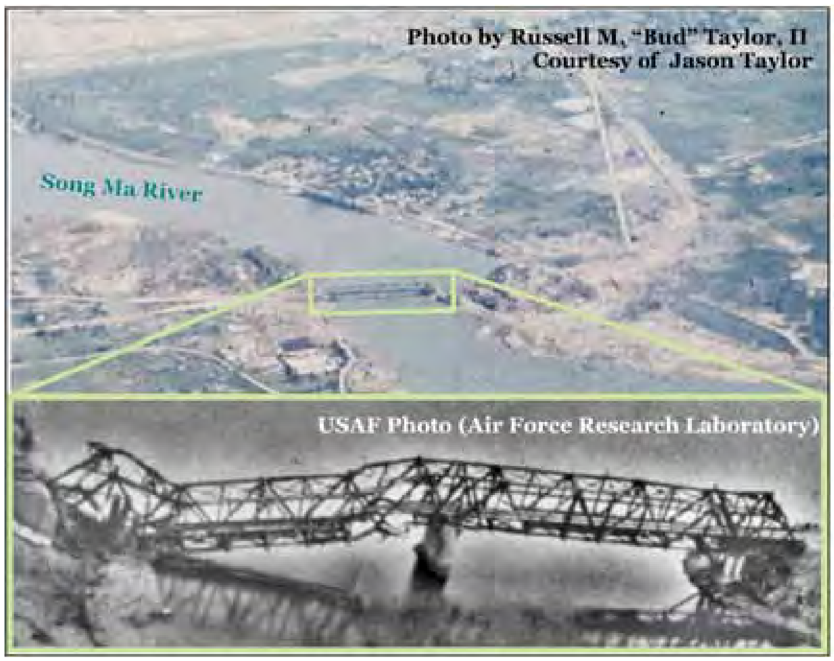
[28] Thompson, *To Hanoi and Back*, p. 235.

[29] Lavalle, *The Tale of Two Bridges and the Battle for the Skies over North Vietnam*, p. 85.

[30] The version of the AGM-12 Bullpup initially used against the Thanh Hoa Bridge only had a 250-lb warhead. The problems experienced with the AGM-62 Walleye are discussed toward the end of this section.

against bridges came to rely almost entirely on LGBs.[31] These munitions also proved lethal against point targets such as North Vietnamese large-caliber anti-aircraft guns or tanks, although the significance of these results do not appear to have been widely appreciated at the time beyond the F-4 aircrews who were directly involved in laser bombing.

Figure 21: The Thanh Hoa Bridge Before and After a May 13, 1972, Strike with LGBs



Instead, the consensus in the Air Force in 1972 seems to have been that the most significant results from LGBs came from strikes against targets in heavily defended areas such as those in and around Hanoi. There, having a designator aircraft maintain a predictable pylon turn around the target at altitudes of 6,000-10,000 was simply asking to be

[31] Thompson, *To Hanoi and Back*, pp. 235, 248. The northernmost areas of North Vietnam assigned to the Air Force were: Package V, North Vietnam above 20°30' north latitude and west of 105°30' east longitude; and Package VI-A, the area east of 105°30' containing Hanoi and extending to the northeast railway.

shot down by anti-aircraft fire or SA-2s. However, at the beginning of April 1972, the 8th TFW had received six Pave Knife laser-designator pods, which could be carried underneath an F-4 on a weapons pylon. These pods contained a gimbal-mounted laser designator that enabled the F-4's backseater to illuminate the target and keep it illuminated throughout the maneuvering of a dive bomb pass and pull-out, thereby permitting laser bombing in the most highly defended areas of North Vietnam. Since there was little prospect of obtaining additional pods in the summer of 1972, General John W. Vogt, the 7th Air Force commander, began designing his part of Linebacker I "to make maximum use of his six Pave Knife pods while preserving them," which meant increasing the support, escort and defense-suppression sorties dedicated to protecting the laser bombers, including the lavish use of chaff to hide them from North Vietnamese radars.[32]

During May-October 1972, then, USAF daylight strike operations in the more heavily defended portions of North Vietnam were increasingly structured around LGBs. The accuracy of these weapons was such that they became the only ones used against targets where collateral damage or civilian casualties were a concern. On June 10, for example, LGBs were successfully used to take out the three generators at the new Lang Chi hydroelectric plant, about 70 miles northwest of Hanoi, without breaching the earthen dam on which they were located.[33] In effect, laser-guided bombs opened up to attack targets that would not have otherwise been accessible due to restrictive ROE that sought to limit infrastructure damage and civilian casualties. In short, the accuracy and reliability of the Paveway I LGBs were without

32 Thompson, *To Hanoi and Back*, p. 231; see also Karl J. Eschmann, *Linebacker: The Untold Story of the Air Raids over North Vietnam* (New York: Ivy/Ballantine Books, 1989), pp. 32-35. Two of the six Pave Knife pods were lost in July, one when a Pave Knife-equipped F-4 was downed by an SA-2 and a second when the F-4 carrying a pod blew a tire on takeoff (ibid.). Pave Knife was boresighted so that the frontseat pilot could put the target within the field of view of its television camera by rolling in and placing the pipper near the aim-point; once the backseater acquired the target, he could then keep laser illumination on it throughout most subsequent maneuvering (Robin deTurk, "Pave Knife," email to Barry Watts, March 10, 2004). Pave Knife also allowed one F-4 to illuminate for other flight members, assuming proper coordination and timing between aircraft during the bomb run.

33 Thompson, *To Hanoi and Back*, p. 251. Vogt, relieved that the dam had not been breached, characterized this strike to a reporter as "the greatest feat in modern bombing history" (ibid.).

precedent compared to prior air-to-ground strike operations. From 1962 to 1973, US aircraft delivered over 8 million tons of ordnance in Southeast Asia.[34] LGBs probably accounted for no more than one third of one percent of this tonnage, but in Linebacker I they "were the key munitions," providing "an estimated 100-fold increase in accuracy and effectiveness" compared to unguided bombs when both accuracy and reliability are taken into account.[35]

Nevertheless, in the aftermath of America's longest war, the US Air Force as an institution did not aggressively pursue the potential of guided munitions, especially LGBs:

> In public discussion [of the Vietnam War], the Air Force tended to emphasize the dramatic contribution of the B-52s in Linebacker II rather than the pathbreaking use of laser-guided bombs against bridges in North Vietnam and tanks in South Vietnam. In contrast to laser-guided bombing, B-52 area bombing was an older technology available at the beginning of the war and useable in any weather.[36]

True, improvements in LGBs continued during the 1970s and into the 1980s. The Paveway II family of LGBs, which remains in service today, was developed during 1973-75 and entered production in mid-1976. The main improvement these kits offered over Paveway I LGBs was to add folding fins (see Figure 22), which somewhat expanded the release envelope for higher altitudes and steeper dive angles. Paveway II kits also facilitated denser carriage, thereby simplifying loading, and helping to make it possible to employ second-

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34 Thompson, *To Hanoi and Back*, p. 306.

35 Wayne Thompson, "PGM & Dumb Bomb Tonnage Dropped in SEA," Gulf War Air Power Survey internal e-mail, December 11, 1992; Mike Worden, *Rise of the Fighter Generals: The Problem of Air Force Leadership 1945-1982* (Maxwell AFB, AL: Air University Press, March 1998), p. 197. Colonel Carl Miller, the 8th TFW commander during Linebacker I, personally led "many of the pioneering laser-guided bombing missions into North Vietnam" in 1972, and he played a crucial role in making LGBs the key weapons in this campaign (Thompson, *To Hanoi and Back*, p. 233). LGBs did not, however, play a significant role in Linebacker II (December 18-29, 1972), when B-52s were finally used against North Vietnam, due to monsoon weather.

36 Thompson, *To Hanoi and Back*, p. 281.

generation LGBs on a wide variety of US and allied aircraft.[37] Over the next decade, the Air Force developed a third generation of LGBs, the Paveway III, to give these munitions some standoff capability and to enable them to be released from the very low altitudes—500 feet above the ground or lower—believed necessary by both the US and British air forces for survivability against Warsaw Pact radar-guided SAMs in the event of a conventional war in Europe.[38] Because the Paveway III low-level laser-guided bombs (LLLGBs) required the addition of an autopilot to enable the weapon to fly itself to a position from which its laser sensor could see laser energy reflected from the target when released well outside that envelope, development of third-generation LGBs was more difficult, costly, and troubled than had been the earlier Paveway weapons.[39] Indeed, in early 1985 Air Force secretary Vern Orr terminated the program with less than ten percent of the original number of kits originally envisioned in the inventory.[40] However, the desire to develop Paveway III kits for the hard-target I-2000 warhead, including a variant adapted for internal carriage aboard the F-117 (the GBU-27), led eventually to further production.

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37 Mets, *The Quest for a Surgical Strike*, pp. 99-101. TI's "bang-bang" (full deflection) control system and canard configuration were retained in the Paveway II weapons. Note, also, that during the Vietnam conflict the Paveway II designation was, confusingly, applied to electro-optical guided bombs, although current usage reserves the term for second-generation LGBs (Ockerman, *An Analysis of Laser Guided Bombs in SEA (U)*, p. 2; William B. Scott, "Killer-Scout Tactics Shaped by Paveway LGB Performance," *Aviation Week & Space Technology*, October 21, 1996, pp. 52-3).

38 The conviction that NATO strike aircraft would be forced to operate at extremely low altitudes to survive the SA-2, -3, -6 and, later, SA-8 threat was the tactical imperative that drove the development of both the Paveway III LGBs as well as the Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) system for the F-15E and F-16C/D. However, after the Israeli Air Force had shown in 1982 how such radar SAMs could be suppressed, the US Air Force abandoned low-altitude penetration tactics during the planning phase of Desert Storm, wisely electing instead to go after Iraq's radar SAMs at the outset to enable Coalition aircraft to operate at medium altitudes, above the reach of AAA and IR SAMs. Only the British tried initially to operate at very low altitudes during Desert Storm, and they abandoned this tactic before the end of the first week of ODS.

39 Mets, *The Quest for a Surgical Strike*, pp. 110-122. Paveway III also incorporated the proportional guidance Autonetics had originally developed when it lost the Paveway I competition to TI and eliminated the gimbaled seeker arrangement of the Paveway I and II LGBs.

40 Mets, *The Quest for a Surgical Strike*, pp. 123-124.

Equally important for the success achieved with LGBs during Operation Desert Storm, the Air Force had fielded laser-targeting systems such as Pave Tack for F-4s and F-111Fs, and a similar system on the low-observable F-117, both of which permitted nighttime target acquisition using imaging infrared and included automatic target tracking by the laser illuminator once the aim-point had been designated.[41] Clear air was still required for successful LGB employment, but the expanded release envelope of Paveway III LGBs combined with automation of the laser designator greatly improved the employment opportunities for these weapons, including a shift from Vietnam-era dive-bombing to level delivery from medium altitudes.

Figure 22: Paveway II and III LGBs

Despite all these improvements during the late 1970s and 1980s, neither the Air Force's nor the Navy's fighter/attack communities went into the 1991 Gulf War persuaded that guided weapons could be, or would be, the key munitions. Even today, one is hard-pressed to offer

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[41] During Desert Storm, only a handful of LANTIRN sets were available for the F-16C/D and the F-15E.

a fully satisfying explanation for what appears to have been institutional myopia, especially on the part of the US Air Force, beyond the obvious one of cultural resistance to change. Again, RAND's insight in 1973 was that LGBs had been so "spectacularly good" in 1972 that they rendered "feasible" tactical missions that had heretofore been impractical due to accuracy limitations.[42] Further, only two years later, in 1975, the DARPA/DNA Long Range Research and Development Planning Program concluded that "near-zero-miss" non-nuclear weapons could provide alternatives to massive nuclear destruction as well as bolster the conventional defense of Western Europe.

Such forward-looking insights notwithstanding, however, throughout the 1970s and into the 1980s Air Force leaders were reluctant to bet very heavily on the future efficacy of guided weapons. After the Second Indochina War, General Vogt became the commander of US Air Forces in Europe (USAFE). Given the key role LGBs had played under his command during Linebacker I, one might have expected him to seek ways to take advantage of them in central Europe. Instead, Vogt focused on their limitations:

> I think the very successful use in Southeast Asia, particularly of the laser guided bomb . . . , has tended to create the impression that they are the answer to all our needs. Well, like any other weapons system, they have limitations. They aren't very good when the weather is bad. The weather is bad most of the time in Europe so immediately you've got a severe limitation on their use over here. During Linebacker II, for example, there was only one eight-hour period during that entire eleven day period that we were able to use those laser guided weapons. The weather wasn't adequate during all the periods of that particular operation. And I would think that the percentages would even be worse . . . [in Europe] because, as you know, for nine months of the year we either have darkness or extremely bad weather. Lasers simply aren't the answer in that kind of environment nor are

42 Blachly, CoNine, and Sharkey, *Laser and Electro-Optical Guided Bomb Performance in Southeast Asia (LINEBACKER 1)*, R-1326-PR, pp. v, vi.

the electro-optical precision guided weapons which the Air Force is buying in great quantities.[43]

Figure 23: Pack Tack Laser-Designator Pod on an F-4E

Vogt's concerns about weather and darkness in Central Europe were certainly not without foundation. However, his inclination as the USAFE commander to be put off by the limitations of Vietnam-era LGBs, rather than seeking ways to overcome them, did little to encourage others in the Air Force to pursue the potential of guided weapons, or even to plan on making maximum use of LGBs in Europe whenever atmospheric conditions would have permitted their employment in the event of war.[44]

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43 General John W. Vogt, taped oral history interview by Robert M. Kipp, USAFE command historian, August 22, 1975, p. 8. That the weather limited LGB employment during Linebacker II was hardly surprising. December is well into the annual northeast monsoon period of poor weather over North Vietnam's Red River Valley (roughly November to April), where Hanoi and Haiphong are located.

44 The "biggest obstacle to employing LGBs in SEA [Southeast Asia] was the weather," and even among those "who had experienced the success of LGBs," there was a general feeling "that those same successes would not be repeated in Europe due to weather constraints" (Robin deTurk, "Laser Guided Bomb Deployment in Southeast Asia," memorandum for Barry Watts, August 27, 1997). Robin deTurk was assigned to the 433rd TFS from March 1971 to March 1972 and had considerable experience with LGBs during his tour.

Starting in the early 1980s, though, improvements began to trickle into selected operational units that ameliorated some of Vogt's concerns. The AN/AVQ-26 Pave Tack laser-designation pod on the F-4 and F-111F addressed LGB employment at night. Paveway III LLLGBs and the Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) system enabled aircraft such as the F-16C/D (and, later, the F-15E) to employ LGBs from the very low altitudes to which NATO strike aircraft had been driven by the threat of Warsaw Pact radar-guided SAMs. LANTIRN sets were expensive, but they did provide a way of adding navigation and laser-targeting capabilities to existing fighters.[45]

How successful these improvements might have been in the event of a conventional conflict in Central Europe during last decade of the Cold War is a matter of conjecture. Not recognized until the late 1980s was the degree to which European humidity degraded laser radiation to a greater extent than it had over Vietnam and Laos.[46] Of course, the preference for low-altitude tactics and the inability to practice delivering live LGBs in Central Europe undoubtedly masked these problems. Still, the very fact that discovery of the reduced emissivity and transmissivity to laser radiation there was not made a decade or more earlier indicates that the pursuit of guided weapons generally, and LGBs in particular, was not a high priority for the US Air Force between the end of the Vietnam war and the 1991 Persian Gulf War. Nor was there any institutional commitment during this period to alternative guidance methods, such as cheap inertial systems, which could have obviated in a stroke the clear-air constraints of LGBs. As will emerge in the JDAM discussion later in this chapter, INS guidance

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45 In 1999 the Air Force listed the prices of a LANTIRN set as $1.38 million for the navigation pod, and $3.2 million for the targeting pod ("LANTIRN," USAF Fact Sheet, October 2005, at <http://www.af.mil/factsheets/factsheet.asp?id=111>, accessed September 2, 2006).

46 James O. Hale, e-mail to Barry Watts, March 18, 2004. When the USAFE study on laser "transmissivity and emissivity factors" was done, Hale was running the command's weapons and tactics shop at Ramstein Air Force Base. This same problem also adversely affected the use of infrared Mavericks for close air support.

kits were successfully tested by both the Air Force and the Navy during the late 1980s and then ignored until after Desert Storm.[47]

Perhaps the major reason for the Air Force's general neglect of guided munitions prior to 1991 was the "smart-jet, dumb-bomb" philosophy that grew up around the F-16. The bombing computer in the F-16, with its continuously computed impact point (CCIP) visible in the pilot's heads-up display, was the first automated bombing system fielded in an Air Force tactical fighter that consistently produced more accurate delivery of unguided bombs than did manual bombing by a skilled pilot. The F-16 was designed to be able to deliver ordnance within 6 milliradians (MILs).[48] In the hands of skilled pilots on peacetime gunnery ranges, the F-16's CCIP bombing system has performed better than 6 MILs, particularly at the Air Force's annual Gunsmoke competitions, which F-16s increasingly dominated during the 1980s. This superior performance relative to other air-to-ground fighters led many in the US Air Force and TAC (now Air Combat Command) to conclude that unguided bombs delivered by an F-16 would be nearly as effective as guided weapons such as LGBs and considerably cheaper.[49] This conclusion also reinforced the instinct of many Air Force leaders to emphasize the procurement of new platforms—getting "rubber on the ramp"—over new munitions, thus raising another cultural barrier to their service's aggressive pursuit of guided munitions.

Not well appreciated prior to Desert Storm, however, was the dependence of the F-16's impressive peacetime dive-bombing accuracy on being able to release from relatively low altitudes, well within the reach of small arms, anti-aircraft fire, and infrared SAMs. Over Iraq in 1991 release altitudes were generally much higher than in peacetime

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47 "Navy, USAF Test Boeing, Northrop Smart Bomb Kits," *Aviation Week & Space Technology*, April 4, 1988, p. 50. The concept tested was low-cost, high-accuracy (CEPs of "tens of feet") inertial-guidance tail-kits for Mark-80 series gravity bombs.

48 Joe Bill Dryden, "F-16 for Close Air Support," *Code One*, October 1989, at <http://www.codeonemagazine.com/archives/1989/articles/oct_89/cas/>, accessed September 2, 2006. The icon in the F-16 heads-up display for the continuously computed impact point showed where on the ground the bombs would impact if the pilot hit the bomb-release (or "pickle") button at that instant. So reliable was this impact point that it came to be known in the F-16 community as the "death dot."

49 For prices on Paveway LGBs, see pp. 202-203.

training in order to minimize losses to these ubiquitous low-altitude air defenses, which were too numerous and widespread to be reliably suppressed. A brief example should illustrate the operational impact of these higher release altitudes. Assuming a 45-degree dive angle and a 5-MIL error in the F-16's bombing system, the miss distance for an aerodynamically perfect bomb released 3,500 feet above the ground (AGL) is around 25 feet—close enough to damage many targets with a 2,000-lb bomb. In Desert Storm, however, release altitudes of 18,000 feet AGL were not uncommon. From this height, the miss distance for the same aerodynamically perfect bomb and 5-MIL error grows to over 127 feet (ignoring, incidentally, the additional errors frequently encountered over Iraq due to unknown winds at lower altitudes). Even with a 2,000-lb bomb, a 127-foot miss means that many, if not most, point targets will survive and, during Desert Storm, all too many of them did when attacked with unguided bombs.[50] To have much chance for success against, for example, a hardened aircraft shelter, much greater accuracy was required. The tactical problem was not that aircraft shelters could maneuver to avoid being hit—they are fixed targets—but that Iraqi shelters like those in Figure 24 were so hardened that LGB-quality accuracy was needed to breach them and destroy any aircraft inside.

Another reason for the Air Force fighter community's inclination to dismiss, ignore or discount the potential of LGBs between 1972 and Desert Storm in 1991 stems directly from aircrew culture. During the 1960s and most of the 1970s, the status of individual pilots was widely based on manual air-to-ground dive-bombing skills. The pilot in the squadron who could consistently drop the best bombs on the gunnery range was considered the "top gun" and respected accordingly by his peers. While aircrew skill was certainly required for success with Paveway I and II LGBs, the accuracy and lethality of these weapons threatened to devalue the manual dive-bombing skills that had long been at the heart of social status in Air Force F-100, F-105, and F-4 units. One cannot help but suspect that some of the resistance to guided weapons in the Air Force after Vietnam had to do with the

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50 The author headed the Gulf War Air Power Survey's task force on effects and effectiveness. Most of the visible damage that could be identified in Desert Storm target folders was due to guided weapons, principally LGBs. Iraqi tanks in revetments in the Kuwaiti Theater of Operations proved a challenge even for 500-lb LGBs with a 3-meter CEP.

changes these new weapons portended for the prevailing social arrangements in fighter units.

Figure 24: LGB Damage against Hardened Aircraft Shelters, 1991

A related but more-subtle obstacle to embracing the potential of guided weapons arose from the natural inclination of aircrews, especially pilots, to identify psychologically with the aircraft they happen to fly instead of the munitions they might expend.[51] This focus on platforms is quite understandable given the time and effort pilots devote to mastering their aircraft. Nevertheless, if the increased prominence of guided weapons means that combat effectiveness depends increasingly on the munitions and associated sensors for employing them, then the pilot's instinctive identification with his (or her) platform constitutes a conceptual barrier to appreciating the longer-term implications of PGMs for the conduct of war. Certainly the emphasis of the Air Force fighter community after Vietnam on getting "rubber on the ramp" first and foremost suggests that this institutional preference hindered the Air Force from grasping the growing potential of guided weapons.

While the institutional Air Force, like the Navy's fighter/attack community, went into the 1991 Gulf War presuming that unguided

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[51] As Perry Smith argued with considerable insight, the foremost reason why airmen have had difficulty being objective about air power lay in "the psychological attachment of the airman to his machine"—Perry McCoy Smith, *The Air Force Plans for Peace: 1943-1945* (Baltimore, MD: The Johns Hopkins Press, 1970). p. 18.

("dumb") munitions would inflict the lion's share of the damage on the adversary, key figures in the "Black Hole" planning cell under the Joint Force Air Component Commander, General Chuck Horner, had other ideas. Then Lieutenant Colonel David Deptula, supported by Colonel John Warden and his CHECKMATE planners in the Pentagon's basement, were both determined to make LGBs and other guided weapons the mainstay of the Desert Storm air campaign—and they proceeded to do so.[52] It is probably fair to say that the intensity and success of "laser bombing in Desert Storm" were a function of several factors, foremost among them "American leadership and planning," but including the open desert terrain in which the war was fought and "improved technology" as well.[53] In the latter category, the low observability of the F-117, which allowed key elements of Iraq's air defense system and other high-priority targets to be attacked during the war's opening moments, surely warrants mention. However, unlike General Vogt in Vietnam, who had a mere six Pave Knife targeting pods during 1972, General Horner in 1991 had more than a hundred strike aircraft, mostly F-111Fs and F-117s, able to find targets and attack them with LGBs whenever weather permitted.[54]

The impact on the institutional US Air Force of the generally successful application of guided weapons during Desert Storm would be hard to overstate. In the aftermath of the campaign, Tactical Air Command, along with the Air Force in general, made an institutional commitment to guided weapons, a commitment from which there has been no retreat.[55] At the campaign level, perhaps the clearest evidence

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52 See Alexander S. Cochran, et al., Gulf War Air Power Survey, Vol. I, *Planning and Command and Control* (Washington, DC: Government Printing Office, 1993), Pt. I, *Planning*, pp. 112-116, 118-121, 123-127, 131, 134-135, 141-142, 171-172, 230-131; also Edward C. Mann, III, *Thunder and Lightning: Desert Storm and the Airpower Debates* (Maxwell AFB, AL: Air University Press, 1995).

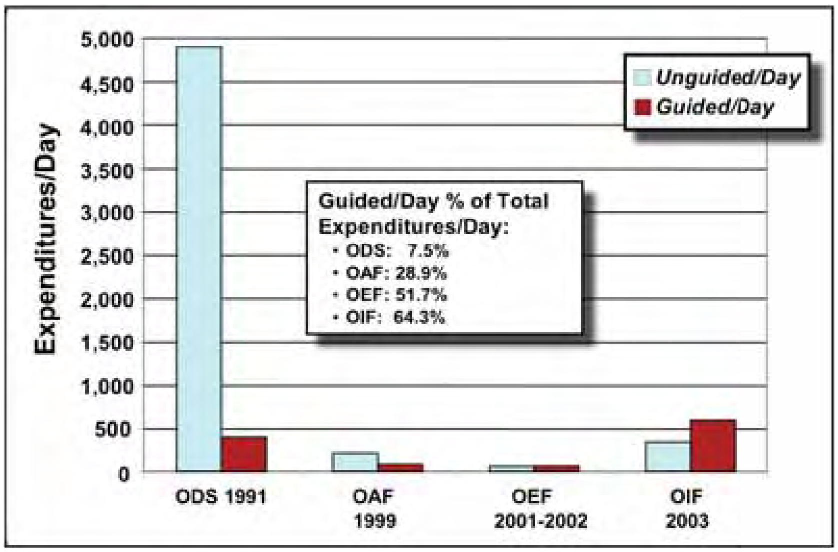
53 Thompson, *To Hanoi and Back*, p. 284.

54 During Desert Storm, weather did interfere with LGB operations. For example, on the second day of the war 22 of 42 LGBs released by F-117s missed due to weather, and on Day 40 the weather was so poor that CENTAF cancelled all F-117 sorties ("F-117 Summary Data," Gulf War Air Power Survey spreadsheet, April 22, 1993).

55 As Deptula reflected a decade after Desert Storm: "Prior to 1991, two separate, leap-ahead military technologies had matured enough to offer an order-of-magnitude breakthrough. The first was low-observable (i.e., stealth) technology, and the second was the development of precision-guided munitions.

of this commitment can be seen in the dramatic reduction in the use of unguided munitions evident in Figure 4. In the Kosovo conflict, Afghanistan, and the second Iraq campaign, "dumb" ordnance expenditures during air operations have been but a fraction of what was expended in Desert Storm. Figure 25 makes the same point using average expenditures per day over the course of these four major campaigns.

Figure 25: Unguided versus Guided Munitions/Day, 1991-2003



As for the attitude of the US Navy's attack community toward guided munitions, the evidence suggests less than whole-hearted acceptance until the Afghanistan campaign of 2001-02. Indeed, the Navy's television-guided AGM-62 Walleye was first used in May 1967, about a year earlier than the Air Force's initial combat trials with LGBs. Due in part to its small (1,000-lb) warhead, though, the initial

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Together, these two capabilities, in conjunction with an effects-based planning methodology, allowed US forces to execute an innovative concept of operations that has come to be known as *parallel warfare*. Simply put, parallel warfare is the simultaneous application of force across the breadth and depth of an entire theater." (Major General David A. Deptula, "Air Force Transformation: Past, Present, and Future," *Aerospace Power Journal*, Fall 2001, p. 86).

version of Walleye had no more success in dropping spans of the Thanh Hoa Bridge during Rolling Thunder than did Bullpups or dumb bombs. Later, during Linebacker I, 2,000-lb Walleye IIs were employed by both the Air Force and Navy. Even then, however, they did not prove as accurate as LGBs, they were never expended in comparable quantities, and they did not assume the central role in Navy strike operations that LGBs came to play for 7th Air Force in 1972.[56] Thus, while the Navy got Walleye into the field in Southeast Asia ahead of the Air Force's BOLT-117 and Mark-84L, the AGM-62 did not ultimately have the impact of the Paveway munitions. Besides the accuracy problems encountered with even the 2,000-lb Walleyes, the limited magazines aboard aircraft carriers in the Gulf of Tonkin prevented naval aviators from employing them on the scale needed to produce campaign-level effects.

During Desert Storm, the magazine constraints on carriers again constrained the impact of Navy guided bombs compared with the Air Force's expenditures. Both services, as well as Coalition allies such as the British and Saudis, possessed LGBs and employed them during the campaign. However, Air Force expenditures dominated the application of guided bombs during ODS. Whereas USAF aircraft expended 8,345 LGBs and 71 GBU-15s during the campaign, Navy aircraft only dropped 632 LGBs and 131 Walleye IIs.[57] After Desert Storm, naval aviators were understandably unhappy with the acclaim their Air Force counterparts received for their exploitation of guided weapons generally and LGBs in particular. In fairness, the limited magazines of the aircraft carriers led naval commanders to husband their LGB kits for the Coalition's ground offensive, which began on February 24, 1991. The upshot, though, was that the Navy expended very few guided bombs prior to February 24th. The ground campaign ended after only 100 hours, leaving few opportunities for using guided bombs to support ground forces. Looking back on Desert Storm, Navy leaders recognized the guided bombs such as the GBU-16, anti-

[56] The first four-ship that attacked the Paul Doumer Bridge on May 10, 1972, carried Walleye IIs. But these munitions were contrast-seekers that tended to drift up and left and were very sensitive to shadows and the position of the sun (Barry D. Watts, "433rd TFS (8th TFW) PGM Employment in 1972," notes from discussion with James O. Hale, August 19, 2002).

[57] Hill, Cook, and Pinker, GWAPS, Vol. V, *A Statistical Compendium and Chronology*, Pt. 1, *A Statistical Compendium*, pp. 550-551. USMC aircraft expended another 266 LGBs during Desert Storm (ibid., p. 552).

radiation missiles, and TLAM had "proven their worth, both militarily and politically."[58] Still, the Air Force got most of the credit and, in fact, had made the greatest use of them by an order of magnitude.

By the time Operation Enduring Freedom began in October 2001, the US Navy's air wings were far more inclined to utilize guided weapons, mainly LGBs and JDAMs, from the outset than they had been in 1991. Nonetheless, Navy performance with laser-guided bombs was disappointing. In the case of air defense targets during the initial months of Enduring Freedom, about half the LGBs dropped by Navy aircraft missed.[59] There appear to have been two basic reasons for these results. First, Navy F-14 and F/A-18 crews had not previously devoted much training time to LGB employment; second, the Nite-Hawk laser-targeting pod used on the F/A-18C was unreliable, had poor magnification, and required manual tracking of the aim-point with the laser designator by the pilot.[60] Both of these shortfalls suggest that, as late as 2002, US naval aviators were still somewhat behind their Air Force counterparts insofar as a strong institutional commitment to guided weapons is concerned.

Laser-guided bombs not only proved basically as accurate and reliable as advertised in their combat debut in Southeast Asia during 1968, but their unit-procurement prices have been, and remain, lower than most other guided munitions. In the case of Paveway II LGBs, their unit prices, while initially perceived as high, are comparable to those of a full-up JDAM round, which has enabled them to be employed in large quantities. Currently, a GBU-10 Paveway II LGB with a Joint Programmable Fuze (JPF) and MXU-650 fin assembly costs around $24,000 with the Mark-84 warhead, whereas a full-up JDAM

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58 Admiral J. T. Howe in Department of the Navy, *The United States Navy in "Desert Shield" "Desert Storm"* (Washington, DC: Office of the Chief of Naval Operations, May 15, 1991), p. 60. The GBU-16 consists of a Paveway II guidance kit and a 1,000-lb Mark-83 warhead.

59 Robert F. Nesbit, briefing of a preliminary Defense Science Board assessment of BDA (bomb damage assessment) from Navy strike operations during the first three months of Operation Enduring Freedom, May 6, 2002.

60 Sandra I. Erwin, "Naval Aviation: Lessons form the War," *National Defense*, June 2002, accessed September 2, 2006, available at <http://www.nationaldefensemagazine.org/issues/2002/Jun/Naval_Aviation.htm>.

with the same warhead and fuze is about $33,000.[61] However, Paveway III LGBs, remain substantially more expensive than JDAM, running $90,000-105,000 for a full-up round with a Mark-84 warhead.[62]

As for effectiveness, over North Vietnam Paveway I LGBs made it possible to take down bridges that had proven extraordinarily resistant to attacks with unguided weapons and permitted attacks in close proximity to dams and populated areas while avoiding inadvertent flooding of the Red River delta. In Desert Storm, Paveway II and III munitions with BLU-109/B "penetrator" warheads were able to breach hardened aircraft shelters, which most observers had previously believed to be nearly invulnerable to bombing. In addition, 500-lb GBU-12s with Mark-82 warhead were accurate enough to make feasible attacks on individual pieces of Iraqi armor even when sheltered in sand revetments. In all these instances, the accuracy of these weapons and their availability expanded American options.

True, laser-guided bombs had limitations, notably the need, which persists to this day, for clear air. On the other hand, when atmospheric and weather conditions allow them to be employed, they have been consistently lethal in the hands of trained aircrews. Gulf War Air Power Survey researchers concluded that during Desert Storm, F-117s pilots hit their selected aim-points with nearly 80 percent of the 2,065 weapons they released.[63] Government Accounting Office (GAO) analysts subsequently invested several years trying to dispute this claim (among many others), eventually arguing that the F-117's hit rate may have been as low as 55 percent—based largely on discounting the claims of the pilots on such grounds as inadequate or, in the case of cockpit videos, poor-quality documentation.[64] However,

[61] Department of the Air Force, *Procurement Program, Fiscal Year (FY) 2007 Budget Estimates: Procurement of Ammunition*, February 2006, pp. 57, 149.

[62] Gregory S. Kuzniewski, email to Barry D. Watts, "RE: Paveway III Costs," November 1, 2006. (Kuznieski's email reflected Raytheon's prices for Paveway III LGB guidance kits.) The costs of both LGBs and JDAMs increase about $10,000 if the BLU-109/B penetrator warhead is used instead of the Mark-84.

[63] Thomas A. Keaney and Eliot A. Cohen, *Revolution in Warfare? Air Power in the Persian Gulf* (Annapolis, MD: Naval Institute Press, 1995), pp. 291-292. This version of the GWAPS summary report contains data that was not included in original 1993 version published by the Government Printing Office.

[64] Government Accounting Office, *Operation Desert Storm: Evaluation of the Air Campaign*, GAO/NSIAD-97-134, June 1997, pp. 125-139.

even if the F-117's hit rate was *only* 55 percent, this lower hit rate would still appear to be more than sufficient to alter, fundamentally, the conduct of future air operations.[65] And that is precisely what the data in Figures 4 and 25 show: an unmistakable trend in America's last three wars away from dumb munitions and toward guided weapons for major air campaigns due to their demonstrated efficiency and lethality.

Nevertheless, the history of LGBs also documents nearly two decades of incomplete acceptance, if not institutional resistance, by the US Air Force's fighter community over their proper role in future air campaigns. Even after the Air Force embraced guided weapons following Desert Storm, the Navy's aviation community accepted them only half-heartedly for another decade. This record of foot-dragging by aviation communities in two different military services reveals much about the role institutions and cultures can play, for good or ill, in the acceptance of new technologies.

The Copperhead Anti-tank Round

In light of the Air Force's success with LGBs in Southeast Asia, it must have appeared eminently sensible to the Army's artillery community to add laser guidance to artillery shells. Those involved appear to have had two motives. First, the tactical fact was that, prior to Copperhead, artillery systems and munitions were "not accurate enough" to have much chance of killing a stationary enemy tank, much less a moving one, "without excessive ammunition expenditure, resupply, and tube wear."[66] Data from World Wars I and II, the Korean War, and Vietnam indicated that only about one percent of all tank kills were by artillery systems.[67] Second, there was the growing problem in Europe of the Warsaw Pact's increasing numerical superiority in land-combat systems exacerbated by the narrowing qualitative gap between NATO and Warsaw Pact armored vehicles first evident in the 1973 Arab-Israeli War. Dealing with this mounting threat—particularly in the case of a surprise attack by echeloned conventional forces—was the same problem that later motivated the Assault Breaker program and,

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[65] Retired Major General Jasper Welch deserves credit for this observation.

[66] James F. Hall, "Precision Guided Artillery: First and Second Generation Projectiles," *Field Artillery Journal*, May-June 1981, p. 9.

[67] Hall, "Precision Guided Artillery," p. 9.

in November 1984, NATO's endorsement of Follow-On Forces Attack as an official part of the alliance's strategy.[68]

Given these challenges as the US Army began to look beyond its involvement in Southeast Asia, developing a 155-mm guided artillery projectile that could kill enemy tanks and other armored vehicles at a distance made sense. After all, the Army's Redstone Arsenal, not the Air Force, had originally pioneered the pulsed laser designator that made such a projectile feasible in a ground-combat setting. David Salonimer had gone to a pulsed laser precisely in the hope of getting a designator small and light enough for a single soldier to carry.[69]

Figure 26: The M712 Copperhead

The result was the world's first guided artillery round. The M712 Copperhead was a 155-mm, semi-active, laser-guided, anti-tank artillery projectile with gun-to-target ranges of 3-16 kilometers. It guided on laser energy reflected from the target. To provide that laser energy, the Army developed laser designators that could locate and illuminate targets at distances of 3-5 kilometers, depending on whether the target was moving or stationary. These designators were small enough to be transported by two soldiers and mounted on helicopters or even remotely piloted vehicles. The Copperhead was first fired at the Army's

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[68] Alan Shaw (project director), Stephen Budiansky, Michael Callaham, Allen Greenberg, Peter Lert, and Nancy Lubin, *New Technology for NATO: Implementing Follow-On Forces Attack* (Washington, DC: Office of Technology Assessment, June 1987), p. 50.

[69] "The Evolution of the Smart Bomb . . . A Story of Technology Transfer," *The Redstone Rocket*.

White Sands Missile Range in 1972, and full-scale development began in May 1975. The projectile transitioned to production in February 1979, entering operational service in December 1982. By 1989, nearly 25,000 Copperhead rounds (and, possibly, several thousand more) were produced for the US Army. When the projectile was properly employed and everything worked as advertised, accuracy was measured in centimeters and the warhead was effective against tanks.

While these basic facts appear, at first blush, indicative of a reasonably successful program, a more detailed examination of Copperhead's programmatic history suggests that this first guided artillery round encountered substantial cost growth and its fielding took considerably longer than initially planned because of engineering problems. Copperhead's base year for cost purposes was FY 1975, although it did not emerge as a major defense acquisition program in the Pentagon's selected acquisition reports until mid-1976. The baseline program was to develop the projectile and procure 133,058 rounds for a total cost of $847.3 million in FY 1975 dollars or just over $3 billion in FY 2006 dollars.[70] By the time production ended in the late 1980s, the total program cost had been reduced about 17 percent in FY 1975 dollars, but the total number of Copperhead rounds procured had been cut sharply to only 24,845. Because research-and-development costs are included in these total-program estimates, they cannot be used to break out Copperhead's procurement or production cost-per-round. However, dividing the baseline and final program cost estimates by corresponding totals of Copperhead rounds shows a cost growth in the neighborhood of 350 percent. This program-level estimate of the Copperhead program's failure to control unit costs is confirmed by Congressional Budget Office (CBO) analysis. The Copperhead program had a high degree of concurrency. According to a 1988 CBO examination of concurrency between development and production in a number of defense acquisition programs, Copperhead's unit cost grew around 550 percent over the course of the program and its initial operational capability (IOC) was 41 months beyond the original date, roughly an 80 percent delay.[71] As for the actual unit-procurement cost

[70] Department of Defense, OASD (Comptroller), "Selected Acquisition Report (SAR) Summary Tables: As of Date: December 31, 1988," March 10, 1989, p. 12.

[71] G. Wayne Glass and William Kostak, *Concurrent Weapons Development and Production* (Washington, DC: CBO, August 1988), pp. 16, 18.

of a Copperhead round, a 1985 Government Accounting Office study put the unit price at $33,300 in FY 1983 dollars ($58,816 in FY 2006 dollars), up over 50 percent from the beginning of production in 1979.[72] Overall, then, the Copperhead program experienced both significant cost growth and schedule delays.

The reasons for these problems appear to have stemmed from the high accelerations that M712 projectiles had to be able to withstand when fired to their maximum range of 16,800 meters. Getting electronic components inside a shell to work after being subjected to accelerations thousands of times the force of gravity was the same challenge that Merle Tuve's Section T of the NDRC had faced and eventually overcome during World War II. Copperhead, however, was considerably more complex than a proximity fuze. After passing the peak of its trajectory, fins and guide wings have to deploy, the sensor has to detect reflected laser energy, and it needs to do so far enough from the target for the projectile to be able maneuver to any point in its calculated footprint to reach the target without stalling. Based on GAO's examination of the program, the contractor initially chose a softer steel for Copperhead's control section on the premise that the required strength could be attained through a heat-treatment process. However, this process distorted the housing and failed to meet tolerances; in addition, problems occurred with the control-actuator base that operated Copperhead's wings and fins.[73] As a result, the unit price per round over the first two production lots, which totaled 3,738 rounds, increased from $32,000 to over $48,000 in FY 1983 dollars (or, approximately $56,700 to $85,200 per round in FY 2006 dollars).

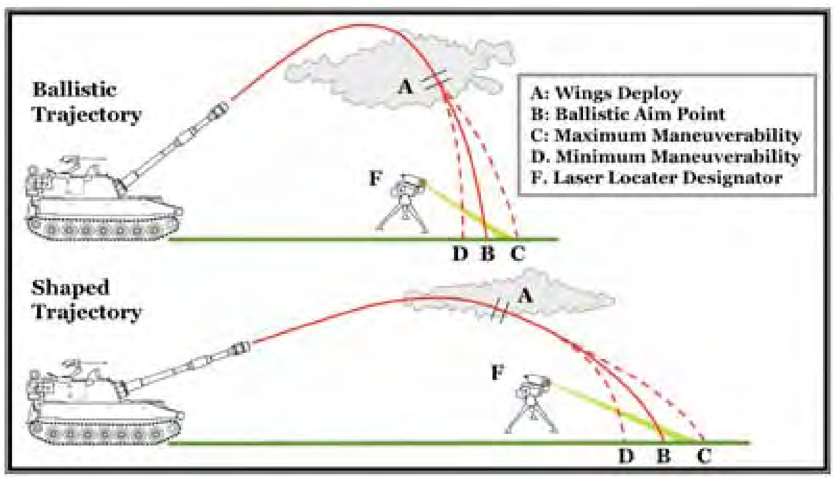
Besides programmatic difficulties during Copperhead's development and production, the munition also turned out to be very complicated to employ. Shells with radar proximity fuzes were, for all intents and purposes, "fire-and-forget" rounds. Copperhead was not fire-and-forget because of the requirement that the target be illuminated with laser energy during the projectile's terminal phase. The upshot was that Copperhead required tight coordination between the artillery bat-

[72] GAO, "Why Some Weapon Systems Encounter Production Problems While Others Do Not: Six Case Studies," GAO/NSIAD-85-34, May 24, 1985, pp. iii, 10. The GAO is now the Government Accountability Office.

[73] GAO, "Why Some Weapon Systems Encounter Production Problems While Others Do Not: Six Case Studies," p. 10.

tery firing the projectile and the forward observer "lasing" the target, doctrinally from distances of 3-5 kilometers. Among other things, the pulse recurrence frequency (PRF) the projectile would "see" had to be set properly before firing to match that of the observation/lasing team's designator.[74] In addition, clear air was required during Copperhead's terminal phase, which meant that it was not entirely an all-weather round. Not only could ground fog and other obscurations prevent its employment, but the height of the clouds over the target had to be taken into account in choosing the appropriate of two trajectories, ballistic or a flatter shaped trajectory (see Figure 27).

Figure 27: Copperhead Trajectories



Copperhead, then, was not an easy munition for soldiers or marines to use on actual battlefields. From the tactical user's perspective, Copperhead turned out to be closer to the Air Force's AIM-4 Falcon in terms of ease of use than to the AIM-9 Sidewinder. On the positive side, the M712 is officially assessed to have a high P_k against both moving and stationary targets, has been extremely lethal even against main battle tanks, and does not exhibit as pronounced a firing signature as anti-tank guided missiles. On the negative side, the

74 A mismatch between the PRF set with a switch in a Copperhead round and that of the forward observer's laser designator would turn the "smart" projectile into a "dumb" one. LGBs have the same requirement, but PRF settings for munitions and designators are usually made prior to takeoff rather than in the heat of battle.

ground/vehicular laser locator designator (G/VLLD) or modular universal laser equipment (MULE) and its operator are vulnerable to suppressive fires, two-way communications are necessary between the artillery battery and the team doing the lasing; effectiveness is limited by the operator's ability to track the target during the last 13 seconds of projectile flight, and the laser illumination can be detected by the target.[75]

The M172 Copperhead not only required clear air during the projectile's terminal phase to work at all, but very close coordination between the firing battery and the forward-positioned observation/lasing team. The 1999 version of Field Manual 6-40/Marine Corps Warfighting Publication 3-1.6.19—a joint Army-USMC document—specified that if Copperhead's calculated time-of-flight to the target is less than 20 seconds, designation should begin concurrent with the round being fired; otherwise illumination should begin 20 seconds prior to round impact.[76] Needless to say, these are very precise timing requirements for soldiers and marines to meet under the stresses and frictions of ground combat operations.

Beyond these complexities, Copperhead faced a cultural impediment. The mindset of American artillerymen has traditionally emphasized fire-and-forget rounds sent down-range in large quantities at map coordinates or, in the case of harassment-and-interdiction fires, at general areas. Since World War I, the underlying paradigm has been one of an industrial approach to warfare in which massive quantities of ordnance have been used to compensate for both imprecisely located targets and the lack of pinpoint accuracy. Copperhead, as a guided munition requiring a precisely located target, did not fit well with this mindset. In the first place, the M712 was anything but fire-and-forget. Even during the final seconds before impact, things could still go wrong for one reason or another. For example, if enemy suppressive fire interfered with keeping the target accurately illuminated or the G/VLLD's batteries failed, Copperhead would yield no gain over

[75] Department of the Army, FM 6-20-40 *Tactics, Techniques, and Procedures for Fire Support for Brigade Operations (Heavy)*, January 5, 1990, Appendix H, p. H-22.

[76] Department of the Army and US Marine Corps, FM 6-40/MCWP 3-1.6.19 *Tactics, Techniques, and Procedures for Field Artillery Manual Cannon Gunnery*, April 23, 1996 (Change 1, October 1, 1999), p. 13-2.

a "dumb" round. Also, because the prevailing paradigm within the Army and Marine Corps field-artillery communities emphasized mass over precision, Copperhead simply added to the huge ammunition burdens of artillery battalions during combat operations. Thus, rightly or wrongly, the artillery communities in both services tended to be suspicious of the M712.

Operation Desert Storm provided the first major opportunity to exploit Copperhead in multi-divisional operations against armored forces. US Army M109 self-propelled howitzer battalions took the M712 round to the desert for the 100-hour ground campaign. However, only about 90 Copperhead rounds were expended, which were probably not enough to validate definitively the munition's effectiveness.[77] Still, in the Army's case it appears that doubts about the reliability of Copperhead persisted in artillery units during Desert Storm—and not without reason. One M109 self-propelled howitzer battalion commander who fought with VII Corps during Desert Storm recalls taking the opportunity, after the ground campaign had ended, to fire some Copperhead rounds against a captured Iraqi tank loaded with fuel and ammunition. The battalion fired four Copperhead rounds using a G/VLLD mounted on an M113 armored personnel carrier. "All rounds came in short and skipped down range past the target," suggesting that the seekers never acquired the laser spot.[78] Later the same battalion did score two hits with Copperhead against truck targets, but in this second trial illumination was provided by an OH-58D helicopter. This battalion commander, whose unit did not use Copperhead during the actual ground campaign—only afterwards—concluded that, overall, the munition's employment involved too many opportunities for failure to be very attractive or useful—especially in the sort of fast moving operations VII Corps conducted in 1991.

Given the success of LGBs in Southeast Asia, Copperhead made sense when the program was initiated. But, like the AIM-4 Falcon, the

77 Anthony H. Cordesman and Abraham R. Wagner, *The Lessons of Modern War, Volume IV: The Gulf War* (Boulder, CO: Westview Press, 1999), pp. 793-794. The citation is to chapter 9 of this out-of-print book, and this chapter can also be found on the Center for Strategic and International Studies' website as a pdf file, dated October 15, 1994.

78 Thomas Davis, email to Barry Watts, "Copperhead Questions/History." March 7, 2004.

munition proved to be more complicated to employ and less reliable than hoped. Certainly Copperhead was not as successful in 1991 as laser-guided bombs had been during 1968-1973.

Moreover, there are later events that suggest portions of the US Army not only remain somewhat ambivalent about guided munitions but show a continuing attachment to the industrial-age, mass-dominated artillery paradigm that goes at least back to the Western Front during 1914-1918. During the summer of 1998, for example, a brigade of the Army's 101st Airborne Division conducted an Advanced Warfighter Experiment (AWE) at Fort Benning, Georgia, with the EFOGM (enhanced fiber optic guided missile). EFOGM is an anti-armor missile with a range of 15 kilometers. Once fired, the EFOGM missile is linked to the operator by an unreeling fiber-optic cable. Over this link, the operator provides steering commands to the missile based on what he could see through the missile's imaging-IR sensor as it approaches the target area, thereby enabling the operator to find targets on the other side of hills, buildings, foliage, or other obstacles. Although limited development and delivery of actual hardware constrained the AWE's ability "to fully assess EFOGM's capability," the 1998 experiment indicated "that simulated EFOGM modules were the second highest tank killer on the battlefield behind the Apache helicopter."[79] Given the high vulnerability of attack helicopters to ground fire evident during OIF, the much lower vulnerability of vehicle-mounted EFOGM fire units suggests that the Army might have been wise to continue further evaluation of this guided antitank system.[80] Nevertheless, the Army chose to let the program die.

EFOGM was followed by DARPA's NetFires. NetFires envisioned using box-like, easily deployed launch units, each containing a mix of 15 loitering and precision attack missiles, for on-call use against enemy armor and other targets. The Loitering Attack Munition (LAM) constituted the more capable of the two missiles because of its ability to loiter over the battlefield and search for targets on its own. In

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79 Director of Operational Test and Evaluation, "Enhanced Fiber Optic Guided Missile (EFOGM)," *FY 1999 Annual Report*, online at <http://www.globalsecurity.org/military/library/budget/fy1999/dot-e/army/99efogm.html>, accessed September 21, 2006.

80 EFOGM fire units, containing eight missiles, were mounted on the Army's High Mobility Multi-purpose Wheeled Vehicle (HMMWV).

2002, retired Army general Paul Gorman, who had overseen the Army's development of the National Training Center, argued that a NetFires-like system could, and should, replace both infantry mortar platoons and cannon artillery battalions in future Army divisions on the grounds than this capability would be more precise and lethal per dollar, per pound, and per square meter than other indirect fire-support systems.[81] Gorman's argument was that Army units haul large quantities of dumb rounds to combat. By replacing them with accurate, guided munitions, the manpower, weight, consumption, logistic, and cost burdens of existing artillery systems could all be greatly reduced.

As of this writing, NetFires has morphed into the Army's Non-Line-of-Sight Launch System (NLOS-LS), which is one element of its Future Combat Systems program. While NLOS-LS is still being pursued, recent indications are that the Army is going to drop LAM. This decision seems unfortunate. LAM not only offers the greatest potential for dealing with fleeting battlefield targets but was designed to provide targeting information for the simpler Precision Attack Munition still being developed for NLOS-LS. Given the similarities of this apparent outcome to EFOGM's fate in late 1990s, it is difficult to avoid the conclusion that portions of the US Army continue to be wary of guided munitions, especially of relatively autonomous or robotic ones like LAM.

Admittedly, the present state of play within the Army's infantry and field artillery communities regarding guided munitions is complex. The infantrymen have long been comfortable with TOW but their community rejected EFOGM. Together with the artillerymen, they now appear poised to abandon LAM too.

Field artillery appears to be even more of a mixed bag. As the Copperhead experience reveals, cannons face greater technical challenges in trying to incorporate precision-guidance into artillery shells than do gravity bombs or missiles. The electronics in a guided 155-mm artillery round, when fired to maximum ranges (40-50 kilometers), must survive accelerations in the vicinity of 20,000 times the force of gravity (20,000 Gs). Further, the shells have to be reliable

81 Paul F. Gorman, three unpublished, undated PowerPoint slides, acquired by the author in March 2002.

even after the round has endured long periods of storage and been manhandled about the battlefield. LGBs, on the other hand, are generally assembled prior to the mission at large bases and would rarely be subjected even to ten Gs prior to release. So getting guided bombs (or missiles) to work reliably the vast majority of the time is far less of a design and manufacturing challenge than those faced by Copperhead or, more recently, the Army's GPS-guided, 155-mm XM982 Excalibur round. Also, Excalibur's unit cost (discussed in the next section) seems likely to limit available inventories for some time to come.

The other complication is that US Army field artillery is not limited to cannons. Since the 1980s, this branch has included both howitzers (self-propelled and towed) and rocket launchers like the M270 Multiple Launch Rocket System (MLRS), which can fire up to twelve rounds in less than 60 seconds.[82] Until quite recently neither the standard MLRS rocket nor the Army Tactical Missile System (ATACMS) had terminal guidance. While the Block-I ATACMS had a fairly accurate ring-laser-gyro guidance system, it could not actively home on the target and, therefore, was not a guided munition as the term has been used throughout this report. However, the Block-IIA ATACMS added GPS guidance, and constituted about 15 percent of the nearly 460 ATACMS expended during OIF in 2003. Since then, GPS guidance has also been added to the extended-range MRLS "rocket," which has demonstrated accuracy in Iraq approaching that of LGBs. Thus, the "rocket/missile" part of the Army's artillery community has begun to embrace guided rounds. Of course, adding guidance to rockets is far easier than it is with 155-mm artillery shells, and the Army's MLRS community was an extremely late adopter of guided munitions—especially compared to the Navy's submariners.

The Joint Direct Attack Munition

Like the laser-guided bomb, the Joint Direct Attack Munition is an unpowered or glide weapon that turns "dumb" bombs into "smart" ones by adding a guidance kit. The JDAM tail-kit utilizes an inertial reference unit aided by precise location and time signals from at least four of the satellites in the GPS constellation. These GPS signals en-

[82] The Army declared IOC with MLRS in 1983 and fielded the first pure-MLRS battalion in Europe in 1986. Starting in 2005, the tracked, 12-round M270 platform has been supplemented by the wheeled, six-round High Mobility Army Rocket System, which is lighter and can be transported by a C-130.

able the munition to calculate its position in three dimensions within a few meters and home on the aim-point's GPS coordinates. The aim-point for each JDAM is supplied by the aircrew on the delivery platform through an electronic interface prior to release.

How was JDAM developed and what were the underlying motivations for the munition? Officially, the acquisition program to develop JDAM got underway in 1991. As might be expected, however, it had antecedents that reached back at least a decade when two aerospace companies, Northrop and Boeing, began thinking about the possibility of guidance tail-kits for Mark-80 general-purpose bombs using state-of-the-art, strap-down inertial measuring units. Northrop, for instance, began investing research funds in developing inertially aided munitions (IAMs) around 1981, and the initial customer Northrop went after was the US Navy.[83] The main components of Northrop's IAM kit, originally designed to be attached to the rear of a Mark-82, 500-lb bomb, consisted of "a standard AMRAAM inertial reference unit, a set of electronic cards containing a digital processor and autopilot, a pneumatic actuation system . . . [controlling] four movable fins, and a thermal battery."[84] A similar line of research took place at Boeing in the early 1980s.

Inside the military services, the IAM concept seems to have first taken root in the Air Force's armament community at Eglin AFB. In 1985 Louis R. Cerrato received a paper on the IAM concept by Eglin's chief scientist. Cerrato was intrigued, quickly seeing the utility of ex-

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83 Northrop, Precision Products Division, "Inertially Aided Munitions: IAM," December 1989, unnumbered briefing slides (with facing text), text accompanying slide "(U) The Problem." Northrop's efforts to develop IAMs illustrate the extent to which the gyro culture that developed inertial navigation systems for American intercontinental missiles failed to produce technologies that migrated to conventional guided weapons. The Advanced Inertial Reference System (AIRS) for the MX ICBM not only proved difficult and costly to manufacture but, with regard to munitions such as JDAM or even CALCM, was a technological dead end (MacKenzie, *Inventing Accuracy*, pp. 226, 230-231). In this regard, Northrop's program manager for GATS/GAM has observed that while the engineers who worked on GAM were in the division that built AIRS, the integrated ring-laser-gyro/INS units used in the tail kits were purchased from Honeywell (Margaret Calomino, "RE: IAM, GAM, JDAM History," e-mail to Barry Watts, March 26, 2004).

84 Northrop, "Inertially Aided Munitions: IAM," text accompanying slide "(U) Inertially Aided Munitions."

ploiting improvements in inertial-guidance technology to land bombs within 30 meters of the aim-point regardless of weather. Convinced of the need for such a capability, he became the visionary inside the Air Force who began pushing for a program to develop inertial-guidance kits for "dumb" bombs.[85]

In 1987, Northrop and Boeing were awarded $4.9 million proof-of-concept contracts by the Air Force to demonstrate IAMs as a joint USAF/Navy technology project; in 1988, captive-carry tests of the weapons were conducted at both the Naval Weapons Center at China Lake in California and Eglin; and, in early 1989, the Air Force completed the first successful drop test of an inert IAM from an altitude of 20,000 feet and approximately five miles from the target.[86] While these early tests provided proof of concept, neither the institutional Air Force nor Navy had sufficient interest to move the technology demonstrations into actual weapons programs. Instead, both services continued to pursue separate developmental efforts for IAMs. However, the success of LGBs in Desert Storm also served to remind both services—especially the USAF—of the clear-air limitation of laser guidance, and during FY 1991 the separate Air Force and Navy IAM programs were merged into the joint program that eventually produced the Joint Direct Attack Munition.[87]

Not only did JDAM offer a solution to the clear-air limitation of LGBs and prove reliable in combat from the outset, but its unit-production price has been so low that the development program under Terry Little has come to be regarded as an exemplar for innovative reform of the Defense Department's long-criticized acquisition process. Reportedly, USAF General Joseph Ralston made Little the JDAM

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85 Vernon Loeb, "Bursts of Brilliance," *Washington Post Magazine*, December 15, 2002, p. 24. The first part of Loeb's article also covers the development of LGBs by the Air Force.

86 "Navy, USAF Test Boeing, Northrop Smart Bomb Kits," *Aviation Week & Space Technology*, p, 50.

87 Acquisition Department, Industrial College of the Armed Forces (ICAF), "A Case Study: Implementing Acquisition Reform: The Joint Direct Attack Munition Experience," November 1999, p. 3. This study was adapted by Thomas C. Hone, then at ICAF, from Lisa Brem and Cynthia Ingols, "Joint Direct Attack Munition (JDAM): Acquisition Reform in Action," July 1998, which was written under contract to the Defense Systems Management College and the Boeing Company.

program manager in 1993 because Ralston believed that Little "would take risks and not follow all the rules."[88] Notable innovations that occurred during Little's leadership of the JDAM program included: establishing a firm upper bound on unit price at the outset and enforcing it, using government/supplier integrated product teams, performance-based competition between competing contractors, letting the contractors manage their own costs, and encouraging the use of commercial parts and processes.

Figure 28: JDAMs

The cost discipline that resulted from these innovations was impressive. The original or "baseline" JDAM program envisioned developing and procuring 89,065 kits for $2.607 billion (current-year dollars as of June 2006), which yields a program-acquisition unit-cost (development as well as production) of $29,267 per kit; today, the JDAM program has been expanded to 199,994 kits for a program-acquisition total of $5.137 billion (again in current-year dollars as of

[88] ICAF, "A Case Study: Implementing Acquisition Reform: The Joint Direct Attack Munition Experience," p. 4.

mid-2006), which yields a program-unit acquisition cost of $25,686 per kit. [89] Through FY 2005, 105,286 JDAM kits had been procured for an average unit-procurement cost of $21,379 each.[90] (Again, this price is for the kit rather than a full-up JDAM round, which includes a JDAM kit, warhead, and a fuze.) Depending on whether a Mark-84 or BLU-109/B warhead is chosen, the full-up 2,000-lb round costs another $8,600 or $17,900, respectively.

Still, the 125 percent growth in the planned JDAM buy would not have occurred if the munition had failed to prove highly successful in combat operations and if procurement costs had not been kept under control. Judged on the basis the total quantities of various guided munitions expended in recent campaigns, JDAM became the guided weapon of choice for both the USAF and Navy during the opening months of OEF in Afghanistan.[91] Granted, cost control was surely aided by that fact that JDAM's underlying INS/GPS-aided guidance technology had been developed earlier for the CALCM, which was fielded prior to Desert Storm in 1991 and employed successfully in that conflict. Nevertheless, in terms of the cost and performance of the munition, the JDAM development was a model acquisition program.

The true measure of JDAM's efficacy, however, lies in its success in generating higher-level effects in actual combat operations. The Joint Direct Attack Munition officially entered operational service in December 1998. However, 20 months earlier, in April 1997, the Air Force declared IOC with a small number of GPS-Aided Munitions (GAMs) on the Block-20 B-2s at Whiteman AFB, Missouri.[92] While around five times as expensive as JDAM because of the limited pro-

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89 DoD, OUSD (AT&L) ARA/AM, "Selected Acquisition Report (SAR) Summary Tables: As of Date: June 30, 2006," August 11, 2006, p. 5. Earlier SARs put the original JDAM buy at the slightly lower total of 88,126 kits.

90 Department of the Air Force, *Procurement Program Fiscal Year (FY) 2007 Budget Estimates: Procurement of Ammunition*, February 2006, p. 96. The average unit price for JDAM kits since FY 2005 has increased due to improvements such as an anti-spoofing module.

91 During the first 176 days of Operation Enduring Freedom, 57.4 percent of the 12,001 guided weapons expended by US forces were JDAMs; LGBs only accounted for 40.7 percent of the total guided munitions. All the weapons in Figure 19's INS/GPS-Aided category for OEF are JDAMs.

92 Grant, *The B-2 Goes To War*, p. 16.

duction run (128 munitions), the GAMs were essentially GBU-31 JDAMs using the Mark-84 warhead.[93] This JDAM antecedent resulted from Northrop's efforts to produce more B-2s than the 20 airframes to which President George H. W. Bush reduced the program in his January 1992 state-of-the-union address to Congress in conjunction with the timing of JDAM's IOC.[94] By then both Air Force officials and the defense contractors had realized that by adding GPS data to off-the-shelf INS guidance systems, the 30-meter IAM CEP could be reduced to about 13 meters.[95] Recognizing that adding this conventional capability to the B-2 would increase its utility in the post-Cold War era, by late 1992 key Northrop managers committed the company to fielding what became the GAM on the B-2 no later than July 1996.[96] Their decision was triggered by the judgment that JDAM would not be available until 1999, if not later. A key component of the implementation on the B-2 was a GATS "relative targeting" system that sought to reduce target-location error, thereby enabling the B-2's CEP to be even lower than the 13-meter goal established for JDAM. To secure Air Force acquiescence for GATS/GAM on the B-2, in early 1993 Northrop agreed to drop out of competition for the JDAM program.

With the help of B-2 supporters in Congress, agreement was reached between the executive and legislative branches to field a small number of GAMs on the B-2 before JDAM became available, thereby affording the 509th B-2 pilots "a chance to develop operational concepts and gain essential experience, without having to wait another three years for JDAMs."[97] They taught themselves how to use the

93 Delivery of 128 GAMs to the 509th Bomb Wing began in June 1996 (Margaret Calomino, "RE: IAM, GAM, JDAM History," email to Barry Watts, March 25, 2004). Calomino was the Northrop program manager for GATS/GAM. Subsequently, a contract extension to the GAM program was negotiated for the conversion of a small number of these kits to the 4,500-lb BLU-113 bomb body developed at the end of Desert Storm.

94 George Herbert Walker Bush, "Address Before a Joint Session of the Congress on the State of the Union," January 28, 1992. Defense secretary Richard Cheney had cut the original B-2 buy of 132 bombers to 75 in 1990. Later, after Bush had terminated B-2 production at 20 aircraft, Congress added funding to convert a test airframe into a 21st operational B-2.

95 "USAF To Demo JDAM's Inertial Guidance in 'Critical Experiment' by March 1993," *Inside the Air Force*, February 14, 1992, p. 1.

96 Northrop, B-2 Division, untitled slides, December 1992, slide 1.

97 Grant, *The B-2 Goes To War*, p. 13.

B-2's synthetic-aperture radar (SAR) to refine GPS coordinates using successive SAR images of the target area, eliminated or found solutions to unanticipated anomalies in the aircraft's systems, and, finally, had an opportunity to test the B-2 with live GAM drops at the Nellis AFB ranges in Nevada.[98] On October 8, 1996, three B-2s dropped a total of 16 live, 2,000-lb GAMs on 16 aim-points, destroying 13, severely damaging two, and significantly damaging the last.[99] The demonstration showed that the B-2 with INS/GPS-aided munitions "could be very accurate, from high altitude, in all weather," that B-2 pilots could do the target-data manipulation to "retarget en route," and that the B-2 could be a player in a theater war.[100] On the basis of this test, Air Combat Command and the 509th Bomb Wing began a campaign to inform overseas theater commands about the B-2's conventional capabilities, thereby setting the stage for the stealth bomber's 1999 combat debut as part of NATO's air campaign against Slobodan Milosevic's Serbian regime.[101]

As Figure 19 indicates, combat expenditures of JDAMs in quantities approaching those of LGB expenditures did not occur until OEF in 2001-2002. By the time Enduring Freedom against al-Qaeda and the Taliban in Afghanistan began on October 7, 2001, JDAM had been implemented on a variety of aircraft, including the B-1B, F-16, and F/A-18. So popular did this all-weather, seekerless munition prove that, toward the end of October, JDAM expenditure rates had climbed to around 80 per day, generating concern in the Pentagon that the inventory of JDAM kits might be exhausted by spring. In hindsight, this concern was probably exaggerated. At the beginning of October 2001, the JDAM inventory was around 11,500 kits and Boeing's production

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98 Because there were so few GAMs, the initial thought was to limit the Nellis demonstration to dropping only two weapons. General Richard Hawley, then head of the Air Combat Command, made the decision to drop sixteen (Grant, *The B-2 Goes To War*, p. 14).

99 "Air Force Announces B-2 Interim Precision Munition Tests a Success," *Inside the Air Force*, October 13, 1996, p. 5; see also Grant, *The B-2 Goes To War*, pp. 14-15.

100 Grant, *The B-2 Goes To War*, p. 15.

101 Grant, *The B-2 Goes To War*, pp. 16-17, 26-27. A crucial point for General Wesley Clark's willingness, as the NATO commander, to use the B-2 in OAF was the assurance from 509th briefers that the wing's pilots were prepared to fly 30-plus hour missions.

rate was building toward 1,000 kits per month.[102] During the initial two months of intense air operations in Afghanistan, the JDAM inventory shrank by some 1,400-1,500 kits a month. Fortunately, these high early expenditure rates were not sustained and, by December, as the intensity of air operations ebbed, the concern over JDAM inventory levels also abated. Nonetheless, in late 2001 the perceived inventory crisis led the Pentagon to fund a second JDAM production line in order to achieve a total production rate of 2,800 kits/month by August 2003.[103] The very fact that a programmatic decision was made to increase the JDAM production rate from 1,500 to 2,800 kits/month speaks volumes about the perceptions of everyone from senior defense officials to campaign planners to aircrews about JDAM's efficacy. Indeed, in reflecting on the cumulative effects of both laser-guided bombs and JDAMs on American strike operations since the late 1960s, one commentator went so far as to suggest that one had to look all the way back to America's brief monopoly in atomic weapons after the Second World War to find a time when the gap in military power between the United States and its adversaries was as great as it appeared to be, in a strict force-on-force contest, by the end of 2002.[104]

If the most significant limitation of the LGB remains the munition's requirement for clear air between the delivery platform and the target from release to impact, then JDAM's most significant feature is

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102 Greg Davenport, "Joint Direct Attack Munitions Slated for Full-rate Production," Air Armament Center Public Affairs, Eglin AFB, March 29, 2001; the Jewish Institute for National Security Affairs, "U.S. Looks To Increase Smart-Bomb Production," August 4, 2002, at <http://www.jinsa.org/articles/articles.html/function/view/categoryid/164/documentid/1640/history/3,2360,656,164,1640>, accessed September 22, 2006.

103 "Boeing Awarded $378 Million Contract for Accelerated JDAM Production," Boeing news release 02-82, September 13, 2002, at <http://www.boeing.com/news/releases/2002/q3/nr_020913m.html>, accessed September 22, 2006.

104 Loeb, "Bursts of Brilliance," p. 8. The caveat about a strict force-on-force context is intended to acknowledge that tactical or operational success in the sense of winning battles and campaigns need not, and often does not, entail the attainment of the political ends for which the war was waged. The American defeat in Vietnam is a well-known case in point, and the jury is still out on whether the United States will ultimately achieve OIF's overarching strategic aim of creating a more democratic, economically successful Iraq in the Middle East.

its ability to be employed regardless of weather or other atmospheric obscurations. While JDAM is considered a "near-precision" munition by the Air Force because its official CEP of 13 meters (42.7 feet) exceeds 9.9 feet but is less than 66 feet, its accuracy improved enough between its initial combat use in 1999 and later combat experience in 2003 to approach within a meter or so of the 8-10 feet (2.4-3.0 meters) CEP typical of LGBs in 1991.[105] The capability of each JDAM to home on a separate set of GPS coordinates has also allowed individual aircraft, such as the B-2, to strike multiple aim-points within a given target area on a single pass.

Figure 29: B-2/JDAM Results, 1999

These advantages of the Joint Direct Attack Munition go far to explain its increasing share of US guided-munition expenditures since 1991. During Desert Storm, the 35 CALCMs launched by B-52s against targets in Iraq on the opening night of the campaign were the only INS/GPS-aided munitions employed. They constituted a mere 0.2 percent of the more than 17,160 guided munitions expended by US bombers, fighter-bombers, attack aircraft, and naval combatants. During Phase 3 of Operation Iraqi Freedom, more than 6,540 JDAMs were expended, constituting 35.6 percent of all air-to-ground guided expenditures as well as some 84 percent of all INS/GPS-aided muni-

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105 John A. Tirpak, "Precision: The Next Generation," *Air Force Magazine*, November 2003, p. 46.

tions employed during March-April 2003. The evident early and growing popularity of JDAM derived from its combination of accuracy, all-weather capability, and low cost suggests that the munition has proven highly successful—even compared to the spectacular performance of "Paveway I" laser-guided bombs during 1972-1973.

This conclusion is easily borne out by examining some of the combat results achieved with JDAM in recent conflicts. Figure 29 shows post-strike imagery of two targets in Serbia, each attacked by a single B-2 bomber during Operation Allied Force. In the case of the Kirvovo Support Base (shown on the left side of Figure 29), the aircrew selected eight separate aim-points, two for each of the four structures associated with the support facility and achieved eight direct hits on a single pass. The before-and-after images of the Novi Sad railway and highway bridge across the Danube River reflect a more complex story. Before the bridge was dropped by eight JDAMs from a B-2, it was attacked twice by fighter-bombers. First an F-15E struck one end of the bridge with 2,000-lb GBU-15 guided bombs; then an F-117 struck the abutment in the bridge's center with LGBs. While these first two attacks undoubtedly inflicted some structural damage, the Serbs were still able to exploit the bridge as a symbol of defiance by crowding people onto it for such things as rock concerts.[106] Finally a B-2, which launched and recovered at Whiteman AFB in Missouri, attacked the bridge. Six 2,000-lb JDAMs were targeted on the center abutment and two others against one end of the bridge.[107] The combination of accuracy and mass—mass precision, if you will—put both spans of the Novi Sad Bridge into the Danube. Here, as with Iraqi hardened aircraft shelters in 1991, the immediate problem was not the Novi Sad Bridge's maneuverability but its "elusiveness" in a more general sense.

Overall, more than 80 percent of the 652 JDAMs and four GAMs expended by B-2As during Operation Allied Force were assessed by

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[106] Colonel Tony Imondi, author's notes from Imondi's 509th Bomb Wing briefing on B-2 operations during OAF, Whiteman AFB, MO, August 31, 1999, p. 7. At the time, Imondi was the 509th's operations group commander. He flew one of the 46 effective B-2 sorties recorded during OAF.

[107] Rebecca Grant, *The B-2 Goes to War* (Arlington, VA: IRIS Publications, 2001), p. 85.

the Air Force to have hit their targets or aim-points.[108] This hit-rate is somewhat better than the 80 percent achieved by F-117s with LGBs during Operation Desert Storm.[109] As for accuracy, recall that JDAM's original goal during development had been a CEP of 13 meters (42.7 feet). During JDAM's initial 22 test drops at Eglin AFB in 1996, the munition achieved a CEP of 10.3 meters (33.8 feet).[110] In late 2001 and early 2002 in Afghanistan—where JDAM was first heavily used by a range of Air Force and Navy strike aircraft—the CEP was in the vicinity of 6-7 meters (19.7-23 feet), substantially lower than the 10.3 meters achieved in the initial test drops.[111] In the case of the B-2, the bomber's GPS-Aided Targeting System enabled the crew to eliminate most of the target location error, which is the largest source of error in the JDAM's error budget.[112] As a result, the advertised JDAM CEP on the B-2 is 6 meters but, during combat operations, the accuracy actually achieved has been closer to 4 meters (13.1 feet). And, during OIF in 2003, the "average miss distance on the JDAM" was "about the length of the bomb," which in the case of the GBU-31 with a BLU-109/B warhead is 3.76 meters (12.3 feet).[113] Although it is still technically accurate to insist, based on USAF definitions, that JDAM is a near-precision weapon, its demonstrated combat CEP is within a few

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108 Imondi, author's notes from, 509th Bomb Wing briefing, p. 6. During OAF, the B-2 was the only US aircraft able to employ JDAM.

109 Cohen and Keaney, *Revolution in Warfare? Air Power in the Persian Gulf War*, pp. 291-292.

110 McDonnell Douglas, "JDAM Gets Go-ahead for Low-Rate Initial Production," press release 97-102, May 6, 1997. The JDAM test program eventually conducted over 120 drops (Kimberly E. Devereux, "B-1B Drops Its First Guided Joint Direct Attack Munition," Air Force News Service, March 10, 1998).

111 Interview with Pat "Doc" Pentland, October 24, 2002. At the time, Pentland was with SAIC, which was the principal supporting contractor to the Air Force for Task Force Enduring Look (TFEL). TFEL was established by General John Jumper in October 2001 to accomplish "Air Force-wide data collection, exploitation, documentation, and reporting" for the Air Force's efforts in the worldwide war on terrorism (TFEL, "Quick Look Report #1," March 2002, p. 1).

112 "Precision Bomb Programs May Merge," *Aviation Week & Space Technology*, September 27, 1993, p. 45.

113 Tirpak, "Precision: The Next Generation," p. 46 (citing then Lieutenant General T. Michael Moseley, the Joint Force Air Component Commander during OIF); USAF Air Armament Center, *Weapons File 2004-2005*, p. 5-14.

feet of qualifying as a precision munition. Finally, due to the improving quality of cheap, solid-state inertial guidance units, the munition's accuracy has not been greatly affected when GPS information was degraded or lost after release.[114] Instead, JDAM has "degraded gracefully" in such situations.

As impressive as JDAM's accuracy in combat has been since its initial use in 1999, even more impressive from an employment perspective has been the munition's through-weather capability when utilized in conjunction with wide-area sensors such as the E-8C Joint Surveillance Target Attack Radar (Joint STARS). During OIF Phase 3, the USAF had enough E-8Cs to be able to maintain 24-hour coverage of the battlefield. When a *shamal* with heavy winds, blowing sands, and rain squalls hit Iraq from the west on March 25, 2003, it appears that many Iraqi army commanders and their troops assumed that the severe weather would protect them from Coalition air attack.[115] When the Iraqis began either repositioning tanks and other heavy equipment under the presumed cover of the three-day *shamal*, or moving to engage Coalition forces, Joint STARS' ground-moving-target-indicator (GMTI) capability and other sensors enabled these movements to be tracked, individual vehicles pinpointed, and then attacked with JDAMs from orbiting strike aircraft such as F-15Es and B-1Bs.[116] The damage inflicted on Iraqi forces during the *shamal* by strike aircraft only became apparent when Army and Marine Corps units resumed their advance toward Baghdad on March 28th and began encountering the "burning hulks of Republican Guard vehicles" littering their path through the Karbala Gap and along the Tigris River.[117] If anything, the

114 Again, to derive precise location information from the GPS constellation, each JDAM needs to acquire at least four of the 24 satellites after release (Pace, et al., *The Global Positioning System: Assessing National Policies*, p. 220).

115 Williamson Murray and Major General Robert H. Scales, Jr., *The Iraq War* (Cambridge and London: Belknap Press of Harvard University Press, 2003), p. 165.

116 Because of their long on-station times and ability to carry 24 2,000-lb JDAMs, the B-1Bs were especially useful in what Air Force planners described as a "roving linebacker" role (Adam J. Hebert, "The Long Reach of the Heavy Bombers," *AIR FORCE Magazine*, November 2003, p. 24). Joint STARS can also use its radar for "spot" SAR imagery of vehicles that have stopped moving and, hence, are no longer "seen" by MTI.

117 Murray and Scales, *The Iraq War*, p. 172.

psychological effects of the US capability to strike Iraqi forces precisely, even through severe weather, day or night, were even more debilitating. Prior to OIF, CENTCOM assessed the Republican Guard's Al-Nida Division to be the best-equipped unit in the Iraqi army. However, the fear engendered in this elite unit by precision air power caused it to melt away from 13,000 soldiers and more than 500 armored vehicles to 1,000 soldiers and some 50 vehicles by the time it had moved to positions in Baghdad *even though it had not been engaged by American ground forces*.[118]

The operational utility of JDAM in conjunction with sensors such as Joint STARS during Phase 3 of Operation Iraqi Freedom is bolstered by two further observations. First, US Army officers were impressed with the joint fire support provided by fixed-wing aircraft carrying JDAM. As the 3rd Infantry Division stated in its OIF after-action report:

> Precision-guided munitions proved to be a lethal combat multiplier. Joint direct attack munitions (JDAM) repeatedly proved . . . [their] value as an all weather weapon. JDAM was the weapon of choice for troops in contact and to destroy structures in an urban environment.[119]

Traditionally, the US Army has designed its combat units with sufficient organic fire support to be able to prevail against opposing ground forces if air support is not available. Given the historical limitations of air power at night or during adverse weather, this approach was eminently sensible. By the mid-1970s, however, the availability of LGBs and targeting systems such as Pave Tack began to make indirect fire support from aircraft as feasible and effective at night as it had been during the daytime. By 2003, the combination of the GPS-aided JDAM with GMTI and SAR sensors linked by targeting networks enabled fixed-wing air power to provide on-demand indirect fire support to US ground forces. As will be discussed in Chapter V, these advances

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118 Kevin M. Woods with Michael R. Pease, Mark E. Sout, Williamson Murray, and James G. Lacey, *The Iraqi Perspective Project: A View of Operation Iraqi Freedom from Saddam's Senior Leadership* (Suffolk, VA: Joint Center for Operational Analysis, JFCOM, 2006), pp. 125-126.

119 *Third Infantry Division (Mechanized) After Action Report: Operation IRAQI FREEDOM* (US Army, 3rd ID, 2003), p. 30.

suggest the possibility of an evolving relationship between land and air power that is shifting toward the latter.

Second, the integration of delivery platforms with all-weather guided munitions and wide-area GMTI sensors—and the command-and-control to tie these elements together in near-real time—satisfy the original Soviet notion of a reconnaissance-strike complex discussed in Chapter II. Persuasive evidence of this conclusion can be seen in an incident that occurred on the afternoon of April 7, 2003. Coalition intelligence received information—presumably from a human source—that Saddam Hussein, his two sons, and up to fifty members of the top Ba'ath leadership were meeting in a bunker located in Baghdad's al-Mansour district. It took 35 minutes to confirm the initial intelligence tip with other sources, reach a decision to act upon the intelligence, forward the target information from the theater to the National Imagery and Mapping Agency (now the National Geospatial-Intelligence Agency) for the development of precise ("mensurated") GPS coordinates, select the best available asset to conduct the strike (an inbound B-1B), "weaponeer" the target in the Combined Air Operations Center in Saudi Arabia, pass the "precision" information to the controlling E-3 AWACS, and, finally, have the E-3 relay the information to the inbound B-1B, which had just finished refueling from a tanker over western Iraq.[120] Twelve minutes later, four 2,000-pound JDAMs hit the target, leaving nothing of the buildings attacked but a deep smoldering crater.[121] The total elapsed time from the initial intelligence tip to weapon impact was 47 minutes. The only aspect of this sensor-to-shooter system that does not correspond exactly to the original Soviet concept of an RUK is that the command-and-control evident in this example was not automated. Instead, the US approach

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120 Adam J. Hebert, "The Baghdad Strikes," *Air Force Magazine*, July 2003, pp. 49-50. For an introduction to "weaponeering," see LCDR Robert F. Blythe (USN), ed. Captain David G. Glasgow, Jr. (USAF), "Weaponeering Familiarization: Student Guide," Joint Targeting School, Dam Neck, VA, September 9, 1998.

121 "B-1 Pilot Telephone Interviews," DoD news transcript, April 8, 2003, on the web at <http://www.defenselink.mil/transcripts/2003/tr20030408-t408phin.html>, accessed September 21, 2006. According to the B-1 pilot and weapon-systems operator, the controlling AWACS passed the GPS coordinates for two desired mean points of impact along with munition selections for each (one GBU-31v3 followed by one GBU-31v1 with a 25-millisecond fuse delay per aim-point).

has been to retain human decision-makers "in the loop" at critical junctures.

Given JDAM's overall success in recent campaigns, it is not surprising that additional applications have been found for the underlying INS/GPS-aided guidance technology. Starting with the F-117's GBU-27, both the Air Force and the Navy have added INS/GPS-aided guidance to selected LGBs, producing dual-mode munitions. When the air is clear enough for laser guidance, these munitions can be employed like ordinary LGBs; but if weather or atmospheric obscurations prevent laser guidance, they can be employed like ordinary JDAMs (albeit with a slight loss of accuracy).[122]

Another application has been GPS-guided artillery rounds. Similar to Copperhead's earlier attempt to apply laser guidance to artillery shells, the US Army's Excalibur program has sought to develop a 155-mm shell with INS/GPS guidance. Current cost data on the program indicate, however, that this development has been substantially more difficult than JDAM's. As presently envisioned, over 30,000 XM982 Excalibur rounds are to be produced. The unit-acquisition price for the planned buy is over $75,600 per round and the unit-procurement price is $47,610 (both prices in current-year dollars).[123] One reason for Excalibur's greater per-round costs compared to JDAM's appears to have been development. Excalibur's research-and-development has consumed over 37 percent of the program cost, whereas the comparable figure for JDAM appears to be under 20 percent. At a unit-procurement cost of nearly $50,000 per XM982 shell, it is not difficult to see why Army spokesman are concerned about how many Excalibur rounds the Army will be able to afford.[124] Just as Copperhead proved more difficult to employ and less useful than LGBs, at least part of a similar pattern may be emerging with Excalibur. Undoubtedly Excali-

122 Raytheon, "Enhanced Paveway™ III Dual Mode GPS/Laser Guided Bombs," p. 1, available at <http://www.raytheon.com/products/paveway/>, accessed September 22, 2006.

123 DoD, OUSD (AT&L) ARA/AM, "Selected Acquisition Report (SAR) Summary Tables: As of Date: June 30, 2006," August 11, 2006, p. 4; Department of the Army, *Procurement Programs, Committee Staff Procurement Backup Book, Fiscal Year (FY) 2007 Budget Submission, Procurement of Ammunition, Army*, February 2006, p. 369.

124 Sandra I. Erwin, "Army To Curtail Procurement of Precision-Guided Weapons," *National Defense*, June 2006, pp. 16-17.

bur will be easier to employ than Copperhead. Nevertheless, for the foreseeable future a role is likely to persist for suppressive fires using traditional unguided shells. It is difficult, for example, to imagine laying down a suppressive barrage on a treeline in which enemy forces *might* be hiding using rounds as expensive as Excalibur.

Figure 30: Block-II GPS Satellites

Excalibur's cost-control difficulties notwithstanding, the success of, first, CALCM in 1991 and, subsequently, JDAM has generated a growing stable of INS/GPS-aided munitions along with other important military applications of GPS such as precise Blue-Force tracking. Not to be forgotten, though, is the dependence of all these capabilities on GPS. As suggested in Chapter I, GPS was "one of the most prominent military technologies" of the 1991 Persian Gulf War, and American dependence on GPS has expanded steadily ever since.[125] The Global Positioning Systems consist of three elements: (1) the space segment, which currently contains 29 Block II satellites in six orbital planes at an altitude of 10,900 nm (20,187 km)[126]; (2) a control seg-

[125] Pace, et al., *The Global Positioning System: Assessing National Policies*, p. 1.

[126] "GPS Operational Advisory 266: Subj: GPS Status 23 Sep 2006," online at <http://www.navcen.uscg.gov/ftp/GPS/status.txt>, accessed September 24, 2006. The launch of a GPS Block-IIR (replenishment) satellite on September 21, 2006, brought the constellation to 15 older-generation Block II and IIA

ment consisting of a master control station at Schriever AFB, Colorado, and five unmanned control stations (Hawaii, Colorado Springs, Ascension Island, Diego Garcia, and Kwajalein); and (3) a user segment containing both military and civilian GPS receivers that can calculate their locations from GPS signals.

Developing, fielding, and sustaining GPS has been a major, ongoing enterprise for the US Air Force, which has been largely funding and operating the system since the 1970s. Including the costs of launches and a detection system for nuclear detonations added in the late 1980s, RAND researchers estimated in 1995 that for FY 1974-1995 the space, control, and military user segments totaled over $8.3 billion (in then-year dollars).[127] Although the design life of the Block-II satellites has improved from 7.5 to ten years with the advent of the Block-IIR birds beginning in 1997, maintaining the constellation has required steady satellite replenishment over and above the annual costs of running the control segment, purchasing new user equipment, and developing the next-generation of Block-III satellites. To give an idea of the replenishment cost of a single Block-IIR GPS satellite, in 2003 the satellite was believed to cost around $42 million while the Delta-2 launch was estimated in the range of $45-55 million.[128]

On the one hand, such large infrastructure costs reveal that the JDAM's low unit-acquisition and unit-procurement prices are not the entire cost story. Recall the observation at the end of Chapter II that the Russians have only managed to have a full GLONASS constellation on orbit in one year (1995) since the first nine satellites were orbited in 1987, and the Russian space agency does not expect to have 24 functioning satellites in orbit until 2011.[129] The high annual recurring cost

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satellites, 13 Block-IIRs, and one IIR-Modernized (M) bird. Full operational capability requires 24 satellites ("Satellite Navigation: What Is GPS?," *Flight International*, posted online as of September 12, 2006 at <http://www.flightglobal.com/Articles/2006/09/12/Navigation/177/208905/What+is+GPS.htm>, accessed September 24, 2006.

[127] Pace, et al., *The Global Positioning System: Assessing National Policies*, p. 270.

[128] "Delta 2 Launches GPS 2R-9," *Space and Tech*, March 31, 2003, online at <http://www.spaceandtech.com/digest/flash2003/flash2003-012.shtml>, accessed September 24, 2006.

[129] Revnivykh, "GLONASS: Status and Perspective," Slide 9.

of maintaining GPS goes far to explain why, over the last decade, the Russians have rarely been able to keep the GLONASS constellation even half populated.[130] On the other hand, the US military has developed so many uses for GPS that apportioning JDAM's share would be analytically challenging to say the least. The broader point, though, is that GPS-aided munitions and other GPS applications such as Blue Force tracking require an infrastructure that very few nations can afford.

TLAM and CALCM

If JDAM's low cost per round has made it one of the cheapest conventional munitions ever fielded for the precision attack of surface targets, then TLAM and CALCM have probably been the most expensive. The Navy's RGM/UGM-109A/B/C/D/E Tomahawk and the Air Force's AGM-86C/D CALCM are long-range, subsonic, cruise missiles with low radar cross sections due mainly to their small size.[131] Both missiles were designed to fly at "extremely low altitudes," following the contour of the terrain.[132] In the early 1980s, and well into the 1990s, low radar cross sections and being able to fly nap-of-the-earth profiles gave these weapons—notably their nuclear variants (the submarine-launched UGM-109A and the B-52-launched AGM-86B)—a high prob-

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[130] As of September 24, 2006, GLONASS had 16 satellites on orbit, of which only ten were operational (available online at <http://www.glonass-ianc.rsa.ru/pls/htmldb/f?p=202:20:12247117569719560644::NO>.

[131] Tomahawk consists of the following variants: (1) UGM-109A, Land Attack Nuclear; (2) RGM/UGM-109B, Anti-ship; (3) RGM/UGM-109C, Land Attack Conventional; (4) RGM/UGM-109D, Land Attack Submunition Dispenser; (5) RGM/UGM-109E, Tactical Tomahawk; the nuclear land-attack (UGM-109A) and anti-ship (RGM/UGM-109B) variants are no longer in service, but the missiles themselves have been converted to conventional land-attack variants (RGM/UGM-109C/D)—Department of Navy, *Fiscal Year (FY) 2005 Budget Estimates: Justification of Estimates, Weapons Procurement, Navy*, Budget Item Justification Sheet P-40, P-1 Shopping List, Item No. 4, February 2004, p. 1. The RGM/UGM-109E is known as the Tactical Tomahawk and began production in FY 2003. A primary goal of the Tactical Tomahawk program is to reduce the unit procurement price to under $600,000. The AGM-86C has a blast/fragmentation warhead while the more recent AGM-86D has incorporated an advanced penetrating warhead and improved the CEP to three meters (see Figure 31).

[132] Kenneth P. Werrell, *The Evolution of the Cruise Missile* (Maxwell AFB, AL: Air University Press, September 1985), p. 139.

ability of being able to penetrate the territorial air defenses of the Soviet Union.

Initial combat employment of the AGM-86C—a late-1980s conventional modification of surplus AGM-86B Air Launched Cruise Missiles (ALCMs)—and the Block-II RGM/UGM-109C/D occurred on January 17, 1991, the opening day of Operation Desert Storm. By the end of the campaign on February 28, B-52Gs had fired a total of 35 CALCMs at Iraqi targets, and US naval combatants (including two nuclear submarines) had launched 298 TLAMs.[133] In 1999, a Royal Navy submarine (HMS *Splendid*) fired some twenty Block-III Tomahawk Land Attack Missiles against Serbian targets in conjunction with the expenditure of 198 by US naval combatants (six ships and three submarines) and 72 CALCMs from B-52s.[134] As these expenditure numbers indicate, starting in 1991 American forces have been willing to expend TLAM and CALCM cruise missiles in quantities of scores to hundreds during major campaigns. These weapons have also been the centerpiece of brief punitive strikes such as Operation Desert Strike in September 1996 and Operation Desert Fox in December 1998.[135] As of this writing, though, only American and British forces have employed TLAM/CALCM-class long-range cruise missiles in actual combat operations against land targets.

Both Tomahawk and CALCM date back to the early 1970s. Starting in 1973, when the Air Force and Navy were directed to "cooperate with each other in developing the key components of cruise missile

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133 Hill, Cook, and Pinker, GWAPS, Vol. V, *A Statistical Compendium and Chronology*, Pt. 1, *A Statistical Compendium*, p. 554. There were evidently some TLAM launch failures. Another GWAPS volume notes that only 282 of the 298 TLAMs expended attained cruise flight and proceeded toward their targets (Richard M. Blanchfield, John F. Guilmartin, et al., GWAPS, Vol. IV, *Weapons, Tactics, and Training and Space Operations*, Pt. 1, *Weapons, Tactics, and Training*, p. 249). In addition, the B-52Gs that employed CALCMs on the opening night of ODS had four missiles go down prior to launch, so only 35 of 39 were actually fired.

134 DoD, *Kosovo/Operation Allied Force After-Action Report* (Washington, DC: DoD, January 31, 2000), p. 92; US Air Force, HQ/XOOC (Checkmate), "ISO Joint Staff 'Quick Look' After-Action Review Panel," December 1999, slide 8.

135 Ronald O'Rourke, "Cruise Missile Inventories and NATO Attacks on Yugoslavia: Background Information," Congressional Research Service, April 20, 1999, p. CRS-3.

technology," the two missile programs began sharing developments in propulsion and guidance.[136] As a result, Tomahawk and the nuclear AGM-86B ALCM have the same 1977 base year as major acquisition programs. These two missiles also entered operational service around the same time, the AGM-86B achieving IOC with the USAF's Strategic Air Command (SAC) in 1982 and Tomahawk with the US Navy in 1984.

Given the time periods in which these missiles were developed and initially deployed, their potential as nuclear weapons influenced talks between the United States and the Soviet Union on limiting long-range nuclear weapons, just as the missiles themselves were, in turn, affected by these negotiations. Although the nuclear-arms agreements signed by Soviet General Secretary Leonid Brezhnev and US President Jimmy Carter in Vienna on June 18, 1979, were not ratified by the US Senate, they were interpreted as potentially making any aircraft equipped to launch cruises missiles with a range greater than 600 kilometers (324 nm) countable as a nuclear-delivery vehicle and the missiles themselves as strategic-nuclear warheads, both of which were constrained by the 1979 agreement.[137] These perceived limitations explain why the United States later reached an understanding with the Soviets that the B-1 bomber was not an ALCM carrier.[138] They also suggest why, if there were ever any thoughts of fielding an air-launched variant of Tomahawk on carrier-based attack aircraft, Navy officials did not entertain them very long.[139]

In ALCM's case there was one other event that helped transform the attitude of the SAC bomber community from resistance to the acceptance of long-range cruise missiles. On June 30, 1977, President

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136 Werrell, *The Evolution of the Cruise Missile*, p. 154.

137 Werrell, *The Evolution of the Cruise Missile*, pp. 175-76.

138 As of September 2006, the 1991 exchange of letters on the B-1's status relative to strategic-arms limitations agreements was available online at <http://www.defenselink.mil/acq/acic/treaties/start1/other/letters_bear_b1.htm>.

139 The only carrier aircraft that could have easily carried Tomahawk in the early 1980s was the A-6. One suspects that the A-6 community would have had little enthusiasm for Tomahawk. The whole thrust of the A-6 was to be able to deliver unguided ordnance with a fair degree of accuracy against defended targets at night or in adverse weather, and the A-6's navigation and bombing systems had been designed with this employment concept in mind.

ceptance of long-range cruise missiles. On June 30, 1977, President Carter cancelled the B-1 bomber, at least partially on the judgment of defense secretary Harold Brown that a penetrating B-1 force without standoff weapons would offer equal capability to B-52s armed with cruise missiles but be "about 40 percent more expensive."[140] As historian Kenneth Werrell wrote in 1985, this decision "shocked the top echelon of the Air Force" but made the ALCM "more important than ever."[141] Thus, the imperative for SAC to embrace ALCM arose, ironically, as much from the desires of president and secretary of defense to minimize investments in strategic-nuclear forces as it did from advances in Soviet air defenses. If the B-52s were not going to be replaced for the foreseeable future, then SAC needed a standoff weapon to preserve the nuclear triad's bomber leg during the 1980s and early 1990s.

Although it is probably fair to consider Tomahawk and the AGM-86B/C as evolutionary outgrowths of the large, unreliable, inaccurate cruise missiles of the 1950s, two technological advances distinguish them from their historical antecedents: the appearance of small, efficient turbofan jet engines; and TERCOM (Terrain Contour Matching) for navigation to the target and DSMAC (Digital Scene Matching Area Correlation) for terminal guidance.[142] In 1967 the Williams Research Company demonstrated that "a 12-inch diameter (24-inch length) engine, weighing 68 pounds, could produce 430 pounds of thrust at a fuel consumption rate of .7 pounds of fuel per hour per pound of thrust."[143] This engine, the WR-19, "was the predecessor of a family of small, efficient engines that power current American cruise missiles" to this day.[144] This new generation of engines opened the door to far smaller cruise missiles than those of the 1950s. For example, the Navy's Regulus I had had a launch weight of over 14,500 pounds, and Northrop's N-69A Snark was several times larger, with a launch weight over 49,000 lbs—comparable to the takeoff weight of an F-4 fighter loaded with air-to-air ordnance and internal fuel.[145] Sam

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[140] Werrell, *The Evolution of the Cruise Missile*, p. 177.

[141] Werrell, *The Evolution of the Cruise Missile*, pp. 177-78.

[142] Werrell, *The Evolution of the Cruise Missile*, pp. 135, 225.

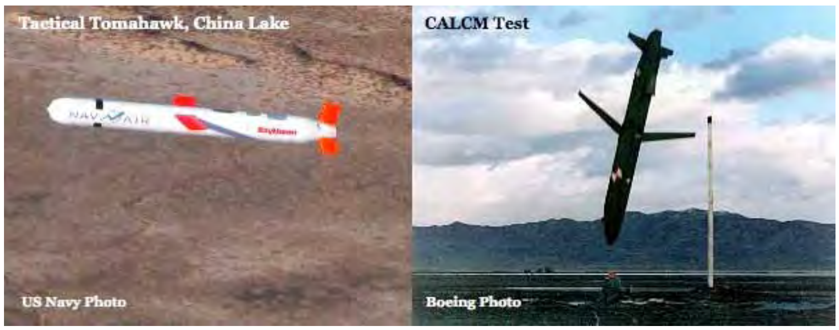
[143] Werrell, *The Evolution of the Cruise Missile*, p. 141.

[144] Werrell, *The Evolution of the Cruise Missile*, p. 140.

[145] Werrell, *The Evolution of the Cruise Missile*, p. 236.

Williams' turbojets provided engines small and light enough to yield substantial reductions in the size and weight of cruise missiles. Without a booster, Tomahawk is some 2,900 pounds at launch and small enough to be fired from the torpedo tubes of a submarine. CALCM is only slightly heavier at 3,150 pounds.[146]

Figure 31: Tactical Tomahawk and CALCM



Similarly, the development of TERCOM increased accuracy while also contributing to the reduced size and weight of Tomahawk and ALCM compared to the Regulus I, Snark, and other 1950s-vintage cruise missiles. From the late 1950s to 1970, the inherent inaccuracy (drift) of inertial systems was reduced from about 0.03 degrees per hour to around 0.005 degrees (or a third of a nautical mile) per hour; concurrently, the size and weight of inertial guidance packages dropped from about 300 to 29 pounds; and, as was true of air-to-air missiles, advances in solid-state electronics—microprocessors and semi-conductor memories on chips—steadily increased the computational power of guidance systems throughout the 1960s[147]

Block-I/II Tomahawks and ALCMs employ INS for basic missile guidance aided by TERCOM navigation. En route to the target, TERCOM provides an external source of location information to correct for INS drift during the time the missile is flying from its launch

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[146] "AGM-86B/C Missiles," US Air Force Fact Sheet, January 2006, online at <http://www.af.mil/factsheets/factsheet.asp?id=74>, accessed September 25, 2006.

[147] Werrell, *The Evolution of the Cruise Missile*, pp. 135-36.

point to the target.[148] Once in the target area, DSMAC is employed to achieve the desired terminal accuracy by comparing a stored image of the target with the actual image sensed by the missile.

TERCOM itself uses a radar altimeter to generate digital contour data of terrain segments around selected checkpoints along the missile's flight path. These contours are then compared with those of preplanned digital maps stored prior to launch in the missile's computer to make en-route corrections of the missile's flight path. TERCOM assumes that the required mapping information is available and accurate; that there are unique land contours at selected checkpoints the system can utilize for navigation; and that the radar and missile computer can do their jobs.[149]

Digital contour maps, consisting of grid squares or cells centered on checkpoints along the route to the target, require both substantial time and effort to produce. Particularly for targets inside the Soviet Union during the Cold War, data from reconnaissance satellites were needed to produce these maps. TERCOM, therefore, constituted a complex, expensive solution to correcting INS drift during the time of flight of a cruise missile (which, on a 1,000 nm mission flying at 350 knots, would take over 2.8 hours).[150] The need for access to "still more-complex and more-expensive systems, such as reconnaissance satellites," meant that the TERCOM approach to cruise-missile navigation to the target was only accessible to "relatively rich nations" such as the United States.[151]

From an employment perspective, preparing the mission data for a given route and target also took time, typically days, thereby limiting the responsiveness and flexibility of early block Tomahawks and ALCMs. Furthermore, the infrastructure required to generate Toma-

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148 Precisely stated, the guidance used in Block-I/II Tomahawks and the original AGM-86B is a TERCOM-aided inertial navigation system.

149 Werrell, *The Evolution of the Cruise Missile*, p. 136.

150 John Stillion and David T. Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks: Technology, Scenarios, and U.S. Air Force Responses* (Santa Monica, CA: RAND, 1999), p. 10.

151 Stillion and Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks*, p. 11. GPS, of course, dramatically reduced the costs of fielding relatively accurate, long-range cruise missiles.

hawk mission data had to be maintained. While the time constraints and mission-planning requirements inherent in TERCOM and DSMAC were undoubtedly less of a problem for ALCM-armed B-52s tasked against targets in the Soviet Union under the Single Integrated Operational Plan (SIOP), they certainly limited how quickly a Tomahawk could be brought to bear against unplanned or emergent targets. Block-III TLAMs overcame this limitation by adding GPS. Until the Block-III Tomahawks became available, though, CALCM mission planning was quicker, easier and more responsive.[152]

With respect to cost, the RGM/UGM-109A/B/C/D Tomahawk and AGM-86C/D CALCM fall at the opposite end of the spectrum from LGBs and JDAMs. Both are very, very expensive munitions by comparison. In constant FY 2006 dollars, the unit-acquisition price (procurement plus research, development and testing) of the 4,201 TLAMs produced through FY 1999 is $4.4 million each.[153] A comparable program-acquisition unit price for the first 272 AGM-86C CALCMs is $5.1 million per round (in FY 2006 dollars).[154] By contrast, the per-

[152] Major Stephen R. Hess, "Conventional Air Launched Cruise Missile Development—Employment and the Costs of Global Presence," Marine Corps University, April 18, 1995, p. 18; available online at <http://www.globalsecurity.org/military/library/report/1995/HSR.htm>. Hess was among the "Secret Squirrels" who participated in the CALCM missions against Iraq at the beginning of ODS; see also John Tirpak, "The Secret Squirrels," *Air Force Magazine*, April 1994, starting on page 56. Due to block upgrades, CALCM offered some in-flight retargeting capability, whereas the Tactical Tomahawk is the first version of TLAM to do so.

[153] DoD, Acquisition Program Integration, OUSD(A&T), "Selected Acquisition Report (SAR) Summary Tables: As of Date: December 31, 1996," April 7, 1997, p. 6; and Department of the Navy (DoN), *Fiscal Year (FY) 2002 Amended Budget Submission: Justification of Estimates, Weapons Procurement, Navy*, Budget Item Justification Sheet P-40, P-1 Shopping List, Item No. 5, June 2001, p. 1. The cited SAR provides program costs for the original TLAM program, excluding Tactical Tomahawk. The cited justification sheet gives the correct total for the number of these missiles produced. DoD deflators were used to convert FY 1977 dollars into FY 2006 dollars.

[154] DoD, "Selected Acquisition Cost Summary: As of Date: December 31, 1985," April 7, 1986, p. 1; Boeing, "U.S. Air Force Demonstrates Precision-Strike Accuracy in CALCM," news release, May 8, 2001, available online at <http://www.boeing.com/news/releases/2001/q2/news_release_010508n.htm>, accessed September 27, 2006; Boeing, "ALCM-86B/C Air-Launched Cruise Missile," at <http://www.boeing.com/history/boeing/alcm.html>, accessed September 27, 2006. The cited SAR provides the base-year program cost of ALCM, the May 2001 Boeing news release gives the conversion cost for

munition program-acquisition cost for 199,994 JDAMs is $26,801 each (again, in FY 2006 dollars).

More difficult to estimate for these munitions are average unit-procurement or production prices that exclude research, development and testing. This is because the relevant budget documents are generally in then-year dollars aggregated over the lives of these programs, which ignores the effects of inflation. One pair of comparable production prices for TLAM and CALCM may be the constant-dollar per-round costs provided to the Gulf War Air Power Survey (GWAPS) after ODS. Converted into constant FY 2006 dollars, the GWAPS figures put the unit-procurement cost of TLAM at $1.5 million and that of CALCM at $1.96 million.[155] However, these prices appear to ignore substantial production-support costs. In TLAM's case they almost certainly omit fleet-support and remanufacturing costs to convert Block-II TLAMs into Block-III variants. Incorporating these costs raises the unit-procurement price for the 4,201 Tomahawks built prior to FY 1999 from around $1.3 to almost $2 million each (in then-year dollars).[156] Therefore, if all production-related costs are included, TLAM's unit-procurement price appears to be in the vicinity $2 million and CALCM's around $3 million.

The price contrast between these long-range cruise missiles and the unpowered JDAM is stark. Again, through FY 2005, the 105,286 JDAM kits procured averaged $21,379 in then-year dollars. Adding the cost of a Mark-84 bomb body and FMU-152/B fuze still leaves JDAM's unit-procurement price under $26,000 per round. Thus, ignoring Tactical Tomahawk (whose unit-procurement price is coming down but still over $900,000[157]), the average production cost of an RGM/UGM-109A/B/C/D TLAM has been about 75 times greater than

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the first 272 AGM-86Cs, and the third reference contains the total number of ACLMs produced (1,751). The program-unit-acquisition cost of the first 50 AGM-86Ds is nearly $6 million per round.

155 Hill, Cook, and Pinker, GWAPS, Vol. V, *A Statistical Compendium and Chronology*, Pt. 1, *A Statistical Compendium*, pp. 550-551.

156 DoN, *Fiscal Year (FY) 2002 Amended Budget Submission: Justification of Estimates, Weapons Procurement, Navy*, Budget Item Justification Sheet P-40, P-1 Shopping List, Item No. 5, June 2001, p. 1.

157 Office of the Under Secretary of Defense (Comptroller), *Procurement Programs (P-1): DoD Budget Fiscal Year 2007*, February 2005, p. N-10.

that of a full-up JDAM, and CALCM's unit-procurement price has been 115 times greater.

Table 8: US TLAM and CALCM Expenditures

Dates	Operation	TLAM	CALCM	Totals
Jan-Feb 1991	Desert Storm	298	35	333
January 1993	Southern Watch	45	0	45
July 1993	Southern Watch	23	0	23
September 1995	Deliberate Force	13	0	13
September 1996	Desert Strike	31	13	44
August 1998	Sudan & Afghanistan	79	0	79
December 1998	Desert Fox	325	90	415
Mar-Jun 1999	Allied Force	198	72	270
Oct-Nov 2001	Enduring Freedom	74	0	74
March 2003	Iraqi Freedom	802	153	955
	Total Expenditures	**1,888**	**363**	**2,251**

Cost differences this large have had far reaching implications for both the quantities of Tomahawks and CALCM cruise missiles that can be procured as well as for the volume in which they can be employed. TERCOM made TLAM and ALCM weapons only countries as rich in military resources as the United States and the Soviet Union could afford. But even for a nation as rich as the United States, defense resources are not unbounded. As Charles Hitch and Roland McKean observed in 1960: "Resources are always limited in comparison with our wants, always constraining our action. (If they did not, we could do everything, and there would be no problem of choosing preferred courses of action.)"[158] Funding constraints have limited the inventories of Tomahawk and CALCM for conventional operations at any one time to, at most, a few thousand missiles. The small size of these inventories, in turn, has constrained their employment to totals ranging from as few as 13 to as many as 955 (see Table 8). OIF witnessed, by far, the largest expenditure of these expensive missiles since 1991: 802 TLAMs and 153 CALCMs. But the second largest expenditure was 415 TLAMs and CALCMs during Desert Fox, and only 333 were expended in Desert Storm, which saw the third-largest expenditure to date. So the quantities of long-range cruise missiles US forces have employed

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[158] Charles J. Hitch and Roland N. McKean, *The Economics of Defense in the Nuclear Age* (New York: Atheneum, 1986 3rd printing; originally Harvard University Press, 1960), p. 24.

in recent wars and various punitive strikes have been limited compared to LGBs and JDAMs. During OIF, for example, US forces expended 8,618 LGBs, 6,542 JDAMs, and 98 EGBU-27s, which had dual laser and INS/GPS guidance.

Starting in 1991, LGBs and, later, JDAMs emerged as the "go-to" guided munitions—able to be liberally employed against the entire gamut of "strategic" and battlefield targets. Together, these truly general-purpose weapons have accounted for over three-quarters (76.4 percent) of the more than 53,500 guided weapons expended during ODS, OAF, OEF, and OIF, whereas TLAM and CALCM together constituted just over three percent of the total.[159]

Further scrutiny of Tomahawk and CALCM employment patterns reveals that they have been used exclusively against fixed targets, predominately heavily defended ones that either needed to be attacked early in the campaign, or against targets that would have risked avoidable losses if attacked with manned aircraft. During the months preceding Desert Storm, for example, air-campaign planners concluded that most of the key targets in the Baghdad area originally considered for Navy A-6Es or Air Force F-15Es, F-16s, and F-111s carrying unguided ordnance would risk aircrew losses and, in the case of Iraq's electric power grid, cause excessive collateral damage as well. As a result, during the opening days of Desert Storm most of these targets were assigned to individual F-117s because of their low observability, or to TLAM and CALCM because they were both precision weapons and unmanned.[160] On the opening day of the war, 18 Tomahawks with special submunitions containing rolls of carbon-fiber wire (designed to short out high-voltage power lines) were targeted against Iraqi transformer yards in and around Baghdad.[161] The aim of these open-

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159 Again, the totals in Figure 19 for US guided weapons expended during ODS, OAF, OEF, and OIF omit air-to-air missiles as well as ground-force guided weapons such as Hellfire. Expenditures by allied forces are also excluded.

160 Alexander S. Cochran, et al., GWAPS, Vol. I, *Planning and Command and Control*, Pt. I, *Planning*, p. 124.

161 Central Command Air Forces, "MAP [Master Attack Plan] for ATO [Air Tasking Order] Day 1 [January 17, 1991]," Excel spreadsheet; David A. Fulghum, "Secret Carbon-Fiber Warheads Blinded Iraqi Air Defenses," *Aviation Week & Space Technology*, April 27, 1992, pp. 18-19; and, Rick Atkinson, *Crusade: The Untold Story of the Persian Gulf War* (New York: Houghton Mifflin, 1993), pp. 30-31.

ing-night TLAM attacks was to shut down electric-power generation without causing long-term damage to Iraq's electric-power grid by destroying the turbines in the generator halls—an objective that simply could not have been pursued without guided weapons and specialized submunitions.[162] In addition, over 80 percent of the 282 Tomahawks that attained cruise flight and proceeded toward their targets were timed to impact during the daytime, the tactical intent being to maintain pressure against various target sets during the daylight hours when F-117s and F-111Fs with LGBs were not active.[163]

These observations should not be taken to imply that long-range cruise missiles have only exerted a marginal influence on conflict outcomes due to the relatively small numbers that have been employed. Their most dramatic success appears to have occurred during Operation Desert Fox, whose stated aim was to degrade Iraq's weapons of mass destruction (WMD) after Iraq had failed to comply with United Nations (UN) Security Council resolutions and had expelled UN Special Commission observers from the country. All told, 325 TLAMs, 90 CALCMs, and some 600 aircraft-delivered munitions were expended during December 16-19, 1998. About 100 facilities were struck during the four nights of this campaign. Targets included SAM sites, Saddam Hussein's military command-and-control infrastructure, airfields, Republican Guard headquarters and barracks, internal Iraqi security forces including Special Republican Guard forces, and a number of facilities involved in Iraq's weapons of mass destruction programs.[164] While there was public skepticism at the time about the strategic impact of this campaign, the US Central Command (CENTCOM) commander, General Tony Zinni, was "amazed when Western intelligence assets in Baghdad reported that Desert Fox nearly knocked off Saddam Hussein's regime."[165] Moreover, after the major combat phase of OIF, David Kay was able to interview or interrogate over 200 officials

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162 Barry D. Watts and Thomas A. Keaney, GWAPS, Vol. II, *Operations and Effects and Effectiveness*, Pt. 2, *Effects and Effectiveness*, pp. 291-292.

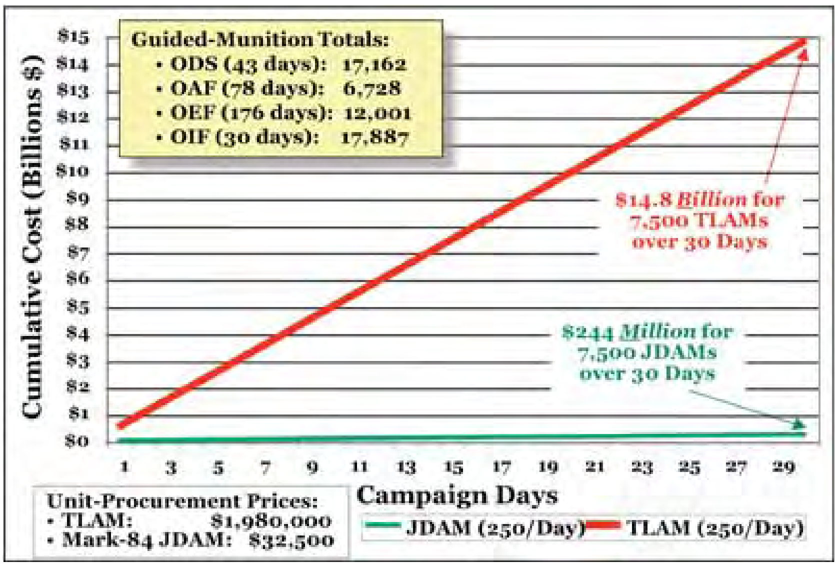
163 Blanchfield, Guilmartin., et al., GWAPS, Vol. IV, *Weapons, Tactics, and Training and Space Operations*, Pt. I, *Weapons, Tactics, and Training*, pp. 249-250.

164 William S. Cohen, "DoD News Briefing," December 19, 1998, online at <http://www.defenselink.mil/transcripts/1998/t12201998_t1219coh.html>, accessed September 27, 2006.

165 Ricks, *Fiasco: The American Military Adventure in Iraq*, p. 19.

from Iraq's WMD programs. Kay's conclusion was that Desert Fox's psychological effects had been so devastating that Saddam Hussein's regime had abandoned its nuclear, chemical and biological warfare programs.[166] Thus, it would be wrong to suggest that the heavy use of TLAMs and CALCMs has only had tactical effects.

Figure 32: JDAM versus TLAM Campaign Costs (250 munitions/day)



Nevertheless, the high unit-production costs of TLAM and CALCM remain an issue. Figure 32 dramatizes the per-round cost differential between the procurement prices of TLAM and a full-up JDAM round by assuming a daily expenditure rate of 250/day for each munition over 30 days. The resulting "campaign" comparison is artificial in that the US Navy neither has 7,500 TLAMs today, nor plans to have that many even if the entire production run of the Tactical Tomahawk (2,790 rounds) is included. On the other hand, the JDAM variant is entirely feasible and affordable based on existing inventories. The total bill for expending 7,500 JDAM rounds with Mark-84

[166] Ricks, *Fiasco: The American Military Adventure in Iraq*, p. 21; see also Woods, et al., *The Iraqi Perspective Project*, pp. 91-92; and Charles Duelfer, "Regime Strategic Intent," *Comprehensive Report of the Special Advisor to the DCI on Iraq's WMD*, Vol. I, September 30, 2004, pp. 64-65.

warheads is $244 million. The $14.8 billion for 7,500 TLAMs, however, is another matter. Granted, Tactical Tomahawk would ease the funding differential relative to JDAM. At the current production price of around $950,000 per RGM/UGM-109E, the 30-day campaign bill drops to around $7.1 billion, and if the production-price goal of $600,000 per round is eventually met, then the bill would be $4.5 billion. Even so, the per-round cost of a $600,000 Tactical Tomahawk would still be more than eighteen times that of a full-up JDAM with a Mark-84 warhead: buying enough to be able to expend 7,500 in a 30-day campaign appears beyond the resources likely to be available to the US military.

Another implication of the data in Table 8 is that CALCMs have only accounted for a modest 16.1 percent of the total US expenditures of long-range, land-attack cruise missiles. The obvious reason is that the available inventory of TLAMs has been considerably greater than CALCM's. Excluding Tactical Tomahawk production, the Navy procured 4,201 TLAMs versus less than 500 ALCM conversions by the Air Force as of 2006.

Why did the Navy field a much larger inventory of non-nuclear Tomahawks compared to the Air Force's inventory of CALCMs. The answer lies in the differing motivations of the war-fighting communities involved. Tomahawk was embraced by the Navy surface community as a way of regaining a foothold in the strike role that had been dominated by naval aviators since World War II. As a result, TLAM ultimately gave both surface combatants and submarines a credible capability for the precision attack of targets ashore, thereby affecting the relationships between the Navy's three main war-fighting communities (surface-fleet sailors, submariners, and naval aviators). CALCM, by comparison, came about as a secondary mission for SAC bombers, and was not a serious challenge to the post-Vietnam dominance of Air Force conventional operations by its fighter community.

Nor would it be fair to say that the Air Force never fielded a significant number of long-range cruise missiles. However, the majority of them were dedicated to the nuclear role. ALCM's original aim was to preserve the bomber leg of the nuclear triad: 1,715 AGM-86s were produced for this purpose followed by another 460 of the low-observable AGM-129 Advanced Cruise Missiles (ACMs).[167] The Air Force's CALCM was developed as a "black" or special-access-required program within SAC and had little, if any, impact on the development of guided weapons for TAC's fighters and fighter-bombers. Furtheremore, while the Air Force did field a substantial inventory of long-range cruise missiles for the nuclear-deterrence mission, only a small number of these munitions were later converted to conventional munitions for heavy bombers. Among other reasons for the limited number of conversions, the Navy's Harpoon was successfully test fired from the B-52G in 1983 and some SAC bombers subsequently acquired a maritime role using the AGM-84.[168] But, again, using B-52s in a maritime role with conventional munitions never became a major focus of Strategic Air Command.

The Air Force's decision in May 1986 to explore the possibility of converting nuclear ALCMs to a conventional cruise missile appears to have been motivated by the difficulties that USAFE F-111Fs encountered in executing strikes against targets in Libya during the night of April 14-15, 1986, after being launched from a base in England.[169] According to the vice wing commander at the time, these problems included the following:

- The length of the mission—some 14 hours sitting on ejection seats in fighter cockpits—placed considerable stress on the aircrews involved.
- The loss of one F-111F over Tripoli, probably to a Libyan SAM.
- The fact that Muammar Qaddafi, though not an explicit target of the raid because pre-mission intelligence had failed to pinpoint his location, survived the raid.

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[167] The originally planned buy of 1,500 ACMs was terminated at 460 by the end of the Cold War, and the last AGM-129 delivered in 1993. SAC itself was disestablished in 1992 and its bombers turned over to TAC's successor, Air Combat Command.

[168] Thomas A. Keaney, *Strategic Bombers and Conventional Weapons: Airpower Options* (Washington, DC: National Defense University Press, 1984), p. 35. The main limitation of Harpoon on the B-52 was that although the missile had a range around 50 miles, in this timeframe the B-52s did not have a radar capable of positively identifying naval targets at that distance (ibid., p. 37).

[169] Hess, "Conventional Air Launched Cruise Missile Development," pp. 2-3.

- And problems in the target area that led to four 2,000-lb LGBs hitting near the French embassy in Tripoli, which caused heavy civilian casualties and protests from the French, who had not allowed overflight of their airspace by the F-111s in the first place.[170]

CALCM, then, was an initiative to develop a capability for striking a few targets anywhere on the globe with conventional ordnance on short notice. At the time, the combination of the B-52's long range and the standoff precision of a long-range cruise missile appeared to be the ideal choice for a near-term solution to the Air Force's perceived need for a global strike capability.

Even after CALCM became operational on the B-52 in January 1988, however, the capability was restricted to a single bomb wing at Barksdale AFB, Louisiana. In fact, the crews who launched 35 CALCMs on the opening night of Desert Storm three years later were required to use cover stories even with their families.[171] So as helpful as the B-52/CALCM combination may have been in enabling the institutional Air Force to challenge the Navy's claim to being the only service able to provide global "presence," the new capability had little effect on the growing dominance of conventional war-fighting or, more crucially, senior USAF leadership positions by fighter generals after Vietnam.[172]

Turning to the contrasting case of the US Navy and Tomahawk, naval aviators, who had dominated the attack of targets ashore since 1944 (save for the special situation of bombarding beaches prior to amphibious assaults), had little enthusiasm for cruise missiles during the 1970s and early 1980s. The introduction into fleet service of the

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170 Robert E. Venkus, *Raid on Qaddafi* (New York: St. Martin's Paperbacks, 1992), pp. 78-80, 96, 109, 154.

171 Hess, "Conventional Air Launched Cruise Missile Development," pp. 7, 15. The US Air Force continues to pursue the kind of global-strike capability first provided by the B-52/CALCM. In fact, its "Global Response CONOPS"—the "ability to globally attack fleeting or emergent, high-value and high-risk targets"—is one of six transformational concepts of operations currently being developed by the Air Force—Department of the Air Force, *The U.S. Air Force Transformation Flight Plan* (Washington, DC: HQ USAF/XPXC, November 2003), pp. 41, 43.

172 See Worden, *Rise of the Fighter Generals*, especially pp. 235-238.

Target-Recognition/Attack Multi-sensor (TRAM) version of the A-6E, starting in 1979, gave the Navy's attack community a fairly robust capability for night and adverse-weather strike with either unguided bombs or LGBs. TRAM included a forward-looking IR (FLIR) system, a laser range-finder and designator, and a laser-spot tracker. The crew could view television-quality images of their targets day or night. A further upgrade, the System Weapons Improvement Program, added short-range standoff weapons such as Harpoon, Maverick, and HARM. Given all these A-6 capabilities and the danger that adding Tomahawk would ensnare naval aviation in strategic-arms limitations with the Soviet Union, the naval aviators had little incentive to embrace a long-range cruise missile. To the contrary, Tomahawk posed a threat to naval aviation's ownership of the attack mission ashore and potentially undermined the established value of manned aircraft able to penetrate to or near targets at night or in adverse weather.

The incentives for the submariners and the Navy surface-warfare community were altogether different. In the judgment of Norman Friedman, James O'Brasky and Sam Tangredi, Tomahawk

> effectively increased the striking range of an individual surface ship from approximately 24 nautical miles (the range of the largest battleship gun) to over 1,500 nautical miles. Effectively demonstrated in Operation *Desert Storm*, by 1998 the sea-launched Tomahawk had become a contingency weapon of choice, being used for strikes in even a completely landlocked country (Afghanistan). Brushing aside the question of whether this was the wisest use of such a weapon, the success of Tomahawk effectively *globalized* naval surface warfare—at least for the surface force of the U.S. navy and her allies. This allows SAGs [Surface Action Groups]—even without the now-decommissioned battleships—to have an independent strike capability that they have not had since the beginning of naval aviation, at a range unfathomable to the classical naval strategists.[173]

[173] Norman Friedman, James S. O'Brasky, and Sam J. Tangredi, "Globalization and Surface Warfare" in Sam J. Tangredi (ed.), *Globalization and Maritime Power* (Washington, DC: National Defense University Press, 2002), p. 376.

Given the high unit-cost and limited inventory of Tomahawk, one could argue that this "independent strike capability" was, and remains, more limited than this passage implies. By mid-2003, nearly 1,900 RGM/UGM-109A/B/C/Ds had been fired in anger, leaving an inventory of perhaps 2,280 missiles plus a small number of Tactical Tomahawks.[174] Yet the US Navy is building toward more than 10,000 Vertical Launch System (VLS) cells capable of firing Tomahawks, Standard Missiles such as the SM-2 for defense against enemy aircraft, or Vertical Launch ASROCs (anti-submarine rockets) throughout the fleet.[175] The 22 improved *Ticonderoga* guided-missile cruisers and the 52 *Arleigh Burke* guided-missile destroyers launched as of September 2006 provide just over 7,500 VLS cells.[176] The other *Arleigh Burke*-class destroyers planned through 2011 (DDG-103 to DDG-112) will add another 960 VLS cells for a total of 8,468 in the Aegis fleet. The 12 VLS cells on the later *Los Angeles*-class and newer *Virginia*-class SSNs will provide roughly another 400-600 VLS cells fleet-wide through 2018, and the four *Ohio*-class ballistic-missile submarines planned for conversion to conventional missiles will add another 616.

A fleet-wide VLS capacity of more than 10,000 cells appears to be roughly double number of existing TLAMs (~2,280) plus the planned Tactical Tomahawk buy (2,790), assuming no more expenditures. While around 300 Vertical Launch ASROCs have been procured, the projected inventory of the SM-2 MR (medium range) and ER (extended range) is 11,667 missiles, of which over 10,700 had been procured through FY 2003.[177] A reasonable assumption, therefore, is that

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174 This estimate of the Tomahawk inventory subtracts known combat expenditure of 1,888 weapons plus 50 more missiles for testing from the known production of 4,201 TLAM-A/B/C/Ds. The Block-IV Tactical Tomahawks produced to date have been ignored because they did not achieve IOC prior to Phase 3 of OIF.

175 Robert O. Work*, The Challenge of Maritime Transformation: Is Bigger Better?* (Washington, DC: CSBA, 2002), p. 83.

176 Norman Polmar, *The Naval Institute Guide to the Ships and Aircraft of the U.S. Fleet* (Annapolis, MD: Naval Institute Press, 17th ed. 2001), pp. 136, 143, 145, 518-519, 525.

177 Currently, the advanced version of the SM-2 being procured is running over $1.9 million per round (DoN, *Fiscal Year (FY) 2007 Budget Estimates Submission: Justification of Estimates, Weapons Procurement, Navy*, Budget Item Justification Sheet P-40, P-1 Shopping List, Item No. 8, February 2006, p. 1).

half or more of the fleet-wide VLS cells would be filled with SM-2s (or, later, SM-3s designed for exo-atmospheric intercepts of short- to medium-range ballistic-missile warheads). Certainly this view fits with the US Navy's emphasis since 1945 on defense against air attack.

However, based on the pattern of Tomahawk expenditures since 1991 in Table 8, one would expect further combat use. Over the next decade, it is not implausible to anticipate another 1,000 or 1,500 being expended, which would have to be subtracted from the maximum planned inventory of around 5,000 rounds. This rough calculation suggests that the Navy is unlikely to procure enough TLAMs to fill all the VLS tubes not loaded with Standard Missiles on operational patrols, even if the fill requirement is only a single salvo. Almost surely, the underlying reason for this situation is a resource constraint stemming from the munition's high cost. Crossing-decking can, of course, somewhat alleviate this problem by having combatants returning from patrols turn their TLAMs over to ships or submarines about to put to sea. But inventory limitations constrained by costs are likely to persist.

Much the same can be said of CALCM. Its high cost and small numbers have limited it to being a niche weapon at best. The contrast with TLAM, however, is that since CALCM's initial employment in 1991, the American bomber fleet has acquired the capability to employ not only JDAM but, in the case of the B-52 in Operation Iraqi Freedom, LGBs as well. So far at least, the Navy's surface-warfare and submarine communities have not been able to field long-range, land-attack weapons that can be fired from VLS tubes with unit costs anywhere near those of JDAMs and LGBs. A navalized version of the Army Tactical Missile System (ATACMS) has frequently been discussed as a complement to Tomahawk for land attack. But ATACMS has not been a cheap missile either. Through FY 2000, the unit procurement cost of the Block 1A version of the missile with an anti-personnel, anti-materiel warhead was nearly three-quarters of a million dollars.[178] Hence, the hard-won independent land-attack capability acquired by the US Navy's surface-warfare and submarine communities since the early 1980s seems destined to remain in the niche-

[178] Department of the Army, *Procurement Programs: Missile Procurement, Army*, February 2004, p. 104.

weapon category for at least another decade due to resource constraints on achievable inventories.

CEC as a Targeting Network

The portrayal of networks as something dramatically new and unprecedented by enthusiasts such as the late Admiral Arthur Cebrowski was raised in Chapter I. As a counterpoint to this outlook, Chapter I made the point that the network of Chain Home radars and control centers the RAF used to defeat the Luftwaffe in the 1940 Battle of Britain not only qualifies as a battle network in the modern sense of the term, but was fundamentally a targeting network as well. This line of thought was carried a step further by the suggestion that modern sensor networks have arisen *in response* to the targeting requirements of guided munitions rather than either the other way around or independent of guided munitions, and the Navy's Cooperative Engagement Capability was offered as evidence. Having explored eight guided-munitions cases, as well as having touched on others along the way, it seems best wrap up the case studies by returning to a more global point: namely, to the realization that sensor-and-targeting networks are an integral component of the guided-munitions regime. The easiest way to underscore this point is to examine CEC in a bit more detail.

The Navy's Standard Missile-2 in Mark-41 VLS cells integrated with the Aegis combat system constitutes the modern descendant of the CICs, radars, and first-generation naval SAMs—Talos, Terrier, and Tartar—that emerged from Project Bumblebee after World War II. As of October 2006, Aegis and SM-2 (or, in very small numbers, SM-3) missiles were in service on 22 *Ticonderoga*-class cruisers and 49 *Arleigh Burke*-class destroyers.[179] Another 13 Aegis destroyers are either under construction or planned, and the US Navy anticipates bringing its Aegis cruiser/destroyer fleet to 84 by 2011.

The basic components of the Aegis combat system are the SPY-1 phased-array radar, Mark-99 fire-control directors (which include three or four SPG-62 radars to handle the terminal engagement of SM-2s with their targets during the last seconds before intercept), and related computers, displays, weapon control consoles, and power

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[179] Naval Vessel Register, <http://www.nvr.navy.mil/nvrships/sbf/fleet.htm>, accessed October 4, 2006.

sources.[180] The SPY-1 employs four fixed antennas, each containing 4,480 radiating elements in an octagonal design measuring 12.5 feet across.[181] On Aegis cruisers and destroyers, these four arrays are distributed to various positions on the superstructure so that each covers a 90-degree quadrant around the ship. The SPY-1 can project hundreds of pencil-thin beams in rapid succession, enabling it to identify and track hundreds of targets simultaneously out to ranges of 200 nm (370 km).[182] The SPY-1 provides target tracking as well as mid-course-guidance corrections to SM-2 missiles. The most significant advance of the SM-2 over the SM-1 is the capacity of each fire-control channel to provide terminal illumination for up five missiles through careful launch scheduling. As a result, Aegis combatants with four SPG-62s can have as many as 20 SM-2s in the air at the same time.

Figure 33: Aegis and SM-2

The defensive firepower even a single Aegis/SM-2/VLS combatant can concentrate against airborne threats is impressive compared with earlier naval air defense systems. One of the motivations that drove the development of this system was the challenge posed by an attack from a Tu-22 Backfire regiment, which could put a large number of anti-ship missiles in the air at one time against an Aegis-

[180] Polmar, *The Naval Institute Guide to the Ships and Aircraft of the U.S. Fleet*, p. 133.

[181] Polmar, *The Naval Institute Guide to the Ships and Aircraft of the U.S. Fleet*, p. 545.

[182] Polmar, *The Naval Institute Guide to the Ships and Aircraft of the U.S. Fleet*, p. 546.

defended carrier battle group. Nonetheless, as the Navy began to think about threats such as sea-skimming cruise missiles, it became clear that the very low, front-aspect radar signatures of these missiles would make them difficult for Aegis to acquire, track, and engage with SM-2—particularly when the missile was aimed at the Aegis combatant. This tactical problem provided the basic motivation for CEC.

Realizing that another Aegis combatant or other sensor such as the radar on the E-2C Hawkeye might be able to detect and track incoming cruises missiles that the targeted vessel could not "see" even with an SPY-1 radar, the idea behind CEC was to provide all combatants in the battle group with the best air-defense picture possible by integrating all available radar data on airborne targets and sharing it with each CEC participant in real time:

> Radar data from individual ships of a Battle Group is transmitted to other ships in the group via a line-of-sight, data distribution system (DDS). Each ship uses identical data processing algorithms resident in its cooperative engagement processor (CEP), resulting in each ship having essentially the same display of track information on aircraft and missiles.[183]

By integrating the unfiltered range, bearing, elevation and, if available, Doppler updates from all radars, CEC would enable "the battle force of units networked in this way" to operate as "a single, distributed, theater defensive system."[184]

CEC began engineering-manufacturing development in May 1995. Congress then mandated that the Navy achieve initial operational capability in FY 1996, and the Navy declared IOC on the Aegis cruisers USS *Anzio* and USS *Cape St. George* in September of that year.[185] Subsequently, however, major interoperability problems sur-

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183 Director, Operational Test & Evaluation, "Cooperative Engagement Capability (CEC)," *DOT&E FY98 Annual Report*, available at <http://www.globalsecurity.org/military/library/budget/fy1998/dot-e/navy/98cec.html>, accessed September 29, 2006.

184 "The Cooperative Engagement Capability," *Johns Hopkins APL Technical Digest*, Vol. 16, No. 4 (1995), p. 378. The Applied Physics Laboratory (APL) at Johns Hopkins played a leadership role in the development of CEC.

185 Captain Daniel Busch and Conrad J. Grant, "Changing Face of War,"

faced in early 1998 between the Baseline 6 Phase 1 update of the Aegis combat system and CEC aboard the cruisers USS *Hue City* and USS *Vicksburg*.[186]

The technical and bureaucratic issues underlying these interoperability problems need not divert the present discussion from the central point.[187] While CEC has been, and remains, the exemplar of the network-centric approach to warfare espoused by Admiral Cebrowski and others, it is fundamentally a *targeting* network for guided munitions, in this case for the SM-2 naval SAM in the context of a surface-fleet defense problem that reaches back to the US Navy's experience off Okinawa in 1945. CEC, therefore, provides strong evidence for the view that modern battle networks have emerged in response to the targeting requirements of guided munitions. To appreciate the force of this conclusion, consider the following question. Would networks alone, in the *absence* of guided munitions, enable war-fighting communities to move beyond massed fires applied in the industrial-age quantities typical of operations during World War I and World War II? The answer is clearly "No." Without the accuracy of PGMs such as LGBs and JDAMs, it would still be necessary to expend massive quantities of "dumb" conventional munitions in order to be confident of achieving the desired effects against most targets with conventional warheads.[188] Again, CEC's original aim was to provide targeting data "of sufficient quality for the firing unit to launch, control during midcourse flight, and perform terminal homing illumination for each SM-2."[189]

Seapower, March 2000, accessed September 29, 2006, at <http://www.navyleague.org/seapower/march2000.htm>. At the time of this article, Busch was the Navy's CEC program manager and Grant had the same position at APL.

[186] According to Bob Work, these interoperability problems were so severe in the case of the USS *Anzio* and USS *Cape St. George* that the two cruisers were out of service for some 16 months.

[187] See Captain Terry C. Pierce, "Sunk Costs Sink Innovation," *Proceedings*, May 2002, pp. 32-35.

[188] I am indebted to my CSBA colleague Bob Work for this argument.

[189] "The Cooperative Engagement Capability," *Johns Hopkins APL Technical Digest*, p. 386.

Nevertheless, having cautioned against the inclination of enthusiasts for network-centric operations to imply that CEC-like systems can fundamentally change the conduct of war *independent* of guided munitions, Cebrowski surely was right to emphasize the growing importance of sensors and networks. As he said in an August 2002 interview:

> We are seeing warfare dominated more by sensors than perhaps any other piece of equipment. The ability to sense the environment, to sense the enemy and to be networked enough to transmit that critical data to all who require it, is a trend line emerging from current operations. . . . The whole world knows that if U.S. military systems can see a target we can kill it. Consequently, potential enemies are working very hard to make it difficult for us to sense their targets, so we are shifting from a weapons game to a sensor game.[190]

In Cebrowski's parlance, networked sensors are all about increasing the information content of US guided weapons despite the best efforts of the enemy to deny that information. Looking back at what the LGB and JDAM cases, in particular, reveal about the difficulties that Air Force and Navy aviators have had in shifting their focus from platforms to weapons, one cannot help but suspect that the American military will find it even harder to internalize the growing primacy of sensors and networks. Yet this direction seems to be precisely the one in which non-nuclear guided weapons have been taking the conduct of modern war since the 1980s.

Higher-Level Effects and Mass

Before turning to the broader questions raised at the end of Chapter II about the overall influence guided munitions have had on the conduct of war in recent decades, some implications need to be drawn out concerning higher-level effects and the transformation of mass. Both issues were mentioned at the beginning of this chapter without much

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190 Information Technology Association of America, "An Interview with the Director," August 2000, p. 1, available online at <http://www.oft.osd.mil/library/library_files/trends_164_transformation_trends_28_october_issue.pdf>, accessed September 29, 2006.

elaboration. The main reason was that both matters lean heavily on the surface-attack cases in this chapter. With that material now in hand, it is much easier to articulate the deeper implications.

Chapter III's platform-on-platform cases focused on interactions between opposing submarines, aircraft, surface combatants, and armored fighting vehicles. The effects brought about by guided weapons in these cases were distinctly tactical in nature. Consider, for instance, the differences between using machine-guns or cannons at ranges generally well under 2,000-feet slant range to shoot down enemy aircraft as opposed to employing modern radar-guided and all-aspect IR missiles, which permit engagements to start with BVR shots outside 20 nm and transition to point-and-shoot tactics whenever opposing fighters close to within visual range. Yes, being able to exploit sensors and guided munitions to establish early air superiority can have higher-level effects on the overall course and outcome of an entire campaign. Nevertheless, the basic effects flowing from air-to-air missiles such as the latest models of the AIM-9, AIM-7, and AMRAAM are fundamentally tactical: they affect engagements first and foremost rather than campaigns or wars as a whole.

By contrast, what emerges from Chapter IV's surface-attack-munitions cases are instances of operational and even strategic effects at the campaign level or higher. The 3rd Infantry Division's drive to Baghdad in 2003 illustrates some of the salient operational consequences of guided munitions and battle networks. The 3rd ID and supporting Coalition forces possessed large numbers of through-weather guided munitions—mainly JDAM—along with battle networks that could track vehicular movements even through an intense *shamal* with heavy winds, blowing sands, and rain squalls. Iraqi forces, on the other hand, were operating largely with unguided munitions and possessed little in the way of modern battle networks. At least within the domain of high-intensity, non-nuclear combat, the outcome of the campaign suggests that industrial-age military forces armed with unguided munitions stand little chance in open battle against forces equipped with guided munitions and effective battle networks.

As for an instance of a strategic effect flowing from the concentrated use of guided munitions, consider again the impact that Desert Fox had on Iraq's WMD programs. While most observers did not realize at the time that the four-night campaign had broken Iraqi resolve to continue active pursuit of chemical, biological, and nuclear weapons, this consequential outcome appears to have been the immediate result of Desert Fox's intense application of TLAMs, CALCMs, and other guided munitions. Granted, the preceding seven years of UN inspections, along with the military and economic pressures created by Operations Northern and Southern Watch and sanctions, undoubtedly contributed to this strategic outcome. Nevertheless, it was Desert Fox that finally pushed Saddam Hussein into abandoning his WMD programs, even if he still refused to admit openly that he had done so in order to preserve his strategic position within the region.

In sum, the guided-munitions cases in Chapter III were mostly about changes in the tactical interactions between opposing platforms. The main effects are at the level of engagements. The operational and strategic effects of guided munitions on the course and outcome of entire campaigns only begin to emerge unmistakably in the surface-attack cases in Chapter IV. It is primarily in these cases that one begins to see evidence of fundamental change in the conduct of war.

What about the traditional concept of mass in the era of guided munitions and battle networks? How has the traditional notion of concentrating combat power at advantageous places and times to achieve decisive results been affected? While Chapter II pointed out that numerical superiority alone does not guarantee victory, a recurring historical pattern in the conduct of war has been the exploitation of mass to overwhelm an adversary. Recall that an explicit motivation behind Assault Breaker was to offset the greater numbers or mass that the leaders of the Warsaw Pact planned to bring to bear against NATO in the event of a conventional conflict in Central Europe. Similarly, it was the need for sheer mass to offset the inaccuracy of World War II bombs that led both the RAF's Bomber Command and the US Army Air Forces to attack so-called "strategic" targets in Germany with what eventually grew to be huge numbers of heavy bombers. For example, on February 3, 1945, over 930 B-17s from the 8th Air Force in England attacked the Tempelhof area of Berlin to impede the movement of Sixth Panzer Army, believed to be passing through to city on the way to the Russian front, and, possibly, to precipitate the collapse of the Nazi government; that same day, another 400 8th Air Force B-24s attacked railway and oil targets around Magdeburg.[191] These attacks

[191] Roger A. Freeman with Alan Crouchman and Vic Maslen, *Mighty Eighth War Diary* (New York: Jane's, 1981), p. 432; and John E. Fagg, "The Climax of Strategic Operations" in Wesley Frank Craven and James Lea Cate (eds.), *The*

exemplify an industrial-era approach to warfare in which massive expenditures of unguided munitions substitute for the lack of accuracy.[192]

Guided munitions and battle networks have rendered this industrial approach to the conduct of warfare largely obsolescent for American forces. Instead of scores or hundreds of planes per target for air-to-ground strike operations, guided munitions now enable the US Air Force and Navy to think and operate in terms of targets per attacking platform. For example, during a demonstration in September 2003, a single B-2 successfully released 80 independently targeted 500-pound JDAMs in less than 30 seconds. While the munitions in this test were inert, each JDAM homed on its own separate aim-point within the target area. This demonstration, which could be characterized as "mass precision," is the antithesis of the Berlin attacks mounted by British and American heavy bombers on January 7, 1945.

Does this imply that mass no longer has a role in strike operations using guided munitions and battle networks? The answer is that mass still has a place, but in a much altered way. In the face of active air defenses—particularly advanced surface-to-missiles—mass in the sense of sufficient salvo density to get one or two guided munitions through the defenses against the important targets is still an effective tactic. Moreover, insofar as future adversaries may find it easier to achieve such target densities against US main operating bases or carrier battle groups from relatively short ranges, a long-term consequence for American forces may be a growing need to operate from bases far enough away that adversaries will not be able to achieve sufficient salvo density to have much expectation of penetrating US active defenses. Alternatively, if either side has to operate close enough to opposing RUKs for them to be able to achieve the salvo densities to penetrate friendly defenses, then survival will require greater dispersion, hardening, mobility, or other measures to mitigate the effectiveness of the guided munitions that do get through. This implication

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Army Air Forces in World War II, Vol. III, *Europe: Argument to V-E Day: January 1944 to May 1945* (Chicago: University of Chicago Press, 1951), p. 725.

[192] During this period, when 8th Air Force was forced to use radar-bombing methods due to weather, the CEP was around two miles (Fagg, "The Climax of Strategic Operations," p. 723).

seems especially relevant for future ground forces. Mass, then, has not been rendered completely irrelevant by guided munitions and battle networks, but its application has been profoundly transformed in most areas of American military practice. The one notable outlier seems to be indirect suppressive fires for ground operations. General Gorman's vision of replacing all dumb mortar and artillery rounds with guided munitions has by no means been embraced by either the US Army or Marine Corps and, perhaps, rightly so. Even if the role of massive suppressive fires with unguided rounds has been significantly diminished, there may still be tactical situations in which industrial-era artillery barrages are the best solution.

V. Implications and Prospects

> A possible area of comparative advantage is that of precision guided munitions. Here is an area in which we appear to be ahead now.
>
> — Andrew W. Marshall, 1973[1]

> The reason that large changes in warfare take several decades is that it takes a good deal of time to develop new concepts of operations, to create the new military organizations that are required to execute these new concepts, for new skills to be acquired, and perhaps for new military careers and specialties to be created. All of these things take time, and . . . it may require generational change within the military establishment for the new ideas and new ways of fighting to establish themselves fully.
>
> — Andrew W. Marshall, 2003[2]

The Guided-Munitions Era as an RMA

Does the emergence, since the 1960s, of an increasingly robust, still-maturing guided-munitions regime constitute a revolution in mili-

[1] Andrew W. Marshall, "Longer-term Goals for Defense Policy," NSC memorandum, August 20, 1973, p. 3.

[2] Andrew W. Marshall in Emily O. Goldman and Leslie C. Eliason (eds.), *The Diffusion of Military Technology and Ideas* (Stanford, CA: Stanford University Press, 2003), pp. xiii-xiv.

tary affairs as understood by individuals such as Marshall, Krepinevich, Hundley and others? This question is perhaps the most fundamental of those raised at the end of Chapter II. However, that chapter also highlighted the many difficulties of classifying any historical period as one of revolutionary, as opposed to evolutionary, change compared to earlier or later periods. Such classifications are always to some degree arbitrary because of the large gaps in the historical record, the inherent imprecision of our conceptual categories, and the lack of ergodic theories of change in virtually any area of human affairs. While these difficulties do not deny that leaps or giant steps forward involving a break in continuity or the emergence of a new order occur, they certainly point to the dearth of precise, unambiguous criteria for identifying such changes. All things considered, therefore, it seems best to let readers reach their own judgments as to whether the maturation of guided weapons and battle networks should be judged an RMA. Rather than advocating a definite answer, this section reviews the differences between the aimed-fires era prior to 1943 and the guided-munitions era that has gradually emerged since the Second World War.

Prior to 1943, most munitions missed their targets or aim-points because they could not correct for initial aiming errors after being fired, released, or launched. The main way military tacticians and planners compensated for aiming errors was with mass. If enough unguided munitions were employed against any particular target, the law of large numbers would eventually put enough munitions close enough to the target to destroy it.[3] One of the most explicit formulations of this view can be found in the 1939 Army Air Corps (AAC) tentative training manual *Delivery of Fire from Aircraft*. Based on statistical analysis of the errors in the records of a considerable number of bombs dropped by AAC bomber crews during 1927-1931, bombardment experts concluded that the errors were normally distributed in both range and azimuth.[4] They therefore went on to treat bombing probabilities as a function of the surface of the "pile" of

[3] In a statistical sense, the law of large numbers is usually understood to imply that the average of a random sample from a large population is likely to be close to the mean of the whole population. When applied to military problems such as bombing a point target, the mean value of the distribution is the aim-point—assuming individual bombing errors are random but the entire population of errors is normally distributed.

[4] The normal distribution, also known as the "bell curve" or Gaussian distribution, was first introduced by Abraham de Moivre in a 1734 article. In 1812

probabilities as a function of the surface of the "pile" of bombs that would accumulate around the target as bomber after bomber attacked it.[5] CEP was defined as the radial distance from the aim-point within which 50 percent of the bombs would fall after an infinite number of trials. The practical result was to generate nomograms that bomber-unit commanders and planners could use to estimate the numbers of bombs—and, hence, the numbers of sorties—required to achieve the desired probability of getting at least one hit on the target.[6]

The gist of this approach is to fire, drop, or launch enough projectiles, shells, bombs, torpedoes, rockets, and other "dumb" ordnance—mass in military parlance—to compensate for the inherent inaccuracies of munitions lacking terminal homing or guidance. Admittedly, relying on "piles of ordnance" is a terribly brute-force, industrial-age solution. But in the absence of guided munitions, mass was, and remains, the only way to make up for the inaccuracies of aimed fires. Reliance on mass, therefore, is a prominent characteristic—if not *the* defining characteristic—of force application in the era of unguided munitions. Reflecting on how the 20th century's two world wars were fought, this dependence on mass drives combatants on both sides toward an industrial approach to war's conduct in which widespread destruction, collateral damage, and civilian casualties become difficult to avoid. This kind of warfare is especially unavoidable when belligerents insist on pursuing war aims as uncompromising as unconditional surrender or the total conquest and subjugation of enemy societies.

The still-unfolding era of non-nuclear, guided munitions, on the other hand, has increasingly provided the means to overcome the limi-

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Pierre Simon de Laplace extended de Moivre's work, using the distribution in analyzing the errors of experiments. For an easily understood spreadsheet introduction to the normal distribution using dice, see Sam L. Savage, *Decision Making with Insight* (Belmont, CA: Brooks/Cole-Thomson Learning, 2003), pp. 30-46.

[5] Air Corps Board, *Delivery of Fire from Aircraft*, Pt. 1, *Precision Bombing*, extract of Chapter IV, "Bombing Accuracy and Probabilities," June 10, 1939, Air Force Historical Research Center 167.86-4, pp. 3-4.

[6] For example, Chart 10 in the Chapter IV extract from the *Delivery of Fire from Aircraft* is a log-log nomogram of single-shot probability versus the number of bombs required "for at least ONE hit" with curves showing probabilities of 50, 60, 70, 80, and 90 percent. Today, of course, nomograms have been largely replaced with software applications on digital computers.

tations of mass-dependent, industrial-age warfare. Consider, once again, Operation Desert Storm in 1991. Prior to this campaign, conventional strike operations had almost universally been envisioned, planned, and executed in terms of the numbers of *aircraft* or *sorties per target*. In the aftermath of combat experience in 1991 with F-117s, Pave Tack-equipped F-111Fs, and a few F-15Es with LANTIRN, the Air Force began moving aggressively into a regime in which operational planners could think in terms of *targets per sortie*. Granted, SAC B-52s had long been tasked with multiple targets on individual sorties under the Single Integrated Operational Plan due to the larger payload of heavy bombers and the destructiveness of thermonuclear weapons, whether free-fall bombs or missiles. Before Desert Storm, however, air-campaign planning based on targets per sortie had been alien and impractical insofar as conventional munitions and fighter aircraft were concerned. The realization that LGBs provided the wherewithal for a single fighter-bomber to attack multiple aim-points or targets on one mission was, as discussed in Chapter IV, a watershed for TAC and the Air Force. The earlier commitment to the "smart-jet, dumb-bomb" mindset soon began giving way to a growing emphasis on PGMs and navigation/targeting pods. Looking back, the prospect that fighter-bombers like the F-111F or F-15E could attack several targets with non-nuclear LGBs or JDAMs on one sortie—much as B-52s had formerly done under the SIOP with thermonuclear munitions—also supported Marshal Ogarkov's 1984 hypothesis that conventional reconnaissance-strike complexes would eventually approach the destructiveness of nuclear weapons.

These changes in conventional warfare were discernible some years before the JDAM proved itself, starting in 1999 over Serbia, able to transcend the clear-air limitations of LGBs. Since then, development of the initial, seekerless version of the Air Force's 285-lb GBU-39 Small Diameter Bomb (SDB), SDB I, has gone from development to employment. In May 2006 the Air Force's 494th Fighter Squadron began receiving the munition. In July 2006, four 494th F-15E Strike Eagles flew a training mission with SDB I during which the planes hit 16 targets on a single pass.[7] Three months later, in early October, a

[7] "SDB Joins the Fight," *Precision Strike Digest*, July-September 2006, p. 9.

pair of 494th F-15Es successfully employed the new munition in Iraq while supporting ground troops.[8]

Figure 34: Guided-Munitions Accuracy

Although SDB I will have projected an average unit-procurement price around $50,000 per round if the costs of 2,000 unique bomb racks are included, Air Force officials have not unfairly characterized the program as being ahead of schedule, under cost, and exceeding requirements.[9] All things considered, this outcome is what one would have expected. After all, SDB I utilizes basically the same INS/GPS guidance technology already combat-proven on CALCM and JDAM. Perhaps the most significant design difference between JDAM and SDB I is the addition of a "Diamond Back" wing that opens after release to give this unpowered munition a range of more than 50 nm

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[8] "IOC for Small Diameter Bomb," *Precision Strike Digest*, 4th Quarter 2006, p. 11.

[9] "IOC for Small Diameter Bomb," *Precision Strike Digest*, p. 11. The Air Force plans to spend $1.2 billion to procure 24,000 SDB Is plus 2,000 Bomb Rack Unit 61/As (ibid.). The target price for SDB I without the specialized bomb racks was around $30,000 each.

when released from 40,000 feet at Mach 0.95 (Figures 34 and 35). Arguably, SDB I is poised to extend the precedent, first noted with LGBs, of guided munitions achieving kill probabilities of over 50 percent virtually from their earliest trials in actual combat. Recall, too, that JDAM was the first guided munition to perform better in combat than it had in developmental testing, and SDB is likely to continue the trend of guided munitions not only performing well in operational testing, but showing little or no significant degradation in actual combat use. While these trends are clearly the result of the maturation of solid-state electronics and the doubling of digital computational power every 18 months in accordance with Moore's "law," they certainly provide grounds for viewing the era of guided munitions as qualitatively distinct from the preceding era of unguided munitions in two ways. Massive application of munitions is no longer needed to compensate for the lack of accuracy, and actual combat conditions no longer dramatically degrade munition effectiveness.

Figure 35: SDB I

Four additional points may help the reader reach his or her own judgment as to whether the evolving conventional guided-munitions regime constitutes enough of a break from the era of unguided munitions to constitute a revolution in military affairs. First, as Figures 31 and 34 make evident, accuracy is no longer much of an issue. Indeed, one could consider it more or less a solved problem, at least in the case of fixed targets.

Second, as the expenditure data in Figure 4 documents, American military practice is moving toward increasing reliance on guided munitions for both strike operations and indirect fire support. If one asks exactly what is the basis for this broad trend, the short answer is that, starting in 1991, major US campaigns have exhibited order-of-magnitude reductions in the quantities of unguided munitions being employed. If anything, the reliance of guided munitions has been even more pronounced in smaller operations such as Southern Watch and Desert Fox. Among other things, moving in this direction has greatly reduced collateral damage and civilian casualties.

Third, as American military practice has moved slowly from the unguided-munitions into the guided-munitions era, the door has been opened to new ways of fighting rather than just making old forms of force-application more efficient. In late 2001, the combination of guided munitions, some dozen Special Operations Forces "A teams," along with Central Intelligence Agency covert operatives and indigenous Afghani opposition forces, were able to overthrow the Taliban in a matter of weeks without inflicting appreciable damage on the country's already threadbare infrastructure.[10] Offhand, one is hard-pressed to envision how this remarkable and unexpected result could have been achieved without guided munitions and battle networks even if its complete causal basis involved several other factors.[11]

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[10] Sean Naylor, *Not a Good Day To Die: The Untold Story of Operation Anaconda* (New York: Berkeley Caliber Books, 2005), p. 126. Stephen Biddle has argued that the US rapid success in Afghanistan may be less a potentially novel and widely applicable way of fighting than some have been inclined to suppose, including defense secretary Donald Rumsfeld (Stephen Biddle, "Afghanistan and the Future of Warfare," *Foreign Affairs*, March/April 2003, pp. 31-32; DoD, "Secretary Rumsfeld Delivers Major Speech on Transformation," January 31, 2002, accessed May 26, 2006, online at <http://www.defenselink.mil/speeches/2002/s20020131-secdef.html>). On the other hand, even Biddle concedes that precision air power was a "necessary," if "far from sufficient," condition for "turning a stalemated civil war into a Taliban collapse in a few weeks" ("Afghanistan and the Future of War," p. 32).

[11] For Biddle's more extended analysis of the roots of American success in Afghanistan, his *Afghanistan and the Future of Warfare: Implications for Army and Defense Policy* (Carlisle, PA: Strategic Studies Institute, November 2002). Biddle's thrust is to emphasize the continuities of Enduring Freedom's outcome with the past while minimizing the discontinuities stemming from the arrival of a guided-munitions regime. By contrast, Rumsfeld's speech in

Nor is Afghanistan the only example of new ways of fighting. In surveying the evolving relationship between ground power and air power in five recent conflicts (ODS in 1991, Bosnia in 1995, Kosovo in 1999, OEF in 2001, and OIF in 2003), David Johnson concluded that air power employing guided munitions and advanced sensors has shown "growing levels of effectiveness and robustness and played commensurately growing roles"—despite the fact that American doctrine, particularly Army doctrine, is not still being revised to "accommodate this new reality."[12] To return to the major-combat phase of Operation Iraqi Freedom, the on-call availability to US ground forces of munitions such as JDAM, day or night, in good weather or bad, together with the ability of systems such as Joint STARS to track individual enemy vehicles during intense sand storms, provide strong evidence of a changed relationship between ground and air power. This evolving relationship seems to be the direct result of how much overall progress the American military has made in embracing the emerging era of guided munitions.

Fourth, guided munitions pose the same problem for the defense of discrete targets as did nuclear weapons: namely, that if just one munition gets through the defenses, there is a high probability that the target will be seriously damaged or destroyed. In the case of atomic and thermonuclear weapons, the yield of the warhead—typically measured in kilotons or megatons of chemical explosives—compensated for any lack of accuracy (albeit at the cost of widespread collateral damage). Modern non-nuclear guided munitions such as LGBs, JDAMs, and TLAMs eliminate the horrific collateral damage inherent in nuclear weapons, but the defender's problem remains essentially the same. From the attacker's point of view, therefore, punching through active defenses is simply a matter of focusing a large enough salvo size against a given target to ensure that one or two munitions will get through. This tactical circumstance explains why the contemporary guided-munitions regime has been so lopsidedly offense dominant.

January 2002—admittedly before Anaconda—emphasized the discontinuities and novelty of Enduring Freedom. When all is said and done, these divergent perspectives simply recapitulate the difficulties of distinguishing evolutionary from revolutionary change raised in Chapter II.

[12] David E. Johnson, *Learning Large Lessons: The Evolving Role of Ground Power and Air Power in the Post-Cold War Era*, (Santa Monica, CA: RAND, 2006), pp. 137-138.

Of course, there remains one important difference between nuclear weapons and conventional guided munitions. With the development of ICBMs and SLBMs, it became possible for the United States and the Soviet Union to bring to bear literally thousands of thermonuclear warheads at intercontinental ranges within very short periods of time. As the Chapter IV discussion of the high unit prices of TLAM and CALCM point out, however, cost more or less independent of the range to the target has not been achieved by the United States with non-nuclear guided munitions. For targets not too distant from the platforms launching, firing, or releasing guided munitions, the US military currently would have little trouble mounting salvo sizes large enough to overcome missile or close-in defenses. With SDB's reach, doing so is feasible out to target ranges of at least 60 nautical miles. Currently, though, cost-per-round remains a significant constraint on salvo size at maximum TLAM and CALCM ranges save for very small numbers of targets.

While this author is unquestionably inclined to see these points as strongly suggestive of discontinuous, revolutionary change in the conduct of war, they neither do, nor can, *prove* the point. Despite Andrew Marshall's emphasis in the second quotation at the beginning of this chapter on the time required for new operational concepts and organizational relationships to emerge in military institutions, a transition period spanning a good five or six decades is long enough for skeptics to insist that the transition from the era of unguided munitions to that of guided munitions was evolutionary. The element of arbitrariness inherent in any application of the evolutionary-revolutionary distinction was the main point of Chapter II's discussion of evolutionary versus revolutionary change in human affairs. The reader is therefore free to reach his or her own judgment concerning the degree of transformation associated with the guided-munitions era into which the American military has been moving for six decades. What does not appear debatable, though, is that in terms of how wars are fought, the era of guided munitions is quite different—qualitatively different—from that of unguided munitions and aimed fires. The most telling example, once again, is the outcome of open combat between Iraqi and American forces in March-April 2003. As Robert Work has observed, against US guided munitions and battle networks, the industrial-age heavy forces of the Iraqi army were virtually reduced to an array of targets and aim-points waiting to be serviced.

Drivers and Causation

Chapter I suggested that the number of dimensions in which the prospective target can maneuver to evade being hit by aimed-fire weapons constituted the principal determinant of whether a given war-fighting community was an early adopter of guided munitions. The US Navy's adoption of guided torpedoes after World War II and the persistence of the Air Force and Navy fighter communities in developing effective radar-guided, air-to-air missiles exemplify need to shift from aimed fires to guided munitions against targets able to maneuver in three dimensions. As Chapter III showed, during the Cold War American SSNs seeking to engage Soviet SSBNs in situations in which escalation to nuclear war was a possibility had no viable alternative to guided torpedoes targeted with acoustic sensors. The ability of targets to maneuver in three dimensions also explains two other instances of the early adoption of guided munitions: the commitment of the US Navy's surface community to naval SAMs and the US Army's air defenders to early SAMs like Nike for continental air defense and, currently, to Patriot for theater air defense.

Reflection on some of the other cases in Chapters III and IV, however, suggests that the number of dimensions in which the target can maneuver does not offer a *complete* account of the reasons individual war-fighting communities ultimately shifted to guided munitions—particularly in cases of delayed or late adoption. Range to the target also appears to have been a factor in at least a few instances. The rapid acceptance by infantrymen of the TOW and similar anti-tank guided missiles probably had less to do with the number of dimensions in which an enemy tank could maneuver than the desire of soldiers to be able to stop advancing armor from a "standoff" distance. Similarly, *fixed* surface targets do not maneuver at all, but hitting them with a terrain-hugging cruise missile launched from a distance of 1,000 nm is unlikely to be viable without both en route and terminal guidance. In some instances, then, distance to the target alone provided the elusiveness that, in the earliest cases, arose directly from the number of dimensions in which the target could maneuver to avoid aimed fire. Much the same point was made in Chapter IV about hardened aircraft shelters in Iraq during Operation Desert Storm and the Novi Sad Bridge in Serbia during Operation Allied Force. Both target types demanded the extreme accuracy first realized by LGBs but both were fixed. The characteristics of these targets that demanded accuracies of 3-meters or less did not arise from spatial maneuverability but from “elusiveness” in a different, but broader, sense than that faced by the submariners or fighter pilots.

This broadening of the causes underlying the inclinations and timing of military communities to embrace guided munitions (and battle networks) requires an additional caveat that is most apparent in the case of the US Army’s failure during the 1960s to succeed in replacing aimed fire from tank main guns with guided missiles. The situation facing the Army’s armored community regarding the primary armament for the main battle tanks that followed the M60A2—the M60A3 and the M1—was different from that of the submarine and fighter communities for two reasons. First, tank-on-tank engagements were more or less confined to a two-dimensional plane. Second, against the steel and ceramic laminate armors that began emerging in the early 1970s, depleted-uranium, fin-stabilized, discarding-sabot, KE penetrators proved a viable alternative out to ranges of at least three kilometers. So the existence of viable aimed-fire alternatives to guided munitions can also leave a military community in a position to persist with unguided solutions.

What influence might the number of dimensions in which the *attacker* is free to maneuver have on the need or incentive to embrace guided munitions? The shooter’s freedom to maneuver can certainly complicate the achievement of accuracy against point targets with aimed fire. However, the number of dimensions available to the target is more fundamental than the number available to the shooter. Why? Because the crews in attacking platforms can constrain or control their maneuvering at the point or moment of release. A classic example is manual dive-bombing. The skill in this technique lies in the pilot’s ability to have the pipper over the target and the plane unloaded while, simultaneously, achieving a specified dive angle and airspeed at the pre-computed release altitude above the ground. Prior to the advent of reasonably reliable and effective bombing computers, manual dive-bombing was not only the standard employment tactic against fixed-targets but, in the Pacific during World War II, proved fairly successful against Japanese surface combatants, most importantly against Japanese aircraft carriers.

Another example of shooters constraining their own movement to achieve accuracy can be seen in main battle tanks before the development of stabilized guns. The original US M60 and early production versions of the M60A1 did not have a gun stabilization system (although most M60A1s were eventually retrofitted with a stabilization system and the M60A3's main gun was fully stabilized in elevation and traverse). Without gun stabilization, the only way to achieve maximum accuracy was for the tank to stop prior to shooting. Gun stabilization enabled tanks to fire accurately while moving.

Both manual dive-bombing and tanks without gun stabilization argue that the attacker's freedom to maneuver in two or three dimensions is a secondary or tertiary motivation for adopting guided munitions. In platform-versus-platform cases, the primary driver is the number of dimensions in which the target platform can maneuver. The reason, once again, is that attacker can, when needed, constrain his or her movement, but the target, particularly in an arena as dynamic as air-to-air combat, remains free to use maneuverability to avoid being hit.

Of course, this conclusion should not be construed as implying that guided munitions have no influence on or connection with the shooter's maneuver requirements. At a basic tactical level, munitions whose accuracy is independent of the distance to the target—at least out to the weapon's maximum range—enable the attacker to engage the target from outside the close-combat arena. It is precisely this fundamental feature of guided munitions that underlies the view raised in Chapter I that one long-term trend in warfare is a movement away from close combat with aimed fires toward engagement from a distance with guided munitions. In this context, suicide bombers and ambush tactics by insurgents or terrorists can, and should, be understood as ways of slipping around the growing lethality and effectiveness of long-range fires based on guided munitions.

There is another way in which guided weapons may ease the maneuver requirements of attackers or shooters employing them. Prior to the advent of the all-aspect AIM-9L, aircrews trying to employ the Sidewinder missile had to maneuver their aircraft into a cone projecting from the rear of the opposing fighter. Against an enemy fighter flying straight-and-level, the early Sidewinder's envelope was symmetric and the attacker had to be within 15-30 degrees angle off the target depending on range. But, if the defender began to turn into the attacker, the size of the available envelope not only shrank, but its shape changed with the majority of the envelope being pushed to the outside of the defender's turn.[13] With the advent of the AIM-9L, the maneuver requirements for a valid Sidewinder shot were reduced, effectively, to a point-and-shoot problem for the attacker. All the attacking pilot had to do was to get the nose of his fighter on the opponent and, when within range, shoot.

To summarize, the most comprehensive description of the drivers behind if and when a war-fighting community embraces guided munitions is the *elusiveness* of the target. In the platform-versus-platform cases, this elusiveness generally hinges on number of dimensions in which the opponent or target can maneuver spatially. The cases in Chapter III argue that communities faced with situations in which the adversary could maneuver in three dimensions are the most likely to be early adopters of guided munitions. However, as these cases also show, this motivation is by no means the end of the story from a causal perspective. Chapter IV's surface-attack cases demonstrate that even fixed targets can be elusive in other ways than maneuverability. Mobile missile launchers exploit mobility to make themselves elusive in a temporal sense by moving rapidly from "hides" to briefly occupied launch positions and, then, quickly fleeing after firing their missiles. Furthermore, the perceived urgency of target elusiveness can be mitigated by the institutional inclinations of war-fighting communities to stick with proven, battle-tested weapons, operational concepts, and organizational arrangements. As the naval historian Elting Morison observed:

> Military organizations are societies built around and upon the prevailing weapons systems. Intuitively and quite correctly the military man feels that a change in weaponry portends a change in the arrangement of his society.[14]

If the target's spatial maneuverability is limited or the tactical problem is not viewed as urgent, and if there are viable alternatives using existing methods and aim-fire weaponry, then the chances are low that a war-fighting community will be an eager, early adopter of guided muntions.

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[13] John R. Boyd, *Aerial Attack Study 50-10-6c* (Nellis AFB, NV: USAF Fighter Weapons School, August 11, 1964), pp. 42-48.

[14] Elting Morison, *Men, Machines, and Modern Times* (Cambridge, MA, and London: The MIT Press, 1966), p. 36.

Consider, once again, the US Air Force's resistance to embracing LGBs during the 19-year hiatus between their spectacular success in 1972 and the even greater efficacy they demonstrated in 1991. The smart-jet, dumb-bomb alternative that emerged with CCIP on the F-16, together with the prevalence in Europe of weather or visibility too poor for LGB employment, seemed, during the late 1970s and 1980s, to be justification for sticking with cheaper, unguided munitions. Only in 1991 did combat experience drive home to the Air Force's fighter community that the smart-jet, dumb-bomb "alternative" was not viable unless pilots released from low altitudes, which meant operating well within the lethal envelopes of AAA and IR SAMs and accepting higher losses to achieve accuracy. A lesson of Operation Desert Storm was that F-117s with GBU-27s, TLAMs, and CALCMs all provided viable alternatives to the dilemma faced by F-16s and F/A-18s with dumb bombs of either releasing too high for accuracy or going lower and accepting otherwise avoidable attrition to low-altitude air defenses. In the case of the F-117, the platform proved capable of attacking even the best-defended targets with near impunity *prior* to rolling back the opponent's integrated air defenses. Stealth plus precision provided a better tactical solution than continuing to use unguided munitions, which was the Air Force's inclination prior to 1991. So while target elusiveness is the overarching causal driver underlying if and when a warfighting community embraces guided munitions, those decisions are also affected by the interplay between unguided alternatives and the cultural proclivities of military communities to stick with known, proven weapons and methods.

Diffusion and Reproducibility

At the very end of Chapter II, the question was raised as to the reproducibility of the guided-munitions regime developed by the US military over the last the last six decades. This question emerged from the observation that no other nation can currently come close to fielding capabilities for prompt precision strike on a global basis comparable to those of the United States. Is this American dominance a temporary anomaly or is it likely to persist? Is the US position in this new "business" more akin to carrier aviation during the Cold War or to *Blitzkrieg* after 1940?

In the RMA debates of the 1990s, the Polish and French defeats in 1939 and 1940 by the Germans were frequently cited as examples of the potential price to be paid by militaries that failed to embrace new means and ways of fighting, in this instance *Blitzkrieg*. A related piece of conventional wisdom is the notion that new weaponry and war-fighting methods are likely to spread easily and rapidly. Neorealist international-relations theory generally assumes that "competition among states inevitably causes pioneering military methods to diffuse rapidly among states."[15]

However, as Emily Goldman and Leslie Eliason have rightly pointed out, the process of military diffusion has not been studied very thoroughly by theorists, and the historical record "reveals far more variation in adoption and emulation across states and cultures than conventional international relations theory assumes."[16] Their recent comparative study of the subject observes that the "extant literature posits four motivations" for military diffusion between nations: (1) "strategic necessity" in the sense of follower nations adopting new means or ways of fighting to avoid catastrophic defeats of the sort that befell the Poles and French; (2) "economic pressures" from a nation's defense, industrial, and financial communities or other power centers inclined to push military innovation; (3) "technology-push dynamics," which may either encourage or impede the adoption of new ways of fighting depending on such things as the capital investment or supporting infrastructure needed; and (4) "institutional pressures" in the sense of existing bureaucracies or institutions using innovation to enhance their autonomy, prestige, claim to resources, and so forth.[17]

What is immediately striking about these traditional explanations for the spread of new weapons and ways of employing them is how inadequate they appear to be in explaining the diffusion of guided munitions in the cases covered in Chapters III and IV. Granted, with the exceptions of America's continuing development of certain guided weapons pioneered by the Germans and the late fielding of Harpoon by the US Navy, the cases in this report do not focus on military diffusion

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[15] Leslie C. Eliason and Emily O. Goldman, "Introduction: Theoretical and Comparative Perspectives on Innovation and Diffusion" in Goldman and Eliason (eds.), *The Diffusion of Military Technology and Ideas*, p. 8.

[16] Eliason and Goldman, "Introduction: Theoretical and Comparative Perspectives on Innovation and Diffusion," pp. 7, 8.

[17] Emily O. Goldman and Andrew L. Ross, "The Diffusion of Military Technology and Ideas—Theory and Practice" in *The Diffusion of Military Technology and Ideas*, pp. 373-374.

across national boundaries. Instead, the diffusion at issue is largely about staying with conventional aimed fires or adopting guided munitions by various segments *within* the US military. Nevertheless, the primary motivations for these decisions during the last six decades examined in the previous section are not even mentioned in the concluding chapter to the study of military diffusion edited by Goldman and Eliason.

Take the case of LGBs. From the standpoint of the US tactical aircrews trying to interdict the flow of men and materiel from North to South Vietnam, the inability during Rolling Thunder to drop the Thanh Hoa Bridge was not only immensely frustrating but a direct threat to their survival. The tactical problem epitomized by this overbuilt structure meant that aircrews were tasked time and again to return it, thereby repeatedly risking their lives and aircraft for at most temporary disruption of rail and truck traffic across the bridge. At the same time, developmental work, first at the Army's Missile Command and later at Eglin AFB on laser guidance, produced what emerged as a viable solution to a whole range of point targets requiring "near-zero-miss" accuracy. This tactical, problem-solving impetus for the original development of LGBs seems to explain what happened far better than the four "motivations" offered in the final chapter of the Goldman-Eliason study. At a minimum, this observation suggests that existing diffusion theories driven by competition among nation states may still need some work. Of course, an alternative—and probably more plausible—conclusion is that the diffusion of military technologies and ideas is a non-ergodic process in the sense explained in Chapter II in discussing Douglass North's views on the process of economic change. In other words, a deterministic, ergodic theory of military diffusion may not be possible due to both the enormous variability of the phenomena involved and the pivotal role that the belief systems of military cultures can play in the diffusion process.

However one may feel about this conjecture, the cases examined in this report do support another conclusion of the Goldman-Eliason study. In the final chapter, Goldman and Andrew Ross observe that "the cultural dimension of the diffusion process remains significant."[18] Not only can institutional cultures be major impediments to the adop-

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[18] Goldman and Ross, "The Diffusion of Military Technology and Ideas—Theory and Practice," p. 391.

tion of promising weapons and new ways of fighting, but they also tend to produce indigenous adaptations whose shape, details, and efficacy are hard to predict. John Lynn's analysis of the cultural resonance between British and Indian society, and how the East India Company exploited that resonance to create the fine Sepoy soldiers of the British Empire is particularly illuminating in this regard.[19] The creation of a native army that by the 1880s outnumbered British troops in India, as well as the development of a pro-British educated elite to administer the crown colony, goes far to explain how the British managed to run a global empire "on the cheap."[20]

Chapters III and IV provide considerable evidence that institutional cultures can be as important in embracing or resisting new means and methods of fighting *within* national militaries as they are *across* national boundaries. Again, it took nearly two decades after Linebacker I for the US Air Force to embrace PGMs as wholeheartedly as the Navy's submariners had done in the case guided torpedoes after World War II, and cultural resistance to the changes portended by guided munitions in the TAC fighter community appears to have been a major factor in the USAF's institutional foot-dragging from 1972 to 1991. Thus, there is every reason to think that Goldman, Eliason, and Ross are right to underscore the significance of institutional cultures in the adoption of or resistance to new weaponry, operational concepts, and organizational adaptations.

Regarding the community-by-community absorption of guided munitions and sensor-targeting networks by the American military over the last six decades, however, the most glaring departure from conventional thinking about military diffusion is that true reconnaissance-strike complexes have not yet diffused appreciably outside the United States. If the first criterion for diffusion is the development by other countries of a capability to mount conventional precision strikes anywhere on the globe on short notice, one could argue that appreciable diffusion has not really begun despite the fact that most of the ele-

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[19] John Lynn, "Heart of the Sepoy: The Adoption and Adaptation of European Military Practice in South Asia, 1740-1805," in *The Diffusion of Military Technology and Ideas*, pp. 33-62.

[20] Niall Ferguson, *Empire: The Rise and Demise of the British World Order and the Lessons for Global Power* (New York: Basic Books, 2003), pp. 173-174, 184-191, 245.

ments of RUKs were first demonstrated in combat in 1991. This is not to imply that both US allies and prospective adversaries have failed altogether to adopt guided weapons such as LGBs or other elements of RUKs on a local or, possibly, regional basis. But in terms of *prompt, all-weather* precision strike anywhere on the globe, not only does the US military currently stand alone, but there is little indication that any other nation will field a comparable capability in the foreseeable future.

The reason for this unusual situation is, of course, the enormous resource burden of independently reproducing such a capability. Electro-optical reconnaissance satellites, the GPS constellation, B-2 bombers, Joint STARS and other air-breathing reconnaissance platforms, F-22s, TLAMs, and CALCMs illustrate both the up-front costs of developing a robust capacity for near-real-time global strike, and the ongoing costs of sustaining it. The simple fact appears to be that for perhaps another decade or two, the United States may well be the only nation able to afford RUK-like systems and capabilities.

If this conclusion is correct, then it dramatically narrows the strategic options available to prospective US adversaries. Head-to-head competition with the American military in long-range precision strike is simply out of the question for countries such as North Korea or Iran, and the desire of Pyongyang and Teheran to develop nuclear weapons becomes understandable as a way of guaranteeing the survival in power of the regimes currently running these countries. In the long term, the leaders of the People's Republic of China (PRC) may aspire to emulate American RUKs, but for the next 10-20 years they are more likely to concentrate on incorporating elements of precision-strike systems into a sufficiently robust anti-access/area-denial capability to hold US forces at arms length.

The other strategic alternative available to prospective American adversaries is, of course, to adopt the terrorist tactics of al Qaeda and the rapidly evolving ambush methods of the insurgents in Iraq as ways of inflicting death, casualties, and destruction on Western forces and nations while avoiding their formidable precision-strike and traditional military capabilities. The unpleasant reality underlying this approach is the growth in recent decades of the lethality of small dissident groups. As Martin Shubik observed in 1998, since the mid-twentieth century the numbers of dead and wounded that "a small, organized group of, say, 10 to 20 trained, dedicated individuals" could inflict in a single action appears to have grown exponentially.[21] Moreover, since this capability, like nuclear weapons, cannot be un-invented, it is likely to remain an enduring option for the disaffected for future decades, if not centuries, to come. Even worse, the exercise of terrorist options by non-state actors against civilian targets in Western homelands appears to be far more difficult to deter than was Soviet nuclear use during the Cold War. An even more frightening possibility is that such groups will eventually gain access to atomic weapons.

To be clear, these disturbing, highly asymmetric options appear, so far, to be the only military options available to nations such as Iran or terrorist organizations such as al Qaeda and its affiliates. Iran, for example, has now witnessed two demonstrations of the lethality and effectiveness of the US military in traditional open battle—most recently during the rapid overthrow of Saddam Hussein's Ba'athist regime in March-April 2003. As much as Western political leaders and societies might wish it otherwise, such demonstrations give the Iranian leaders powerful incentives to acquire nuclear weapons to deter US conventional supremacy. In the current international security environment, nuclear weapons are "the logical asymmetric weapon of choice for nations that which to confront the United States."[22] As attractive and effective as guided munitions have been in solving a series of operational problems that have confronted the US military since the end of World War II, the accumulation of those capabilities across a growing number of conventional war-fighting areas has had some surprising and unintended consequences in the decade and a half since the break-up of the Soviet Union.

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[21] Martin Shubik, "Terrorism, Technology, and the Socioeconomics of Death," Cowles Foundation for Research in Economics at Yale University, Cowles Foundation Paper No. 952, 1998, pp. 406-407; available at <http://cowles.econ.yale.edu/P/cp/p09b/p0952.pdf>, accessed October 1, 2006.

[22] S. Enders Wimbush, "The End of Deterrence: A Nuclear Iran Will Change Everything," *The Weekly Standard*, January 11, 2007, online at <http://www.weeklystandard.com/Content/Public/Articles/000/000/013/154auoqp.asp>, accessed January 2007. Henry A. Kissinger has made the same point: see his "Iran: A Nuclear Test Case," *The Washington Post*, March 8, 2005, p. A15.

Characteristics of the Precision-Strike Regime

Chapter II ended by posing seven specific questions about the evolving guided-munitions era. Most of these questions were originally raised by Andrew Marshall and Charles Wolf in the report on the future security environment that they produced in support of Commission on Integrated Long-Term Strategy in the late 1980s, which was chaired by Fred Iklé and Albert Wohlstetter. Marshall, who has been the Pentagon's Director of Net Assessment since his appointment by James Schlesinger in October 1973, reiterated most of these questions in 2003 during discussions of the initial research that gave rise to this report. Given the conclusions reached to this point regarding guided munitions in conjunction with their associated targeting networks and supporting infrastructure, the present juncture seems an appropriate place to address these questions one-by-one.

The suggestion offered at the beginning of this chapter regarding whether or not the maturation of guided munitions and battle networks constitutes enough of a leap forward or discontinuity to warrant being categorized as a revolution in military affairs was to review the evidence but leave final judgment to the individual reader. The only point worth adding at this juncture concerns war's nature versus war's conduct. Regardless of whether one assesses the evolving guided-weapons era as evolutionary or revolutionary, that judgment does not alter war's fundamental nature, which remains, as Clausewitz observed, a "continuation of political intercourse, with the addition of other means." While this point was advanced early in Chapter II, it has been overlooked or ignored enough times in American RMA discussions to merit reiteration.

Have guided munitions given rise to new operational concepts or organizational arrangements? The least controversial part of this question to address is that of new operational concepts. Time-sensitive targeting (TST), to use a later term of art, emerged during Operation Allied Force as "flex targeting," which was a systematic approach employed by the Combined Air Operations Center (CAOC) to strike new targets as rapidly as possible.[23] In the case of the B-2, which generally took 14 hours to fly from Whiteman AFB to Serbia, the rule that emerged in the CAOC was that new targets had to be passed to the inbound aircrew an hour before their arrival time over the tar-

[23] Grant, *The B-2 Goes to War*, pp. 78-79.

get.[24] During Operation Enduring Freedom in late 2001, the ROE required approval from the secretary of defense in order to strike most emergent targets—a requirement that sometimes imposed significant delays in getting ordnance on target. By Operation Iraqi Freedom in 2003, though, these sorts of procedural delays had been greatly reduced. The April 7 B-1 strike against Ba'ath Party leadership in Baghdad's al-Mansour district showed that the CAOC's TST cell had driven the time from the decision to attack to JDAMs on target down to 12 minutes. Moreover, the capacity to change targets after strike aircraft had been launched grew dramatically from 1991 to 2003. During Operation Desert Storm only 20 percent of the sorties received their targets or had them changed after launch; during Operation Iraqi Freedom initial data showed that more than 90 percent of sorties received updated target information en route.[25] Time-sensitive targeting on this scale would appear to qualify as a new operational concept associated with guided munitions and their sensor-and-targeting networks.

Have guided munitions begun changing the planning of military operations or altered the kinds of operations being executed? Arguably, the rise of TST answers the part of the question about changes in the kinds of operations being conducted. As for changes in the planning of operations, the shift from sorties-per-target to target-per-sortie speaks to the other part.

Are guided munitions and battle networks altering the allocation of roles or missions between or within military services? David Johnson's assessment of the changing role of land power and air power in the area of indirect fires certainly argues that the division of labor between the US Army and the US Air Force ought to be changing based on guided-munitions developments. However, as he also has observed, cultural factors stemming from the reluctance of these two services to trust one another has, as of this writing, remained a powerful barrier to the accommodation of this new reality in American military doctrine, particularly in US Army doctrine.[26]

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[24] Grant, *The B-2 Goes to War*, p. 80.

[25] HQ USAF/XPXC, *The U.S. Air Force Transformation Flight Plan*, November 2003, p. 54.

[26] Johnson, *Learning Large Lessons*, pp. 137-138.

Does the growing reliance of the US military on guided munitions mean that militaries able to employ them in significant quantities will increasingly move away from close combat whenever and wherever possible? Most operational communities in the American military have, reluctantly or not, embraced guided munitions, or have committed themselves to doing so in future. Those communities still showing signs of resistance appear to be mainly in certain branches of the ground forces. But even in these cases, there are indications of a willingness to move deeper into the unfolding guided-munitions regime. For example, the Army's plans to develop "transformed," modular units equipped with its Future Combat Systems family of advanced sensors, munitions, and vehicles currently envisions heavy reliance on guided missiles and smart rounds.[27] Given the continuing inclination of the Defense Department to minimize collateral damage and civilian casualties, it is increasingly difficult to make compelling arguments for the massive employment of munitions that mostly miss their targets and aim-points—even if there may still be occasions when suppressive fires with dumb rounds offer the handiest solution for what may be a shrinking set of tactical situations. The overarching trend, then, seems clear. Especially in light of the longstanding American preference to substitute technology for friendly casualties to the greatest extent possible, it seems likely that US forces will increasingly prefer to avoid close combat with aimed fires. Again, guided weapons and battle networks make this approach more and more feasible.

Might one consequence of guided munitions and networks be to drive increased levels of coordination and integration between diverse force elements, even they are if widely separated? In the case of the Army's Stryker BCTs, greater dispersion of increasingly distributed force elements already appears to be well underway. Experience to date in Iraq tends to confirm the results of the 2003 Stryker CERTEX and OPEVAL at the Joint Readiness Training Center, which indicated that the increased SA of this networked force provides an order-of-magnitude improvement in effectiveness when compared with a non-digitized light-infantry brigade.

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[27] See Charles A. Cartwright and Dennis A. Muilenburg, "Future Combat Systems—An Overview" at <http://www.army.mil/fcs/articles/index.html>, accessed October 6, 2006.

Finally, might guided munitions and battle networks reinvigorate offensive strategic warfare in the sense of rendering exchanges with long-range weapons against vital target systems between major powers once again "thinkable"? Presently it is impossible to answer this question with much more than conjecture. The reason stems from the resource barriers to other nations emulating or replicating US capabilities for prompt, global precision strike. Until such a "peer" competitor begins to emerge, it will be difficult to give a confident answer to this question.

Having explicitly addressed the questions raised at the end of Chapter II, what are some of the other prominent features of the precision-strike regime? One interesting trend is that, as accuracy and reliability have improved, there has been an inclination to move toward guided munitions with smaller and smaller warheads. During the Second Indochina War, the majority of LGBs were 2,000-lb class munitions, and the USAF even employed some 3,000-lb LGBs. In Operation Desert Storm, nearly half of the laser-guided bombs expended by US forces were 500-lb class GBU-12s. During Operation Iraqi Freedom in 2003, over 80 percent of the LGBs expended were GBU-12s, although 2000-lb class warheads did predominate in JDAM expenditures. Currently, the 250-lb class SDB gives every indication of continuing this trend toward smaller warheads for precision attack.

There appear to be a couple reasons behind this trend. One, of course, stems from concerns over collateral damage. During Operations Northern and Southern Watch, which enforced no-fly zones over Iraq from the 1991 Gulf War to 2003, some non-explosive (inert) concrete shapes were substituted for explosive warheads in LGBs to allow Coalition aircraft to attack Iraqi air defenses positioned next to mosques, schools or other buildings that would have been off-limits to munitions even with Mark-82 warheads. The other principal driver behind this trend seems to be magazine capacity. This constraint has already been mentioned in the case of the Navy's aircraft carriers. Obviously a carrier's magazine can hold more 500-lb or 1,000-lb warheads than larger 2000-lb ones. As for the Air Force, the SDB's small size has been dictated by the limited space inside the F-22's main weapon bays, which were originally designed for air-to-air missiles rather than air-to-ground ordnance. Understandably, eight SDBs are viewed as a superior load-out for ground attack than two 1,000-lb JDAMs the F-22's weapon bays can accommodate.

In the future, a logical extension of this trend could be the emergence of so-called "non-kinetic" attacks to supplement those executed with traditional warheads, whether explosive or inert. This possibility appears to make the most sense in considering how best to defend against strikes from US battle networks employing guided munitions. As has already been mentioned, the guided-munitions era has been heavily offense dominant, meaning that strike forces have usually been able to get through integrated air defenses one way or another, despite ongoing improvements in radar-guided SAMs and their associated sensor networks. Future adversaries confronted with American reconnaissance-strike complexes may, therefore, pursue non-kinetic attacks against US battle networks as a more promising option, or supplement, than an exclusive dependence on active defenses. Besides indicating a possible direction in which the guided-munitions regime may evolve, this prospect also suggests that it might become more difficult in the future to distinguish clearly between precision attacks and information operations.

Prospects for Change: Robotics, Directed Energy, Precision Information

What else can be plausibly said about the future course of conventional guided munitions and battle networks—especially in the longer term? There appear to be three main prospects for major change: robotics, directed-energy weapons (DEW), and improvements in the targeting information available for precision attack. The emergence of the kinds of more-autonomous robotic systems currently envisioned seem likely to reinforce the current guided-weapons regime rather than precipitate ways of fighting dramatically different from those of the last six decades. The same is true of improvements in the information content of guided weapons. By contrast, laser weapons—as opposed to laser illuminators, range-finders, or sensors—promise to propel the military forces fielding them into an entirely new war-fighting regime.

Currently the most promising technology demonstration program for developing a truly autonomous robotic weapons is probably the Low Cost Autonomous Attack System. Robotic combat systems already exist. An AIM-9 Sidewinder, once launched at an enemy aircraft, is entirely autonomous in the sense of functioning on its own without human control or intervention. But even today the constraints within which a Sidewinder can be employed are quite narrow.

Among other things, the pilot of a fighter employing it has to put the heat source from the target within the field of view of the AIM-9's seeker. The pilot also had to be within the Sidewinder's maximum and minimum range parameters before firing if the munition is to have any chance of scoring a kill. The significance of LOCAAS is it relaxes significantly the very tight constraints within which "robotic" munitions such as Sidewinder currently operate.

Figure 36: LOCAAS

As mentioned in Chapter I, LOCAAS is a DARPA-USAF advanced technology demonstration. Figure 36 shows the current vehicle configuration as well as an actual test against an SA-8 SAM. Since 1998, the LOCAAS ATD has sought to develop the technologies for an affordable, standoff munition that can autonomously search for, detect, identify, attack, and destroy a variety of targets, including mobile ballistic missile launchers, SAMs, and armored vehicles using a catalog of on-board target signatures. Key technologies include a laser detection and ranging (LADAR) seeker, autonomous target recognition (ATR) and a multi-mode warhead. Performance goals include a standoff range of 100 kilometers, a search area of 50 square kilometers per munition, and high probability ATR with a low false target rate. While the ATR algorithms were viewed as the most challenging part of the ATD, this part of the demonstration appears to have been surprisingly successful.

As for unit cost, in late 2005 the LOCAAS program manager at Lockheed Martin estimated that the average unit-procurement price would be around $75,000 a round based on a buy of 50,000 rounds.[28] This unit cost is a considerable increase over the original estimate of $33,000 in FY 1998 dollars that DARPA set as a target production

[28] Myron Mills, "RE: LOCAAS Update," email to Barry Watts, November 7, 2005.

price when the LOCAAS transitioned from an unpowered to a powered munition. On the other hand, even at $100,000 per round it would still be a bargain compared to a CALCM or TLAM—especially if the ATR algorithms are robust and reliable.[29]

Regarding operational utility, consider the challenge of targets as elusive as mobile ballistic missile launchers. As the Air Force discovered during Operation Desert Storm, mobile launchers that only come out of "hides" long enough to fire from pre-surveyed sites and then quickly disappear can be a very difficult target. After ODS, Gulf War Air Power researchers were unable to confirm beyond reasonable doubt that a single Iraqi "Scud" missile launcher had been destroyed by Coalition fixed-wing aircraft despite aircrew wartime claims of around 100—a box score that probably exceeded Iraq's total inventory by a factor of four. Potentially, then, a munition like LOCAAS, which could be dispensed in quantity over a broad area to search out and attack such targets, could go a long way toward providing a solution to elusive missile launchers, particularly if an adversary's tactics involve attempting to fire scores of missiles within a short period of time to overwhelm any terminal defenses.

Nevertheless, as of this writing, all indications are that the Air Force is going to let LOCAAS die rather than moving it into production. While many DARPA programs have suffered the same fate, the core problem in this instance appears to be the cultural reluctance of senior military leaders to embrace a truly autonomous strike system. One piece of evidence for this view occurred after the powered-

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[29] Another DARPA robotics program has been to sponsor a nation-wide competition to develop fully autonomous vehicles capable of completing an under-300 mile, off-road course in the Mojave Desert. While the best-performing vehicle in the March 2004 "Grand Challenge" only managed to complete 7.4 miles of a 150-mile course, in October 2005 four entries completed the 132-mile course under the 10-hour time limit and a fifth finished in 13 hours. The software in the winner, Stanford University's "Stanley," employed a statistical pattern-analysis approach that enabled the vehicle to cope with incomplete and ambiguous data from its sensors (laser, video, GPS and odometer), an approach that came closer than traditional rule-based artificial intelligence to capturing "how humans think" (Joshua Davis, "Say Hello to Stanley: Robot Race Car Champion of the World," *Wired*, January 2006, pp. 135-136). While these vehicles are still a long way from fully autonomous combat robots, DARPA's success during the second race suggests that progress is being made toward developing intelligent systems.

LOCAAS ATD got underway in 1998. Although the whole point of the program was to demonstrate an *autonomous* munition that could search an area, identify targets, and attack them on its own, the unsettling contrast with the direct human oversight possible right up to the moment of impact in employing an LGB led the Air Force to insist that a data link be added so that a human could remain in the loop to preclude the robot from running amok.[30] Another piece of evidence for cultural resistance to genuinely autonomous strike systems was the Army decision to cancel the loitering attack missile associated with NLOS-LS. LAM was essentially a version of LOCAAS tailored to the "missiles-in-a-box" NetFires concept that has evolved into the NLOS-LS component of the Army's Future Combat Systems program. As mentioned in Chapter IV, the Army has evidently decided to drop LAM. Might the same worries about robots running amok that led the Air Force to add a data link to LOCAAS have led to LAM being dropped? While other considerations such cost may have contributed to the Army's decision, it appears that cultural resistance to robotic combat systems is affecting decisions about what guided munitions to develop in both the Army and the Air Force.[31]

In the long run, it seems inevitable that autonomous robotic combat systems will be fielded. One guesses that they will reinforce the offense-dominant aspects of the evolving precision-strike regime that this report has traced back to 1943. In the meantime, though, the main barrier to the fielding of truly robotic strike systems by the US military does not seem to be technological maturity. It may not even be unit cost. Instead it appears to lie in a cultural disinclination to turn attack decisions over to software algorithms, even within an area

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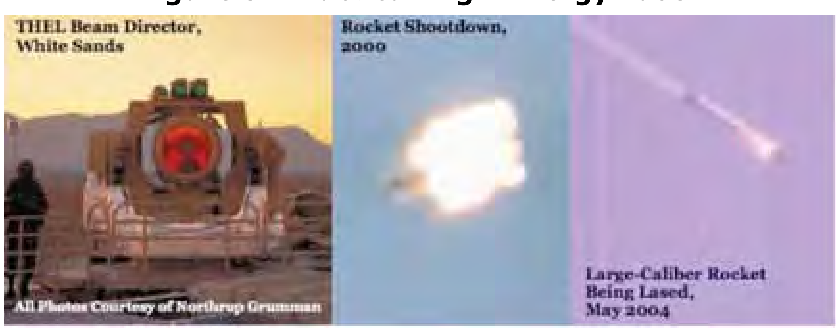
[30] In the case of an LGB, the time of flight is typically under 30 seconds, and by shutting off the laser illuminator a human operator can change the decision to hit the aim-point even within these last seconds. Given the industrial accidents, including human fatalities, that have occurred since manufacturing robots were introduced in 1981, the issue of robots running amok is a serious one. For a recent discussion, see "Trust Me, I'm a Robot," *The Economist Technology Quarterly*, June 10, 2006, pp. 10-11.

[31] As of February 2006, NLOS-LS was estimated by the Army to be a $1.3 billion development-and-demonstration program that included both PAM and LAM (Department of the Army, *Descriptive Summaries of the Research, Development, Test and Evaluation: Army Appropriation Budget Activities 4 and 5*, Vol. II, February 2006, p. 442). However, concerns about LAM's cost were reflected in this justification exhibit.

as small as 50 square kilometers. Whether potential adversaries such as the Chinese will have similar inhibitions remains to be seen.

From the standpoint of the current guided-munitions regime, directed-energy weapons appear, on balance, to be a disruptive technology that could eventually produce changes in the conduct of war that would be more radical and far-reaching than, say, the initial successes of *Blitzkrieg* during 1939-1940. Recall the observation at the end of Chapter III that the high speed of M1A1 rounds (over 1,600 meters/second) combined with the short distances over which they are fired (nominally 3-4 kilometers maximum) were critical to the continuing preference for aimed fires for tank-versus-tank engagements. The projectile speed and range involved produce a time interval between trigger squeeze and target impact in the vicinity of two seconds—not enough time for most targets to get out of the way. Directed energy offers the possibility of speed-of-light weapons, and they could not only breath new life into aimed-fire weapons, but, in an application such as the boost-phase intercept of ballistic missiles, extend the maximum feasible range of aimed, line-of-sight weapons to several hundred kilometers. Needless to say, laser weapons could radically transform the conduct of future warfare.

Figure 37: Tactical High-Energy Laser



The two main developments now underway to turn chemical lasers into useful weapons are the US Air Force's Airborne Laser (ABL) program and the US Army-Israeli Tactical High-Energy Laser (THEL) program. ABL aims at fielding a megawatt-class chemical-oxygen-iodine laser on a modified Boeing 747-400 airframe to provide boost-phase-intercept capability against ballistic missiles. According to the Missile Defense Agency, the first airborne test of the ABL is now scheduled for late 2008. THEL is a ground-based, tactical system.

The developmental test article at the White Sands Missile Range in New Mexico has shot down artillery and mortar rounds as well as some 122-mm Katyusha rockets both singly and in salvos of as many as three rounds. THEL uses a deuterium-fluorine laser to heat incoming projectiles until their warheads detonate, leaving the debris to fall short of the aim-point.[32] Current estimates are that, once deployed on a battlefield vehicle for mobility, each THEL vehicle would be capable of around a dozen shots before needing to be refueled. Given the massive rocket attacks mounted by Hezbollah against Israel during July-August 2006, some variant of THEL may well become the first battlefield laser weapon system to be fielded. However, to be capable of significantly larger numbers of shots before needing to be refueled, first-generation THEL systems designed to defend Israel against the kinds of projectiles used by Hezbollah would probably not be mobile and at least scores of firing units would be required to cover the entire country.

Looking a bit further ahead, solid-state lasers are being pursued to obviate the logistics burden chemical lasers would impose on mobile, battlefield weapon systems due to their refueling requirements. However, especially for mobile, battlefield systems using solid-state lasers, dealing with the heat gradients associated with operation of the laser has been the major obstacle to reaching outputs greater than 1,000 watts with decent beam quality. Lawrence Livermore National Laboratory and companies such as Northrop Grumman have been working on this problem. Currently the goal of their efforts is to demonstrate a 100-kilowatt solid-state laser in 2008. Nevertheless, for mobile battlefield systems, the cooling issue is likely to be a major constraint for some time to come. Additionally, solid-state lasers are unlikely to be "eye safe," which raises some complex employment problems in battlefield environments pervaded by Clausewitzian friction. These facts, together with the logistics burden of chemical lasers, suggest that there remain substantial technical challenges that lasers will have to overcome before they begin appearing in tactical weapon systems.

The technical challenges of useful laser weapons notwithstanding, their potential to change the conduct of war appears considerable.

[32] Significantly, the wave length of THEL's laser is far enough outside the visible light spectrum that it does not pose a risk of blinding humans.

Both ABL and THEL are defensive rather than offensive applications of high-energy laser technology. The existing guided-munitions regime has been heavily offense-dominant despite considerable investments over the years in defensive systems such as Nike, the Standard Missile family of naval surface-to-air missiles, and, in Russia's case, successive generations of SAMs ranging from the venerable SA-2 to the SA-10 and SA-20 (the S-300 and S-400 using Russian designations). One possibility is that speed-of-light, line-of-sight laser weapons with relatively deep "magazines" could, over time, begin to shift the balance between offense and defense increasingly in favor of the latter. If nothing else, the likely cost-per-shot would probably be at least an order-of-magnitude cheaper than an SM-2 or SM-3. A related possibility, already manifest in THEL, is that laser weapons could provide relatively leak-proof defenses against many guided munitions so long as weather or other atmospheric obscurations did not intervene.[33] While such disruptive changes may have to await the development of megawatt-class solid-state lasers, the potential for such far-reaching changes in how wars will be fought is certainly there.

For the time being, though, conventional military operations by US forces and those of close American allies are firmly implanted in an evolving guided-munitions era, and that era is by no means at an end. The central problem is no longer the accuracy or reliability of guided munitions. Certainly for the precision attack of all but the most elusive surface targets, accuracy independent of range to the aim-point can be considered a solved problem—even if much work still remains to be done to make per-round cost also relatively indifferent to range.

What is the remaining challenge in guided munitions? The short answer is to improve the information content of this class of weapons. Retired USAF Major General Jasper Welch made precisely this point a decade ago. At that time he foresaw at least one order-of-magnitude improvement in the lethality-per-ton of guided munitions expended being achievable based on progress in the better matching of warheads to individual targets, better timing of attacks to periods of high target vulnerability or value, and improving the ability to exploit the vulnerabilities of entire targets systems as opposed to that of individual tar-

[33] Since THEL would have to be cued by a sensor such as the AN/TPQ-36 or AN/TPQ-37 Firefinder radars, THEL would not be totally incapacitated by a cloud layer. On the other hand, to get useful targeting data for laser shots handed off from other sensors would also require a sophisticated network.

gets.[34] For example, it is far better to destroy a mobile-missile launcher before it has fired than immediately afterwards. Given the ongoing efforts of prospective adversaries to deny US forces this sort of high-quality targeting information, improvements down the path indicated by General Welch are more a two-sided competition over time than a technical problem to be solved. Nevertheless, he was surely correct in highlighting the information content of guided weapons as an area in which significant progress could still be made.

There are at least two ways of thinking about the information challenges that will confront guided munitions and battle networks in the foreseeable future. One perspective is to focus on the more difficult or information-intensive target classes. Consider, for example, moving targets. Although LGBs are limited to clear air, they have been used successfully against moving vehicles and even individual enemy combatants. All that is required is for the operator on the attacking platform to keep following the moving target with the laser spot up to the moment of impact. By comparison, a basic JDAM that homes exclusively on GPS coordinates cannot adjust for target displacement after release. To address the need for an all-weather capability against moving targets, DARPA and the Air Force instituted the Affordable Moving Surface Target Engagement (AMSTE) program. AMSTE has demonstrated the feasibility of using MTI sensors to provide the sufficiently real-time location information on moving vehicles and ships over a data link to enable a modified JDAM to hit them.[35] This view of the moving-target problem program, however, is a rather narrow, technical one.

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[34] Jasper Welch, "Prospects for Improvements in Lethality-to-Weight for Air-to-Ground Ordnance," unpublished paper written for the Northrop Grumman Analysis Center, August 19, 1996, p. 3.

[35] However, since JDAM is seekerless, the MTI sensors must be able to update the target's location during the time between munition release and target impact. The higher the update rate, the more accurate the JDAM can be against a moving target, but higher update rates entail higher-capacity data links. Because a vehicle moving at 25 miles per hour changes its location almost 37 feet every second, multiple updates per second are generally required to hit the vehicle. An attractive feature of LOCAAS and LAM is the prospect of avoiding the need for high-capacity sensor-to-munition data links by "offloading" terminal-phase target updates to the munition's ATR algorithms. Doing so also eliminates the possibility of the munition being defeated by enemy jamming of the data-link's frequency.

A more strategic perspective on the information challenges of the guided-munitions/battle-network regime can be gained from considering the likely demands of dominant contingencies in the near- to mid-term. In support of the Pentagon's 2006 Quadrennial Defense Review, RAND analysts spent a year exploring the major mission requirements likely to occupy the US Air Force in the foreseeable future. While this effort did not neglect major combat operations against state adversaries, its most interesting findings were in the areas of the counterterrorism, counterinsurgency, and national-building missions. There the RAND researchers identified four broad types of "resources" that they saw as increasingly central to the conduct of future warfare:

- *Finders*, which provide detailed and sustained situational awareness about a region, its inhabitants, and their circumstances;
- *Influencers*, which are dedicated to training, advising, and assisting friendly host nations and play a critical role in shaping the perceptions of both host-nation regimes and their populations;
- *Responders*, which provide important non-combat capabilities and support such as air mobility forces; and
- *Shooters*, which bring to bear actual combat power where and when needed.[36]

The first two of these resource categories obviously focus on information challenges—particularly in applying force to achieve higher-level effects—and the third enables force application. In light of this resource topology for future warfare, its authors concluded that the "next Air Force might do well" to have fewer "shooters" overall, but many more "finders."[37] Given the importance of precision information in the current guided-munitions/battle-networks regime, one cannot help but think this prescription may be applicable to the US Navy and, with due regard for sufficient numbers of "boots on the ground," to the US Army and Marine Corps as well.

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[36] Dave A. Shlapak, *Shaping the Future Air Force* (Santa Monica, CA: RAND, 2006), TR-322-AF, p. 11.

[37] Shlapak, *Shaping the Future Air Force*, p. 22.

Final Thoughts

Guided munitions and their associated battle networks have been evolving for a good six decades. The early problems of accuracy and reliability having been largely overcome by the emergence of solid-state microelectronics and Moore's "law." In this context, the sensor-and-targeting networks that make modern PGMs "smart" have become increasingly more critical to their lethality and effectiveness than the munitions themselves, and this trend is likely to continue. Granted, battle networks still have a long way to go, as the interoperability problems that emerged in the late 1990s between Aegis and CEC illustrate. Still, it does not seem overly optimistic to speculate that, in the long run, these sorts of difficulties will eventually be tamed, if not solved, as military systems migrate to open software architectures. What cannot be eliminated by technical advances is the capacity of adversaries to discover new ways of preventing our networks from acquiring the precision information they need. There are no signs that this source of Clausewitzian friction is likely to disappear anytime soon.

The long journey from industrial-age warfare, based on employing massive quantities of unguided munitions that mostly miss their aim-points, to guided weapons that mostly hit is by no means at an end. Andrew Marshall, who has long exhibited a better feel than most for the pace and duration of fundamental change in military affairs, speculated in the spring of 2006 that the US military is perhaps midway through the guided-munitions era. In his oft-used analogy to the interwar years 1918-1939, he estimates that we are roughly in the equivalent of 1928 or 1929.

As with most periods of fundamental change in how wars are fought, there have been unexpected and unintended consequences. At this juncture the most critical unintended consequence stemming from the rise of guided munitions and battle networks is surely the narrow military options—terrorism or WMD—to which the US dominance of prompt, global precision strike has constrained America's military adversaries. In this sense, the era of guided munitions and battle networks has not turned out the way most observers would have predicted back in the 1970s when Albert Wohlstetter started thinking about the implications of "near zero miss" weapons, Soviet theorists began speculating that reconnaissance strike complexes would one day approach the lethality of nuclear weapons, and DARPA initiated Assault Breaker.

A longer-term question is how long the US military should expect to enjoy a near monopoly in its capabilities for prompt, global, non-nuclear precision strike based on the large American lead in guided munitions and battle networks. Again, for now, the Chinese appear to be focused on exploiting guided munitions and battle networks primarily as an anti-access/area-denial barrier to US capabilities. But in the long run, China may be the most likely country to field reconnaissance-strike complexes capable of opposing the American reconnaissance-strike complexes in a head-to-head or symmetrical contest. Thus, the US military's challenge of maintaining its warfighting edge is one its various military communities will continue to struggle with as far as one can plausibly peer into the future of warfare. American preeminence somewhere midway through the guided-munitions era offers no reason for thinking that competition in this area has come to an end—even if the immediate challenges are likely to be more asymmetrical than they were during the Cold War.

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