The Military Use of Space:
A Diagnostic Assessment

Barry D. Watts

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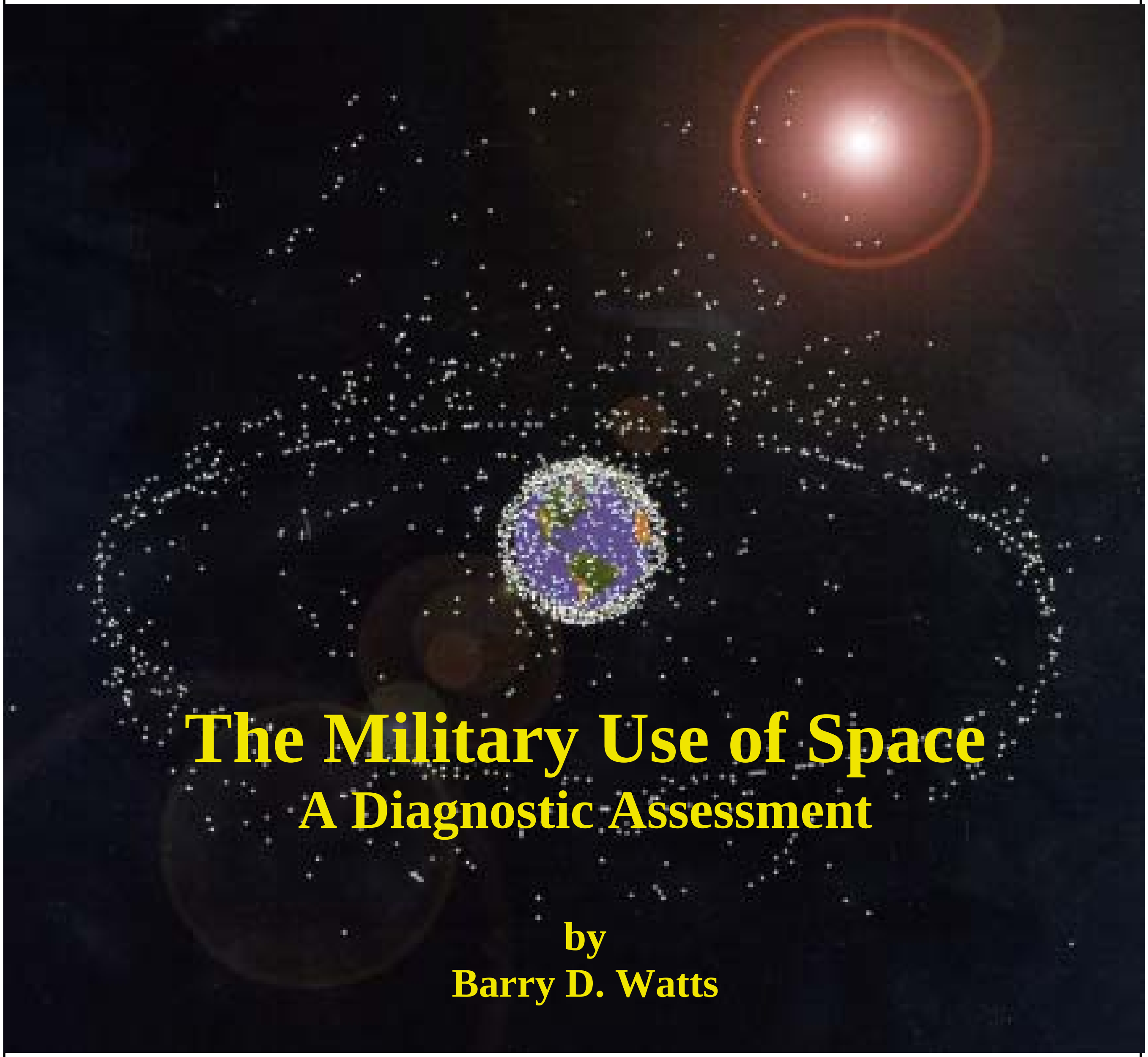

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by
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Center for Strategic and Budgetary Assessments

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PREFACE

Andrew Krepinevich asked me to undertake this assessment on behalf of the Center for Strategic and Budgetary Assessment because he had believed that I could conduct the kind of net assessment Andrew W. Marshall has been doing in the Pentagon for nearly three decades. In this capacity, Marshall is almost unique in his ability to take the long view of the core defense issues facing the US military services, the Joint Staff, and senior managers such as the secretary of defense. Thus, while our two primary aims were to assess the current state of military competition in near-earth space, and to say what can be said about how that competition may unfold over the next quarter century, we also had a tertiary goal in mind: to continue the diagnostic style of comparative analysis pioneered by Marshall, who has been a mentor to both of us.

There are differences between this assessment and most of those done by Marshall. The balance papers and assessment done in his Office of Net Assessment have usually been highly classified. They have also generally been written for the secretary of defense and a few other senior managers in the Department of Defense. With a few exceptions, distribution of Marshall's assessments has been fairly limited. By comparison, the present assessment of the military competition in near-earth space is unclassified and intended for wide distribution.

The main analytic challenge in developing this assessment was that the military use of space is a vast topic—particularly if one begins to delve into technical details. Orbital mechanics and the economics of satellite versus fiber-optic telecommunications, for example, are complex subjects in and of themselves, and one could conceivably devote a number of pages to the fundamentals and complexities of each. A constant difficulty in developing this assessment, therefore, was focusing on that small percentage of all that could be discussed which, when woven together into a whole, might give the reader genuine insight into the unfolding military competition in near-earth space.

This report makes extensive use of Internet websites. Having long ago become habituated to relying on libraries and archives to do research, I was astonished at how much material pertaining to orbital space is now available "on-line," even if one sticks mainly with US government, university, and corporate websites. The reader will find extensive references to Internet addresses throughout this report.

When I began this project, I had not looked closely at the military use of space for some two decades. This circumstance had an unanticipated benefit: I was sufficiently out of date that I had to concentrate on the basic, first-order questions regarding the military use of near-earth space. The result, in the view of those who reviewed various drafts of this report, was a sense that I had managed to identify most of fundamental issues about this realm of military competition, thereby providing a useful and coherent framework for thinking about the subject.

In the end, of course, I sought to do more than identify the central questions. Ultimately I sought to suggest answers based on evidence and careful analysis. I leave it to the reader to judge how successful I have been.

ACKNOWLEDGEMENTS

Erwin Godoy at the Center for Budgetary and Strategic Assessments (CSBA) provided invaluable research assistance. He contacted with a number of individuals knowledgeable about space and the space industry. His diligence in chasing down numerous sources, as well as in nailing down some of the more elusive facts, was critical to the ultimate product.

Larry Stern, formerly with the National Aeronautics and Space Administration, and Bruce Mahone, currently with the Aerospace Industries Association, were both willing to sit down and discuss the future course of the military use of space when this assessment was in its early stages. Their insights helped to focus subsequent research and highlight some of the major issues.

A number of individuals were kind enough to offer comments and criticisms on various drafts of this assessment. Special thanks are due Andrew W. Marshall, who patiently reviewed a succession of partial drafts and, as always, offered many helpful suggestions, particularly regarding key judgments. In addition, Colonel Dave Anhalt in Marshall's office not only provided an early sounding board on organization. He also hosted a June 2000 workshop on space, coordinated by CSBA's strategic studies group, that led to major revisions of the draft, particularly concerning possible paths to greater militarization of orbital space. In this regard the insights and comments of Brigadier General Peter Worden, Colonel Robert Ryals, Lieutenant Colonel Peter Hays, Colonel (USAF, Ret.) Bob Preston, and John Moyle were especially helpful. Chapter V, in particular, benefited greatly from their inputs.

A number of other individuals provided inputs and critical comments on various versions of the draft. Those whose criticisms and interactions markedly improved the final product include Bruno Augenstein, Lieutenant Colonel Tom Ehrhard, David P. Fichtner, Lieutenant Colonel (USAF, Ret.) Mike Kaufhold, and Major General (USAF, Ret.) Jasper Welch.

The originality of Ivan Bekey's concepts about what might be feasible in space in the long run did not sink in until after the initial draft was completed. However, I did endeavor to take his ideas into account, especially in Chapter IV.

Plausible projections regarding space-based weapons proved more difficult than I had anticipated. Bob Preston, now with the RAND Corporation, provided quantitative insights on the logistics and performance of orbital basing for weapons such as lasers and inert, kinetic-energy rods. Gerry Sears also furnished insights on space-based kinetic-energy rods based on his developmental work on these weapons while at RAND.

Both Terry Mahon and Bob Preston provided page-by-page criticisms, corrections, and suggestions on the penultimate draft. I am grateful for their inputs on issues both large and small, especially on technical matters.

Once I got a reasonably mature draft, CSBA's Alane Kochems did the final editing of the text. Her flexibility as an editor made her a pleasure with which to work. More importantly, she will-

ingly put in the long hours needed to smooth my prose and make the final text as error-free and readable as possible.

While the help, criticisms, and suggestions of knowledgeable colleagues are always valued, the opinions, conclusions and recommendations in this assessment are mine alone. They do not necessarily reflect the views of any elements of the Department of Defense or any other agencies of the US Government.

EXECUTIVE SUMMARY

The principal aim of this report is to assess the evolving capabilities of nations and other actors to exploit near-earth space for military purposes over the next 20-25 years. The broad thrust of the assessment can be encapsulated in the following judgments:

- At the dawn of the 21st century, the preeminent user of near-earth space for military purposes is the United States, and the preeminent American use of space is to support operations by traditional air, sea and land forces within the earth's atmosphere. For the United States, the military value of orbital systems rests almost exclusively in force enhancement rather than force application, whether the term "force application" is construed in the narrow sense of space-to-earth strikes or broadly enough to include space control.

- The United States is currently far ahead of any other nation in the capability to exploit orbital systems for the enhancement of terrestrial military operations. However, American requirements for global power projection suggest the United States is also more dependent on space systems than other countries, and future opponents may be able to offset many of the advantages the American military derives from space without a major space program.

- The 1990s were a period of transformation in *how* the American military uses space systems to support terrestrial military operations. Whereas US space efforts had concentrated on the *pre-conflict* aspects of central nuclear war and the military competition in central Europe during 1957–91, over the last decade the US military has sought to redirect its space efforts toward the *real-time* enhancement of ongoing, nonnuclear military operations within the earth's atmosphere.

- While the American military is currently far ahead of other militaries—friendly ones as well as those of potential foes—in the ability to exploit information from space systems during current operations, even the United States has probably realized no more than a small fraction of space's potential for force enhancement.

- The near-monopoly on access to advanced orbital systems and capabilities that the US and Soviet governments enjoyed during the Cold War is rapidly coming to an end, and the large margin of relative military advantage access has given the United States in particular is likely to grow harder to sustain in the years ahead. One thing that may prove more important than access to dedicated military space systems may be the rates at which various militaries are able to incorporate commercial and dual-use technologies driven by market forces rather than government programs. In this area, the US military may be far more constrained bureaucratically than many of its prospective adversaries.

- Presuming that no other nation acquires both the resources and the strategic imperative to field space-based weapons, there is a better-than-even chance that the predominant military use of near-earth space will remain force enhancement through 2020–25 rather than becoming an arena of overt military competition, much less an actual battleground.

- Yet, it is not difficult to imagine trigger events, as well as more gradual paths, that could prompt an earlier-than-expected transition of near-earth space from a force-enhancement to a force-application role. Indeed, if force application is construed broadly enough to include terrestrial-based applications of military force aimed at affecting orbital systems and their use, one can argue that space warfare has already arrived even though no space-based weapons are currently deployed.

- The strategic logic of space power argues that weapons will one day be based in near-earth space because nations will eventually feel compelled to defend their strategic interests there by fielding military capabilities to control orbital space. However, that day may lie further in the future than is generally thought, especially by space enthusiasts.

As will become apparent, these judgments require considerable explanation and elaboration to be understood in context. They are also substantially incomplete because, in the interests of brevity, they omit crucial evidence, interrelationships and implications. Take the point about the near-monopoly on space access long enjoyed by the United States and Soviet Union. The number of space-faring nations is growing, and access to satellite systems and services is expanding even more rapidly as commercial capabilities proliferate. Today an increasing number of nations, commercial enterprises and even individuals are gaining access to space services, such as high-resolution images, that were long the exclusive preserve of the American and Soviet governments. It by no means follows, though, that increasing access by non-space-faring nations and various non-state actors entails a reduction in the margin of US military advantage derived from systems in orbital space. True, that could be the long-term outcome—particularly should the American military prove unable to protect its growing dependencies on commercial and military satellites. However, if space-derived military advantage hinges increasingly on having the trained personnel, connectivity, information architectures, command and control, and organization arrangements to make more timely and more effective use of information derived from orbital systems than the adversary, then it is conceivable that the United States could retain something close to its current margin of advantage for years, if not several decades.

How so complex an issue as the degree of relative American military advantage derived from orbital systems will actually play out over the next quarter century is difficult, if not impossible, to predict with much confidence. At the crux of the matter will undoubtedly be several interrelated issues, including the approaches taken by space-faring nations to space control, the extent to which growing American dependency on space systems presents exploitable vulnerabilities to adversaries, and whether and when weapons are deployed in orbital space. On the one hand, the US Space Command (USSPACECOM) in Colorado Springs, Colorado, has been assigned the mission of space control.[1] On the other hand, the command appears to lack the capabilities and

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[1] The official roles and capabilities of USSPACECOM are four: (1) space support, which includes launch activities and the control of military satellites; (2) force enhancement, which encompasses of military satellite communications, navigation aids such as the Global Positioning System (GPS) constellation, threat warning and attack assessment, environmental monitoring, the collection of geospatial and classified information, and surveillance and reconnaissance; (3) space control, which spans space surveillance, battle management, and ensuring US use of space while denying such use to adversaries; and, (4) force application, which currently means treaty-compliant research into ballistic-missile defense, but "No capabilities . . . for the application of force from space" (Department of Defense (DoD), *Space Program: Executive Overview for FY1999–2003*, (Washington, DC: DoD, February 1998), p.

forces to execute this mission in all but the most limited situations. American treaty obligations prohibit deploying nuclear weapons in space and limit the use of orbital space for ballistic missile defense. In addition, US national-security policy has basically eschewed allowing any weapons—whether nuclear or not—to be deployed in orbit. USSPACECOM, then, is tasked with ensuring uninterrupted access to space for US forces and their allies, ensuring friendly freedom of operations in space, and, if necessary, denying others the use of space. Yet, insofar as these tasks require space-based weapons, the command neither possesses them nor currently plans more than tentative research that might one day lead to their development. True, these tasks could be addressed in many contingencies by terrestrially based weapons and forces. Anti-satellite (ASAT) weapons launched from the earth's surface could enable American forces to deny the use of specific space systems to an adversary, as could special-forces attacks or air strikes on key satellite ground stations. However, USSPACECOM is not currently assigned operational control of theater forces capable of attacking the ground segment of adversary space systems and US ASAT capabilities are currently limited to research rather than operational systems.

These observations have two implications. First, they highlight gaps between US Space Command's assigned responsibilities for space control and its capabilities to execute this mission. Second, they reveal some of the subtleties of interpretation attached to the judgment that the predominant military use of near-earth space is more likely than not to remain force enhancement through 2020–25. Because USSPACECOM and US Air Force definitions limit the term "force application" to attacks on terrestrial targets by space-based weapons, air or special-forces attacks on satellite ground stations to deny the enemy use of space systems falls officially under space control, not force application. Arguably the more inclusive and natural understanding of force application would be to include *any* application of military force either utilizing space systems directly in a lethal kill chain or aimed at affecting orbital assets. Only with this alternative meaning in mind does the full import of the judgment that near-earth is unlikely to shift predominately to force application emerge. While the terminological ambiguity in this instance is possibly the most extreme example the reader will encounter in this assessment, it emphasizes how much needs to be filled in for the key judgments to be understood in their intended context.

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6). Note that in the lexicon of the American military, force application is limited to attacking terrestrial targets with space-based weapons and excludes space control (see, for example, US Air Force, *Space Operations*, Air Force Doctrine Document 2-2, August 23, 1998, p. 11). USSPACECOM documents embrace these same categories.

I. OVERVIEW AND KEY JUDGMENTS

This assessment examines the evolving capabilities of nations and various non-state actors to exploit near-earth space for military purposes. Its principal objectives are: first, to characterize the overall state of military competition in space at the dawn of the 21st century; and, second, to say what can be said—based on now-visible indicators, trends, asymmetries, and other considerations—concerning how the military use of near-earth space may change by 2020–25.

The approach to these aims is fundamentally diagnostic. The model is the comparative style of net assessment that the Pentagon's Director of Net Assessment, Andrew W. Marshall, has pursued since 1973 to describe how the current and projected military capabilities of the United States stack up against those of major, long-term competitors such as the former Union of Soviet Socialist Republics (USSR).[2] This type of assessment most closely resembles "scanning the environment" to estimate how one side is doing relative to the other.[3] In Marshall's view, net assessment is a discipline or art that relies, above all else, on genuine understanding of the enterprise or business involved rather than sophisticated models, complex systems analysis or abstract theory.[4]

Given this approach, the reader seeking explicit policy recommendations on what the US government or the Department of Defense (DoD) ought to do in coming years to shape the emerging military competition in space will probably be disappointed. True, some of the judgments reached have clear policy implications, especially if American political leaders remain determined in coming decades to maintain anything approaching the margin of advantage US space systems have conferred on American military forces today, relative to opponents such as Saddam Hussein's Iraq in 1991 and Slobodan Milosevic's Serbia in 1999. Nevertheless, the focus will be on describing the current state of military competition in near-earth space and suggesting how that competition may change over the next 20–25 years.

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[2] George E. Pickett, James G. Roche and Barry D. Watts, "Net Assessment: A Historical Review" in *On Not Confusing Ourselves: Essays on National Security Strategy in Honor of Albert & Roberta Wohlstetter*, ed. Andrew W. Marshall, J. J. Martin and Henry S. Rowen (Boulder: Westview Press, 1991), pp. 177–80. Marshall has been the Director of Net Assessment since October 1973. From 1973 to 1998, the Office of Net Assessment was part of the Office of the Secretary of Defense (OSD). Starting in 1998 Marshall's office was transferred under the administrative support of the National Defense University, although Marshall himself retained an OSD position and his office remained in the Pentagon. During the Cold War, Marshall's office produced classified balance papers on such topics as US and Soviet strategic-nuclear forces, military investments by the two competitors and the force balance between the North Atlantic Treaty Organization (NATO) and the Warsaw Pact. With the collapse of both the Warsaw Pact and the Soviet Union itself, Marshall's office has turned to other topics, including the possibility of a revolution in military affairs and the use of space for military ends.

[3] A. W. Marshall, "Net Assessment in the Department of Defense," OSD/Net Assessment memorandum for the record, September 21, 1976, p. 1.

[4] Andrew W. Marshall, personal communication to Barry D. Watts, January 6, 2000. Marshall would add that net assessment "is not a specific technique or analytic tool," but an "even-handed look at both sides" that usually included "side-by-side, head-to-head, and major systems comparisons, as well as data on trends, qualitative factors, and examinations of key asymmetries" (Marshall, "Net Assessment in the Department of Defense," p. 1).

While discussions of space systems can be highly technical, this assessment will largely avoid delving deeply into the engineering details and scientific aspects of space systems. The reader will not find, for instance, a tutorial on orbital dynamics.[5] Instead, the focus will be on the principal measures and indices underlying America's current advantages in the military exploitation of near-earth space, trends and asymmetries that may affect the relative margin of US advantage over the next couple of decades, and potential triggers or other developments that could change fundamentally the nature of the military use of space. Discussion of technical issues will be limited to top-level judgments in areas where the relevant engineering or physics appear either to constrain or to suggest the possibility of substantial change.

As an example of the sort of technical discussion that will generally be avoided in this assessment, an important recent development in US commercial satellites is the shift from predominately chemical to electric (or ion) on-board propulsion for orbital space vehicles. The Hall effect, first observed by E. T. Hall in 1879, provides a way to accelerate ions, or charged particles, using magnetic and electric fields. The Russians first harnessed this effect for space-flight in the 1970s.[6] Since then, the technology has been brought to the West, improved, and will soon appear on US commercial satellite buses. "The adoption of Hall-effect thrusters (HETs) in the West," planned to begin in 2000, "marks a transition from predominately chemical to electric on-board propulsion for satellites."[7] The foremost advantage of Hall-effect thrusters is that they use "one-fifth as much propellant as chemical propulsion systems," thereby permitting significant trades in satellite design.[8] Because chemical propulsion systems "can take up to two-thirds of a satellite's mass, saving propellant allows tradeoffs in payload mass, satellite life, or the number of satellites launched on one booster rocket."[9] All indications are that the transition to HET propulsion offers substantial gains in satellite design and efficiency. Nevertheless, this development does not promise any fundamental change in the nature of the satellite business, either for the US military or for commercial firms. Satellites with Hall-effect thrusters will offer improved tradeoffs between satellite weight, service life and maneuver capability, but these tradeoffs portend improved efficiency rather than any new or novel on-orbit functionality.

By comparison, genuine breakthroughs in rocketry for satellite launch would alleviate the relatively high barriers to placing payloads in orbit that have existed since the Soviets orbited the

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[5] Those interested in a non-mathematical account of basic orbital dynamics may wish to consult pages 23–41 in James E. Oberg's *Space Power Theory*, which is available online at www.peterson.af.mil/usspace. For a more rigorous approach, see Jerry Jon Sellers, with William J. Astore, K. Stephen Crumpton, Chris Elliott, and Robert B. Giffen, *Understanding Space: An Introduction to Astronautics*, ed. Wiley J. Larson (New York: McGraw-Hill, 1994). The Sellers book was supported by the Department of Astronautics at the US Air Force Academy.

[6] Linda Voss, "New Thrust for U.S. Satellites," *Aerospace American*, February 2000, p. 36.

[7] Ibid. For an overview of the various propulsion options for space vehicles, including comparisons of the burn times required to accelerate a 25-ton payload from low-earth orbit to escape velocity, see George Musser and Mark Alpert, "How To Go to Mars," *Scientific American*, March 2000, pp. 46–47.

[8] Voss, "New Thrust for U.S. Satellites," p. 37.

[9] Ibid. "For example, for the 15-year life of a geostationary communications satellite, a HET would save 882 lb. over chemical propulsion. That weight savings could mean a $20-million difference between a Delta and a larger class Atlas launch vehicle."

first artificial satellite, Sputnik, in October 1957.[10] At present there are some eighteen commercially available expendable-launch vehicles for placing payloads in low-earth orbit (LEO), including Delta, Atlas, Ariane, Pegasus, Proton, Long March, and Soyuz. The average price-per-pound of orbited payload for these launchers is $3,600–4,580 to LEO (see Appendix 4).[11] The cost-per-pound for placing payloads in geosynchronous transfer orbits is substantially higher, averaging $9,200–11,200.[12] Using this measure, military expendable launch vehicles have been, and remain, more expensive than commercial rockets due to their higher overhead costs.[13] Indeed, the stated goal of the US Air Force's Evolved Expendable Launch Vehicle (EELV) is for military and national payloads to be "able to get access to space at fundamentally commercial prices."[14] The American Space Shuttle, of course, is at least partly reusable. While the large fuel tank for the orbiter's main engines and two solid-fuel boosters are expended on each launch, the orbiter itself is reused. However, the Space Shuttle, whose payload costs have been pegged at as much as $15,000 per pound to LEO, is even more expensive than expendable military launchers, although it should be kept in mind that Shuttle prices are not market prices.[15] In short, space launch remains highly expensive on a per-pound basis even today.

What are the prospects for order-of-magnitude (factor of ten) or greater improvement during the next 10–15 years? They appear dim; existing technologies and designs show little promise of substantially overcoming the limits imposed by the physics of rocket-based space launch. If this perception proves accurate, then foreseeable progress in transforming the economics of space launch is likely to be on the margin, much as it has been for the past couple decades. Conversely,

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[10] Research in the United States on potential military uses of earth satellites predates Sputnik by more than a decade. As early as 1945, the US Navy approached the US Army Air Force about the possibility of a joint program for satellite development. This prompted Curtis LeMay, then the Army Air Force's deputy chief of staff for research and development, to commission a feasibility assessment by Project RAND of the Douglas Aircraft Corporation. The resulting report, *Preliminary Design of an Experimental World-Circling Spaceship*, has been recently reissued and can be ordered online at www.rand.org/publications/classics. RAND recommended that the US Air Force "proceed with the development of a strategic reconnaissance satellite" in 1954.—Bernard A. Schriever, "Military Space Activities: Recollections and Observations," *The US Air Force in Space: 1945 to the 21st Century*, ed. R. Cargill Hall and Jacob Neufeld (Washington, DC: US Government Printing Office, 1998), p. 13. The Hall-Neufeld volume contains the proceedings of an Air Force Historical Foundation symposium on the US Air Force's historical experience in space that was held at Andrews Air Force Base, Maryland, September 21–22, 1995.

[11] Greg Lucas and Charles Murphy, "The Space Launch Services Industry: Indicators and Trends," presentation to the AIAA Defense and Civil Space Programs Conference, September 29, 1999, slides 17 and 18.

[12] Ibid.

[13] By the early 1990s, the total cost of a launch using the US Air Force's heavy-lift Titan had risen to $250–300 million due to declining American launch rates (General Thomas S. Moorman, Jr., "The Explosion of Commercial Space and the Implications for National Security," *Airpower Journal*, Spring 1999, p. 13; available online at www.airpower.maxwell.af.mil).

[14] Sheila E. Widnall quoted in Peter Grier, "The Investment in Space," *AIR FORCE Magazine*, February 2000, p. 52. Oberg has recently noted that the cost of putting a pound of payload in orbit has been in the range of $4,530–$13,600 per pound over the last twenty years, and that there has been "no measurable improvement" during this period (Oberg, *Space Power Theory*, p. 92).

[15] "NMD: The Hard Sell," *Jane's Defence Weekly*, March 15, 2000, p. 23. The Shuttle has large fixed infrastructure costs. Hence the cost of a mission can vary widely depending on the number flown in a given fiscal year. In 1995 the US Air Force's Scientific Advisory Board (SAB) put the cost of placing payloads in low-earth orbit at $8,000–16,000 per pound, and the cost of getting things to geosynchronous orbit as "approximately $30,000 per pound"—*New World Vistas: Air and Space Power for the 21st Century*, Daniel E. Hastings (chair, Space Technology Panel), *Space Technology Volume* (Washington, DC: USAF SAB, 1995), p. 12.

breakthroughs able to produce order-of-magnitude reductions in the costs and risks of space launch would remove the principal obstacle to putting space operations on a footing more akin to civil and military air operations. Hence, space launch illustrates the kind of technical issue that cannot be ignored by this assessment.

Regarding how the military value of space systems may evolve or change over the next quarter century, suggestions based mainly on now-visible trends or possible discontinuities in the nature of the situation cannot, of course, be predictive. As the abrupt and largely unexpected end of the long cold war between the United States and the former Soviet Union illustrates, human ability to predict the long-term future in areas as complex as relations between nations is extremely limited.[16] Most military-historical predictions of the future turn out to be wrong in important ways—in no small measure because the sorts of overarching national-security developments we desire most to predict are so riddled with nonlinear processes exhibiting sensitive dependence on prior conditions that detailed prediction is simply not possible. In such domains, gathering more data, or processing the available data faster, does not, and cannot, help.[17] In the well-known case of predicting the exact weather at a given spot on the earth (temperature, winds, humidity, cloud conditions, the presence or absence of precipitation, etc.), nonlinearity appears to render accurate forecasts impossible beyond about two weeks in advance.[18]

Before considering the key judgments of this assessment, two further clarifications are necessary. The first concerns the spatial bounds of "military space" at the beginning of the 21st century. Outer space is often taken to encompass everything beyond the earth's atmosphere. The United States awards astronaut wings for manned operations reaching 50 miles above the earth's surface, and 60 miles up (96.6 kilometers) is generally considered the minimum altitude for LEO satellites.[19] Does space for contemporary military purposes encompass everything beyond an altitude of 50–60 miles above the earth's surface? The answer is plainly "No." The vast majority of space systems having any intelligence, military, scientific, or commercial value today are operational satellites in earth orbits whose maximum altitudes are less than 10 percent of the mean distance to the moon (~239,000 miles).[20] If one dates the space age from the successful orbiting of Sputnik in 1957, less than four percent of the payloads orbited since that time have been space probes that left earth orbit.[21] As of January 2000, the active or operational satellites orbiting the

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[16] The historian John Lewis Gaddis has argued, with considerable justification in this author's opinion, that none of the three general approaches to international-relations (IR) theory that have evolved since 1945 came anywhere close to anticipating how the Cold War ended (Gaddis, "International Relations Theory and the End of the Cold War," *International Security*, Winter 1992/93, p. 53). The US intelligence community did no better at predicting the collapse of Soviet power than IR specialists and other academics. For a review of the Central Intelligence Agency's performance in anticipating the end of the Cold War, see Melvin A. Goodman, "Who Is the CIA Fooling? Only Itself," *The Washington Post*, December 19, 1999, pp. B1 and B4.

[17] James P. Crutchfield, J. Doyne Farmer, Norman H. Packard and Robert S. Shaw, "Chaos," *Scientific American*, December 1986, p. 46.

[18] Edward Lorenz, *The Essence of Chaos* (Seattle: University of Washington Press, 1993), pp. 77–110 and 181–84. See also, David Ruelle, *Chance and Chaos* (Princeton, NJ: Princeton University Press, 1991), pp. 45–47.

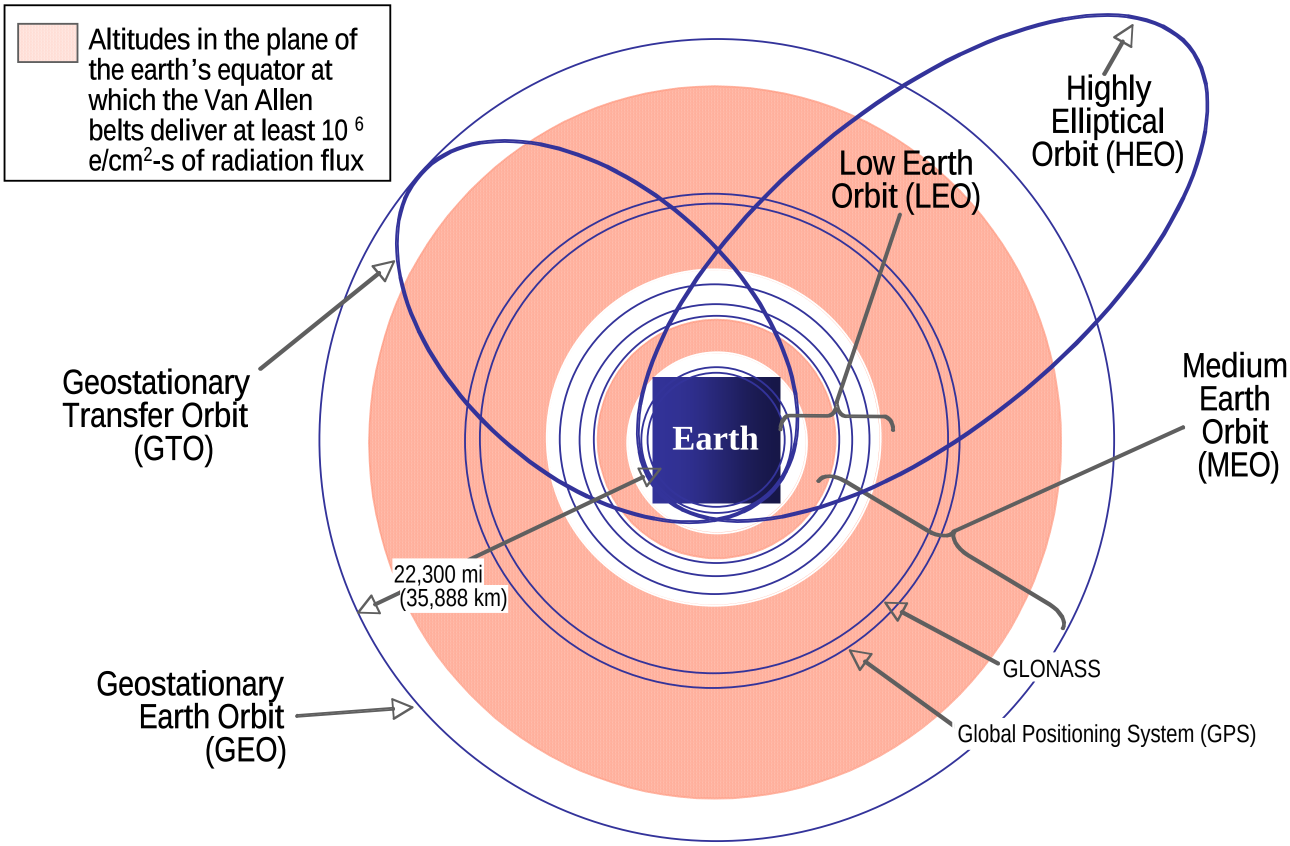
[19] Tamar A. Mehuron, "Space Almanac 1999," *AIR FORCE Magazine*, August 1999, p. 27.

[20] The moon's distance from the center of the earth ranges between 221,460 miles at perigee and 252,700 miles at apogee—Patrick Moore, *The Atlas of the Universe* (New York: Rand McNally, 1970), p. 86.

[21] US Space Command (USSPACECOM) surveillance data downloaded January 3, 2000 from

earth comprised only about 7 percent of the more than 8,700 "softball-size or larger" objects being tracked by the US Space Command.[22] Of these active satellites, more than 85

Figure 1 Altitudes and Orbit Types for Earth Satellites (Ignoring Differences in Orbital Inclination)



Note: The dividing line between LEO and Medium Earth Orbit (MEO) varies widely among sources and does not appear to be well defined. Oberg suggests that LEO extends to altitudes of 932 miles (1,500 kilometers) above the earth's surface (Oberg, *Space Power Theory*, p. 39). Other sources put the demarcation as low as 300 miles (483 kilometers) and as high as 3,728 miles (6,000 kilometers). More significant than the altitudinal division between LEO and MEO are the orbital periods associated with various satellite altitudes. For example, historically the most-valued orbit at MEO was the semi-synchronous orbit with an altitude of 20,700 kilometers. Satellites at this altitude have a period of 12 hours; if they have the proper inclination as well, they repeat an identical track or ground trace on the earth's surface every 24 hours (Ibid., pp. 39–40). See Figure 2 for a depiction of orbital inclination.

percent orbit at altitudes not exceeding roughly 22,300 miles (35,888 kilometers) above the earth's surface—this altitude being the geosynchronous distance at which the period of a satellite

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http://www.peterson.af.mil/usspace/boxscore.

[22] Ibid. In comparison with other sources, USSPACECOM's unclassified estimate that about 7 percent of the objects it is tracking are active satellites seems low. Other sources on active satellites such as the Futron Corporation and Analytic Graphics indicate that a more current estimate as of January 2000 would be that slightly over 8 percent of the objects USSPACECOM tracks are active satellites.

moving eastward in a circular orbit matches the rotational period of the earth.[23] While some active satellites follow highly elliptical orbits with apogees as high as 50,000 miles, most of the space systems available to support terrestrial military operations operate at the geosynchronous altitude or below.[24] Military space today, therefore, is largely the near-earth space shown in Figure 1. For purposes of this assessment, therefore, the terms "space," "orbital space," and "near-earth space" will be used more or less interchangeably, and the emphasis will be on this small portion of outer space immediately surrounding the earth. For a more forward-looking military geography of outer space, see Appendix 1.

The other needed clarification concerns the extent to which near-earth space systems have, to date, been used for force application in the inclusive sense of applying military force either to affect space-based capabilities or to achieve destructive effects via the direct involvement of orbital assets the kill chain. Since the first successful Corona spy-satellite mission by the United States in August 1960, imagery satellites—also known throughout the Cold War as "national technical means of verification" (usually shortened to NTM as an acronym)—have been exploited, first, by the United States and, later, by the Soviet Union to track the other's force developments and deployments.[25] In the American case, the KH-1 Corona satellite—the first American photo-reconnaissance or imagery satellite—was followed by communications and navigation satellites, as well as by collection systems for signals intelligence (SIGINT), which included communications and electronics intelligence (COMINT and ELINT, respectively). The military role of these various overhead systems, however, has been essentially that of support, meaning the enhancement of traditional military operations within the atmosphere. Orbital assets have not heretofore been directly involved in force-on-force combat on a real-time basis, much less used to attack terrestrial targets. As mentioned in the executive summary, while USSPACECOM now has a space-control mission, it has little, if any, capability to use destructive or lethal force to control near-earth space, and certainly no space-to-earth weapons in orbit.[26] During the 20th cen-

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[23] Sellers, et al., *Understanding Space*, p. 150. Geosynchronous orbits (GEO) are those with a period of 24 hours and some inclination relative to the plane of the earth's equator. If a circular, geosynchronous orbit lies in the same plane as the earth's equator (zero degrees inclination), a satellite moving eastward along the orbit will remain more or less stationary over a point on the earth's surface. Such satellites are termed "geostationary" and lie along the Clarke Belt named for space visionary and science-fiction writer Arthur C. Clarke.

[24] "Q 'n A: Answers to Your Questions," downloaded from: http://www.spacetoday.org/Questions/PolarSats.html.

[25] Area photo coverage of the Soviet Union on the first successful Corona mission was more than 5,659,000 square kilometers; all the U-2 photo missions of the Soviet Union from July 4, 1956, through May 1, 1960, only covered 3,430,000 square kilometers (Analytical Graphics, www.stk.com). Details on the KH-1 can be found at www.nro.odci.gov/corona/sysinfor2. For an authoritative treatment of the decisions that produced the KH-1, including the choice of a film-recovery design, see R. Cargill Hall, "Civil-Military Relations in America's Early Space Program" in *The U.S. Air Force in Space: 1945 to the 21st Century* ed. R. Cargill Hall and Jacob Neufeld, (Washington, DC: US Government Printing Office, 1998), pp. 23–30. For an overview of the Keyhole (KH) imaging satellites based on unclassified materials, see Jeffrey T. Richelson, "Scientists in Black," *Scientific American*, February 1998, pp. 49–50; a more detailed account can be found in Richelson's *America's Secret Eyes in Space: The U.S. Keyhole Spy Satellite Program* (New York: Harper and Row, 1990). The KH-1 through KH-9 satellites returned canisters of exposed film to earth for development; by comparison, the KH-11 and advanced KH-11 return their imagery virtually instantaneously via a relay satellite ("Scientists in Black," p. 49). Richelson states that the KH-1 through KH-9 programs encompassed 144 satellite launches between 1960 and 1972 (ibid.). The KH-10 camera was intended by the US Air Force to be flown aboard the Manned Orbiting Laboratory (*America's Secret Eyes in Space*, p. 85). Cancellation of the laboratory ended the KH-10.

[26] "Control of Space requires USCINCSPACE [US Commander in Chief Space] to achieve five interrelated objectives: (1) *assure* the means to get to space and operate once there; (2) *surveil* the region of space to achieve and

tury, the ability to use lethal ordnance from air-to-air fighters and strike aircraft to gain control of the air came to be a hallmark of American force application. In neither analogous sense does USSPACECOM appear—yet—to have become a force-application organization.

Nor has any other country clearly crossed this threshold. It is believed that in October and November of 1975, the Soviets used intense beams of radiation to interfere with three American satellites, although the US government later officially explained these incidents as having been caused by forest fires or volcanoes.[27] More recently, disruption of satellite systems—by Russia against satellite phone communications being used by Chechen rebels and by Iran against Western satellite broadcasts—has been reported.[28] Also, one could interpret American air attacks on Iraqi satellite ground stations early in the 1991 Persian Gulf War as space control insofar as the intent was to deny Iraq access to overhead systems. Nonetheless, lethal or destructive force application from, to, or within near-earth space basically lies in the future.

The exploitation of orbital assets by the US-led Coalition before and during the 1991 Persian Gulf war (January 17-February 28, 1991) reinforces this conclusion. The *preponderant* utilization of space assets during this conflict was force enhancement of terrestrial operations. The United States and its allies made heavy use of communications satellites for both inter-theater and intra-theater command and control as well as for long-distance communications. Sixteen military and five commercial communications satellites were utilized by Coalition forces; taken together, these systems provided a transmission rate of some 200 million bits per second, or about 39,000 simultaneous telephone calls.[29] Imagery satellites—both electro-optical (EO) and radar—were employed for order-of-battle and target intelligence, as well as for bomb damage assessment (BDA) following coalition air strikes.[30] Additionally, ELINT and SIGINT satellites

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maintain situational understanding; (3) *protect* our critical space systems from hostile actions; (4) *prevent* unauthorized access to, and exploitation of, US and allied space systems and, when required, (5) *negate* hostile space systems that place US and allied interests at risk" (US Space Command, *Long Range Plan: Implementing USSPACECOM Vision for 2020*, April 1998, p. 20; available online at http://www.peterson.af.mil/usspace/LRP). The United States "to date has deployed no—repeat—*no* forces to effect many elements of the space-control mission" (Colin S. Gray and John B. Shelton, "Space Power and the Revolution in Military Affairs: A Glass Half Full?" *Airpower Journal*, Fall 1999, p. 23; available online at www.airpower.maxwell.af.mil/airchronicles/apj/ap99/fal99/fal99.html).

[27] Paul B. Stares, *The Militarization of Space: U.S. Policy, 1945–1948* (Ithaca, NY: Cornell University Press, 1985), p. 146.

[28] In late 1999, Russian military sources told the ITAR-TASS news agency that the mobile phone network in the northern Caucasus had been subjected to "radio-electrical jamming" in order to "disrupt communications between Chechen field commanders."—Foreign Broadcast Information Service, "Ministry Spokesman Admits Phone Jamming in N. Caucasus," serial AU2411101599, source Paris AFP (North European Service) in English 106 GMT, November 24, 1999. Details on Iranian jamming in 1997 of evening broadcasts of Simay-e Moghavemat on AsiaSAT and ArabSAT can be found at www.iran-e-azad.org/english/ncr/970812.html.

[29] Thomas A. Keaney and Eliot A. Cohen, *Gulf War Air Power Survey; Summary Report* (Washington, DC: US Government Printing Office, 1993), p. 193.

[30] At the time of the Gulf War, the United States is believed to have had at least one Lacrosse radar imaging satellite on orbit in addition to EO KH-11s (Craig Covault, "Secret Relay, Lacrosse NRO Spacecraft Revealed," *Aviation Week & Space Technology*, March 23, 1998, p. 27). The advantage of Lacrosse over the EO KH-11, of course, was that it could provide synthetic aperture radar (SAR) imagery through clouds. As of April 1999, the NRO is reported to have three visible/infrared, advanced KH-11s and two Lacrosse-type satellites imaging targets in Yugoslavia (Craig Covault, "Recon, GPS Operations Critical to NATO Strikes," *Aviation Week & Space Technology*, April 26, 1999, p. 35). A third Lacrosse was reportedly launched on August 17, 2000 (Vernon Loeb, "Wearing a Secret on

were used to establish Iraqi electronic order-of-battle and to monitor the operation of such things as Iraqi air defenses and military communications.[31] By and large, though, none of these activities employed space systems as an integral, real-time element of lethal kill chains during combat operations.

Granted, one can point to a few borderline cases that could be construed as constituting near-real-time involvement of space systems in ongoing strike operations. US Navy aircraft launched a total of seven AGM-84 Standoff Land Attack Missiles (SLAMs) during Operation Desert Storm. While these weapons did not utilize space assets for terminal guidance, they did depend on GPS satellites for navigation en route to their targets. Also, some efforts were made by American forces during Desert Storm to get satellite-derived location information on Iraqi radars into the hands of controllers who could pass coordinates to strike aircraft. Similarly, infrared sensors on Defense Support Program (DSP) satellites were exploited to localize the positions from which Iraq's extended-range Scud missiles had been fired.[32] Satellite systems detected most of Iraq's 88 ballistic-missile launches and, as the conflict unfolded, efforts were made to pass DSP-derived data on launch locations to the aircrews of strike aircraft such as the F-15E quickly enough to attack the mobile launchers before they could escape.[33] Nevertheless, aside from the massive use of space assets to *enhance* Coalition operations, these few, relatively marginal instances of involving overhead systems directly in sensor-to-shooter kill chains do not undermine the judgment that the *preponderant* use of near-earth space in the Gulf War was force enhancement of terrestrial operations. Orbital systems were used mainly for long-haul communications, command and control, passing information in and out of the theater, refining Iraqi order-of-battle, developing target lists, and providing post-strike BDA. To give a sense of how marginal the borderline cases were, efforts to utilize DSP satellites to enable fixed-wing aircraft to destroy fleeing Iraqi Scud launchers apparently did not produce even a single kill.[34] Nor were DSP satellites able to cue Patriot missile batteries to intercept incoming Scud warheads.[35]

Their Sleeves: Shoulder Patch Reveals Rocket's Payload, Some Say," *The Washington Post*, August 30, 2000, p. A23).

[31] Constant Source, whose products include Tactical Related Applications (TRAPS) broadcasts, sought to provide theater commanders with tactical information on Iraqi electronic order-of-battle during Desert Storm (David A. Fulghum, "Talon Lance Gives Aircrews Timely Intelligence from Space," *Aviation Week and Space Technology*, August 23, 1993, p. 71).

[32] DSP satellites provide the United States with global coverage and near-real-time warning of ballistic missile launches, nuclear detonations and other "events" ("Snapshots of Space," *AIR FORCE Magazine*, January 2000, p. 58). The number of DSP satellites currently on orbit is classified. However, the 20th satellite in the series since the first launch in 1970 was orbited on May 9, 2000, after the 19th DSP satellite was stranded in a useless orbit in April 1999 ("Titan Rocket and Satellite Launched by Air Force," *The New York Times*, May 9, 2000). The DSP satellites are operated by the US Air Force's 2nd Space Warning Squadron at Buckley Air National Guard Base, Aurora, Colorado; the other DSP ground site is in Woomera, Australia (Sellers, et al., *Understanding Space*, p. 531).

[33] John F. Guilmartin, *Gulf War Air Power Survey*, vol. IV, part 1, *Weapon, Tactics, and Training* (Washington, DC: US Government Printing Office, 1993), pp. 280–81. DSP detections of Scud launches in Desert Storm occurred mostly "under near ideal night time conditions," but the system "lacked the stereo processing and communications needed to provide timely and accurate warning messages"—*New World Vistas: Air and Space Power for the 21st Century*, Michael I. Yarymovych (chair, Space Applications Panel), *Space Applications Volume* (Washington, DC: USAF SAB, 1995), p. 51.

[34] The principal authors of the *Gulf War Air Power Survey* reached the following judgments about the success of Coalition efforts to destroy Iraqi mobile-missile launchers during Operation Desert Storm: ". . . the fundamental

With these clarifications in mind, the current state of military competition in near-earth space can be loosely summarized in four judgments:

- Today, the preeminent user of near-earth space for military purposes is the United States, and the preeminent American use of space is to support operations by traditional air, sea and land forces within the earth's atmosphere. For the United States, the military value of orbital systems rests almost exclusively in force enhancement rather than force application, whether "force application" is understood in the official sense of space-to-earth strikes or broadly enough to include space control.

- Second, the United States is currently far ahead of any other nation in the capability to exploit orbital systems for the enhancement of terrestrial military operations. In this sense, "the United States is the pre-eminent military power in space" today.[36] However, American needs for global power projection suggest the United States is also more dependent on space systems than other countries, and future opponents may be able to offset many of the advantages the American military derives from space with few, if any, assets in orbit. If so, then regional adversaries may develop approaches to the military use of space very different from those taken by the US military.

- Third, the 1990s were a period of transformation in *how* the American military uses space systems to support terrestrial military operations. Whereas US space efforts during the Cold War had concentrated on the *pre-conflict* aspects of central nuclear war and the military competition in central Europe, over the last decade the US military has sought to refocus its space efforts toward the *real-time* enhancement of ongoing, nonnuclear military operations within the earth's atmosphere. By comparison, Soviet Cold War efforts to use space assets for over-the-horizon targeting of such things as American carrier battle groups have atrophied, and no other country, large or small, is in the same league as the American military in terms of being able to exploit space-derived information for ongoing military operations.[37]

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sensor limitations of Coalition aircraft, coupled with the effectiveness of Iraqi employment tactics (including the use of decoys), suggests that few mobile Scud launchers were actually destroyed by coalition aircraft or special forces during the war. Given the level of effort mounted against mobile missile launchers, a few may have been destroyed, but nowhere near the numbers reported during the war. Once again, there is no indisputable proof that Scud mobile launchers—as opposed to high-fidelity decoys, trucks or other objects with Scud-like signatures—were destroyed by fixed-wing aircraft." (Keaney and Cohen, *Gulf War Air Power Survey: Summary Report*, pp. 89–90).

[35] "Horner Says DSP Limited to 'Civil Defense' in Korea, Gulf War," *Aerospace Daily*, April 8, 1994, p. 44. General Charles A. Horner, who was the Joint Forces Air Component Commander during Operation Desert Storm, stated at the US Space Foundation's 1994 annual space symposium that it was a "myth that DSP cued Patriots" in 1991 (ibid.).

[36] USSPACECOM, *Long Range Plan*, p. 10. The assessment that, at the dawn of the 21st century, the United States is the preeminent military power in near-earth space is shared by US Space Command, the US Air Force, and other elements of the DoD along with the American intelligence community.

[37] Beginning in 1974, the Soviets began operating pairs of Radar Ocean Reconnaissance Satellites (RORSATs) and ELINT Ocean Reconnaissance Satellites (EORSATs) not merely to track US Navy vessels, but to provide targeting information to naval aviation bombers (Stares, *The Militarization of Space*, pp. 142–43). Even in the late 1980s, the Defense Department characterized these systems as "unique spaced-based targeting systems to support combat operations"—DoD, *Soviet Military Power: Prospects for Change 1989* (Washington, DC: US Government Printing Office, February 1989), p. 54.

- Fourth, while the American military is currently far ahead of any other military in the ability to exploit space systems, even the United States has probably realized no more than 10–15 percent of space's potential for force enhancement. While near-real-time use of targeting information from space sensors has been repeatedly demonstrated since the late 1980s in experiments such as the Talon Sword technology demonstrations of 1993–94, experience during the NATO's 1999 air campaign against the Federal Republic of Yugoslavia (FRY) suggests that the United States has yet to integrate space sensors into sensor-to-shooter kill chains on either a regular or widespread basis.[38] Historically, security and organizational barriers limited what US military users knew about American space capabilities, while the space community, especially within the US Air Force, was dominated by a research-and-development mindset which "knew or cared little about the operational needs and preferences of the space user communities."[39] Also, the bulk of the vast amounts of data collected by American overhead sensors could not be processed or fused into tactically meaningful, cockpit-friendly information quickly enough for operational use. Although Congress had directed the military services as early as 1977 to create offices to facilitate operational exploitation of national overhead systems, a lament from Desert Storm was that, while these systems provided lots of information, "too little was available to the warfighter."[40] Even today, operational exploitation of national systems appears to remain, at best, an "applique" that continues to be unevenly utilized across Services and from one contingency to the next.[41]

These judgments about the military role of space today raise a number of questions about how nations—and, possibly, non-state actors as well—may come to exploit space for military purposes in coming decades. Is the substantial margin of advantage in the military use of near-earth space enjoyed by the United States today likely to grow, persist or diminish over the next 20–25 years? Is the predominant military use of space likely to shift from force enhancement to force application (broadly construed) during this period? And, more crucially, even if the United States manages to sustain something close to its present margin of advantage in the military exploita-

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[38] The Talon Sword sought to demonstrate the possibility of "a near real-time, precision targeting, sensor-to-shooter capability using existing national and tactical assets" (Gerald Green, "Global Sword Demonstrates Advantages of Fusing Emerging Technologies," *Journal of Electronic Defense*, September 1994, p. 15). In the initial Talon Sword test in early 1993, orbiting ELINT sensors detected a simulated enemy surface-to-air missile (SAM) radar and passed location data to an EA-6B and a Block 50 F-16 in time for non-line-of-sight firings of High-speed Anti-Radiation Missiles (HARMs) against the emitter (James R. Asker, "F-16, EA-6B to Fire Missiles Cued by Intelligence Satellites," *Aviation Week & Space Technology*, April 19, 1993, p. 25). Further Talon Sword experiments occurred in early 1994 (Commander Randy E. Nees, "Talon Sword—Keeping Their Heads Down," *Proceedings*, December 1994, pp. 78–79). The Talon Sword demonstrations were conducted under the Tactical Exploitation of National Capabilities (TENCAP) initiative, which sought to get information from national intelligence systems into the hands of the "warfighters" (David A. Lynch, "Spacepower Comes to the Squadron," *AIR FORCE Magazine*, September 1994, pp. 67–70).

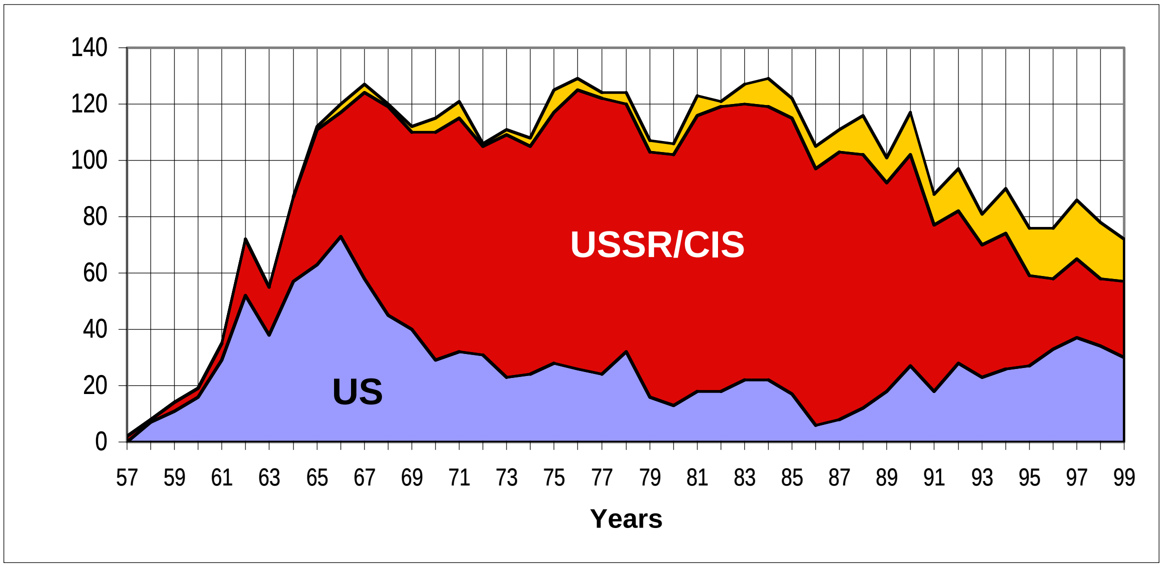
[39] Peter L. Hays, "Struggling Towards Space Doctrine: U.S. Military Plans, Programs, and Perspectives during the Cold War," Ph.D. dissertation, Fletcher School of Law and Diplomacy, Tufts University, May 1994, p. 248.

[40] David A. Fulghum, "Talon Lance Gives Aircrews Timely Intelligence from Space," *Aviation Week and Space Technology*, August 23, 1993, p. 71. The congressionally mandated program was TENCAP. Congress directed the Services to create TENCAP offices in 1977 (Hays, "Struggling Towards Space Doctrine," p. 386).

[41] Lieutenant General Roger G. DeKok and Bob Preston, "Acquisition of Space Power for the New Millennium" in *Spacepower for a New Millennium: Space and U.S. National Security*, ed. Peter L. Hays, James M. Smith, Alan R. Van Tassel and Guy M. Walsh, (New York: McGraw-Hill, 2000), p. 64.

tion of near-earth space, is this space-derived superiority likely to entail commensurate margins of strategic or operational advantage in future conflicts?[42]

Figure 2: Annual Space Launches



Source: US and Soviet/CIS launches through 1998: Mehuron, "Space Almanac," pp. 38 and 47; 1999 and other launches (China, the European Space Agency, etc.) have been drawn from two sources: Jonathan C. McDowell's master launch log at hea-www.harvard.edu/QEDT/jcm/space, and Analytic Graphics' all-satellites database at www.stk.com. Among the twelve members of Commonwealth of Independent States are Russia, Ukraine, Belarus, and Kazakhstan, which contains the Baikonur cosmodrome at Tyuratam. The "Other" category includes launches by Brazil, China, the European Space Agency, France, India, Israel, and Japan.

Before hazarding preliminary answers to these questions, three areas warrant discussion by way of providing contextual background: the post-Cold War contraction of the former-Soviet space industry; the growing commercialization of the worldwide space industry; and a short review of the degree to which weapons have been deployed in near-earth space. A fundamental feature of spending on space systems during the US-Soviet Cold War (1947–89) was that the governments of these two space-faring nations made the bulk of the investments. Following the break-up of the Soviet Union in 1991 and a series of subsequent economic implosions in the Russian economy, however, Moscow's space program has undergone a dramatic contraction—especially compared to that of the United States. Annual launch rates for the United States versus the Soviet Union (and, after 1991, the Commonwealth of Independent States (CIS)) provide a gross indicator of what has happened to the Russian space program over the last decade (see Figure 2). While much of the decline can be traced to post-Soviet political and economic turmoil in Russia, the fact is that the Russian space program today is but a shadow of the Soviet program during 1975–84, a decade in which the Soviet Union averaged around 90 launches a year.[43]

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[42] Bob Preston suggested this third question in commenting on an earlier draft of this assessment.

[43] For a good overview of the Russian space program in the mid-1990s, see James Oberg, "Russia's Space Program: Running on Empty," *IEEE Spectrum*, December 1995, pp. 18-35. This article was informed by firsthand visits to Baikonur in 1990 and 1995. Oberg's basic conclusion was that "at current levels of support, Russia's present output of space activities is not sustainable" (ibid., p. 18).

Not only did the Russian space program decline dramatically during the 1990s, but, starting in the early 1990s, worldwide commercial revenues began growing rapidly compared to worldwide spending by governments. As Figure 3 shows, worldwide government expenditures on space have shown little growth since the mid-1980s, whereas commercial revenues from space have increased steadily. The upshot of these trends is that worldwide commercial revenues—meaning purely commercial revenues that exclude revenues from government contracts—overtook worldwide government spending during the late-1990s, although there is some disagreement over exactly when the crossover occurred.[44]

A study led by the accounting firm KPMG Peat Marwick pegged 1996 as the year "when worldwide commercial revenues in space for the first time surpassed governments' spending on space."[45] Futron Corporation analysts believe the crossover year was 1997. Regardless, it is important to realize that the bulk of the growth during the early 1990s in commercial revenues from space is due to the explosion in consumer services such as direct television, not to more traditional sources of space business such as building satellites and launch vehicles, providing launch services or operating satellites. Thus, the aggregate crossover between commercial revenues from space and government spending conceals the role played by consumer services.

This crossover has not yet been reached within the United States. Because US government spending on space has remained substantial compared to those of other governments, purely commercial American revenues from space have not yet overtaken government expenditures. US Air Force leaders estimate that total spending on space by the US government was some $30 billion in 1999, and they project private industry "will reach and then surpass this level early in the 21st century."[46]

There is every indication that the worldwide trend toward increasing commercialization of space activities will continue. The data in Figure 4 are representative of the global trends in the main categories of commercial space revenues during the late 1990s. How they will eventually affect the military value of space systems in coming decades remains to be seen. Nevertheless, the overall direction is clear. In contrast to the situation that prevailed throughout the Cold War—when the majority of investment in space systems came from the American and Soviet govern-

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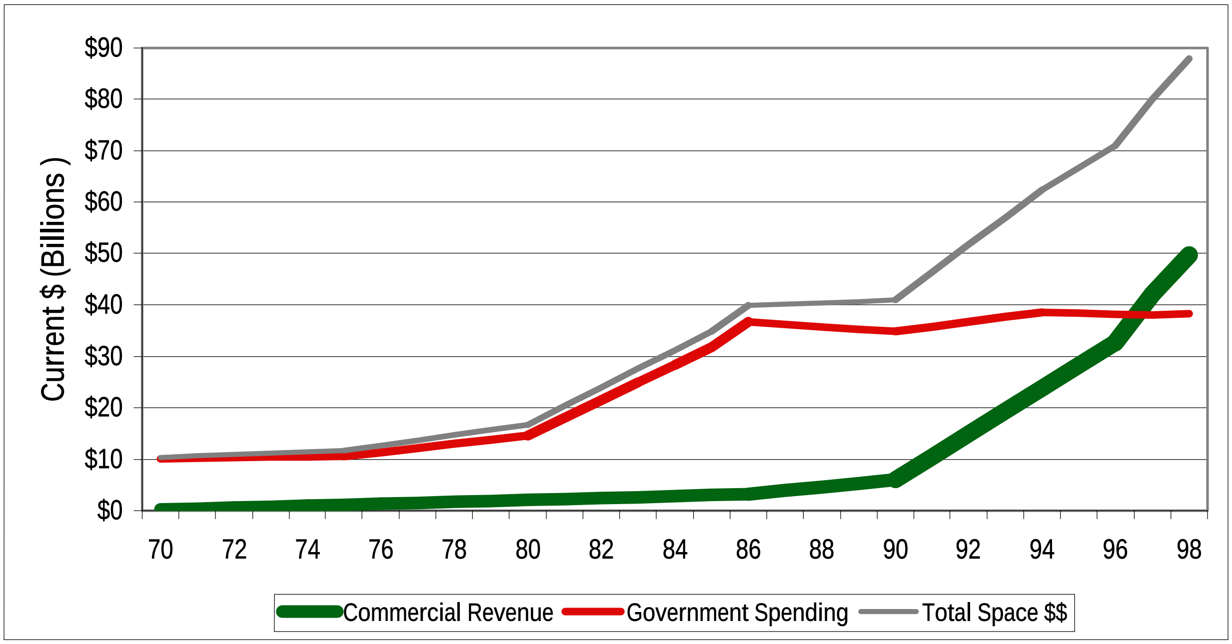
[44] Greg Lucas, Futron Corporation, e-mail to Barry Watts, February 3, 2000. For 1998, Futron analysts put the purely commercial worldwide revenues from space at $49.7 billion. If revenues to prime contractors from government contracts are included, the 1998 total rises to $57.4 billion—Futron Corporation in partnership with the Satellite Industry Association and George Washington University's Space Policy Institute, *Space Almanac* (Bethesda, MD: Futron, 1999), p. xi. If revenues paid to subcontractors and suppliers by primes on government space contracts are included, the total for worldwide commercial revenues climbs to $65.9 billion (ibid.). This last figure includes some double counting. For example, if the US government let a $1 billion contract for a radar satellite in 1998, and if the prime paid $500 million to subcontractors, then the total amount reflected in the $65.9 billion figure would be $1.5 billion, even though the government only spent $1 billion (ibid., p. x). Note that even higher estimates for worldwide commercial space revenues can be found. Excluding indirect revenues, Space Publications put worldwide revenues from government and commercial customers in 1998 at $85.24 billion, which is nearly $20 billion higher than the comparable Futron figure of $65.9 billion—*1999 State of the Space Industry* (Space Publications in collaboration with International Space Business Council), p. 7.

[45] Tim Beardsley, "The Way To Go in Space," *Scientific American*, February 1999, p. 81.

[46] General Michael E. Ryan, quoted in Grier, "The Investment in Space," p. 50.

ments—the early 21st century will see an increasingly larger share of the economic investment in and economic revenues from space systems coming from the commercial sector.

Figure 3: Worldwide Commercial Revenues from Space versus Worldwide Spending on Space by Governments



Source: Data provided by the Futron Corporation

Note: The major uncertainties in these totals are for the governmental spending on space by countries with non-market economies. As anyone can attest who participated in the Cold War arguments about intelligence estimates of the Soviet defense burden, calculating the dollar value of activities in non-market economies poses difficult problems even for the most diligent economic analysts.

Turning to the issue of military weapons being tested or fielded on any significant scale in orbital space, here the long-term trend is less apparent than it is regarding commercialization. Since 1957 there has been limited testing, but no lasting deployments, of weapons in orbit. One partial exception to this statement was Soviet testing, during the mid-1960s, of a fractional orbit bombardment system (FOBS) for delivering nuclear warheads against the United States using low orbital altitudes rather than the higher apogees typical of intercontinental ballistic missiles (ICBMs).[47] However, Soviet FOBS tests indicated that the payloads would be brought back to earth before one full orbit, and the public position of the American secretary of defense at the time, Robert S. McNamara, was that the Soviets would have been better off investing the money in more accurate intercontinental ballistic missiles.[48]

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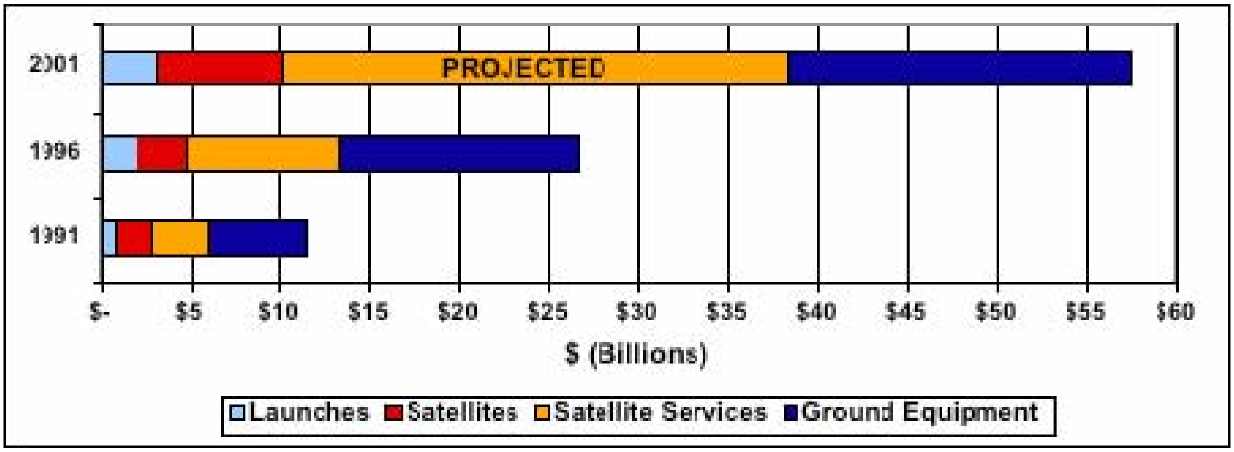
[47] Oberg, *Space Power Theory*, pp. 82–83.

[48] Stares, *The Militarization of Space*, pp. 99–100. McNamara did not reveal the concerns of the Joint Chiefs of Staff and the US Air Force over FOBS' first-strike potential stemming from the fact that it would attack targets in the US from the south, thereby avoiding much of the American early-warning system (Hays, "Struggling Towards Space Doctrine," p. 225).

Figure 4: Trends in Worldwide Commercial Space Revenues



Source: US Air Force Scientific Advisory Board, *A Space Roadmap for the 21st Century Aerospace Force; Volume 1: Summary* (Washington, DC: November 1998), SAB-TR-98-01, p.10.

Another partial exception to the view that space-based weapons have yet to materialize has been the researching, testing and fielding of anti-satellite weapons. The United States conducted research on a number of ASAT possibilities during the late 1950s and early 1960s. The first successful American satellite intercept against an orbital target was achieved by a modified Nike Zeus missile in May 1963.[49] The system (known as Program 505 and MUDFLAP), was armed with a nuclear warhead and declared operational that same year. The Army thereafter maintained at least one missile ready for launch until the ready requirement was dropped after 1964; the system was then phased out by 1967.[50] Nike-Zeus was supplanted by the US Air Force's Thor-based ASAT, which also had a nuclear warhead. The Thor system (also known as Program 437) became operational in 1964, but received direction in 1970 to be phased out as early as possible, although it remained nominally operational in a stand-by status until 1975.[51] By this time, it had become clear that the use of nuclear warheads to disable Soviet satellites would also jeopardize the more valuable US reconnaissance satellites, and American ASAT efforts turned to developing nonnuclear systems.[52]

The first unambiguous Soviet test of a co-orbital ASAT weapon occurred in 1968. Soviet testing of ground-launched, orbital interceptors using radar (and, later, optical-thermal) guidance and a nonnuclear, pellet-type warhead continued until 1971.[53] Testing of this system was then suspended for five years, until 1976, although the Defense Department argued during the 1980s that this system had achieved operational status starting in 1971 and had remained operational at the

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[49] Stares, *The Militarization of Space*, p. 119.

[50] Ibid., p. 120.

[51] Hays, "Struggling Towards Space Doctrine," pp. 271–72.

[52] Stares, *The Militarization of Space*, pp. 127–28; Hays, "Struggling Towards Space Doctrine, p. 215.

[53] For an artist's depiction of the Soviet co-orbital ASAT intercepting a target satellite, see DoD, *Soviet Military Power: 1983* (Washington, DC: US Government Printing Office, March 1983), pp. 65–66. This ASAT system was assessed capable of intercepting satellites at altitudes up to 5,000 kilometers above the earth's surface.

Baikonur cosmodrome, Tyuratam, Kazakhstan, at least through the end of the Cold War.[54] Once the Soviets resumed orbital tests in 1976, they continued until 1982, after which the Soviets declared a moratorium on further testing of ASAT weapons.[55] By 1983 American development of a nonnuclear anti-satellite weapon, the Miniature Homing Vehicle (MHV), was well underway, but had not yielded an operational system. The MHV was the third stage of a three-stage ASAT vehicle to be launched from an F-15 fighter, use infrared sensors to lock onto and guide to its target, and kill by directly ramming the enemy satellite at speeds high enough to preclude the need for an explosive warhead.[56] Although the MHV achieved at least one successful test against an orbiting US Air Force satellite in September 1985, the program became ensnarled in rancorous high-level policy debates over the strategic need for an American ASAT and the prospects for ASAT arms control with the Soviets.[57] Among other things, Congress imposed varying restrictions on MHV from one fiscal year to the next starting in 1983, and the US Air Force never strongly supported the program.[58] In December 1987 the US Air Force itself proposed canceling the program, thereby ending a decade-long effort to develop a non-nuclear US ASAT. As early as 1986, however, Pentagon accounts of Soviet military power began insisting that the Soviet Union was "maintaining the world's only operational antisatellite (ASAT) system."[59] The failure of the MHV program to produce an operational American ASAT capability enabled the Department of Defense to continue making this point through the end of the Cold War.

Strictly speaking, then, the American and Soviet ASAT systems developed during the Cold War did not weaponize space in the narrow sense of permanently basing weapons there. While these systems could be plausibly categorized as space weapons—both because they were designed to destroy orbiting satellites and because, by doing so, they would degrade enemy space capabilities, thereby exerting space control—their history so far does not gainsay the earlier judgment that the testing weapons in near-earth space has been limited and permanent deployments of weapons there have yet to occur. Again, American military definitions would categorize ASAT capabilities as space control rather than force application, thereby exempting them from the latter category. As has been suggested more than once, however, ASAT systems clearly do involve

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[54] DoD, *Soviet Military Power: 1984* (Washington, DC: US Government Printing Office, April 1984), pp. 34–35.

[55] Stares, *The Militarization of Space*, pp. 135–40, 143–46 and 222–23. Western researchers generally agree that the Soviets conducted some twenty ASAT tests from 1968 to 1982. These tests involved, first, orbiting a target satellite and, then, launching an interceptor. In addition, the Defense Department has assessed the nuclear-armed GALOSH antiballistic missile (ABM) system around Moscow to have "an inherent ASAT capability" against low-altitude satellites—DoD, *Soviet Military Power: 1986* (Washington, DC: US Government Printing Office, March 1986), p. 51. In the 1980s, the SH-01 GALOSH was replaced by two missiles. The longer-range of these more modern ABM systems, the SH-11 GORGON, was also assessed by the US intelligence community to have a latent capability against satellites in very low earth orbit, although there have been no reports of it being tested in this mode.

[56] Stares, *The Militarization of Space*, pp. 206–7. The first stage was a modified Boeing short-range attack missile (SRAM), the second stage a Vought Altair III booster and the final stage was the MHV kinetic-kill vehicle itself (Hays, "Struggling Towards Space Doctrine," p. 388).

[57] Hays, "Struggling Towards Space Doctrine," pp. 387 and 391. According to Hays, on September 13, 1985 a MHV destroyed a US Air Force P78-1 in a low-earth orbit. The satellite, launched in 1979 into an orbit 319–335 nautical miles in altitude, had been designed to study the sun's corona and was still operational when the successful intercept occurred (ibid., p. 395).

[58] Ibid., p. 391.

[59] DoD, *Soviet Military Power: 1986*, p. 41.

force application in a broader, more natural sense of the term. After all, the ASAT kill mechanisms involved in Program 505 (Nike Hercules) and Program 437 (the Thor-based system) utilized nuclear warheads.

In retrospect, it seems safe to suggest that both the United States and the Soviet Union could have gone further than they actually did in placing weapons in space during the Cold War. What restrained the natural inclination of the two superpower adversaries to undertake arms competition in orbital space? Sporadic inclinations toward arms control aside, an important part of the answer undoubtedly lies in the threat that nuclear use in orbital space posed to the strategic reconnaissance satellites on which both the United States and Soviet Union came to depend to monitor the other's strategic-nuclear forces and deployments. For the United States, this threat to imagery and other LEO satellites emerged from exo-atmospheric nuclear tests during the late 1950s and early 1960s. The American "Teak" shot in July 1958 used a rocket to detonate a 2–2.5 megaton device some 252,000 feet above Johnston Island in the Pacific; this test disrupted the ionosphere for several hours and blacked out trans-Pacific high-frequency, short-wave communications as far away as Australia.[60] Four years later, in July 1962, the United States detonated a 1.4 megaton weapon—"Starfish Prime"—at an altitude of about 250 miles above Johnston Island to test the effects of high-altitude nuclear explosions on radio communications and radar over a wide area. Besides setting off burglar alarms and burning out street lights on Oahu in the Hawaiian Islands, the interaction of the prompt radiation from the nuclear detonation generated large numbers of high-energy electrons that then were trapped by the earth's magnetic field, producing an intense artificial radiation belt which began damaging orbiting weather and communications satellites.[61] The artificial radiation belt destroyed seven satellites in seven months and lasted until the early 1970s.[62] Similar Soviet tests also generated enhanced radiation belts capable of degrading the solar panels and unhardened microelectronics common in commercial LEO satellites today.[63]

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[60] Chuck Hansen, *US Nuclear Weapons: The Secret History* (Arlington, Texas: Aerofax, 1988), pp. 78–79 and 81.

[61] Ibid., pp. 84 and 87. Most of the energy produced by an efficient nuclear weapon is released as electromagnetic radiation in the form of massless photons traveling at the speed of light. While this photon radiation spans much of the electromagnetic spectrum from microwaves to gamma rays, the energy release peaks in the soft X-ray region for a typical nuclear fireball at 400 million degrees Kelvin—Richard Rhodes, *Dark Sun: The Making of the Hydrogen Bomb* (New York: Simon and Schuster, 1995), pp. 457–59. The shorter the wave length of these photons, the more energetic they are and the stronger their interactions with matter. X rays have wave lengths from one to 100 Angstroms, where one Angstrom is 10^{-10} meters (Sellers, et al., *Understanding Space,* p. 352). Gamma rays have even shorter wave lengths. When x-ray and gamma-ray radiation interacts with matter, including gas molecules in the atmosphere, these high-energy photons knock electrons out of their atomic shells, generating an electromagnetic pulse (EMP) of electrons within physical objects such as satellites and all manner of electrical components. Both the radiation flux and EMP phenomenon resulting from a nuclear detonation are prompt, short-lived effects, regardless of whether the detonation occurs within or outside the earth's atmosphere. The photon radiation from a nuclear detonation lasts only a few microseconds. However, when a nuclear detonation occurs high enough above the atmosphere, the EMP interaction with the atmosphere can extend over long distances (hundreds of miles) and generate enough high-energy electrons to create an artificial radiation belt than may endure for years. The radiation belts, whether natural or artificial, are shaped by the earth's magnetic field.

[62] R. C. Webb, "Implications of Low-Yield High Altitude Nuclear Detonation," Defense Special Weapons Agency (DSWA), presentation to an OSD/Net Assessment workshop on nuclear weapons and the revolution in military affairs, September 16–17, 1997, slide 43.

[63] Ibid., slide 42.

Given this experience with exo-atmospheric nuclear detonations, it is not surprising that the western powers made a series of proposals between 1959 and 1962 to bar the use of outer space for military purposes, particularly to prohibit the basing or use of nuclear weapons there. Today it is widely believed that the underlying American motive was no less than to eschew military use of orbital space and make it safe for US NTM, which in itself constituted a militarization of space. In any event, a treaty governing the exploration and use of outer space, including the moon and other celestial bodies, was eventually negotiated; the US Senate gave unanimous consent to its ratification on April 25, 1967, and it entered into force on October 10, 1967.[64] The treaty has since been embraced by 91 nations, including the People's Republic of China, Iran and Iraq. One notable exception to the list of signatories is North Korea.

The main prohibitions of the 1967 outer-space treaty are to ban weapons of mass destruction from both outer space and celestial bodies, and to reserve the moon and other celestial bodies for peaceful purposes—meaning no military bases, weapon testing or military maneuvers. Literally interpreted, these prohibitions do not bar conventional or nonnuclear weapons from orbital space. Nor does the 1967 space treaty explicitly prohibit a space-based laser being placed in earth orbit and used against terrestrial targets. Presumably, the arms-control difficulties with a space-based laser able to destroy targets deep within the atmosphere or on the earth's surface lie elsewhere. Such a system would be capable of destroying ballistic missiles in flight and, under the 1972 ABM Treaty between the United States and the Soviet Union, both parties undertook "not to develop, test, or deploy ABM systems or components which are . . . space-based . . ."[65]

Of course, arms-control agreements between nation-states have not always been followed, especially when their leaders have judged continued adherence no longer in their national interests. Despite the prohibitions of the outer space treaty, the fact remains that the detonation of a small nuclear weapon—meaning yields as low as 50 kilotons—at an altitude of approximately 155 miles (250 kilometers) could dramatically degrade the operating lives of a number of LEO satellites due to the cumulative radiation dose incurred from repeatedly transiting weapon-enhanced ("pumped") electron belts.

While this possibility is one that has been played in American war gaming of future conflicts in recent years, it is almost certainly not the most likely threat to growing western and American dependence on orbital systems. The trend toward increasing commercialization of near-earth space is being driven by the growing economic utility of space systems for a range of services, including wireless voice (telephone) communication, telephone trunking, data transfer and communication, broadcast and cable television, remote earth sensing (including imagery and weather data), and precision navigation. This very success also creates increasing vulnerability should these systems be lost—a vulnerability that increasingly extends to the US military. Currently, the United States is the only nation with truly global military commitments and capabilities. The

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[64] Narrative comments on the history of the 1967 Treaty on Principles Governing the Activities of States in Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies are available online at: http://www.state.gov/www/global/arms/treaties/space1.html#1.

[65] Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Limitation of Anti-Ballistic Missile Systems, signed May 26, 1972, Article V; available online at: http://www.state.gov/www/global/arms/bureau_ac/treaties_ac.html.

projection of military power anywhere on earth—whether for a major contingency, peacekeeping, or something in between—has become the principal purpose of the American military. Global force projection within the time frames now contemplated depends more and more on space systems. Adversaries with access to launch vehicles and nuclear weapons could opt to level the playing field by exploding a nuclear device above the atmosphere. A far easier and less destructive approach, however, may be simply to attack the ground segment of US military and commercial space systems. Saboteurs, terrorists willing to sacrifice themselves for a cause, special forces units, and conventional precision munitions could all be used to degrade or destroy satellite ground stations or other critical elements of American military and commercial space systems. Jamming and other forms of electronic interference offer even more benign ways of offsetting or negating the considerable military advantages US forces now derive from orbital systems. Finally, as more and more systems develop portals into publicly accessible computer networks, the prospects for cyber warriors to corrupt computer data or mount other kinds of attacks on computer networks seem likely to expand exponentially.

With the preceding points in mind, what can be said concerning whether, in coming decades, the United States can sustain its current margin of military advantage derived from overhead systems, whether the American margin of advantage, if sustained, will yield proportionate degrees of strategic and operational advantage, and if, by 2020 or 2025, the military use of space will have shifted from predominantly force enhancement to predominantly force application? Despite the inability to predict the next quarter century in detail, four main judgments appear warranted.

- First, now-evident and emerging trends suggest that the large margin of relative military advantage the United States currently enjoys, based strictly on its access to orbital systems may grow more difficult to sustain in the years ahead. The high barriers to entry once controlled by the American and Soviet governments limited access to such things as high-resolution imagery of the earth's surface to the two superpowers. Growing commercialization, coupled with explicit US policy to make, for instance, one-meter resolution imagery available to any government, organization or individual with the money to buy it,[66] indicate that, in the long run, space services will become, if not commodities, far more accessible to even small states and groups of individuals than they have been in the past. Indeed, in the case of the Navstar GPS, the system may well become, for all intents and purposes, an international public utility.[67] Also, foreign militaries may be able to operationalize market-driven commercial and dual-use space technologies such as satellite communications and remote sensing more rap-

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[66] As John Pike recently observed, "The price of admission to the spy satellite business used to be a billion dollars. Now, anybody with a credit card" can buy 1-meter resolution images (Vernon Loeb, "Spy Satellite Will Take Photos for Public Sale," *The Washington Post,* September 25, 1999, p. A3). Loeb's article focused on the Ikonos satellite whose high-resolution, color imagery is now being sold to the public through Space Imaging, Inc.

[67] GPS is a constellation of 24 navigation satellites (21 primaries and three spares) orbiting at an altitude of more than 12,427 miles (20,000 kilometers)—Thomas A. Herring, "The Global Positioning System," *Scientific American*, February 1996, p. 48. At this altitude, GPS satellites are considered to be in medium-earth orbit. "The current generation of GPS satellites provides about 60 m horizontal positioning accuracy, or circular error probable (CEP), to commercial users using the coarse acquisition (CA) code and 10 m CEP to military users who have access to the precision (P) code. The next generation of GPS satellites, the Block 2R system, will deliver 20 m accuracy to commercial users using the CA code and 6 m accuracy to military users having access to the P code."—Daniel Gonzales, *The Changing Role of the US Military in Space* (Santa Monica: RAND Corporation, 1999), MR-895-AF, p. 11.

idly than a US Defense Department burdened with Cold War programming, budgeting, funding, and acquisition processes overseen by numerous congressional committees and subcommittees. If these insights do prove prescient, then the ability of the US military to sustain disproportionate advantages from near-earth space seems destined to hinge less on pure-and-simple access than on how quickly and effectively American military can capitalize on space systems before and during terrestrial military operations.

- Second, the uncertainties as to whether military exploitation of space will have shifted appreciably from force enhancement to force application by 2020–25 are not as easily bounded, much less eliminated. As commercial investments in orbital space grow relative to governmental investments, and as more and more nations come to depend on space systems and services, fewer and fewer nations are likely to judge wholesale destruction of space systems as in their best interests. USSPACECOM's current long-range plan observes that the United States has more than $100 billion invested in space today, and that more than 1,100 commercial companies across 53 countries are developing, manufacturing and operating space systems.[68] Given the many ways of degrading, interfering with or attacking US military space systems without bearing the economic and diplomatic costs of fielding space-based weapons, there appears to be a better-than-even chance that force application broadly construed will not become the dominant military use of space over the next quarter century. Of course, this judgment by no means precludes substantial growth in what might be termed "space warfare by terrestrial means." Indeed, one can argue that space warfare in this sense has already arrived.

- Third, however, it is not difficult to imagine events that could either trigger rapid deployments of weapons in near-earth space, or start at least some nations gradually sliding—perhaps almost unnoticed—down a slippery slope toward a security environment in which some weapons deployed in space would be seen as a natural next step. Whether, for example, space-based systems for boost-phase intercept of ballistic missiles would still be eschewed by all nations in the wake of a nuclear-armed ballistic missile being used against a target on the earth's surface remains to be seen. We really do not know how the United States or other nations would react to such an event. Without a doubt, the appearance of military weapons in near-earth space by 2020 is certainly a conceivable outcome of such a trigger event.

- Fourth, while the logic of the situation suggests that near-earth space will become an arena of human conflict in the long run, that day may lie further in the future than is commonly thought. The economic and military stakes in orbital space are not yet obviously great enough to compel states to initiate military competition there, and various costs of placing weapons there remain high. Moreover, there are less overt ways of offsetting US military advantages derived from space systems than throwing treaties aside and deploying weapons in orbit or elsewhere in outer space.

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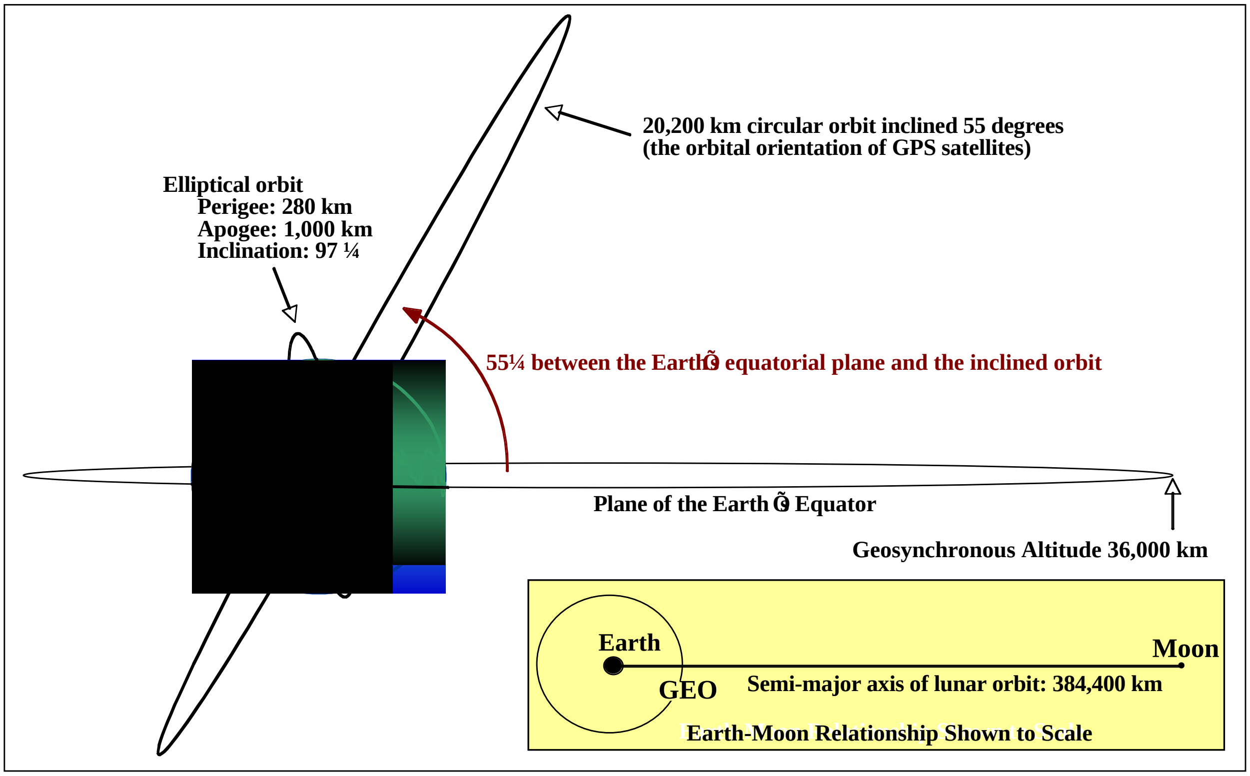
[68] USSPACECOM, *Long Range Plan*, p. 3.

Figure 5: Selected Relationships in Near-Earth and Lunar Space Shown to Scale in Relation to Earth's Diameter



These four judgments about how the military use of space may unfold through 2020–25, when combined with the four earlier judgments regarding the current state of military competition based on orbital systems, constitute the basic conclusions of this assessment. As has already been mentioned, however, they omit much. The remainder of the report, therefore, aims at filling in the context, evidentiary detail, additional evidence, and intervening conclusions needed to explain and justify them.

II. HOW TO THINK ABOUT THE MILITARY VALUE OF NEAR-EARTH SPACE

> . . . the conceptual problems in constructing an adequate or useful measure of military power have not yet been faced. Defining an adequate measure looks hard, and making estimates in real situations looks even harder. —A. W. Marshall, 1966[69]

> Suffice it to say that for most higher-order problems adequate measures of merit have yet to be devised. Even if some improvement may be hoped for, the irreducibly subjective element in such measures will remain substantial. —James R. Schlesinger, 1967[70]

> . . . simple numerical indicators of capability will be central to most debates over the various components of relative national power.
> —Aaron L. Friedberg, 1988[71]

One of the more difficult problems of net assessment is determining how to think about the area of competition at issue. How should the assessment be structured? What are the important comparisons to make? What are the objectives, strategies and perceptions of each competitor or side? What indices or measures of merit, quantifiable or not, will provide genuine insight into the fundamental nature of the military business being assessed? What trends, asymmetries and other developments may enable one side to catch or surpass the other?

These questions are never easily answered. They are particularly difficult when the area being assessed is as different from traditional military competitions as the military exploitation of near-earth space appears to be. This chapter, therefore, aims less at attempting definitive answers to the problems of structuring an adequate assessment of the military value of space than at illustrating some of those problems and suggesting tentative solutions.

One approach to introducing the problems of assessing military competition in space is to revisit some of the difficulties that arose in Cold War assessments of the competition in strategic-nuclear arms between the United States and the Soviet Union. So-called static measures, such as the numbers of nuclear warheads and intercontinental nuclear delivery vehicles each side possessed, were widely used in the West to compare American and Soviet capabilities, as were dynamic measures such as calculations of the number of surviving nuclear warheads each side would have following an all-out nuclear exchange in a given scenario. Comparisons based solely on such measures, however, fell well short of providing an adequate net assessment of the US-

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[69] A. W. Marshall, “Problems of Estimating Military Power,” RAND Corporation, P-3417, 1966, p. 9.

[70] James R. Schlesinger, *Selected Papers on National Security 1964–1968* (Santa Monica, CA: RAND Corporation, September 1974), P-5284, p. 93.

[71] Aaron L. Friedberg, *The Weary Titan: Britain and the Experience of Relative Decline, 1895–1905* (Princeton, NJ: Princeton University Press, 1988), p. 291.

Soviet competition in long-range nuclear forces. The main US goal in this competition was not to achieve strategic superiority in some form or another; rather, the major American aim was to deter a nuclear attack on the continental United States in the first place. As a result, Soviet assessments of the competition with the United States in strategic arms constituted a vital perspective in any adequate assessment of the strategic balance.[72] Furthermore, a Soviet-style assessment could not simply be "the standard US calculations done with slightly different assumptions about missile accuracies, silo hardness, etc."[73] By the early 1980s, if not earlier, there was good reason to believe that Soviet assessments were structured differently than our own, made different assumptions about scenarios and objectives, focused attention on different variables, and, at a technical level, performed different calculations and used different measures of effectiveness.[74] These differences had important implications for American assessments of the strategic-nuclear competition, one of which was that US policy makers tended to misread the motivations behind Soviet strategic-force developments, particularly with regard to whether the Soviets truly believed that they could fight and win a nuclear war.[75]

In the case of military competition in space, issues such as choosing appropriate measures, or adequately taking into account the goals and assessments of potential competitors to the United States, are at least as complex and ill-suited to precise quantification as was the protracted Cold War competition in strategic-nuclear arms. If anything, these problems would appear to be more acute in the case of space. To begin with, there are some fundamental differences between traditional military operations by armies or air forces and operations outside the atmosphere with orbital spacecraft. The engineering and physics of maneuvering a tank, a nuclear submarine or a jet aircraft differ in important ways from those involved in placing a payload into earth orbit or changing a space vehicle's orbit once established. Consequentially, intuitions about space operations derived from everyday terrestrial experience can be misleading. Take the problem of bringing an orbiting vehicle back into the earth's atmosphere. One might suppose that the most effi-

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[72] By 1982, Marshall was arguing that an adequate net assessment of the US-Soviet strategic-nuclear competition required at least three perspectives: the efficacy of US long-range nuclear forces for deterrence, taking into account the likelihood that Soviet assessments differed substantially from American assessments; how well American forces would perform in attaining US and Western objectives should deterrence fail; and, effects of the competition on the perceptions of American allies and other major third parties.

[73] A. W. Marshall, "A Program To Improve Analytic Methods Related to Strategic Forces," March 11, 1982, p. 2. This paper appeared in *Policy Sciences,* 15, 1982, pp. 47–50.

[74] Ibid. p. 2. After 1991, direct discussions with Soviet participants in the Cold War competition confirmed Marshall's judgment that Soviet assessments and calculations differed from American ones. To cite one instance among many, the Soviet General Staff, using different data, models and measures of effectiveness for the disabling of silo-based intercontinental ballistic missiles than their American counterparts, concluded that air bursts "were only one-fourth as effective as ground bursts in knocking out ICBMs."—John G. Hines and Daniel Calligaert, *Soviet Strategic Intentions, 1973–1985: A Preliminary Review of U.S. Interpretations*, (Santa Monica, CA: RAND Corporation, December 1992), WD-6305-NA, p. vi.

[75] While National Intelligence Estimate 11-3/8-82 acknowledged statements by Soviet leaders "that nuclear war with the United States would be a catastrophe that must be avoided if possible," the estimate went on to state that the Soviets sought "superior capabilities to fight and win a nuclear war . . . , and have been working to improve their chances of prevailing in such a conflict" (Director of Central lntelligence, *Soviet Capabilities for Strategic Nuclear Conflict, 1982–92*, NIE 11-3/8-82, February 15, 1983, I, *Key Judgments and Summary*, p. 5). Nevertheless, interviews with Soviet General Staff officers after the fall of the Berlin wall in 1989 indicated that Soviet military leaders "understood the devastating consequences of nuclear war" and were "genuinely intent on preventing it" (Hines and Calligaert, *Soviet Strategic Intentions, 1973–1985,* p. 5).

cient way to do so would be to apply "downward" thrust to the vehicle, meaning directly toward the center of the earth. It turns out, though, that it is about four times cheaper in terms of the required velocity change (or "delta-V") to apply the thrust opposite to the direction of vehicle's orbital motion (a "retrograde burn").[76] Such disconnects with everyday earthly experience suggest that terrestrial analogies for thinking about the military value of near-earth space may contain even larger pitfalls than those commonly encountered in trying to measure more familiar forms of military power.

Nevertheless, analogies to more familiar forms of military competition have been a recurring point of departure for thinking about the military use of near-earth space. USSPACECOM's current vision document provides a clear illustration of this tendency. Those who crafted the document saw parallels between near-earth space and the rise of navies to protect maritime commerce, the westward expansion of the United States and the development of air power:

> Historically, military forces have evolved to protect national interests and investments—both military and economic. During the rise of sea commerce, nations built navies to protect and enhance their commercial interests. During the westward expansion of the continental United States, military outposts and the cavalry emerged to protect our wagon trains, settlements, and railroads.
>
> As air power developed, its primary purpose was to support and enhance land and sea operations. However, over time, air power evolved into a separate and equal medium of warfare.
>
> The emergence of space power follows both of these models. Over the past several decades, space power had primarily supported land, sea, and air operations—strategically and operationally. During the early portion of the 21st century, space power will also evolve into a separate and equal medium of warfare. Likewise, space forces will emerge to protect military and commercial national interests and investment in the space medium due to their increasing importance.[77]

How useful are these analogies—especially as a guide to the future? On the one hand, they provide familiar points of departure for anyone trying to think about the current and future military significance of near-earth space. On the other hand, the more plausible historical analogs break down when closely examined, thereby revealing ways in which the military use of space differs qualitatively from terrestrial military experience on land, at sea and in the air.

Consider the development of British sea power in relation to the objectives of protecting the British Isles from invasion, securing economic benefits for Britain from maritime commerce, and, eventually, sustaining a worldwide colonial empire. England's naval history is often dated from

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[76] Oberg, *Space Power Theory*, p. 26.

[77] US Space Command, *Vision for 2020*, p. 4 (of the pdf version found online at: http://www.peterson.af.mil/usspace/). The formulation of historical analogies for the development of orbital space in USSPACECOM's *Vision for 2020* seems preferable to those in the command's more recent *Long-Range Plan* because the latter is, as Colin Gray and John Shelton have observed, somewhat ambiguous about whether space power's future lies in force enhancement or force application (Gray and Shelton, "Space Power and the Revolution in Military Affairs: A Glass Half Full?" p. 24).

the reign of Queen Elizabeth, who ascended to the throne in 1558 and, in the 1570s, began using privateers such as Francis Drake and John Hawkins to raid the maritime commerce and treasure fleets of Spain under Philip II.[78] After a decade of depredations by the English and the Dutch, Philip II dispatched an "invincible" armada of 130 ships manned by some 7,000 sailors and 17,000 soldiers to destroy Protestant sea power.[79] Following some initial skirmishes off the English coast and Dutch intervention to preclude the planned Spanish landing at Dunkirk, Drake caught up with the Armada as it struggled up the Flemish coast near Gravelines. English gunnery and seamanship enabled Drake's ships to keep their distance and inflict broadside after broadside on the Spanish vessels, which "were never able to apply a continuous close-range cannonade" against the English.[80] While a sudden squall ended the engagement, the English inflicted enough damage to prevent the Armada from landing, and only a remnant of the great fleet survived the homeward voyage around Scotland to return safely to Spain. This defeat marked the advent of the Royal Navy as a high-seas fleet capable of operating at long range.[81]

British dominance of the world's oceans can be dated from the Battle of Trafalgar on October 21, 1805. This costly victory ended Napoleon Bonaparte's attempts to contest British control of the sea and "confined the victorious arms of France to Continental Europe."[82] Thereafter, revolutionary France's only naval option was commerce raiding (the *guerre de course*).[83] With the final defeat of Napoleon, Britain became the world's dominant naval power and also controlled most of Europe's colonies. "A salient feature of the eighty years following Trafalgar was that no other country, or combination of countries, seriously challenged Britain's control of the seas."[84] Britannia's rule of the waves, in turn, provided the military foundation that enabled Britain to achieve the world's highest per capita income and become, by the late 1860s, the "superdominant economy" in the world's trade structure.[85] This period, like our own, was an era in which the steady and, later, spectacular growth of "an integrated global economy drew ever more regions into a transoceanic and transcontinental trading and financial network."[86]

What does this maritime history suggest about the current value and future development of military capabilities in near-earth space? US Space Command's conclusions are clear enough. Space

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[78] Lynn Montross, *War Through the Ages* (New York: Harper and Brothers, 1960), 3rd ed., p. 255. Montross notes that English naval history predates the Elizabethan period by some three centuries. "As far back as 1214 a fleet of vessels commanded by Hubert de Burgh won a great victory over 80 French ships under a monk named Eustace, noted as a medieval naval tactician. This engagement of sailing ships, as chronicled by Matthew Paris, is said to have been the first recorded instance of manoeuvres to seize the 'weather gage;' i.e., the offensive advantages of a wind allowing ships to steer straight for the opponent" (ibid.).

[79] Ibid., p. 256.

[80] Geoffrey Parker, *The Military Revolution: Military Innovation and the Rise of the West 1500–1800* (Cambridge and New York: Cambridge University Press, 1996), 2nd ed., p. 95.

[81] Ibid., p. 99.

[82] Geoffrey J. Marcus, *The Age of Nelson* (Sheffield, England: Applebaum Ltd, 1971), p. 295.

[83] Ibid., p. 361.

[84] Paul Kennedy, *The Rise and Fall of the Great Powers: Economic Change and Military Conflict from 1500 to 2000* (New York: Vintage Books, 1989), p. 154.

[85] Ibid., pp. 138–39 and 192.

[86] Ibid., p. 143.

forces, the command's vision document asserts, "will emerge to protect military and commercial national interests and investments in the space medium due to their increasing importance"; American space systems "will be targets," implying that "space superiority is essential."[87] The implicit logic, of course, is that the analogy between sea power and space power, if not exact, is close enough.

Notwithstanding the argument by some observers that the parallels between space and "the maritime and air environments could hardly be clearer," however, there do appear to be difficulties.[88] Long before the Royal Navy came to rule the waves during the 19th century, English shipping had been repeatedly subjected to piracy as well as commerce raiding by the navies of other nations. Why? First and foremost because of the economic wealth associated with the growth of maritime commerce that followed the discovery of the New World. Drake and Hawkins originally made their names raiding Spanish galleons bringing gold and other treasure back to Spain from the Americas.

By contrast, over four decades into the space age, no nation has tried to seize or mount destructive attacks against the operational satellites of another, including the two Cold War adversaries. Although both accidental and intentional interference with the functioning of satellites has occurred, attacks aimed at destroying satellites have not. While ASAT systems have been tested and fielded in the past, US capabilities are currently limited to a US Army developmental program for a kinetic-kill vehicle launched by a Minuteman missile, and one cannot help but wonder about the readiness of the Russian nonnuclear ASAT system inherited from the Soviet era. Again, one must wonder why this happens to be so. And the most straightforward answer is that orbital assets have yet to acquire the economic import of Spanish treasure galleons.

In the case of space, therefore, one is hard pressed to point out the equivalent of the great-power navies that shaped the Royal Navy and its adversaries from the time of Queen Elizabeth to the early 20th century, or even strong parallels to high-seas piracy against commercial shipping. True, these points do not establish that explicit parallels will not emerge one day—when orbital systems acquire sufficient economic, political or other value to nations. They do reveal, though, a crucial area in which the analogy between naval forces and space forces breaks down, at least as of this writing. Colin Gray and John Shelton have recently offered the "assumption" that the "strategic history of space power is likely to follow the pattern already traced clearly by sea power and airpower."[89] So far, however, Gray and Shelton's prediction has not been borne out, and seemingly because a key condition has yet to be met. Moreover, and even if they prove right in the very long run, the issue of timing remains relevant for real-world decision makers.[90] It

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[87] US Space Command, *Vision for 2020,* pp. 4 and 7.

[88] Gray and Shelton, "Space Power and the Revolution in Military Affairs: A Glass Half Full?" p. 31.

[89] Ibid., p. 26.

[90] Even Gray and Shelton concede that fighting in space from space, and into space "may be slow to arrive" (ibid., pp. 26–27). It is difficult to disagree with their insistence that "Space power, space warfare, and the geography of space are not beyond strategy" (ibid., p. 28). But neither are space power, space warfare and the geography of space beyond the laws of physics, the economics of the marketplace or the politics of arms control.

matters greatly whether the economic, political or other conditions on which their prediction hinges are met in ten years or 50.

Nor is the absence to date of space-based weapons or attacks on satellites the only problem with the naval analogy. Since 1957, the value of space systems has resided largely in the information they can relay from one point on the earth to another or else provide to their owners and operators by virtue of their vantage point in the high ground of orbital space, not in the transportation of material goods from one location on the earth's surface to another. Seizing at sea or sinking ships transporting the crude oil on which a competitor's economy depends could easily pose a direct threat to that nation's economic prosperity in time of peace, if not to national survival in time of war. Posing such a threat to England's economy was the French motivation for pursuing *guerre de course* against British shipping from 1803 to 1815.[91] Attacking satellites in the early 21st century, by comparison, poses a less direct, less vital threat to the nations utilizing them than cutting off energy supplies or other raw economic materials. Again, one option for a nuclear-armed state seeking to deny the advantages of space to US forces would be to level the playing field by detonating a nuclear weapon at a high enough altitude to destroy or degrade the world's on-orbit inventory of LEO satellites. Such an act, however, would be a blunt instrument to say the least and would affect every nation dependent on satellite services as well as a large number of active satellites. Currently, over 40 percent of the world's active satellites are in low-earth orbits (see Figure 1).[92] Presumably many nations around the world would be as disinclined to let such an act of wanton destruction go unpunished as was the American-led coalition in 1990–91 to allow Iraq to seize Kuwait and gain control of 20 percent of the world's proven oil supplies.[93] It seems unlikely that the use of nuclear weapons for the wholesale degradation of LEO satellite constellations would be tolerated by organizations such as the NATO, and that such a use of weapons of mass destruction would also have the disadvantage of denying the benefits of low-earth satellite services to the perpetrator as well as to the rest of the world.

Further, while such an indiscriminate attack would take down most of the LEO satellites over a period of weeks, many satellites at higher altitudes—particularly those not line-of-sight with the nuclear burst at the time of its detonation—would continue to function. Some satellite communications, then, would persist, and terrestrial alternatives such as fiber-optic cables, which gained market share at the expense of satellite communications on high-density routes throughout the 1990s, would offer alternative communications paths.

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[91] "The French government held firmly to the belief that a war directed against the commerce of Great Britain was a sure and certain means of destroying her" (Marcus, *The Age of Nelson*, p. 361).

[92] Hans ten Cate and Charles Murphy, "Space Transportation and the Global Space Commerce Market: Issues and Indicators," Futron Corporation presentation at the AIAA Defense and Civil Space Programs Conference, October 28, 1998, slide 14. Using ten Cate and Murphy's data, the number of active LEO satellites is over 340 vehicles.

[93] David Kay, who led some of the early United Nations Special Commission (UNSCOM) teams into Iraqi after Operation Desert Storm, concluded that on January 17, 1991 Iraq was "probably only 18 to 24 months away from its first crude nuclear device and no more than three to four years away from more advanced, deliverable weapons" (David A. Kay, "Denial and Deception Practices of WMD Proliferators Iraq and Beyond," *The Washington Quarterly*, Winter 1995, p. 85).

Finally, it is far from clear that a country planning on or engaged in fighting the United States would appreciably reduce the amount of military power the United States could ultimately bring to bear by attacking LEO satellite constellations with a nuclear burst above the sensible atmosphere. Yes, the growing dependence of the American military on commercial satellites for reachback to data and information systems in the continental United States means that their loss would impose delays and problems for US operations. On the other hand, critical satellite components of DoD's communications architecture, such as the geosynchronous MILSTAR I/II satellites, are nuclear hardened.[94] Consequently, even an exo-atmospheric nuclear burst seems unlikely to be as serious for the United States—economically or militarily—as would, say, a complete cessation of the flow of crude oil from the Persian Gulf to the developed countries. The costs of such a wantonly destructive act would be high and the likely benefits for the perpetrator, at best, fleeting and short term.

A more sensible option than an exo-atmospheric nuclear burst would probably be the selective disabling or destruction of individual satellites using hit-to-kill kinetic-energy ASATs, whether augmented with nonnuclear warheads or not. Of course, selective attacks with nonnuclear kill-mechanisms against key American satellites would be more difficult to execute with high confidence of success, although the technology involved is not beyond reach for any of the space-faring nations as well as for a number of others. In addition, the effects on both the US economy and the US military would probably be minimal—inconvenient pin pricks at best. One can also imagine situations in which the number of American on-orbit assets of a specific type—for example, radar imaging satellites—might be small enough that a handful of ASATs could significantly reduce American capabilities for surveillance from orbital space. Still, the foreseeable results do not even remotely approach constituting a direct threat to American economic prosperity, much less to US survival.

If this analysis is correct, then the analogy between the development of navies in response to *guerre de course* and the emergence of space-based military capabilities in response to prospective attacks on satellites breaks downs in important ways. Sinking a nation's ship on the high seas, whether a military or commercial vessel, has long been viewed as an act of war. Article VIII of the 1967 Outer Space Treaty states that any party "on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body." In 1996, the United States declared as national policy that the space systems of any nation are "national property with the right of passage through and operations in space without interference."[95] Nevertheless, damaging or destroying satellites does not seem to have quite the same status as damaging or sinking a nation's

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[94] DoD, *Space Program: Executive Overview for FY1999–2003*, p. 16. MILSTAR is the US military's most secure and advanced communications satellite. Two Block I MILSTAR satellites, each carrying a low-data-rate payload (75 to 2,400 bits/second), were launched during 1994–95; both remain operational (Glenn W. Goodman, Jr., "Long-Distance Communications: Army Warfighters Rely on Satellite Links To Stay in Touch," *Armed Forces Journal International*, March 2000, p. 20). The Block II MILSTAR features the low-data-rate payload as well as a medium-data-rate (4.8 kilobits to 1.544 megabits per second) capability (ibid.). However, the first Block II launched in April 1999 was stranded in a useless orbit due to a launch failure.

[95] National Science and Technology Council (NSTC), The White House, "Fact Sheet, National Space Policy," September 19, 1996, introduction, paragraph (3); available online at http://www.aiaa.org/policy under the heading AIAA Position Papers.

ships and killing its crew. Satellites may have owners and operators, but, in contrast to sailors, they do not have mothers. Granted, the destruction of a KH-11 or comparable satellite at a key juncture in a crisis with a major regional power would be taken very seriously by American leaders. Whether this act would inevitability lead to war, however, is far from clear.

> (1) For over three decades, the United States has led the world in the exploration and use of outer space. Our achievements in space have inspired a generation of Americans and people throughout the world. We will maintain this leadership role . . .[96]
>
> (3) The United States is committed to the exploration and use of outer space by all nations for peaceful purposes and for the benefit of all humanity. "Peaceful purposes" allow defense and intelligence-related activities in pursuit of national security and other goals. The United States rejects any claims to sovereignty by any nation over outer space or celestial bodies, or any portion thereof, and rejects any limitations on the fundamental right of sovereign nations to acquire data from space. The United States considers the space systems of any nation to be national property with the right of passage through and operations in space without interference. Purposeful interference with space systems shall be viewed as an infringement on sovereign rights.[97]
>
> (6)(g) Consistent with treaty obligations, the United States will develop, operate and maintain space control capabilities to ensure freedom of action in space and, if directed, deny such freedom of action to adversaries. These capabilities may also be enhanced by diplomatic, legal or military measures to preclude an adversary's hostile use of space systems and services. The US will maintain and modernize space surveillance and associated battle management command, control, communications, computers, and intelligence to effectively detect, track, categorize, monitor, and characterize threats to US and friendly space systems and contribute to the protection of US military activities.[98]

To push the parallel between maritime commerce and space a bit further, is there not a similarity between the notion of freedom of the seas and that of freedom to use near-earth space? While current American space policy commits the United States to maintaining its leadership role in the exploration and use of outer space, this goal is framed within the context of a commitment to the peaceful use of outer space by all nations and an aversion to basing weapons or forces there. The United States has not even had an operational capability to destroy an orbiting satellite with an earth-based ASAT since the mid-1970s. By contrast, the US Navy has long been doctrinally committed to seeking sea control through direct force application *at sea*, with emphasis on putting the enemy's fleet on the bottom of the ocean during fleet-on-fleet engagements as the preferred option. Thus, the historical American approach to orbital space in general, and to space control in particular, diverges substantially from traditional approaches to sea control involving offensive force application into and within the maritime medium.

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[96] Ibid., para. (1).

[97] Ibid., para. (3).

[98] Ibid., para. (6)(g).

The same can said of air control. Traditionally air forces have achieved control of the air first and foremost through offensive force application—shooting down enemy fighters in air-to-air combat, attacking enemy air bases and suppressing enemy air defenses. Yet, as we have seen, USSPACECOM has not fielded parallel capabilities, and orbital navies have not appeared. Thus, more than four decades after Sputnik, the analogy between space forces and air forces does not appear to hold up at the level of either national policy or of fielded capabilities for controlling the medium.

> Space power is as important to the nation as land, sea, and air power. Space forces support military operations by providing information lines of communication enabling information superiority, contributing to deterrence, and ensuring freedom of space.[99]

One possible explanation for the problems with the comparisons between space power and air or sea power is that people have simply chosen the wrong analogies. Instead of concentrating on the force-on-force aspects of sea power or air power, perhaps a better parallel is the role of railroads in land conflicts starting in the second half of the 19th century. In the American Civil War of 1861–65, for instance, railroads were used to transport troops and supplies—particularly from one theater to another by the Union. While Confederate forces such as the Army of Northern Virginia remained foraging armies to the war's end, the Union army used rail transport to develop the first industrial-age logistic system, thereby giving rise to a core competence at which American forces have excelled ever since. The revolution inherent in the Union's growing exploitation of railroads from 1861 to 1865, combined with the South's inability to do so, was fundamentally one of mobility and logistics, not one of direct force application.[100] Railroads, though in their infancy during the American Civil War, "made it possible for the armies to attain strategic mobility and to accomplish logistic miracles."[101] Whereas airplanes during World War I shifted rapidly from reconnaissance to air-to-air and air-to-ground combat operations, trains, having a different role in industrial-age warfare, have not made the parallel transition to this day.

Insofar as space systems are, at present—if not for the foreseeable future—valued first and foremost for their ability to move or transport information, they may be more comparable to railroads than to early airplanes or capital ships of the line. Particularly attractive is the fact that railroad tracks, once laid, are enormously expensive to move, much as the orbital plane of a satellite,

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[99] William S. Cohen, *Annual Report to the President and Congress* (Washington, DC: US Government Printing Office, 2000), p. 84.

[100] "Soon after the first great battle [of the American civil war] failed to end the struggle, it began to appear that important railroad junction points were to become major military objectives, and, as time passed, many of the bloodiest battles of the war were fought in defense of them. Now famous campaigns were planned and conducted for the primary purpose of capturing or destroying railroad lines of particular value to the enemy. As each successive year ended, it became increasingly apparent that the side which controlled the railroads held a tremendous advantage, and in the end it was the Confederate loss of two railroads which led to the surrender at Appomattox."—George Edgar Turner, *Victory Rode the Rails: The Strategic Place of Railroads in the Civil War* (New York: Bobbs-Merrill, 1953), p. ix.

[101] *The West Point Atlas of American Wars*, Brigadier General Vincent J. Esposito (ed.), vol. I (New York: Praeger, 1959), p.17.

once established, is enormously costly in terms of energy to change.[102] Indeed, an even closer analogy than railroads may be the advent of telegraphs and other land-line forms of communications in military operations. Not only was information transported by these systems used for military purposes, but military units have been far more inclined to extend land-line communications forward into enemy territory during offensive operations than they have been to lay down new railroad tracks.

Whether one sees railroads or telegraphs as the more useful analogs to space systems in the early 21st century, these alternatives to combat aircraft and naval combatants raise the distinct possibility that USSPACECOM's vision of how space forces will evolve in coming decades suffers from having seized upon the wrong analogies. True, the more obvious historical analogies to naval and air forces provide handy, familiar points of departure. However, as matters now stand, they appear to break down when scrutinized closely, thereby revealing ways in which space systems appear to be qualitatively different from more traditional, terrestrial combat systems.

The alternative offered by the prospective parallels between railroads or telegraphs and space assets is also unsettling for those persuaded that the deployment of weapons in near-earth space is inevitable—simply a matter of time. Neither the railroad nor telegraph analogy obviously supports the inevitability of space becoming a battleground in the foreseeable future.

In light of these findings, it should not be surprising to suggest that we lack sound measures of effectiveness and analytic constructs for capturing space's military value today, much less in coming decades. Early in the space age, the costs and technological difficulties of putting payloads in orbit limited access to the United States and the Soviet Union. Barriers to entry were extremely high. Today, the growing commercialization of space—including the availability of recent earth imagery over the Internet—argues that the formerly formidable barriers to access are rapidly becoming far less of a constraint than they were in the 1960s or 1970s. Similarly, the cost of putting a pound of payload in orbit has long been viewed as a good quantitative measure of launch efficiency and ease of access to space. However, as miniaturization and other efficiencies enable each pound of a satellite to grow more valuable in terms of the services that pound can provide once in orbit, and as the service lives of satellites increase, this measure may also become less useful.

Lastly, there remains the problem of adversary assessments of the emerging military competition in space. A decade into the post-Cold War era, there is considerable uncertainty as to which nations, if any, will turn out to be the main challengers to the advantages the American military de-

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[102] Marshall H. Kaplan, *Modern Spacecraft Dynamics and Control* (New York: Wiley and Sons, 1976), p. 90; also, Sellers, et al., *Understanding Space*, pp. 189–94. The Sellers book gives a sample calculation for the velocity change (Δv) needed to alter the inclination of a GPS satellite 29 degrees (see Figure 5). The answer is 3.88 kilometers/second, and the book goes on to comment that this is 50 percent of the velocity needed to orbit a GPS satellite in the first place. In this example, the Δv for a one-degree inclination change is about 135 meters/second. Satellites using chemical-rocket propulsion typically arrive in orbit with enough fuel for a total velocity change of 250 meters/second; this amount of fuel is enough to change the inclination of the original orbital plane some two degrees (Major Rick Walker, "Weaponization," presentation, USACOM/J-9 Joint Experimentation Futures seminar, Fort Monroe, Virginia, June 29, 1999). The hope for the Space Maneuver Vehicle is that it can be injected into low-earth orbit with enough Δv for orbital inclination changes as great as 20 degrees.

rives from near-earth space. Might mainland China one day force the weaponization of space despite the 1967 outer space treaty? Or might China instead find ways to offset American advantages derived from orbital systems by contesting American control of near-earth space using terrestrial military means? About all that can be said with confidence is that Chinese views concerning the utility and proper use of military power appear to be substantially different from American attitudes and beliefs. For example, new Chinese materials published since 1988 have undermined the common American belief that Beijing's intervention on the Korean Peninsula in 1950 was "caused by Washington's failure to heed Chinese warnings."[103] Instead, Mao Tse-tung's October 2, 1950, decision to intervene was taken before UN troops were approaching the Yalu River and was apparently made on the misperception that the annihilation of an American unit or two would cause the United States to abandon the peninsula, thereby eliminating the threat of an imminent American attack on mainland China from Taiwan, Korea and Indochina.[104] More broadly, recent research indicates that Chinese analysts are showing renewed interest in the Warring States period that produced a series of classic texts on statecraft warfare and culminated in the founding of China around 249 BC[105] Chinese defense scholars find the post-Cold War multi-polar security environment "amazingly" similar to the Warring States era, and the relevance of ancient Chinese statecraft from that period has been endorsed by a commission of China's generals.[106] Chinese military thought about the military use of space, therefore, is likely to be conditioned by metaphors, historical examples and even quantitative calculations about the relative power of states, which are quite different from those common in the West.

Suffice it to say, we are at an early stage in the development of sound approaches, analytic tools and appropriate measures for assessing military competition in space, either today or in coming decades. In fact, we may not have even found the right metaphors and historical analogies for thinking about the military use of near-earth space. This chapter sought to make the reader aware of the challenges. Implicitly, the structure of this report, along with the comparisons, measures, trends, and asymmetries utilized, constitutes a tentative response to the challenges of assessing the military value of space.

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[103] Michael Pillsbury, *Dangerous Chinese Misperceptions: The Implications for DoD*, undated paper for the Office of Net Assessment, p. 41. This paper was printed as a pamphlet for the Office of Net Assessment and circulated within the Pentagon. It was part of a very early draft of Pillsbury's *China Debates the Future Security Environment* (Washington, DC: National Defense University Press, 2000).

[104] Bin Yu, "What China Learned from Its 'Forgotten War' in Korea," *Strategic Review*, summer 1998, p. 5; Pillsbury, *Dangerous Chinese Misperceptions*, p. 41.

[105] Pillsbury, *China Debates the Future Security Environment*, p. 315. The Warring States period ended in 249 B.C., when King Chao of Ch'in liquidated the Chou dynasty, thereby giving birth to China—Sun Tzu, *The Art of War*, trans. Samuel B. Griffith (Oxford: Oxford University Press, 1963), p. 1. Sun Tzu's *The Art of War* is one of the classic texts that emerged from this period.

[106] Pillsbury, *China Debates the Future Security Environment*, p. 315.

III. THE CURRENT AMERICAN ADVANTAGE IN THE MILITARY USE OF NEAR-EARTH SPACE

> For the greater part of the space age, the United States and the Soviet Union dominated all human activity in space. As the only players in the game, they literally wrote the "rules of the road" for space, both by their practices and in their proposals for international agreements. Key among these rules was unfettered access to space and noninterference with national activities in space.
>
> —Frank Klotz, 1998[107]

> . . . the [US-Soviet] dispute over satellite reconnaissance and the absence of an arms race in space were the results of a convergence of national interests, military disincentives and technical constraints, which were buttressed at important times by *formal* agreements. . . . US policymakers from the outset wanted to avoid an arms race in space but not at the price of limiting their freedom of action to use space for military purposes, particularly satellite reconnaissance. . . . Although the United States was clearly the main beneficiary of satellite reconnaissance, the Soviets were also attracted by its potential military applications.
>
> —Paul Stares, 1985.[108]

> . . . the photo reconnaissance satellite is one of the most important military technological developments of this century, along with radar and the atomic bomb. Without it, the history of this century would be very different. Indeed, without it history might well have ceased.
>
> —Jeffrey Richelson, 1990[109]

The overview reached four judgments about the state of military competition in near-earth space today. First, the United States is far ahead of any other nation on earth in its capabilities to exploit orbital systems to gain military advantage. Second, current American usage of near-earth space is mainly, if not exclusively, force enhancement of terrestrial operations, not force application (even broadly construed). Third, during the 1990s the United States began to transition from a mostly pre-conflict use of national-technical means to exploiting orbital systems for the enhancement of ongoing military operations. Fourth, US forces have tapped no more than a small fraction of the information collected by satellite systems. The aim of this chapter is to elaborate upon and further support these key judgments.

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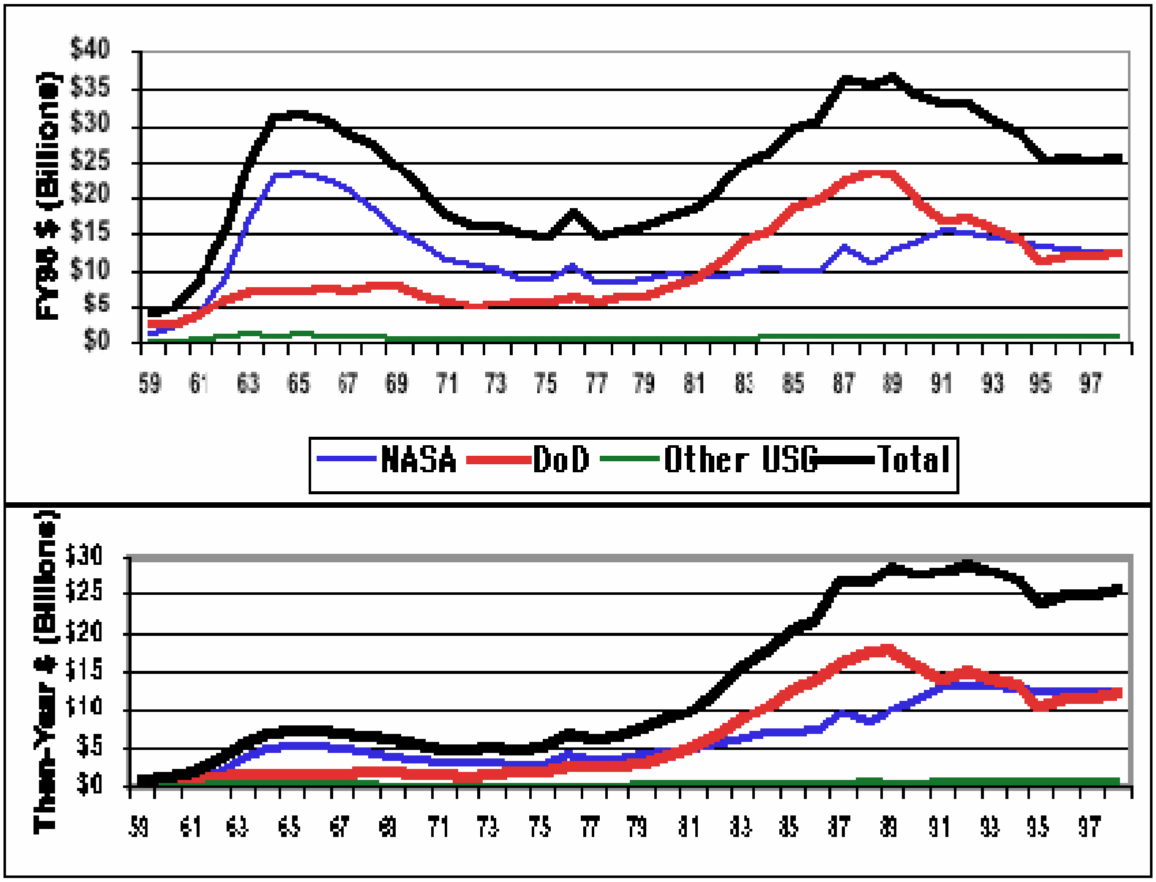
[107] Frank G. Klotz, *Space, Commerce, and National Security* (New York: Council on Foreign Relations, 1998), p. 5.

[108] Stares, *The Militarization of Space*, pp. 237–38.

[109] Richelson, *America's Secret Eyes in Space*, p. vi.

Figure 6: DoD, NASA and Other US Government (USG) Spending on Space, 1959–98



Source: The Director of Investment for DoD Space, Office of the Comptroller, Pentagon.

Note: How much of the NRO's budget is included in the DoD total has been a matter of speculation among those not privy to the classified details of the US intelligence budget. John Pike believes that the space budget data released by the Defense Department and other government agencies "include only Defense Department spending, and exclude the CIA [Central Intelligence Agency] portion of the NRO [National Reconnaissance Office], thereby understating by several billion dollars the total national security space budget" ("NRO Budget," available at: **www.fas.org/irp/nro/nrobud.htm**). Regardless the US Air Force and the NRO maintain they are responsible for "more than 90 percent" of US spending on "international security space activities" (Keith Hall, "Organizing for Space Based Intelligence Gathering" in *Spacepower for a New Millennium*, p. 204).

One place to start is with some quantitative data bearing on the judgment that the United States' efforts in orbital space are currently far ahead of those of any other nation. Figure 6 shows annual expenditures by DoD, the National Aeronautics and Space Administration (NASA) and other elements of the federal government in both constant 1998 dollars (that is, with the effects of inflation removed) as well as in then-year dollars.[110] In real terms—meaning constant dollars—DoD spending on space did not surpass annual NASA budgets of the 1960s, when the

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[110] NASA was created in 1958 to administer a civil space program devoted to the peaceful use of space for the benefit of all mankind (ibid., p. 8). The National Aeronautics and Space Act of 1958 also "explicitly established—in law and policy—a separate and independent military space program" (ibid.). The initial aim of the American civil space program was, of course, "to put a man in space before the Soviets" (Sellers, et al., *Understanding Space*, p. 45).

United States was trying to land a man on the moon before the Soviets, until the late 1980s. Annual civil spending on manned spaceflight during the 1960s was substantial even compared to the peak DoD spending levels of the mid-1980s. A second point evident in Figure 6 is that US government spending on space since the late 1990s reflects the overall decline in defense spending that followed the end of the Cold War and the break up of the Soviet Union. Third, to put these expenditures in a somewhat broader context, in the late 1990s very few nations had defense budgets that exceeded overall US government spending on space. For example, in 1997 only six other countries besides the United States—China, France, Germany, Japan, Russia, and the United Kingdom—had defense budgets greater than $25 billion a year. Although annual US government space budgets are merely a measure of inputs, with all the limitations of input measures as opposed to actual outputs, they do indicate the large capital-investment advantage the American military and civil space programs have enjoyed in recent decades.

Another way of putting US government space expenditures in context is displayed in Figure 7. It shows US government spending on space relative to the total worldwide investment from Figure 3 (worldwide purely commercial revenues plus worldwide government spending). For the years 1970–89, some 56 percent of worldwide investments in space were made by elements of the US government. This dominance of investment in space by the American government lessened during the 1990s for two reasons. There was, first, some decline in total US government spending on space. A bigger factor, though, was the growth in worldwide commercial revenues from space that began around 1991. As Figure 3 indicates, worldwide government spending was more or less flat during the 1990s whereas commercial revenues underwent steady growth. As a result, the US government's share of worldwide investment in space for the years 1990–98 dropped to about 42 percent. Most observers of the commercial space industry believe that this trend will continue, with the majority of the commercial growth coming from satellite and ground services (see Figure 4). Whether this projection proves accurate remains to be seen. Regardless, the cumulative capital investment that the US government has made in space since the mid-1980s dwarfs that of any other nation. Given the decline in the Russian space program over the last decade, the input measure of government spending begins to suggest why the United States is so far ahead in the military use of near-earth space.

Figure 7: US Government Spending on Space Compared to All Other Worldwide Spending/Revenues (Including US Commercial Revenues)

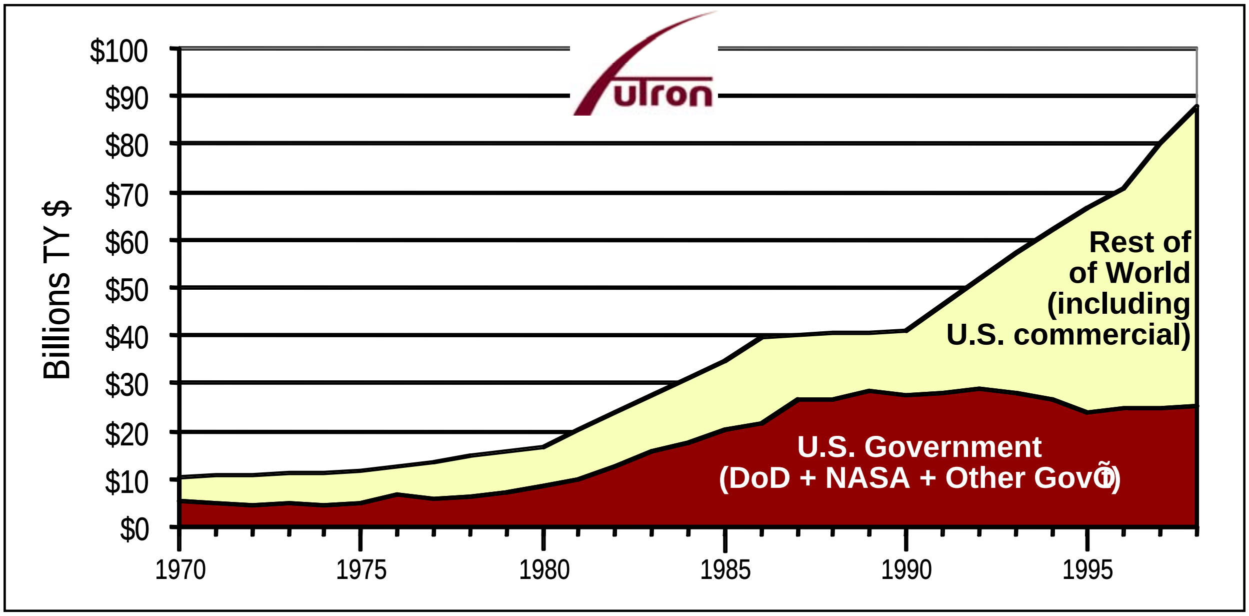
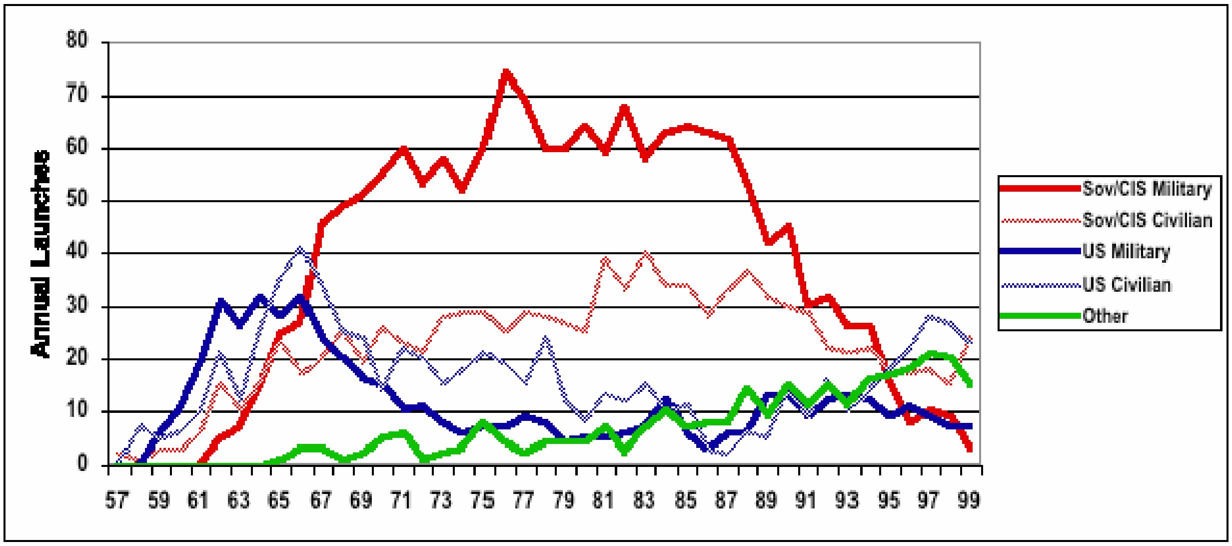


Figure 8 offers a more detailed breakout of the annual launch data shown earlier in Figure 2. Again, the data reinforce the perception of increasing US preeminence since the late 1980s. Particularly striking in Figure 8 is the sharp decline in CIS military launches during the 1990s. Also of interest is the upsurge in Soviet non-military launches late in the decade has depended heavily on using Russian and Ukrainian launch vehicles to place Western commercial payloads in orbit. Note, though, that the data hide some important details, such as the increasing dominance of heavy-payload launches to geosynchronous altitudes by the European Space Agency.

Figure 8: US and USSR/CIS Military and Civilian Annual Space Launches



Source: Data from Mehuron, *Space Almanac*

Over and above the sort of quantitative data in Figures 6–8, there are qualitative considerations that lend further support to the judgment that the United States today enjoys a large margin of advantage in the military use of near-earth space. Consider the use of satellite constellations to provide precision location on or near the surface of the earth. Both the United States and the Soviet Union have orbited satellite constellations—GPS and GLONASS (Global Navigation Satellite System), respectively—for this purpose.[111] The United States currently has 27 operational GPS satellites in orbit (including three spares). A constellation of 18 to 24 satellites is necessary to ensure that a receiver anywhere on the earth will always be in line of sight with at least four satellites, which is the minimum needed to ensure the three-dimensional position accuracy for guiding precision weapons.[112] Ironically, the United States is now finding that the on-orbit GPS satellites are lasting longer than anticipated—8.6 versus 6 years—which is slowing down their replacement.[113] Most of the 18 existing replacement GPS satellites now waiting to be launched are older models lacking the jam-resistant military M-code, two additional civil signals and the higher power level now needed, and USSPACECOM officials are concerned that the earliest launch for the first improved GPS satellite may not occur until 2007.[114]

By comparison, the Russians have placed some 68 GLONASS satellites in orbit since December 1982; yet, of the ten still on orbit as of early 2000 (see Figure 1 for their orbital altitude in relation to GPS), only eight were usable.[115] In fairness, from the outset the Soviets portrayed GLONASS as a 9-to-12 satellite system.[116] Still, only the United States has been able to sustain a navigational constellation able to provide three-dimensional precision location worldwide, whereas the Russians are now unable to maintain the minimum number of satellites even for the smaller GLONASS constellation. While the eight operational GLONASS satellites may still suffice for the needs of Russian rocket forces, the difference between the two systems not only provides an indicator of the large margin of American advantage in the use of orbital space, but also raises the possibility that GPS will become the worldwide standard for such things as precision navigation by commercial aircraft. If GPS does become the standard outside of the Russian Federation, this outcome will further reinforce the overall American advantage in using space systems for military purposes.[117]

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[111] For an overview of how GPS works, see Herring, "The Global Positioning System," *Scientific American*, February 1996, pp. 44–50. For discussion of the policy issues associated with GPS see Scott Pace, Gerald Frost, Irving Lachow, David Frelinger, Donna Fossum, Donald K. Wassem and Monica Pinto, *The Global Positioning System: Assessing National Policies*, (RAND, 1996); available at http://www.rand.org/publications/MR/MR616. The Soviets used digital signal-processing data from GPS documents to develop GLONASS (DoD, *Soviet Military Power: An Assessment of the Threat 1988*, (Washington, DC: US Government Printing Office, April 1988), p. 63).

[112] DoD, *Soviet Military Power 1988,* p. 63.

[113] Keith Hall, Assistant Secretary of the Air Force (SPACE) and Director, National Reconnaissance Office, "Space Policy, Programs and Operations," statement to the Committee on Armed Services, Subcommittee on Strategic Forces, United States Senate, March 22, 1999; available online at www.nro.odci.gov/index4.html.

[114] Grier, "The Investment in Space," p. 50.

[115] The official Russian GLONASS website: http://rssi.ru/SFCSIC/english.html.

[116] DoD*, Soviet Military Power 1988*, p. 63.

[117] The head of USSPACECOM has, in fact, observed that GPS "has become not only a national utility but an international utility or commodity" ("Air Force Wants To Charge Other Services To Use Its Satellites," *Defense Week*, January 10, 2000, p. 1).

One last indication of the decline of the Russian space program was the plan put forward in the late 1990s by Russian Space Agency and NASA for a controlled destructive re-entry of the Mir space station in 2000. This plan was prompted by the inability of the Russian government to provide sufficient funding, given its commitments to the International Space Station, to keep the aging Mir in operation. While it now appears probable that international funding aimed at exploiting Mir for commercial purposes will enable the Russians to keep their space station operating through 2005, this development further underscores the inability of the post-Soviet Russian economy to sustain a space program comparable to that of the United States.[118]

There is, then, no lack of evidence for the view that the United States, at the beginning of the 21st century, is without peer in the military exploitation of near-earth space. In light of this evidence, the next logical question to consider is how space-faring nations such as the United States have chosen to exploit orbital systems for military purposes. Given the long dominance of orbital space by the United States and the Soviet Union, this question can be largely answered by reviewing the military uses made of space systems by the two superpowers during the period 1947–91.

From the outset of the Cold War, the development of nuclear weapons and space systems were closely interconnected for the United States and the Soviet Union. The space systems of both superpowers played important, if often concealed, roles in the US-Soviet competition in intercontinental nuclear forces. Space systems provided strategic (meaning nuclear) attack warning, reconnaissance, communications, and navigational aids for nuclear forces. For instance, the original purpose of the American DSP satellites "was to provide high confidence warning of a Soviet nuclear attack to the National Command Authority (NCA) as early as possible."[119] US communications satellites furnished "worldwide connectivity from the NCA to forward deployed strategic force elements," while reconnaissance satellites "monitored arms production and storage facilities and the status of military forces deep inside the Soviet Union."[120] Moreover, photo-reconnaissance satellites were crucial to the targeting of US ballistic missiles because, unlike aircraft photos, satellite images were directly registered in geodetic coordinates.[121] Finally, early US navigation satellites also focused on nuclear targeting. The US Navy's Transit Navigation System, designed by Johns Hopkins University's Advanced Physics Laboratory, enabled American ballistic-missile submarines to fix their position several times a day to accuracies of 0.1 nautical miles.[122]

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[118] "Mir History Unfolds," Moscow, Itar-Tass News Agency, February 17, 2000; story downloaded from http://library.northernlight.com/FC20000217230000069.html?cb=0&sc=0#doc.

[119] Gonzales, *The Changing Role of the U.S. Military in Space*, p. 26.

[120] Ibid.

[121] Jasper Welch, e-mail to Barry Watts, March 10, 2000. The problem with early U-2 photos of Soviet targets was that the plane's position in geodetic space when it photographed a given facility was not precisely known. For purposes of targeting ICBMs, U-2 imagery simply would not do. Welch notes that the original decision to target Soviet cities with nuclear weapons came about before information from the Keyhole satellites became available. Prior to imaging satellites, the United States targeted cities with ICBMs because cities were large enough to cover the target-location error.

[122] Robert J. Danchik, "An Overview of Transit Development," *Johns Hopkins APL Technical Digest*, 19, no. 1 (1998), p. 18. The first operational Transit satellite was orbited in 1963 and the system was declared operational in

Given the importance of satellite systems to the United States in the strategic-nuclear competition with the Soviet Union, it is not surprising that a special organization was set up to field and operate so-called national technical means. The long-covert NRO was established in late 1960 to design, build and operate all the United States' strategic reconnaissance satellites including Corona.[123] Over time the United States came to depend on these systems not only to track Soviet strategic force developments and deployments, but also to monitor Warsaw Pact forces opposite NATO, as well as to track Soviet treaty compliance without the need for on-site inspections. However, while the NRO provided tight, responsive control of NTM intelligence data and resources to decision makers at the highest levels of the US government, this arrangement, which included classifying NTM data above TOP SECRET, also created a situation in which "this most valuable of all military reconnaissance information was generally not directly available to the military, even during wartime."[124]

Early in the Cold War, it was far from clear that satellite systems would perform all these roles. In 1962, in response to American success with the KH-1 Corona photo-reconnaissance satellite, the Soviets undertook a diplomatic offensive to prohibit satellite reconnaissance from space.[125] The Soviets, of course, were working on their own imaging satellites at the time. The first successful Soviet photo-reconnaissance satellite was launched in April 1962 into an orbit that provided coverage of targets throughout the United States.[126] The Soviet Union achieved sufficient success with film-return reconnaissance satellites that, in July 1963, Nikita Khrushchev offered to show satellite photos to the Belgian foreign minister.[127] While Soviet diplomatic objections persisted a few more months, progress on nuclear test-ban negotiations, which hinged on the use of NTM in lieu of on-site inspections, coupled with the prospect of eventually banning nuclear weapons from space, led Moscow to cease serious objections to satellite reconnaissance in September 1963.[128] In sum, during the first decades of the Cold War both superpowers developed satellite reconnaissance, and both came to embrace these systems as a stabilizing influence on their competition in intercontinental nuclear weapons.

1964. The Transit system, later known at the Navy Navigational Satellite System, continued to provide position and timing data until 1996. Users received time history of the Doppler data and orbital ephemeris (position and velocity as a function of time) from the Transit satellite as it passed overhead and, from this information, could compute their positions.

[123] David N. Spires, *Beyond Horizons: A Half Century of Air Force Space Leadership* (Washington, DC: US Government Printing Office, 1998), p. 85. According to Spires, the NRO was created from the Air Force's Office of Missile and Satellite Systems. The NRO would eventually be responsible for coordinating US Air Force, Central Intelligence Agency, US Navy, and National Security Agency intelligence reconnaissance activities. NRO personnel are assigned from the Department of Defense and the Central Intelligence Agency (NRO, "Who We Are," www.nro.odci.gov/index6.htm). The US government did not publicly acknowledge the existence of the NRO until September 1992 (Hays, "Struggling Towards Space Doctrine," p. 181).

[124] Hays, "Struggling Towards Space Doctrine," p. 191. Throughout the Cold War, data from American satellites were classified specially compartmented intelligence (SCI) and access was generally granted on a need-to-know basis only.

[125] Stares, *The Militarization of Space*, p. 59.

[126] Jeffrey T. Richelson, *A Century of Spies: Intelligence in the Twentieth Century* (Oxford: Oxford University Press, 1995), p. 300.

[127] Ibid., p. 71.

[128] Ibid.

A striking feature of American use of satellite systems throughout the Cold War was the exploitation of overhead assets focused almost exclusively on the pre-conflict phase of central nuclear war. Should a nuclear exchange have been initiated by one side or the other, satellites would have made some contributions to US performance in the ensuing conflict. They would have provided weather data for American heavy bombers. Positional updates for American ballistic-missile submarines using Transit navigation satellites would have improved the accuracy of their ballistic missiles. By and large, however, the US military did not seek to use space systems during the actual nuclear exchange, much less to enhance non-nuclear operations on anything approaching a real-time basis.

Soviet intelligence satellites were initially put to much the same preconflict uses as American NTM. Soviet satellites developed precise targeting data on US nuclear forces, especially American ICBMs, and monitored the status and deployments of US nuclear forces; mapped areas of general military interest, particularly those bordering the Soviet Union; monitored the development and testing of new systems in the United States and China; and, collected information on large-scale military and naval activities.[129] Over time, the Soviet space program grew quite large and developed some capabilities that went beyond the preconflict dimensions of all-out nuclear war. By the mid-1980s, the Soviet Union was maintaining some 160 active satellites in space, of which only a small portion—about 5 percent—were assessed by the US intelligence community as being for purely civilian or scientific use.[130] By then the Soviets had the world's only operational ASAT system as well as EORSAT and nuclear-powered RORSAT systems for which the United States had "no counterpart."[131] These ocean-reconnaissance satellites were intended to "detect, locate, and target US and Allied naval forces for destruction by antiship weapons launched from Soviet platforms" such as Backfire bombers.[132] While these capabilities were never tested in actual combat between American and Soviet forces, they reflected an inclination to exploit space systems *during* terrestrial combat operations not evident in American utilization of orbital assets virtually to the end of the Cold War.

This asymmetry between American and Soviet proclivities in exploiting orbital systems began to reverse in the early 1990s. The immediate causes of this reversal were the dissolution of the Soviet Union and the 1991 Gulf War. On the Russian side, the basic constraint became funding for military space programs. When Iraq invaded Kuwait in August 1990, the Soviet Union is believed to have had at least one operational photo-reconnaissance satellite with real-time data return in orbit. Prior to the beginning of Coalition combat operations on January 17, 1991, the Soviets launched three more imagery satellites, including a second real-time system in December 1990.[133] However, the operational lives of the two film-return satellites launched in August and

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[129] These missions were attributed to Soviet reconnaissance satellites in National Intelligence Estimate 11-1-67, *The Soviet Space Program*, March 2, 1967, cited in Richelson, *A Century of Spies*, pp. 307–08.

[130] DoD, *Soviet Military Power: Prospects for Change 1989*, p. 54.

[131] DoD, *Soviet Military Power: 1985* (Washington, DC: US Government Printing Office, April 1985), p. 58.

[132] Ibid.

[133] Richelson, *A Century of Spies*, p. 419. Jonathan McDowell's master launch log (hea-www.harvard.edu/QEDT/jcm/space) indicates that the Soviet imagery satellites mentioned by Richelson are Cosmos 2072 (launched April 3, 1990), Cosmos 2089 (August 3, 1990), Cosmos 2102 (October 16, 1990), and Cosmos 2113 (December 21, 1990).

October 1990, respectively, were both under 60 days, which meant they were not available by the beginning of Operation Desert Storm.[134] As a result, during the first three weeks of Coalition offensive operations, the Soviets were limited to the two real-time imaging satellites to monitor the conflict, although, following the launch of a third film-return satellite on February 7, 1991, they had three imagery satellites for the war's final three weeks.[135]

Nevertheless, by the late 1990s the collapse of the Russian space program had not only produced intermittent coverage gaps, but significant deterioration in entire Russian satellite constellations. For example, in June 2000 the American press reported that the Russians had only one geostationary missile-warning satellite in operation, and this satellite, Cosmos 2224, was no longer in one of the eight geostationary locations reserved from these warning satellites.[136] If, as reported, only four of the nine Russian missile-warning satellites in highly elliptical orbits are active, then the Soviet missile-warning system may provide only reduced warning time of US launches at best, and fail to provide any warning of launches by American Trident submarines at worst. If this deterioration in Russian satellites for intercontinental-nuclear-attack warning is any indication, it appears doubtful that the financially strapped Russian space program has been able to maintain less vital satellite capabilities such as EORSAT and RORSAT systems for the detection and targeting of American naval vessels at sea. Far more likely is that these Cold War capabilities for theater conflicts have largely atrophied along with the Russian space program as a whole.

The American military, by contrast, began moving in the opposite direction during the 1990s. Even before Operation Desert Storm had ended, some American airmen began to characterize the conflict as having been "the first space war."[137] Vague as this characterization may have been, military leaders—especially airmen—sensed instinctively that space-based sensors and command-and-control capabilities had enabled the US-led coalition to achieve "information dominance" over Iraq, meaning that space had handed coalition commanders and planners the "ability to observe the whole theater, to rapidly assess threats and opportunities, to identify targets, and to navigate precisely to those targets."[138] As General Thomas Moorman later wrote, Desert Storm "opened the eyes of senior military leaders" to the military value of space.[139] In light of this changed perception, it is not surprising that many in the American military anticipated increased help from space assets in future conventional conflicts. Coincidentally, the break up of the Soviet Union in December 1991 also led members of the US intelligence community to

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[134] Cosmos 2089, launched on August 3, had a mission duration of 59 days; Cosmos 2101, launched on October 16, operated 57 days (Encyclopedia Astronautica, www.friends-partners.org/~mwade/chrono/chrono.htm). Thus, neither of these satellites provided coverage of Desert Storm.

[135] Cosmos 2124 returned a total of three film capsules during its 59-day mission (Encyclopedia Astronautica, www.friends-partners.org/~mwade/chrono/19911.htm#4119).

[136] David Hoffman, "Russia Blind to Attack by U.S. Missiles," *The Washington Post*, June 1, 2000, pp. A1 and A19.

[137] Merrill A. McPeak, "The Air Force's Role in Space," April 15, 1993 speech in *Selected Works 1990–1994* (Maxwell AFB, Alabama: Air University Press, August 1995), p. 207. McPeak was the chief of staff of the US Air Force from October 30, 1990 to October 25, 1994.

[138] Ibid. Arguably, satellites first aided theater operations during the Vietnam War. During that conflict, "meteorological and communications satellites provided vital near-real-time data essential for mission planning and execution" (Spires, *Beyond Horizons*, p. 169).

[139] Moorman, "The Explosion of Commercial Space and the Implications for National Security," p. 6.

see their future as hinging more and more on the ability to deliver such information to the operators, or warfighters, in a timely manner. This post-Cold War alignment of interests between American warfighters and the US intelligence community led to a concerted effort during the 1990s make the fruits of NTW available to theater commanders *during* ongoing nonnuclear operations.

How much progress did the American military make during the 1990s in linking space systems to the real-time warfighting needs of regional commanders-in-chiefs (CINCs) and their commands? The obvious place to seek an answer is Operation Allied Force, the 78-day air campaign NATO conducted against the Federal Republic of Yugoslavia (FRY) from March 24 to June 9, 1999. This campaign sought to stop further ethnic cleansing of Albanian Kosovars in the FRY province of Kosovo by the Yugoslav government headed by Slobodan Milosevic. As President William J. Clinton explained to the American people on the evening of March 24, 1999, the aims of Allied Force were to "demonstrate the seriousness of NATO's purpose," to "deter an even bloodier offensive against innocent civilians in Kosovo and, if necessary, to seriously damage the Serbian military's capacity to harm the people of Kosovo."[140] After 78 days of bombing and over 38,000 sorties by NATO aircraft, Milosevic acceded to the demands of the NATO nations in Kosovo. Although fifteen of the nineteen NATO nations contributed aircraft to the air campaign, US aircraft flew about 60 percent of the total sorties and the United States was the only participant able to bring to bear such advanced systems as the B-2 with Joint Direct Attack Munitions (JDAMs), Tomahawk Land Attack Missiles (TLAMs), the Joint Surveillance Target Attack Radar System (Joint STARS), and a large array of military satellites.[141]

As in Desert Storm, space systems were used during Allied Force to provide NATO forces with such things as high-resolution imagery for targeting and mission planning, ELINT and SIGINT on threat systems and order of battle, communications, BDA, command and control, and reachback to the United States for targeting information. US forces again depended heavily on commercial satellite communications. USSPACECOM's post-conflict estimate was that 80 percent "of the spaceborne communications used in the Kosovo campaign traveled on commercial systems."[142]

Most of these increasingly traditional—at least for US forces—military uses of orbital systems need not be reviewed. By and large, they were not fundamentally different in Allied Force than they had been in Desert Storm. Instead, to give a sense of how far the United States has come since 1991 in making overhead assets serve the warfighter, it will suffice to examine two areas which had evolved considerably by 1999: the use of GPS to guide weapons to their aim points; and the effort to achieve tighter, more timely connectivity between sensors and shooters via

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[140] "Remarks by the President to the Nation on Kosovo," Press Release, The White House, Office of the Press Secretary, March 24, 1999, 8:01 P.M. EST; available at www.whitehouse.gov/library.

[141] Department of Defense, *Report to Congress: Kosovo/Operation Allied Force After-Action Report* (Washington, DC: US Government Printing Office, January 13, 2000), p. 78. This report is available online at: www.defenselink.mil/pubs/kaar02072000.pdf.

[142] Grier, "The Investment in Space," p. 50.

reachback to the United States to reduce and analyze targeting data collected by sensors located in the theater.[143]

The American military first made battlefield use of the Global Positioning System in 1991. At that time, the constellation was not fully populated and, during Desert Storm, salvaging one older satellite with a broken attitude-control system was necessary to provide enough coverage of the war zone.[144] Demand was so great that some 15,000 commercial GPS receivers were procured for military use.[145] As a result, GPS location information was widely available to American forces during Desert Storm and enabled US ground units to navigate across the desert areas of southeastern Iraq without getting lost. Prior to that conflict, coordinating two corps over large areas of featureless desert had been viewed as difficult-to-impossible by most armies, including those native to the Middle East.[146] Handheld GPS receivers obviated this longstanding problem of desert warfare in February 1991 for US forces. General Norman Schwarzkopf's famous left hook around Iraqi forces in Kuwait would have been far more difficult to execute without GPS.[147]

To illustrate in more detail what the availability of GPS meant for American ground forces in 1991, consider the US VII Corps' ability to reunite two detached artillery units during the night of February 26/27, 1991. Toward the end of the day on February 26, two corps artillery battalions had been detached from their assigned unit, 3rd Armored Division, and were some 90 miles behind the rest of the division's 155mm howitzer and multiple-rocket launcher system (MRLS) assets. By virtue of having GPS, the two detached units were able to rendezvous with the rest of 3rd Armored Division by the morning of February 27th despite having to move at night across featureless desert.[148] Thus, these units were on hand when 3rd Armor ran into Republican Guard heavy units later on the 27th. Without GPS, such a rendezvous probably would not even have been attempted, and the division would have engaged Iraqi forces two artillery battalions short.

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[143] DoD, *Report to Congress: Kosovo/Operation Allied Force After-Action Report*, p. 55.

[144] Sellers, et al., *Understanding Space*, p. 518.

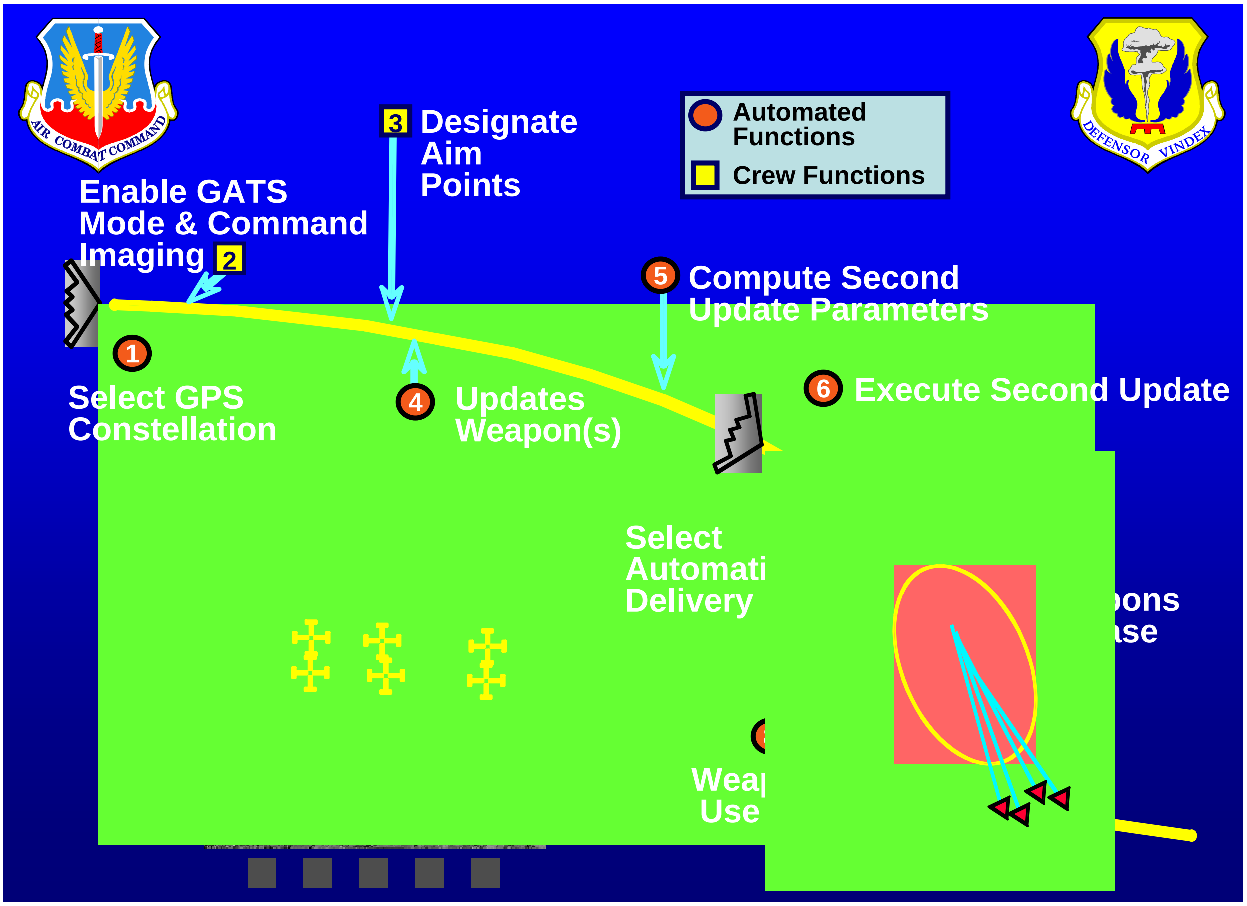
[145] *New World Vistas*, Yarymovych, *Space Applications Volume*, p. 5.

[146] In Erwin Rommel's Africa Korps during World War II, one third of the German forces were usually lost on a given day during offensive operations (Colonel M. Thomas Davis, who participated in Desert Storm's left hook with the US VII Corps). Davis derived this insight into the Africa Korps' operations from a veteran of Rommel's campaigns in North Africa during World War II.

[147] For an overview of the 100-hour Desert Storm ground campaign with maps, see DoD, *Conduct of the Persian Gulf War: Report to Congress pursuant to Title V of the Persian Gulf Conflict Supplemental Authorization and Personnel Benefits Acts of 1991 (Public Law 102-25)* (Washington, DC: US Government Printing Office, April 1992), pp. 243–96. For more detail on the left hook, see Tom Clancy with General Fred Franks, Jr., *Into the Storm: A Study in Command* (New York: G. P. Putnam's Sons, 1997), pp. 232–33 and 246–84.

[148] M. Thomas Davis, April 2000. Then Lieutenant Colonel Davis was an MRLS battalion commander in the 3rd Armored Division during Desert Storm.

Figure 9: The B-2's GPS-Aided Targeting System



● Automated Functions

■ Crew Functions

1 Select GPS Constellation

2 Enable GATS Mode & Command Imaging

3 Designate Aim Points

4 Updates Weapon(s)

5 Compute Second Update Parameters

6 Execute Second Update

Select Automati Delivery

ons ase

Weap Use

Source: 509th Bomb Wing, "Decade of Success," Whiteman Air Force Base, Missouri, July 17, 1999, Slide 17. These slides were briefed after Allied Force by Brigadier General Leroy Barnidge, then the 509th wing commander; July 17, 1999 was the tenth anniversary of the maiden flight of the B-2. This briefing also contained numerous post-strike images of targets struck by B-2s during Allied Force.

Impressive as this use of GPS was for rejoining separated units at night across trackless desert, Allied Force saw the exploitation of GPS for actual combat operations taken a step beyond 3rd Armored Division's experience in 1991. In 1999 American forces employed four weapons that used GPS signals for guidance: two standoff missiles—the US Navy's sea-launched TLAM and the US Air Force's air-launched Conventional Air-Launched Cruise Missile (CALCM)—as well as two direct-attack weapons—JDAM and the Joint Standoff Weapon (JSOW).[149] While all of these weapons offered some inherent capability for near-precision attack regardless of weather, fog or other target-area obscurations, the most impressive use of GPS was made by B-2s dropping JDAMs. The B-2 was the only platform that employed JDAMs during Allied Force.[150] As Figure 9 indicates, the B-2 did more than simply release coordinate weapons. By using its on-board radar to take two successive SAR images of the target, the B-2 could mostly eliminate the

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[149] DoD, *Report to Congress: Kosovo/Operation Allied Force After-Action Report*, p. 89.

[150] Ibid., p. 91–97. The 509th Bomb Wing launched 49 B-2 sorties during Allied Force, of which 45 entered the combat area and dropped munitions; those 45 sorties delivered 656 JDAMs, including four 4,700-lb GBU-37s (ibid., pp. 91 and 97).

largest source of error in weapons designed to home on GPS coordinates: error in the location of the aim-points in GPS space. Consequently, the B-2's circular error probable (CEP) with JDAM was less than half the 13 meters specified for unaided JDAMs. In fact, post-strike imagery documents that the B-2/JDAM combination was, on occasion, able to achieve genuine precision with the aid of its GPS-aided targeting system (GATS) during Allied Force. For instance, during a single pass against Obrva airfield in April 1999, a B-2 from the 509th Bomb Wing placed a 2,000 pound JDAM squarely on each of an airstrip's six runway-taxiway intersections, thereby precluding any operations by Serb fighters until repairs had been made to all six bomb craters. All these weapons were released from an altitude of around 40,000 feet, and the accuracy achieved against the six discrete aim-points was independent of weather.

Where does this use of GPS satellites by the B-2 fall in terms of force enhancement as opposed to force application? It undoubtedly lies closer to force application than the use of GPS for navigation by American ground forces during Desert Storm. After all, real-time locational information from a GPS constellation at medium-earth-orbit altitude was used to achieve stunning through-weather accuracy against aim-points in Serbia. Yet the delivery platform, sensors and munitions involved were all located within, and operated strictly inside of, the earth's atmosphere. Clearly the B-2/JDAM case does not qualify as force application in USSPACECOM's narrow sense of attacking terrestrial targets with space-based weapons. If force application is broadly construed as *any* application of military force utilizing space systems directly in a lethal kill chain or aimed at affecting the military value of orbital assets, then the B-2/GATS/JDAM combination during Allied Force becomes a much more borderline case. One could probably argue that it lies slightly closer to force enhancement than force application broadly construed. Still, it appears to fall very close to force application.

That said, the results achieved by the B-2 against targets such as Obrva in 1999 unquestionably reinforces the view that the United States is far ahead of other nations in its ability to enhance terrestrial military operations with space systems. No other nation today possesses the capability for *through-weather* attack that the United States demonstrated during Allied Force with the B-2 and JDAM.[151] In air campaigns as disparate in time and the technology available as the 1943–45 Combined Bomber Offensive (CBO) and Desert Storm, weather was judged by key planners to have been a greater impediment to bombing operations than the enemy air force.[152] Yet, in 1999,

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[151] Other countries are beginning to market GPS tail kits for gravity bombs. A case in point is Ordtech Military Industries S.A., which is advertising "platform independent" Seirina tail kits for 500 and 1,000 kilogram gravity bombs (*Jane's Defence Weekly*, February 16, 2000, p. 22). Being platform independent, however, the Seirina kits cannot achieve true precision accuracy or have the flexibility to deal with imprecisely located targets that the B-2 demonstrated during Allied Force with GATS and JDAM. The French, too, are beginning to experiment with GPS-aided guidance kits for gravity munitions such as the MK-84 general-purpose, high-explosive bomb ("Raven GGM To Take First Flight This Year," *Jane's Defence Weekly*, March 8, 2000, p. 13). And in June 2000, Israel became the first nation to buy JDAMs from the US ("Israel First Foreign Nation To Buy Joint Direct Attack Munition," *Inside the Air Force*, June 9, 2000, p. 5).

[152] In the case of the CBO, the post-war assessment of the lead planner was that that "most implacable of all our enemies, the ever present bad weather," was actually "a greater hazard and obstacle than the German Air Force." Major General Haywood S. Hansell, Jr., *The Air Plan That Defeated Hitler* (Atlanta, GA: Higgins-McArthur/Longino and Porter, 1972), pp. 121 and 270. In a post-Desert Storm interview, (then) Major General Buster Glosson, who headed the offensive planning effort for the Desert Storm air campaign, made virtually the same observation about the Gulf War: "Weather was our #1 problem! The first three weeks of the war were absolutely unreal. I was constantly fighting the weather." (Glosson, notes taken by Barry D. Watts during an April 14,

the United States was finally able to exploit orbital systems to overcome a constraint on bombing—bad weather—that had bedeviled airmen from the earliest days of air-to-ground bombing operations.

The American efforts made during Allied Force to increase connectivity between sensors and shooters through space provide a less complete story than the advent of GPS-aided munitions for through-weather, near-precision and precision attack. Sensor-to-shooter connectivity is very much a work in progress, and much remains to be done. Nevertheless, sensor-to-shooter connectivity is another area in which American forces took steps to enhance the effectiveness of ongoing military operations in ways that strengthen the judgment that the United States is far ahead of any other nation in the military exploitation of space. Illustrative of the kind of reachback American space systems provided during Allied Force was the ability to send sensor data on targets collected in the theater back to the United States for data reduction and analysis. At least two factors made this capability important: the strong desire of the NATO nations to avoid collateral damage and civilian casualties; and the use of weapons such as JDAM that home in on GPS coordinates. In-theater sensors—particularly imaging sensors—could not generally provide the very precise ("mensurated") coordinates needed for satellite-aided weapons. A SAR image from a U-2, for instance, does not come with GPS coordinates embedded in the imagery. At the same time, both a strength and weakness of coordinate weapons like JDAM is that they go to the coordinates given them. A JDAM is an inexpensive munition—under $20,000 per round—precisely because it lacks a terminal sensor. However, without a terminal sensor, the weapon, once released, cannot adjust for error in the target's location. To deal with these limitations in the case of the U-2, an arrangement was developed to send U-2 sensor images via satellite "all of the way back to Beale Air Force base on the West Coast of the United States" in order to get "processed" coordinates that could be used with some of the GPS-aided weapons available to US forces.[153] As the air campaign focused more and more on attacking Serb ground forces in Kosovo, the challenge to such arrangements was to get the mensurated coordinates back into the theater before a particular tank, artillery piece or other non-fixed battlefield target had time to move.

The arrangement to use communications satellites to send U-2 images containing ground targets from Kosovo to Beale, develop targeting-quality coordinates there and then transmit the coordinates back to the theater for use in strike operations was part of what US Air Force leaders have described as the "first-ever distributed ISR [intelligence, surveillance and reconnaissance] architecture."[154] This system, which took many weeks to assemble, eventually included units at Beale

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1992, Gulf War Air Power Survey interview). Even in Allied Force, adverse weather was a major impediment to air operations in general. In the blunt words of the Joint Force Air Component Commander: the weather "just kicked our butts for the first 45 days" (John A. Tirpak, "Short's View of the Air Campaign," *AIR FORCE Magazine*, September 1999, p. 47).

[153] General John P. Jumper, "Operations in Kosovo: Problems Encountered, Lessons Learned and Reconstitution," transcript of hearings before the Military Readiness Subcommittee, Committee on Armed Services, 106th Congress, 1st Session, October 26, 1999, HASC No. 106-2, p. 35; available online at http://commdocs.house.gov/committees/security/has299030.000/has299030_0f.htm.

[154] Lieutenant General Marvin R. Esmond, "Lessons Learned from the Kosovo Conflict," statement to the Military Procurement Subcommittee, Committee on Armed Services, October 19, 1999; available online at: http://www.house.gov/hasc/testimony/106thcongress/99-10-19esmond.htm.

AFB, California; Offutt AFB, Nebraska; Washington, DC; Ramstein AFB, Germany; and several other locations. Its intent was to provide targeting and intelligence support for real-time strike operations during Allied Force. Needless to say, the system would not have been feasible without space assets. At present, the US military is alone in possessing or having access to the satellites, sensors, global connectivity, command and control, and analytic capabilities to stand up a distributed architecture capable of turning theater sensor data into targeting-quality coordinates at disparate locations around the globe and, then, getting those coordinates into the hands of shooters in short enough times for the information to be actionable.

In light of these sorts of "flex targeting arrangements," it is easy to see why US military leaders judged Allied Force to have been "a truly space enabled war."[155] Again, space systems were used for force enhancement rather than force application (broadly construed). However, the adverse weather and stringent rules of engagement aimed at minimizing collateral damage created a situation in which the exploitation of space systems was, arguably, even more important in 1999 than it had been in 1991.

Of course, it is worth keeping in mind that the space-enabled flex-targeting capability was assembled only by the final weeks of Allied Force. Despite widespread perceptions after Desert Storm of the increased value of space systems to American warfighters, such arrangements were still not available as *routine*, off-the-shelf capabilities even by 1999. Yes, the space-enabled ISR architecture just described offers additional evidence that the United States today is far ahead of any other nation in the exploitation of space for ongoing military operations. It also underscores just how much the American use of space has changed since the Berlin Wall fell in late 1989. The current emphasis on using orbital systems to enhance actual military operations in near-real time is quite different from the pre-conflict orientation of the US military space program during the Cold War. Nevertheless, one cannot escape the impression that, as late as 1999, the American military still had not managed to do more than scratch the surface regarding the full potential of orbital assets to enhance everyday nonnuclear operations by generating and delivering time-critical information. American command-and-control architectures remain focused on passing the commander's orders downward rather than facilitating the timely fulfillment of requests for time-critical information from operational units at the bottom of the system.[156] As a result, during Desert Storm, much of the overhead imagery passed to the theater from Washington, DC, did not filter down to the operational users who needed it most.[157] By all indications, these problems had not been solved by the end of Operation Allied Force in June 1999.[158]

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[155] General Richard B. Myers, DoD press briefing, January 5, 2000, 10:45 a.m. EST; available at http://www.defenselink.mil/news/Jan2000/t01052000_t104myer.html.

[156] Lieutenant General Jay W. Kelley, "Long Term Prospects for the Air Force in Space" in *The U.S. Air Force in Space: 1945 to the 21st Century,* R. Cargill Hall and Jacob Neufeld (ed.), (Washington, DC: US Government Printing Office, 1998), p. 159.

[157] Not only were there problems in 1991 getting imagery to operational units such as the F-117 wing, in some cases air planners responsible for generating the daily master attack plan that structured the air tasking order discovered that their own air-intelligence organization had withheld imagery until after the campaign ended (personal communications with then Lieutenant Colonel David Deptula, who developed the daily master attack plan for the coalition's air campaign throughout the Gulf War). One of the mysteries Gulf War Air Power Survey researchers never

The shift during the 1990s in the thrust and focus of American efforts to exploit orbital assets for terrestrial military advantage further suggests that the leading indicators of how a nation is doing relative to others in obtaining military advantages from orbital systems may be changing. In general, assessing the capabilities of nations and other actors to exploit near-earth space is likely to be more difficult in the 21st century than it was in the 20th. During the Cold War, fairly simple measures could be used to gauge how the American space program was doing vis-a-vis the Soviet effort. For instance, in 1969, the United States beat the Soviet Union in the race to be the first to land a man on the moon. In addition, American versus Soviet spending levels (Figure 6) and launch rates (Figures 2 and 8) provided reasonable indicators of how each side was doing in the competition, as well as leading indicators of how their relative positions might change over time.

Yet, if Allied Force is any indication, these traditional measures will almost certainly grow less useful over time. Among other reasons, the ability of a nation to deploy and use a distributed ISR architecture is not well captured in overall space investment levels or the numbers of successful launches per year. In coming years, this sort of capability may hinge more on such things as organizational arrangements and training than on how much a competitor spent on military space systems in recent years. Similarly, the ability of nations around the world to employ GPS-aided munitions may not depend at all on their ability to orbit satellites and operate them—especially if GPS becomes part of the "global commons" open to all for civil uses such as air traffic control and precision landings by commercial aircraft.[159] In that event, shutting off GPS—even locally—is unlikely to be a viable option for the United States, and a much better indicator of the capabil-

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managed to run to ground was exactly how and why so much of the intelligence information sent to the theater was misplaced, side-tracked or simply lost.

[158] General John P. Jumper's post-Allied Force assessment of these issues stressed the need to find ways to ensure that "the crew in the cockpit has the same information as the guy in the AOC [Air Operations Center] making the decision" (General John P. Jumper, COMUSAFE, "The Limits of Doctrine," presentation, Slide 21).

[159] The term "global commons" has been borrowed from Lyntiss Beard, "Space: 21st Century Strategies," a background paper for the Phase I report of the United States Commission on National Security/21st Century, *New World Coming: American Security in the 21st Century*, September 15, 1999. The term harks back to Mahan's characterization of the sea as a "wide common, over which men may pass in all directions." Alfred Thayer Mahan, *Mahan on Naval Strategy: Selections from the Writings of Rear Admiral Alfred Thayer Mahan* (Annapolis, MD: Naval Institute Press, 1991), p. 27. This description can be found in the opening paragraph of Chapter I of Mahan's *The Influence of Sea Power Upon History 1660–1783* (Boston: 1890).

ity of various nations to employ GPS-aided weapons may simply be whether they are building or buying them. Moreover, building munitions similar to the US JDAM will surely be easier to conceal than a series of space launches. Consequently, the evolving value of space for military ends implies the need for new measures. The direction in which the military exploitation of near-earth space is now moving argues that the relative capabilities of nations to gain military advantages from orbital systems will become more difficult to judge than they were in the past.

IV. TRENDS, NON-TRENDS AND ASYMMETRIES

> We are now transitioning from an *air* force into an *air and space* force on an evolutionary path to a *space and air* force. The threats to Americans and American forces from the use of space by adversaries are rising while our dependence on space assets is also increasing. The medium of space is one which cannot be ceded to our nation's adversaries. The Air Force must plan to prevail in the use of space.
>
> —*Global Engagement*, 1996[160]

> Our Service views the flight domains of air and space as a seamless operational medium. The environmental differences between air and space do not separate the employment of aerospace power within them. . . . [O]ur vision includes a mix of air and space capabilities interacting for maximum effect throughout the aerospace continuum. This vision encompasses aerospace capabilities to find, fix, assess, track, target, and engage any object of military significance on or above the surface of the Earth in near real time.
>
> —*The Aerospace Force; Defending America in the 21st Century*, 2000[161]

> It has been argued that "space is a place, not a mission." I believe space, however, is more than just a place. Space permits you to see over not just the next hill, but over all the hills. In space you do not inhabit just one time zone but all time zones. Space is more about time than means.
>
> —Lieutenant General Jay W. Kelley, 1995[162]

> Space is a place. . . . not a mission.
>
> —General Michael E. Ryan, 2000[163]

The burden of this chapter is to say what can reasonably be said about how the military use of space may evolve or be transformed between now and 2020–25 based on discernible trends and asymmetries. Given the inherent uncertainties of trying to peer a quarter century into the future, the analysis will be more speculative than was assessing the current state of military competition in space.

One question, of course, is the prospect for genuine transformation in the military value and use of near-earth space. Will the next 20–25 years see weapons deployed there on any significant

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[160] US Air Force, *Global Engagement: A Vision for the 21st Century Air Force*, section "Air and Space Power for the Next Century," available at www.xp.hq.af.mil/xpx/21/nuvs.html.

[161] US Air Force, *The Aerospace Force; Defending America in the 21st Century*, (Washington, DC: Department of the Air Force, May 2000), pp. i and iii. The second section of this white paper—titled "The Journey from 'Air and Space' to 'Aerospace'"—makes clear that the current leaders of America's youngest Service have rejected the possibility of evolutionary progress toward distinct, much less separate, space and air forces. Whatever one's personal view on this issue may be, the contrast with the 1997 vision statement reveals the discomfort with which the fighter generals now dominating the US Air Force view the possibility of a separate space service. Certainly there is trend toward a separate space service in US Air Force vision statements. The re-adoption of the term "aerospace" harks back to the 1950s.

[162] Kelley, "Long Term Prospects for the Air Force in Space," p. 162.

[163] ". . . Space Commission," *Defense Daily*, June 26, 2000, p. 1.

scale, or does this most fundamental of changes lie further in the future? Obviously the issue of likely timing will be critical to how one answers this question. Even if one is convinced that overt military competition and force application outside the atmosphere are unavoidable in the long run, it is still open to debate as to whether the transition will occur in the first quarter of the 21st century or later. As suggested in Chapter II, it is far from self-evident that the economic, political and other incentives necessary to motivate warfare in and from space will materialize by then.

The other global question to be addressed in this chapter is whether the large margin of military advantage the United States now enjoys as a result of its various capabilities to exploit near-earth space will grow, persist or diminish. The thought advanced in the introduction was that, insofar as access to space systems is concerned, the margin of American advantage will grow harder to sustain in the years ahead as the formerly high entry barriers are eroded by increasing commercialization and by the trends toward near-earth space becoming a global commons. Whether that change is the whole story remains to be seen. After all, US requirements for global power projection suggest that the American military may need orbital assets more than its foreseeable regional adversaries, and smart opponents may devise largely terrestrial means for degrading or negating US military advantages derived from space systems. In any event, maintaining anything close to today's margin of advantage in the military use of space will almost certainly grow more difficult for the American military in the years ahead.

In this regard it should be stressed there can be no guarantee that the United States will retain its present commanding margin of advantage indefinitely. Consider, after all, how far ahead the Royal Navy was in carrier aviation at the end of World War I. By the time the guns fell silent on the Western Front ending the Great War, the Royal Naval Air Service had grown to some 5,000 officers and 55,000 men operating nearly 3,000 planes and seaplanes.[164] The Royal Navy possessed eleven aircraft carriers at a time when no other naval power had even one; these eleven carriers included the newly commissioned, but not yet operational, HMS *Argus*, whose fully flush deck made her the first true aircraft carrier.[165] Yet by the eve of World War II some twenty years later, at least two other navies, those of Japan and the United States, had not only caught up with the Royal Navy in carrier aviation but, arguably, surpassed the British in a form of naval power that, by 1945, would dominate the world's oceans. The lesson, then, is clear. An early lead in a new way of fighting, no matter how large or seemingly overpowering, can be lost even when competitors seek equivalent capabilities.

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[164] Geoffrey Till, "Adopting the Aircraft Carrier," *Military Innovation in the Interwar Period*, ed. Williamson Murray and Allan R. Millett (Cambridge: Cambridge University Press, 1996), p. 194.

[165] Given the loss of HMS *Campania* on November 5, 1918, the Royal Navy appears to have had the following carriers on November 11, 1918: *Furious*, *Argus*, *Vindictive*, *Nairana*, *Pegasus*, *Vindex*, *Ark Royal*, *Manxman*, *Engadine*, *Empress*, and *Riveria*—Norman Friedman, *British Carrier Aviation: The Evolution of the Ships and Their Aircraft* (Annapolis, MD: Naval Institute Press, 1988), pp. 47 and 90. These vessels ranged from early seaplane carriers, such as *Empress* and *Riveria*, to *Ark Royal*, the first ship largely designed and built as an aircraft carrier, and *Argus*, the first flat-deck carrier (ibid., pp. 29, 30, and 65). In September 1916, the British achieved success in making arrested landings with an Avro 504 biplane equipped with a hook; it appears to have been these experiments that encouraged the decision to complete the liner *Conte Rosso* as the carrier flat-deck *Argus* (ibid., p. 61).

Might the US military suffer a similar fate to the Royal Navy with respect to its current advantages in orbital space over the next 20–25 years? A number of areas will need to be explored before an answer to this question can be advanced. Among them are trends in satellites, the lack of any hopeful trend in dramatically reducing the costs of reaching low-earth orbit, the broad trend toward commercializing near-earth space, the main asymmetry between the United States and other countries regarding the military use of orbital space, whether the technical barriers to possibilities such as spaced-based lasers are likely to be overcome by 2020–25, and, last but not least, the prospects for orbital space becoming an economic, military or political center of gravity over the next quarter century.[166] Only with greater insights into these complex and interrelated issues will it be possible to reach a conditional assessment of how much strategic and operational advantage the US military may be able to expect from near-earth space.

SATELLITE TRENDS

In the October 1945 issue of *Wireless World*, Arthur C. Clarke raised the possibility of using satellites in geostationary orbits for global communications.[167] During the Cold War, both the United States and Soviet Union developed military communication satellites. In the West, the first commercial communications satellites (comsats) were owned by large consortia of governments such as the International Telecommunications Satellite Organization (INTELSAT).[168] After starting operations with the Early Bird satellite in 1965, INTELSAT launched additional spacecraft to geostationary orbits to cover the three major ocean regions and, by 1969, had established the first global satellite communication system, thereby realizing Clarke's 1945 vision.[169] INTELSAT subsequently provided global television coverage of the historic Apollo lunar landing, implemented the world's first international digital voice communications service, and, in 1974, activated a direct hot line link between the White House and the Kremlin. While INTELSAT's Assembly of Parties voted in 1998 to restructure and eventually commercialize the organization, as of 1996 INTELSAT was "the largest provider of satellite services in the world."[170]

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[166] Carl von Clausewitz is usually given credit for introducing the term "center of gravity" into the military lexicon. While Clausewitz undoubtedly borrowed the concept from the Newtonian physics of his day, he portrayed the opponent's center of gravity as "the hub of all power and movement" arising from the "dominant characteristics of both belligerents," and "the point against which all out energies should be directed"—Carl von Clausewitz, *On War*, ed. and trans. Michael Howard and Peter Paret (Princeton, NJ: Princeton University Press, 1976), pp. 595–96. The American military, since its rediscovery of Clausewitz in the 1980s, has tended to talk of multiple centers of gravity at every level of war—tactical, operational, strategic, and political. Clausewitz himself suggested that the fighting forces of each belligerent—whether a single state or an alliance of states—having some cohesion "will possess certain centers of gravity, which, by their movement and direction, govern the rest" (ibid., pp. 485–86).

[167] Clarke's article "Extra-Terrestrial Relays: Can Rocket Stations Give World-wide Radio Coverage?" can be found at http://www.lsi.usp.br/~rbianchi/clarke/ACC.ETRelays.html.

[168] Gonzales, *The Changing Role of the U.S. Military in Space*, p. 1. INTELSAT is a consortium of government-appointed signatory organizations conceived in the 1960s to provide switched connectivity and offer radio and television transmission among all countries (Michael A. Einhorn, "INTELSAT: A Reform Proposal," Economic Analysis Group, US Department of Justice, July 15, 1996, p. 1; available at: www.citi.columbia.edu/history/einhorn.htm. INTELSAT currently provides satellite interconnection to around 180 nations using geostationary satellites (www.intelsat.com).

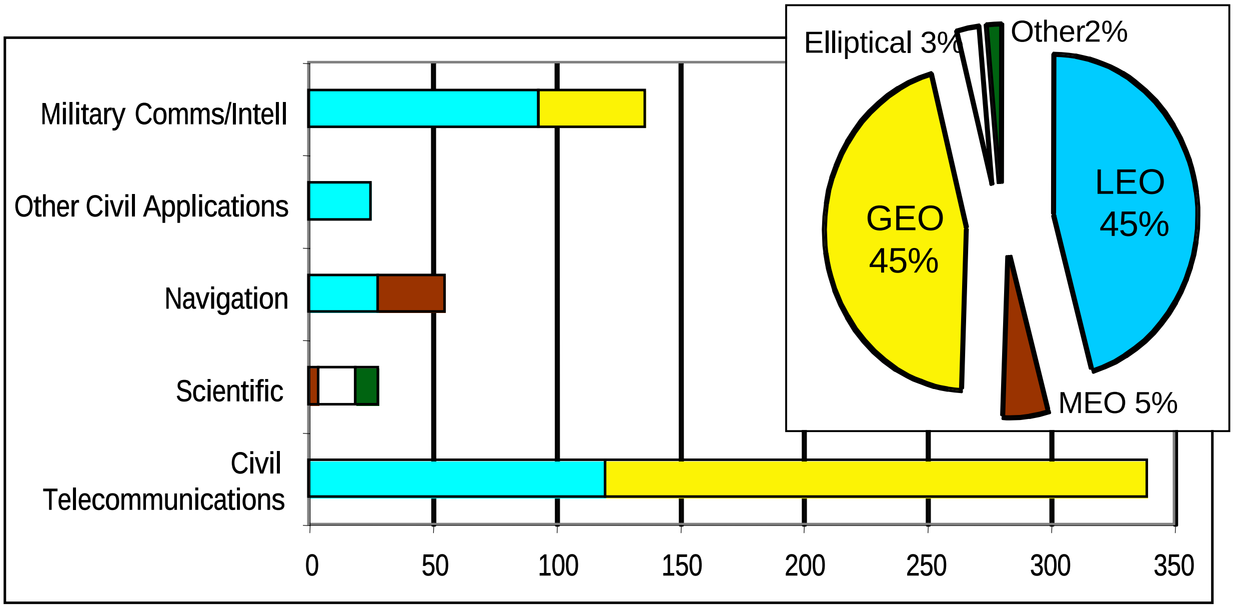
[169] "We're Not Just Another Global Satellite Provider—We Invented It," obtained online at http://www.intelsat.com/about/notjust.htm.

[170] Einhorn, "INTELSAT: A Reform Proposal." COMSAT is the US owner of the INTELSAT system.

Today INTELSAT operates seventeen geostationary satellites with at least fifteen transponders dedicated to international voice and data services and plans to launch another seven. The other operators in this market niche—GEO international voice and data satellites with at least 15 transponders—are APSTAR, Eutelsat, GE Americom, Loral Skynet, New Skies Satellites, PanAmSat, and Satmex.

Comsats dominate near-earth space to this day. Figure 10 categorizes all active satellites, as of August 1999, by altitude and function except for roughly 100–150 belonging to the Russians.[171] Of the active satellites in Figure 10, some 58 percent perform non-military telecommunications functions. This category includes wireless telephony, telephone trunking, direct-to-home (DTH) television, television relay, mobile data services, Internet applications, and civil communications. If military communications satellites are added, the telecommunications category rises to nearly 65 percent of the total, and this percentage does not change much even if the excluded Russian satellites are all assumed to be operational and added to those shown in Figure 10. Comsats of one sort or another, therefore, comprise the lion's share of the operational satellites currently circling the earth.

Figure 10: Active Satellites by Function and Altitude Band (Excluding Russian)



Source: Data from Futron Corporation, August 1999. The data were augmented by Greg Lucas of Futron (e-mails to Barry Watts, March 8 and 10, 2000).

The vast majority of these non-Russian comsats are at either LEO or GEO altitudes. The GEO comsats maintain positions above the earth's equator. Given the numbers involved—around 250 if Russian GEO comsats are included—it is not difficult to see why the allocation of geostationary orbit slots will almost certainly become a source of increasing friction among nations in the early 21st century. Spacing between geostationary satellites started at five degrees but has dwindled to two degrees over the years; even so, some parts of the geostationary arc (or Clarke Belt)

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[171] Russian satellites have been excluded because the operational status of many of them is not known.

are quite crowded.[172] While the Federal Communications Commission (FCC), World Radiocommunication Conferences (WRC) and the International Telecommunications Union (ITU) have sought to settle disputes over spectrum allocation and orbital slots, "it is expected that these problems will get progressively worse as the demand for orbital telecommunications increases."[173] The judgment of the US Air Force's Scientific Advisory Board in 1995 was that the saturation of orbital positions at synchronous orbit "is almost upon us."[174] Note, though, that some GEO comsat companies have been known to operate more than one satellite in a single, two-degree orbital slot on the Clarke Belt.[175]

With these observations as background, what are the main trends in satellites? First, the population of active satellites is large and projected to grow substantially in coming years. A December 1999 Defense Science Board (DSB) report estimated that 1,700–2,000 commercial satellites will be launched during the first decade of the 21st century—a number which is consistent with most other estimates.[176] Second, the design and actual service lives of satellites have continued to grow. For example, Futron Corporation data indicate that the designed service lives of GEO satellites increased from roughly nine to fourteen years during 1987–97.[177] Third, the maximum mass at launch of GEO satellite buses has increased over the last couple decades, with most current models exceeding 5,000 kilograms.[178] Fourth, in the case of GEO comsats, the number of transponders per satellite grew from 26.3 in 1994–95 to 30.5 in 1998–99, and Futron estimates indicate that the number will exceed 39 for 2000–01.[179] When these trends are combined with the transition to Hall-effect thrusters now underway, the obvious implication is that the value of each satellite pound placed in orbit increased during the 1990s, and the increase in value per pound can be expected to grow even more rapidly during the first decade of the 21st century.

The large number of commercial satellites forecast to be launched over the next decade is one of the underpinnings behind projections of growing commercial revenues from satellite systems (Figure 4). Both suggest a trend toward greater telecommunications capacity in near-earth orbit. During the late 1990s, the area of the world experiencing the greatest growth in number of satel-

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[172] Larry Stern, interview with Barry Watts and Andrew Krepinevich, September 2, 1999.

[173] World Technology (WTEC) Panel, *Global Satellite Communications Technology and Systems* (Loyola College, MD: International Technology Research Institute, December 1998), executive summary (page numbers not available in electronic version); available online at http://itri.loyola.edu/satcom2/toc.htm. The National Science Foundation and NASA sponsored this report. The panel consisted of Joseph N. Pelton (Panel Chair), Alfred U. Mac Rae (panel chair), Kul B. Bhasin, Charles W. Bostian, William T. Brandon, John V. Evans, Neil R. Helm, Christopher E. Mahle, and Stephen A. Townes.

[174] *New World Vistas*, Yarymovych, *Space Applications Volume*, p. xvii.

[175] Futron analyst Carlissa Bryce Christensen stated in a November 21, 2000, seminar that one GEO comsat company was operating seven comsats in a single slot.

[176] Donald A. Hicks (Chairman), *Final Report of the Defense Science Board Task Force on Globalization and Security* (Washington, DC: Office of the Under Secretary of Defense for Acquisition and Technology, December 1999), p. 24.

[177] Lucas and Murphy, "The Space Launch Services Industry: Indicators and Trends," Slide 12.

[178] Ibid., Slide 10.

[179] Ibid., Slide 11.

lite transponders available overhead was East Asia. For 1995–98, the number of C-, Ku-, and Ka-band transponders over East Asia more than doubled.[180] In addition, many of the advanced LEO and MEO comsats planned for initial deployment in the next few years will include new capabilities such as on-board circuit switching and networking capabilities.[181]

While satellite telecommunications capacity is clearly expanding both quantitatively and qualitatively, it does not follow that orbital systems enjoy a growing market share in long-haul communications. A case in point is voice telephone traffic between countries. INTELSAT's market share of international telephone traffic, which peaked at about 70 percent some years ago, had declined to 25–30 percent by the late 1990s, and "is likely to decrease still further."[182] According to more comprehensive data, undersea cables now carry 80 percent of the world's transoceanic messages and data, whereas they accounted for only 2 percent as recently as 1988.[183]

The reason for this dramatic shift from satellites to undersea cables for international communications is fiber-optic technology, whose exponential growth in data-rate capacity has revolutionized the telecommunications market over the last decade. The first undersea fiber-optic cable was laid between the United States, Great Britain and France and went into service in 1988. Since then a number of other trans-Atlantic cables have been laid, as well as both east-west and north-south fiber-optic cables in the Pacific. As a result, fiber-optic capacity overtook worldwide comsat capacity in the mid-1990s and has continued to grow much faster than satellite capacity ever since. For example, a joint venture between Global TeleSystems Group and FLAG Telecom plans to begin operation of a cable system, FLAG Atlantic-1, in early 2001 with 2.4 Tbps (terabits/second) of protected capacity.[184] This single cable will exceed all the world's satellite capacity combined by at least one order of magnitude. At the same time, technologies such as ultra-dense wave-division multiplexing with different colors of light, optical amplifiers and optical switches—all of which now appear to be in hand—have overcome the main limitations of early fiber-optic cables.[185] Finally, solutions to the last mile problem of bringing high-speed access to individual users from fiber-optic gateways are on the brink of reaching the marketplace.[186] The

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[180] Gonzales, *The Changing Role of the U.S. Military in Space*, p. 2.

[181] Ibid., p. 3.

[182] WTEC Panel, *Global Satellite Communications Technology and Systems*, chapter 2.

[183] Mel Mandell, "120000 Leagues Under the Sea," *IEEE Spectrum*, April 2000, p. 50.

[184] www.flagatlantic.com/gts_and_flag_131099.htm. One terabit/second equals 10^{12} bits/second. In computer science the term "bit" is short for "binary digit" and is the smallest unit of information used in a digital computer. The word "bit" for binary digital was introduced in 1946 by John Tukey, who was a major figure in 20th-century statistics ("How Software Got Its Name," *The Economist*, June 3, 2000, p. 80). A bit can take on either of two absolute values, 0 or 1. A byte is a string of bits used to represent a number, letter, or symbol in a computer. Bytes normally consist of eight bits, but 16 are also used.

[185] "Fiat Lux: In Telecommunications, the Long Day of the Electron Has Reached Its Twilight," *The Economist*, February 5, 2000, p. 73.

[186] In August 2000, San Diego-based AirFiber planned to begin shipping a wireless optical network of rooftop nodes that will beam gigabytes of information through the air using lasers operating near infrared (Michael Menduno, "622-Mbps Laser Tag," *Wired*, August 2000, p. 88). At an initial price of about $20,000 for each birdhouse-sized installation, AirFiber's OptiMesh promises to reduce substantially the cost of fiber access to individual buildings. OptiMesh boasts data rates about 400 times faster than a T1 line (ibid.). A T1 line is typically rated at 1.544 Mbps. One megabit/second equals 10^6 bits/second.

fiber-optic or "photonics" industry, therefore, appears to be moving toward providing "almost unlimited bandwidth" while rapidly eclipsing satellite communications in terms of capacity or "bandwidth" for high-data-rate communications.[187]

Given the inherent price advantage of terrestrial cable over satellite transponders, these breakthroughs in fiber optics and associated photonic technologies are reshaping the long-haul telecommunications industry. As recently as the late 1970s, the international telecommunications market was dominated by comsats. Today, on the busier routes, it is possible to argue that the era of satellite dominance has passed into history.[188]

This breath-taking resurgence of terrestrial-cable telecommunications relative to satellite systems argues that commercial comsats will face increasingly stiff competitors for the telecommunications market share in the years ahead. To draw out the obvious implication of this development, commercial satellite ventures that fail the test of the marketplace are unlikely to survive.

The recent history of Iridium is an instructive case in point. The Iridium Limited Liability Corporation (LLC) declared itself the world's first global phone and paging system on November 1, 1998, but was forced into a comprehensive financial restructuring under a voluntary Chapter 11 filing the following August (although its global phone service was not interrupted at that time).[189] Then, on March 17, 2000, after failing to find a "qualified" investor to rescue the venture, Iridium LLC terminated service, leaving the Department of Defense with at least $140 million invested in Iridium equipment, handsets, telephones, pagers, accessories, and air-time services.[190] The fate of Iridium's $5-billion system remained uncertain until December, when the Department of Defense awarded Iridium Satellite LLC a $72-million contract to provide communications services to 20,000 government users for two years.[191] Thus, while Iridium failed as a commercial venture, DoD eventually found the money to bail out the enterprise in the near term.

One can argue, of course, that Iridium business planners were slow getting their system to market, misjudged how rapidly cellular phones would mature into a formidable competitor by offer-

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[187] WTEC Panel, *Global Satellite Communications Technology and Systems*, Chapter 2. "Within a decade it will be possible to send 10,000 wavelength streams down a single fiber thread and emergent ebrium all-optical broadband amplifiers will permit communications transport at the speed of light. Fiber circuits will provide almost unlimited bandwidth, greater reliability, less noise and at modest cost." (*New World Vistas*, Yarymovych, *Space Applications Volume*, p. 59).

[188] For encyclopedic detail on oceanic cables and the geostationary satellite systems for international telecommunications, see Telegeography's *International Bandwidth 2000*. The overview to this report is available at http://www.telegeography.com/Publications/ib00_execsum.pdf.

[189] "Iridium LLC Initiates In-Court Financial Restructuring," August 13, 1999 press release; available at http://www.iridium.com/corporate/news/1999/august/docs/991308.html. The Iridium system is a network of 66 LEO satellites combined with existing terrestrial cellular systems.

[190] Paula Shaki Trimble, "DoD Takes Loss in Stride," *Federal Computer Week*, March 27, 2000; available at http://www.fcw.com/fcw/articles/2000/0327/news-dod-03-27-00.asp. The March 17, 1999, notification that Iridium was suspending service can be found at http://www.motorola.com/satellite/info/.

[191] "Department of Defense Announces Contract for Iridium Communications Services," News Release No. 729-00, 6 December 2000, available at http://www.defenselink.mil/news/Dec2000/b12062000_bt729-00.html.

ing cheaper phones and service rates, and may well have chosen the wrong market segment by targeting well-heeled business travelers.[192] Nonetheless, Iridium's financial collapse reiterates the point that commercial satellite telecommunications ventures, whatever their technological merits, must also be able to survive the test of the marketplace. Even before Iridium LLC initiated service in November 1998, John Evans noted that the system's economic viability seemed "to depend very much" on signing up "a million or so international travelers" whose needs might also be served by cellular adapted to operate in different areas of the world.[193] Some now believe that a million business travelers constitutes the entire worldwide market. If so, Iridium LLC's business plan might well have proven overly optimistic even if it had begun service in 1996 or 1997.

Iridium's apparent failure to meet the test of the marketplace notwithstanding, the overriding trend in satellites is expanding value and functionality per pound placed in earth orbit. In 1972 an aircraft reconnaissance payload consisting of a television camera and a microwave downlink weighed about 100 kilograms; today the same payload functionality can be realized in less than a gram.[194] This trend toward more functionality in smaller packages seems likely to continue for some time in the case of satellites. The first orbital experiments have already been carried out with so-called "picosatellites," which are the size of a cigarette pack and weigh some 250 grams.[195] (Satellites are categorized by weight, and picosats, the smallest orbited to date, are those weighing less than one kilogram.[196]) A total of six picosats, housed in a mothership satellite designed to dispense them in space, were launched from Vandenberg Air Force Base, California, on January 26, 2000, and orbited at an altitude of 640 kilometers (about 400 miles).[197] The basic aim of the experiment was to demonstrate "mothership and daughtership technologies," including the launch of the picosats and communications between them.[198]

While the picosats in this early experiment had little functionality, the vision of enthusiasts is that the various functions and subsystems of today's large satellites could be distributed across a

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[192] Ben Iannotta, "Overcoming the 'Iridium Effect'," *Aerospace America*, February 2000, p. 34. Iridium phones were large, heavy, initially cost $3,000, and did not function indoors. The usage charge was $4–7 a minute per call. By March 1999 Iridium claimed to have 10,294 paying customers, but the number was not enough to recoup the project's $5-billion cost.

[193] John V. Evans, "New Satellites for Personal Communications," *Scientific American*, April 1998, p. 76. Evans also suggested that Globalstar, in contrast to Iridium, offered "good prospects for a successful business because its space segment is not expensive and because the cost of the ground segment is borne by the franchised operators of the system" (ibid.). In any event, Carissa Christensen, Futron Corporation's director for space-market forecasting, stated at a March 23, 1999, conference hosted by *Aviation Week & Space Technology* that "Commercial demand will support only one robustly profitable major LEO telephone system."

[194] Alan H. Epstein, "The Inevitability of Small," *Aerospace America*, March 2000, p. 30.

[195] "Small is Beautiful," *The Economist*, February 5, 2000, p. 75.

[196] Other classes of satellites are: nanosatellites, which range from 1 to 10 kilograms; microsats at 10 to 100 kilograms; small sats, 100 to 1,000 kilograms; and standard satellites, 1,000 kilograms or more. The smallest category of satellite envisioned is the femtosat, less than one-tenth of a kilogram, a satellite that would handle very simple missions ("Picosat Technology Gets Serious," October 11, 1999, available at http://spacedaily.com/spacecast/news/nanosat-99e.html).

[197] "OSP Space Launch Vehicle Launched," press release no. 00-0109, Vandenberg AFB, California; available at: http://www.VANDENBERG.AF.MIL/news_flash/index.html.

[198] "QUICK FACTS" at http://ssdl.stanford.edu/Opal/QuickFacts.html.

swarm of much smaller satellites. Doing so would yield a distributed satellite whose components could be launched at relatively low cost using low-end launch vehicles. The replacement of malfunctioning parts would simply require orbiting new pieces, and the swarm would be harder to track and destroy with nonnuclear ASATs than would be normal-sized satellites. Of course, there would undoubtedly be some complications. Swarms of picosatellites might well lead to traffic congestion at certain altitudes, and communications between individual picosats would be critical to system functionality. Still, the idea appears promising. As the US Air Force's Scientific Advisory Board observed, distributed constellations of smaller satellites not only offer better prospects for "global, real-time coverage," but also offer "advantages in scaling, performance, cost, and survivability."[199]

If this experiment is the beginning of a long-term trend toward miniaturization and distributed functionality in space systems, then the satellites and satellite constellations in orbital space—particularly at LEO altitudes—could look quite different in 2020 from what one sees today. Swarms of satellites, rather than smaller numbers of large, complex ones could begin to predominate for many tasks. At a minimum, such developments would ease the costs of access to space. The Zenit 2 launch vehicle operated by the National Space Agency of Ukraine is currently advertising the capability to place up to 30,000 pounds in low-earth orbit at less than $1,700 per pound.[200] Even incremental progress in the efficiency of rocket-powered launch vehicles, combined with the trends toward increasing value per pound due to satellite miniaturization, suggest that the logistics of launching and operating a given function or service in near-earth space could improve significantly in coming years.

Nevertheless, the changes likely to accrue over time from these trends will probably be gradual and incremental. By comparison there are other, lower-probability trends which could give rise to far larger changes in the logistics of operating in near-earth space. Ivan Bekey has pointed out that a major limitation on the size of space systems today is the insistence on rigid structures using beams and trusses more suited to the gravitational environment at the earth's surface than to orbital space.[201] He suggests at least two ways to progress toward antenna arrays for optical and radio-frequency (RF) imaging sensors with effective maximum diameters ranging, respectively, from 300 meters to 100 kilometers.[202] One concept is thin-membrane surfaces that use such things as gravity gradients and tethers to eliminate most of the structure; the other approach involves sparse arrays with little or no structure.[203] In both cases, the underlying idea is to substi-

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[199] Gregory Canavan, David Thompson, and Ivan Bekey, "Distributed Space Systems" in *New World Vistas*, Yarymovych, *Space Applications Volume*, p. 123.

[200] Lucas and Murphy, "The Space Launch Services Industry: Indicators and Trends," slide 17.

[201] Barry Watts, notes from Ivan Bekey's presentation on advanced space system concepts and enabling technologies, Pentagon, Office of Net Assessment, April 24, 2000.

[202] Ivan Bekey, *Advanced Space System Concepts and Enabling Technologies for the 2000–2030 Time Period* (Annandale, VA: Bekey Designs, Inc., July 7, 1998), pp. 13 and 24.

[203] The Russians experimented with thin-membrane reflectors from the Mir space station in 1993 and 1999, although deployment problems led to the failure of the second Znamya experiment (http://www.space-frontier.org/EVENTS/Znamya/). The Znamya-2.5 reflector used a membrane 7 microns thick. It was designed to provide 5–10 full moons illumination of a spot on the earth 5–7 kilometers in diameter and was described by the Russians as "the world's first controlled global demonstration of space to Earth beamed solar power."

tute information and information processing for physical structure. In the case of sparse arrays, for instance, the individual elements could use precise station-keeping to achieve the desired antenna resolution.

Bekey believes that the technologies and materials for large arrays with little or no structure exist.[204] If he is right—and there is no reason at the level of physics to doubt him in the long run—then the Americans, the Europeans or others could begin moving toward far larger radio-frequency and optical sensors than any now in orbit. Today, imaging RF and optical sensors reside mostly in low-earth orbits to achieve useful resolutions. Looking ahead, Bekey's ideas about substituting information for structure raise the possibility of eventually migrating imaging radar and optical systems to altitudes as high as GEO. An advantage of moving all the way to GEO—if comparable resolutions to LEO could be achieved—would be to permit staring coverage of most of the earth's surface with relatively few satellites. Of course, the tradeoffs between GEO and, say, a 6-hour MEO orbit around 10,000 kilometers altitude would have to be carefully considered in light of specific surveillance needs due to the severe trades between aperture size and resolution as orbital altitude increases. A MEO constellation of 10–11 satellites might well give prompt and frequent (or ubiquitous) access to any area of the globe on demand for a price comparable to that for staring surveillance from GEO with as few as four satellites; also, a geostationary orbit would not provide the relative motion needed for through-weather imaging with synthetic aperture radar.[205] Regardless of how these trades might turn out, there is currently no discernible trend toward moving high-resolution, imaging surveillance, whether at radar or optical/IR wavelengths, to MEO or GEO altitudes. Nevertheless, as Bekey argues, such a line of development appears possible, and, should it materialize, would certainly affect American perceptions concerning the altitudes of near-earth space offering the greatest value for military reconnaissance and surveillance. In a sense, movement in this direction might change the orbital terrain even more than existing trends toward miniaturization and increasing value per satellite pound.

In the near to mid term, trends toward satellite miniaturization promise to increase the value of each pound placed in orbit. While the full implications of these changes are hard to foresee at this early stage, the most probable is that the near-monopoly on space access long enjoyed by a few space-faring nations—pre-eminently the United States and the Russian Federation—will come to an end. How soon significant movement toward very large arrays may be realized is difficult to say, although eventual migration of high-resolution imaging sensors to MEO or GEO would alter the present topography of orbital systems and increase the military value of these higher orbits. Significantly, however, none of these changes indicate any fundamental transformation in the underlying functionality of satellites as we know and utilize them today.

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[204] Bekey, *Advanced Space System Concepts and Enabling Technologies for the 2000–2030 Time Period*, pp. 19 and 25.

[205] Bob Preston, annotated comments to an earlier draft of this assessment, June 19, 2000; also, private telephone discussion, September 6, 2000. Preston feels that GEO is best suited for optical and infrared surveillance of a specific region, whereas MEO would be preferable for ubiquitous global access.

LAUNCH TRENDS

In the early 1990s, American civil efforts to develop launch vehicles began to focus on single-stage-to-orbit (SSTO) solutions. Examples of this launch type include the now-defunct vertical-takeoff/vertical-landing DC-X/DC-XA demonstrator and the still-ongoing X-33/VentureStar project.[206] While the motivations behind this focus stemmed from a number of considerations, the most pressing was the high ownership costs of the Space Shuttle program.[207] The Shuttle or Space Transportation System (STS) was sold as a way of achieving relatively cheap, routine access to low-earth orbit with a manned vehicle.[208] To gain Congressional approval for the program, NASA, in conjunction with the US Air Force, argued that "the Shuttle would fly more than 720 times by its 20th year of operation, lifting hardware to space at $400 per pound."[209] As Figure 11 attests, the four-orbiter STS fleet has generated no more than a tiny fraction of the number of missions envisioned when the program was sold to Congress.[210] From the first flight in April 1981 to the 11-day radar topography mission of February 2000, American space shuttles have logged only 96 successful missions. The cost of each pound placed in orbit by the Shuttle remains more than an order-of-magnitude greater than originally hoped—due, among other things, to the Shuttle fleet's large ground infrastructure, and the fact that, while the orbiters are reusable, they take off mated to large, expendable rocket boosters and an expendable main-engines fuel tank. The Shuttle, then, did not reduce launch costs, nor did it make access to space routine in any defensible sense of the term.

Given this background, there was every reason for NASA to begin working on a successor to the Shuttle fleet in the 1990s. Single-stage-to-orbit was particularly attractive from the standpoint of overcoming the most obvious limitations of the Shuttle: its high annual operating costs. A completely reusable SSTO launch vehicle, if technically achievable, would open the door to great improvements in direct-launch costs and efficiency over the current STS.

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[206] The DC-X demonstrator first flew in 1993 and was funded by the Ballistic Missile Defense Organization (BMDO) (Michael A. Dornheim, "DC-X Makes Second Flight," *Aviation Week & Space Technology*, September 20,1993, p. 39). The demonstrator was later converted to the DC-XA and flew again in 1996 (Michael A. Dornheim, "DC-XA Demonstrates One-Day Turnaround," *Aviation Week & Space Technology*, June 17, 1996, p. 32). The DC-XA lost to Lockheed Martin's VentureStar demonstrator for NASA's X-33 reusable launch vehicle program (Michael A. Dornheim, "Follow-on Plan Key to X-33 Win," *Aviation Week & Space Technology*, July 8, 1996, pp. 20–22). The vehicle was destroyed during a NASA test flight on July 31, 1996 ("Disconnected Hose Blamed for Clipper Graham Accident," *SpaceViews Update*, January 15, 1997, available at www.seds.org/spaceviews/970115/toc.html).

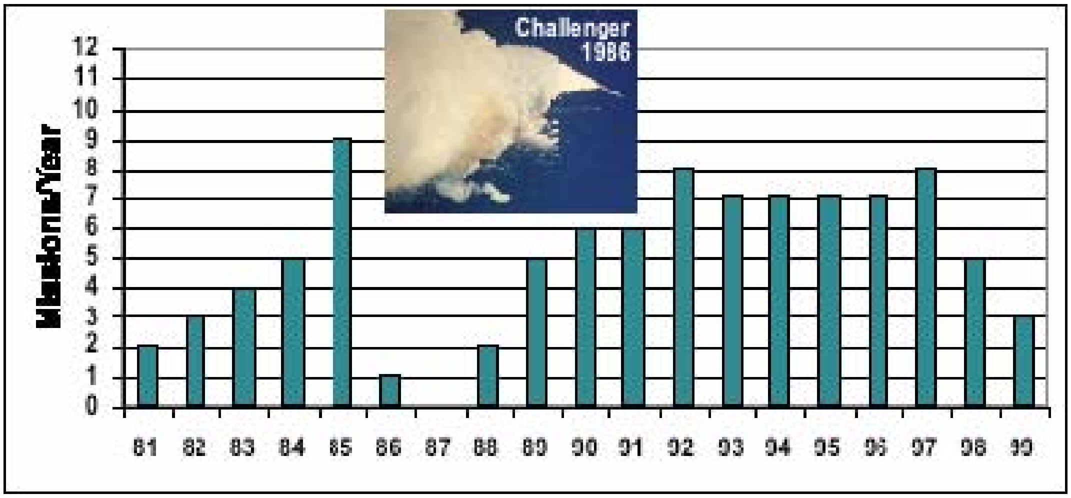
[207] For details on a typical Space Shuttle mission profile, see Sellers, et al., *Understanding Space*, pp. 341–42.

[208] NASA had "central responsibility for Shuttle design and development," and supplied the "bulk of project funding" (Spires, *Beyond Horizons*, pp. 180–81).

[209] "NMD: The Hard Sell," p. 23. Spires indicates that Air Force advocacy for the Shuttle "stressed the economic advantage of saving up to 50 percent of projected launch expenses" (*Beyond Horizons*, p. 181). Whatever the cost-savings claimed for the Shuttle when NASA and the Air Force were trying to sell the program to Congress, McDougall is correct in arguing that the Shuttle, far from reducing the cost per pound of launching payloads into orbit, actually "increased the cost several times over that of the old Saturn 5 rocket," atop which the first American astronauts to set foot on the moon began their historic flight—Walter A, McDougall, . . . *the Heavens and the Earth: A Political History of the Space Age* (Baltimore and London: Johns Hopkins University Press, 1997 ed.), p. xvi.

[210] Four shuttle orbiters were originally built: *Columbia*, *Challenger*, *Discovery*, and *Atlantis*. After *Challenger* was destroyed in 1986, a fifth orbiter, *Endeavor*, was built and delivered to NASA in 1991.

Figure 11: Space Shuttle Missions 1981–99



Source: http://www.spaceflight.nasa.gov/shuttle/archives/

Given this background, there was every reason for NASA to begin working on a successor to the Shuttle fleet in the 1990s. Single-stage-to-orbit was particularly attractive from the standpoint of overcoming the most obvious limitations of the Shuttle: its high annual operating costs. A completely reusable SSTO launch vehicle, if technically achievable, would open the door to great improvements in direct-launch costs and efficiency over the current STS.

Today, the leading candidate for a SSTO launch vehicle is the NASA/Lockheed Martin VentureStar. A roughly half-size experimental version, the X-33 demonstrator, is being built at Palmdale, California, to test critical VentureStar technologies, such as the linear-aerospike engine and composite, multi-lobe cryogenic fuel tanks.[211] The X-33 is a suborbital demonstrator, and will not reach earth orbit. Like the Space Shuttle, the X-33 and the full-size VentureStar will launch vertically and glide to a horizontal landing.[212] NASA plans to invest almost $1 billion to develop the X-33, but hopes that Lockheed-Martin will invest another $5 billion to develop the full-scale, operational VentureStar vehicle.[213]

By late 1999 the X-33 program was experiencing severe technical problems with the vehicle's composite fuel tanks. More importantly, VentureStar LLC, the private industry group formed to build and operate the X-33's full-size follow-on, has not been able to line up any financing.[214] This situation is not surprising. Given the history of broken promises about low-cost launch ve-

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[211] Beardsley, p. 87.

[212] "X-33 Flight Operations Center," fact sheet, available online at: http://www.venturestar.com/pages/x33dem/operations/factsheet_ls.html.

[213] Erick Schonfeld, "The Space Business," *Fortune*, November 24, 1997, p. 150.

[214] Bill Sweetman, "Space Giants Step Up Efforts To Win Low-cost Launch Race," *Jane's International Defence Review*, March 2000, p. 30.

hicles, Wall Street investors and venture capitalists been “rightly skeptical” about backing enterprises such as VentureStar.[215]

Nevertheless, during the late 1990s, SSTO and VentureStar did appear to embody the emerging trend toward reusable space launch. The US Air Force, for instance, “was counting on the VentureStar program both to meets it future launch needs and to provide technology for a military spaceplane.”[216]

In reality, the putative trend toward SSTO may have been a non-trend due more to the constraints of physics than engineering. To achieve low-earth orbit with rocket engines burning chemical fuels, the mass of the unfueled (or dry) vehicle, including its payload, cannot exceed 10 percent of the fully fueled vehicle’s mass at liftoff.[217] This constraint is imposed by the laws of physics and the strength of the earth’s gravitational field. Unfortunately, a 15 percent dry/fueled mass fraction is about the best contemporary structural materials and rocket fuels have been able to deliver, and shaving off another 5 percent appears to be a difficult challenge through 2010 or even 2015. The possibility that the X-33’s complex fuel tanks will end up being made of aluminum rather than composites reinforces the suspicion that the full-scale VentureStar may end up with a dry-to-liftoff mass fraction too high to be useful as a launch vehicle even to LEO. One can argue that the problem is one of rocket fuels and structural materials rather than the laws of physics. Still, unless the mass fraction can be reduced to 10 percent or less, the laws of physics will leave SSTO tantalizingly beyond practical reach.

In February 2000, NASA announced that the agency would commit $6 billion between 2001 and 2005 to demonstrate key technologies for reusable launch vehicles.[218] The important change from the 1990s appears to be a willingness to settle for two-stage-to-orbit (TSTO) solutions. This shift in focus has emerged from a Space Transportation Architecture Study (STAS) NASA launched in late 1998. “The first-round STAS reports—including those from Boeing and a team comprising Orbital Sciences and Northrop Grumman—declared unequivocally that an RLV [reusable launch vehicle] could replace the Space Shuttle” by 2010, but most of the concepts to be explored under the new program will be TSTO systems.[219]

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[215] Jess Sponable, “The Next Century of Flight,” *Aviation Week & Space Technology*, May 24, 1999, p. 94. Sponable was the program manager for DC-X. His view is that what is needed is not newer launch technology but the application of existing technologies to build reusable launch vehicles “designed to fly with aircraft-like operational efficiencies” (ibid.). “Low-cost, two-stage spaceships using commercially available Russian engines,” he adds, “are potentially far cheaper to operate” than the much more complex new technology vehicles.

[216] Sweetman, “Space Giants Step Up Efforts To Win Low-cost Launch Race,” p. 30.

[217] Ibid., p. 32. For a short discussion of the rocket equation that produces this result, see Dave Sonnabend, “The Rocket Equation,” *Launchspace*, January/February 1999, p. 10. The materials for Marshall H. Kaplan’s three-day Launchspace course “Launch Vehicle Systems Design and Engineering” puts the point as follows: “The maximum allowable dry-mass fraction for single-stage-to-orbit vehicles using current technology propulsion systems is about 10%, including payload mass.” Kaplan’s conclusion is that for SSTO to become a reality, “much higher performance in rocket engines and much lighter materials” are needed. For the derivation of the rocket equation, see Sellers, et al., *Understanding Space*, pp. 483–86 and 502–05.

[218] Sweetman, “Space Giants Step Up Efforts To Win Low-cost Launch Race,” p. 30.

[219] Ibid., p. 32.

What are the prospects for dramatic—order-of-magnitude or more—reductions in the per-pound costs of lifting payloads into orbit? Reductions in the neighborhood of 15–20 percent are probably achievable over the next decade or so. It remains to be seen, however, whether much more than gradual, incremental improvement will be possible using available rocket science. Ivan Bekey, whose instinct is to be optimistic about space technology in the long run, posits the cost-per-pound to LEO declining by two orders-of-magnitude—nominally to $100-per-pound—within twenty years, and becoming almost free, even to GEO, within forty years (after post-rocketry techniques, such as beaming energy to the vehicle after launch and using air for reaction mass, have been developed).[220] Bekey is also bullish on the long-term feasibility of manufacturing carbon nanotubes with lengths sufficient for composite launch vehicles, thereby reducing their structural weights by factors of 100 to 1,000 while greatly increasing structural strengths.[221] At least one of the other participants in the *New World Vistas* space applications panel is now inclined to "side with Bekey" if the timeframe is 2030 and beyond, which leaves the amount of progress in space launch that will actually be realized in the 2015–30 timeframe anybody's guess.[222] Clearly the willingness of space-faring nations to make the long-term investments needed to realize Bekey's predictions about space launch on a timeline close to his predicted one will be a critical factor in how these issues unfold. Based on NASA's performance during the 1990s and the current political environment surrounding US space policy, though, one is inclined to suggest that Bekey's timelines in this area are likely to be optimistic by a decade or more.

> One issue that will continue to constrain space applications is the cost and difficulty of space launch. No fundamental breakthroughs in propulsion technology are foreseen in the near future in any studies conducted to-date. While incremental changes promise some improvements, we have to accept for now the limitations in space launch. However, advances in micro-electronics and sensors are leading to order of magnitude changes in satellite size and capabilities, leading to much smaller more operationally friendly or more economical launchers to achieve similar mission performance.[223]

Moreover, the dry-to-liftoff mass fraction is only part of the space-launch problem. There is also the service life of the vehicles and their reliability. The US Air Force Scientific Advisory Board noted in 1995 that "space launch is more akin to a science experiment than to a routine takeoff," and that the use of space "has been limited by the high cost of placing satellites in orbit."[224] What

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[220] Watts, notes from Bekey presentation, April 24, 2000; also, Bekey, *Advanced Space System Concepts and Enabling Technologies for the 2000–2030 Time Period*, pp. 35, 38, and 46.

[221] Bekey, *Advanced Space System Concepts and Enabling Technologies for the 2000–2030 Time Period*, pp. 41–44. Carbon nanotubes are descendants of buckminsterfullerene, the soccer-ball-shaped molecule of 60 carbon atoms ("Tantalizing Tubes: Hype Aside, Applications for Carbon Nanotubes Progress—Slowly," *Scientific American*, June 2000, p. 40). To date, however, buckytubes have only been grown to lengths on the order of one millimeter, and thoughts of a 35,800-kilometer-long nanotube rope for earth tethered satellites "are still a bit premature" (ibid.). The most promising near-term applications of carbon nanotubes, discovered in 1991 by Sumio Iijima of NEC, are in microelectronics.

[222] Greg Canavan, e-mail to Barry Watts, April 25, 2000.

[223] *New World Vistas*, Yarymovych, *Space Applications Volume*, pp. 5–6.

[224] *New World Vistas: Air and Space Power for the 21st Century*, Gene H. McCall (study director) and Major General John A. Corder (deputy director), *Summary Volume* (Washington, DC: USAF SAB, 1995), pp. 44–45.

is striking is that the SAB had “no specific solutions” to suggest for reducing the high costs and risks of catastrophic failure inherent in space launch beyond endorsing “long-term research.”[225] The costs and risks of reaching orbital space have been high since the dawn of the space age. If there is any trend toward lowering the costs or risks of access, it is extremely gradual, and it is far from clear that the situation will have been transformed by 2020 or 2025.

From a military perspective, the most worrisome problems with current launch vehicles may be reliability and the lengthy pre-launch preparation times required rather than cost per se. As one observer commented, the prevailing approaching to space launch in the United States is akin to arriving at an airport to catch a commercial flight to your destination only to be deposited at the end of the runway to wait for the airline to assemble your airliner from its component parts.[226] Current American expendable launch vehicles are derived from the ballistic missiles of the 1950s and require on-pad check-out times ranging from 50 days for Atlas to 180 days for Titan IV.[227] A string of recent launch failures which destroyed military payloads worth $3–4 billion have heightened concerns about reliability; these failures included the loss of a MILSTAR communications satellite in April 1999 and a National Reconnaissance Office payload in August 1998.[228] While the US Air Force’s EELV program is also intended to reduce launch costs, much shorter on-pad preparation times and higher reliability are undoubtedly important—if not overriding—goals for military and NRO payloads.

All in all, are the discernible trends in launch systems likely to ease space access to the point that, over the next 20–25 years, reaching earth orbit will be more comparable to a flight on a commercial airliner in terms of costs, risks and on-time takeoffs? In the absence of more rapid technological progress than now appears likely, the short answer must be “no.” True, in some important areas of space launch, the United States appears to be far ahead of most other nations. Certainly no other country is operating a shuttle fleet or experimenting with technologies such as the X-33’s linear-aerospike engine. Nor, at present, is any other nation making the long-term investments in reusable launch vehicles on the scale currently being supported by NASA, the Defense Department and commercial investors in American firms. On the other hand, the Europeans have spent a lot of money developing the Ariane 5, and one could argue that it is more advanced than any current American expendable launch vehicle. Still, one does not see either the levels of investment nor the political commitment by space-faring governments that took American astronauts to the moon in the span of some eight years. Even by 2020, therefore, space launch is likely to remain more akin to a costly, high-risk science experiment than to catching an airliner from Washington to New York.

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[225] Ibid., p. 44.

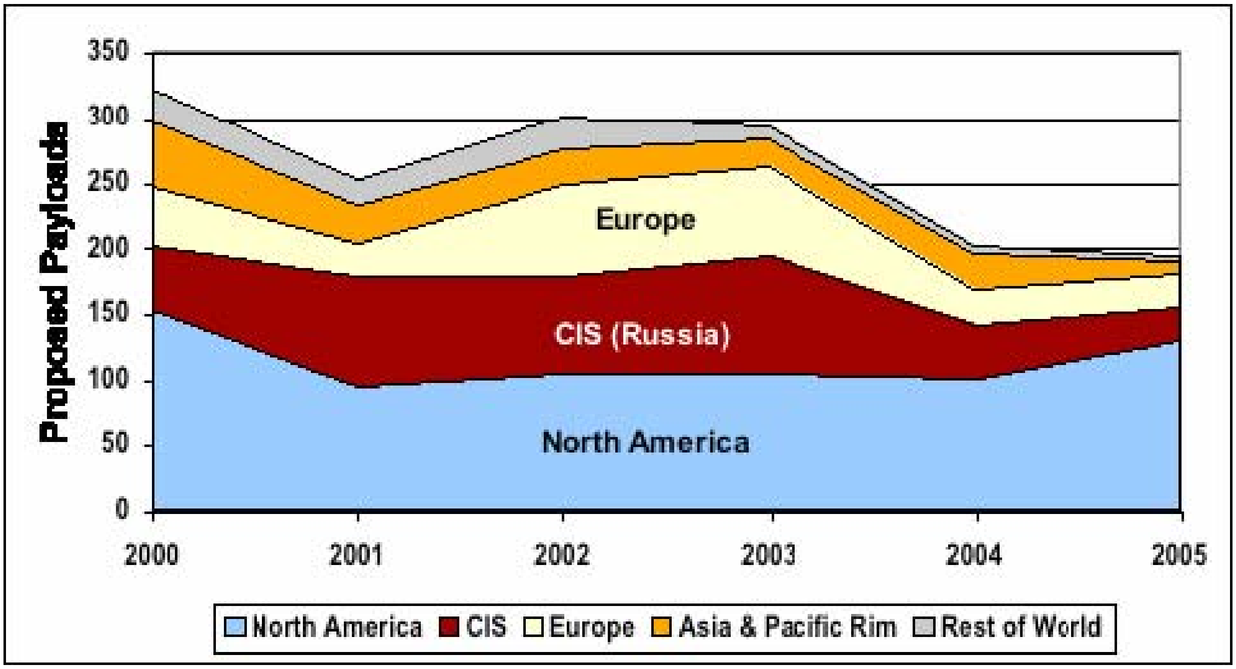
[226] Kelley, “Long Term Prospects for the Air Force in Space,” p. 159.

[227] *New World Vistas*, Yarymovych, *Space Applications Volume*, p. xix.

[228] Grier, “The Investment in Space,” p. 50. From August 1998 to April 1999, three military spacecraft were lost in Titan IV launches as well as the commercial payloads lost in two Delta 3 launches. As Bill Sweetman has wryly observed: “Short of warfare, space launch is the fastest way of destroying a $1 billion-plus investment ever invented” (“Space Giants Step Up Efforts To Win Low-cost Launch Race,” p. 30).

If the governments of the leading nations in near-earth space seem unlikely to break the logjam of space launch by 2020, might commercial ventures do so? Again, it is difficult to justify an affirmative answer. Despite more optimistic forecasts during the mid-1990s, demand for space launch will probably not expand dramatically over the next decade because individual satellites will be able to provide ever-greater levels of service or functionality per pound.[229] There is a curious parallel to Joseph Heller's "catch-22" in the space-launch business.[230] Given the decline in annual launches since the end of the Cold War, together with projections for further declines through 2005 (Figure 12), it is difficult for existing or planned launch vehicles to achieve the economies of scale needed to drive down the cost-per-pound of placing tonnage in orbit more than marginally. Yet, without increased demand for launch services, the typical costs-per-pound-to-orbit seem destined to remain at or near current levels.

Figure 12: Payloads Proposed for Launch 2000–05



Source: "Growth in Proposed Payloads Slows," *Aerospace America*, May 2000, p. 16. The data source cited in the *Aerospace American* article is the Teal Group, which in 1992 began keeping track of all payloads being proposed for launch into earth orbit.

A related issue is the competitive position of the US launch industry. To a surprising degree, the Americans have allowed the Europeans to close the gap, if not surpass American firms, in commercial space launch. "Approximately half the large commercial satellite launch service business is provided by Arianespace (dominated by the European Union), with the United States a close second, followed by Russia." China and Japan have also entered this business, and other new

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[229] Lucas and Murphy, "The Space Launch Services Industry: Indicators and Trends," slide 27.

[230] The "catch-22" was that any crew member who continued flying combat missions after numerous close-calls had to be crazy, and could be grounded if only he asked the unit flight surgeon; however, anyone "who wants to get out of combat duty isn't really crazy" and, therefore, could not be grounded—Joseph Heller, *Catch-22* (New York: Simon and Schuster, 1955), p. 45.

competitors are emerging such as the Sea Launch international consortium.[231] While Arianespace's Kourou spaceport (Figure 13) has yet to be opened to non-Europeans, the on-pad preparation time for Ariane 5 missions is advertised as "only 20 working days."[232] In addition, the main American launch facilities have become quite antiquated. The US eastern and western missile-test ranges have radar coverage, respectively, from Cape Canaveral in Florida to the west coast of Africa, and from Vandenberg in southern California to Kwajelin Island in the Pacific. The radars and their associated cabling, which have to be manually reset for each mission, are three decades old, and increasingly prone to failures.[233] Launch periods at these ranges for a mission are typically 48 hours. Between poor weather, radars going down, and other associated range problems, there have been an increasing number of cancellations, even though the ranges have been handling more commercial launches. Present trends indicate that commercial launches will "shortly dominate the schedule" at the US ranges, but a "recent study found that the average interval between incidents where range-related problems impacted launches has dropped by a factor of three since 1996.[234] Commercial customers who borrow to finance their missions lose money when launches have to be re-scheduled. Delays due to range problems, in turn, cut into commercial profits. There is every reason, then, to anticipate that commercial customers will gravitate to more modern launch facilities such as Kourou unless the Canaveral and Vandenberg ranges are upgraded. Whether the US Congress will provide the necessary money remains to be seen.[235]

Another factor in the declining position of the American space-launch industry has undoubtedly been a certain amount of technological hubris. As of the mid-1990s, Russian rocket engines represented "the current state of the art in rocket propulsion . . . particularly with respect to liquid oxygen/hydrocarbon engine development, tri-propellant engines, and operations."[236] While US launch manufacturers have been slow to adopt Russian engine technology, there are encouraging signs of change. Lockheed Martin's new Atlas III expendable launch vehicle will use the Russian Energomash RD-180, and at least two of American reusable launch vehicle programs—Kelly Space and Technology's Astroliner and Kistler's two-stage K-1—are considering Russian engines.[237]

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[231] WTEC, *Global Satellite Communications Technology and System*, Executive Summary. For a description of the Sea Launch system, see Bruce A. Smith, "Sea Launch Prepares for Demonstration Mission," *Aviation Week & Space Technology*, November 30, 1998, pp. 56–58.

[232] http://ww.arianespace.com/spaceport_3_intro.html.

[233] Bruce Mahone, interview with Barry Watts, Andrew Krepinevich and Erwin Godoy, Aerospace Industries Association, Washington, DC, November 15, 1999.

[234] John M. Borky, "Range Modernization, Part II," prepared statement to the House Science Committee, Subcommittee on Space and Aeronautics, US House of Representatives, June 29, 1999; available at http://www.house.gov/science/borky_062999.htm

[235] The Aerospace Industries Association (AIA) has been lobbying Congress for $1.6 billion over five years to modernize the US launch ranges (Bruce Mahone, "Space Issues Overview," AIA Space Council, November 1999, Slide 6).

[236] *New World Vistas*, Hastings, *Space Technology Volume*, p. 17.

[237] Craig Covault, "Russian-Powered Atlas To Challenge Ariane," *Aviation Week & Space Technology*, November 22, 1999, p. 52; and, Associate Administrator for Commercial Space Transportation (AST), *2000 Reusable Launch*

Figure 13: Worldwide Space-Launch Facilities

Credit NASA Goddard Space Flight Center Image by Reto Stokli

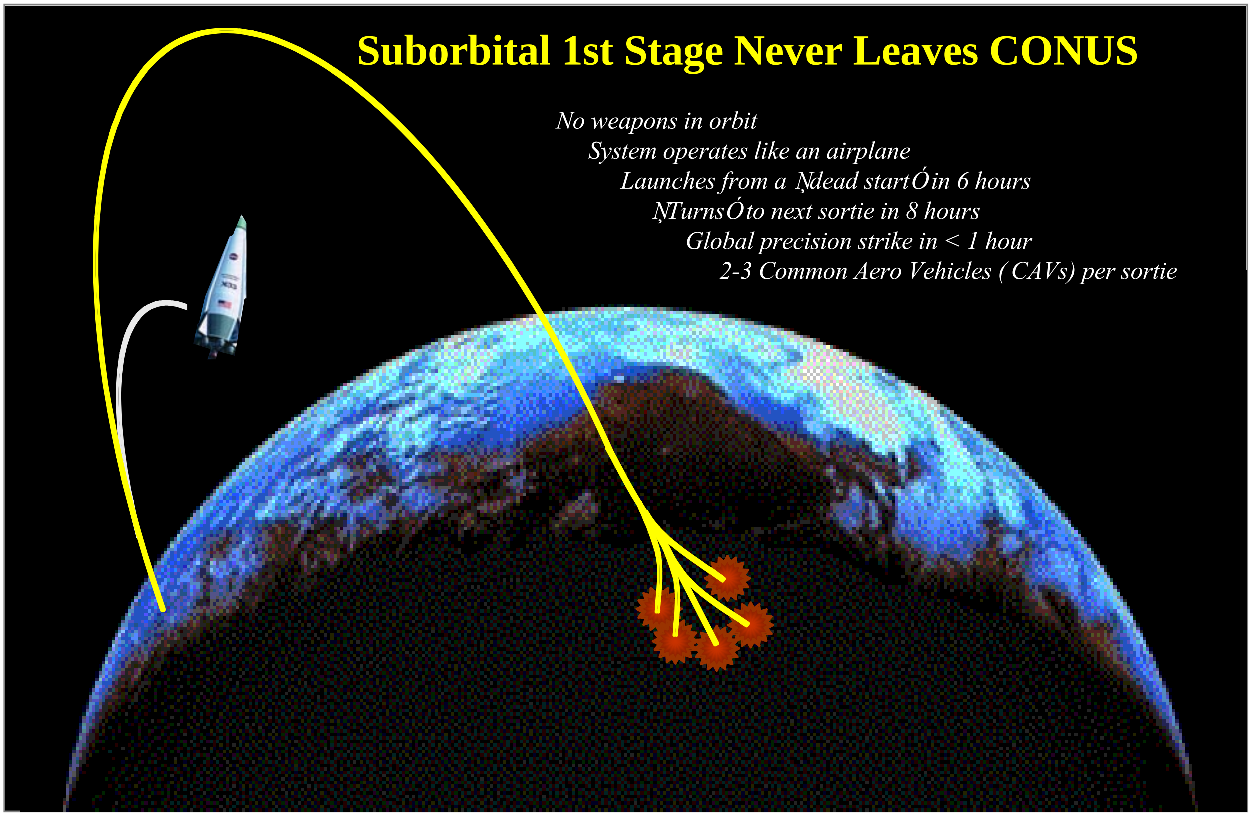
Note: The first orbital mission from the Kodiak Island spaceport is scheduled for the second half of 2000 (Frank Sietzen, Jr., “First Orbital Mission from Kodiak Island Announced,” *SpaceDaily*, April 26, 1999; available at http://www.spacedaily.com/spacecast/news/lm–99h.html). Figure 13 does not include some older sites, such as White Sands in New Mexico, which are no longer used for orbital launches but were in the past. Plesetsk has been the most prolific launch site on earth. “More than 1,500 boosters have been launched from the pads and silos at Plesetsk over the years, delivering more than 1,900 spacecraft to Earth orbits. That amounts to 38% of the total number of spacecraft launched worldwide and 60% of the Russian spacecraft ever launched” (“Plesetsk Upgrades May Cut Russian Space Payments to Kazakhstan,” *Aerospace Daily*, March 1, 2000, p. 320). As of the end of 1997, the only site with more launches than White Sands was Plesetsk (“Worldwide Launches by Site, 1957–97,” *AIR FORCE Magazine*, August 1998, p. 31).

As a final observation on launch trends, even though SSTO reusable launch vehicles may not become a reality by 2020, the viability of TSTO solutions argues that a platform revolution in near-earth space is possible. A suborbital first-stage could be built to place either a second-stage space maneuver vehicle (SMV) in low-earth orbit, or to release boosted precision weapons which could cover aim-points as distant as halfway around the earth. Figure 14 depicts a concept for a suborbital first stage able to boost 2–3 Common Aero Vehicles (CAVs) to an altitude and velocity from which a short burn by each CAV’s thruster would enable it to deliver precision submunitions over global distances—even though the reusable first stage would remain over the continental United States (CONUS) throughout its flight. The point is not to advocate developing these systems as a matter of policy but to be clear that they are well within the reach of current technology. In fact, a version of a suborbital vehicle able to deliver CAVs was offered as a developmental option in a 1998 Defense Science Board (DSB) summer study, and USSPACECOM

Vehicle Programs & Concepts with a Special Section on Spaceports (Federal Aviation Administration, January 2000), pp. 6–7.

developed a draft concept of operations for a spaceplane, able to lift a 5,400-kilogram payload to a speed around Mach 16–17 (that is, 16–17 times the speed of sound).[238]

Figure 14: A Concept for Global Precision Strike



Suborbital 1st Stage Never Leaves CONUS

No weapons in orbit
System operates like an airplane
Launches from a Ņdead startÓ in 6 hours
ŅTurnsÓ to next sortie in 8 hours
Global precision strike in < 1 hour
2-3 Common Aero Vehicles (CAVs) per sortie

Source: Lieutenant Colonel William Bruner, presentation slide.

In sum, although there is no shortage of proposals and research programs for reusable SSTO and TSTO launch systems, there is as yet little cause for optimism that a major cost breakthrough will be achieved anytime soon. Even so, the United States does need to make some wise investments in launch vehicles and launch facilities. The American Space Shuttle program will be two decades old in 2001, and its performance to date argues that the United States desperately needs a more efficient, lower-risk follow-on. In general, reusable launch vehicles promise to be cheaper to operate than expendable launchers, no matter how evolved.[239] Also needed are launch vehicles with very high reliability and greatly reduced on-pad preparation times. The crucial near-term operational issues in space launch appear to be reusability and reliability. While there is no tech-

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[238] Donald Latham and Larry Welch (co-chairs), *The Defense Science Board 1998 Summer Study Task Force on Joint Operations Superiority in the 21st Century* (Washington, DC: Defense Science Board, October 1998), pp. H-1 to H-7; Sweetman, “Space Giants Step Up Efforts To Win Low-cost Launch Race,” p. 32. The minimum speed for LEO is Mach 25, although the lack of air at this altitude makes the use of Mach numbers somewhat inappropriate. The suborbital vehicle USSPACECOM has been exploring would cover a ground distance of 1,367 miles (2,200 kilometers). Three bases in the continental United States would provide six possible launch paths.

[239] For a comprehensive overview of reusable launch vehicles (RLVs), see AST, *2000 Reusable Launch Vehicle Programs & Concepts with a Special Section on Spaceports*. This report covers US government, US commercial and international RLV programs.

nological reason to preclude first-generation, small-payload two-stage-to-orbit reusable launch vehicles from appearing by 2010, it is unclear whether commercial firms will find the financing or governments will invest the resources to develop them. In addition, there is growing competition from abroad. The Saturn launcher that carried Americans to the moon "flies no more, and we did not build Energia or Ariane."[240] Looking further ahead, even if Bekey's long-term optimism is not realized as early as he hopes, suborbital launch vehicles with clear applications for global-precision strike and space control are technologically within reach. Whether the United States or any other nation will undertake fielding a fleet of such vehicles by 2025 remains to be seen. The technology to do so exists. Finally, the functionality of each pound of satellite mass placed in orbit is growing due to such trends as miniaturization. As a result, satellite launch may slowly become less of a constraint than it has been in the past, even if the costs and difficulties of space launch do not greatly improve over today.

INCREASING COMMERCIALIZATION AND THE NEAR-EARTH GLOBAL COMMONS

In September 1996, the United States promulgated a new national policy on space, which the administration described as "the first post-Cold War assessment of American space goals and activities."[241] This policy formalized two earlier decisions aimed at fostering the commercialization of near-earth space. First, President Clinton directed that GPS begin evolving toward becoming as much a civil system as a military system. Although GPS had previously been a DoD program, the Department of Transportation was brought into its administration, and the Department of State is now working "to make GPS the world's navigation system standard."[242] In addition, the president promised to terminate by 2006 the Selective Availability (SA) program that degraded the accuracy of the unrestricted GPS signal, however SA was switched off on May 1, 2000, five years earlier than promised.[243] Granted, the Europeans, concerned about being dependent on a US-controlled navigation system that could in theory be shut down selectively or entirely, are considering placing their own global navigation satellite system (Galileo) in orbit.[244]

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[240] Kelley, "Long Term Prospects for the Air Force in Space," p. 162.

[241] "President Clinton Issues New National Space Policy," Press Release, The White House, September 19, 1996; available at: www.pub.whitehouse.gov/uri-res/I2R?urn:pdi://oma.eop.gov.us/1996/9/20/1.text.1.

[242] Keith R. Hall, "Space Policy, Programs and Operations."

[243] Bruce D. Nordwall, "Degrading GPS Signal May End," *Aviation Week & Space Technology*, April 17, 2000, p. 44; "DoD Switches Off GPS Selective Availability after Completing Tests," *Aerospace Daily,* May 2, 200, p. 169. Selective Availability was intended to deny pinpoint GPS accuracy to potential military adversaries of the United States. However, by 1996 it had become clear that the dithered signal was entirely adequate for many hostile military applications, and the civil community had developed differential GPS (DGPS) that gave greater accuracy despite the dithered signal. The decision to terminate SA in 2000 came after testing showed that the Defense Department could switch off the more precise signal in a given region during an armed conflict.

[244] Bill Gregory, "Dual-Use Success Story," *Armed Forces Journal International*, March 2000, p. 36. Gregory notes that the gradual modernization of GPS now underway is being "driven as much by civil users as by the US military" and describes GPS as "a universal resource" (ibid.).

Nevertheless, as a result of American policy decisions, GPS and similar systems appear to be well on the way to becoming part of a global commons available to all.[245]

The second decision reflected in the new US space policy was President Clinton's 1994 directive clearing the way for American commercial firms to develop high-resolution, electro-optical imaging systems and make the images from these systems available to anyone willing to pay for them.[246] Non-military satellites such as LANDSAT have been providing optical images of the earth's surface since the 1970s. The first LANDSAT satellite, ERTS-1 (Earth Resources Technology Satellite), was launched in 1972 and provided 80-meter resolution, which permitted it to show towns but not buildings, and forests but not trees.[247] Space Imaging's LANDSAT 5, launched in 1984, provided 30–80 meter resolution imagery over swaths 185 kilometers wide; the latest SPOT (*Satellite Pour l'Observation de la Terre*) imaging satellite, launched in 1998 by Maltra Marconi Space for France and the United Kingdom, can return 10-meter resolution images.[248]

Figure 15 shows the long-term trend in earth imaging by commercial enterprises. As the LANDSAT and SPOT data make clear, high-resolution imaging systems were the exclusive domain of the American and Soviet governments until quite recently. The Clinton Administration's decision to permit, if not encourage, high-resolution earth imaging as a commercial enterprise in the United States may have simply reflected recognition that the worldwide satellite industry would eventually field systems with resolutions under one meter. Hence, the decision may well have been taken in hopes of giving American firms such as Space Imaging, Orbital Sciences, and EarthWatch a head-start in the emerging business of high-resolution, remote sensing.[249]

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[245] GPS allows receivers to establish their location "by calculating the difference between the current receiver time and the time transmitted in the pulse train" (Sellers, et al., *Understanding Space*, p. 414). Each GPS satellite contains two cesium and two rubidium atomic clocks and a communication package (ibid.). Thus, precise timing is both at the heart of GPS as well as something GPS signals provide in addition to the receiver's location and velocity. Cellular phone networks in the United States are now relying on precise GPS time references, and timing errors can shut these networks down.

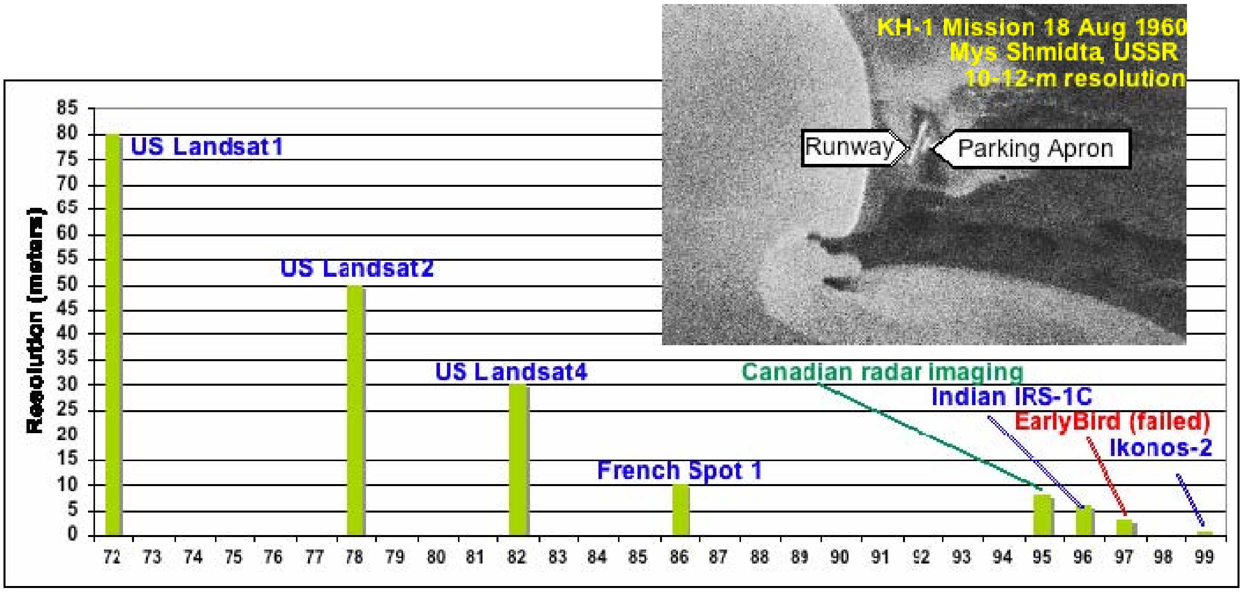
[246] Joseph C. Anselmo, "Shutter Controls: How Far Will Uncle Sam Go?" *Aviation Week & Space Technology*, January 31, 2000, p. 55.

[247] Anselmo, "Shutter Controls: How Far Will Uncle Sam Go?" p. 56. The ERTS program was renamed LANDSAT (land satellites) in 1975 (Sellers, et al., *Understanding Space*, p. 374).

[248] Hicks, *Final Report of the Defense Science Board Task Force on Globalization and Security*, p. 106.

[249] The three American firms that are moving into the high-resolution imagery business are Space Imaging, Orbital Sciences and EarthWatch. Space Imaging was first to market when it orbited an Ikonos satellite in September 1999. For details on EarthWatch's Quickbird, see http://www.tec.army.mil/CCIO/QUICKBIRD.htm. For a description of Orbital Sciences' OrbView-3 and OrbView-4, see http://www.orbimage.com/products/cities.html. Orbital Sciences' OrbView-1 was launched in 1995, and OrbView-2 in 1997. OrbView-2 was launched with Orbital Sciences' Pegasus rocket. These earlier Orbital Sciences satellites are not high resolution.

Figure 15: Commercial Earth-Imaging Trends

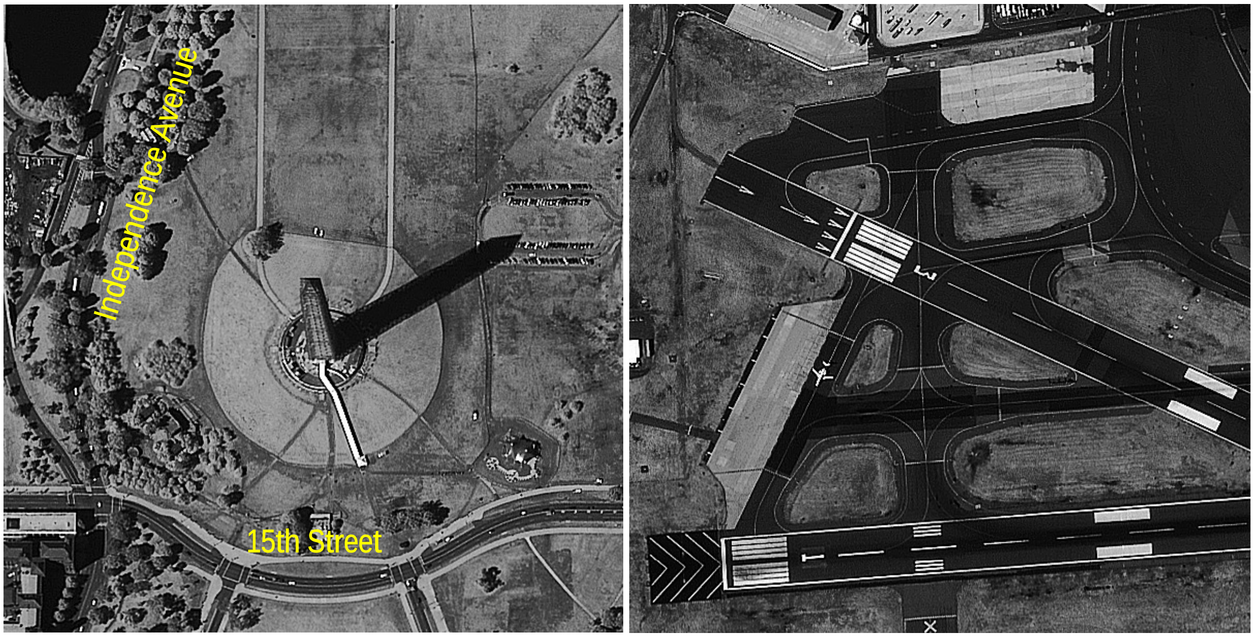


Source: Data from Anselmo, “Shutter Controls: How Far Will Uncle Sam Go?” p. 56. To provide a visual standard of comparison for the commercial resolutions in the graphic, the 10-12-foot resolution achieved with a C camera during the first successful Corona spy-satellite mission has been superimposed on the figure. The initial resolution of the KH-1 in 1960 was apparently comparable to Spot 1 in 1986.

Note: Current NRO imaging systems such as the advanced KH–11 have superior resolution to Ikonos. During Allied Force in 1999, the NRO’s three advanced KH-11–type visible/infrared electro–optical imaging satellites were called upon to “image refugees—lines of individuals—from orbits of 170 X 620–mi. altitude,” which experienced space–reconnaissance analysts judged “a remarkable technical achievement” (Covault, “Recon, GPS Operations Critical to NATO Strikes,” p. 35).

Whatever the administration’s reasoning, the image in Figure 16 of the area around the Washington Monument taken by an Ikonos satellite on September 30, 1999, has sufficient resolution to allow anyone to distinguish passenger cars from buses and trucks. Indeed, close examination of the Washington Monument reveals that the scaffolding on the outside of the monument during its restoration was still in place when this image was taken. The second image in Figure 16, which was taken during the same Ikonos pass that captured the Washington Monument, shows part of Reagan National Airport. The image permits one to read the numbers on the ends of the runways and to distinguish among airliner types.

Figure 16: 1-Meter Resolution Images of the Washington Monument and Reagan National Airport Taken by Space Imaging's Ikonos Satellite



Source: Space imagery by: spaceimaging.com

It does not take a rocket scientist to appreciate that imagery of this quality could be exploited for military purposes. With 0.9-meter resolution, one can not only distinguish bombers and transports from smaller fighters, but tell an F-15 from an F-16.[250] Ikonos is capable of 0.82-meter resolution black-and-white images, which is more than adequate for distinguishing passenger cars from buses and trucks, detecting the deployment of American combat aircraft to overseas airfields, or monitoring in detail the build-up of US forces over time. For fixed facilities such as airfields and ports, it should not be difficult to develop mensurated target coordinates from such imagery for targeting precision weapons. Ikonos orbits the earth every 98 minutes at an altitude of 680 kilometers (367 nautical miles) and, due to the eastward rotation of the earth underneath the satellite's orbit, passes directly overhead a given spot on the surface every three days.[251]

In late April 1999, while Allied Force was underway, Space Imaging launched the first Ikonos satellite. Reportedly there was much concern in the Pentagon at the time that the "company could have sold photos of NATO air bases or troop encampments to, say, Serbian operatives."[252] As things turned out, Pentagon officials did not have to take any action to limit the use of this satellite. Due to a malfunction, Ikonos-1 ended up plunging into the Pacific Ocean east of New Zea-

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[250] Gonzales, *The Changing Role of the U.S. Military in Space*, p. 16.

[251] "Satellite Pictures: Private Eyes in the Sky," *The Economist*, May 6, 2000, p. 71. Ikonos' 3-day revisit interval is for a 0.82-meter resolution images from a position directly overhead the target. If the user can accept slightly reduced resolution from a more oblique angle, earlier revisit times are possible. Captured images are transmitted from orbit to a network of ground stations from which they are sent to Space Imaging's Denver headquarters for ortho-rectification. Note that Ikonos has a second sensor that is capable of 4-meter-resolution multispectral (or color) images.

[252] Richard J. Newman, "The New Space Race," *U.S. News & World Report*, November 8, 1999, p. 30.

land about 30 minutes after liftoff.[253] However, the incident highlights the potential ramifications of commercial imaging satellites with 1-meter resolution for American military operations.

Such imagery can also be exploited by individuals and organizations attempting to influence government policy. Indeed, this has already happened. In early January 2000, the Federation of American Scientists (FAS) posted Ikonos imagery of the North Korean missile-launch facility at Rodong on its website (www.fas.org).[254] The apparent intent of FAS' John Pike was to downplay the seriousness of the North Korean missile threat to the United States.[255] More recently FAS ordered Ikonos images of military facilities in Pakistan, analyzed those images with the Institute for Science and International Security, and then argued publicly, on the eve of President Clinton's trip to South Asia, that Pakistan was developing mobile missile launchers.[256] In short, the commercial availability of high-resolution overhead imagery has enabled individuals and organizations to dispute US government threat assessments using their own satellite images. This development has also enabled individuals such as Pike to lift somewhat the veil of secrecy on classified US military facilities. In April 2000, "Mr. Pike obtained the first one-metre images of Groom Lake, better known as Area 51, the most secret military complex in America, where—to the disappointment of conspiracy theorists—there were no flying saucers to be seen."[257]

For many US intelligence officials, the public availability of imagery once carefully controlled by the government is a move into uncharted waters. Granted, the deeper issue is the use future adversaries may be able to make of high-resolution imagery. Martin C. Faga, who directed the NRO during the Gulf War, has observed that collecting a bunch of imagery is one thing, whereas "understanding it enough to act on it is quite another."[258] Further, the US government retained shutter control rights over American firms, allowing government officials to limit distribution or to stop picture taking during a national-security crisis.[259] Also worth recalling is that SPOT and LANDSAT images were denied to Iraq in 1991. Additionally, so far at least, the Israelis have been able to restrict commercial firms from taking or selling one-meter resolution images of Israel, albeit mainly because the highest resolution available from non-American satellite-imaging firms are Russian two-meter images.[260]

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[253] Analytic Graphics, all-satellites database, www.stk.com, launch event 89904.

[254] See www.fas.org/nuke/guide/dprk/facility/011100nkorea-missile.htm.

[255] On its website, FAS described Rodong as "a primitive facility without transportation links, propellant storage or staff housing."

[256] James R. Asker (ed.), "Candid Camera," *Aviation Week & Space Technology*, March 20, 2000, p. 33. For details, see www.fas.org/eye/ and www.isis-online.org. These images were returned by Ikonos-2 launched in September 1999.

[257] "Satellite Pictures: Private Eyes in the Sky," p. 73.

[258] Robert Holzer, "Tactical Surprise May Be Obsolete," *Defense News*, April 3, 2000, p. 44.

[259] Anselmo, "Shutter Controls: How Far Will Uncle Sam Go?" p. 55. The administration gave shutter control to the Secretary of Commerce, who must consult with the Secretaries of State and Defense (ibid.). This assignment of primary responsibility suggests that PDD-23 was driven more by commercial than national-security considerations.

[260] "Satellite Pictures: Private Eyes in the Sky," p. 72.

Still, the American decision to encourage public access to high-resolution earth imagery is not without long-term consequences for the US military. In the future US firms are unlikely to be the only sources of high-resolution imagery. By 2003 at least eleven private firms from a range of countries—Canada, France, India, Israel, Russia, the United States, and possibly China—expect to offer high-resolution imagery.[261] Further, new technologies such as hyper-spectral and radar imaging are not far behind. A plausible projection is that, in the near-term, American adversaries will be able to take advantage of such imagery for pre-conflict target planning and, possibly, gaining initial indications of American deployments to regional bases and ports of entry. Presumably US opponents would be quickly cut off from American firms once military operations began. Ikonos, for example, would probably not be available to US adversaries for wartime targeting or BDA, especially against mobile or relocatable targets. Nevertheless, the situation hastened by the new US space policy means that the American advantage stemming from access to high-resolution imaging satellites will not be as lopsided in the future as it has been in the past. A recent paper by the Carnegie Endowment for International Peace argues that attempts "to control access to high-resolution satellite imagery are bound to fail" in the long run as more and more countries and commercial companies begin operating such satellites.[262] Thus, to follow this argument to its logical conclusion, it is quite possible—if not likely—that by 2020 the US military will be confronted with conducting a campaign against an opponent with access to high-resolution imagery during at least the opening phases of the conflict. In that case, any advantages the American military derives from space imagery will hinge mainly on two considerations: whether US forces can make better, more timely use of imagery products than the other side; and asymmetries between the two sides in their dependence on such information.

The public availability of high-accuracy GPS signals and high-resolution imagery are elements of a broader trend toward the growing commercialization of near-earth space. Another thread in this wider trend is the US government's willingness to allow consortia such as INTELSAT to be privatized. COMSAT was chartered in 1962 as the US owner of the INTELSAT fleet of geostationary communications satellites.[263] In August 2000 COMSAT's independence ended with its acquisition for $2.1 billion by the Lockheed-Martin Corporation.[264] This development can be seen as simply one more datum substantiating a worldwide trend toward the privatization of satellite systems and services. Nor was COMSAT the first satellite consortium to be privatized. INMARSAT, headquartered in London, was established in 1979 to "serve the maritime industry

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[261] Jason Bates, "Policy-Makers Not Ready For New Imagery," *Defense News*, April 3, 2000, p. 44; also Yahya A. Dehqanzada and Ann M. Florin, *Secrets for Sale: How Commercial Imagery Will Change the World* (Washington, DC: Carnegie Endowment for International Peace, 2000), pp. vii and viii; available online at www.ceip.org. An important issue is whether the market will support all these firms. Space Imaging's backers alone have invested some $750 million; yet the worldwide market for satellite imagery is a mere $154 million according to Frost & Sullivan analyst Ron Stearns ("Satellite Pictures: Private Eyes in the Sky," p. 72). Projections of the future value of this market vary widely. Whereas Stearns estimates it will only grow to about $420 million by 2005, Tom Watts of Merrill Lynch projects a global market of $2.5 billion (ibid.).

[262] Dehqanzada and Florin, *Secrets for Sale*, p. vii. Florin as well as writers at *The Economist* argue that, try as they might to restrict or control these eyes in the sky, "governments will simply have to get used to them" ("Satellite Pictures: Private Eyes in the Sky," p. 73).

[263] www.comsat.com.

[264] Greg Schneider, "Comsat Moves in Lockheed Orbit," *The Washington Post*, August 3, 2000, p. E1.

by developing satellite communications for ship management and distress and safety."[265] Two decades later INMARSAT became "the first intergovernmental 'treaty' organization to privatize and become a limited company."[266] The current trend toward ending longstanding government monopolies on space systems and services, then, seems both unmistakable and likely to continue.

The presumption of most observers today is that the growing privatization of orbital systems is merely one component of a widening trend toward a global economy whose emergence and continued expansion is inevitable. *The Economist*, however, has recently cautioned that the presumption of unstoppable economic globalization may be "a big mistake."[267] This caution was repeated in *The Economist*'s January 2000 review of *Globalization and History* written by the economists Kevin O'Rouke and Jeffrey Williamson. *Globalization and History* investigates the first great globalization, which lasted from around 1849 to 1914. What O'Rourke and Williamson argue is that this earlier globalization "provoked a backlash that stemmed the cross-border flows of goods, people, and money"—a backlash which, they argue, "could all too easily happen again."[268] Prior to World War I,

> . . . a political backlash developed in response to the actual or perceived distributional effects of globalization. The backlash led to the reimposition of tariffs and the adoption of immigration restrictions, even before the Great War. . .The record suggests that unless politicians worry about who gains and who loses, they may be forced by the electorate to stop efforts to strengthen global economy links, and perhaps even to dismantle them. . . . Economists who base their views of globalization, convergence, inequality, and policy solely on the years since 1970 are making a great mistake.[269]

For present purposes, this caution seems worth noting less to insist that current trends toward the commercialization of space systems will end before 2025 than to realize that they could. If the increasing globalization of the world's economy continues into the third decade of the 21st century, then there is every reason, based on presently observable trends, to anticipate that more of the world's space systems will be in the hands of commercial firms. However, linear extrapolations of observable trends for a quarter century into the future cannot be made with much confidence. In detail, the future remains as unpredictable as the local weather. Today's prevailing wisdom about the inevitability of continuing economic globalization and the increasing privatization of near-earth space systems could prove as mistaken as was Norman Angell's contention, in the years just before World War I, that major war had become so economically destructive

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[265] Gavin Trevitt, "Facts about INMARSAT," pdf file available at www.inmarsat.com/index3.html.

[266] Ibid.

[267] "Trade Before the Tariffs," *The Economist*, January 8, 2000, p. 83.

[268] Ibid.

[269] Kevin H. O'Rourke and Jeffrey G. Williamson, *Globalization and History: The Evolution of a Nineteenth Atlantic Economy* (Cambridge, MA: The MIT Press, 1999), p. 287.

that its pursuit would be disastrous to victors and vanquished alike, thereby rendering wars between the great powers irrational and self-destructive.[270]

Having noted that continuing economic globalization is not inevitable, what might an increasingly privatized global commons in near-earth space be like, and what might its emergence imply for US military power in coming decades? A Defense Science Board task force chaired by Donald Hicks began exploring these questions in the fall of 1998. The task force's views on the commercialization of orbital space included the following judgments:[271]

- The next 10–15 years will see the emergence of a worldwide commercial space industry with annual revenues of "several hundred billion dollars."
- LEO and MEO telecommunications satellite constellations "will provide reliable wide band internet access to the most remote parts of the globe," and the surveillance satellite market "will evolve fairly rapidly with four or five suppliers providing visible, multi-spectral and SAR images of one meter or better quality to commercial customers as well as military customers of many smaller nations."
- The Defense Department will either find ways to deliver positioning and timing information worldwide "without threat of interruption" or alternatives will be "provided by commercial enterprises," with the result that GPS or similar systems "will give potential enemies unprecedented and relatively cheap weapons targeting capability."
- Point-to-point and broadcast satellite communications, as well as substantial low-resolution space surveillance, "will be available to all at a reasonable price and will be most reliable and uninterruptable because of the very large multinational assets involved."
- The US military "will not be a large and important customer" for commercial satellite services.
- "Using space will become a legitimate and uncontestable means of gathering information," if not of transmitting it as well.
- Although distributed constellations will render most space communications relatively invulnerable to individual satellite attack, "except for an all-out nuclear or space war," comparatively small nuclear detonations at the right altitudes could "create enough trapped radiation [in the Van Allen Belts] to greatly curtail the lifetime[s]" of commercial satellites.

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[270] Kennedy, *The Rise and Fall of the Great Powers*, p. 537; also, John Mueller, *Retreat from Doomsday: The Obsolescence of Major War* (Basic Books, 1990), pp. 27–29, 33, and 50. As Kennedy has observed, Angell's book *The Great Illusion: A Study of the Relation of Military Power to National Advantage* was an international bestseller at the same time European general staffs were quietly finalizing their war plans (*The Rise and Fall of the Great Powers*, p. 537).

[271] Hicks, *Final Report of the Defense Science Board Task Force on Globalization and Security*, pp. 95–96. Reportedly, the main member of this task force behind the forecasts on the future directions of commercial space was Michael I. Yarymovych, who chaired the *New World Vistas* space-applications panel.

These judgments all appear to be sensible extrapolations of now-visible trends in the development and exploitation of near-earth space for both commercial purposes as well as military ends. Only one caution need be added. Even if the relative trends described are all borne out, they do not necessarily argue that space will soon become an economic or military center of gravity for the United States or any other nation. The earlier discussion of comsat market share for long-haul communications relative to the explosive growth of terrestrial fiber-optics offers important context for these DSB conclusions.

Still, taken together, the DSB's conclusions imply that the margin of advantage the US military currently enjoys, based on near-exclusive access to space systems, will be less in 2015 or 2020 than it is today. To be more precise, space systems and capabilities to which only the United States and a few other developed nations had access during the 1990s will be available to many smaller nations, including prospective American adversaries. In this sense, near-earth space does appear to be on a path toward becoming a global commons over the next couple decades, and continued movement down this path does suggest a lessening US advantage in terms of raw access. Again, it is likely that over the next quarter century the American military will find itself conducting military operations against opponents with initial access to space communications, if not to some real-time imaging systems.

However, some major uncertainties remain. The 1998 DSB judgments just summarized are agnostic as to whether weapons and direct-military competition will move from the earth to orbital space over the next couple decades. Also unmentioned and undiscussed by the task force is the extent to which prospective American adversaries will be successful in converting greater access to space services and capabilities into tactical, operational and strategic advantages in future conflicts. Having satellite imagery is one thing; possessing the command and control, connectivity, trained personnel (including operationally savvy analysts), doctrine, procedures, and organizational arrangements to be able to exploit that imagery in real time for ongoing military operations is quite another. American experience during Operation Allied Force in 1999 suggests that even the US military has a long way to go in many, if not all, of these areas. The underlying problems, moreover, are not easily solved by well-established, successful military institutions encumbered by entrenched bureaucracies. The US military struggled off and on with problems such as sensor-to-shooter connectivity throughout the 1990s. The United States has a considerable head start, but it also is encumbered by powerful stakeholders with limited interest in organizational or conceptual transformation. Whether future US adversaries will be similarly encumbered remains to be seen. It is certainly possible, however, that an opponent lacking NASA and four entrenched space commands could approach the problems of exploiting orbital systems for military advantage with less baggage than the US military currently carries.[272]

Before speculating further about the US military's chances of retaining a considerable advantage in terms of being better able than opponents to make timely, focused use of the information and

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[272] Navy Secretary Richard Danzig recently observed in a speech to Navy admirals that the Pentagon is the last genuine communist system, complete with five-year plans and a command economy, run not by market pressures but by directives from the top (Thomas E. Ricks, "Churning the Waters," *The Washington Post*, September 9, 2000, p. A12). As he went on to note, this approach "didn't work for the Soviet Union," and one could suggest that it is unlikely to benefit the US military in the long run.

other capabilities provided by space systems, the question of relative dependence on orbital space will have to be considered. This will be the focus of the next subsection. However, there is one additional implication regarding the likelihood of continued commercialization of near-earth space that warrants mention. Simply put, if commercialization continues, the US military will have less and less say in the design and capabilities of the bulk of the systems in orbit. Iridium offers an instructive case in point. The crews of American nuclear submarines operating at high latitudes, such as the Arctic Ocean, found Iridium to be a wonderfully effective voice-communication system. Prior to Iridium LLC's suspension of service in March 2000, the Defense Department had also established an Iridium gateway in Hawaii for the sole use of the federal government.[273] Given these considerations, it is easy to see why the Defense Department eventually opted to pay a premium to retain Iridium services through the end of 2002.

Growing dependence on commercial systems by American military services argues that Iridium will not be the last instance in which militarily desirable capabilities become hostage to market forces. The Pentagon is devoting some 20 percent of its $2.5 billion annual spending for satellite communications to pay for commercial transponders, and during the 1991 Gulf War the US Air Force purchased more than 100 SPOT images of downtown Baghdad.[274] Needless to say, such use of commercial satellite services is quite different from the Cold War, when national intelligence requirements drove the design and capabilities of most of the systems placed in earth orbit. While the long-term effects of this changed situation are hard to predict, the dominance of market forces does pose a genuine challenge for the cultures that evolved during the Cold War in organizations such as the NRO and those portions of the US Air Force and other Services involved in space.[275] Except for DoD systems funded by Pentagon budgets, the US military will no longer be in the driver's seat in near-earth space. Instead, "market forces—as opposed to military acquisition and procurement practices—will play a far greater role in developing and fielding new technologies critical to military operations."[276]

As a footnote, this concern is not purely theoretical. Indications are that some of the US military services have been considering the possibility of not fielding certain follow-on communications satellites on the premise that any capacity needed in future conflicts will be readily available from commercial firms.[277] The marginalization of the comsat industry by fiber-optics, however, suggests that this assumption may not be supported in the long run by market forces.

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[273] Trimble, "DoD Takes Loss in Stride."

[274] Klotz, *Space, Commerce, and National Security*, pp. 13–14

[275] Currently, military space programs receive over $7 billion annually, and Air Force Space Command gets the largest piece of this funding, more than 90 percent (Theresa Foley, "Space: 20 Years Out," *AIR FORCE Magazine*, February 2000, p. 28).3

[276] Klotz, *Space, Commerce, and National Security*, p. 14.

[277] Colonel David Anhalt, e-mail to Barry Watts , September 11, 2000. The economic concern is not that comsats will disappear. The capacity of the world's telecommunications satellites is still growing. However, over time competitive pressure from fiber optics may push comsats increasingly toward broadcast services. In that event, it is conceivable that there might not be enough of the right kind of commercial satellite communications readily available for use by the US expeditionary forces.

A KEY ASYMMETRY

> Improvements in information and systems integration technologies will also significantly impact future military operations by providing decision makers with accurate information in a timely manner. Information technology will improve the ability to see, prioritize, assign, and assess information. . . . Advances in computer processing, precise global positioning, and telecommunications will provide the capability to determine accurate locations of friendly and enemy force, as well as to collect, process, and distribute relevant information to thousands of locations. Forces harnessing the capabilities potentially available from this system of systems will gain dominant battlespace awareness, an interactive "picture" which will yield much more accurate assessments of friendly and enemy operations within the area of interest.
>
> —*Joint Vision 2010*[278]

Although nearly a decade has passed since the break up of the Soviet Union, the United States remains the one nation on earth with the territory, population, economic strength, military power, technological prowess, and political assertiveness of a global superpower. Even security analysts from the People's Republic of China who have long predicted America's eventual decline relative to China acknowledge America's pre-eminent position in international relations today.[279] Will the United States continue to pursue and exercise its global pre-eminence over the next two or three decades? As a point prediction, the question cannot be answered with certainty. Unquestionably "a strong strain of isolationism has run through this country at least since the end of World War I."[280] Nevertheless, no American president "for the last 50 years, and no serious presidential candidate, now or in prospect, has advocated anything like isolationism"; in fact, neither sitting presidents nor serious candidates have "proposed that this country be anything other than the world's dominant military power . . ."[281] Hence, the most likely course, by far, is that the United States will remain politically and military engaged around the globe over the first quarter of the 21st century—despite the continuing difficulties theorists of international affairs have in specifying, on the basis of general principles, the precise circumstances in which the United States should intervene with military force.[282]

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[278] General John M. Shalikashvili, *Joint Vision 2010* (Washington, DC: Joint Staff, July 1996), p. 13. The term "system of systems" was popularized by Admiral William Owens, then the vice chairman of the Joint Chiefs of Staff; see in particular William A. Owens, "The Emerging System of Systems," *Proceedings*, May 1995, pp. 35–39. Admiral Owens went so far as to argue that the "emerging system-of-systems promises the capacity to use military force without the same risks as before" and even suggests that will enable the American military to "dissipate the 'fog of war.'" (William A. Owens, "System-of-Systems,' *Armed Forces Journal International*, January 1996, p. 47).

[279] Pillsbury, *China Debates the Future Security Environment*, pp. 63–64.

[280] Norman Podhoretz, "Strange Bedfellows: A Guide to the New Foreign-Policy Debates," *Commentary*, December 1999, p. 25.

[281] Eliot A. Cohen in "Air Power—For What?" *Commentary*, January 2000, p. 25.

[282] Regarding the difficulties international relations theorists have specifying when and where the United States should intervene with military force, consider the following candid admission from Norman Podhoretz. "What are the limits that should be set for American intervention? Where, if anywhere, are the lines to be drawn? Are we as a nation willing to pay for the defense capability such a policy requires, and to shed the blood that will be spilled in its implementation? Are we—we, who do not exactly have a brilliant record as exporters of democracy—wise enough and competent enough to bring about the desired result? I freely confess that I too am bothered by this additional list of questions, to which I also freely admit I do not have answers that are even partially satisfactory." (Podhoretz, "Strange Bedfellows," p. 31).

For purposes of advancing this assessment, therefore, it is eminently reasonable to assume that the United States will not withdraw from the world stage between now and 2020–25. In that case, a principal task for the American military will be to project military force over long distances in pursuit of US policy objectives around the world. For the foreseeable future the United States will be in the long-range-power-projection business to a degree neither approached by nor required of any other nation on the planet. American opponents may get by with local or regional military capabilities, but a globally committed United States cannot.

The geographic and strategic circumstances in which the American military will exercise long-range power projection in the early 21st century have, of course, changed from those representative of the Cold War. For one thing, the robust overseas-basing structure that the United States inherited at the end of World War II and, thereafter, manned throughout the decades of containment has been greatly reduced since 1989–91. For example, along with reductions in overseas manpower, aircraft and other equipment, the US Air Force's permanent forward-basing structure has been shrunk by two-thirds over the last decade.[283] Thus, a growing portion of the US military is based in the United States rather than abroad. Inherently this reduction in physical forward presence means that the timely and effective engagement of US military force abroad will depend increasingly on timely and effective long-range power projection.

There has also been change in the American style of war. The United States has come to place unprecedented emphasis on minimizing friendly casualties, collateral damage, civilian casualties, and even enemy casualties. A graphic illustration of American aversion to inflicting avoidable casualties even on enemy forces is evident in the haste with which the 1991 Persian Gulf War was brought to an end after only 100 hours of offensive ground operations, with the result that Saddam Hussein was left in power in Iraq, where he remains to this day.[284] General Colin Powell's eagerness to end the ground offensive after 100 hours appears to have been influenced by press coverage of air attacks along the so-called "Highway of Death" leading north from Kuwait City, which he characterized as having turned into "a shooting gallery for our fliers" that "was starting to make it look as if we were engaged in slaughter for slaughter's sake."[285] Whether this interpretation is completely accurate or not, General Powell's successors have increasingly elevated the desire to avoid American casualties to a recurring planning assumption for the employment of US forces abroad. President Clinton's decision to rule out the use of American ground forces at the beginning of Allied Force in 1999 is simply the most recent evidence of this aversion to casualties.[286]

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[283] Lieutenant General G. S. Martin, "Air Operations into the 21st Century," Office of the Assistant Secretary of the Air Force for Acquisition, December 1999, slides 6–7.

[284] The theater commander, the Chairman of the Joint Chiefs of Staff, President George Bush, and his national-security advisor Brent Scowcroft all argued after the fact that there were no serious options between ending the war when they did and a prolonged occupation of Iraq that would have led to the country's break up. See, for example, George Bush and Brent Scowcroft, *A World Transformed* (New York: Alfred A. Knopf, 1998), pp. 488–89. Paul Wolfowitz has disagreed with this view ("Iraqi Rebels with a Cause Rising Up," *The New Republi*c, December 7, 1998, p. 12).

[285] Colin L. Powell with Joseph E. Persico, *My American Journey: An Autobiography* (New York: Random House, 1995), p. 520.

[286] "Interview of the President by Dan Rather, CBS," March 31, 1999, White House transcript.

Last but not least, the kind of weaponry and command-and-control systems the US military is currently acquiring manifests a growing, if not unprecedented, dependence on computers and information. The point is not just the obvious one that modern weapon systems contain more computers and software than ever before. Instead, the important insight is that precision weapons require precision information to function as intended. In Allied Force, B-2s were able to deliver up to sixteen GPS-aided munitions from a pair of rotary launchers, one in each bay, containing the wiring to transmit individual target coordinates to each individual weapon prior to release. The Air Force is now considering upgrading the B-2's bomb racks so that the crew could individually target as many as 80 500-pound JDAMs on a single sortie. This modification alone would mean a fivefold increase in the targeting information a B-2 would require on each mission.

Without a doubt, the mounting information requirements of US military forces offer enormous potential for improved performance and effectiveness, as well as for reduced casualties and collateral damage. However, they also entail new vulnerabilities—especially in space. Long-range power projection with increasingly information-intensive forces not only means greater dependence on surveillance and communications systems in near-earth space, but, very possibly, greater relative dependence than that of prospective American adversaries. There is every reason to think that in coming decades, US forces will lean more heavily on space systems to be successful than will their opponents. The power-projection business involves applying force in the opponent's back yard, so to speak. The kind of reachback utilized in Allied Force to develop mensurated target coordinates is critically dependent on space systems.

How fast is American dependence on things such as space communications growing? RAND Corporation research on Desert Storm indicated that US forces used about 100 Mbps (megabits per second) of data-rate capacity, of which about 75 percent was supplied by military satellites.[287] RAND also concluded that in 1991 a "great deal of intelligence information was not electronically transmitted to the theater because of insufficient bandwidth."[288] Estimates of the data rates US forces might need for two major theater wars vary almost an order-of-magnitude from 2.5 to 20 Gbps (gigabits per second, where one gigabit equals 2^{10} or 1,024 megabits), depending on whether integrated-, functional-, or emerging-requirements databases are used.[289] Nonetheless, it appears that American dependence on satellite communications is growing due to such trends as the increasing use of computers on the battlefield at all echelons, growing use of reachback, and the chance that American forces will have to fight in remote regions of the world lacking a modern communications infrastructure.

Adversary dependence on space systems, by contrast, is unlikely to expand as rapidly as the American military's. To execute an anti-access strategy aimed at preventing, for instance, the deployment of substantial American forces into the local region, cellular phones networked through a fiber-optic grid might be more than sufficient—especially if aided by access, even if

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[287] Gonzales, *The Changing Role of the U.S. Military in Space*, p. 18.

[288] Ibid., pp. 19–20.

[289] Ibid., pp. 18–19.

limited—to commercial imagery and American GPS. Further, many foreign entities today are procuring very small aperture terminals (VSATs), which are not only highly mobile but ideal for controlling small, dispersed force elements such as mobile missile launchers.[290] Hence, a key asymmetry—if not the key asymmetry—in the military use of orbital space is that American forces are likely to be far more dependent on full, continuous access than their adversaries.

When coupled with the trends toward increasing commercialization and the emergence of many space services as elements of a global commons, the case for suspecting that the United States will not be able to sustain its current margin of advantage in orbital space seems strengthened. Adversaries may be able to make due with limited or intermittent access to satellite systems whereas, if the United States is to project power anywhere on the globe with extreme precision and discrimination, American forces will need more or less uninterrupted access to the full panoply of available space assets.

This asymmetry suggests two further points. First, rapidly expanding American dependence on information imposes the added burden on the US military of being able to manage the timely processing, analysis, filtering, and focused distribution of mission-critical information through and from orbital space. If the American military services fail to gain control over these processes, they may find themselves drowning in information during future conflicts rather than exploiting it for military advantage. Second, insofar as information assurance is desired, if not necessary, space control seems destined to become more and more of an issue for the United States military when projecting military power overseas. Corrupted targeting information that is taken to be authentic could prove worse than no information at all.

Another complication is that the American military and intelligence communities have very little insight into how future adversaries may choose to compete in space—especially over the long haul. All indications are that the focus of American collection efforts remains on hardware and visible events such as launches rather than on how orbital assets may or may not be utilized. If so, then this orientation suggests a further American vulnerability. Should adversaries seek to exploit near-earth space in ways divergent from those preferred by the American military, the potential dangers are unlikely to be recognized early. Again, competitors could choose to contest US space-derived advantages using largely terrestrial means rather than by placing satellites in orbit that mirror large, expensive American systems.

Ironically, the United States may have greater insight into the thinking about space of friends and allies than it does into the views of prospective enemies. Consider the French. Based on what occurred during Desert Storm, the main French concern about space assets seems to be political rather than operational. French leaders were more worried about having their own imagery sources independent of US systems than in the real-time exploitation of that imagery for operational use on the battlefield. As of this writing, neither the French military, nor those of most NATO countries, have shown much interest developing the people, organizations and other wherewithal needed to exploit space in real time for ongoing military operations. In fact, the impression of US allies during Allied Force seems to have been one of surprise at how much pro-

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[290] Ibid., p. 13.

gress the United States had made since Desert Storm in being able to gain operational advantages from the exploitation of overhead systems. Nor can one readily point to any other country, with the possible exception of Soviet Russia, which has made space assets serve the needs of the warfighter to the degree that the American military managed to do so during the 1990s. Again, the United States has a long way to go in making space serve terrestrial warfighters—particularly in the area of preparing military leaders to plan to use orbital assets. However, the fact that the United States has more than a decade head start suggests that the American lead in the military use of space may persist longer than indicated by the asymmetry between the United States and other nations in their inherent dependence on orbital systems.

> It's possible to make senior military rank without having a clue as to what these [space] systems are. . . . I impress upon [the service chiefs] the need to organize, train and equip to use this stuff if they're going to rely on it, and not just call up the NRO and say, 'Can you do this for us?' when we're engaged in an operation.[291]

A curious consequence, however, is that American adversaries may have great difficulty accurately assessing evolving US capabilities to utilize space for military advantage. If the actual margin of US advantage rests more and more on the analytic skills, information-system architectures, real-time command and control, trained personnel, and organizational arrangements needed to capitalize on the information provided by orbital systems—especially to improve the situation awareness and decisions of US warfighters—then those outside the American system may have precious little insight into actual American capabilities.

SPACE SURVEILLANCE, GEODETIC DATA AND GLOBAL SURVEILLANCE

> Space surveillance—the ability to detect, identify, track, and predict the position of space objects—is an essential element of space control. Space surveillance is a required ingredient for providing situation awareness of the space environment, identifying friendly and hostile space systems, and predicting when potentially hostile space systems will overfly an area of operations or interest.
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> —Daniel Gonzales, RAND, 1999[292]

The term "space surveillance" can be used in two senses: the detection, identification and tracking of objects *in* near-earth space, which is the more common usage; and, the monitoring of things in the earth's atmosphere and on its surface *from* orbital space, including the use of military and commercial satellites. Capabilities for surveillance of the earth from orbit have evolved considerably since the early Corona satellites first returned images of the Soviet Union via a film-return system. Today's EO imaging satellites not only have much greater resolution, but can return digital data to ground stations in real time. Over the last couple decades, American capa-

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[291] John Donnelley, "NRO Chief: Services Ill-Prepared To Work with Spy Satellites," *Defense Week*, July 12, 1999, p. 2. Hall's comments were made, of course, in the wake of Operation Allied Force.

[292] Gonzales, *The Changing Role of the U.S. Military in Space*, p. 45.

bilities for the terrestrial surveillance of objects in space have not undergone comparable improvements, nor the degree of commercialization evident in comparing the early Corona photographic satellites to Space Imaging's Ikonos.

Currently space surveillance in the first sense—finding and tracking objects in orbital space—is done from the earth's surface. The United States originally developed a space-surveillance network, employing ground-based radars and optical telescopes, to provide early warning of Soviet ballistic missiles launched over the north pole toward the continental United States.[293] Today, the American Space Surveillance Network (SSN) contains dedicated, contributing and collateral sensors located around the globe, with the contributing and collateral sensors providing support through contractual arrangements.[294] The sensors range from active C-band radars to passive radio-frequency collectors and optical systems. The active radars provide all-weather surveillance, whereas the optical sensors, though less costly to field and operate, require cueing for LEO objects, need clear skies and can only see satellites in sunlight.[295] Currently, the dedicated sensor locations are Maui in Hawaii, Eglin in Florida, Tyngsboro in Massachusetts (the Haystack radar), Feltwell in England, Diego Garcia in the Indian Ocean, and Misawa in Japan.[296] Data from SSN sensors, DSP, and other sources are processed in the Cheyenne Mountain Operations Center located in Colorado Springs, Colorado, and provide real-time information on the space environment around the earth.[297] The system tracks nearly 9,000 objects, of which almost 70 percent are debris. Like the missile-test ranges at Vandenberg and Canaveral, the SSN was established in the early years of the space age, and the majority of the active radars are mechanical trackers.

The American space-surveillance network is superior to that of any other nation. Soviet space surveillance systems have atrophied considerably since the end of the Cold War, and French officials have only gotten to the point of expressing a desire to have their own network, independent of the United States. It is probably fair to say, therefore, that the United States operates the only worldwide network for locating, identifying, and tracking objects throughout the altitude regime shown in Figure 1. Nevertheless, the United States has no SSN sensors in the southern hemisphere and the American system has instantaneous coverage gaps as well.[298]

As already indicated, there are a lot of objects to track in near-earth space. Since Sputnik was orbited in 1957, rockets have lifted more than 20,000 metric tons of material into orbit, of which some 4,500 tons remain; only 5 percent of the material in orbit consists of functioning spacecraft.[299] At LEO altitudes, USSPACECOM can track space debris down to ten centimeters.[300]

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[293] Ibid., pp. 45–46.

[294] US Air Force, *Space Operations*, p. 18.

[295] Gonzales, *The Changing Role of the U.S. Military in Space*, p. 46.

[296] "On the Spacetrack PE and the Space Surveillance Network," Air Staff background paper, January 10, 2000.

[297] The American Space Surveillance Network tracks objects in "near-earth space"—meaning to altitudes of 5,875 kilometers—and in "deep space"—meaning ranges greater than 5,875 kilometers ("On the Spacetrack PE and the Space Surveillance Network," January 10, 2000).

[298] Gonzales, *The Changing Role of the U.S. Military in Space*, p. 47.

[299] Nicholas L. Johnson, "Monitoring and Controlling Debris in Space," *Scientific American*, August 1998, p. 62.

[300] *New World Vistas*, Yarymovych, *Space Applications Volume*, p. 55.

The majority of the operational and break-up debris from satellites and rockets, all the solid-rocket-motor slag particles, and most paint flakes are smaller than 10 centimeters, which means they cannot be tracked by USSPACECOM. The greatest source of debris larger than 0.1 millimeters is, by far, the breakup of satellites and rockets. Keeping track of this sort of debris is difficult because, over a period of about nine months, slight asymmetries in the earth's gravitational field will disperse the debris pieces from a given source into "essentially random orbits."[301] Hence, US space-surveillance capabilities probably need to be upgraded just to deal with the growing debris problem. Paint chips are capable of damaging spacecraft at orbital speeds, and radar observations now estimate the number of debris pieces larger than 4 millimeters, the threshold for inflicting serious damage on most spacecraft, to be around 300,000.[302] Even smaller pieces of debris can cause damage. In 1983 a paint flake only 0.2 millimeters (0.008 inches) in diameter made a 4 millimeter (0.16 inches) crater in *Challenger*'s front windshield.[303]

Concerns about debris have led NASA to state a need to track objects as small as one centimeter, an order-of-magnitude smaller than the smallest that the US SSN can track today. Some analysts, however, have argued that modifying existing C-band radars to detect one-centimeter objects would be difficult and costly, while developing X-band radars with the needed power and resolution, also a costly proposition, "could be viewed as a violation of the ABM treaty."[304] Given these considerations, the best solution over the next decade might well be to place a network of optical sensors in orbit to augment aging ground-based radars.[305] Regardless of what solution is chosen, improvements to the aging US SSN seem needed, especially for purposes of space control. "Space surveillance is intimately connected with space control, just as air surveillance is a prerequisite for achieving and maintaining air superiority."[306]

Turning to the surveillance of the earth from orbital space, an important step forward for the employment of precision weapons against terrestrial targets has been the beginning of the precision-elevation mapping of planet earth. In February 2000, the shuttle *Endeavor* conducted an eleven-day radar topography mission that collected 7.8 terabytes of SAR data covering some 80 percent of the earth's landmass.[307] The "plan was to map nearly 80% of the terrain twice to provide a three-dimensional look from two different aspect angles" with a "16 meter absolute vertical height accuracy.[308] While some eighteen months will be required to reduce the data collected by

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[301] Johnson, "Monitoring and Controlling Debris in Space," p. 64.

[302] Ibid. The SAB, however, argued in 1995 that the "likelihood of a piece of debris of any size colliding with an Air Force satellite is so slight that it is apparently appropriate to ignore it and self-shield against the threat" (*New World Vistas*, Yarymovych, *Space Applications Volume*, p. 55).

[303] Sellers, et al., *Understanding Space*, p. 70. Figure 3–14 on page 70 in Sellers is a photograph of the damage.

[304] Gonzales, *The Changing Role of the U.S. Military in Space*, p. 49. Bob Preston notes that satellite-tracking radars have generally been viewed as not being restricted by the ABM treaty.

[305] The idea of optical surveillance from space was suggested by Lieutenant Colonel Thomas Ehrhard.

[306] Gonzales, *The Changing Role of the U.S. Military in Space*, p. 50.

[307] "SRTM Quick Facts," http://www.jpl.nasa.gov/srtm/home_quickfacts.html. The National Imagery and Mapping Agency (NIMA) was one of the sponsors of the radar-topography mission.

[308] Craig Covault, "Shuttle Maps the World, Proves Large Space Structure," *Aviation Week & Space Technology*, February 21, 2000, p. 45; also, http://www.jpl.nasa.gov/srtm/home_quickfacts.html.

Endeavor's crew, the ultimate product will be digitized terrain elevation data (DTED) of unprecedented accuracy.[309]

The data will eventually be made available to scientists, commercial companies and civilian users as well as to the US military. Needless to say, military applications that depend on the accuracy of terrain-elevation data, including mission planning and the targeting of many precision weapons, will be substantially improved by the elevation data collected on this shuttle mission, as will numerous civilian applications ranging from improved maps and city planning to better placement of cellular phone towers. The availability of high-accuracy topographic data is a natural extension of the commercialization trend in optical and radar imagery. However, its availability to businesses, scientists and civilians means that the Pentagon will probably not be the only military beneficiary of improved terrain-elevation data in the long run, and even more accurate elevation data will undoubtedly be collected in the future.

Currently, the main US space-reconnaissance program to improve capabilities for intelligence surveillance of the earth is the Future Imagery Architecture (FIA), which envisions a new generation of imaging satellites, including radar imaging satellites.[310] The developmental program for FIA is estimated at $4.5 billion and the manufacturing of satellites may cost as much as $15 billion through 2012.[311] The main concern about FIA raised by members of Congress has been whether the NRO and the intelligence community will fully fund the ground equipment, software and data links needed to utilize the vast amounts of data the new satellites will collect. Historically, these kinds of satellites have been able to collect far more data than the intelligence community could analyze in time to serve the immediate warfighting needs of theater commanders. Hence, legislators on the congressional intelligence committees have insisted that sufficient investment be made in tasking, processing, exploitation, and dissemination (TPED) to ensure a better balance between collection and exploitation.

While imaging satellites have been operated by the United States since the 1960s, their forte has been so-called strategic reconnaissance, meaning primarily the monitoring of fixed facilities over periods of days, months and years. With the launch of the first KH-11 in late 1976, the latency of images became less of an issue for the United States because the KH-11's images could be downlinked to ground stations in real time.[312] Real-time image return did not, however, solve the problem of sufficient dwell time in the target area for tracking moving targets over periods of hours of days. Today, tactical surveillance of enemy aircraft in a combat theater ashore, or of moving vehicles on the ground, is largely done from airborne sensors—notably the E-3 Airborne Warning and Control System (AWACS) in the case of airborne targets, and the E-8 Joint STARS

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[309] The various levels of DTED data have to do with the density of the elevation points. Prior to the *Endeavor* mission, the best DTED data had a separation of at least 100 meters between adjacent points; STS-99 reduced this distance to 30 meters.

[310] David A. Fulghum and Robert Wall, "Discoverer-2 Goals: Spying, Arms Targeting," *Aviation Week & Space Technology*, May 8, 2000, p. 30.

[311] "Boeing's Spy Satellite Cash Safe—For Now, Lawmakers Say," *Defense Week*, December 6, 1999, p. 3.

[312] According to unclassified, but generally accurate, launch data bases, the first KH-11 was launched from Vandenberg Air Force Base, California, on December 19, 1976 (Mark Wade's Encyclopedia Astronautica, http://www.friends-partners.org/partners/mwade/chrono/19764.htm#1946**).**

in the case of ground targets such as tanks and armored combat vehicles.[313] Starting with *New World Vistas*, there has been renewed interest in migrating these kinds of sensors to orbital space, in part because the US Air Force elected to host both AWACS and Joint STARS on Boeing 707 airframes, which are increasingly costly to man and operate year-in and year-out. The hope is that satellite constellations with advanced radar sensors could provide these same capabilities for far lower operating costs once the up-front investment to develop and deploy the satellites had been made.

The Discoverer II program—jointly sponsored by the Defense Advanced Research Projects Agency (DARPA), the US Air Force, and the NRO—hoped to demonstrate the feasibility of affordable designs for a high-range-resolution (HRR) spaced-based radar capable of providing Ground Moving Target Indicator/Synthetic Aperture Radar (GMTI/SAR).[314] The plan was to orbit two radar satellites to demonstrate the feasibility of moving Joint STARS to space. The program, however, was recently terminated by Congress.

Nevertheless, migrating wide-area air-to-air (AWACS) and air-to-ground (Joint STARS) surveillance of moving targets to space makes eminent sense in the long run. However, there are reasons for suspecting that it may take a couple decades to do so—especially if Bekey's notions about minimal-structure apertures are ignored. Even a 48-satellite Discoverer II constellation using conventional satellite designs would not provide a 24-hours-a-day, 7-days-a-week, staring surveillance system across the earth's entire landmass, much less over the planet's entire surface. In fact, a 24-satellite constellation would have been needed to provide short-revisit-rate coverage of, at most, two areas of operations such as the Kuwait Theater of Operations during the 1991 Persian Gulf War.[315] Besides these limitations, Discoverer II also faced significant economic hurdles. Given the number of satellites envisioned—24 to 48—the program sought to keep the price of each satellite under $100 million which meant an order-of-magnitude reduction in cost compared to many past NRO satellites. The biggest obstacle to achieving the holy grail of space-based radar has always been cost; to get the tracking quality desired the spacecraft had to operate in low orbits, but LEO meant that large numbers of satellites—24 to 48—would be needed for global coverage.[316] In light of these technical and economic challenges it is not surprising that Congress terminated Discoverer II. Even if the program is resurrected in coming years, the fielding of a GMTI/SAR constellation will probably not occur before 2020.

Air-to-air surveillance from space using traditional spacecraft and structures may lie even further in the future because it appears substantially more difficult than GMTI/SAR. For technical reasons having to do with things such as satellite duty cycles and the power-aperture product needed

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[313] *New World Vistas*, McCall and Corder, *Summary Volume*, p. 20; also, Moorman, "The Explosion of Commercial Space and the Implications for National Security," p. 19.

[314] Colonel Mark T. Hughes, "Spaced Based HRR-GMTI/SAR Demonstration Program," presentation, November 5, 1998, slide 14.

[315] A constellation of 24 Discoverer II satellites would provide an interval of about 15 minutes between the appearance of one satellite and the next over a given spot on the earth between 65-degrees north and 65-degrees south latitude (David A. Fulghum, "DARPA Pitches Small Sats for Tactical Reconnaissance, "*Aviation Week & Space Technology*, June 9, 1997, p. 30),

[316] Moorman, "The Explosion of Commercial Space and the Implications for National Security," p. 19.

for space-based radars to achieve AWACS-like performance, a space-based AWACS is "not likely to be affordable" and, regarding a bistatic alternative, the "prospects are not encouraging for the next decade."[317]

The implications suggested by these considerations is that active, all-weather, day-night, staring surveillance of most or all of the earth's landmass from orbital space is unlikely before 2020–25 unless considerable progress is made in substituting information for rigid structure. Granted, DSP and its more ambitious successor, the Spaced-Based Infrared System (SBIRS), do provide staring, wide-area coverage of thermal events such as rocket exhaust plumes rising out of the atmosphere or nuclear detonations. However, these systems are not capable of tracking armored vehicles under dense cloud cover or of providing the kind of imagery American decision makers have come to expect at morning intelligence briefings. Thus, worldwide, continuous surveillance of the earth's surface from space—true global surveillance—probably lies beyond 2025, and prompt or ubiquitous global access from MEO may appear as an intermediate step.

ORBITAL POWER GENERATION, TREATIES AND WEAPONS IN SPACE

In an era of global warming accelerated, if not caused, by the accumulation of greenhouse gases from fossil-fuel consumption in the earth's atmosphere, the idea of converting solar energy to electric power and beaming it to receiving stations on the earth has considerable appeal—especially in the long term. True, the average power density (energy flux across an area) available from the wind or even geo-thermal heat is comparable to that available in space once differences are taken into account such as the fact that winds can blow at night whereas orbital power stations at lower altitudes might spend as much as 40 percent of each orbit in the earth's shadow.[318] Hence, there are terrestrial alternatives to non-polluting, green energy from orbital space, and the most probable outcome over time may well be an evolving mix of non-fossil energy sources. Still, tapping solar energy from orbit has much to recommend it if the technical obstacles can eventually be overcome and economic viability attained.

The technical obstacles alone are daunting. One of them is whether sufficient scale can be achieved. The solar panels on a large satellite such as the 9,600-pound MILSTAR produce some 5,000 watts of power.[319] To run large cities or urban areas, orbital power stations would probably need to approach the megawatt level. Solar-power arrays in the megawatt range would be well beyond anything placed in orbit to date, which means there are, at a minimum, issues of scaling

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[317] *New World Vistas*, McCall and Corder *Summary Volume*, pp. 20–21 and 23. The range at which a radar can detect a target of a given radar cross section increases as the 1/4th power of average transmitted power and the square root of the effective antenna area—George W. Stimson, *Introduction to Airborne Radar* (Mendham, NJ: SciTech Publishing, 1998), pp. 148–49. As a result, the product of transmitted power and antenna area—power-aperture product—is often used as an indicator of radar performance. Suffice it to say, however, that discussions of technically feasible radar performance from LEO altitudes quickly becomes quite technical.

[318] Major General (USAF, ret.) Jasper Welch. Welch is a nuclear physicist who has worked on nuclear-weapon design. He has, on occasion, endeavored to think through the first-order physics of power generation from solar arrays in orbit from first principles.

[319] DoD, *Space Program: Executive Overview for FY1999–2003*, p.18.

to be overcome if traditional solar-panel arrays are used. Another problem megawatt-level power stations in space will face—whether powered by solar cells or nuclear energy—is being able to reject large amounts of heat into space.[320] Ivan Bekey, not surprisingly, has a concept for a lightweight, very-high-capacity heat radiator to deal with this problem. Instead of sheet radiators, he proposes transferring heat to spherical, ferromagnetic dust particles, ejecting them into space where they cool rapidly by radiation, and then collecting the cooled particles for recycling.[321] Bekey also emphasizes that great improvements have been made over the years in the efficiency of solar cells for converting solar energy into electricity. Planar arrays with a single cell type and no concentration achieved only 14–22 percent efficiencies, whereas experiments Bekey commissioned while at NASA with four cell types yielded efficiencies as high as 52 percent.[322] Even if no ways are found to circumvent the theoretical limit to solar-cell efficiency of 60 percent, efficiencies above 50 percent are impressive. By combining his dust-particle radiator with such techniques as magnetically tensioned thin films and a spectrally split, bandgap-matched solar array, Bekey believes that a one-megawatt power module can be developed weighing as little as 2,000 kilograms for a cost of only about $20 million dollars.[323]

This claim is surely optimistic between now and 2025, especially from an economic standpoint. When solar power beamed to the earth from satellites was first proposed in the late 1960s, the concept was deemed “technically feasible,” but economic analysis indicated “only a slight chance” that satellite power stations could be competitive with terrestrially generated electric power.[324] The latest revisit of this issue, done at the request of Congress, was a NASA-formed Independent Economics and Market Analysis Group on Solar Space Power. This group concluded that satellite solar power’s “time in the sun has not yet arrived, and is unlikely to do so within the next two decades.”[325] The main hurdles to be overcome are achieving very low-cost transportation to LEO and a very advanced telerobotics capability. Until both requirements are satisfied, the development, deployment and operating costs will not be competitive with terrestrial power generation.

Even if power generation from orbit lies beyond 2025, there are a few things that can be said on this topic. First, there would still be environmental questions. Can engineers find efficient ways of transmitting heat-energy through the earth’s atmosphere without affecting weather and climate?[326] Second, orbital power stations in the megawatt range could undoubtedly be converted to weapons. Orbital directed-energy weapons able to transfer destructive amounts of energy to targets within the earth’s atmosphere will require precisely the large amounts of power megawatt orbital power stations would supply. Third, power-generation from space sufficient for large cities and urban areas would transform the economic stakes at risk in near-earth space far beyond

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[320] Bekey, *Advanced Space System Concepts and Enabling Technologies for the 2000–2030 Time Period*, pp. 29–30.

[321] Ibid., p. 30.

[322] Ibid., p. 29.

[323] Ibid., p. 30.

[324] Joel S. Greenberg, “Space Solar Power: The Economic Realities,” *Aerospace America*, May 2000, p. 42.

[325] Ibid., p. 46. Greenberg was a member of the 1998 working group on solar power from space.

[326] Stern, interview with Watts and Krepinevich, September 2, 1999.

anything that we see today. Granted, pager blackouts throughout the northeast United States are a major inconvenience to people who have grown accustomed to them. Nonetheless, the loss of a pager or cell-phone pales in comparison to energy blackouts across even a portion of developed countries such as the United States. Thus, large-scale energy generation in near-earth space, when it becomes economically competitive, will open up new military possibilities as well as raise the economic stakes for nations there.

Article IV

> . . . Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner.
>
> The Moon and other celestial bodies shall be used by all States Parties to the Treaty exclusively for peaceful purposes. The establishment of military bases, installations and fortifications, the testing of any type of weapons and the conduct of military maneuvers on celestial bodies shall be forbidden. . . .[327]

Turning to weapons in space, the principal questions are two: will treaties and international law prevent their deployment through 2025, and should weapons be deployed, what effects might they exert on the course and outcome of terrestrial conflicts? Regarding treaties and international law, most of the existing prohibitions on sovereign states stem from treaties originally negotiated between the United States and the Soviet Union. The 1967 treaty on the use of outer space and the 1972 ABM treaty contain a number of restrictions, including strictures against:

- national appropriation of outer space, including the moon and other celestial bodies, by claims of sovereignty, by means of use or occupation, or by any other means;

- placing in orbit or on any celestial body weapons of mass destruction;

- establishing military bases, installations or fortifications on the moon or other celestial bodies;

- testing any types of weapons or conducting military maneuvers on the moon or other celestial bodies;

- interfering with “national technical means of verification”;

- deploying space-based “ABM systems or components”; and

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[327] Treaty on Principles Governing the Activity of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, signed in Washington, London and Moscow, January 27, 1967; available at http://www.state.gov/www/global/arms/bureau_ac/treaties_ac.html

- developing new ABM systems "based on other physical principles" than those employed in current systems without first discussing them in accordance with the ABM Treaty's provisions for consultation and amendment.[328]

The outer-space treaty also requires parties to render all possible assistance to astronauts "in the event of accident, distress or emergency landing on the territory" of another party or on the high seas, and gives ownership, control and right of return to the nation launching objects into space or landing them on other celestial bodies. There is a growing body of space and international law dealing with commercial activities and international property rights, and international bodies such as the WRC and ITU are important in preventing interference between communications satellites by allocating frequencies as well as slots on the Clarke Belt.

The emphasis on weapons of mass destruction reflects the historical linkage between intercontinental-nuclear weapons and space systems for the Americans and the Soviets. The prohibition against interfering with national technical means of verification arose from concerns over the stability of the nuclear balance between the two Cold War superpowers. Given this orientation, it may not be surprising that there is no specific prohibition in either the outer space or ABM treaties against placing non-nuclear weapons in orbital space so long as they are not components of ballistic-missile defenses. Missile defenses, whether nuclear or not, clearly run afoul of the ABM treaty. The premise at the time was that limiting effective anti-ballistic missile defenses "would be a substantial factor in curbing the race in strategic offensive arms and would lead to a decrease in the risk of outbreak of war involving nuclear weapons."[329] An additional concern of many in 1972 was that effective ballistic-missile defenses would be technically difficult and prohibitively costly even for the United States.

Are these limitations and restrictions on weapons in space likely to persist through 2025? The Cold War ended in 1991, the threat of a Russian nuclear attack on the United States has receded considerably over the last decade, and the ballistic missiles now of most concern to American decision makers are small numbers in the hands of states such as North Korea, which may also have a few nuclear weapons. Nevertheless, these changes in the international-security environ-

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[328] The ABM treaty is available at:
http://www.state.gov/www/global/arms/bureau_ac/treaties_ac.html.

[329] The quotation is from the preamble to the 1972 Treaty between the United States of America and the Union of Soviet Socialist Republics on the Limitation of Anti-Ballistic Missile Systems. The American hope that limiting missile defenses would convince the Soviets that they did not need to continue deploying ever-larger numbers of more capable strategic-nuclear systems and warheads was not justified by subsequent Soviet behavior. American arms-control theory posited that if national missile defense (NMD) was limited, reductions in Soviet ICBMs would be forthcoming because Soviet missiles would get, as Henry Kissinger put it, a "free ride" to American targets and the Soviets, therefore, could agree to reductions. What happened was quite different. "For the two decades following the ABM Treaty, the Soviet Union pursued a massive buildup of 'destabilizing' ICBMs capable of threatening US strategic deterrent forces. To be specific, the number of such deployed Soviet ICBMs increased from 308 in 1972 to over 650 sixteen years later, with a related increase in the number of Soviet countersilo warheads from roughly 300 to well over 5,000. As a result, US ICBMs became vulnerable to a Soviet pre-emptive strike." (Keith Payne, "Hearing on US National Missile Defense Policy and the Anti-Ballistic Missile Treaty," statement to the House Armed Services Committee, House of Representatives, October 13, 1999, downloaded from http://www.house.gov/hasc/1999schedule.htm#Oct99). Payne's bottom line on this occasion was that "the ABM Treaty was built on arms control and deterrence theories that now can be demonstrated empirically to be mistaken" (ibid.).

ment have not led to any consensus in the United States on abandoning the ABM treaty or other international restrictions on weapons in space. In fact, American discussions with the Russians in January 2000 sought Russian acquiescence to a possible US decision to begin deployment of a limited ABM capability by emphasizing that the system would be restricted to 100 interceptors, only capable of dealing with "a dozen single warhead missiles . . . launched from North Korea or the Near East/Persian Gulf regions," and would "be incapable of threatening Russia's strategic deterrent at the level of START-II or START-III."[330] On the evidence, then, the Clinton Administration has sought to preserve Cold War-era arms-control treaties.

The question, however, is less about the past than the future. Are limitations in treaties and international law on weapons in near-earth space likely to last another quarter century? A precise, point prediction is probably not even worth attempting. Nevertheless, there are a few things that can be said. First, because the treaties in question are between sovereign nations not subject to any higher authority, parties can elect to end compliance. In the name of national interest, the leaders of a country can always choose to set aside or ignore the restrictions against weapons of mass destruction in space, interference with NTM or deploying ABM systems (or components) in space. Second, no nation has found a compelling interest in casting these arms-control agreements aside. The two nations most capable of trying to dominate near-earth space militarily during the Cold War—the United States and the Soviet Union—did not perceive any overriding economic or military reasons for jettisoning an arms-control agreement aimed at lessening the risk of all-out nuclear war. Third, thinking in the United States on this issue may be starting to change. A decade after the Cold War's end, a group containing members from both political parties is raising the radical idea that traditional arms control "simply might not be working anymore."[331] Finally, calculations of the costs and benefits of agreements such as the outer space and ABM treaties could certainly change, as the stakes for various nations in orbital space grow over time. Assuming neither abrupt precipitating event nor gradual slippage toward weaponization, the constraints on space launch alone suggest that national stakes in near-earth space may not grow enough over the next couple of decades for governments to conclude that it is necessary or imperative to begin placing weapons in orbit. It is also unlikely that the economic stakes in near-earth space will increase to the point of compelling nations to do so. Still, as improbable as the deployment of weapons in orbit by 2025 now appears to be, it is impossible to insist that weaponization could not occur by then.

What effects might weapons in space have on the course and outcome of future conflicts, especially terrestrial conflicts? One way to address this question is to consider how the main classes of space weapons might affect terrestrial conflicts, and whether those effects would justify the logistic costs of orbital basing. Using a dichotomy recently suggested by a RAND researcher, there are two main classes of weapons that could be applied in terrestrial conflicts: those "that must deliver significant mass to their targets for destructive effects and weapons that deliver de-

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[330] US State Department, "ABM Treaty 'Talking Points'," January 20, 2000, available at http://www.bullatomsci.org/issues/2000/mj00/treaty_doc.html.

[331] Carla Anne Robbins, "Bipartisan Thinkers Look Past Traditional Arms Control," *The Wall Street Journal*, May 18, 2000, p. 28.

structive energy directly to their targets."[332] Mass-to-target weapons generate destructive effects through the kinetic energy produced by the weapon's mass and velocity—that is, by releasing the stored energy of a warhead (stored chemical energy in the case of nonnuclear warheads). Directed-energy or energy-to-target weapons, by comparison, use particle or electromagnetic beams to transfer destructive energy directly to their targets.[333] Inert projectiles depending strictly on their kinetic energy at impact to inflict target damage illustrate a purely inertial mass-to-target weapon. For such projectiles to achieve hypervelocity damage effects more akin to meteoroids than traditional bombs or bullets, they would either be deorbited from space or delivered by a ballistic missile using a high-loft trajectory. A space-based laser (SBL) is an example of an energy-to-target weapon. In the case of a laser weapon operating in space, energy would be transmitted to the target at the speed of light.

Physical laws entail limitations and costs for both classes of weapons. In the case of mass-to-target weapons, earth-based, reusable, suborbital launch vehicles able to release second-stage weapons at apogee (see Figure 17) may well be a better logistic bargain than space basing when the full burden of maintaining and replenishing a constellation of space-to-earth nonnuclear weapons is taken into account. On the other hand, space basing of kinetic-energy rods would make it difficult for an opponent to detect the deorbiting of these weapons prior to atmospheric reentry, and a constellation of them might be less costly over a period of years on a target or aim-point basis than the full burden of maintaining trained fighter units and then deploying them to an overseas theater for traditional strike operations. Laser weapons based in space face comparable constraints, especially if focused on the boost-phase intercept of ballistic missiles launched from any point on the globe. The main difficulty is that the attacker always has the option to ensure that some warheads leak through the SBL constellation by launching a large enough salvo size at the right time.

Two points should be borne in mind in exploring the military utility of these two classes of weapons. First, whatever one may think of their legal, political, logistic, financial, and technical costs, space-based mass-to-target and energy-to-target weapons are not weapons of mass destruction. They could have military utility in terrestrial conflicts without directly threatening the catastrophic damage inherent in large-scale use of nuclear weapons. Second, any nation contemplating the deployment of weapons in orbit between now and 2025 would have to weigh carefully their military utility against their considerable political, logistic, and other costs. For states without a significant space program, the financial costs alone might be a bridge too far. Further, if roughly the same military affects could be achieved against most targets with terrestrially based weapons such as cruise and ballistic missiles, then it is difficult to perceive compelling incentives for placing nonnuclear weapons in orbit. At the end of the day, it may well be that the military utility of space-based mass-to-target and energy-to-target weapons is rather narrow and of

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[332] Bob Preston suggested this framework and provided much of the detailed information that follows about kinetic-energy rods for attacking terrestrial targets as well as space-based lasers. The detailed information was largely supplied in May and June 2000 over the course of a series of conversations and e-mail exchanges. These conversations and exchanges will henceforth be referenced as Preston, May/June 2000.

[333] Preston, May/June 2000.

greatest benefit to the United States for certain time-critical missions, such as boost-phase ballistic missile defense.[334]

With these two cautions in mind, what kinds of damage might be achieved against terrestrial targets with mass-to-target weapons such as inert rods impacting targets at hyper velocities? Achieving hypervelocity damage effects with inert projectiles is thought to require impact velocities in the neighborhood of 4–6 kilometers/second.[335] A good material for such projectiles is tungsten, which weighs 19.25 metric tons per cubic meter (compared to 7.87 metric tons for iron) and has the high-heat capacity to survive reentry.[336] To achieve the desired impact velocities after transiting the atmosphere, the projectiles themselves must employ long, rod-like shapes, and their impact trajectories would need to be within 30 degrees of the vertical.[337] These constraints limit plausible rod lengths to a meter or two, assuming a patterned laydown by a bundle of 15–20 rods to cover a given aim-point.[338] The prevailing view, based on empirical research on small-scale and homogeneous materials, is that the impact damage hypervelocity rods would inflict on targets will resemble that associated with a shaped charge, with the rod being consumed at the rod-target interface during penetration. On this view of the impact physics, most of the damage would be done in the direction of the rod's trajectory, and the depth of damage would be proportional to the square root of the ratio of projectile density over target density.[339] While 1–2 meter tungsten rods would not be able to reach very deep underground facilities, they could be useful against tall buildings, low buildings containing flammable materials, missile silos, large ships (if they do not move too unpredictably or too far during the final 15–20 seconds prior to impact), and hardened aircraft shelters. Soft, area targets such as airfield facilities could be addressed with packets of 100–200 4–5 inch rods per weapon bus.[340] Thus, deeply buried bunkers and fast-moving vehicles such as individual tanks become the main target types not suited to inert, kinetic-energy rods de-orbited or dropped from space.[341]

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[334] Terry Mahon, electronic comments on the penultimate draft of this assessment. Mahon noted that ballistic missiles would be far less provocative than any space-based weapon. However, if evidence surfaced of the pending deployment of space-based weapons by a potential US adversary, that discovery could very well invite a pre-emptive American response.

[335] Preston, May/June 2000. Below 4 kilometers/second, impact dynamics revert to those of ordinary bombs and projectiles. RAND work on these kinds of weapons during the Cold War used impact velocities of 20,000 feet/second (6.096 kilometers/second)—Gerry Sears, telephone conversation with the author, May 30, 2000.

[336] Preston, May/June 2000.

[337] Ibid. The shape for these projectiles is basically an elongation of traditional ballistic-missile reentry vehicles.

[338] Sears, telephone conversation with the author, May 30, 2000. Sears worked on this class of weapon for roughly a decade starting in the late 1970s. He has only felt free to discuss this work openly in light of an unclassified Defense Science Board report that described inert rods delivered from space and impacting at orbital speeds—see *Report of the Defense Science Board Summer Task Force on Joint Operations Superiority in the 21st Century*, vol. 2, *Supporting Reports* (Washington, DC: October 1998), pp. 32–34. For an even earlier open-source discussion of such weapons, see Kenneth Roy, "Ship Killers from Low Earth Orbit," *Proceedings*, October 1997, pp. 40–43.

[339] Bob Preston, e-mail to Barry Watts, May 3, 2000.

[340] Sears, telephone conversation with the author, May 30, 2000. Preston questioned whether rods this small would have the ballistic coefficient to retain hypervelocity after transiting the atmosphere.

[341] Preston, May/June 2000; also, author's telephone conversation with Bob Preston, May 26, 2000. The difficulty with a bunker 100 feet underground is that the rod would probably need to be 50 feet or longer, which would result

An important caveat, however, must be appended to this discussion. As far as the author is aware, the detailed empirical testing required to validate this understanding of the impact dynamics has not been done with 1–2 meter rods made of dense materials such as depleted uranium or tungsten.[342] Thus, there is empirical uncertainty about how they would really affect various targets.

Orbital basing of inert, kinetic-energy rods raises issues concerning response times and accessible impact areas on the earth's surface. The principal basing variables are altitude, circular versus elliptical orbits, target urgency relative to the average delay before some orbiting weapons move into position relative to the targets, and the expected numbers of targets. The lower the altitude, the shorter the response time from orbit (from several hours to as little as 12 minutes). On the other hand, higher altitudes yield larger reachable footprints on the earth's surface from any position along the orbit.[343] Elliptical orbits orientated toward the northern hemisphere permit fewer satellites to provide target coverage throughout most of the hemisphere, but two elliptical deployments orientated toward the northern and southern hemispheres, respectively, would have difficulty covering targets along the earth's equator. Time urgency and the number of aim-points to be covered during a single orbit would drive the numbers and types of rod buses needed for an adequate constellation.

The implication of these considerations is that inert-rod weapons have both advantages and disadvantages. Advantages include: access to the target without political constraints on overflight or passage; the reach to engage targets around the globe in comparatively short periods of time (nominally 30 minutes to a few hours); the impossibility of defending against inert projectiles transiting the atmosphere at velocities of 4–6 kilometers/second; and the difficulties of detecting the deorbiting of individual buses until very late in the drop sequence.[344] However, there is a logistic-transportation price to be paid for orbital basing of 3–5 kilometers/second, which is comparable to that required to deliver kinetic-energy rods from short-to-medium range ballistic missiles on high-loft trajectories.[345] Whether this cost exceeds the full costs of covering the same targets with fighter-bombers operating from in-theater bases after overseas deployment is, as has already been suggested, a question that undoubtedly merits analysis.[346] Whatever the answer, the technology required is available to any country that has developed intercontinental ballistic missiles and spacecraft. In fact, actual tests of rod-penetrators conducted by the US Navy in 1993 demonstrated the feasibility of reentry for long, metal rods, as well as the feasibility of GPS-

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in a single rod weighing a couple metric tons. Preston's recent analysis of these weapons focused on a 1-meter rod weighing around 100 kilograms (ibid.).

[342] The 1998 Defense Science Board report on *Joint Operations Superiority in the 21st Century* identified impact phenomenology for target damage as an enabling technology (Vol. 2, p. 32).

[343] Sears' work favored elliptical orbits with apogees as high as 40,000 miles. Orbits this high yielded drop times up to eight hours but provided footprint coverage spanning whole continents. Preston prefers lower-altitude orbits to achieve shorter drop times.

[344] Preston, May/June 2000. An object reentering from LEO initially has a velocity of some 8 kilometers/second (Sellers, et al., *Understanding Space*, p. 336). By keeping the trajectory steep (at least 60 degrees) and using long, slender, conical-shaped rods, more than half of that velocity can be retained to impact.

[345] Preston, May/June 2000.

[346] Sears, telephone conversation with the author, May 30, 2000.

guidance prior to the weapon reentering the atmosphere and becoming engulfed in a plasma sheet that blocks electromagnetic transmissions.[347]

Given the US need to deploy its military around the globe on relatively short notice, the ever-present possibility of strategic surprise, and the decline in American forward-based forces since 1991, a constellation of inert-rod weapons has appeal from a strictly military perspective. How other nations might respond to the deployment of such weapons in earth orbit is another matter, and one can see potential political, as well as economic, advantages to terrestrial basing. Since the demise of Strategic Air Command in 1992, no senior military decision makers in the Department of Defense have pushed for such weapons, whether based in space or on earth. Perhaps the explanation lies in the commitment of the dominant subcultures within the current American military services to attacking targets with manned aircraft delivering traditional explosive munitions.[348] Whatever the reason, mass-to-target, space-based weapons, like ASATs, constitute options the United States has been willing to forego for decades.[349]

Are space-based directed-energy weapons any more attractive than overhead mass-to-target weapons? Directed-energy weapons offer advantages over mass-to-target weapons by freeing one from the burden of moving mass with its associated inertia. These weapons can also produce a range of militarily useful effects other than destroying targets. RF energy, for example, can be used to jam or interfere with communications satellites, or even degrade the electronics of a satellite, gradually enough that the hostile act would be difficult to distinguish from environmental degradations or component failures.

The amount of energy that directed-energy weapons need to deliver at the target depends on the coupling between the weapon's energy and the target.[350] Factors affecting the efficiency of this coupling include the target's materials, configuration and orientation to the beam, as well as the type of energy transmitted. Laser energy interacts with the surface of the target, whereas high-energy particles are able to penetrate somewhat deeper.[351] The material used for the target's skin (aluminum or steel in the case of most ballistic missiles), skin thickness, coatings, any target rotation, the precise aim-point on the target (and, in the case of a missiles, whether it is under thrust

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[347] Robert Holzer and Neil Munro, "US Navy Tests Non-Nuclear Trident: New Ballistic Warhead Targets Buried Bunkers," *Defense News*, November 13–19, 1993, p. 4; Preston, May/June 2000.

[348] Gerry Sears, now retired from RAND, believes that the decision to leave US space forces in the hands of a US Air Force increasingly dominated by fighter pilots was not a wise one, and Senator Bob Smith has been even more outspoken in criticizing the air force's handling of space.

[349] A concern Bob Preston raised is that the potential of inert, kinetic-energy projectiles reentering the atmosphere around 6 kilometers/second (19,685 feet/second) may not be lost on other nations even if the American military remains uninterested. Given the potential lethality of such weapons against pre-positioned ships containing American weaponry and equipment, against US aircraft carriers or even against targets in the continental United States, one can speculate that these weapons might have appeal to prospective US adversaries determined to field the military capabilities for an anti-access strategy designed to keep American military forces from deploying into their backyard. Again, however, developing such weapons would be a major undertaking for most prospective American adversaries, and the benefits would also have to be weighed against likely political and other costs.

[350] Preston, May/June 2000.

[351] Ibid.

or not) can all yield different effects.[352] Applying laser energy to a non-burning stage of a multistage, solid-propellant missile, for instance, may be more like trying to puncture an uninflated tire, whereas the same incident energy might cause catastrophic destruction if applied to a burning stage.[353] In addition, the intensity of directed-energy weapons decreases in proportion to the reciprocal of the square of the range from weapon to target. This rapid decrease in incident energy as range to the target increases tends to drive up the requirements for laser power and constellation size.

The directed-energy application that has received the most funding and research has been the possibility of using laser weapons for ballistic-missile defense. According to most sources, the ability of an individual laser to concentrate energy on a target depends primarily on the size of optics.[354] Another critical parameter in designing a space-based-laser constellation for missile defense, particularly one intended to provide global coverage, is the maximum kill-rate the system could achieve. To determine whether achievable kill-rates come close to satisfying required kill-rates, one has to assume that the adversary would launch missile salvos carefully timed to provide the best chance of overwhelming the SBL constellation.

From a defender's standpoint, the optimum intercept period is during the boost phase of the enemy missiles, while they are under thrust and before payload fractionation or the deployment of penetration aids can occur. The time periods available for boost-phase intercepts, however, are short. A short-range ballistic missile launched against a target 875 kilometers away typically burns out after 85 seconds at an altitude of just over 50 kilometers; an intercontinental missile fired to a range of 7,825 kilometers burns out after 180 seconds at an altitude of almost 250 kilometers.[355] Depending on the frequency of the laser, some of the burn time will be lost because the SBL constellation cannot penetrate to the bottom of the earth's atmosphere.

What level of salvo size can be handled with plausible SBL constellations? A reasonable base case suggested by Bob Preston would consist of 24 SBLs in circular orbits at 1,248 kilometers altitude, four satellites evenly spaced in each of six orbital planes, a megawatt-class laser on each satellite, a target-damage threshold of 10,000 joules per square centimeter, the optics to provide this level of energy over a spot no smaller than 10 centimeters in diameter, and, for the threat, a salvo launch of medium-range ballistic missiles (MRBMs) from North Korea against Guam.[356]

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[352] Lieutenant Colonel William H. Possel, "Lasers and Missile Defense: New Concepts for Space-based and Ground-based Laser Weapon*s*," Center for Strategy and Technology, Air War College, Maxwell AFB, Alabama, July 1998, Occasional Paper No. 5, pp. 12-13. In 1995, the Air Force Scientific Advisory Board estimated that effective engagement of a boost-phase ballistic missile would require about a megajoule of energy from a laser weapon—*New World Vistas: Air and Space Power for the 21st Century*, Major General Donald L. Lamberson (chair, Directed Energy Panel), *Directed Energy Volume* (Washington, DC: USAF SAB, 1995), p. 34.

[353] Preston, May/June 2000.

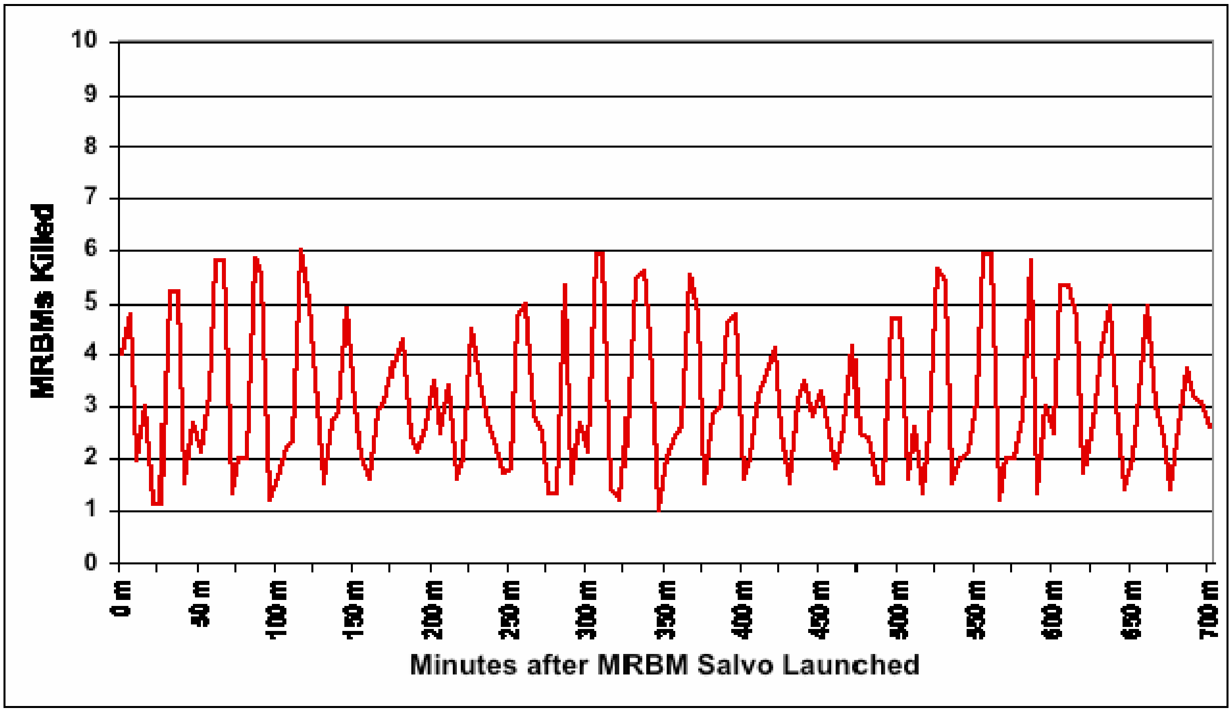
[354] *New World Vistas*, Lamberson, *Directed Energy Volume*, p. 26; also, Preston, May/June 2000.

[355] Preston, May/June 2000.

[356] Ibid. "With its shorter wavelength and therefore smaller optics, the hydrogen fluoride laser is considered a leading contender for the Ballistic Missile Defense Organization's Space-Based Laser program" (Captain William J. McCarthy, USN, "Directed Energy and Fleet Defense: Implications for Naval Warfare," Center for Strategy and Technology, Air War College, Maxwell AFB, Alabama, May 2000, Occasional Paper No. 10, p. 21). A hydrogen fluoride laser operates around 2.7-2.9 microns, wavelengths that are absorbed in the lower portion of the earth's at-

Depending upon the precise timing of the launch relative to the positions of the satellites in the SBL constellation, the number of achievable kills for this base case is 1-6 ballistic missiles.[357] The number of kills achievable varies from minute to minute, with the rapid, short-period variation being driven by the location of the nearest satellite to the launch point in the closest orbital plane, and the long-period variation being driven by the rotation of the earth beneath the six-plane constellation.[358]

Figure 17: Calculated Performance of a 24-Satellite SBL Constellation Against a Salvo of MRBMs from North Korea to Guam



Achieving 1-6 kills against a salvo of relatively hard medium-range ballistic missiles are, needless to say, less than overwhelming. Many SBL proponents would be inclined to argue that this result is simply too conservative. Varying elements of the base-case system—such as altitude and number of SBLs, the power and frequency of the lasers, as well as the range of the threat missiles and their hardness to laser energy—can yield better SBL performance.[359] Intercontinental ballistic missiles, for example, have longer burn times, and, against an ICBM threat, a lower-

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mosphere below 36,000 feet altitude (ibid., pp. 21 and 23-24). TRW's Mid-Infrared Advanced Chemical Laser (MIRACL) is a megawatt-class deuterium fluoride laser. Using the SEA-LITE beam director, MIRACL has destroyed a short-range *Bryant* missile in flight and demonstrated the ability to illuminate satellites on orbit (ibid., p. 21).

[357] Preston, May/June 2000.

[358] Ibid.

[359] Preston commented that the assumed target hardness was toward the upper end of a range that varied hardness levels previously published in unclassified or open sources, and that the aim of the base case was to "illustrate the fundamental characteristics and trends as parameters vary" (electronic comments inserted into a draft of this report, July 19, 2000).

altitude constellation with five times as many satellites might produce 12-18 kills.[360] Focusing on the exact kill numbers from a given constellation against a specific threat salvo, however, misses a broader point about SBL constellations; namely, that opportunities for the attacker to maximize the chances of overwhelming SBL defenses are frequent and, because the SBL satellites move in accordance with orbital mechanics, predictable.[361] Like any static defense, an SBL constellation can be saturated in space and time, and a determined opponent can be expected to evolve the weapons and tactics to do so.

These findings do not mean that an SBL constellation would have little or no military value. They do suggest, though, that the considerable costs of orbiting and maintaining a constellation may not be very attractive unless it is part of a multi-layer ABM system. Consider, for instance, the fact that three kills from the megawatt-class laser postulated in the base case described above against boost-phase missile at a range of 1,700 kilometers would consume 500-700 kilograms of fuel.[362] In light of such logistic constraints, the factors currently weighing against near-term development of space-based-laser weapons include the "high cost, large weight, and relatively few shots available from such systems."[363] In addition, given the limited choice of viable chemical-laser systems, the enemy is likely to know the wavelength and be able to "take passive countermeasures to reduce the optical interaction on the target."[364] When combined with enemy options to use salvo size and launch timing to overwhelm the system, SBL appears relatively costly compared to the limited returns it can now deliver.

How likely are technological advances to make space-based directed-energy weapons feasible by 2020 or 2025? In 1995, the *New World Vistas* volume on directed energy offered the following bottom line:

> SBLs are the ultimate realization of the military dictum "seize the high ground," and have the potential to revolutionize warfare. However, current technology does not support that potential. Breakthrough advances are needed that greatly reduce the cost of launching payloads to orbits and in optics technology that will permit the use of very large aperture beam directors.[365]

While this passage goes on to assert that concepts exist that may provide the needed breakthroughs, the weight of the evidence indicates that SBLs are unlikely for another decade, if not

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[360] Preston, May/June 2000.

[361] Ibid.

[362] Ibid. TRW's Alpha program, a hydrogen fluoride laser selected in late 2000 for the Space-Based Laser Integrated Flight Experiment (SBL-IFX), has demonstrated megawatt power in a low-pressure, simulated space environment (Possel, "Lasers and Missile Defense," p. 16; also "Team SBL-IFX Awarded $97 Million for Next Phase of Space-Based Laser Program," 6 November 2000, http://www.defense-aerospace.com/data/communiques/data/2000Nov3805/).

[363] *New World Vistas*, Yarymovych, *Space Applications Volume*, p. 86. Hydrogen fluoride and deuterium-fluoride lasers consume 2-3 kilograms of fuel per second of operation per megawatt of power generated (Preston, May/June 2000).

[364] *New World Vistas*, Hastings, *Space Technology Volume*, p. 61.

[365] *New World Vistas*, Lamberson, *Directed Energy Volume*, p. 26.

two. The requirement for a breakthrough in space launch is especially troubling, and argues that operational SBLs will probably not be attainable at acceptable costs before 2020, at the earliest.

Bob Preston, currently at RAND, has reached very similar conclusions regarding directed-energy weapons. While a number of nations around the world could use directed-energy devices to cause interference or disruption of satellite systems, generating and directing the more destructive effects from or through space is a stretch even for Americans and Russians.

Currently the greatest technical obstacle appears to be the need for large, deployable optics.[366] Bekey's ideas about very-large-aperture arrays offer one possible solution, although they have yet to be seriously pursued. Progress toward economically feasible, militarily useful directed-energy weapons in space over the next two decades is certainly conceivable. Some progress is not just possible, but likely. Yet, when one factors in political issues, the usual bureaucratic disagreements within the US government, and the fact that much effort will undoubtedly be wasted, it is also quite conceivable that such weapons will not be deployed by 2020 or even 2025.

A DIAGNOSTIC ASSESSMENT

The trends and developments detailed so far suggest many ways in which orbital space could look different in 2020 than it does today, at least on the surface. For example, swarms of smaller satellites with modest sensor and communications capabilities that cooperate to perform a given task not only offer "advantages in scaling, performance, cost, and survivability," but would produce constellations quite different in appearance than those in orbit today.[367] If one adds Hall-effect-thruster propulsion and flywheel technology for power storage, the individual satellites in these functionally distributed arrays would also have considerably more maneuverability and longer lives than satellites using chemical rockets and batteries.[368]

Yet, as significant as these changes are on the surface, they do not suggest any qualitative transformation in satellite functionality or the basic uses made of them by military forces. In fact, one is hard pressed to point to any visible trends or developments mentioned to this juncture that, either individually or collectively, lead inexorably to the conclusion that the military use of near-earth space will be essentially different in 2020 or 2025 than it is today; i.e., focused on the gathering and transmission of information to enhance military operations within the earth's atmosphere. Granted, the US military is likely to grow more and more dependent over time on information gathered by or relayed through space systems, but even greatly increased efficiencies in the processing, correlation and dissemination of such information would not, in themselves,

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[366] Preston, May/June 2000.

[367] *New World Vistas*, Yarymovych, *Space Applications Volume*, p. 123.

[368] For an overview of flywheel technology, see Charles Platt, "Re-energizer," *Wired*, May 2000, pp. 114, 116, 118, 122, 124, 126, 128–30, and 132. The basic idea is that flywheels made of composites and other advanced materials and running at very high revolutions per minute could provide lighter, cheaper, and far longer lasting electric-power storage than traditional batteries. Proponents claim that flywheel power-storage devices could save billions of dollars over the lifetime of the International Space Station if substituted for the current nickel-hydrogen batteries (ibid., p. 122.).

transform the basic military use of orbital assets from force enhancement to force application (broadly interpreted).

One piece of pivotal evidence in this regard is the exponential growth in fiber-optic telecommunications since the early 1990s. While satellite telecommunications capacity is also continuing to grow (albeit at a much slower rate), the crucial point is that terrestrial alternatives to Comsat based on photonics suggest that orbital space is unlikely to acquire the economic importance that maritime commerce acquired during the heyday of the British Empire. The declining trend in launch demand over the next decade, coupled with the likely continuing high costs and risks of space launch, reinforce this conclusion. Despite the conventional wisdom, it is surprisingly difficult to make a persuasive case that orbital space *will* become an economic center of gravity for the United States by 2020 or 2025.

Another important piece of evidence relative to the notion that functionality will not change greatly over the next quarter century is the realization that space-based weapons are unlikely to have anything approaching the impact of nuclear weapons at the outset of the Cold War. A space-based laser constellation could have military utility for the United States, especially for boost-phase intercept of enemy ballistic missiles. However, nonnuclear space-based weapons would not threaten direct or second-order effects on anything approaching the levels of destruction likely to have followed a large-scale US-Soviet nuclear exchange. Moreover, the political, financial and technical costs of space-based weapons are considerable compared to the limited military utility they would offer most nations when weighed against terrestrial alternatives for performing the same missions. Consequently, there is a better than even chance that the basic functionality and military use of systems in near-earth space in 2020–25 will not differ substantially from what it is today.

Given this assessment, will the US military services be able to maintain anything like their current margin of advantage in the exploitation of orbital space relative to prospective adversaries? As has been argued, to the extent that the United States remains in the power-projection business, the American military will be inherently more dependent on space systems than its opponents. True, the American military has a long head-start in the difficult task of learning how to make more timely, more efficient and more effective use of the information provided by space systems for operational purposes—especially in near-real time. Imagery analysis and coordinate-mensuration capabilities, for example, do not generally appear in order-of-battle comparisons of opposing military forces. Yet these are precisely the kinds of capabilities that will be needed to wring the most military advantage from space assets for those nations inclined to adopt an American approach to near-earth space, meaning to field many of the essential space-based capabilities that the US military hopes to exploit to its strategic and operational advantage in future conflicts. In these softer areas of space-based military capabilities—trained operators of space systems, automated imagery processing, data-fusion, analytic capabilities, and near-real-time dissemination—the United States is now, by all indications, well ahead of all other nations, including American allies.

Further, there are not that many nations with the technical expertise to replicate essential US capabilities for the near-real-time exploitation of space systems during terrestrial operations, and many of those that do are American allies. The most credible candidates are China, France, Germany, India, Israel, Italy, Japan, Russia, and the United Kingdom, which is to say that the list is fairly short. An important observation, however, is that several of these nations, as followers, might be able to field some credible, American-style space-based capabilities with much lower total investments than the United States has made over the years. The trick would be to avoid retracing American developmental and organizational paths that added considerable cost and imposed many bureaucratic constraints on US military space efforts.[369] For example, a space shuttle program and three separate service space commands, in addition to a national space command, would not be needed to develop a long-range, precision-strike capability able to utilize targeting data from orbital sensors. Thus, the nations in the list would not necessarily need the gross national product of the United States to be a credible military competitor in orbital space.

Currently, though, there are few indications that any of the nations with the basic technical capacity to compete head-to-head with the United States in advanced military space capabilities is making the long-term financial, developmental and human investments to do so. It is possible, therefore, that the US military could retain, for another decade or two, very close to its current margin of advantage relative to the capabilities of other nations to make sophisticated, American-style use of satellite systems for waging high-technology warfare, particularly over global distances.

The rub, of course, is that potential adversaries may not elect to emulate American approaches to the military use of orbital space. A regional opponent primarily concerned with preventing the United States from projecting its military power into its region of the world could choose to exploit space assets in very different ways than mirroring American capabilities. Some focused capabilities in orbit along with a willingness to combat or negate US advantages derived from space using terrestrial means could very well go far to level the playing field between the United States and a future regional opponent. For example, a redundant fiber-optic network coupled with a few overhead transponders for relaying mobile communications could turn the enemy's in-theater command and control into a system the United States could find nearly impossible to take down. If targeted with data from commercial or military imaging satellites, the system could permit prompt precision-missile strikes against any theater bases and airfields bases being utilized by American forces. This sort of asymmetric response to US power-projection capabilities could be quite effective with only the most limited use of satellite assets, and the trend toward orbital assets becoming a global commons makes denying the enemy access to any commercial satellites a difficult proposition. In such a scenario, the far superior and more sophisticated space capabilities of the US military might yield little overall strategic or operational advantage.

In sum, the odds are that the functionality of orbital space will not change very much by 2025. The predominant military use by all nations, including the United States, is more likely than not to remain force enhancement. And, even if the American military retains a considerable margin of advantage in the sophistication and breadth of its capabilities to exploit space assets, an asymmetric regional competitor might still make long-range power projection a real challenge.

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[369] Bob Preston deserves credit for making this point to me more than once.

This conditional assessment assumes, of course, that there are no abrupt trigger events or hard-to-predict policy changes to prompt one or more nations to begin placing weapons in orbital space, nor any slippery slopes down which nations might gradually arrive at the same end-state. Examining some prospective paths to the weaponization of orbital space by 2025 is the task of the next chapter.

V. WEAPONIZATION, TRIGGER EVENTS, SLIPPERY SLOPES, AND POLICY CHOICES

> It may be in the national interest of the US to develop and deploy capabilities to disrupt, degrade or even destroy the space assets of adversaries with great precision and discrimination while also having the capability to protect US national security and commercial assets by passive and active means. . . . "Owning the high ground" of space is indispensable to the country which leads the world.
>
> —*New World Vistas*, 1995[370]

> The strategic logic of space power says that the greater our motivation to use space for military purposes, the greater must be the motivation of our foes to deny us the ability to use space. . . . [S]pace control cannot be achieved with conventional terrestrial forces, by electronic means, or by hopes and prayers. Space control, indeed space power, requires the deployment of dedicated space forces.
>
> —Colin S. Gray and John B. Shelton, 1999[371]

> Throughout our nation's use of orbital space for national security, the Air Force's warfighting operations have been restricted to atmospheric war fighting. This will change early in the first half of the twenty-first century.
>
> —Lieutenant Colonel Cynthia McKinley, 2000[372]

Compared to the present situation, the most consequential change in the military use of near-earth space that could occur over the next quarter century would be its transition from mainly providing force enhancement for terrestrial combat operations within the atmosphere to becoming an arena of force application in its own right, whether space-to-earth, earth-to-space or space-to-space. The thrust of this chapter is to explore some of the paths by which this transition could occur.

Some have argued that the weaponization of near-earth space occurred long ago—at the time the first nuclear-armed ballistic missiles were deployed. A point usually made is that if nuclear-tipped intercontinental ballistic missiles had been used in anger, they would have transited exo-atmospheric space, and, therefore, should be viewed as opening the door to space weapons even though they were based on land or aboard ballistic-missile submarines. If one accepts this view, the weaponization of near-earth space can be pushed back to September 1944 when the Germans began firing V-2 (or A-4) rockets at targets in England.[373]

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[370] *New World Vistas*, Yarymovych, *Space Applications Volume*, pp. xvii and 48.

[371] Gray and Shelton, "Space Power and the Revolution in Military Affairs: A Glass Half Full?" pp. 30–31 and 36.

[372] Lieutenant Colonel Cynthia A. S. McKinley, "The Guardians of Space: Organizing America's Space Assets for the Twenty-First Century," *Aerospace Power Journal*, Spring 2000, p. 39; available online at www.airpower.maxwell.af.mil/airchronicles/api/apj00/spr00/mckinley.

[373] United States Strategic Bomber Survey, *V- Weapons (Crossbow) Campaign* (Washington, DC: Military Analysis Division, January 1947), 2nd ed. European War (Report #160), p. 7.

This interpretation of when and how the weaponization of orbital space occurred fails on two counts. First, there are no weapons—nuclear or otherwise—based in near-earth space today. To reiterate history previously covered, the two original space-faring nations—the United States and the Soviet Union—reached a consensus early in the Cold War regarding "their common interest in avoiding military conflict and competition in space."[374] One can argue that the development and exploitation of satellite reconnaissance by both superpowers *militarized* near-earth space, but the fact remains that it has not yet been *weaponized* to any appreciable extent. Second, the assumption that the transit of a medium by projectiles is tantamount to weaponization of that medium does not stand up to close examination as an analogy. Once launched, the trajectories of ballistic missiles are governed by the same physical laws that shape the trajectories of artillery rounds after they have cleared gun muzzles. Yet who would seriously contend that aerial warfare began with the artillery revolution of the 15th century because cannonballs transit the aerial medium?[375] Despite their greater range, V-2s and ICBMs seem best understood as extensions of terrestrial artillery, not the dawn of space warfare.

The weaponization of orbital space, then, is a threshold that nation-states and mankind have yet to cross to any appreciable degree. Placing space-to-earth or space-to-space weapons in orbit on either a long-term or permanent basis would obviously cross that threshold. As will become clear, though, there are less obvious ways in which the boundary might be crossed. How, for example, should we think about a ground-based laser able to inflict physical damage on the sensors of a LEO satellite? While the weapon is unquestionably earth-based, it does appear to cross an important threshold with regard to making orbital space an arena for military competition and overt conflict. Among other things, blinding a satellite sensor with a ground-based laser is certainly closer to force application than to force enhancement. However one may be inclined to categorize this particular example, suffice it to say that exploring how and when orbital space may become an arena of military conflict in its own right is currently a legitimate question because the transition still lies in the future.[376]

The thrust of this chapter is to argue that the shift of near-earth space into an arena of overt military competition or actual conflict is both conceivable and possible, even if unlikely before 2025. There are at least two paths by which orbital space might become a battleground for human conflict. One consists of dramatic, hard-to-miss trigger events such as the use of nuclear weapons to attack orbital assets. The other class involves more gradual changes such as a series of small, seemingly innocuous steps over a period of years that would, only in hindsight, be recognized as having crossed the boundary from force enhancement to force application. For reasons stemming from the railroad analogy introduced in Chapter II, the slippery slope of halting, incremental steps toward force application may be the most likely path of the two.

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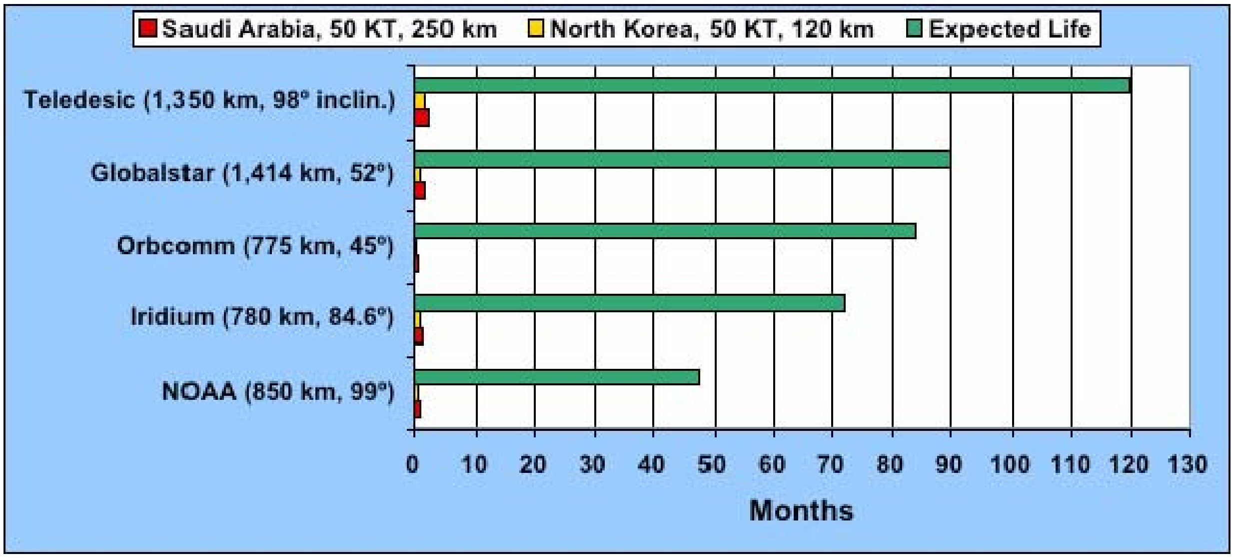
[374] Stares, *The Militarization of Space*, p. 237.

[375] The artillery revolution in early modern Europe is usually dated around 1420–40—Clifford J. Rogers, "Military Revolutions of the Hundred Years War" in *The Military Revolution Debate: Readings on the Military Transformation of Early Modern Europe*, ed. Clifford J. Rogers (Boulder, CO: Westview Press, 1995), p. 64.

[376] This discussion of what is meant by the weaponization of orbital space owes much to the participants in a seminar on space issues hosted by the Office of Net Assessment on June 6, 2000. Bob Preston was especially helpful in challenging me to clarify my usage of terms such as "weaponization" and "militarization."

What kinds of dramatic trigger events might bring about a rapid weaponization of near-earth space? One possibility has already been discussed: the detonation of a nuclear warhead above the earth's atmosphere. Studies by the Defense Threat Reduction Agency (previously the Defense Special Weapons Agency) have concluded that the detonation of a single 50-kiloton nuclear weapon at altitudes of 120–250 kilometers "could destroy billions of dollars worth of low-earth-orbit satellites" due to the increased flux of the charged-particle radiation belts through which the satellites would have to transit during every orbit.[377] Figure 18 shows the estimated reductions in the operational service lives of various LEO satellite constellations for detonations over the Middle East and the Korean peninsula. Reducing, for instance, the service life of a commercial satellite designed to operate 90 months to a mere 0.9–1.6 months does appear tantamount to destroying the satellite, and the damage inflicted applies to entire constellations, not just to individual satellites. Due to the indiscriminate nature of the results, such an attack seems more akin to carpet bombing than precision attack.

Figure 18: Estimated Effects of Low-Yield, High-Altitude Nuclear Detonations on the Service Lives of Selected LEO Satellites



Source: Data from Webb, "Implications of Low–Yield High Altitude Nuclear Detonation," slides 47 and 64.

The argument advanced in Chapter II about this possibility was that the sheer magnitude and global character of the economic damage an exo-atmospheric nuclear detonation would make it unlikely that the United States and other nations would let the perpetrator go unpunished. Put somewhat differently, the argument assumed that even pariah states could generally be deterred from taking such an action so long as their leaders paid attention to the likely costs of punishment compared to the relatively marginal, short-term benefits. There are, however, some additional issues concerning high-altitude nuclear detonations that were not explicitly discussed in Chapter II.

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[377] R. C. Webb, "The Effects of a Nuclear Detonation in Space," Defense Special Weapons Agency, presentation to US Army Space Command, April 1998, slide 25.

The first concerns the chances that a nation with elementary launch and nuclear capabilities might be able to employ a nuclear weapon to pump up the earth's magnetic belts without being identified. Since both the rocket plume from the launcher and the nuclear detonation itself would be within the field of view of DSP (or, later, SBIRS-high) sensors, the chances of a surreptitious launch and detonation seem minimal.[378] The perpetrating nation—or at least the point on the globe from which the launch occurred and fact of the nuclear detonation—would be known to USSPACECOM within minutes.

The second issue concerns whether significant punishment—presumably military action—would, in fact, swiftly and certainly follow such an act. Some have argued that a nation determined to strike a blow against the United States could detonate a nuclear weapon in space and still plausibly deny that it had intended to harm any satellites, much less American ones.[379] If, for example, the guilty nation managed to paint the detonation as an experiment gone awry, it could be difficult for the US government to justify bombing launch and related facilities in the perpetrator's territory.

The view that the United States would be hard-pressed to take such a step—even as billions of dollars worth of satellites began to deteriorate due to repeated transits of pumped-up radiation belts—ignores the context in which the detonation would be embedded. If the context turned out to be peacetime, and the nuclear detonation came out-of-the-blue, one suspects that a US, NATO, United Nations (UN), or coalition military response would not occur overnight. Again, degrading satellites is not the quite same as a sinking a vessel on the high seas with the loss of all aboard. Yet, it is also unclear what advantage the perpetrator could hope to gain, unless its leaders went to war immediately, other than the satisfaction of striking a blow against the global economy in general, and the worldwide telecommunications industry in particular. On the other hand, if the attempt to take down LEO satellite constellations occurred during a military conflict involving the United States, then the barriers to swift military retaliation would presumably be minimal. Thus, the context of such an act matters, and the motivations that might trigger an exo-atmospheric nuclear detonation in the peacetime context in which plausible deniability could have some chance of working are, to say the least, neither clear nor compelling.

To push the contextual issue one further step, however, the preceding comments tended to presume that the nation detonating the exo-atmospheric nuclear device is not a major power such as Russia or China. In the case of a shooting conflict with such states, the incentives to take out the LEO constellations might be different, especially if doing so was seen as conferring significant strategic advantage.

This insistence on context suggests that the exo-atmospheric detonation of a nuclear weapon by other than a major power to degrade, indiscriminately, all but EMP hardened satellites in lower

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[378] The current architecture for the high-altitude component of SBIRS high is four geostationary satellites plus two more in highly elliptical orbits ("Space-Based Infrared System," Air Force fact sheet, available at http://www.laafb.af.mil/SMC/PA/Fact_Sheets/sbirs_fs.htm). SBIRS low is currently envisioned as containing 24 LEO satellites, although the exact number is still to be determined.

[379] John Donnelly, "New Chip To Make Satellites Nuke-Proof," *Defense Week*, December 7, 1998, p. 1.

earth orbits is more remote and more deterrable than one might initially think. That said, the military history of the 20th century also argues that aggression by nation-states cannot always be deterred. One of the major points in Gerhard Weinberg's *A World at Arms* is that Adolf Hitler's aggressive campaigns of conquest could not have been deterred by the Western Allies.[380] More recently, Brent Scowcroft, George Bush's national security advisor during the 1991 Gulf War, has suggested that Saddam Hussein's invasion of Kuwait in August 1990 may likewise have been "unavoidable."[381] Deterrence, in short, can fail.

The third issue concerns the military options available to the United States should some nation, for whatever reasons, attempt an exo-atmospheric nuclear detonation. For the foreseeable future, military options to prevent the catastrophe are extremely limited. If one makes the heroic assumptions that the United States receives timely warning, and that the US government is willing to undertake pre-emptive military action, then destroying the launch site and related facilities prior to launch is a possibility. Nevertheless, it is also a remote possibility at best. From Pearl Harbor to Iraq's invasion of Kuwait and Slobodan Milosevic's wars in the Balkans during the 1990s, the evidence strongly confirms that Roberta Wohlstetter was right when she wrote that "surprise at any time lies in the conditions of human perception and stems from uncertainties so basic that they are not likely to be eliminated."[382] Moreover, American presidents during at least the last half century so consistently saw the use of military force as a measure of last resort—after all other options had been thoroughly exhausted—that force-as-a-last-resort has become an unwritten principle of American foreign policy. Hence, the prospects for successfully averting an exo-atmospheric nuclear detonation through pre-emptive military action must be judged as minimal to non-existent.

What about destroying the rocket or missile after launch but prior to detonation? Again, the prospects for success are not encouraging. To have some chance of success, the United States would need a staring surveillance capability at least as good as the full SBIRS array—both the high- and low-altitude components—as well as on-orbit interceptors or directed-energy weapons able to execute boost-phase attacks around the globe within very short time intervals (perhaps 80 seconds maximum and possibly as little as half that).[383] The most promising candidate for the weapons component of such a system would probably be a constellation of space-based lasers. It would take a very dense constellation of mass-to-target interceptors to be able to meet the stringent time requirements over any point on the globe. The Brilliant Pebbles solution, proposed to provide the initial layer of a ballistic-missile defense against an all-out Soviet nuclear attack, envisioned *thousands* of individual hit-to-kill interceptors in a constellation oriented toward the Soviet missile fields.[384] Even its scaled-down Global Protection Against Limited Strikes

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[380] Gerhard L. Weinberg, *A World at Arms: A Global History of World War II* (Cambridge: Cambridge University Press, 1994), pp. 7, 28–29, 37, 42–43, 46–47, 276, and 270.

[381] Bush and Scowcroft, *A World Transformed*, p. 313.

[382] Roberta Wohlstetter, *Pearl Harbor: Warning and Decision* (Stanford, CA: Stanford University Press, 1962), p. 397.

[383] Preston, May/June 2000.

[384] Donald R. Baucom, telephone conversation with Barry Watts, May 29, 2000. Baucon is currently the Ballistic Missile Defense Organization historian. Brilliant Pebbles became part of the US Strategic Defense Initiative Organization (SDIO) architecture in 1989. The main difference from the previous approach was to fractionate the intercep-

(GPALS) configuration involved hundreds of individual orbiting interceptors oriented toward well-known missile fields. True, salvo size might not be a problem in the case of a rogue state trying to detonate a single high-altitude nuclear weapon. Still, given the short response times available and the likelihood of some seconds being lost for human-in-the-loop decision making, a constellation of SBLs would have a much better chance of responding before the weapon could be detonated. That said, it also seems doubtful that this relatively remote threat could justify the costs of deploying and maintaining a constellation of the size required for global coverage, whether using hit-to-kill interceptors or SBLs for the kill mechanism.

These observations suggest that, for the next 15–20 years, the most sensible stratagem for preventing an exo-atmospheric nuclear detonation is a combination of deterrence and hardening the satellites themselves. Undoubtedly on-board satellite electronics could be hardened against the effects of a nuclear detonation in space, although doing so would impose additional costs.[385] Solar panels able to withstand the effects of greatly increased charged-particle flux are also technically feasible but, again, impose added expense. The immediate obstacles to hardening American commercial comsats, therefore, are not technological but financial. To date, Defense Department officials have been unable to persuade the leaders of American comsat firms to decrease their profit margins by voluntarily hardening their satellites. A National Defense Industrial Association (NDIA) study completed in December 1998 summarized the prevailing attitude within the American space industry by observing that telecommunications firms see “no business basis” for spending money to add protection.[386] Presumably the US government could require hardening of American commercial comsats if the government was willing to foot the added costs. However, no policy decision along these lines has been reached. In addition, due to post-Cold War force reductions and rising commitments of the American military to peace-keeping, peace-enforcement and small-scale contingencies over the last decade, the Pentagon has not been in a position to finance additional protection on commercial satellites. Nonetheless, the chances of a rogue state using a nuclear burst to impose indiscriminate destruction on LEO constellations now appear remote, and the event itself may be deterrable with appropriate declaratory policies and military preparations. Deterring a China or Russia in the context of a major engagement with US forces would, of course, be more difficult.

> We do consider the potential consequences of space becoming a battlefield, but it really doesn’t compare with things like financial risk, or technical risk of pushing the envelope to gain competitive advantage.
>
> We see that commercial guys aren’t going to do anything unless and until their bottom line is affected.

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tors. Prior to Brilliant Pebbles, the SDIO approach was to place ten or so interceptors in a single garage. This meant Soviet ASATs could aspire to take out ten interceptors with one ASAT shot. By giving each interceptor its own garage, ASATs became untenable against the space-based component of the proposed US ABM defense.

[385] Donnelly, “New Chips To Make Satellites Nuke-Proof,” p. 1.

[386] National Defense Industrial Association, “Space Study ‘98,” December 1998, slide 23. The evidence cited by the NDIA study included the results of a May 27, 1998 symposium on “The Future of Space: Protecting Future Equities.” The symposium was sponsored by the CIA, USSPACECOM, the NRO, the National Intelligence Council, and the Office of Net Assessment. It was developed and run by Toffler Associates.

> I think the threat to space assets is overstated . . . the growing dependence of all nations on space makes hostile actions in space a cut-your-own-throat proposition.
>
> It's a culture thing … Your whole reason for being is protection of the country, thinking in terms of reducing or eliminating every possible threat and risk … We think in terms of opportunities and how to maximize them … It's a totally different value system, we have much less problem living with risk.[387]

How might a nuclear detonation above the atmosphere that reduced the service lives of most LEO satellites to the degree indicated in Figure 18 trigger the deployment of weapons in space? In the aftermath of the event, American political leaders might feel compelled to field boost-phase anti-missile capabilities as rapidly as possible to prevent a recurrence. A boost-phase anti-ballistic-missile system, in turn, is unlikely to be feasible without moving sensors and kill-mechanisms to earth-orbit. Consequently, a direct military response aimed at precluding a recurrence could entail fielding weapons in space.

Another event that could trigger the weaponization of near-earth space would be a failure of nuclear deterrence within the atmosphere. The use of a nuclear-armed ballistic missile to devastate a city, whether American or not, or to prevent the projection of American forces into an overseas theater, could change American enthusiasm for ballistic missile defense overnight. Instead of funding protracted research into treaty-constrained, limited defenses, unlikely to be very effective against anything but the most feeble threats, a consensus could coalesce very quickly to develop missile defenses for the United States despite the considerable technical challenges, funding requirements and political costs.

Again, the reason this consensus would be likely to trigger the weaponization of near-earth space stems from the inherent difficulties of terminal-phase, non-nuclear ballistic missile defenses. Terminal defenses involving earth-based sensors and interceptors can, like any static defense, always be overwhelmed by the attacker. In March 1983, when President Ronald Reagan initiated a program of long-term research and development into defenses that "could intercept and destroy strategic ballistic missiles" before they reached American soil or that of US allies, the hope was to work toward multi-layered missile defenses which, as they improved over time, would be able to defeat an increasing portion of an all-out Soviet attack of intercontinental ballistic missiles.[388] The initial deployment of national missile defenses now envisioned by the Ballistic Missile De-

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[387] Toffler Associates, post-symposium write-up, Symposium on "The Future of Space: Protecting Emerging Equities," Chantilly, Virginia, May 27, 1998. The quotes are from space-industry officials who participated in the symposium. Richard Szafranski of Toffler Associates kindly provided the write-up of the conference results as a Microsoft Word file. Among the conclusions reached by Toffler Associates after the symposium was that there was "no consensus among commercial space players that there is any credible threat to space or space assets that would justify overt protective measures by the government" (ibid.). As a participant in the May 1998 conference, the author can confirm that there was no meeting of the minds whatsoever between Pentagon officials and industry representatives on this issue.

[388] As Don Baucom has pointed out, President Ronald Reagan's so-called Star Wars speech neither used the term "shield," nor insisted on the feasibility of a "leak-proof" defense (Ronald Reagan, "Address to the Nation on Defense and National Security," March 23, 1983, available at: http://cnn.com/SPECIALS/cold.war/episodes/22/documents/starwars.speech/).

fense Organization[389] is much more limited. The C1 capability, involving a single site in Alaska, only provides "operational effectiveness against a limited threat comprised of a few re-entry vehicles," and even the C3 capability would be limited to ground-based, terminal-phase, hit-to-kill interceptors.[390] This means that the defense would concentrate exclusively on intercepting incoming warheads in the terminal phase of their trajectories, long after the point at which the attacker could fractionate the payload by deploying multiple reentry vehicles, penetration aids and so forth. Fractionation, therefore, offers an obvious way to confuse and overwhelm a purely terminal-phase missile defense. At a technical level, maneuvering re-entry vehicles can probably defeat any existing American program for theater or national missile defenses.[391]

How might these shortcomings of terminal-only missile defenses be remedied? Again, if the solution is to be sought through military means, then the logical answer is to move anti-missile targeting sensors and weapons into orbital space as part of a multi-layered defense able to intercept enemy missiles during the boost and mid-course phases of their trajectories as well as during the endgame. In the judgment of retired Air Force general Thomas Moorman, "the most effective and efficient way to defend the United States from missile attack would utilize a space-based system."[392]

A multi-layered missile defense with orbital interceptors would not, of course, comply with existing treaties on anti-ballistic missile defenses or the use of outer space. Such a system would also be likely to entail an inherent anti-satellite capability. However, it is conceivable that television coverage of the aftermath of a city struck by a nuclear-armed ballistic missile could so alter public attitudes on these matters in the United States that movement toward the deployment of US defensive weapons in near-earth space would begin forthwith.

This observation assigns no probability to the trigger event at issue. Instead, the point is simply to insist that the future employment of a nuclear weapon against a terrestrial target using a ballistic-missile delivery vehicle could very well change the American political landscape regarding the weaponization of space as quickly and decisively as the December 7, 1941, Japanese attack on Pearl Harbor galvanized the American people to resist and, eventually, defeat fascism during World War II.[393]

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[389] BMDO is the successor to the Strategic Defense Initiative Organization established by President Reagan.

[390] BMDO, *1998 Report to the Congress on Ballistic Missile Defense*, (Washington, DC: July 1998), p. 38.

[391] Earl W. Rubright, "Existing Theater Missile Defense Capabilities," presentation, 1999, slide 4. At the time, Rubright was the science advisor to US Central Command.

[392] Moorman, "The Explosion of Commercial Space and the Implications for National Security," p. 20.

[393] In the years preceding World War II, the American playwright Robert Ardrey embraced the liberalism of the times, including disbelief in honor, glory and patriotism, as well as acceptance of the pacifist sentiment that "wars accomplish nothing"—Robert Ardrey, *The Territorial Imperative: A Personal Inquiry into the Animal Origins of Property and Nations* (New York: Atheneum, 1968), pp. 234–35. Yet, within an hour of learning of the Japanese attack on Pearl Harbor, Ardrey reports that he and his social familiars were voluntarily and spontaneously converted to fervent patriots eager to make whatever sacrifices might be necessary to defend the United States (ibid., pp. 232–233).

A variant of this trigger event would be a crisis between the United States and an opponent willing to threaten nuclear use via ballistic missile against the continental United States, American forces overseas or an American ally. If the US president elected not to undertake the military action or overseas intervention that provoked the nuclear threat, the United States would be perceived as having backed down, thereby undermining the credibility of American security guarantees and US power in general. Insofar as some weaponization of space might come to be seen as a way of regaining American freedom to protect its interests and those of its allies around the globe, it is no difficult to imagine subsequent American decisions aimed at deploying some weapons in orbital space.

While trigger events of these sorts could certainly provoke the United States or other space-faring countries to begin placing weapons in near-earth space within relatively short periods of time, there are more gradual, slippery-slope paths to weaponization. Perhaps the most likely arises from taking the railroad analogy in Chapter II to heart. The fundamental notions underlying this analogy are two: first, orbital mechanics makes satellites more like railroads than aircraft or capital ships; second, the main function of these orbital railroads is to collect and transport information to users on earth, particularly information about enemy forces and capabilities. If this information collection-and-transport use is the main value of satellite systems, then it follows immediately that there are a lot more ways to interrupt space-based or space-dependent information flows than physically destroying satellites. For instance, if an enemy happened to be deriving military information about American force deployments from commercial satellites, an entirely non-lethal solution would be to use diplomatic pressure to cut off the opponent from further information. Other approaches could range from jamming vulnerable segments of the information chain to using terrestrial forces to interdict the satellite ground stations or other nodes through which the information was being routed.

These possibilities have an important implication for our understanding of space warfare. If a terrestrial attack on an adversary’s satellite ground station can deny use of certain space-dependent information, then it is plausible to argue that capabilities for space warfare exist today, even though lethal weapons are not currently deployed in orbital space.

It is not difficult to foresee, then, how nations could begin gradually sliding down a slippery slope toward the weaponization of near-earth space without being fully cognizant of the eventual end state. Over a period of years nations could engage in numerous activities short of outright weaponization that, in the long run, could lead to an environment in which the deployment and use of weapons in or from space would emerge as a logical and natural next step. Consider the following activities:

- using earth-based lasers to dazzle the optical arrays of electro-optical imaging reconnaissance satellites whenever they appear above the horizon;

- active jamming of imaging radar satellites;

- widespread jamming of GPS location and timing information;

- positioning satellites in orbit in close proximity with the satellites of one’s military, economic or political competitors;

- the use of satellites with active, high-power radars to degrade the electronics of adversary satellites; and

- capturing or corrupting the data streams to or from competitors’ satellites.

None of these actions clearly cross the line between force enhancement and force application. However, if the frequency and extent of such activities gradually grew over a period of years, one can imagine the governments of one or more space-faring nations contemplating next steps that could lead to the basing of weapons in space. For instance, if one nation used electromagnetic emissions from its satellite to degrade a competitor’s, one could certainly imagine the victim deploying defensive ASATs to protect its satellites. And, from there, it might seem no more than a small step to begin introducing other weapons into orbit to achieve positive, reliable space control.

Yet another slippery-slope path to the weaponization of orbital space could arise from the strategic logic that the more American economic and military preponderance depends on near-earth space, the greater motivation potential adversaries will have to deny the United States those economic and military advantages. This logic argues that, sooner or later, the United States will have to confront the issue of space control—not just being able to deny the use of near-earth space to adversaries, but fielding the offensive military capabilities to ensure uninterrupted access and use by American forces. Rather than a single trigger event, it is conceivable that a long series of disputes over the use of space systems by and against the United States could lead to a gradual rethinking of longstanding American policies developed during the US-Soviet Cold War. After all, an exo-atmospheric nuclear detonation that pumped up portions of the Van Allen belts would not give the perpetrating nation access to or use of LEO; instead it would deny use to all other countries, starting with the United States. Thus, recurring disputes over locations on the geostationary belt, frequency allocations, space debris, or any number of similar issues involving the commercial use of orbital space could gradually lead the American public and US political leaders to see space commerce as being valuable enough to warrant overt military protection. Again, however, there are terrestrial means for exerting space control and, in any event, the emergence of compelling economic stakes in near-earth space probably lies beyond 2025.

Another gradual path to the weaponization of orbital space could arise from the development of earth-based ASAT weapons by China, Russia, or possibly even some smaller countries. Faced with this threat to the survivability of American satellites in time of war, it is conceivable that US leaders might come to perceive the deployment of weapons in orbital space as a plausible counter or deterrent. Such a perception, even if not especially defensible on careful examination, could push the United States into taking the lead in placing weapons in space for, so to speak, the best of reasons.

One final possibility bears mention: a worst-case scenario in which the United States falls behind an emerging power in the development of military capabilities in orbital space. Today, the prevailing American policy preference is to avoid the deployment of weapons in near-earth space until a serious competitor begins to pose a clear and present danger. This preference, once again, is deeply rooted in Cold War concerns about deterrent stability between US and Soviet intercontinental nuclear arsenals—concerns that have become enshrined in arms-control agreements between Washington and Moscow. Given the momentum these Cold War arrangements have accumulated, it is certainly conceivable that an emerging power might decide to go all-out in developing some essential military capabilities in space while the American policy establishment elects to avoid the provocation of building up US capabilities until the competitor has gained significant areas of advantage.[394]

Although this chapter has certainly not covered every imaginable path to the overt weaponization of orbital space—meaning its transition into an arena of direct military competition and conflict—there are many possibilities, some more plausible than others. These possibilities fall into two classes: relatively dramatic, unmistakable trigger events, and much more gradual, incremental paths. On the whole, slippery-slope paths involving numerous tiny steps toward force application over periods of a decade or more appear to be the most probably route to the eventual deployment of weapons by one or more nations in near-earth space. That said, the trends and developments in Chapter IV did not support the presumption that orbital space will become an economic or military center of gravity for the United States, or any other nation, before 2025. If so, then it is difficult to see the compelling national-security case for any nation, including the United States, to take the lead in placing weapons in orbit.

Conceivable trigger-events and possible slippery slopes not withstanding, the emergence of space-based weapons and combat outside the atmosphere is certainly not inevitable over the next quarter century.[395] The development of terrestrially based ASAT weapons by some potential American adversaries is a distinct possibility, but whether further weaponization of near-earth space occurs is very likely to be at the discretion of the United States.

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[394] This worst-case scenario is the one that most worries Bruno Augenstein.

[395] This final paragraph was suggested by Terry Mahon.

VI. IMPLICATIONS AND OBSERVATIONS

> . . . there is no reason to believe, as [Konstantin] Tsiolkovsky did, that space colonies would be free of greed, envy, politics, and war.
>
> —Walter McDougall, 1985[396]

> The current condition of the world . . . where war among major powers is hard to conceive because one of them has overwhelming military superiority and no wish to expand, will not last.
>
> —Donald Kagan, 1995[397]

> Unrestricted use of space has become a major strategic interest of the United States.
>
> —National Defense Panel, 1997[398]

> Space . . . is increasingly at the center of our national and economic security. . . . [S]pace is not just a military, but also an economic center of gravity, and unarguably, a vital national interest.
>
> —General Richard Myers, 1999[399]

> Now after the Cold War, we see that human spaceflight has not proven to be so dramatic after all. . . . [T]he biggest reason why so few promises have been fulfilled is that we are still blasting people and things into orbit with updated versions of 1940s German technology.
>
> —Walter McDougall, 1997[400]

> If the Air Force can not embrace space power, we in Congress will drag them there kicking and screaming as necessary or perhaps set up an entirely new service.
>
> —Senator Bob Smith, 2000[401]

One of the first points made in the introduction was that the overriding aim of this assessment is diagnostic rather than prescriptive. The intent from the outset was to describe how the current and projected capabilities of the United States to exploit near-earth space for military ends stack up against those of prospective competitors through 2020–25. The approach employed was the comparative, scanning-the-environment style of analysis that Andrew W. Marshall has pursued over the last quarter century. As should be evident, this approach emphasizes the understanding of each competitor's goals, as well as the differences in how various competitors view the com-

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[396] McDougall, *. . . the Heavens and the Earth*, p. 451.

[397] Donald Kagan, *On the Origins of War and the Preservation of Peace* (New York: Anchor Books Doubleday, 1995), p. 568.

[398] National Defense Panel, *Transforming Defense: National Security in the 21st Century* (Arlington, VA: National Defense Panel, December 1997), p. 38.

[399] General Richard B. Myers, "Implementing Our Vision for Space Control," address to the US Space Foundation, Colorado Springs, April 7, 1999; available at http://www.spacecom.af.mil/usspace/speech15.htm.

[400] McDougall, *. . . the Heavens and the Earth*, p. xvii.

[401] Linda de France, "Sen. Smith Lambastes AF Lack of Support for Space Power," *Aerospace Daily*, May 15, 2000, p. 245.

petition, trends, asymmetries, and potential trigger events or slippery slopes that could fundamentally change the nature of the competition.

Much of the introduction was devoted to providing enough context for the intended meaning of the key judgments to be accessible. With the supporting evidence and detail now in hand, these judgments can be reiterated as follows:

- At the dawn of the 21st century, the preeminent user of near-earth space for military purposes is the United States, and the preeminent American use of space is to support operations by traditional air, sea and land forces within the earth's atmosphere. For the United States, the military value of orbital systems rests almost exclusively in force enhancement rather than force application broadly construed.

- The United States is currently far ahead of any other nation in the capability to exploit orbital systems for the enhancement of terrestrial military operations. However, American requirements for global power projection argue that the United States is also more dependent on space systems than other countries, and future opponents may be able to offset many of the advantages the American military derives from space without a major space program—that is, through space control by largely terrestrial means.

- The 1990s were a period of transformation in *how* the American military uses space systems to support terrestrial military operations. Whereas US space efforts had concentrated on the *pre-conflict* aspects of central nuclear war and the military competition in Central Europe during 1957–91, over the last decade the US military has sought to redirect its space efforts toward the *real-time* enhancement of ongoing, nonnuclear military operations within the earth's atmosphere. The Russians, by contrast, have moved in the opposite direction over the last decade.

- While the American military is currently far ahead of other militaries in the ability to exploit information from space systems during current operations, even the United States has probably realized no more than a small fraction of space's potential for force enhancement. Indeed, reflection on the limited progress in better exploiting national space assets over the last 15–20 years suggests that the United States may be more encumbered by organizational constraints and legacy approaches in this area than some of its potential competitors.

- The near-monopoly on access to advanced orbital systems and capabilities that the US and Soviet governments enjoyed during the Cold War is rapidly coming to an end, and the large margin of relative military advantage access has given the United States in particular is likely to grow harder to sustain in the years ahead. Access alone, however, seems less likely to be the key to deriving military advantage from space systems in coming decades than the capacity to make timely, focused, effective use of information gained through, or derived from, orbital systems. Moreover, the critical issue is not whether the US military can make more advanced or sophisticated use of orbital assets than can its future military opponents, but whether American advantages in the exploitation of near-earth space give rise to commensurate strategic and operational advantages in future conflicts.

- There is a better-than-even chance that the predominant military use of near-earth space will remain force enhancement through 2020–25 rather than becoming an arena of overt military competition, much less an actual battleground. The presumption that orbital space will become an economic or military center of gravity for the United States, or any other nation, before 2025 is not supported by the now-visible trends and asymmetries in the development of near-earth space.

- Yet, it is not difficult to imagine trigger events, as well as more gradual paths, that could prompt an earlier-than-expected transition of near-earth space from a force-enhancement to a force-application role. Indeed, if force application is construed broadly enough to include terrestrial-based applications of military force aimed at affecting orbital systems or their use, one can argue that space warfare has already arrived even though no space-based weapons are currently deployed.

- The strategic logic of space power argues that weapons will one day be based in near-earth space because nations will eventually feel compelled to defend their strategic interests there by fielding military capabilities to control orbital space. The odds are that this logic will not drive nations, including the United States, to deploy weapons in orbital space by 2025.

It should be apparent by now that these judgments do not constitute a complete assessment of evolving military competition in near-earth space—especially over the next quarter century. For example, the point that the United States is far ahead of any other nation in the exploitation of space assets to enhance terrestrial military operations by no means establishes that the American military has managed to tap anywhere near the full potential of orbital systems to enhance force application within the atmosphere. Nor does it address the possibility that a regional opponent might be able to negate many of the advantages the US military plans to derive from orbital space with modest resources and relatively limited capabilities outside the atmosphere compared to those enjoyed by the American space community. To fill in the main linkages and connections required to justify these global findings, a number of additional observations are needed.

- The inherent difficulties, high costs and considerable risks of getting payloads to low-earth orbit represent a constraint not likely to be overcome by 2020, although emphasis on fully reusable, two-stage-to-orbit launch vehicles would certainly be an improvement over the Shuttle and EELV. Nonetheless, cheap, reliable access to orbit is an overarching constraint on what can be done in near-earth space today, and access will probably remain a major constraint for another decade or longer. Neither breakthrough launch technologies nor growth in launch demand are foreseeable in the next ten to fifteen years. As a result, economically viable power-generation from orbit, truly global, staring surveillance and space-based-laser weapons are all constrained as practical ventures by the high risks and costs of space launch.

- Increasing commercialization of near-earth space plus likely growth in satellite functionality and value, increasing miniaturization and the possibility of moving from large, full-function satellites to swarms with distributed functionality, provide ample grounds for seeing orbital space become a global commons rather than the elusive preserve of a handful of space-faring nations and consortia over the next decade or two.

- The increasing commercialization of orbital systems also means that the test of the marketplace will play a greater and greater role over time in determining what systems and capabilities are available to all in the orbital global commons, especially in comparison with the preferences of the US military services, the Pentagon's acquisition system and the resource-starved Russian military. For the Defense Department, economic profitability is a very different filtering criterion than those that guided the choice of space systems during most of the Cold War.

- The commercial availability of one-meter-resolution imagery has already enabled organizations to attempt to influence American policy using space systems. This trend will accelerate as commercial radar- and hyper-spectral sensing systems come online. Whether the increased transparency across international borders will have a positive effect overall remains to be seen, but it is unlikely that governments will be successful in restricting or controlling these new eyes in the sky.

- Before 2020, the chances are high that the US military will find itself conducting combat operations against an opponent with access to high-resolution imagery, GPS and other space services during at least the opening phases of the conflict, if not longer. Especially in cases in which the United States has to project power overseas and fight in the opponent's backyard, what the enemy might require from space to execute a relatively successful anti-access strategy could be considerably less than what American forces will need to overcome that strategy. In this sense, American military forces seem certain to be far more dependent than their adversaries on such things as broadband, and uninterrupted access to space systems, while low-tech, terrestrial counters to sophisticated US space systems are not only conceivable but likely. In fact, some fairly effective ground-based counters to American reconnaissance satellites have been played by Red Teams in recent US space war games.

- Favoring American retention of its current margin of advantage is the fact that access to space systems may count much less than the analytic skills, information-system architectures, real-time command and control, trained personnel, and organizational arrangements needed to capitalize on the information provided by orbital systems. In these areas, the American military may have a decade-plus head start. However, the US military is also encumbered by a lot of institutional baggage and legacy systems that make unfettered exploitation of near-earth space extremely difficult to implement on a routine basis.

- Additionally, the United States has little insight into how prospective opponents may attempt to exploit space systems to gain military advantages or to further their own strategic aims in future conflicts.

- Continuous or staring, all-weather, truly global surveillance of the earth's surface seems doubtful before 2020. However, a constellation capable of ubiquitous global access with rapid revisit is possible within this time frame.

- Weapons such as inert, tungsten rods impacting terrestrial targets around six kilometers/second could offer utility in future conflicts, although similar effects on comparable time lines could probably be achieved with suborbital vehicles dispersing boosted weapons at apogee. Space-based lasers able to achieve the more destructive effects envisioned by enthusiasts probably require substantial technical advances in optics. Applied to boost-phase missile defense, SBLs are vulnerable to leakage when confronted with large-enough salvos, and fuel replenishment on-orbit would impose a heavy logistic burden given current and foreseeable launch costs. As with truly staring global surveillance of the earth's entire surface, it is far from clear that SBL constellations will appear by 2020 or even 2025.

- Space-based weapons, though, do have military utility in terrestrial conflicts and, unlike thermonuclear weapons, they do not threaten destruction so widespread that the victors will be indistinguishable from the losers of a conflict in which they are employed.

- While many paths to the weaponization of near-earth space by 2025 are conceivable, a path often played in American war games during the late 1990s has been the detonation of an exo-atmospheric nuclear weapon to create artificial radiation belts at LEO altitudes. This contingency may be more remote and more deterrable than has generally been thought, although the inability of the Defense Department to develop policies and funding for the hardening of commercial satellites is not helping the situation.

- Other paths to the weaponization or orbital space are possible. A somewhat more probable trigger event than an exo-atmospheric nuclear detonation aimed at carpet bombing LEO satellites may be the ballistic-missile delivery of a nuclear weapon against a terrestrial target, ending the hiatus on nuclear use dating back to the atomic bombings of Hiroshima and Nagasaki at the end of World War II. The more likely paths, though, appear to be slippery slope ones in which a long series of provocations, non-destructive acts and other interference with a competitor's access to information produced by, or transported via, orbital systems gradually pushes some nation to the point of judging the deployment of weapons in space as a logical or natural next step in defending its interests.

- Conceivable trigger events and slippery-slope paths not withstanding, the emergence of space-based weapons and combat outside the atmosphere is not inevitable by 2025, and the decision to begin placing weapons in orbital space before then may ultimately be up to the United States.

In closing, three points warrant reiteration. The first concerns the military value of space systems versus mere access to them. The argument about near-earth space becoming a global commons, as a result of growing commercialization and recent American space policy, has to do with access. As has been suggested more than once, sustaining the skilled personnel, command-and-control arrangements, doctrine, operational concepts, and organizations to be able to have the information and connectivity afforded by space access is one thing, whereas the ability to make timely use of them to gain significant advantages in future conflicts is another. In addition, the American military is far ahead of any other nation in fielding, in quantity, weapons such as GPS-aided precision munitions able to capitalize on orbital systems. Not only does the US military have a large lead in these less visible areas, but it may turn out that the most important developments in the military use of orbital space in coming decades will take place mainly on the ground. This possibility presents challenges both to the measures used to assess how the United

States is doing relative to other nations in the military exploitation of near-earth space, as well as to the ability to focus intelligence collection and analysis on the right trends and indicators.

The second point worth repeating one more time concerns the strategic logic of space power. While the more obvious analogies between space power and air or naval power tend to break down when pushed, Gray and Shelton are probably on solid conceptual ground in arguing that, *in the long run*, space control "cannot be achieved with conventional terrestrial forces, by electronic means, or by hopes and prayers." The critical link in their argument, however, is the assumption that near-earth space will be an economic and military center of gravity for the United States in the foreseeable future. Yet it is precisely this assumption that seems open to question—at least between now and 2025.

Third and last, it is difficult to avoid the impression that the US approach to the use of near-earth space is one of dilatory drift, encumbered by the legacies of operational concepts, doctrines and organizational arrangements developed during the long Cold War with the Soviet Union. How else can one explain the difficulties the American military has had since Desert Storm in making the near-real-time, effective exploitation of time-critical information from overhead systems a routine, everyday, 24/7 feature of US operations? Experiments such as Talon Sword, in which targeting data from satellites was delivered to fighter cockpits in less than two minutes, reveal that underlying problems are not technical.[402] Indeed, the problems are no more technological than were the reasons for the Royal Navy's failure to preserve its large early lead in carrier aviation from 1918 to 1939. This observation highlights the possibility that an opponent unencumbered by American legacies in the military use of space could catch up quickly—especially if the adversary nation concentrated on exploiting orbital space to achieve its strategic objectives rather than mirroring American approaches and systems. In short, the core issue is not whether American capabilities for the military exploitation of near-earth space are superior to the opponent's capabilities, but whether US superiority in the exploitation of orbital assets give rise to *commensurate* strategic and operational advantages in the campaigns and wars of the future.

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[402] USSPACECOM unclassified video tape describing the Talon Sword experiments; a copy was provided by James O. Hale, who ran these tests as a US Air Force colonel while assigned to USSPACECOM.

VII. AFTERWORD

Much of the writing on the military use of space by American military officers—particularly those in the US Air Force—concerns the once and future role of space power relative to land power, sea power and air power.[403] Little has been said of such matters in this assessment, and for good reason. Doctrinal debates over the merits of competing forms of military power have little bearing on the sort of diagnostic assessment this report set out to accomplish. That leaders of the American defense establishment have chosen, on grounds of geo-strategic circumstances, Service preferences and proclivities arising from Cold War history, to make US forces increasingly dependent on orbital systems is more a fact about American strategic behavior than a choice to be debated within the bounds of this report. Nevertheless, a few comments seem in order on the role of space systems in modern strategy, where strategy is taken in the Clausewitzian sense of "*the use made of force and the threat of force for the ends of policy*."[404]

The conceptual framework that has run the length and breadth of this assessment has been the dichotomy between force enhancement and force application. Again, "force application" is taken to span the use of lethal or destructive force from, to, or within near-earth space, and "force enhancement" is simply any military use of space systems, including their ground segments, that falls short of force application. On these definitions, space power today is an immature form of military power precisely because it has yet to transition to anything approaching strategic force application in and of itself. Whatever one may think about the future of space power, it has not reached even the "full adolescence" attributed by the US Strategic Bombing Survey to air power in 1945 immediately after the "strategic bombing" of Germany and Japan.[405]

An unmistakable implication of this assessment is that space power may well not reach a comparable stage by 2025. Space-power enthusiasts may not be pleased with this conclusion, but it is where the evidence led. The continuing costs, risks and unreliability of space launch have made the first four decades of the space age diverge sharply from the first four decades of air power with regard to progress toward strategic force application. And a persuasive case has yet to be made that near-earth space has become, or is about to become, an economic or military center of gravity for the United States or any other nation.

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[403] For an excellent compendium of space-power and related issues, see Hays, Smith, Van Tassel, *Spacepower for a New Millennium*. US military officers, however, are not the only ones involved in the debate over space power. See, for example, Senator Bob Smith, "The Challenge of Space Power," *Airpower Journal*, Spring 1999, pp. 32–40. Among the more forward leaning statements in this article, which was adapted from a speech given in November 1998, is the following: "Ultimately—if the Air Force cannot or will not embrace space power and if the Special Operations Command model does not translate—we in Congress will have to establish an entirely new service" (ibid., p. 38).

[404] Gray, *Modern Strategy*, (Oxford: Oxford University Press, 1999) p. 17.

[405] Franklin D'Olier (chairman), *The United States Strategic Bombing Survey: Over-all Report (European War)* (Washington, DC: US Strategic Bombing Survey, September 30, 1945), p. 1. The referenced passage reads in full: "Air power in the last war was in its infancy. Behind the dogfights and hit-and-run tactics there were some glimmerings of the concept of using air power to attack the sustained resources of the enemy, but these bore only a hint of future developments. In this war, air power may be said to have reached a stage of full adolescence."

Yet one feels compelled to append at least one caveat to these observations. As Jeffrey Richelson has written, it may well be that the development of reconnaissance satellites gave both American and Soviet leaders enough knowledge about the other's strategic-nuclear capabilities to enable them to avoid having their Cold War competition erupt into an all-out nuclear exchange that could have ended, if not history, at least human history. Granted, there is no way to prove beyond reasonable doubt that in the absence of photo-reconnaissance satellites, general nuclear war would have occurred. About the most one can claim is that while the possibility of general nuclear war was certainly real during the Cold War, the more one learns about the long-covert role played by national technical means of verification, the more plausible is the claim that they lowered the probability of a large-scale US-Soviet nuclear exchange.[406] Even from this more cautious perspective, it seems defensible to assert that space systems have exerted strategic effects since their advent in the late 1950s, even if they have not yet achieved the level of strategic force application and remain, militarily, in their infancy.

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[406] Gray, however, is probably right to note that "operational crisis stability was always less reliable than policymakers assumed," and that in neither of the US-Soviet nuclear crises of October 1962 and October 1973 "did American policymakers worry as seriously as perhaps they should have done about the possibility that technical or operational instabilities might trigger a war that neither side intended" (*Modern Strategy,* p. 62).

GLOSSARY

ABM	Anti-Ballistic Missile (System to destroy ballistic missiles in flight.)
AIA	Aerospace Industries Association
ASAT	Anti-Satellite
AST	Administrator for Space Transportation
AWACS	Airborne Warning And Control System (The E-3 AWACS provides airborne surveillance and tracking of aerial targets.)
BDA	Battle Damage Assessment
bit	Binary Digit (The smallest unit of information used in a digital computer.)
BMDO	Ballistic Missile Defense Organization (Formerly the Strategic Defense Initiative Office.)
byte	A series of adjacent bits, most commonly 8, used to represent a number or letter.
CA Code	Coarse Acquisition Code (Civilian code for GPS.)
CALCM	Conventional Air-Launched Cruise Missile (A variant of the AGM-86 Air Launched Cruise Missile in which the original nuclear warhead has been replaced by a conventional one.)
CAV	Common Aero Vehicle (A proposed new family of maneuvering reentry vehicles that would dispense nonnuclear weapons.)
CBO	Combined Bomber Offensive (The strategic bombing campaign conducted by the United States and Britain against Germany during 1943–45.)
CEP	(Circular Error Probable) A measure of the probable accuracy of a weapon. A CEP of 10 meters means that 50 percent of the weapons can be expected to impact within a circle of 10-meter radius.
CIA	Central Intelligence Agency
CINC	Commander in Chief (CINCs are in charge of the regional and functional areas of responsibility. They are now referred to as *combatant commanders*.)
CIS	Commonwealth of Independent States

COMINT	Communications Intelligence (Intelligence based on monitoring enemy communications signals.)
COMSAT	Communications Satellite
CONUS	Continental United States
DARPA	Defense Advanced Research Projects Agency (In the past, this organization has also used the shorter title Advanced Research Projects Agency.)
DGPS	Differential Global Positioning System (An adaptation by the civil community to increase the accuracy of the dithered GPS signal.)
DoD	Department of Defense
DSB	Defense Science Board
DSP	Defense Support Program (Satellites designed to detect missile launches using infrared sensors. DSP satellites are in GEO.)
DSWA	Defense Special Weapons Agency
DTED	Digitized Terrain Elevation Data
DTH	Direct To Home (For instance, direct-to-home television.)
EELV	Evolved Expendable Launch Vehicle (The US Air Force's newest generation of expendable launch vehicles; now under development.)
ELINT	Electronic Intelligence (Intelligence predominately derived from monitoring and analyzing radar signals.)
EMP	Electro-Magnetic Pulse (Energy in the form of photons or electro-magnetic radiation. The majority of the energy produced by an efficient nuclear explosion is released as a prompt, short-duration electro-magnetic pulse.)
EO	Electro-Optical
EORSAT	ELINT Ocean Reconnaissance Satellite
ERTS-1	Earth Resources Technology Satellite-1 (The first LANDSAT placed in orbit.)
FAS	Federation of American Scientists
FCC	Federal Communications Commission

FIA	Future Imagery Architecture (The next generation US imaging reconnaissance satellites, now under development by the NRO.)
FOBS	Fractional Orbit Bombardment System (A nuclear-delivery system developed by the Soviets using one variant of the SS-9 ICBM.)
FRY	Federal Republic of Yugoslavia
GATS	GPS-Aided Targeting System (A system that exploits the B-2’s radar to eliminate most of the target-location error associated with GPS-aided munitions.)
Gbps	Gigabits per second (One gigabit = 1,073,741,824 bits.)
GEO	Geosynchronous Earth Orbit (A circular orbit at 22,300 miles altitude above the earth’s surface.)
GLONASS	Global Navigation Satellite System (Soviet equivalent of American GPS.)
GPALS	Global Protection Against Limited Strikes (A scaled-down version of Brilliant Pebbles.)
GPS	Global Positioning System (A system of US MEO satellites that provides precise location and timing information to receivers anywhere on the earth’s surface.)
HARM	High Speed Anti-Radiation Missile
HET	Hall-Effect Thruster
HRR	High-Range Resolution (A radar-processing technique designed to improve the locational accuracy of MTI tracking data by improving the target-to-clutter ratio.)
ICBM	Intercontinental Ballistic Missile
INMARSAT	(INMARSAT satellites and services are run by the International Maritime Organization, which was established in 1979 to serve the maritime industry by developing satellite communications for ship management, distress and safety.)
INTELSAT	(International Telecommunications Satellite Organization (Founded in 1964 to provide global satellite communications using geostationary comsats.)
INS	Inertial navigation system
IR	International Relations
ISR	Intelligence, Surveillance and Reconnaissance

ITU	International Telecommunications Union
JDAM	Joint Direct Attack Munition (A low-cost guided munition that achieves accuracy by adding an INS/GPS guidance kit to a gravity bomb.)
Joint STARS	Joint Surveillance and Target Attack Radar System (The operational system has been designed for the E-8C. It consists of a large GMTI/SAR radar implemented on a 707 airframe.)
JSOW	Joint Standoff Weapon (A glide weapon that uses GPS guidance.)
KH	Keyhole (Codename introduced for the Corona series of US reconnaissance satellites.)
LANDSAT	(Refers to a series of American non-military, earth imaging satellites. ERTS-1 was the first LANDSAT orbited.)
LEO	Low Earth Orbit (LEO starts at about 60 miles above the earth's surface and extends to MEO. Various sources put the altitude at which LEO transitions to MEO from as low as 300 miles above the earth's surface to as high as 930.)
LLC	Limited Liability Corporation
Mbps	Megabit per second (1 megabit = 1,048,576 bits.)
MEO	Medium Earth Orbit (Used by GPS and some comsats. The altitude at which LEO ends and MEO begins is not well defined—see the entry for LEO.)
MHV	Miniature Homing Vehicle (A US ASAT launched from an F-15 fighter; this system was never fielded.)
MILSTAR	(GEO satellites and ground stations that make up the military satellite communications (MILSATCOM) system. It is the most sophisticated US military communications satellite system.)
MRLS	Multiple-Rocket Launcher System
MTI	Moving Target Indicator (MTI radar's exploit changes in the doppler frequencies of reflected waveforms caused by the target's motion relative to the radar, thereby enabling the radar to distinguish moving targets from ground clutter. The technique is particularly valuable when operating at low altitude or looking down at the ground.)
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization

NCA	National Command Authority
NDIA	National Defense Industrial Agency
NIMA	National Imagery and Mapping Agency
NRO	National Reconnaissance Office
NTM	National Technical Means (of verification) (Strategic reconnaissance systems, primarily the Keyhole series of imaging satellites on the American side and their Soviet counterparts.)
OSD	Office of the Secretary of Defense
P Code	Precision Code (Military code for GPS. The signal is not dithered.)
RF	Radio Frequency
RLV	Reusable Launch Vehicle
RORSAT	Radar Ocean Reconnaissance Satellite
SA	Selective Availability (Limitation on GPS accuracy for civilian users; terminated in 2000.)
SAB	Scientific Advisory Board
SAM	Surface-to-Air Missile
SAR	Synthetic Aperture Radar (Uses the motion of the radar to create a synthetic aperture; processing of the returning waveforms can create photo-like images of stationary targets.)
SBIRS	Space-Based Infrared System (The follow-on to DSP, now in development.)
SBL	Space-Based Laser
SCI	Specially Compartmented Intelligence (The classification of American satellites during the Cold War.)
SDIO	Strategic Defense Initiative Organization
SIGINT	Signals Intelligence (Intelligence derived from monitoring electro-magnetic signals. SIGINT includes both ELINT and COMINT.)
SLAM	Standoff Land Attack Missile (A US Navy cruise missile.)

SPOT	Satellite Pour l'Observation de la Terre (French imaging satellites.)
SRAM	Short-Range Attack Missile
SSN	Space Surveillance Network (American worldwide system of ground stations used to observe and track objects in earth orbit.)
SSTO	Single-Stage-To-Orbit
STAS	Space Transportation Architecture Study
STS	Space Transportation System (Official name of the American space shuttle.)
Tbps	Terabits per second (One terabit = 1,099,511,627,776 bits.)
TENCAP	Tactical Exploitation of National Capabilities
TLAM	Tomahawk Land Attack Missile (US Navy cruise missile with a conventional warhead; designed for use against targets ashore. Launched from ships or submarines.)
TPED	Tasking, Processing, Exploration, and Dissemination (TPED focuses on making use of data collected by satellite sensors.)
TRAPS	Tactical Related Applications
TSTO	Two-Stage-To-Orbit (Refers to the number of stages a launch vehicle uses to put its payload in orbit.)
UN	United Nations
UNSCOM	United Nations Special Commission
USCINCSPACE	US Commander in Chief for Space
USSPACECOM	United States Space Command
USSR	Union of Soviet Socialist Republics
VSAT	Very Small Aperture Terminal (Communications system that uses very small satellite dishes.)
WRC	World Radiocommunication Conferences
WTEC Panel	World Technology Panel

APPENDIX I: A BROADER LOOK AT THE MILITARY GEOGRAPHY OF SPACE

Chapter I adopted a geography for the military use of space that emphasized the near-earth, orbital region actually exploited today to enhance terrestrial military operations. An implicit judgment was that the military exploitation of deeper regions of space is unlikely over the next quarter century. One can, however, take a longer view. If one looks far enough into the future, then the military geography changes.

Such a longer-term perspective surfaced during a 1982 conference on the international security dimensions of space sponsored by Tufts University's Fletcher School of Law and Diplomacy. Although nearly two decades old, the broad-ranging discussion of space geography from this conference remains worth reading. The excerpt reproduced below covers both doctrinal and geographic concerns.

> **Military Doctrine And The Geography Of Space**[407]
> From the outset, conference participants lamented the absence of serious doctrinal discussion in the United States with respect to the utilization of space for military purposes. Technological imperatives, it was said, rather than clearly defined mission requirements, had been the key determinants of whatever space doctrine now existed in the United States—a situation not unknown in others fields of military endeavor. There was, in effect, too much "technology push" and not enough "requirements pull." In order to rectify this situation, an essential first step, several participants argued, is a better understanding in the American policy community of the particular sectors in space that will be of greatest importance strategically. Considerable attention, therefore, was given to what might be called the "geography of space," and to its potential impact on the evolution of military doctrine.
>
> According to one participant, outer space may be divided into three separate geographical regions, each having distinctive characteristics that will influence military activities. The first region—near earth orbit—may be further subdivided into two zone of operation, namely low earth orbit and geosynchronous orbit. Low earth orbit, which extends from the earth's surface to about 300 miles in altitude, is the present operational range of the Shuttle, and the first large structures in space will be deployed there. It is quickly and easily accessible from earth at a high cost in fuel, but it is also an unstable orbit, decaying eventually, so that objects placed there will burn up unless fuel is expended to maintain their orbit. Low earth orbit, therefore, is useful only for short-term operations.

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[407] Robert L. Pfaltgraff, Jr., and Uri Ra'anan, *International Security Dimensions of Space: Eleventh Annual Conference, April 27–29, 1982* (Cambridge, MA: Institute for Foreign Policy Analysis, 1982), pp. 2–3. Printed with permission of the International Security Studies Program, The Fletcher School of Law and Diplomacy, Tufts University.

> Hence, there is a growing interest in geosynchronous orbit, some 22,300 miles high, with the unique characteristic that an object placed there will remain stationary relative to a point on the equator of the earth. Once there, an object will remain in place indefinitely at little cost in fuel. For these reasons, geosynchronous orbit, it was argued, is a perfect site for large structures—very costly to maintain over long periods in a lower orbit—while it is already crowded with a variety of communications and earth monitoring satellites. Moreover, its present position at the top of the earth's "gravity well," where movement and maneuver in space are less constrained, would make geosynchronous orbit a preferred locale for space-based military forces. In essence, control of geosynchronous orbit means control of all near earth space.
>
> The second major geographical region of space—known as cislunar space—encompasses the entire earth-moon system and commands all access routes between these two celestial bodies. In comparison to near earth orbit, transportation costs are lower, because it takes relatively small changes of velocity (Delta Vs) to travel great distances in cislunar space. More important still, within cislunar space, there are two points—the Trojan libration points L_4 and L_5—where the gravitational effects of the earth and moon cancel each other out, and an object placed there would remain in stable location. These are the two logical points at which to place large space structures, such as factories, colonies or military bases; as the industrialization of space proceeds, L_4 and L_5 could effectively create a security umbrella reaching from the lunar surface to geosynchronous orbit.
>
> As in the case of near earth orbit, the third region of space—translunar space—can be divided into two separate parts. The first comprises the inner solar system, extending from the orbit of the moon out to the asteroid belt. The second is the outer solar system from the asteroids to the orbit of Pluto. No immediate uses are foreseen for this second area; but serious considerations have been given to the first, primarily due to the great mineral wealth of the asteroids. Specifically, it is thought that the mining of asteroids in support of space industry may be a viable economic proposition, since the low Delta Vs prevailing in cislunar and translunar space would make it cheaper to move an asteroid to L_5, for example, or to geosynchronous orbit, than to bring the equivalent amount of material up from earth. If an asteroid mining industry were to develop, moreover, it would give rise to a network of rather extended space lanes of communication, follow the paths of lowest Delta V required. Such paths are called Hohmann Transfer Orbits, and their defense would be the primary military mission in translunar space. In addition, given the great distances involved, a self-sufficient deep space fleet would be needed eventually to patrol the asteroid belt and beyond. From the perspective geopolitics, then, those charged with the responsibility for developing long-range doctrines for space may draw useful insights from the evolution of maritime doctrine on earth, concerned as it is with sea access and denial through the control of critical passage ways and choke points.

John Collins took a similar approach to the military geography of space in 1998, although he did not look beyond the earth-moon system. His key points about orbital space and the earth-moon system are also worth reiterating:

- The term "aerospace" is a misnomer, because air and space are distinctively different geographic mediums.

- Military space activities currently are confined to unmanned reconnaissance, surveillance, target acquisition, tracking, communications, navigational, meteorological, missile warning, and arms control mission in support of armed forces on Earth.

- Many items needed to mount and sustain large-scale, extended military operations on the Moon and elsewhere in space remain to be invented, but could become technologically feasible.

- Few strategies, tactics, organizations, weapon systems, equipment, and little training designed for use by armed forces on Earth would be suitable for military operations in space.

- Orbital options will remain predictable until technologists devise innovative ways to maneuver spacecraft in a vacuum.

- The Moon, lunar libration points L-4 and L-5, and the geostationary orbit path above the Earth's Equator are strategic locations within the Earth-Moon System.

- Military space operations of any kind demand extensive Earth-based command, control, communications, logistical, and administrative support for the foreseeable future.[408]

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[408] John M. Collins, *Military Geography for Professionals and the Public* (Washington, DC: National Defense University Press, 1998), p. 150.

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APPENDIX II: SELECTED US GOVERNMENT SATELLITES[409]

SYSTEM	MISSION	CONSTELLATION	ORBIT	SATELLITE CHARACTERISTICS	SYSTEM PERFORMANCE
MILSTAR I/II	Worldwide protected & survivable communications for tactical & strategic forces	2 MILSTAR I & 4 MILSTAR II satellites	GEO: 36,000 km (22,300 mi)	Mass: 4,536 kg (≈10,000 lbs) Power: 5,000 watts Length: 42.3 m (116 ft) including solar panels	LDR: 192 channels of 75 - 2,400 bps MDR: 32 channels of 4.8 kbps – 1.544 Mbps 24 hrs/day coverage 65º S to 65º N
Defense Satellite Communications System (DSCS) III	Secure, wideband, high-data-rate communications for U.S. military forces	5 satellites on orbit (plus residuals)	GEO: 37,385 km (23,230 mi)	Mass: 1,170 kg (≈2,580 lbs) Power: 980 watts Length: 11.5 m (≈38 ft) including solar panels	6 SHF transmitters with 50-85 MHz each UHF: 1 AFSATCOM single channel transponder transmitter 24 hrs/day coverage 80º S to 80º N
UHF Follow-On (UFO)	Over the-horizon communications to tens of thousands of stationary & mobile users via low-cost, lightweight terminals	8 satellites on orbit (plus 1 spare)	GEO: 36,000 km	Mass: 1,542 kg (3,400 lb) Power: 2,400 watts Length: 18.6 m (60 ft) including solar panels	UHF: 18 25 kHz (F1-F10), 21 5-kHz (F1-F10) EHF: 11 LDR chan (F4-F6), 20 LDR chan (F7-F10) GBS: 4 24 Mbps (F8-F10) at Ka band
National Polar-	Tri-agency pro-	3 satellites on	Sun-	Mass: 3,023 kg	Multispectral visible & in-

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[409] Except for the KH-11 and Lacrosse, all satellite data in Appendix 2 are from the Defense Department's pamphlet *Space Program: Executive Overview for FY1999-2003*. Sources for the KH-11 and Lacrosse are *Aviation Week & Space Technology* (21/28 December 1998, p. 125; 26 April 1999, p. 35; and, 13 September 1999, p. 26) and Mark Wade's Encyclopedia Astronautica website.

Orbiting Operational Satellite System (NPOESS)	gram (DoD, Dept. of Commerce & NASA) for timely, high-quality, global weather data	orbit (minimum), 2 U.S. & 1 European	synchronous polar, 833 km (433 nm)	(6,665 lbs) Flexible GaAs solar array	frared, microwave, & space environmental sensors
Space-Based Infrared System (SBIRS)	Initial warning of ballistic missile attack on U.S., its deployed forces, or its allies (replaces DSP)	SBIRS High: 6 satellites (+ 1 spare) SBIRS Low: to be determined	SBIRS High: —GEO: 4 satellites plus 1 spare —HEO: 2	SBIRS High is in engineering development. SBIRS Low is currently characterized as around 24 LEO satellites (although numbers as high as 48 have been discussed).	Tracking & characterization of ballistic missiles in their boost phase; also tracking during post-boost, mid-course, reentry phases. Doubts about the affordability of SBIRS Low are now being raised.

SYSTEM	MISSION	CONSTELLATION	ORBIT	SATELLITE CHARACTERISTICS	SYSTEM PERFORMANCE
Global Positioning System (GPS)	Space-based radio positioning, navigation, & time distribution to provide precise location, speed, & time to an unlimited number of military & civilian users worldwide	24 satellites in 6 orbital planes	20,200 km (10,900 nm), circular, 55º, 12-hour period	IIA: 844 kg, 700 watts, 5.3 meter span, 7.5 years service life IIR: 1,075 kg, 1,136 w, 11.6 m, 7.5 years IIF: 2.136 kg, 1,510 w, 17.4 m, 15 years	Two L-band frequencies for navigation data S-bank link for control by ground segment (which includes 5 monitoring stations, 4 ground antennas, & a master control station at Falcon AFB, CO
KH-11	EO and infrared imaging (advanced KH-11)	3 advanced KH-11s were reported operational during Allied Force in 1999	LEO: elliptical, 280 km perigee, 1,000 km apogee, 97º inclination	Early KH-11s were reported to weigh over 13,000 kg	Digital imagery downlinked in real time
Lacrosse	All weather, day/night imaging synthetic-aperture radar	2 were reported operational during Operation Allied Force	LEO: 666 km perigee, 679 km apogee, 58º & 68º	~30,000 lbs	Data downlinked in real-time to White Sands?

APPENDIX III: CURRENT OR PLANNED COMMERCIAL COMMUNICATIONS PROJECTS

L, S bands: Telephony; VHF, UHF: Messaging; Ka, Ku bands: Broadband Communications

SYSTEM	OPERATOR	PRIME CONTRACTOR	ALTITUDE, INCLINATION	CAPABILITY	CONSTELLATION + SPARES	STATUS AS OF MID-2000
Equatorial Constellation COmms (ECCO)	Constellation Communications	Orbital Sciences	2,000 km, 0º for 1st 12; 62º for later sats	L-band	12 (plus 42 later)	Initial service planned for 2001 with 12 equatorial satellites
ELLIPSO	Ellipso	Boeing (system integrator)	~520 x 7800 km, 116º & ~8,000 km, 0º	L-band (uplink) S-band (downlink)	14 + 3	First launch planned for 2001 and an operational constellation in 2002, but Iridium failure has made these dates uncertain
FAISAT	Final Analysis Comm	Final Analysis Inc.	1,000 km, 51º & 83º	VHF/UHF	32 + 6; 2 polar (83º), 36 at 51º	Two experimental satellites orbited in 1995 and 1997, respectively
GLOBALSTAR	Globalstar LP	Space Systems/ Loral	1,414 km, 52º	L/S-band	48 + 8	52 operational satellites in orbit; began service in "limited areas" in the lst quarter of 2000
GONETS D/R	Smolsat	AKO Polyot	1,400 km, 82.6º	UHF and S/L-band	81 + 0	Doubtful due to lack of financing
ICO (New ICO)	ICO-Teledesic Global	Hughes	10,355 km, 45º	S-band	12 + 2? (11 satellites being built; 3 more planned for New ICO)	Emerged from Chapter 11 in May 2000 & has merged with Teledesic; service planned for 2003.
IRIDIUM	Iridium LLC	Motorola	780 km, 86.4º	L/S-band	66 + 6	In Chapter 11 & service suspended; ultimate fate of satellites & system is unknown
LLMS/IRIS	SAIT-RadioHolland	OHB Systems	1,000 km, 83º	UHF	2 + 0	One payload in orbit on board a Russian satellite; by 2003 the constellation should comprise 6 orbiting payloads.
LEO One Worldwide	LEO One Worldwide	DRG	950 km, 50º, 8 planes	VHF/UHF	48 + 0	Scheduled to be operational in 2002

SYSTEM	OPERATOR	PRIME CONTRACTOR	ALTITUDE, INCLINATION	CAPABILITY	CONSTELLATION + SPARES	STATUS AS OF MID-2000
ORBCOMM	ORBCOMM	Orbital Sciences Corp.	785 km, 45º / 70º	VHF	28 + 7	35 satellites in orbit and fully operational; Chapter 11 as of September 2000.
SAFIR	OHB Teledata	OHB Systems	680 km, 98º	UHF	6 + 0	Two satellites in orbit
SKYBRIDGE	SkyBridge	Alcatel	1,457 km, 55º	Ku-band	64 + 4; 2 symmetrical Walker sub-constellations of 32 satellites each	Launches to begin in 2002, service in 2003.
TELEDESIC	Teledesic Corp	Motorola	1,357 km, 85º	Ka-band “Internet-in-the-Sky”	70-120 satellites (previously 288)	Will be fully operational in 2004. First launch will occur 12-18 months prior.
TEMISAT	Telespazio	Kayser-Threde	938 km, 82º	UHF	7 + 0	One satellite launched in 1993, however current status is unknown.
VITAsat	Volunteers In Technical Assistance	Various	1,000 km, 83º	VHF/UHF	3 + 0	No satellites in orbit; lost only satellite in 1998; next launch unknown.

L, S bands: Telephony; VHF, UHF: Messaging; Ka, Ku bands: Broadband Communications

APPENDIX IV: CURRENT COMMERCIAL LAUNCH COSTS[410]

Launch Vehicle	Service Provider	Pounds to LEO	Pounds to GTO	Minimum Launch Cost ($M)	Maximum Launch Cost ($M)	Minimum Cost/lb to LEO ($)	Maximum Cost/lb to LEO ($)	Minimum Cost/lb to GTO ($)	Maximum Cost/lb to GTO ($)
Ariane 4	Airanespace	21,000	10,900	$100 M	$125 M	$4,762	$5,952	$9,174	$11,468
Ariane 5	Airanespace	39,600	15,000	$150 M	$180 M	$3,788	$4,545	$10,000	$12,000
Delta 2	Boeing	11,220	4,060	$45 M	$ 55 M	$4,011	$4,902	$11,084	$13,547
Delta 3	Boeing	18,280	8,400	$75 M	$90 M	$4,103	$4,923	$ 8,929	$10,714
Long March-2C	China Great Wall Industry	7,040	2,200	$ 20 M	$ 25 M	$2,841	$ 3,551	$ 9,091	$11,364
LM-3B	China Great Wall Industry	29,900	9,900	$50 M	$ 70 M	$1,672	$2,341	$5,051	$7,071
Atlas 2	International Launch Services (ILS)	19,050	8,200	$90 M	$105 M	$4,724	$5,512	$10,976	$12,805
Proton	ILS	44,200	10,150	$75 M	$95 M	$1,697	$2,149	$7,389	$9,360
Zenit 2	Ukraine National Space Agency	30,000	—	$35 M	$50 M	$1,167	$1,667	—	—
Sea Launch	Sea Launch	35,000	11,050	$75 M	$95 M	$2,143	$2,714	$6,787	$ 8,597
Soyuz	Starsern	15,400	—	$ 35 M	$40 M	$2,273	$2,597	—	—
Molniya	Starsern	3,970	(polar)	$ 30 M	$40 M	$7,557	$10,076	—	—
Pegasus	Orbital Sciences	3,300	—	$12 M	$15 M	$3,636	$4,545	—	—
Tarus	Orbital Sciences	3,100	1,290	$18 M	$20 M	$5,806	$6,452	$13,953	$ 15,504
Athena	Lockheed Martin	4,350	—	$22 M	$26 M	$5,057	$5,977	—	—
Rockot	Eurockot	4,100	—	$12 M	$15 M	$2,927	$3,659	—	—
Cosmos	Puskovie Uslugi	3,100	—	$12 M	$14 M	$3,871	$4,516	—	—

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[410] Source: Futron Corporation briefing— Greg Lucas and Charles Murphy, “The Space Launch Services Industry: Indicators and Trends,” presentation to the AIAA Defense and Civil Space Programs Conference, 29 September 1999, slides 17 and 18.

START	Puskovie Uslugi	1,543	—	$ 5 M	$10 M	$3,240	$6,481	—	—
Average Cost-per-lb to LEO for 18 Commercial Launchers						**$3,632**	**$4,587**		
Average Cost-per-lb to GEO Transfer Orbit (GTO) for 10 Commercial Launchers								**$9,243**	**$11,243**

APPENDIX V: CURRENT OR IN-DEVELOPMENT REUSABLE LAUNCH VEHICLES[411]

Vehicle	Manufacturer/ Developer	Stages	Power-plants	Market/ Performance	1st Launch	Launch Method	Recovery Method	Launch Contracts	Government Funding
COMMERCIAL PROGRAMS									
Astroliner	Kelly Space & Technology	3	Considering NK-33, Aerospike & RS-27, or RD-180; upper stages Star 71 or Orbus 21	LEO constellation satellites & GTO payloads 4,700 kg to 300km 28.5º LEO; 2,072 kg to GTO	2002	Air-launched	Horizontal landing	Yes	No
K-1	Kistler Aerospace Corporation	2	1st stage: 3 AJ-26 2nd stage: AJ-60	LEO satellites Standard Payload Module: 4,000 kg to 400 km 45º LEO; Extended Payload Module: 2,000 kg to 400 km 98º LEO	TBD	Vertical launch	Parachutes & air bags (both stages)	Yes	No
Pathfinder	Pioneer Rocketplane Company	2	2 F-100 jet engines; 1 RD-120	LEO constellation satellites 2,100 kg to200 kg equatorial; 1,450 kg to 1,000 km polar	2001	Horizontal takeoff	Horizontal landing	No	Yes
Rotan C-9	Rotary Rocket Company	1	Cluster of several engines derived from Fastrac	LEO constellation satellites 3,600 kg to 275 km 35º LEO; 2,250 kg to 550 km 90º LEO	2000	Vertical launch	Vertical landing	No	No

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[411] Associate Administrator for Commercial Space Transportation (AST), *2000 Reusable Launch Vehicle Programs & Concepts with a Special Section on Spaceports* (Federal Aviation Administration, January 2000).

Vehicle	Manufacturer/ Developer	Stages	Power-plants	Market/ Performance	1st Launch	Launch Method	Recovery Method	Launch Contracts	Government Funding
SA-1	Space Access LLC	2 (LEO) 3 (GTO)	Ejector LOX/hydrogen ramjets	Medium-class LEO & GTO payloads; ISS resupply or human spaceflight 6,200 kg to GTO	2005	Horizontal takeoff	Horizontal landing	No	No
Space Cruiser System	Vela Technology Development, Inc. Space Adventures	2	Lower stage: 2 JT8D/F100-class turbojets Upper stage: 3 rocket & 2 JT15D-class turbojet engines	Sub-orbital space tourism or micro-gravity experiments, & aerospace training 6 passengers & 2 crew to 100 km suborbital	2001	Horizontal takeoff	Horizontal landing	Yes	No
Venturestar (full-scale version of X-33)	Lockheed Martin	1	7 RS-220 linear aerospike engines	Heavy classes of LEO payloads 22,700 kg to LEO	2004	Vertical launch	Horizontal landing	No	Yes
UNITED STATES GOVERNMENT PROGRAMS									
Space Shuttle	Rockwell, Rocketdyne, Lockheed Martin	2	3 LOX/hydrogen Shuttle main engines	24,700 kg to 204 km, 28º LEO; 18,600 kg to 204 km , 57º LEO	1981	Vertical launch	Horizontal landing	Yes	Yes
X-33	Lockheed Martin	1	2 J-2S linear aerospike engines	Subscale, suborbital prototype for Venturestar Mach 13.8 at 91 km	2000	Vertical launch	Horizontal landing	No	Yes
X-34	Orbital Sciences Corporation	1	1 kerosene/LOX Fastrac or 1 Russian NK-39	Mach 8 at 76 km (veh. A3) 181 kg payload allocation	2000	Air-launched	Horizontal landing	No	Yes