Space Operations: Through The Looking Glass
(Global Area Strike System)

A Research Paper
Presented To

Air Force *2025*

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Contents

Chapter *Page*

Disclaimer ii

Illustrations v

Tables vi

Executive Summary vii

1 The World of 2025 1
- The Space Operations Mission 2
- The Topic of Discussion 3
- Issues Involving Space Operations in 2025 4
  - Manned Versus Unmanned Systems 4
  - Large Versus Small Satellites 5
  - Ground Versus "Anywhere" Processing and Delayed Versus Near Real-Time Information 5
  - Military Versus Cooperative/Commercial Endeavors. 6

2 Required Capability 8
- Timeliness 8
- Responsiveness 9
- Flexibility 10
- Survivability and Reliability 10
- Precision and Selective Lethality 11

3 The Integrated System-of-Systems 13
  - Weapon Platforms 14
  - Weapon Classes 16
- Directed-Energy Weapons—Incoherent Light 16
  - Capabilities 17
  - Countermeasures 18
  - Evaluation 18
- DEW—Coherent Light (Lasers) 18
  - Capabilities 20
  - Countermeasures 24
  - Evaluation 24
- Neutral Particle Beam 25
  - Capabilities 26
  - Countermeasures 27
  - Evaluation 27
- Electromagnetic Pulse 27
  - Capabilities 28
  - Countermeasures 30
  - Evaluation 30

Chapter *Page*

High-Power Microwave 31
Capabilities 32
Countermeasures 33
Evaluation 33
Illusion 34
Capabilities 34
Countermeasures 34
Evaluation 35
Projectile Weapons 35
Projectile Weapons—Ballistic Missiles 35
Capabilities 36
Countermeasures 37
Evaluation 37
Projectile Weapons—Kinetic Energy 37
Capabilities 39
Countermeasures 40
Evaluation 40
Space Sortie—Transatmospheric Vehicle 40
Capabilities 43
Countermeasures 46
Evaluation 47
Summary —The System-of-Systems 47
Capabilities 50
Countermeasures 51

4 Concept of Operations 59

5 Investigation Recommendations 68
Directed-Energy Weapons 69
Projectile Weapons 69
Space Sortie 70
General Considerations 70

Appendix *Page*

A Global Presence 72
Some Important Definitions 73

B The System of Systems 75
SAT/BDA 75
Surveillance 77
Acquisition and Targeting 77
Battle Damage Assessment 79
Utilities 79
Communications 80
Navigation 81
Weather 82

Bibliography 84

Illustrations

Figure		*Page*
1-1.	The View from Space	4
3-1.	A Notional Space-Based Laser	19
3-2.	Precision Laser Strike on Aircraft	22
3-3.	The TAV in its Native Environment	41
3-4.	Pop-Up Maneuver	45
3-5.	Pop-Up Enables Flexible Transpace Operations	46
4-1.	TAV Employing Kinetic-Energy Weapons	61
4-2.	Notional Space-Based Mirror Deployment Using Inflatable Mirror Technology	62
4-3.	The Crowded "Skies" of 2025	65
4-4.	A TAV in *Space-strike* Mode	66
A-1.	Space Operations Missions	73
B-2.	Battlespace Awareness	76

Tables

Table *Page*

1 Summary Evaluation of Potential Weapon Systems 48

Executive Summary

America's capability to operate in space is increasing with every passing day. Space operations are already recognized as a crucial part of all American military operations. Military space operations may be indirect, through such staples as navigation, communications, and surveillance/reconnaissance support to the war fighter, or direct, through development and fielding of a range of responsive directed energy and kinetic energy weapons. A modest fleet of flexible, mission-tailored transatmospheric vehicles (TAVs) has an important place in any thoughtful space operations architecture, providing the only conceivable way to insert human presence rapidly into the fast-breaking crises of 2025. Space represents the future—a future in which aerospace power will increasingly be projected through space systems.

This paper advocates a "system-of-systems" architecture for an American global space-strike capability in 2025. This architecture recognizes the importance of the global information network (surveillance and reconnaissance combined with the intelligence system), the military command and control system, the perennial space "utilities" (communications, navigation, and weather), and a robust readiness and sustainment system to enable the fielding of space-based or space-borne weapon systems. The weapon system itself is described as a smaller system-of-systems composed of the weapon, its platform, and a primarily off-board surveillance, acquisition, and tracking/battle damage assessment capability provided through the global information network.

After a review of the alternatives for a global space-strike system in 2025, the optimum solution appears to be combining a prompt response capability with a complementary flexible response capability. The prompt response capability is best provided by a system of Continental United States(CONUS)-based laser devices that bounce high power directed energy beams off a constellation of space-based mirrors. Inherently precise, megawatt-class, light-speed weapons can potentially act within seconds or minutes to resolve the rapidly developing crises of 2025. Flexible response is best provided with a small CONUS-based fleet of TAVs equipped with a variety of payloads, including kinetic-energy weapons, compact laser

weapons, and special forces squads. Responding within a few hours of notification, a TAV can precisely deliver force and/or adaptable human judgment to crisis locations anywhere on earth.

The balance of influence in the information technologies has shifted from the Department of Defense to commercial organizations. This trend will continue and accelerate between now and 2025. The crucial importance of detailed, timely knowledge and rapid, ultrawideband communications to military space operations will demand the extensive use of commercial (possibly international) space systems and technologies. The world of 2025 will see a crowded "sky" filled with space systems shared by military and government organizations on the one hand and commercial concerns on the other.

Chapter 1

The World of 2025

Once again a small but capably armed country is threatening to seize its smaller but resource-rich neighbor. The Global News Network reports that the border has been violated. The same old story? No, the plot twists as a sophisticated satellite surveillance and reconnaissance system tracks the belligerent nation's leader. As he steps to the podium to incite his troops to greater violence, a blinding light from above vaporizes him and his podium leaving even his bodyguards untouched. His smarter brother, the second in command, countermands the invasion orders and in 12 hours the borders are restored. Stability, if not peace, reigns again.

This is not science fiction, but a mission well within the capabilities of Space Operations in ***2025***. By that year space operations will become the key to a wide range of military missions. Current US military space systems are an important force multiplier, but they do "not yet provide the seamless, reliable, rapidly delivered information needed by the modern war fighter."[1] To resolve this deficiency, space system designers must make a clean break with the expensive, large-scale, hand-built designs of 1996 and move to a new approach that emphasizes economy, efficiency, and operational utility in dynamic balance with rapidly evolving technological developments.

This paper highlights the importance of the full range of space operations while emphasizing the point that, in 2025, the United States must have a global space-strike capability. Why is this capability essential for military operations in 2025? All nations are becoming highly dependent on space assets for communications, weather forecasting, navigation and positioning, and surveillance and reconnaissance, and this dependency is growing at an exponential rate. To preserve the ability to use space and to deny space to aggressors, the US

must have control of space. This need to control space w ill quickly overcome the political will to oppose weapons in space. Once this line is crossed—and its crossing is inevitable—we must be equipped to make use of space in a variety of novel ways.

The rapidly accelerating rate of technological change virtually assures that, by 2025, even the poorest nations will have access to electronic information and decision-making aids only dreamed of today. The average time required to complete an Observation, Orientation, Decision, and Action (OODA) loop will be much shorter in 2025[2]. In such a world, the US must be able to take rapid action (measured in minutes or perhaps even seconds) to resolve conflict situations before they can grow out of control. The essential capabilities of timeliness or responsiveness can certainly be provided by a properly designed space-strike system and perhaps only by such a space-strike system.

Because the world of 2025 will provide smaller countries and organizations with far greater abilities to disrupt our nation and its allies, we will need measures flexible enough to produce effects across the full range of the "spectrum of force," ranging from the nonlethal (deceit, delay) to the lethal (damage, destruction). The requirement to produce the right effect on the right target at the right time is as desirable in a space-strike system as it is in today's more familiar combat systems.

The Space Operations Mission

The heart of the space operations mission is the *global presence* concept as encapsulated in the following summary from the Department of the Air Force Global Presence 1995 document:

> "As we peer into the future, we should view *Global Presence* as one route the Services can take to achieve our country's ever evolving national security objectives. We in the military possess the means, physical and virtual, to provide America continuous awareness of world events and a force capable of projecting military power worldwide, in minutes or hours, with little or no warning."[3]

While the notion of global presence is a concept of 1996, its principle will remain a constant for decades to come. The name may change, but the mission will remain crucial as long as the United States wished to remain a world power. Much of America's global presence already depends on the world's highest technology systems operating freely from "the high ground of space." The only essential element missing in 1996 is a force projection capability operating through the space environment. (see appendix A).

In the fast-paced world of 2025, the volume of space near earth (at and below geosynchronous orbit) will be filled with the space assets of many, if not all, nations. The commercial, civil, and military possibilities inherent in the high ground of space will be fully exploited. These future space systems will be distributed and interconnected in ways we can only dimly imagine today. It may even be impossible to point at any single piece of space hardware and say "this belongs to the United States." Instead, a nation and nongovernmental organizations (NGOs) may use various parts of various space assets at different points in time.

The Topic of Discussion

The military's space support and space-control missions in 2025 are described in other AF *2025* white papers. The force enhancement mission is addressed from several points of view in other white papers involving surveillance and reconnaissance and information operations.[4] This paper will concentrate primarily on the space force application mission and those elements of force enhancement which relate directly to the military application of force through the medium of space.

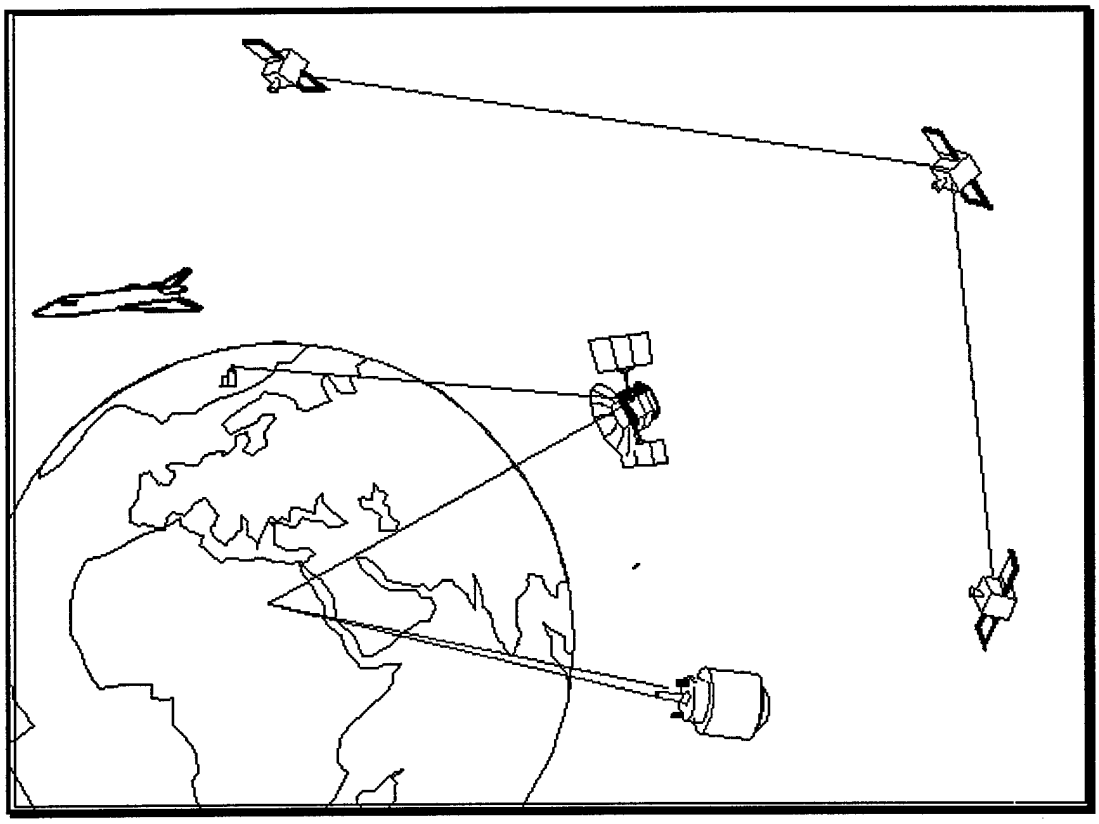


Figure 1-1. The View from Space

Issues Involving Space Operations in 2025

Several trends are already evident in the world of 1996 that will fundamentally influence all future operations in space. Although the precise impact of these trends cannot be predicted with confidence, certain broad conclusions appear inescapable.

Manned Versus Unmanned Systems

For years, the "proper place" for manned and unmanned space vehicles has remained unchanged. Deep space, long-duration planetary exploration has been performed by unmanned robotic space probes. Space-based communication, remote sensing, weather and navigation missions are also performed with sophisticated unmanned platforms well suited to operation in the hostile environment of space. Manned missions are limited to complex scientific and (frankly) public relations endeavors.

Considering the likely advances in telepresence, virtual reality, and wideband communications linked with secure, reliable, remote piloting techniques, there will probably be no requirement for a sustained human presence in space through at least the 2025 time frame, at least in regard to military missions. With the single exception of limited space sorties delivered by transatmospheric vehicles (TAV), all of the space systems discussed in this paper are hosted by unmanned platforms.

Large Versus Small Satellites

The conventional approach to space systems involves large satellites (weight in excess of 500 kilograms) containing as many multimission payloads as will fit on the booster. The emphasis on high-volume, high-weight satellites has contributed to the enormous cost of developing and fielding space systems. A recent, and very attractive, alternative involves the use of small (weight below 500 kilograms) or even micro (weight below 50 kilograms) satellites launched by cost-effective boosters such as the Orbital Sciences Corporation's Pegasus. Commercial remote-sensing satellites are already being developed with a panchromatic spatial resolution as good as one meter and multispectral resolutions below 20 meters.[5] Other uses for small and microsatellites will develop naturally as an outgrowth of continuing advances in the areas of materials, small sensors, miniaturized electronic and mechanical systems, inexpensive space launch, and packaging.[6] Soon, satellites will no longer need to be large, heavy structures overloaded with redundant systems. Small and microsatellites will be able to perform all the functions carried out by today's large, "one of a kind" satellites.

Ground Versus "Anywhere" Processing and Delayed Versus Near Real-Time Information

The volume of scientific and intelligence data, including high-resolution imagery, is growing at an alarming rate. To handle this increased traffic, it will be necessary to install ever more capable onboard processing power on satellites equipped with advanced visible, infrared, and radar sensors. By 2025, it should be possible to process even the most complex images onboard in real time.[7] Full image data sets will no longer need to be transmitted to central ground stations for slow postprocessing. These real-time images can then be "fused" with other forms of militarily significant intelligence information, in near real time, and at

any location desired—all made possible by microprocessors perhaps a million times more capable than anything we possess today. Combined with high-volume, high-bandwidth communications (perhaps laser communications), the military commander's dream of understandable, near-real-time information on demand will finally be possible. The "fog of war" will not be fully lifted in this way, but it will be significantly thinned.

Military Versus Cooperative/Commercial Endeavors.

The end of the cold war and the subsequent decline in military budgets has forced the US Air Force to reconsider its traditional posture on space operations. Every day, more foreign governments and commercial concerns are gaining access to space, turning near-earth orbit into a very busy place. Technologies once driven solely by US government dollars are increasingly dominated by private funding. Clearly, significant opportunities exist for the US Air Force to share the assets (and technological developments) of commercial concerns and even foreign governments to accomplish important missions such as communications and remote sensing.[8] In particular, the large civilian investments in electronics, sensors, advanced communications, and information systems will soon exceed the military's research budget in these areas. Long before 2025, the US military must learn to adapt the technological developments of others to meet national security needs. This will not exempt us from our need for space superiority, and actually will drive our need for greater technological superiority in a variety of areas.

In the year 2025, military space operations will be augmented by vastly improved passive and active sensors, producing the nearly continuous global surveillance and reconnaissance capability (sometimes called "global awareness") required to project power on a global scale flexibly and effectively. These improvements will include the capability to detect and track fixed and mobile targets in all weather conditions with sensors accurate enough to provide useful battle damage assessment.[9] This will be possible not through military-specific technological advancements but through synergistic civil, military, and international developments. All of these abilities will again be essential for a nation that desires space superiority and the capability to project force from space.

[1] David J. Lynch, "Spacepower Comes to the Squadron," *Air Force Magazine* 77, no. 9 (September 1994): 66. According to Brig Gen David L. Vesely, first commander of the Air Force Space Warfare Center, "When we got to the war, space resources were available, but were not tailored to the war fighter's problem. Tactical warning was just not there. Likewise, reconnaissance data all arrived, but we did not get what was tactically useful."

[2] John R. Boyd, "A Discourse on Winning and Losing" A collection of unpublished briefings and essays. Air University Library, Document No. M-U 43947, August 1987.

[3] Gen Ronald E Fogleman, USAF, and Sheila E. Widnall, *Global Presence 1995* (Washington, D.C.: HQ USAF, Pamphlet, 1995), 16.

[4] Lt Col Bruce W. Carmichael, et al., "Strikestar ***2025***," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996). See also CDR Clarence E. Carter, et al., "The 'Man in the Chair' - Cornerstone of Global Battlespace Dominance," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996); Lt Col Edward F. Murphy, et al., "Information Operations: Wisdom Warfare for ***2025***," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996); Lt Col William, Osborne, et al., "Information Operations: A New Warfighting Capability," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996); and Maj Michael J. Tiernan, et al., "In-Time Information Integration System (I^3S)," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996.

[5] Sarah L. Cain, "Eyes in the Sky: Satellite Imagery Blasts Off," *Photonics Spectra*, (October 1995): 90–104 and Maj Timothy Hawes, USAF, "Commercial Use of Satellite Imagery," *Program Manager* 24, no. 2 (March-April 1995): 44–47.

[6] Gregory Canavan, and Edward Teller, "Strategic Defense for the 1990s," *Nature* 334 (19 April 199): 699–704.

[7] Information obtained from a senior US Air Force professional speaking to the Air War College under the promise of nonattribution.

[8] Lt Col Larry D. James, USAF, "Dual Use Alternatives for DoD Space Systems," Maxwell AFB, Ala.: Air War College Research Report, April 1993, 31.

[9] Canavan and Teller, 699.

Chapter 2

Required Capability

The US must ultimately control the high ground of space by attaining and maintaining space dominance through the use of space systems. A system-of-systems space-strike architecture must be developed that consists of five major components: (1) a global information network (surveillance and reconnaissance system, intelligence system), (2) a secure command and control system, (3) certain key utilities (communications, navigation, and weather), (4) a comprehensive readiness and sustainment system, and (5) a space-strike weapon system or combination of weapon systems. The architecture for a particular mission might consist of the weapon plus sensors and/or communications integrated on a single, space-based platform, or all parts of the system might be distributed across a number of platforms based in different mediums (space, air, sea, land, subsurface). The actual location of the various components should be determined by the outcome of a complicated systems analysis process that considers many cost-effectiveness and mission-effectiveness factors. Only mission-effectiveness factors will be addressed in this chapter.

Every weapon system possesses, to greater or lesser degree, the capabilities of timeliness, responsiveness, flexibility, survivability, reliability, precision, and selective lethality. The following discussion centers on these major capabilities required by a global space-strike system in 2025.

Timeliness

The space-based, high-resolution surveillance and reconnaissance, high-bandwidth communications, and ultraprecise navigational systems of 2025 will make it far easier to see, move, talk, and shoot. These space systems will be fully interconnected and, because of broad based commercialization, available to

practically every nation and major organization on the planet. Key aspects of the interconnected system-of-systems will be common spacecraft bus modules, the use of industry (and probably international) standards, small and microsatellites (particularly as a means of improving technology insertion), and fully transparent tasking. The user will interact with information, not with discrete instruments. A real-time, redundant, seamless link will exist between space-based assets and assets operating within the earth's atmosphere.[1] Tailored, near-real-time information will be readily available to war fighters and their weapon systems. Every weapon system in 2025, including the global space-strike system, must be designed to make the best use of this timely information (called in-time information in the AF ***2025*** white paper entitled "In-time Information Integration System").[2] A more complete view of the near-real-time information system outlined above is available in various AF ***2025*** white papers dealing with surveillance and reconnaissance systems and information operations.[3]

Responsiveness

Force application missions usually begin as contingency operations, which are rapid responses to crises. A crisis may come without any notice and produce a tremendous amount of stress to disseminate information quickly and accurately. Decision makers need complete information on the developing crisis in near real time (the actual speed depends on the time available to decide and take proper action). A near-absolute assurance of connectivity is critical for a distributed information system, because if the total system does not maintain its connections it cannot be effective—in this case, responsiveness is meaningless. The key to an effective global space-strike is, therefore, to affect a crisis or conflict decisively before it can grow out of control. The response action must occur at a rate faster than the opponent can react—"within the enemy's OODA loop" in the words of Col John Boyd.[4] In the fast-paced world of 2025, the US military's "system-of-systems," and its global space-strike system, must be more responsive than anything that exists today. The United States's OODA loops may well need to "turn" in minutes or even seconds.

Flexibility

The fog and uncertainty of war, ancient and modern, has taught military commanders to always keep their options open. At the tactical level, this means the military commander does not commit to any one course of action, nor to any fixed allotment of forces to any task, until the proper (usually the last) moment. Even then, the effective military commander must always retain the ability to switch forces from one objective to another as the conflict unfolds.[5] Surprise is an uncomfortable and unwelcome, but sadly ever-present, bedfellow for the commander.

Conflict can be characterized by the level of objective intent. The most common definition of the "spectrum of force" identifies three levels of intensity: low, medium, and high. High intensity is generally characterized by continuous engagement and an exchange of lethal blows between conventional or nuclear-capable forces with the intent of totally destroying the enemy. At the lowest end of the spectrum, the conflict involves the limited uses of force embodied in subversive, partisan, terrorist, and guerrilla tactics. Even in the slower-paced world of 1996, most military missions are at the lower and politically far more sensitive end of the spectrum. The US military must possess flexible combat systems capable of projecting force at all levels of power.

Survivability and Reliability

A system that cannot survive the outbreak of hostilities is not a useful system. A force-application system, in particular, must be "robust"—it must be available to the commander whenever it is needed. The desirable global space-strike system is one that is resistant to the enemy's attempts to render it inoperative (a <u>survivable</u> system) and that is relatively easy (in terms of cost and effort) to maintain and sustain (a <u>reliable</u> system). This is a particularly sensitive and important issue for space systems, since they are often deployed far from US support bases.

Precision and Selective Lethality

The US public recently discovered (during Operation Desert Storm) what its military has long known: the enormous value of being able to strike military targets with great precision. Precision reduces the total cost required to engage targets for two basic reasons: the total number of munitions assigned to a given target can be reduced once you are assured each attempt will probably strike, and a less active agent (explosive, pyrotechnic, etc.) is required for each munition once you can select the target's most vulnerable point for engagement. More importantly, precision attacks require fewer sorties and thereby reduce the exposure of combat personnel to the danger of injury or death.

An important corollary of precision attacks involves the potential for selective lethality. A selectively lethal attack has two attributes: it strikes the desired target and *only* the desired target (thereby greatly reducing collateral, generally civilian, damage) and it can be "tuned" to levels of less than lethal force. A strategic nuclear bomb can be a precise combat system (fitted with an appropriate guidance system), but it cannot be a selectively lethal combat system—the nuclear bomb can only destroy its target.

An example will make the value of selective lethality clear. Consider the case of an important communications node (e.g., a microwave tower) standing next to a children's hospital. The task at hand is to "put the communications node out of commission." This can certainly be done by successfully dropping an iron bomb directly on the tower, but only with severe risk to the nearby children's hospital. A selectively lethal combat system might accomplish the same job with greater force economy by precisely striking the tower's antenna feeds and associated electronics and over heating or melting them. The hospital is completely safe and the tower remains standing for potential postconflict use by friendly forces once the feeds and electronics have been replaced.

Notes

[1] *New World Vistas* Study Group Briefing, subject: Surveillance & Warning, April 1995.

[2] Maj Michael J. Tiernan, et al., "In-Time Information Integration System (I^3S)," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996.

[3] Lt Col Bruce W. Carmichael, et al., "Strikestar ***2025***," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996). See also CDR Clarence E. Carter, et al., "The 'Man in the Chair' - Cornerstone of Global Battlespace Dominance," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996); Lt Col Edward F. Murphy, et al., "Information Operations: Wisdom Warfare for ***2025***," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996); Lt Col William Osborne, et al., "Information Operations: A New Warfighting Capability," AF ***2025*** Study (Maxwell AFB, Ala: Air War College, 1996); and Maj Michael J. Tiernan, et al., "In-Time Information Integration System (I^3S)," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996.

[4] John R. Boyd, "A Discourse on Winning and Losing." A collection of unpublished briefings and essays. Air University Library, Document No. M-U 43947. August 1987.

[5] Air Force Manual 1-1, Vol. II, March 1992, 283.

Chapter 3

The Integrated System-of-Systems

In this paper, the "weapon system" will be narrowly defined as the weapon itself; the platform on which it is carried; and the autonomous but interconnected surveillance, acquisition, tracking, and battle damage assessment (SAT/BDA) system needed to operate the weapon system in the desired "fire and forget" mode. The weapon system is a system-of-systems (weapon-platform-SAT/BDA) embedded in and interconnected with a much larger system-of-systems. Without a national global surveillance and reconnaissance system and associated intelligence system, no target will ever be found, assessed, and handed off. Without a secure, high-bandwidth global command, control, and communication (C^3) system, sensor information and command decisions cannot get where they need to go. Without a robust, distributed information system, the many types of raw sensor data can never become the fused all-source information essential to battle management. Without adequate support in the area of readiness and sustainment, a weapon system can not be counted on to do its job. The weapon system concepts described in this white paper must be understood in this context. By 2025, no weapon system will be truly autonomous— to operate most effectively, the weapon systems of 2025 will depend on the smooth, high-speed functioning of the total US military war-making system.

The distributed nature of the system-of-systems described above can be its greatest strength or its greatest weakness. Any critical physical or intangible nodes in the distributed system could be attacked, rendering the entire system useless. The system-of-systems must be designed carefully to minimize or eliminate all critical nodes. Critical nodes that cannot be eliminated must be protected by deception, added defenses (hardening, placement within a secure environment), or redundancy. Ideally, the space weapon system itself should be so well distributed no sensible adversary would contemplate a preemptive strike.

Only the potential weapon system concepts will be discussed in the Space Operations white paper. Some concepts for integrating the weapon system into the global information network are contained in appendix B. The information, C^3, and surveillance/reconnaissance and intelligence systems are addressed in other Air Force ***2025*** white papers.[1]

Weapon Platforms

The weapons themselves may be mounted on or fired from a space-based platform (space-based) or they may be mounted on platforms that traverse the space medium, such as an inter-continental ballistic missile (ICBM) or transatmospheric vehicle (TAV) (space-borne). Each scenario has its advantages and disadvantages, which will be detailed for each weapon system.

The space-based platform is the most responsive, because it operates immediately from the high ground of space. Possessing the unique perspective of space, space-based weapons can immediately cover a large theater of operations. This potential advantage grows as the platform's orbital altitude is increased, reaching its peak with platforms placed at geosynchronous orbit, which effectively provides access to almost half the earth's surface from a single platform. Of course, the higher the orbit, the farther the platform is from its targets. Alternatively, if the platform can be placed in low earth orbit (LOE), the range to the target can be minimized at the cost of reduced ground (and time) coverage for each platform. Given the immense volume of near-earth space, a space-based constellation can consist of many platforms, providing reliability through redundancy. A weapon system with enough space-based platforms at the proper orbital altitude(s) can potentially ensure global, full-time coverage and provide the ability to conduct prompt and sustained operations anywhere on the planet.

As hinted above, space-based platforms are not without their limits. The inexorable laws of physics demand that low earth orbit platforms have orbital periods measured in tens of minutes. Global, full-time coverage for low earth-orbiting systems will therefore require numerous platforms and/or new propulsion concepts, such as the "Hoversat," which could potentially, given enough fuel, provide loiter time by installing a jump-jetlike propulsion system on each platform.[2] Since orbits are regular and predictable, any gaps in coverage could easily be exploited by a clever adversary. Each platform must also be lifted into orbit at great cost in energy and money, unless inexpensive space lift is available by 2025. Once in orbit, each platform is

automatically difficult to service and maintain. Additionally, a truly effective constellation of platforms could easily become a high-value target in plain sight for a determined adversary. If the US is the only nation possessing such a constellation, this could invite massive active or passive antisatellite (ASAT) countermeasures that would flood near-earth orbit with debris. This debris cloud would threaten the entire world's space assets. By 2025, the ramifications of such a catastrophe would be truly global, affecting every person on the planet. This potential vulnerability could be reduced by miniaturizing and stealthing space-based platforms.[3]

The class of platforms called "space-borne" platform is the most flexible, since it can potentially begin its operation under direct human control within the terrestrial environment (on land, sea, or in the air). Servicing and maintenance are less difficult for such platforms, because they are much more accessible to human technicians. Space-borne platforms can be less vulnerable, because they can be held within the confines of sovereign US territory. Their vulnerability is also reduced because they can be made highly maneuverable much more easily than a space-based system. Promising lift concepts for space-borne platforms in 2025 are described in the AF ***2025*** Space Lift white paper.[4]

The most familiar space-borne platform is the ICBM. American ICBMs are currently configured to deliver nuclear weapons to any location on earth within 30 minutes.[5] Given the apocalyptic nature of this weapon, nuclear-tipped ICBMs are generally regarded as the ultimate weapon of deterrence—a weapon no one really wants to use (ever). American ICBMs already exist with a circular error of probability (CEP) measured in feet.[6]

The debate on the desirability of putting man in space is a long and acrimonious one. No machine can come close to the breadth and depth of mankind's abstract reasoning ability, but it is a very costly task to develop systems to launch and sustain a manned presence in space. A Spacecast *2020* White Paper (section H) makes the argument for a manned space-borne platform called a TAV, the "Black Horse."[7] The biggest advantage of the manned TAV is that it is probably the most flexible platform yet proposed for space operations simply because it is under the continuous control of a human. Given an appropriate design, the manned TAV could be quickly reconfigured to deliver special operations teams, high-value equipment and supplies, or a wide variety of munitions (in much the same fashion as a high-speed bomber).[8] Most important

of all—the TAV can put a few well-trained people at the site of a developing conflict anywhere on Earth within 60 minutes from launch.[9]

The most important disadvantage of space-borne platforms is their relative lack of responsiveness. A TAV can reach anywhere on earth within 40 minutes once it has reached orbit, but this cannot compare with a speed-of-light attack from a directed energy weapon in orbit above a target. If a space-borne platform is not already hovering "near station," this single disadvantage may be fatal in an era when response times have improved to minutes or even seconds.

Weapon Classes

The potential space-strike weapons can be broadly grouped into four categories: directed energy, projectile, space sortie and information. Information "weapons" are discussed in white papers prepared by other AF *2025* teams.[10] The rest of the weapons systems will be described in terms of their capabilities and shortfalls, and countermeasures for each system, will be discussed. Finally, each system is evaluated in light of timeliness, responsiveness, flexibility, precision, survivability, reliability, and selective lethality (desired capabilities described in chapter 2). The final result will be selection of a credible space-force application system-of-systems.

Directed-Energy Weapons—Incoherent Light

Unfiltered by the atmosphere, the sun provides an enormous flux of natural (incoherent) light in near-earth orbit. Our best measurements of this flux put the available power density at 0.1395 W/cm^2.[11] Currently, this vast power source is tapped with solar arrays to power satellites. It is conceivable that large focusing mirrors equipped with pointing and tracking and maneuvering systems could be placed in orbit to intercept and redirect solar energy onto the battlefield.[12] Single, very large mirrors (on the order of kilometers in diameter) or large arrays of smaller mirrors working in concert would be needed to make this concept useful. Even in LEO orbit, these mirrors would need pointing and tracking accuracies of 10 to 100 nanoradians to qualify as precision aimed weapons.

Optical systems (primarily collecting apertures) currently under study have been limited artificially to a size of four meters for potential launch on the space shuttle.[13] The optical substrates are made from ultralow-expansion, rigid glasses such as Zerodur[R] that are made lightweight with acid-etching techniques.[14] Larger, still lightweight structures could potentially be made from advanced aerogel materials, advanced ceramics (such as SiC), engineered composites, structurally supported optically coated plastics, suspended or spun-reflective liquids (a liquid mirror), or inflatable mirrors (reflective films on an inflatable substrate).[15] All these approaches have been demonstrated at the earth's surface with structures measured in feet or at most a few meters.[16]

Capabilities

The most likely incoherent light weapon would consist of an orbiting array of mirrors in the 10-to 100-meter class. With the proper constellation, the orbiting mirrors could intercept and redirect sunlight onto the earth's surface. The simplest use of the system would be to provide battlefield illumination on demand. Depending on the area illuminated, useful illumination could be provided by one to a 100 mirrors operating in concert. By focusing the light from many mirrors onto a single spot or series of spots, battlefield temperature could also be raised (a potential form of weather modification— see the AF ***2025*** white paper "Weather as a Force Multiplier") and optical sensors (including human eyes) could be temporarily blinded.[17] Emergency electrical power could be "beamed" to lightweight solar panels erected to intercept the redirected sunlight. To achieve more permanent effects, such as melting, as many as 100 mirrors might need to point and track on a single hardened target for a period ranging from several tens to hundreds of seconds. Spotlight beams from a few mirrors could also be used to aid search and rescue or special operations missions at night. Incoherent light weapon systems are limited in the rate at which they cause permanent damage by the fact that incoherent light, unlike coherent (laser) light, cannot be focused onto extremely small spots.

Countermeasures

Incoherent light is difficult to focus; easy to block with broadband reflective, scattering, or absorptive barriers (such as aerosol clouds); and can be decoupled from target surfaces with reflective coatings. The last two countermeasures can be defeated, however. Reflective coatings tend to degrade naturally, especially in the battlefield environment, and they can be deliberately attacked with abrading materials (sand) or absorptive liquids (paints/dyes). Blocking barriers can be attacked and eliminated by cooperative land, sea, or air forces. In particular, blocking clouds of aerosols (e.g., smoke) can be rapidly eliminated with heavy liquid sprays. A clever adversary can also delay damage to his assets by spreading the absorbed heat through rotating some targets (such as missiles) or by insulating targets with inexpensive materials like cork.[18]

Evaluation

The biggest advantage of an incoherent light weapon (if the technology could be adequately developed) is the endlessly available power supply. The range of lethality is also attractive assuming the precision pointing and tracking problems could be conquered. However, the flexibility and survivability of mirrors that may need to be hundreds of meters or even kilometers in size negates this as a viable weapon system. Furthermore, if the constellation were placed in a LEO for better accuracy, sustainment, and reliability, there would have to be many of these very large mirrors just to ensure good timeliness and responsiveness; this is neither practical nor cost-effective.

DEW—Coherent Light (Lasers)[19]

Lasers can be built as either continuous wave (CW) or pulsed devices. CW laser effects are generally described in terms of power density on target in W/m^2; pulsed laser effects are described in terms of energy density on target in J/m^2.[20] Although significant advances in this technology have been made by both Ballistic Missile Defense Office (SDIO/BMDO) and the USAF Phillips Laboratory Airborne Laser (ABL) organizations, laser technology still needs further development.[21] To date, ground-based chemical lasers have been built in the megawatt class (the ALPHA laser).[22] Phillips Laboratory is also developing a

hundred-kilowatt-class short wave CW chemical laser (SWCL) based on the oxygen-iodine chemical system.[23] Weapons-class pulsed lasers have also been built, but primarily for effects and materials research.[24]

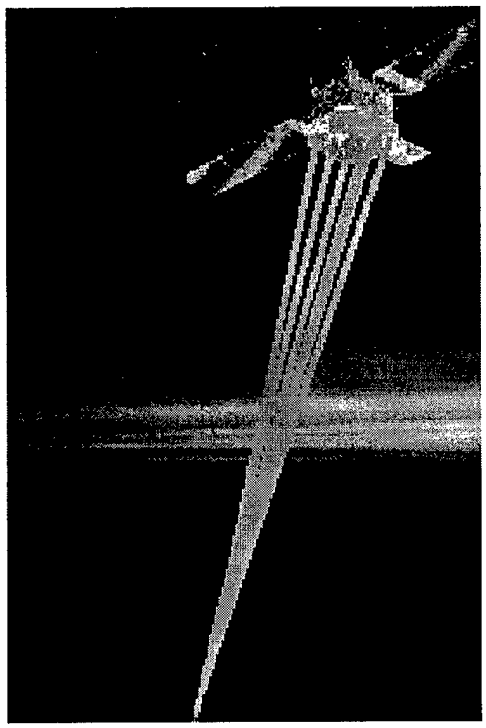


Figure 3-1. A Notional Space-Based Laser

For the space-earth geometry (see fig. 3-1), multimegawatt power is required for a CW weapons laser and hundreds to thousands of joules of energy per pulse is required for a pulsed weapons laser (depends on pulse length and pulse repetition frequency).[25] Total power or energy requirements are correspondingly higher for the earth-space-earth geometry. Constellations employing only a few space platforms (e.g., laser stations for the space-earth geometry, laser mirrors for the earth-space-earth geometry) would have to compensate for long slant ranges and correspondingly higher-atmospheric distortion by using even more powerful beams.[26] Lasers are not all-weather systems. The laser wavelength, and therefore the laser gain medium and optics train, must be carefully chosen to permit good atmospheric propagation. Clouds absorb and scatter laser light, removing power from the beam and distorting the beam's "footprint."

The size of the optics necessary to point and focus a laser beam depends on the frequency of the laser and the range to the target. For visible and near-infrared lasers, the frequencies under study for use at long

range, optics in the four to 20 meter diameter should suffice for a system in low earth orbit.[27] For a brief review of research trends in large optics, see the discussion on incoherent light weapons (see page 20).

To achieve the status of a precision-aimed weapon, laser weapon systems will require pointing and tracking accuracies in the 10 to 100 nanoradian range for systems in low earth orbit.[28] The SDIO/BMDO acquisition, tracking, pointing, and fire control program has already demonstrated a pointing stability to "below the program goal of less than 100 nanoradians."[29] It has, however, not yet been proven that large structures in earth orbit can be stabilized to these levels. This is a challenge of particular importance for a distributed laser weapon system consisting of an earth-based laser and a constellation of space-based mirrors. In this scenario, the laser beam must be relayed by several space mirrors before it reaches some targets.

Adaptive optics techniques such as the Guide Star System have been developed to correct atmospheric distortions to low-power laser beams projected from earth to space and back again.[30] Adaptive optics systems developed to date depend primarily on deformable mirrors—mirrors with small actuators that change the mirror's shape to pre-compensate the beam and correct anticipated or premeasured distortions. Further advances will be required in this technology, both in terms of bandwidth and number/size of actuators, to make this technology work for weapons class lasers. Current advances in microelectromechanical machines and nanotechnology show great promise in this area.[31] The bandwidth problem on the processing side will probably "handle itself," given the current rate of growth in semiconductor technology and continued commercial/government interest in optical processing techniques.[32] Advances in high-speed (10 Gbits/sec and up) laser communication systems are also likely to yield solutions of interest to the laser weapon designer.[33]

Capabilities

Lasers are extremely flexible weapons, producing effects that cover the full "spectrum of force." At low power, laser beams can be used as battlefield illumination devices, but with a potential added benefit over incoherent illumination. Using an invisible laser beam (near infrared) at a specifically chosen wavelength and special tuned vision devices similar to night-vision goggles, one could render the battlefield visible only

to friendly troops.[34] At low to medium power, laser beams can be used to designate targets from space, blind sensors in the laser's optical band, ignite exposed flammable objects, raise the temperature in localized regions (possible weather modification effect—see the AF ***2025*** white paper "Weather as a Force Multiplier"),[35] perform as an emergency high-bandwidth laser communication system, and serve as a laser probe for active remote-sensing systems.[36] At slightly higher powers, the enhanced heating produced by the laser can be used to upset sensitive electronics (temporarily or permanently), damage sensor and antenna arrays, ignite some containerized flammable and explosive materials, and sever exposed power and communications lines. The full power beam can melt or vaporize virtually any target, given enough exposure time. With precise targeting information (accuracy of inches) and beam pointing and tracking stability of 10 to 100 nanoradians, a full-power beam can successfully attack ground or airborne targets by melting or cracking cockpit canopies, burning through control cables, exploding fuel tanks, melting or burning sensor assemblies and antenna arrays, exploding or melting munitions pods, destroying ground communications and power grids, and melting or burning a large variety of strategic targets (e.g., dams, industrial and defense facilities, and munitions factories)—all in a fraction of a second.

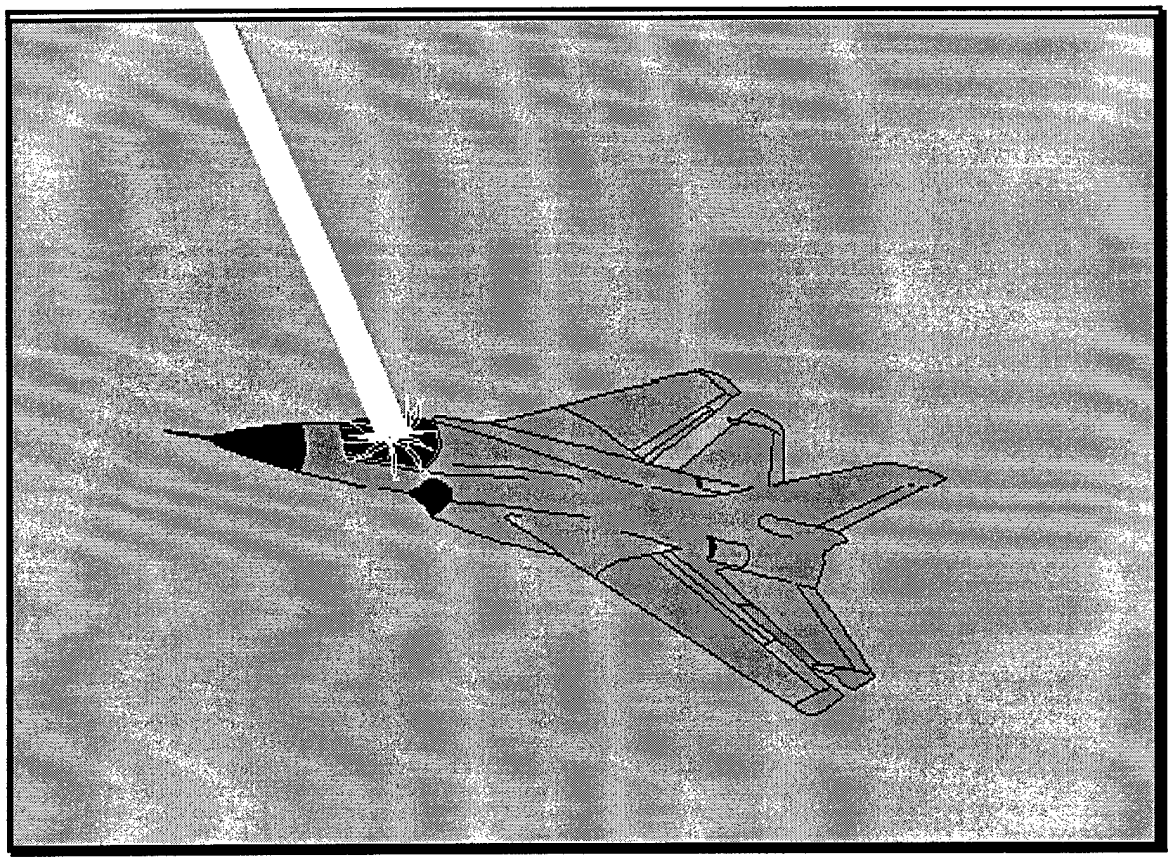


Figure 3-2. Precision Laser Strike on Aircraft

Pulsed lasers can also produce additional effects based on their ability to deliver rapidly a large amount of energy in a small amount of time. Weapons-class pulsed lasers can vaporize target surfaces so rapidly that an effect very like a rocket firing occurs. In essence, the target experiences a shove or impulse with every laser pulse. If a strong enough impulse is delivered, the laser can discriminate between valid air- or space-borne targets and lightweight decoys (although the details of this process are very difficult to satisfy).[37] If the impulse can be delivered at an object's resonant frequency, cracking and breaking will occur. Similarly, a pulsed laser trained on an object at the proper pulse-repetition frequency can stimulate infrasound vibrations, a potential form of nonlethal force projection that disrupts a target with penetrating, low-frequency oscillations.

Perhaps more significantly, the large space-based mirrors of a distributed laser weapon system (laser is ground based) can also be used as a high-quality, passive remote-sensing system.[38] By training ground-based, high-power optical telescopes on the mirrors, America's "eyes" can literally be carried to every corner of the earth. Cued by a broader area search, this capability could be the primary surveillance, battle

damage assessment, and targeting system for the laser space-strike weapon or a valuable adjunct to America's existing national technical means. With a large constellation of space-based mirrors in LOE, America's opponents could literally never be sure when they are being watched, closing the existing coverage gaps. Rather than depending on a few large, expensive assets that will inevitably become tempting targets, we can protect our surveillance and reconnaissance capability by increasing the number of "eyes" in orbit.

A weapons-class laser is useful only so long as it has fuel. This is a particular problem for a space-based laser, since it can be expensive to lift large quantities of fuel into orbit. This problem could be mitigated by using solid-state or diode laser systems that can be configured to operate on electrical power.[39] Such systems are also attractive because of their relatively high efficiency. Diode laser systems have been built with electrical efficiencies as high as 50 percent at room temperature and cooled diodes have demonstrated efficiencies of 90+ percent.[40] The most powerful contemporary diode laser arrays are still low-power systems (1 - 100 Watts), although the technology appears to be scaleable.[41] Enormously powerful pulsed glass laser systems have been built as elements of the DOE inertial confinement fusion program, but these systems are huge, inefficient, and quite fragile.[42] Clearly, further technology work is required to make these systems deployable.

Atmospheric interactions are another challenge for weapons class lasers. Aside from the obvious scattering and absorption problems, high-power CW lasers are known to cause "thermal blooming" (e.g., a severe defocusing of the beam) and "beam steering" (unintended shifts in beam direction) when they pass through the atmosphere.[43] Pulsed high power lasers, with their attendant powerful electric fields, can stimulate nonlinear optical effects such as "harmonic generation" (e.g., the inadvertent generation of other colors of light) that rob power from the main beam and make it difficult to focus the laser on the target.[44] Laser beams of higher frequency are more easily focused on the target, requiring smaller control optics and mirrors. Unfortunately, high-frequency lasers are inherently more difficult to develop, usually requiring dangerous exotic fuels and exhibiting much lower efficiencies.[45] High-frequency lasers, particularly those above the green region of the spectrum, also scatter very strongly in the atmosphere and are increasingly subject to the nonlinear optical effects previously discussed.

Current weapons-class lasers all produce beams in the near infrared (short-wave infrared or SWIR). These frequencies are strongly affected by clouds and suspended particles, and cannot always be depended on to engage targets below the cloud tops at about 30,000 feet.[46]

Countermeasures

Lasers are subject to the same basic countermeasures as incoherent light weapons and can be aided by the counter countermeasures outlined above. An additional phenomenon known as the laser supported combustion (LSC) wave can occur when a high-power laser beam strikes a target surface.[47] As the laser vaporizes surface material from the target, the hot gas can absorb even more energy from the laser beam. If enough energy is present on a short enough timescale, the hot gas is rapidly ionized, producing a hot, dense plasma. The plasma absorbs all the incident energy, essentially shielding the target surface from the direct effect of the beam. This phenomenon is generally a problem for high-power pulsed lasers and represents the upper limit to the amount of laser power one should generally attempt to put on target. At even higher incident powers, the LSC develops into a detonation wave or LSD that swiftly travels back up the laser beam, further decoupling the laser from the target.

Evaluation

The coherent light laser is an extremely attractive space-strike weapon for several reasons. It is highly responsive and timely (e.g., could strike within seconds after a decision is made to take action), it has already demonstrated high-precision capability (especially in recent ABL and SDIO/BMDO tests), and it has inherently high flexibility and selective lethality (from "lighting the battlefield" to temporarily disturbing sensors and electronics to melting or burning large or small targets). Additionally, the ground-based lasers could be relayed to or independently pointed at the space systems of aggressor nations (or organizations), serving as an important US space-control asset as needed. When not needed as a force-application or space-control weapon system, the space-based mirrors can form the basis for a very effective, survivable space-based global surveillance and reconnaissance system.

In a LEO constellation, a 20-meter mirror is certainly not as daunting as a kilometer sized one, but it is still awkwardly large and therefore expensive and less survivable. In fact, each space-based mirror would need a covering until it is used, lest it be damaged by simple antisatellite attacks or by space debris and contamination (e.g., altering the surface and rendering the mirror useless for relaying high-power laser beams). Reliability is also a concern due to the large amounts of power required by the ground-based laser and the lamentable effect of weather (clouds) on the operational availability of the system. However, a distributed laser space-strike system with ground-based lasers could certainly be maintained and even upgraded much more easily than a completely space-based system, thereby increasing the overall reliability. In sum, ground-based CW lasers coupled to space-based mirrors seem a highly effective and feasible option for a space-strike weapon system in 2025.

Neutral Particle Beam

A Neutral Particle Beam (NPB) weapon produces a beam of near-light-speed-neutral atomic particles by subjecting hydrogen or deuterium gas to an enormous electrical charge.[48] The electrical charge produces negatively charged ions that are accelerated through a long vacuum tunnel by an electrical potential in the hundreds-of-megavolt range. At the end of the tunnel, electrons are stripped from the negative ions, forming the high-speed-neutral atomic particles that are the neutral particle beam. The NPB delivers its kinetic energy directly into the atomic and subatomic structure of the target, literally heating the target from deep within.[49] Charged particle beams (CPB) can be produced in a similar fashion, but they are easily deflected by the earth's magnetic field and their strong electrical charge causes the CPB to diffuse and break apart uncontrollably. Weapons-class NPBs require energies in the hundreds of millions of electron volts and beam powers in the tens of megawatts.[50] Modern devices have not yet reached this level.[51]

Particle beams are an outgrowth of conventional atomic accelerator technology. Weapons-class particle beams require millions of volts of electrical potential, powerful magnetic fields for beam direction, and long accelerating tunnels. Current technology accelerator devices with these capabilities weigh in the hundreds of tons and require enormous power sources to operate.[52] Composed of neutral atoms, NPBs proceed in a straight line once they have been accelerated and magnetically pointed just before neutralization in the

accelerator. An invisible beam of neutrally charged atoms is also remarkably difficult to sense, complicating the problem of beam control and direction.[53]

Capabilities

Like lasers, NPBs are essentially light-speed weapons. More difficult to control and point than the light weapon, the NPB is strictly a line-of-sight device (cannot be redirected). Moreover, a NPB would be difficult and expensive to place in orbit. Many tons of material must be lifted and a complex device must be constructed under free-fall conditions. This means the power supply, accelerator, beam line, magnetic focusing and pointing device, stripper, maneuvering system, and SAT/BDA system must all be located on a large platform on orbit. A useful constellation of NPB systems in LOW must contain many platforms (dozens) to avoid gaps in coverage. A constellation in higher orbit would require fewer platforms, but it would be correspondingly more difficult to control the beam and put it on target.

In addition, the NPB is strongly affected by passage through the atmosphere, attenuating and diffusing as it passes through dense gas or suspended aerosols (e.g., clouds, and dust).[54] A space-based NPB is therefore most useful against high flying airborne or spaceborne targets. At relatively low powers, the penetrating beam can enter platforms and payloads, producing considerable heat and uncontrollable ionization. Thus, the NPB is useful at the low end of the spectrum of force, producing circuit disruption without necessarily permanently damaging the target system. At higher powers, the NPB most easily damages and destroys sensitive electronics, although it is fully capable of melting solid metals and igniting fuel and explosives. Like the laser, the NPB is inherently a precision-aimed weapon. To be most effective, an NPB weapon should therefore receive very precise targeting information (inches) and must have a pointing and tracking system with extreme stability (10 to 100 nanoradians). With this level of support, the NPB would be able to quickly disable targets by centering its effect on vulnerable points (e.g., fuel tanks, control cables, guidance and control electronics, etc.).

Like the pulsed laser weapon, the NPB can be used to discriminate against decoys in a ballistic missile defense scenario (e.g., a very difficult, but theoretically possible mission). When the beam penetrates a target, the target's atomic and subatomic structure produce characteristic emissions that could be used to determine the target's mass or assess the extent of damage to the target. The SDIO/BMDO has already

researched and demonstrated detector modules based on proportional counter and scintillating fiber-optics technologies that are reportedly scaleable to weapon-level specifications.[55]

Countermeasures

Rapid maneuvers and dense shields are the best countermeasures for an NPB. If the beam can be generated successfully and pointed at the target, it is difficult to defend against. Since the beam deposits its energy deep into the target's atomic structure, the primary weapon effect is penetrating heat deposited so rapidly it causes great damage.

Evaluation

It does not appear feasible to develop an NPB weapon system as a space-based system even by 2025 due to the weight, size, power, and inherent complexity of the NPB. Also, due to the line-of-sight restrictions, the timeliness and responsiveness would be low to moderate as the weapon "waited" for the target to move within view. The flexibility and selective lethality of the NPB is also moderate in that it can range from temporary to permanent damage. Precision is excellent in theory, but questionable in use due to earth's magnetic field and countermeasures. Since the beam is strongly affected by passage through the atmosphere, ground-or sea-based targets probably could not be targeted. Finally, the reliability of such a complex, easily-affected weapon is moderate at best. The NPB weapon system does not appear to be practical in 2025.

Electromagnetic Pulse

An electromagnetic pulse (EMP) is a sudden, high-intensity burst of broad-band electromagnetic radiation. The range of electromagnetic frequencies present depends on the source of the EMP. The high-altitude airburst of a nuclear weapon produces an intense EMP which, because of the relatively long duration of the explosion, contains strong low-frequency components (below 100 MHz).[56] Conventional EMP devices built with explosively driven, high-power microwave technology produce a less intense, very short (nanoseconds) burst composed primarily of microwave frequencies (100 MHz - 100 Ghz).[57] The range of the

EMP effect depends on the strength of the source, as the initial electromagnetic shock wave propagates away from its source with a continuously decreasing intensity.[58]

The gamma radiation produced by a fission or fusion bomb interacts with the atmosphere, creating a large region of positive and negative charges by stripping electrons from atmospheric gasses.[59] The motion of these charges create the EMP. The pulse enters all unshielded circuits within range, causing damage ranging from circuit malfunction and memory loss to overheating and melting.[60]

Militarily useful EMP can also be created by mating a compact pulsed power source (gigawatt range), an electrical energy converter, and a high-power microwave device such as the "vircator" (virtual cathode oscillator).[61] An advantage of a conventional EMP device is that it can be triggered in a shorter amount of time, thereby putting more output energy into the higher microwave frequencies (above 100 MHz). Since modern electronics operate primarily in these microwave bands, the EMP produced by conventional devices is potentially very effective in shutting down electronics. Explosively pumped EMP devices such as the vircator have another advantage: it is possible to design them to focus their EMP in a particular direction. Even a focused EMP effect produced by a conventional device will probably have a lethal radius measured only in hundreds to thousands of meters, depending upon the strength of the power source and atmospheric absorption (particularly at frequencies above 20 Ghz).[62]

Finally, the USAF Phillips Laboratory has produced compact plasma toroids with energies in the range of 10 kilojoules.[63] Directed at solid targets, the plasma toroids induce rapid heating at the surface, producing extreme mechanical and thermal shock as well as a burst of X rays.[64] The X-ray burst can also be used to generate EMP. While theory predicts the toroids will be rapidly dissipated by the atmosphere, there may well be a method of delivering high-energy plasmas to the vicinity of a target that does not involve long paths in air.

Capabilities

The few experiments with nuclear bursts in space have revealed that the size of the nuclear EMP effect is related less to the yield of the bomb than to the altitude of the burst. A 100-kiloton burst at an altitude of 60 miles would create damaging EMP over an area equal to half the US. At 300 miles, the same burst would

create EMP over an area equal to the entire US plus most of Mexico and Canada. The gamma burst from a (purely theoretical) microyield nuclear device might be used to create a more manageable EMP effect.[65]

Electrical devices exposed to an EMP burst experience effects ranging from temporary electronic disruption at the outer edge to destructive electrical overvoltages near the center. Modern semiconductor devices, particularly those based on MOS (metal oxide semiconductor) technology such as commercial computers, are easily damaged by these high-voltage transients.[66] Long ground lines, such as electrical transmission wires, act as enormous antennas for the EMP burst.[67] Power transmission and communication grids are therefore extremely vulnerable and will probably be destroyed by the burst. Any system containing semiconductor electronics, including airborne platforms, would be shut down or burned out by the burst unless it was completely protected with heavy, expensive electrical and magnetic shields, well designed electrical filters, and careful grounding. An extremely effective area weapon, the EMP produced by a nuclear airburst would undoubtedly produce severe damage to the civilian infrastructure.

A more flexible form of EMP weapon system would employ either a microyield nuclear weapon (yield below two kilotons), a conventional explosively driven EMP device or plasma technology to produce the EMP.[68] Microyield nuclear weapons or conventional EMP devices could be delivered to the vicinity of the target as a bomb (perhaps by a TAV) or as the warhead of a missile. Given the unpredictable but damaging effect of EMP on electrical and electronic equipment, these EMP "explosions" are best used against enemy platforms and facilities that depend on sophisticated electronics, particularly the enemy's command, control, and communications system (strategic target) and the enemy's air defenses (operational target).[69] Missiles equipped with EMP warheads are also effective weapons in the fight for air superiority, since modern high-performance fighter aircraft depend heavily on sophisticated, and therefore vulnerable, electronics.

The main difficulty with the nuclear EMP effect is its indiscriminate nature. The pulse travels in every direction and covers large areas of the planet, potentially damaging friendly assets just as greatly as those of the enemy. Another impediment to the use of nuclear-driven EMP weapons is the worldwide aversion to nuclear weapons, particularly nuclear weapons on orbit. Once a nuclear bomb explodes in space, the charged particles produced can easily be trapped in the earth's Van-Allen radiation belts. This would greatly increase the radiation exposure for any satellite passing near the radiation belts, disrupting or destroying poorly

shielded satellites. The charged particles would remain in the radiation belts for an extended period of time, denying the use of space to friend and foe alike.[70]

Countermeasures

Nuclear-driven EMP is omnidirectional, spraying large areas with damaging, broadband electromagnetic radiation. EMP created using more conventional technologies is characterized by directionality, relatively short range, and electromagnetic output centered in the damaging microwave frequencies. Arriving at light speed, the broadband nature of EMP makes it extremely difficult and expensive to defend against.[71] Thus, the primary countermeasure for EMP weapons is electromagnetic shielding. Shielding must be provided separately against the electric and magnetic field components of EMP and it must take into account the broadband nature of the pulse. Since a great range of frequencies are present in EMP, the designer must shield against low, medium, and high frequencies. The designer must also install protective electrical filters wherever an electrically conductive channel enters electrical systems (e.g., power cables, transmission lines, antenna inputs, etc.). Since filters perform differently at different electrical frequencies, this is a difficult task.[72] A single mistake in grounding, filter design, or shielding geometry is enough to provide entry for damaging amounts of EMP, especially in high-speed computer circuitry. This suggests the appropriate counter countermeasure. The antagonist need only break a few electrical grounds, shift the output spectrum of his EMP attack, or penetrate the shielding at a few critical points to render this countermeasure worthless. Once the energy from an EMP effect has entered a region's power grid, communications grid, or computer grid, the entire network can be disrupted for a period of time or even destroyed.

Evaluation

Due to its indiscriminate nature, nuclear-driven EMP is only appropriate in total war scenarios (zero flexibility). The conventional EMP weapon, on the other hand, shows more flexibility in that it could be directional and its effects could be localized. Both forms of EMP weapons are at least moderate in their timeliness and responsiveness, since an EMP "bomb" could potentially reach its target within 30 minutes after launch (by means of a delivery vehicle similar to the modern ICBM). The precision of the EMP weapon

is relatively low—it is generally useful only for area targets (e.g., enemy towns, large facilities, or a squadron of enemy aircraft). The survivability and reliability of EMP weapons are moderate to high, particularly if the weapons themselves are ground based (as the payload of an ICBM or surface launched ballistic missile [SLBM]). Finally, and most unfortunately, the selective lethality of EMP weapons is low. The effect of an EMP burst on any given electrical system is highly unpredictable, since it depends in great detail on the precise geometry of the engagement, the exact design of the electrical system under attack, and even the current state of the atmosphere. In sum, the conventional EMP weapon has very interesting possibilities as a potential future weapon. However, the currently unpredictable lethality, limited flexibility, and questionable precision make it unattractive as the primary component of a space-strike weapon system in 2025.

High-Power Microwave

A high-power microwave (HPMW) device also employs electromagnetic radiation as its weapon effect. Not as powerful as nuclear-driven EMP weapons, HPMW weapons create a narrower band of microwave electromagnetic radiation by coupling fast, high energy pulsed power supplies to specially designed microwave antenna arrays. Microwave frequencies (tens of megahertz to tens of gigahertz) are chosen for two reasons: the atmosphere is generally transparent to microwave radiation (all-weather capability) and modern electronics are particularly vulnerable to these frequencies. Unlike most EMP weapons, HPMW weapons produce beams defined by the shape and character of their microwave antenna array. HPMW beams are broader than those produced by NPBs and lasers, and this space-strike weapon system does not require extreme pointing and tracking accuracies (100 nanoradian stability and one meter target accuracy are adequate). HPMW weapons can be trained on a target for an extended period of time, provided the power supply and HPMW circuitry can withstand the internal currents. As a rough point of comparison, HPMW systems produce 100 - 1,000 times the output power of modern electronic warfare (EW) systems.[73]

Capabilities

This light speed weapon can be understood as a microwave "floodlight" that bathes its targets in microwave radiation. More directional and controllable than EMP, the general effect of this weapon on electrical systems is well described in the section on EMP. Unlike conventional EW techniques, the effects of a HPMW weapon system usually persist long after the "floodlight" is turned off (depends on power level employed).[74]

Laboratory experiments have revealed that modern commercial electronic devices can be disrupted when they receive microwave radiation at levels as low as microwatts/cm^2 to milliwatts/cm^2.[75] The more sensitive the circuit, the more vulnerable it is. While many electronic devices can be shielded using the same techniques outlined in the section on EMP weapons, most sensors and high-gain antennas cannot be shielded without preventing them from performing their primary functions.

HPMW weapons are inherently limited by the fundamental laws governing electromagnetic radiation. A space-based HPMW weapon must have an antenna or array of phased antennas with an area measured in acres to point and focus its beam properly on terrestrial targets. The resources necessary to construct such huge structures could be expensive to lift into orbit, and difficult to assemble in the free-fall environment. Like the NPB, the HPMW weapon is a line-of-sight device that must "see" its target before it can fire.

The level of pulsed, electrical power required to produce weapon-level microwave fluxes is now becoming available (for ground-based systems). Compact, scaleable laboratory sources of narrow-band, high-power microwaves have been demonstrated that can produce gigawatts of power for 10 to a few hundred nanoseconds. Ultrawideband microwave sources are less well developed, but research in this area appears promising.[76] A HPMW weapon should, however, be able to temporarily disrupt circuits and jam microwave communications at low-power levels.

A space-strike HPMW system would consist of a constellation of satellites with very large antennas or arrays of antennas. The farther out in space the constellation resides, the fewer the number of satellites required. However, there is a corresponding increased requirement for more power and larger antennas. Another possibility is to overlap "spot" beams from many smaller HPMW satellites on each target, gaining the benefit of high power on centroid (but a very much larger combined spot) at the cost of satellite proliferation. A useful distributed HPMW weapon system of this type might resemble the Iridium or

Teledesic constellations of LEO communication satellites (many tens to hundreds of satellites; however, the HPMWs would not be small satellites).

At low powers, the HPMW weapon system is fully capable of jamming communications when pointed at the opponent's receiving stations or platforms, in addition to its obvious uses against an enemy's electrical and electronic systems at higher power levels. Since water molecules are also known to absorb certain bands of microwave frequencies, it is also possible a properly designed HPMW weapon system could be used to modify terrestrial weather.

Countermeasures

Modern advances in microelectromechanical devices and nanotechnology could eventually result in devices and sensors so small that they are only a tiny fraction of a microwave wavelength in size. Minute devices, if small enough, could be immune to HPMW weapons simply because microwave frequencies cannot couple enough energy into them to cause damage. Advances in optical computing and photonic communications could also be a useful countermeasure. Optical devices are inherently immune to microwave radiation, although the sections of optical circuits where light is converted back into current would still have to be shielded. The countercountermeasures outlined in the section on EMP weapons are also useful for HPMW weapons.

Evaluation

The all-weather characteristics of the HPMW make it very attractive for a 2025 weapon. With a space-based version, this light-speed weapon would be high in timeliness and responsiveness. However, the flexibility and precision characteristics are similar to the nuclear EMP device—low. In addition, like the NPB, it is limited by line-of-sight restrictions. Moreover, its requirement for acres of antenna for each of the satellites required for a LEO constellation simply make it impractical. Finally, selective lethality is, like EMP, somewhat unpredictable. And by 2025, if nanotechnology is perfected and incorporated widely into electronic systems, this could negate much of the effects of a HPMW. Thus, the HPMW weapon system is not deemed suitable for space-force application in 2025.

Illusion

Sun Tzu said "all war is based on deception."[77] Military commanders have always sought to hide their intentions, capabilities, and forces from their opponents. The most prominent modern example of deceptive techniques is stealth technology, which seeks to hide platforms from sensors by reducing the various sensor cross sections (i.e., radar, optical, infrared, acoustic, etc.). Modern advances in holographic technologies suggest another possibility: weapons that project false images to deceive the opponent.[78]

Holograms are produced by scattering laser light or intense bursts of white light off objects and forming three-dimensional interference patterns. The information contained in the interference pattern is stored in a distributed form within solid emulsions or crystals for later projection with a source of light similar to that used to produce the interference pattern.[79]

Capabilities

Full color holograms can only be produced with white light sources, and even the best modern white-light holograms are imperfect.[80] It is certainly possible to make holograms of troop concentrations, military platforms, or other useful objects, although the larger the scene the more difficult it is to produce the proper conditions to create a convincing hologram. No credible approach has been suggested for projecting holograms over long distances under real-world conditions, although the Massachusetts Institute of Technology's Media Lab believes holographic color projection may be possible within 10 years.[81] Holographic and other, less high-technology forms of illusion may became a potent tool in the hands of the information warriors (see the AF *2025* information warfare white papers).[82]

Countermeasures

The best countermeasure for holographic illusions is the use of multiple sensor types. The most convincing optical illusion could easily be exposed by its lack of an appropriate infrared or radar signature. The likely proliferation of sensors and sensor types on the battlefield of 2025 makes the use of merely optical illusions a temporary expedient, at best. Nevertheless, considerable confusion could be created, at least

temporarily, by projecting false infrared signatures (platform exhausts) or radar signatures (missiles) or by concealing one type of platform within the illusion of another type (or of nothing at all— a form of camouflage).

Evaluation

Illusion weapons are and will probably continue to be too limited in the 2025 time frame. The flexibility is low, precision uncertain, survivability and reliability are low, and the selective lethality involves deception only. With the proliferation of sensor devices projected for 2025, the attempt at deception would likely be detected so quickly as to have little effect.

Projectile Weapons

Projectile weapons are most easily described by dividing them into two classes: ballistic missiles (BM) and kinetic-energy weapons (KEW). The ballistic missile is commonly used as a high-speed means of delivering a weapons payload over long distances with adequate precision to strategic targets. The kinetic-energy weapon works on the simple concept of delivering a mass at extremely high velocities to the target. The basic kill mechanism for a KEW is its kinetic energy (KE) as calculated by the simple formula KE = 0.5 x (total mass) x (velocity)^2.[83] In general, the more kinetic energy delivered, the more damage done to the target. This places a premium on achieving high speeds, since the kinetic energy depends on the square of the weapon's velocity.

Projectile Weapons—Ballistic Missiles

Ballistic missiles are popular with many countries today due to their capability to deliver a payload to the country next door or to a country on the other side of the world. They can even be used to deliver satellites into space (Atlas and Titan IVs are popular in the US). Their fuel can be liquid or solid and they are fairly reliable. The guidance systems can use global positioning system (GPS) receivers or inertial navigation systems and US systems are known to be very precise (measured in feet). Finally there is a wide

range of possible payloads: nuclear warheads, chemical/biological devices, submunitions, solid masses, satellites, nonlethal payloads like foams or a debilitating gas, and so forth.

Capabilities

The modern ICBM/SLBMs are strategic weapons of deterrence. As such, they inevitably carry devastating nuclear payloads. However, this is not the only possibility. With a CEP already measured in feet, ballistic missiles (theater or intercontinental) could be configured to carry more conventional payloads.[84] The simplest useful payload is a solid tip (essentially a ton of cement in the nose). Few fixed targets could resist the sheer momentum of several tons of material delivered precisely at high speed from space. A simple variation on this approach replaces the solid tip with a high explosive charge. Equipped with the proper high speed fuse and possibly a shaped charge, this weapon could be very effective against many hardened facilities, especially shallowly buried bunkers or tunnels.

A ballistic missile could also be configured to carry a variety of submunitions. A reentry vehicle could be equipped with many long, dense rods that, when properly dispensed at high speed, would be excellent bunker busters. Alternatively, the reentry vehicle could contain hundreds or thousands of metal or ceramic flechettes (darts) designed to shred area targets such as enemy bases, weapon-making facilities, or threatening troop concentrations. The conventional EMP bombs described previously could be delivered to enemy C^4I, air defense, and industrial facilities, disrupting or damaging all electronics without necessarily exacting a high cost in lives. Finally, a ballistic missile could be configured to deliver some form of nonlethal payload such as hardening foam, irritating gas, or foul smelling liquid.[85]

As regional wars in the Middle East have recently demonstrated, it is also possible to deliver chemical and biological weapons (CBW) with ballistic missiles. These unsettling, but potentially very effective area weapons share several disadvantages with nuclear weapons. CBWs are condemned by most nations as cruel and unusual weapons. Preemptive use of these weapons certainly invites worldwide condemnation. CBW devices are also uncontrollable once released—the areas affected are denied to friend and foe. Worse yet, chemical and biological agents are spread uncontrollably by environmental and natural vectors (e.g., insects and animals). In their current form, CBW devices are decidedly not precision weapons.

Countermeasures

Ballistic missiles, whether theater or strategic in nature, are a particularly high-value target for space-strike laser weapon systems. Ballistic missiles spend tens to hundreds of seconds in the boost phase (theater ballistic missile [TBM] versus ICBM) followed by tens of seconds to tens of minutes in the postboost phase.[86] These missiles are easily detected by their plumes only during boost phase, the shortest phase of their trajectory. During this brief interval of vulnerability, a light-speed kill by a space-based or space-borne laser weapon system can settle the problem before it has the opportunity to deploy MIRVs (multiple independently targeted reentry vehicles). In general, ballistic missile countermeasures have been addressed in great detail by the Ballistic Missile Defense Organization. The solutions range from direct interception by high-speed rockets and missiles to airborne and ground based-high energy laser strikes.[87]

The appropriate countercountermeasures are obvious. Stealthy reentry vehicles could be built that elude ground- and space-based sensors, although the designer would be forced to address optical, infrared, and multifrequency radar problems simultaneously. Alternatively, very small, very agile reentry vehicles that greatly complicate the problem of terminal defense could be designed.

Evaluation

Most of these missile-delivered weapons could be built today. All of the essential technologies, including precise delivery, are already available. The flexibility of the/a ballistic missile system is moderate, precision good, survivability may be tenuous in 2025, reliability is good, and selective lethality is limited with this system. Because of these limits on selective lethality and potential survivability problems, the ballistic missile will probably not be suitable for space force application in 2025.

Projectile Weapons—Kinetic Energy

This type of projectile weapon is closely related to the solid-tipped ballistic missile. Kinetic-energy weapons come in two classes related to their velocity—the Kinetic Energy Penetrator (KEP) and the Hydrodynamic Penetrator (HP).[88] The KEP has a maximum impact velocity of 3 kilofeet per second (kfps),

about the maximum speed of an SR-71 Blackbird. The KEP destroys the target by shattering it with an enormous blow. Since some areas of a target are more vulnerable to shattering blows than others, precise targeting is necessary for an effective KEP.

The HP has a minimum impact velocity of 8 kfps. When a penetrator strikes a target at this extreme velocity, both target and penetrator react to the collision as if they were fluids (their behavior described by hydrodynamic equations of motion). The impact attacks the molecular composition of the target, spreading dense impact shocks at enormous speed.

A nagging problem for KEW systems is the heat and shock generated on reentry. This can affect the precise delivery of the weapon. An exciting new concept has been proposed that promises to ameliorate this problem. By concentrating a laser beam in the area immediately in front of the hypervelocity KEW, it is possible to create a laser-supported detonation wave (called an "air spike") that partially shields the KEW. The air spike transforms the normal conical bow shock into a much weaker, parabolic-shaped oblique shock.[89] Researchers estimate that a properly designed air spike could decrease the effects of shock and heat on a hypervelocity object by over 75 percent (making Mach 25 seem like Mach 3).

Researchers have also experimented with enhancers for the two basic classes of KEW. Pyrophoric compounds might be added to increase lethality by generating intense heat. Provided extremely high-speed fuses could be developed, explosive charges might be added to increase the weapon's ability to penetrate the target's outer shell. The dense rods or flechettes mentioned above as submunitions for ballistic missiles might also be used by a KEW to increase its area of effect, provided the submunitions could be dispersed properly at these enormous velocities. It has been suggested that low-speed submunitions or dispersed EMP bombs might be used to help the KEW penetrator overcome defensive systems and reach the target.[90]

The high velocities needed by KEW systems can be generated chemically (by rockets) or electromagnetically (by the "rail-gun"). The rail-gun consists of a long, usually evacuated, tube containing electrically conducting rails and surrounded by high-power electromagnets.[91] The projectile is the only moving part. The projectile is placed on the rail and a large current is generated within the rail and the projectile. Simultaneously, time-varying magnetic fields are induced in the magnets with powerful pulsed power supplies. The resulting electromagnetic force rapidly accelerates the projectile to extreme velocities. Rail-guns are being actively studied by the US military, although to date researchers have only been able to

accelerate small masses to hypervelocity. Velocities achieved 20 years ago have not been exceeded to this day. Navy technologists report that their main problem lies in developing small, high-power, stress-resistant power supplies.[92]

Finally, an interesting variation on the HP concept involves the use of meteorites as a weapon.[93] Naturally occurring meteorites at least the size of large houses (necessary to survive drag-induced heating in the atmosphere) could be intercepted in space and redirected to a terrestrial target. If done with sufficient stealth and subtlety, the impact could even be "plausibly denied" as a natural occurrence. Meteorites 30 feet in diameter could be counted on to generate nuclear weapon-size explosions (20 kilotons), but without the lingering radiation.[94]

Capabilities

The capabilities of a kinetic-energy projectile would be similar to the better known precision guided missiles (PGMs). The kinetic-energy projectile would most likely be a PGM without explosives, but which travels so fast it can take out surfaces as well as targets buried hundreds of feet underground. Moreover, the kinetic-energy projectile can take out single targets or area targets (using hundreds of flechettes or rods). Besides precision, perhaps its most attractive capability is that it is an all-weather weapon. Finally, KEW are versatile in that they could be safely launched from the US and find their targets anywhere in the world within 30 minutes or they could reside in relatively small satellites (storage containers) in LEO waiting to be dispensed and reach their target within a few minutes. These rather simplistic satellites could easily be integrated with the global information network (GIN), the "utilities," and a command and control system.

Meteors can be hundreds of magnitudes more deadly than KEW. However, there are several significant shortfalls to meteorites as weapons. They are hardly a timely weapon— the war fighter must patiently wait for nature to deliver his "ammunition." The uneven shape and heterogeneous composition of meteorites makes it highly unlikely they can be guided precisely to a target. Since it is also impossible to predict how much of the meteorite will survive the fall from space, meteors are best classified as area weapons with a very uncertain radius of effect.

Countermeasures

The countermeasures against KEWs are basically the same as for ballistics missiles, except that the KEWs are envisioned to be considerably smaller. Thus, they would be more difficult, if not impossible, to attack once they begin their descent from space. The countermeasure would best be applied against the KEW delivery platform be it a small satellite, a TAV, or some sort of pod.

If the KEW uses GPS for terminal guidance, it may be possible to jam the GPS signal. This may be especially effective for protecting mobile targets (the KEW GPS receiver would require real-time updates to hit these mobile targets). However, this would do nothing to prevent the use of KEWs that work strictly on trajectory or an internal guidance and targeting system against static targets.

Evaluation

Meteors, as a weapon, are impractical, even in 2025. Of course, since KEW technology is available today, it will certainly be even more precise and deadly in 2025. A few hundred KEW "storage containers" placed in a LEO would make the timeliness and responsiveness very high (within a few minutes). Precision and reliability would also be high. However, the flexibility and selective lethality would be low—total destruction would be the only choice, unless used as a demonstration of power. Thus, the KEW would not be the ideal weapon of 2025. Due to its all-weather capability, however, it would be a good complement to some other weapon capability.

Space Sortie—Transatmospheric Vehicle

There are numerous single-stage-to-orbit (SSTO) vehicle concepts under active study that should result in development of a TAV. These TAV concepts, sometimes referred to as reusable launch vehicles (RLVs), are plausible enough that McDonnell/Boeing, Lockheed/Martin, and Rockwell are all investigating proprietary concepts. Both the Rockwell and Lockheed/Martin RLV concepts are vertical take-off/horizontal landing, have longitudinal payload bays (like the shuttle), and are being designed for commercial payloads. The McDonnell Douglas/Boeing RLV concept is similar except it is a vertical take-off/vertical landing.[95] The US Government (USAF, NASA) is in partnership with McDonnell/Boeing, Lockheed/Martin, and

Rockwell to develop a military/commercial version currently called the X-33. They expect to fly the X-33 RLV in 1999.[96] The McDonnell Douglas/Boeing RLV is a vertical take-off/landing system with eight rocket engines. It navigates using GPS, will use 200-foot pads instead of runways, and is designed for low maintenance and infrastructure. Development costs are expected to be about the same as a new commercial airliner (Boeing 777).[97]

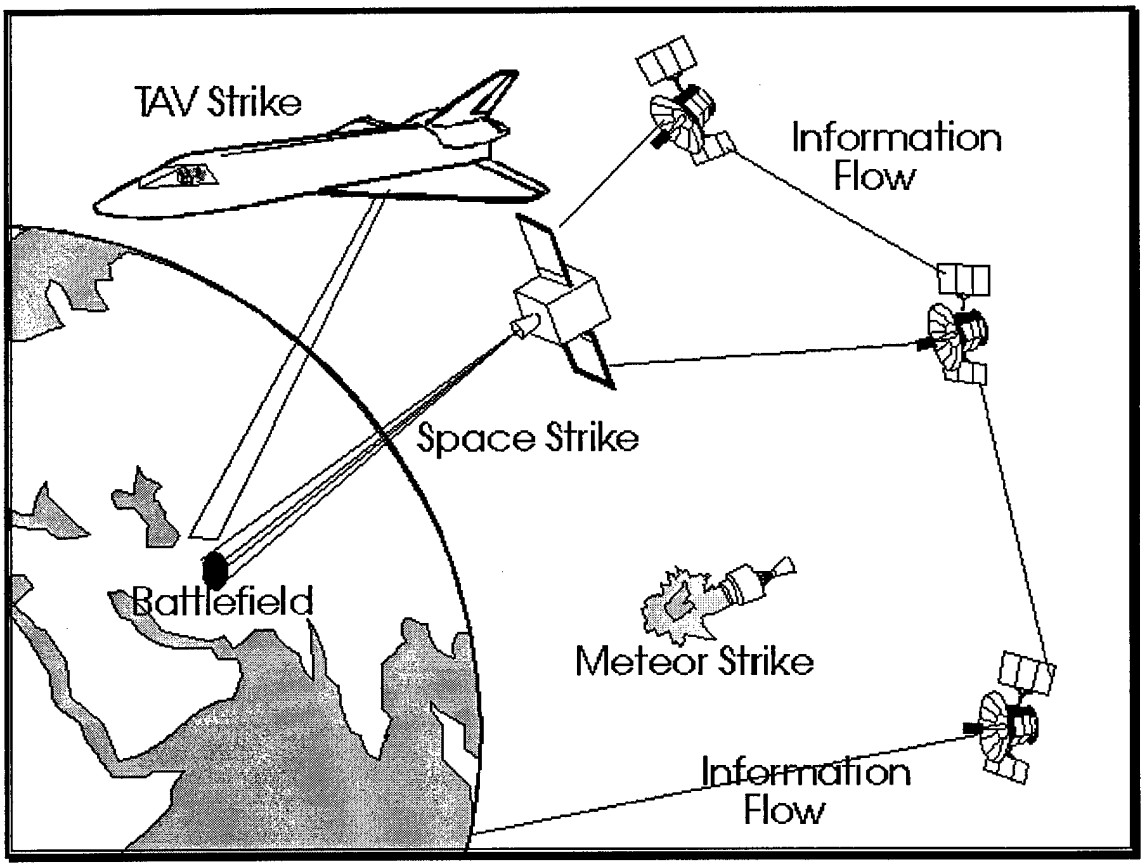


Figure 3-3. The TAV in its Native Environment

Whichever concept the US government and industry decide to pursue, a revolution must occur in TAV engine technology before it becomes viable.[98] Conventional rockets have low dry weight (without fuel) and high gross take-off weight (lots of fuel and oxygen) to reach the Mach 25 speeds necessary to reach space. Rockets give up maneuverability and ease of handling in the atmosphere by being so configured. Air breathers, on the other hand, have high dry weight and low take-off weight because they use the oxygen in the atmosphere as part of their fuel. They have great maneuverability, but have considerably lower top speeds.

Furthermore, the major costs of a TAV are its dry weight components. Fuel, although relatively inexpensive, consumes 80+ percent of the total gross weight, leaving only 3-6 percent for cargo. The 2025 TAV must have moderate dry weight and gross weight, which may be obtained using a combination of rocket and air-breathing technology called a rocket-based combined cycle air-augmentation.[99] This will require a revolution in rocket technology. But three pieces of this revolution will very likely be available by 2025.

The first piece of the revolution deals with the advanced technology "pulse detonation wave" combustion process in a rocket instead of the conventional "constant volume combustion" process. Researchers believe this technology would increase the pressure during detonation by 20 to 40 times and significantly increase the specific impulse (I_{sp}) of the fuel. More importantly, it will decrease (by 20 to 40 times) the pressure, heating, and wear and tear on the fuel turbine-feed pumps that are the cost, reliability, and safety concerns of rocket engines.[100] Thus, rocket engines could be made cheaper, smaller, and more reliable by orders of magnitude. Rocketdyne and Adroit have both been working aggressively in this area.

The second piece of the revolution concerns the "air augmentation" portion of the engine. The leading concept involves wrapping sheet metal with an inlet around the base of the engine. This technique, properly applied, should "squeeze" every bit of oxygen possible out of the "sensible atmosphere" and make it available as part of the fuel. This would make the air-breathing part of the engine useful at altitudes of up to 120,000-140,000 feet and increase the thrust by 300 percent. This alone could double the payload.[101]

The final piece deals with the combuster in the air-breathing portion of the engine. The combuster creates the highest pressure in the engine as the fuel mixes with oxygen, burns, and then provides thrust. As speed increases, between one-third and one-half of the thrust comes not from the fuel, but from the heat and pressure within the engine. Under these conditions, the fuel is not efficient and energy losses increase dramatically, heat increases, and sheer stresses increase resulting in lower final speeds. However, a revolutionary premix, shock-enhanced (oblique standing detonation wave) combustion engine could increase the I_{sp} by 30 percent. This would allow the combuster to be reduced in length by 75 percent, thus decreasing the weight of the engine significantly.[102]

The final design entails placing the rocket engine inside the air breather. At low Mach speeds, the air breather would be used alone. At Mach 15 to 20 during pull up to space, the rocket would light up and pressurize the air breather, keep burning atmospheric oxygen (would not have to carry nearly as much), and

create a synergistic effect using both the rocket and the air breather. The result could be a highly efficient, viable engine for the 2025 TAV.

Lightweight structures are another must for the 2025 TAV. Dr Dennis Bushnell, Chief Scientist for NASA at Langley, Virginia, reported that the Japanese are working on a Carbon-60 (Fullerine) material that is lightweight, but is an order of magnitude stronger than the most modern of composites. He also stated that advances in static stability will help the TAV of ***2025***.[103] Currently, spent uranium is placed in the nose of vehicles for ballast (keeps center of gravity forward of center of pressure to prevent tumbling); researchers, however, are investigating placing "longitudinal vortices" and using active controls to maintain this positive stability instead of weights. This would allow designers to move things around for efficiency without worrying as much about the center of gravity. Finally, Dr Bushnell reported that the Navy is aggressively researching "designer aerodynamics" and circulation control of air-breathing vehicles. With sensors and actuators, this could give the TAV "bird-like flight" characteristics. Thus, it truly could become an airplane and a space plane.[104]

In addition, the 2025 TAV should be easily upgradeable as technology improves. We must not produce a TAV that will become obsolete and difficult to maintain even as we are trying to build it. Modularity of design will be important. For example, as guidance system technology is improved and further miniaturized, maintenance workers can expect to pull out a "black guidance box" and replace it with a new, improved version (lighter, less volume).

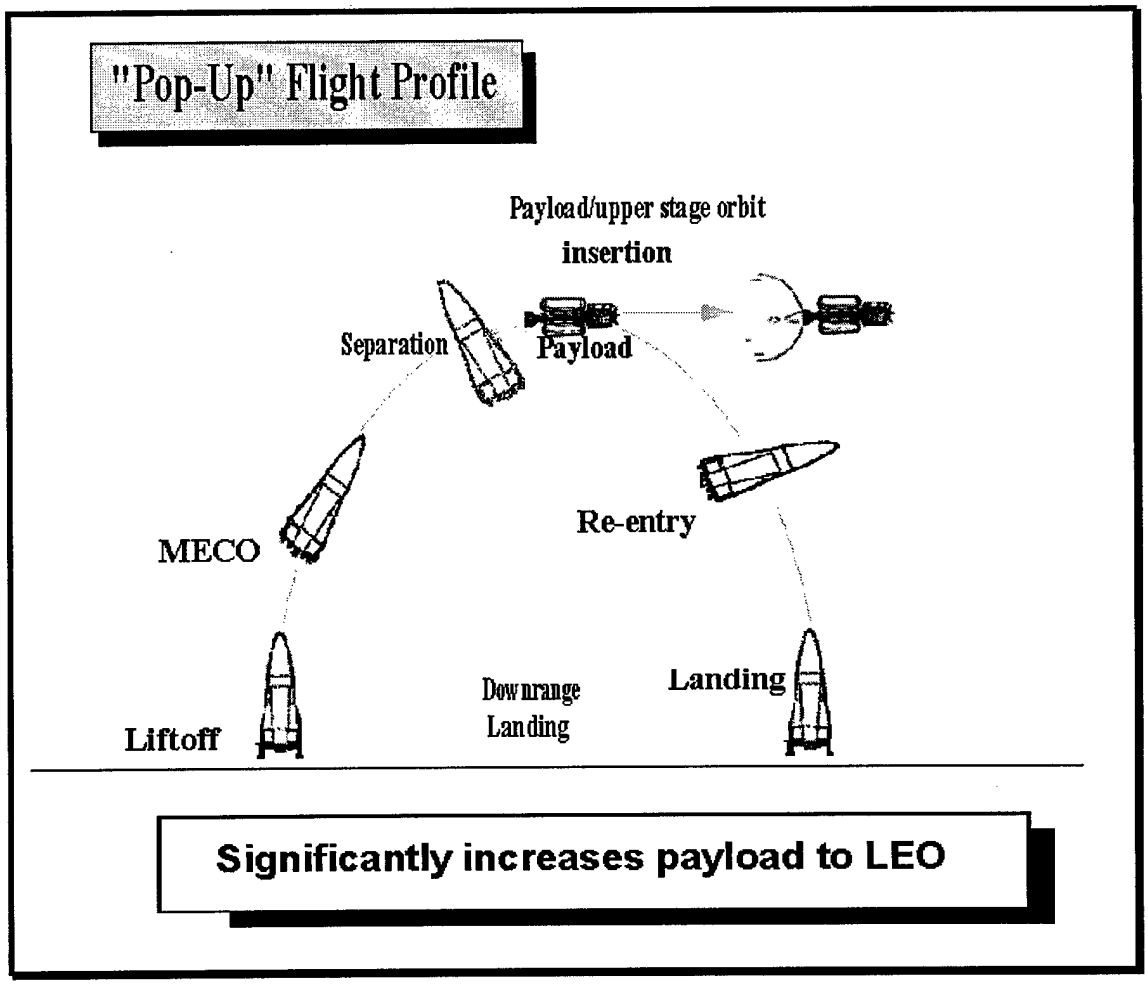
Finally, all the systems of the TAV must be integrated with all the other systems that interface with it. On-board (guidance, maneuvering) and off-board (surveillance, some processing) systems must all work together as a distributed "system-of-systems."

Capabilities

The TAV "fleet" of 2025 will possess incredible capabilities. The TAVs will have highly efficient, reliable engines that perform equally well in the atmosphere or in space; the TAV structures will be made of strong, lightweight composites that are easily replaceable; and the payload capability (weight and volume) will be versatile and adaptable to many different types of payloads and missions. Commercial carriers will

exist that are capable of lifting 20,000 to 40,000 pounds into LEO.[105] The Black Horse TAV concept calls for a payload of approximately 5,000 pounds into a LEO (although some critics believe that due to design flaws, it cannot take any payload into orbit),[106] whereas the X-33 concept proposes a payload of 10,000 pounds (polar orbit) to 20,000 pounds (eastern LEO).[107] The military requirement will probably be in the 10,000 to 20,000 pound range. A versatile TAV should certainly be able to carry payloads for at least three basic missions: 1) to deploy/retrieve small to medium satellites (large satellites are "dinosaurs") for many, although not all, missions; the trend is towards small/microsatellites; thus, all of the TAV concepts should suffice for low and medium earth orbit missions; 2) to carry a small team of special operations forces along with their operational gear to crisis spots throughout the world (TAVs would probably need a 2,000 pound capacity to carry four-man teams[108]); and 3) to perform as a sensor and weapon platform (for short periods of time analogous to aircraft sorties).

The satellite deployment/recovery capability could be critical for fielding or reconstituting space-based components of weapon systems in 2025. In fact, using a "Pop-up" flight profile (see fig. 3-4), the TAV could potentially launch multiple satellites and grant access to all orbits (e.g., LEO, Polar, Sun Synchronous, Molniya, geosynchronous earth orbit (GEO). In an eastern LEO, the TAV would be able to deploy 15 1,000-pound small satellites and pick up four to bring back. It could deploy as many as four satellites to a GEO orbit..[109] This capability should make the TAV extremely flexible for space-force applications.

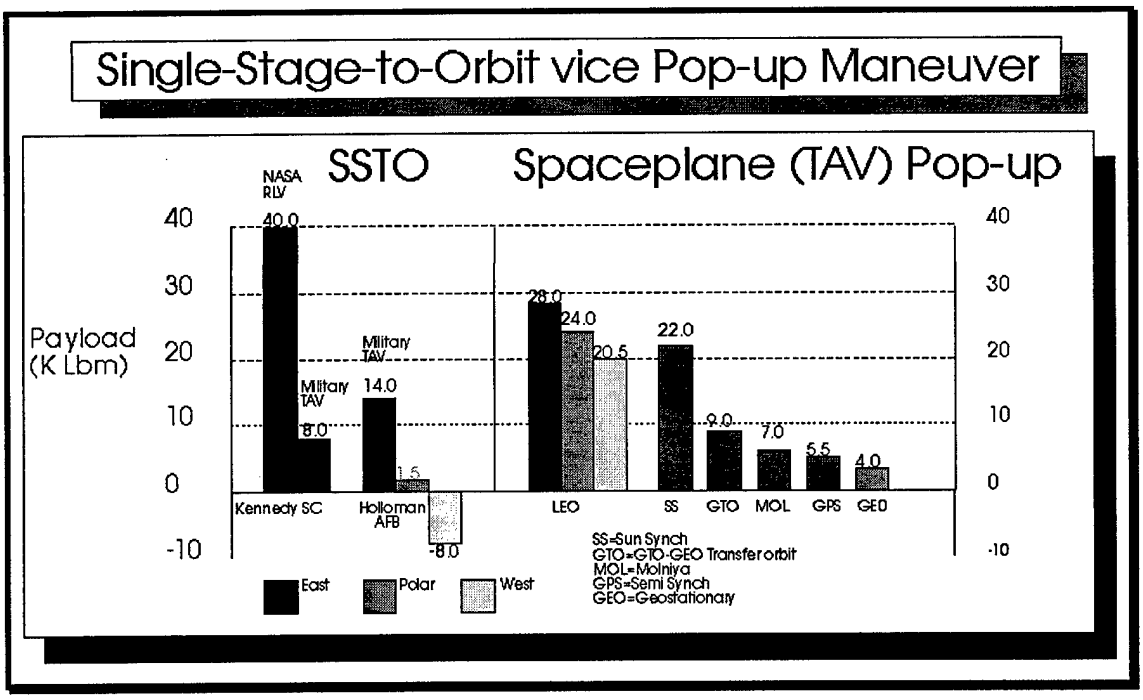


Source: Briefing, Phillips Laboratory PL/VT-X, "Military Spaceplane Technology and Applications," January 1996

Figure 3-4. Pop-Up Maneuver

Other necessary capabilities/requirements for a TAV-type vehicle include all-weather performance, rapid call-up time, short turn-around time, long service life, low-maintenance engines, vibration-resistant systems and structures (to survive reentry and "hypercruise" speeds near Mach 25), all azimuth earth access, global range of operation, and the ability to be upgraded easily and inexpensively.[110] The requirements for all azimuth access and global range of operation mean that the TAV will probably need refueling capability. A study by W. J. Schaeffer Associates (4 February 1994) on the feasibility of an aerially refueled "spaceplane" concluded this capability "appears feasible and practical."[111] Refueling could occur in the atmosphere or in space. Call-up times on the order of a few hours and turn-around times of from six hours

(emergency) to 24 hours (routine) will probably be required.[112] More importantly, the TAV of 2025, once launched, will reach anywhere in the world within 60 minutes or less. Of the 60 minutes required, approximately 20 minutes would be from launch to space plus another 40 minutes to the target area (a TAV could be over the most likely target areas after only 20-30 minutes in space).[113] The 2025 TAV could also deliver multiple payloads (e.g., laser, KEW, reconnaissance, satellites, strike team, ASAT weapon, etc.) depending on the mission.



Source: Briefing, Phillips Laboratory PL/VT-X, "Military Spaceplane Technology and Applications," January 1996

Figure 3-5. Pop-Up Enables Flexible Transpace Operations

Countermeasures

Like aircraft, TAVs are naturally vulnerable on the ground and would need protection. Moreover, TAVs emit a variety of easily detected signatures (e.g., radar, enhanced infrared due to high-speed passage through the atmosphere, and acoustic) and are also vulnerable to attack during launch and landing. TAV launch facilities could be safely located in the continental United States (CONUS) but if a team of "space marines" must be landed outside the CONUS, the TAV and its payload would be vulnerable to a variety of weapons (space-based, airborne, or terrestrial) and tactics. Fortunately, a force of three or four TAVs (analogous to a

flight of modern combat aircraft in tactical formation) could be extremely difficult to attack if at least one is used as protection for the others. Another consideration is that, during conflict, any US spacecraft (particularly if it is a manned platform) would instantly become a high-value, high-priority target. Thus, ASAT-type weapons could be directed against a TAV in endo- or exo-atmospheric flight. However, the highly maneuverable TAV, if configured to carry high-speed precision weapons onboard, could itself become an "anti-ASAT" weapon—the attacking ASAT would then become the target.

Evaluation

Flexibility, provided by its ability to put human judgment at the developing crisis location rapidly, is the greatest asset of the TAV. Responsiveness and timeliness, while not in the same class as space-based light-speed weapons, are at least moderate (hours for call up followed by 60 minutes maximum flight time). Since a TAV could carry a broad range of payloads (e.g., many different types of weapons, a special forces unit, or even limited space maintenance and repair facilities), it rates high in precision, survivability, and selective lethality. Reliability as a weapon system for force-application or space-control missions (see AF ***2025*** counterspace white paper) could be very high, since the TAV could launch active radar or inertially- uided weapons (such as KEW devices) through weather conditions that would baffle directed-energy weapons, provided the developmental problems that have plagued spaceplanes can indeed be solved.[114] When not needed as a weapon system, the TAV could "earn its keep" through a variety of useful, nonbelligerent missions such as rapid replenishment/repair of small satellites, high-value airborne/spaceborne surveillance and reconnaissance sortie, emergency clandestine low probability of intercept (LPI) communications or command and control link, or (properly configured) even as a truly high-speed airborne warning and control system (AWACS)/joint surveillance, tracking, and radar system (JSTARS) platform. A small fleet of TAVs would be a highly flexible, adequately responsive component of an effective space-strike system in 2025.

Summary —The System-of-Systems

A careful evaluation of the weapon systems discussed in this chapter leads us to eliminate most candidate systems based on the desired capabilities of timeliness, responsiveness, flexibility, precision,

survivability, reliability, and selective lethality. A summary of the evaluation can be found in table 1, where the following potential weapon systems are listed: the distributed laser (DL) (e.g., earth-based laser or space-based mirror), the space-based laser (SBL), the TAV itself, the space-based HPM, the EMP weapon (as a small, conventionally triggered bomb only), the hypervelocity KEW (as a payload on a TAV), other projectile weapons (ballistic missile payloads or BM), space-based NPB, and the "illusion weapon" concept (ILL). Each potential system's "score" against a desired capability is given as high, medium, or low.

Table 1

Summary Evaluation of Potential Weapon Systems

	DL	SBL	TAV	HPM	EMP	KEW	BM	NPB	ILL
TIMELINESS	HIGH	HIGH	MED	HIGH	MED	MED	MED	MED	HIGH
RESPONSIVENESS	HIGH	HIGH	MED	HIGH	MED	MED	MED	MED	HIGH
FLEXIBILITY	HIGH	HIGH	HIGH	HIGH	HIGH	LOW	MED	LOW	MED
PRECISION	HIGH	HIGH	HIGH	LOW	MED	HIGH	HIGH	HIGH	MED
SURVIVABILITY	MED	LOW	HIGH	LOW	HIGH	MED	HIGH	LOW	MED
RELIABILITY	MED	MED	MED	MED	MED	HIGH	HIGH	MED	LOW
SELECTIVE LETHALITY	HIGH	HIGH	HIGH	MED	MED	LOW	MED	MED	LOW

Large space-based weapon platforms are eliminated because they are not considered to be survivable in 2025 or practical in terms of weight, cost, size and in most cases power requirements (incoherent light, NPB, HPMW weapons). EMP weapons are eliminated because they lack flexibility, are not precise enough to limit collateral damage, and their selective lethality is at best questionable. Projectile weapons, while very precise, are eliminated because they are not considered to be highly flexible or capable of providing selective lethality. ILLs are ruled out because they do not provide the redundant signatures (e.g.., optical, infrared, radar, and so on) that would make them sufficiently believable and because these notional weapons, too, do not provide selective lethality.

As we carefully studied the characteristics and capabilities of the various candidate weapon systems, it became evident there was no one "super weapon system" that could do all the things the US government

would require in 2025. This is not a surprising conclusion—earth-based weapon systems have always complemented each other. We call the weapon system-of-systems that best addresses the US government's likely requirements in 2025 and incorporates an optimum mix of desirable capabilities the *Global Area Strike System* (*GLASS*). GLASS consists of: 1) a directed-energy weapon (DEW) system based on the continuous wave laser described previously, and 2) a TAV system (manned or unmanned), which will be used primarily as a weapons platform. The DEW system is composed of powerful earth-based lasers that "bounce" their high-energy laser beams off of space-based mirrors to reach the target. The desired TAV is a flexible platform capable of employing compact, onboard DEWs and KEWs when the space-based mirrors are out of range, disabled, or otherwise unavailable for use. The TAV can also deliver KEWs to mobile or stationary targets; drop special operations strike teams to any hotspot in the world; carry EMP bombs, jamming devices, or a myriad of more conventional weapons; and carry small satellites into space or retrieve them from orbit. Perhaps most significantly, the TAV can also be used to sustain and maintain the GLASS constellation of space-based mirrors.

What would the GLASS system of systems look like? The DEW system would consist of a distributed complex of earth-based lasers (located in the CONUS) that direct their beams (continuously variable in output power) to a constellation of adaptive, space-based mirrors (10 - 20 meter diameter depending on the laser wavelength and spot size desired at the target). The mirrors would have moveable covers to protect their surfaces when they are not in use, solar cells and/or chemical fuels for prime power (with small, efficient batteries for backup), an advanced pointing and tracking system, an on-orbit attitude control and maneuvering system and adaptive beam-sensing and control system (a more capable version of today's Guide Star technology), and a communications package for C^3 and for linking with the global information network described in appendix B. The mirrors would be placed in one or more low earth orbits (250 - 500 nm) to reduce the target range, thereby minimizing the amount of laser power required to accomplish the mission and decreasing the pointing and tracking requirements. The use of a number of different orbits and inclinations might be necessary to increase the survivability and operational availability of GLASS. According to reputable studies, at least 24 - 32 orbiting platforms would be needed to ensure reasonable global access.[115] However, the requirement for near instantaneous response could drive the size of the space-based

constellation to over one 100 mirrors. Obviously, the actual size of the constellation of mirrors must be determined by a detailed technical analysis beyond the scope of this white paper.

Capabilities

The capabilities previously discussed separately for the laser, the KEW, and the TAV apply to the GLASS. It will be able to perform strategic, operational, and possibly tactical missions. All of these will involve targeting and applying force to both static and mobile targets. The effects on and types of targets for the lasers, the KEWs, and other possible weapons (using the TAV as a platform) were discussed at length earlier in chapter 3.

It is important to note that the laser and/or TAV (with KEWs/other weapons) give the GLASS a full range of lethality—from temporary denial and disruption to partial damage to complete destruction (as described in the sections on the laser and KEW weapons). The laser provides near instantaneous response time, a light-speed attack that negates all conceivable forms of active defense, and the ability to strike anywhere on the planet. The requirement for a global, all-weather strike capability might be met by using a different laser wave length to "burn" a hole through clouds, smoke, or aerosols (using the same mirror or a different one) or by employing alternative weather-control techniques before striking for effect. With a well-designed, distributed laser network based in the CONUS, there should always be several ground-based lasers with clear enough skies to fire. However, when times arise when it is impossible to use the laser (e.g., when the target itself is "weathered in"), the TAV will be able to respond to crises on short notice (2 - 6 hours depending on container package required), putting human judgment and human adaptability "on site" as needed.

In the world of 2025, the GLASS can become America's "forward presence without forward basing." This system-of-systems can be used to extend America's eyes and fists around the globe in near real-time while minimizing the need for vulnerable overseas infrastructure and forward deployment of personnel. The GLASS can be global power and global awareness all in one package, and without actually placing any weapons in orbit (TAVs carry weapons *through* space in a manner entirely analogous to the modern ICBM).

The GLASS is a powerful concept, but it cannot function independently. Both the DEW and TAV-mounted KEW will require real-time external handoff of precise target location (and possibly target

characteristics); a credible "identification - friend or foe" (IFF) capability; and a secure command and control system. The DEW will also require real-time information on battlefield, atmospheric, and space weather conditions that could affect beam propagation and target coupling. Beam-control systems with submicroradian pointing and tracking accuracies with active satellite vibration and thermal control systems for space-based platforms will also be needed. Powerful SAT/BDA with onboard processing systems will be essential to acquire and track mobile targets. The TAV will also require real-time information on battlefield conditions (especially to avoid fratricide and "friendly" kills). When the TAV-mounted KEW is used, it will require hypervelocity flight control, high-g and high-temperature flight hardening, and smart fusing. A method for maintaining tracking and control during the terminal phase despite the sheath of hot, shocked gas surrounding the reentry projectile may also be required.

To fully exploit the global omnipresence of sensors and the proliferation of sensor types in 2025, the SAT/BDA system should be given near real-time access to the global surveillance and reconnaissance and communication systems. The ability to receive and interpret other views of the target will greatly enhance the mission success rate, and might prove to be the enabling capability for some weapon concepts.

Countermeasures

The countermeasures previously discussed in this chapter for the coherent light laser and the TAV still apply when they are employed separately to engage targets. However, when employed as a system, the enemy would have to target the ground-based lasers (virtually all of them) and the TAV launch sites (again, nearly all of them) to disable GLASS—a daunting task when you realize that most of GLASS's components are based in the CONUS. If the enemy only attacked a few space-based mirrors or a few TAVs, the remaining CONUS-based TAV fleet could quickly (within a day) reconstitute a significant portion of GLASS's constellation of orbiting mirrors. Moreover, the enemy must remember that these two components of the GLASS, the laser and the TAV, are also very robust. That is, not only can they apply force upon the enemy, they can protect each other. The laser can hit targets, in space or on earth, that threaten the TAV launch sites, the ground-based lasers, or the mirrors, and the TAV can likewise respond to these same threats, but with more flexibility (launched quickly into any orbit with a wide variety of weapons).

Weather and atmospheric conditions will always be a concern for the GLASS. As stated before, the laser can be blocked or at least degraded by cloud cover. The weather modification concepts discussed in the associated AF ***2025*** white paper may therefore be needed to provide all-weather, space-strike capability.[116]

The cost of the GLASS is a large concern. Space systems are inherently expensive due to the high cost of space lift and the difficulty of designing and building systems to operate for long periods of time in the hostile space environment. Moreover, projecting what a system will cost 30 years in the future is quite risky (especially using technologies yet to be developed) —planners have not had great success in projecting system costs accurately even two to five years in the future.

McDonnell/Boeing claims that the cost of developing a TAV system would be the same as the development cost of the Boeing 777—about $5 billion. This estimate may be close, considering that a Boeing 777 has about 80,000 parts, whereas a TAV, although operating in space, would only have about 30,000 parts.[117] The cost to produce a single TAV would probably be similar to the cost to produce a B-2 bomber—$750 million to $1 billion. However, if the government does not drastically improve its cumbersome acquisition process, these costs could rise dramatically in the coming decades. Fortunately, with the many space mirrors and the fleet of TAVs required by GLASS, and the hundreds (if not thousands) of satellites proposed both in other AF ***2025*** white papers and in advertised commercial space systems (Iridium, Teledesic), government and industry should be able to develop stable production lines that produce relatively inexpensive, identical satellites vice the large, hand-built, unique satellites of today. The US must certainly keep an assembly line (both commercial and military) going for production of the TAV. America's TAV must not become merely an advanced version of the Space Shuttle—available in small numbers at astronomical cost and with limited usability.

The cost of a directed-energy weapon system that includes ground-based continuous wave laser stations and a constellation of space-based mirrors is more difficult to project since there is no present space-based weapon system to use as a baseline. The USAF is currently developing an airborne laser system (ABL) as a boost-phase ballistic missile defense system. The USAF expects to spend approximately $5 billion to design, test, and field a small number of operational airborne laser systems.[118] Development costs alone for a distributed system with a space-based element (the mirrors) would be at least as great as this.

The likely cost of some individual components of the DEW element of the GLASS can also be forecast. A high-quality, properly figured and polished laser mirror about 15 to 20 meters in diameter will cost between $20 and $30 million for the substrate alone (coatings will cost more). The total cost of the support structure and mirror will be in the range of $60 to $90 million. Provided the technological challenge of power scaling for solid-state and/or diode lasers can be met, the cost of a single ground station including a megawatt-class laser and its associated infrastructure will be on the order of approximately $100 to $200 million (USAF experts forecast the cost of a 100 megawatt chemical laser alone at $50 to $100 million).[119]

Notes

[1] CDR Clarence E. Carter, et al., "The 'Man in the Chair' - Cornerstone of Global Battlespace Dominance," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996); Lt Col Edward F. Murphy, et al., "Information Operations: Wisdom Warfare for ***2025***," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996); Lt Col William Osborne, et al., "Information Operations: A New Warfighting Capability," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996); and Maj Michael J. Tiernan, et al., "In-Time Information Integration System (I^3S)," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996).

[2] ***2025*** concept, no. 900610, "Hoversatt," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[3] ***2025*** concept, no. 900338, "Stealth Technology," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[4] Lt Col Henry Baird, et al., "Spacelift - Integration of Aerospace Core Competencies," AF ***2025*** study (Maxwell AFB, Ala.: Air War College, 1996).

[5] US GAO Report, "Ballistic Missile Defense - Information on Directed Energy Programs for FY 1985 Through 1993" (Washington, D.C.: Government publication, GAO/NSIAD-93-182, June 1993), 13.

[6] Personal interview with Dr M. Yarymovitch, 7 February 1996.

[7] *Spacecast 2020,* "Refueled Transatmospheric Vehicle" (Maxwell AFB, Ala.: Air University Press, 1994), H-1.

[8] ***2025*** concept, no. 900046, "Space Marine Operational Theater," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900202, "Space-based Special Operations Forces," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900696, "Global, Rapid Response Space Sortie," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900265, "Space Storage Modules To Establish Space-sourced Air Drop Capability," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900654, "Parts Locker," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[9] Briefing, subject: "Military Spaceplane Technology and Applications," January 1996, Phillips Laboratory PL/VT-X Slide 17.

[10] Lt Col Edward F. Murphy, et al., "Information Operations: Wisdom Warfare for ***2025***," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996); and Lt Col William Osborne et al., "Information Operations: A New Warfighting Capability," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996.

[11] Robert C. Weast, Editor-in-chief, *Handbook of Chemistry and Physics*, Boca Raton, Fla.: CRC Press, Inc., 1984), F-162.

[12] ***2025*** concept, no. 900163, "Solar Energy Weapon," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[13] *Spacecast 2020* "Force Application" (Maxwell AFB, Ala.: Air University Press, 1994), O-18.

[14] Personal observations made one of this paper's authors at the Litton-Itek Corporation and the University of Arizona in March 1992 and February 1993.

[15] Personal interview with Dr M. Yarymovitch, 7 February 1996.

[16] Information obtained from senior DOD professionals speaking to the Air War College under the promise of nonattribution.

[17] Lt Col Brad Shields, et al., "Weather as a Force Multiplier - Owning the Weather in ***2025***," AF ***2025*** Study (Maxwell AFB, Ala.: Air War College, 1996).

[18] st *Spacecast 2020,* "Force Application" (Maxwell AFB, Ala.: Air University Press, 1994), O-18.

[19] ***2025*** concept, no. 900181, "Blackhorse Type Outer Atmosphere Low Orbit Vehicle," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 200018, "Space-Based Laser Designator," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900420, "Laser Attack Station," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900452, "Space based Satellite Body Guard," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 200034, "Missile Laser," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[20] Information from Air Force Institute of Technology (AFIT) graduate course in Laser Effects, Dr William Bradley, 1984.

[21] "Visions" briefing, slide 21.

[22] Briefing, subject: On-going Research in the Directorate, Phillips Laboratory's Lasers and Imaging Directorate, provided to AF ***2025*** study team in November 1995.

[23] Ibid.

[24] Information obtained through personal interviews obtained by one of this paper's authors with industrial experts in 1981, 1993, and 1994 under the promise of nonattribution.

[25] *Spacecast 2020,* "Force Application" (Maxwell AFB, Ala.: Air University Press, 1994), O-18. Information on energies required for weapons-class pulsed laser obtained from one author's personal course notes, AFIT graduate course in Laser Effects, 1984.

[26] *Spacecast 2020*, "Force Application" (Maxwell AFB, Ala.: Air University Press, 1994), O-18.

[27] The aperture sizes were determined by simple optical diffraction calculations at low earth orbit ranges (hundreds of kilometers vertically; a few thousand kilometers slant range) for wavelengths from 5 microns to 0.45 microns assuming a Gaussian beam with 99%+ energy on target and a circular aperture. For more information on how to perform these calculations, see (for example) Anthony E. Seigman, *Lasers*, Mill Valley, Calif.: University Science Books, 1986, Chapter 18.4 (Aperture Diffraction: Circular Apertures), 727. For aberrated beams, even larger mirrors would be required.

[28] These numbers obtained by a simple geometric calculation. At an orbital altitude of 300 to 1,000 km, angular accuracies in this range are required to achieve pointing stability on the order of inches.

[29] US GAO Report, "Ballistic Missile Defense - Information on Directed Energy Programs for FY 1985 Through 1993" 38.

[30] Briefing, subject: On-going Research in the Directorate Phillips Laboratory's Lasers and Imaging Directorate,, provided to AF ***2025*** study team in November 1995.

[31] John L. Petersen, *The Road to 2015* (Corte Madera, Calif.: waite Group Press, 1994). 58–60, 297–298. Intriguing ideas based on nanotechnology and microelectromechanical machines (MEMS) were also submitted as ***2025*** concept, no. 900518, "Electronic Grid - Throwaway Sensors," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 200023, "Surveillance Swarm," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900231, "Gnat Robot Threat Detectors," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***,

1996); ***2025*** concept, no. 900288, "Swarms of Micromachines," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[32] For information on advances in low-dimensional electronic systems see the discussion in Paul Davies ed. *The New Physics*, (Cambridge, UK: Cambridge University Press, 1989), 228–234. The same text has an excellent, very brief discussion of the essential elements of optical computers on page 315. For a nontechnical discussion of trends in microprocessors see Petersen, John L., *The Road to 2015* (Corte Madera, Calif.: Waite Group Press), 1994, 28–32.

[33] Information obtained from senior DOD professional speaking to the Air War College under the promise of nonattribution.

[34] Briefing, subject: On-going Research in the Directorate, Phillips Laboratory's Lasers and Imaging Directorate, provided to AF ***2025*** study team in November 1995.

[35] Lt Col Brad Shields, et al., "Weather as a Force Multiplier - Owning the Weather in ***2025***," AF ***2025*** study (Maxwell AFB, Ala.: Air War College, 1996).

[36] ***2025*** concept, no. 900426, "Atmospheric Disturbance," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900552, "On-demand Tactical Recce Satellite Constellation," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 200018, "Space-Based Laser Designator," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996). See also the briefing by Phillips Laboratory's Lasers and Imaging Directorate, provided to AF ***2025*** study team in 1995.

[37] US GAO Report, "Ballistic Missile Defense - Information on Directed Energy Programs for FY 1985 Through 1993" 19.

[38] The core of this idea can be found in the briefing charts from the 10 April 1995 working session of the New World Vistas team in the section on the Directed Energy group (chairman Donald Lamberson, Maj Gen, USAF (Ret.)). See also briefing by Phillips Laboratory's Lasers and Imaging Directorate, subject: On-going Research in the Directorate, provided to AF ***2025*** study team in November 1995.

[39] Amnon Yariv, *Introduction to Optical Electronics,* 2nd ed. (New York, N.Y.: Holt, Rinehart, and Winston, 1976), 166–167, 176–186.

[40] Anonymous assessor comment on first draft of Space Operations white paper, ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[41] Briefing, subject: On-going Research in the Directorate, Phillips Laboratory's Lasers and Imaging Directorate, provided to AF ***2025*** study team in November 1995.

[42] Personal visit by one of the authors to the Lawrence Livermore National Laboratory's inertial confinement fusion facilities in 1984.

[43] Information from Air Force Institute of Technology (AFIT) graduate course in Laser Effects, Dr William Bradley, 1984.

[44] Amnon Yariv, 210.

[45] Peter W. Milonni and Joseph H. Eberly, *Lasers* (New York, N.Y.: John Wiley and Sons, 1988), 4.

[46] US GAO Report, "Ballistic Missile Defense - Information on Directed Energy Programs for FY 1985 Through 1993," 14.

[47] Information from Air Force Institute of Technology (AFIT) graduate courses in Plasma Physics, Dr Phillip Nielson, 1978 and Laser Effects, Dr William Bradley, 1984.

[48] US GAO Report, "Ballistic Missile Defense - Information on Directed Energy Programs for FY 1985 Through 1993," 28.

[49] Spacecast 2020 "Force Application" (Maxwell AFB, Ala.: Air University Press, 1994). O-22, O-23.

[50] US GAO Report, "Ballistic Missile Defense - Information on Directed Energy Programs for FY 1985 Through 1993," 30.

[51] Ibid., 30.

[52] Visions briefing, slide 18.

[53] US GAO Report, "Ballistic Missile Defense - Information on Directed Energy Programs for FY 1985 Through 1993," 31.

[54] Personal interview with Dr M. Yarymovitch, 7 February 1996.

[55] US GAO Report, "Ballistic Missile Defense - Information on Directed Energy Programs for FY 1985 Through 1993," 31.

[56] Carlo Kopp, "A Doctrine for the Use of Electromagnetic Pulse Bombs" (Fairbairn ACT, Australia: Air Power Studies Centre (ISBN 0 642 19343 6), July 1993); 1, 11.

[57] Ibid., 3.

[58] J. D. Jackson, *Classical Electrodynamics,* 2nd ed. (New York, N.Y.: John Wiley and Sons, 1975), 271.

[59] John Moyle, memorandum entitled "Thoughts on the Revolution in Military Affairs," from the Strategic Assessment Center to Mr Jeff McKitrick and Colonel Richard Szafranski, 5 January 1996, 9.

[60] Ibid. 3.

[61] Carlo Kopp, 10.

[62] Ibid., 3–5.

[63] Dr William Balcer, Phillips Lab, "Transient Electromagnetic Technology and Future Space-control," Briefing on 20 Oct 1993, to AF Spacecast 2020 study. Also see Spacecast 2020 abstract paper AO112 (Compact Toroids).

[64] Spacecast 2020, "Force Application" (Maxwell AFB, Ala.: Air University Press, 1994), O-19.

[65] John Moyle, 9.

[66] ***2025*** concept, no. 900270, "EMP Pills," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[67] Carlo Kopp, "Air Warfare Applications of Laser Remote Sensing" (Fairbairn, Australia: Air Power Studies Centre), 2.

[68] ***2025*** concept, no. 200009, "Pyrotechnic Electromagnetic Pulse (PEP)," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900270, "EMP Pills," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[69] Carlo Kopp, "A Doctrine for the Use of Electromagnetic Pulse Bombs," 15.

[70] John Moyle, 10.

[71] Carlo Kopp, "Air Warfare Applications of Laser Remote Sensing," 3.

[72] Carlo Kopp, "A Doctrine for the Use of Electromagnetic Pulse Bombs," 9.

[73] Briefing, subject: On-going Research in the Directorate, Phillips Laboratory's Advanced Weapons and Survivability Directorate, provided to AF ***2025*** study team on 4 December 1995; 8, 38, and 40. This was extracted from a brief technical note attached to the briefing by Dr John T. Tatum, US Army Research Laboratory, Adelphi, Md. entitled "A New Threat to Aircraft Survivability: Radio Frequency Directed Energy Weapons (RF DEW)."

[74] Ibid., 10.

[75] Information obtained from senior technical and management personnel in the American aerospace industry under the promise of nonattribution.

[76] Briefing, subject: On-going Research in the Directorate, Phillips Laboratory's Advanced Weapons and Survivability Directorate, provided to AF ***2025*** study team on 4 December 1995; 10, 32, and 33.

[77] George E. Thibault, *The Art and Practice of Military Strategy* (Washington, D.C.: National Defense University Press, 1984), 47.

[78] ***2025*** concept, no. 200015, "Distortion Field Projector," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900313, "Spaceborne/Airborne Hologram," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900570, "Deceptive Holographic Imaging," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900390, "Holographic Battlefield Deception," ***2025*** concepts database (Maxwell

AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900756, "Holographic Deception Operations," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900792, "Holographic CCD," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[79] Amnon Yariv, 408–409.

[80] Peter W. Milonni and Joseph H. Eberly, Lasers (New York, N.Y.: John Wiley and Sons, 1988), 606–609.

[81] John L. Petersen, *The Road to 2015* (Corte Madera, Calif.: Waite Group Press, 1994), 62.

[82] CDR Clarence E. Carter, et al., "The 'Man in the Chair' - Cornerstone of Global Battlespace Dominance," AF ***2025*** study (Maxwell AFB, Ala.: Air War College, 1996); LtCol Edward F. Murphy, et al., "Information Operations: Wisdom Warfare for ***2025***," AF ***2025*** study (Maxwell AFB, Ala.: Air War College, 1996); LtCol William Osborne, et al., "Information Operations: A New Warfighting Capability," AF ***2025*** study (Maxwell AFB, Ala.: Air War College, 1996); and Maj Michael J. Tiernan, et al., "In-Time Information Integration System (I^3S)," AF ***2025*** study (Maxwell AFB, Ala.: Air War College, 1996.

[83] David Halliday, and Robert Resnick, *Fundamental of Physics,* 3d ed. (New York, N.Y.: John Wiley and Sons, 1988), 134.

[84] Personal interview with Dr M. Yarymovitch, 7 February 1996.

[85] *Spacecast 2020*, "Force Application" (Maxwell AFB, Ala.: Air University Press, 1994), O-15 and O-8.

[86] John Moyle, 12–13.

[87] US GAO Report, "Ballistic Missile Defense - Information on Directed Energy Programs for FY 1985 Through 1993, 12.

[88] Briefing, subject: "Mission Area Vision - Force Application," 10 November 1992 S. J. Navickas,.

[89] Stanley W. Kandebo, "'Air Spike' Could Ease Hypersonic Flight Problems," *Aviation Week & Space Technology*, 19 May 1995. 66.

[90] ***2025*** concept, no. 200010, "Suppression Cloud," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900270, "EMP Pills," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[91] Personal observation by one of the authors at the AF Phillips Laboratory and the University of Texas, Austin in 1981 and 1989.

[92] Considerable information on this topic can be found at the following Worldwide Web available from: www.pas.nps.navy.mil/railgun.html.

[93] ***2025*** concept, no. 900168, "Meteors as a Weapon," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[94] William J. Broad "Meteoroids Hit Atmosphere in Atomic-Size Blasts," *New York Times* 25 January 1994.

[95] Briefing, subject: "Military Spaceplane Technology and Applications," January 1996, Phillips Laboratory PL/VT-X, slides 9,10, 11, and 30.

[96] Ibid. slide 7.

[97] Information obtained from the internet, Internet 14 February 1996, available from: http://www.contribu.cmu. edu/usr/fjo4/.

[98] Dr Dennis Bushnell, Chief Scientist for NASA Langley Research Center, telephone interview, 26 Feb 96.

[99] Ibid.

[100] Ibid.

[101] Ibid.

[102] Ibid.

[103] Ibid.

[104] Ibid.

[105] Briefing, subject: "Military Spaceplane Technology and Applications," January 1996, Phillips Laboratory PL/VT-X, slide 20.

[106] *Spacecast 2020,* "Space Lift: Suborbital, Earth to Orbit, and On-Orbit," (Maxwell AFB, Ala.: Air University Press, 1994), H-1.

[107] Briefing, subject: "Future Expansions in Space," 25 June 1995, McDonnell Douglas/Boeing, chart Y505403.1M18BA76.

[108] Briefing, A Discussion Paper-as-Briefing, 26 January 1996 "Space and the Army's Future", slide 5.

[109] Briefing, subject: "Military Spaceplane Technology and Applications," January 1996, , Phillips Laboratory PL/VT-X, slide 19.

[110] Briefing, subject: "Future Expansions in Space," 25 June 1995 McDonnell Douglas/Boeing,, chart Y505403.1M18BA76. The X-33 program predicts this can be done in from hours to a few days. Briefing, Col Ted Wierzbarowski, subject: "National Aerospace Plane and Airbreathing Single-Stage-to-Orbit," 19 October 1993, chart D2270.010.

[111] W. J. Schaeffer Associates, Memorandum to Capt Clapp, USAF, 4 February 1994.

[112] Briefing, subject: "Future Expansions in Space," 25 June 1995, McDonnell Douglas/Boeing, chart Y505403.1M18BA76.

[113] Briefing, subject: "Military Spaceplane Technology and Applications," January 1996, Phillips Laboratory PL/VT-X, slide 31.

[114] Lt Col Robert H. Zielinski, et al., "Star Tek - Exploiting the Final Frontier - Counterspace Operations in ***2025***," AF ***2025*** study (Maxwell AFB, Ala.: Air War College, 1996).

[115] Personal interview with Dr M. Yarymovitch, 7 February 1996.

[116] Lt Col Brad Shields, et al., "Weather as a Force Multiplier - Owning the Weather in ***2025***," AF ***2025*** study (Maxwell AFB, Ala.: Air War College, 1996).

[117] Information obtained from the internet, Internet 14 February 1996 available from: http://www.contribu.cmu. edu/usr/fjo4/ and conversations with representatives at a briefing on the military spaceplane, 6 March 1996.

[118] Ralph Vartabedian, "Lasers Next Great Hope to Beam Defense Systems into Future," *Los Angeles Herald,* 3 December 1995.

[119] Maj Michael Roggemann, Air Force Institute of Technology (AFIT) professor, telephone interview with author, 28 March 1996.

Chapter 4

Concept of Operations

The threat-dependent concept of operations for the GLASS is relatively straightforward. Threats could be slowly developing situations, fast developing crises, or surprise attacks from a country or a terrorist-type group (where some quick retaliatory response is required). In addition, the intensity of the threat could vary over a broad range from mere intimidation to an isolated terrorist attack, a small war or battle, or (inevitably) total war. No matter what type of threat or situation develops or what its intensity, the global coverage provided by GLASS will allow decision makers to direct action that is responsive and timely (i.e., near instantaneous), flexible in terms of the full spectrum of lethality (i.e., from "lighting up" the battlefield to destroying platforms and assets), precise (i.e., pinpoint accuracy if necessary), survivable (i.e., dispersion of vulnerable space-based assets, self-protection capability, and CONUS-basing of the highest-value components), and reliable (i.e., TAV will be able to serve as backup). In summary, GLASS provides global coverage and a broad range of nearly instantaneous responses without extensive forward basing.

In the first instance of a slowly developing situation involving the US and its allies, the GLASS would be used primarily as a deterrence weapon. However, it is much more flexible than today's nuclear-deterrent weapon. The nuclear bomb may well have prevented a catastrophic total world war, but it has not stopped any of the hundreds of relatively minor conflicts (at all levels) that have continued to rage since 1945. The GLASS, able to project force across a wide spectrum of outcomes, could actually be employed in scenarios ranging from humanitarian operations (i.e., in its surveillance or illumination modes) to major regional conflicts (i.e., to disrupt, damage, or destroy the enemy's strategic assets). These operations do not necessarily have to be lethal. That is, the US could select a benign target, notify the rogue government of the time and place at which the offending item will be neutralized, and then disable or destroy the target (and

only the target) with a laser beam and/or hypervelocity projectile. After a few demonstrations of this capability, even the most isolated totalitarian rogue state would realize none of its offensive assets are safe and (just as important) there will be no collateral damage to show the news cameras. Clearly, in addition to the straight-forward destruction of military targets, the GLASS could be used for deterrence, intimidation, persuasion, or just to forcefully signal America's resolve.

GLASS could also be put to effective use in the most fast-developing crisis. For example, suppose a country in northern Africa masses tanks on its border to invade a nearby country and their leadership will not listen to American or UN requests to reverse this provocative action. A cluster of small projectiles could be dropped from a TAV to destroy a critical tank concentration while laser beams "from heaven" are burning holes through advancing combat aircraft and blowing up fuel storage areas and munitions dumps. Even a modern war machine could be stopped dead in its tracks before it even gets started, since the GLASS can strike strategic, operational, and tactical targets, simultaneously performing strategic attack, interdiction, and even close support missions.

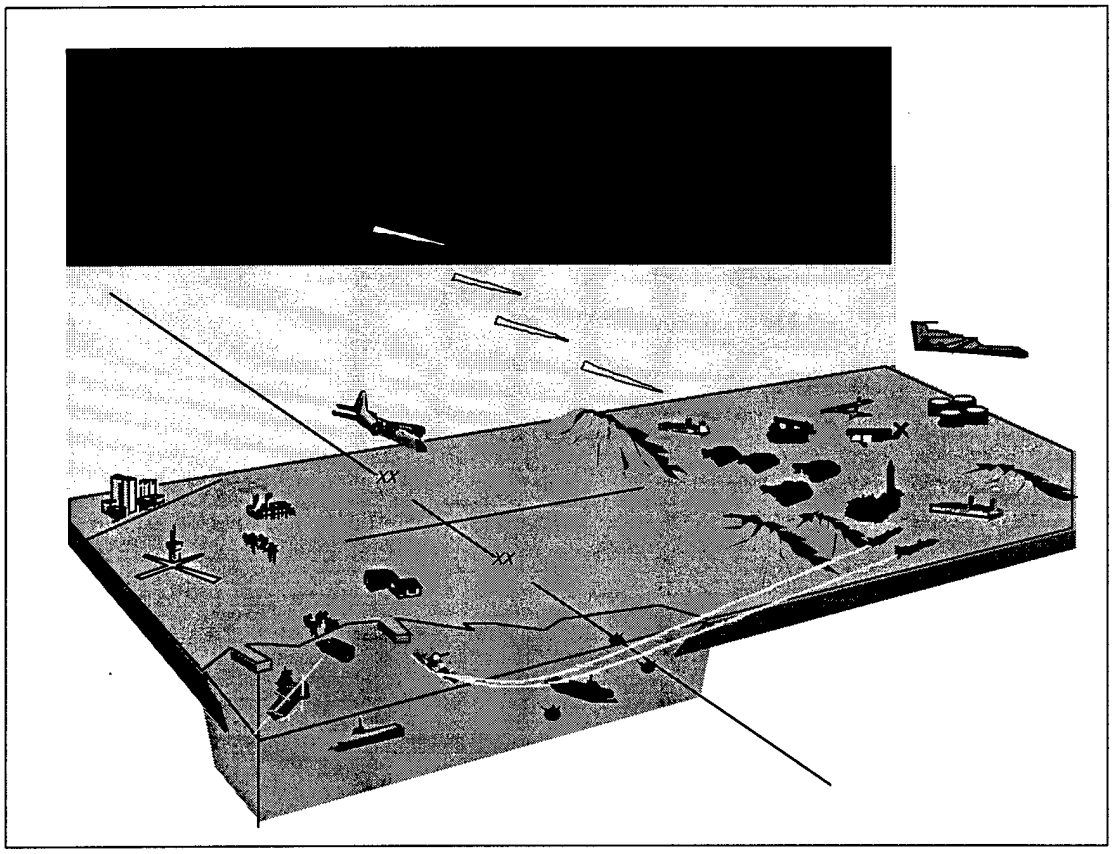


Figure 4-1. TAV Employing Kinetic-Energy Weapons

In the third situation, where an attack has already occurred and a response is required, the GLASS could be used in a myriad of ways to retaliate and with a speed limited only by the time required for US leadership to make its decisions. For example, the mission may be to eliminate the leadership of a terrorist organization located at a "safe house" in the largest city of a rogue state. A precision projectile could be dropped from an orbiting TAV that was launched only an hour before and within minutes, the house along with the leadership would be destroyed. It would not matter if the "safe house" was reinforced with concrete or buried underground; with good intelligence, literally no target on earth would be safe from the GLASS. More importantly, there would be no political fallout from collateral damage. Current weapon systems must generally make do with targeting data accurate to one to 10 meters at best.[1] This is not the optimum situation for precision-guided or precision-aimed weapons. Such enormous destructive power must be controlled precisely to avoid unnecessary collateral damage. Acceptable targeting data in 2025 will be measured in centimeters, not in meters.

If an area is not covered by the weapon constellation (this will occur at times), the TAV would be sent up with a mobile mirror for the ground-based laser and/or a container of hypervelocity projectiles to cover the target area. Although not as responsive as space-based assets, a TAV could reach anywhere on earth within 60 minutes after its crew climbs on board.[2] The TAV could also carry other types of weapons such as some of those discussed in chapter 3. For deterrence, the US could launch numerous TAVs in unpredictable orbits that remain in space until the crisis is resolved. Three TAVs could provide coverage of most of the earth's current trouble spots every 90 minutes.[3] Of course, the TAV would also be ideal for space-control and space superiority. These issues are further explored in other white papers.[4]

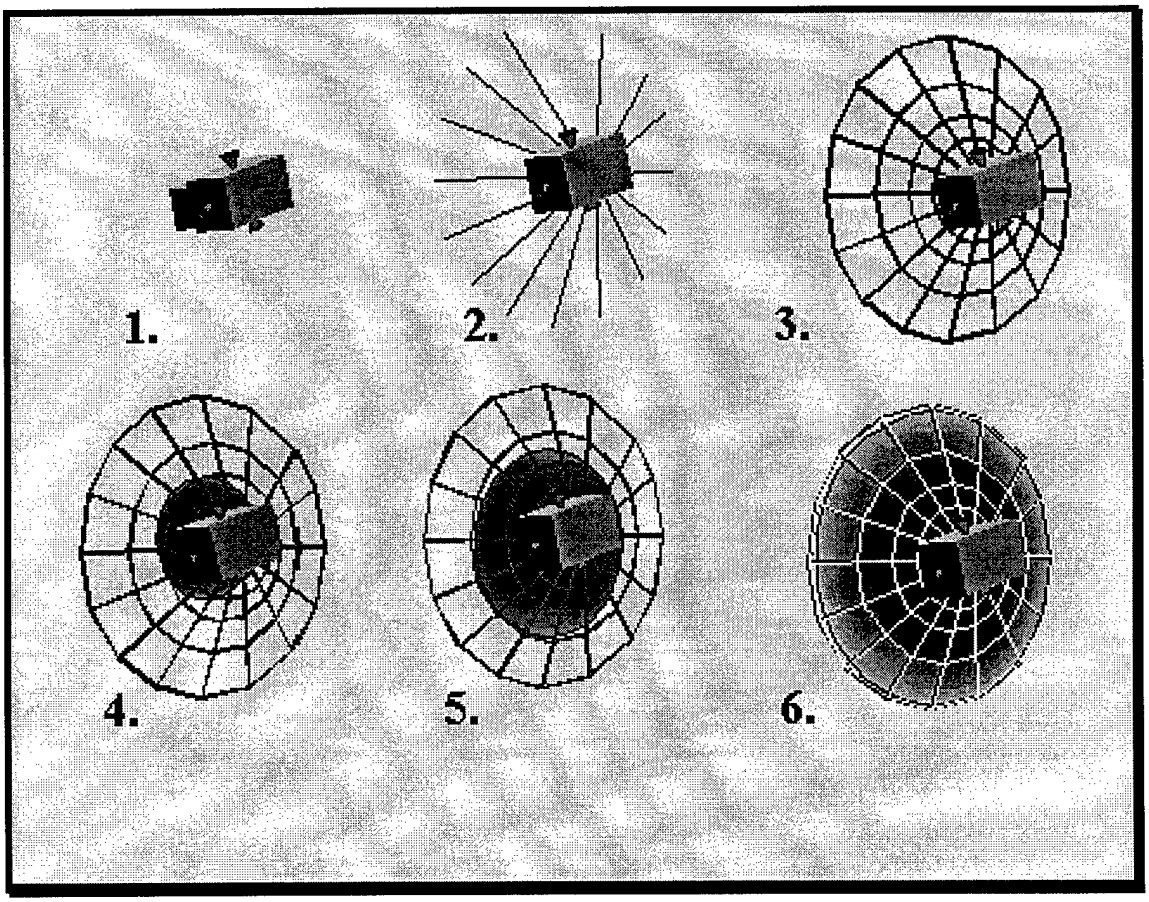


Figure 4-2. Notional Space-Based Mirror Deployment Using Inflatable Mirror Technology

The GLASS would also be ideal for counterproliferation operations. The engagement would involve a system-to-system interaction with fixed or mobile ground targets with support from communication, navigation, and surveillance systems. Using the GLASS, the US would not need permission from neighboring nations for landing or overflight rights and could strike a rogue state with a "launch or lose" mentality without

any prior warning. These desirable functions could be performed without forward deployment of forces, drastically reducing the danger to US military personnel. The flexibility and response time of the GLASS in its role as a counterproliferation asset would be unmatched.[5]

The laser portion of the GLASS has three important characteristics: the weapon itself (photons) travels at light speed, it can be precisely controlled and aimed (not *inherently* a weapon of mass destruction), and it is not necessarily a line-of-sight weapon (i.e., it can be relayed by mirrors). Possession of a light-speed weapon would revolutionize the conduct of future wars. John Moyle of the Strategic Assessment Center describes this capability as the way to "get inside" the opponent's OODA loop, since, "The means with which one can destroy an enemy's system . . . operates at the same speed as of the flow of information, the critical component of the enemy's ability to counter/defend against the strike in the first place."[6] It may be impossible to mount an active defense against a light-speed weapon.

Geometry is another aspect of the concept of operations. The question, "from where to where?" captures the essence of military space operations and frames the geometry of different force-application missions. Regardless of the purpose of an operation, its beginning and ending locations have tremendous impact on the nature of the operation and its success. The basic geometries for military space systems include earth-space-earth and space-earth. The GLASS employs the earth-space-earth geometry through both the TAV and the DEW system (which is both distributed and dispersed in two mediums—earth and space). That is, the GLASS begins its mission within the earth's atmospheric envelope, traverses the space environment, and then applies force to resolve or influence a conflict occurring primarily within the earth's atmospheric envelope (we do not foresee wars *in* space by 2025). This application of force may involve physical destruction or more subtle effects such as battlefield illumination, support for deceptive information-warfare attacks, or C^2W/EW against an adversary's electronic communications and/or electronic order of battle. The latter distinction is crucial since, in 2025, an adversary's center of gravity may not be a physical object at all, but rather an intangible communications link, information flow, or public attitude.

Basing is also a prime consideration. The laser beams of the DEW system will originate from powerful facilities dispersed around remote parts of the CONUS. Sunny, clear areas such as the American southwest would be the most likely choices. With a laser system that uses space-based mirrors, there are several advantages to using an earth-based laser located in the US (or its possessions): no forward basing is

required, there are no concerns about foreign governments demanding removal of US assets from their territories, no weapons are actually placed in space, and the most expensive and maintenance-intensive portions of the system are all ideally placed for access by the US sustainment system. Yet the US would still have tremendous capabilities for power projection. Dispersion of the laser stations is also desirable to enhance the security, reliability, and flexibility of the system and to provide concentration of mass in strategic attacks by allowing GLASS to focus several laser beams on a single hardened target simultaneously.

The TAV element of the GLASS is projected to operate out of at least six CONUS locations and seven locations outside the CONUS, including Alaska, Guam, and Hawaii. This also allows for security and flexibility. If TAV take-off/landing is vertical, pads of 200 square feet with airplane-like facilities are required. If the TAV is a horizontal take-off/landing system, then runways of 8,000 feet will probably be required—less than that needed for most modern jets today. Thus, the TAV fleet could be based at many possible locations (with a large number of already existing backup landing sites).[7]

The infrastructure for the TAV would be similar to that of aircraft today. That is, the ground site would need a fueling capability, a loading capability (change containers in and out), maintenance facilities, and 200-foot-square launch pads (if it evolves into a horizontal landing vehicle, it would also require an 8,000 foot runway). With miniaturization of electronics (thus, portable maintenance equipment), "black box" concepts, "containerized" payloads, and so forth, the number of supporting ground personnel and equipment should be greatly reduced in comparison with that required for today's military aircraft. In short, the logistics tail would be greatly reduced. Thus, the TAV would have "home bases," but it would be capable of rapidly deploying into many locations during times of tensions and increased hostilities.

The ground-based laser would necessarily require a large power source, a cooling system (possibly employing a high flow of chilled water), and relatively clear skies. This would require relatively isolated basing away from population centers. The power sources would be similar to those that exist today, but they would be more compact, self-contained, and more easily maintained. Of course, the power sources and lasers would be fixed, so significant ground-based security forces, and possibly point defenses against ballistic missiles, would be required. The more ground sites available, the less vulnerable the system is to attacks, the more targets could be hit simultaneously, and the greater the likelihood the system would be available to attack a given target at need. In addition, tracking, monitoring, and control sites would be required for the

mirrors. However, these would not necessarily have to be dedicated sites. That is, they could be integrated into the same system the US uses to track, monitor, and control other space assets. The idea would be to automate as much as possible, build in reliability and maintainability, and standardize procedures and equipment from the beginning of development.

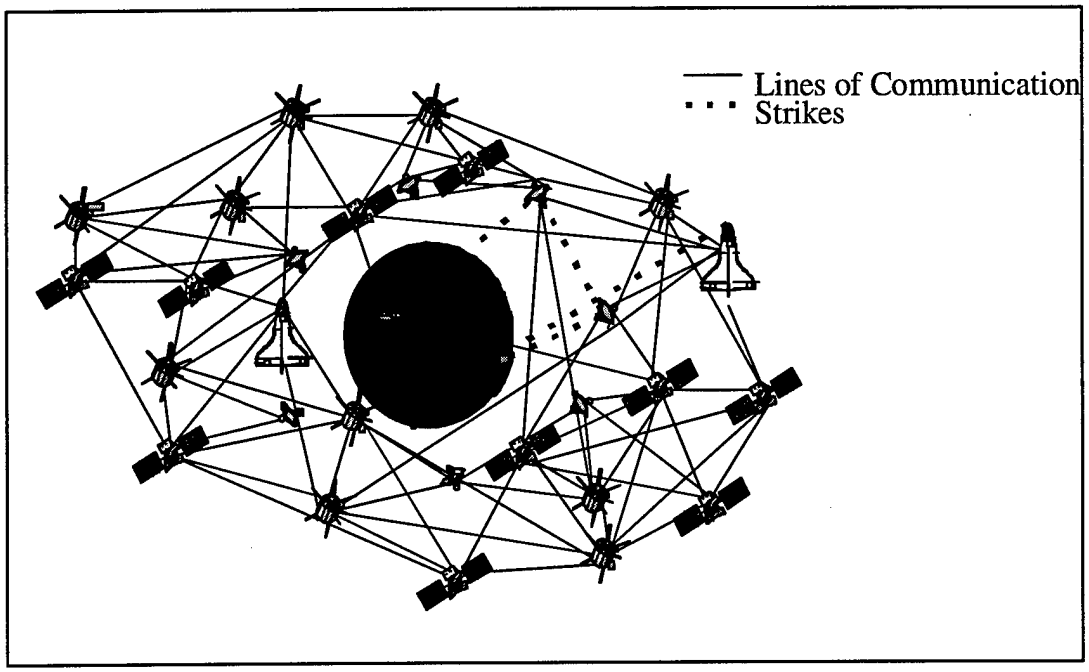


Figure 4-3. The Crowded "Skies" of *2025*

The total number of TAVs the US should procure depends upon the other missions, besides GLASS, that are required. For our purposes, however, the US should procure 12 to 16 operational TAVs. These would be divided into three Combat Space Squadrons, each having the following missions: precision attack, reconnaissance/surveillance, space lift, satellite support, and "other missions as required."[8] These squadrons would fall under a central controlling authority that would also control the laser stations or bases. Thus, the synergistic effects of the laser and the TAV would be realized.

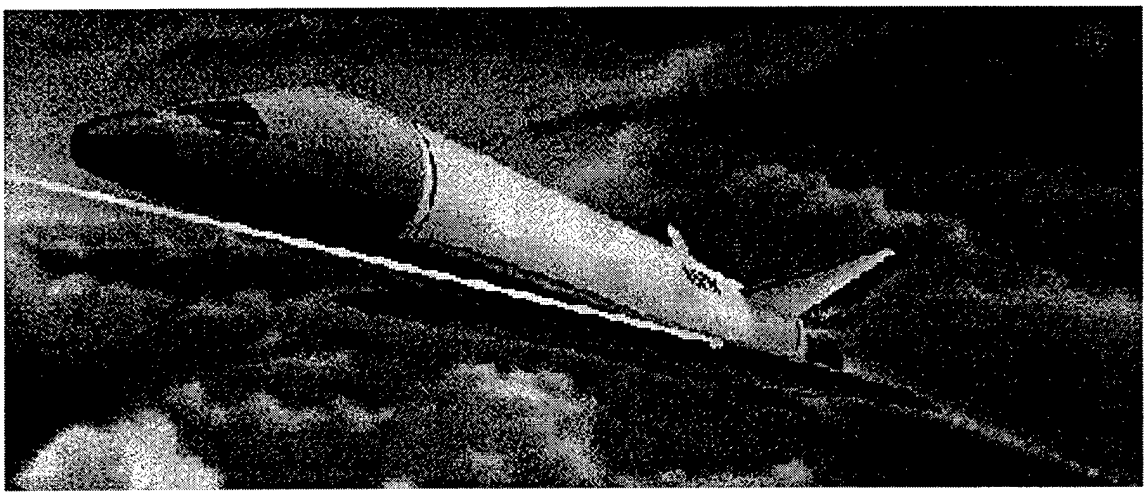


Figure 4-4. A TAV in *Space-strike* Mode

A TAV could be used to perform a myriad of space operations. The possibilities include deployment, repair, or retrieval of satellites (other than just the GLASS); deployment of smart munitions other than the KEW (usually from LEO); and functioning temporarily as a space-borne command post.[9] TAVs could respond quickly to contingencies with tailored mission packages. Missions ranging from emergency satellite repair/deployment, to dropping a special operations team in the middle of a hostile environment, to mending a gap in a critical satellite constellation would all be possible. In addition, a small fleet of TAVs could allow for the placement of mass (in limited quantities) at critical nodes in a conflict situation. Perhaps the most important advantage might be the psychological effect of possessing such a capability. America's enemies would always have to factor in an almost immediate American response into their hostile actions.

The human in the loop concept is, by itself, neither an advantage nor a disadvantage. That is, humans will certainly be "in the loop" at the critical point in any application of force. This critical point could involve action on the ground or in space. If force is being applied by a light-speed, directed-energy weapon, the delay between the decision to take action and "fire on the target" might only be measured in seconds, but human decision and human judgment would still be intimately involved.

There are decided disadvantages to putting humans in space. To begin with, a human in space would immediately become a prime target during a conflict, especially if the human is the critical link in the weapon system. Moreover, space is a hostile environment—especially near the Van Allen radiation belts; thus, the necessary safety factor increases the overall cost and complexity of the weapon system. In addition, the space

operations missions involving the TAV are limited, since current TAV concepts are designed only for LEO operations (limits access to space assets). Timeliness or responsiveness is also relatively limited for manned space systems. An on-orbit, unmanned space-based weapon could take action in a fraction of a second; a manned TAV might require up to an hour to arrive at the crisis location. The TAV is also extremely vulnerable during takeoff, orbit insertion, and landing. A nation could attempt to keep man in space at all times, but the costs involved are believed greater than those of the TAV, on orbit logistics is extremely expensive, and a permanent manned presence in orbit invites "hostage-taking" via ASAT. Thus, there will always be risks for this integral part of the GLASS weapon system.

Notes

[1] Maj, James G. Lee, USAF, "Counterspace Operations for Information Dominance," (Maxwell AFB, Ala.: Air University Press, October 1994), 14. See also Capt Kimberly M. Walker, USAF and Capt Tery L. Donelson, "Space Operations Training Course - Chapter 10: Navstar Global Positioning System" (Peterson AFB, Colo.: 1994), 152.

[2] 1992 Global Reach-Global Power White Paper.

[3] Briefing, subject: "Military Spaceplane Technology and Applications," January 1996, Phillips Laboratory PL/VT-X, slide 27.

[4] Lt Col Robert H. Zielinski, et al., "Star Tek - Exploiting the Final Frontier - Counterspace Operations in ***2025***," AF ***2025*** study (Maxwell AFB, Ala.: Air War College, 1996).

[5] Briefing, subject: "Military Spaceplane Technology and Applications," January 1996, Phillips Laboratory Laboratory PL/VT-X, slide 12.

[6] John Moyle, Memorandum entitled "Thoughts on the Revolution in Military Affairs," 1.

[7] Briefing, subject: "Military Spaceplane Technology and Applications," January 1996, Phillips Laboratory PL/VT-X, slides 12 and 21.

[8] Ibid.,, slide 2.

[9] ***2025*** concept, no. 900265, "Space Storage Modules to Establish Space-Sourced Air Drop Capability," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900654, "Parts Locker," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996); ***2025*** concept, no. 900249, "Geosynchronous Manned Command and Control Module," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

Chapter 5

Investigation Recommendations

> *We know from even the most casual study of military history how fallible man is in matters concerning war and how difficult it has been for him, mostly because of the discontinuity of wars, to adjust to new weapons. Yet compared to the changes we consider now, those of the past, when measured from one war to the next, were almost trivial. And almost always in the past there was time even after hostilities began for the significance of technological changes to be learned and appreciated.*
>
> —Bernard Brodie[1]

The concepts discussed in this paper directly address the needs of the military's most forward-thinking senior planners. Volume four (Future Capabilities) of Joint Planning Document FY 98-03 states that, to achieve joint war fighting objectives, we must develop the "capability to destroy selected targets with precision while limiting collateral damage. Includes precision guided munitions, surveillance and targeting capabilities. Requires advances in sensors, guidance and control, and lethality."[2] Joint Vision 2010 calls for

> "long range precision capability, combined with a wide range of delivery systems . . . the ability to generate a broader range of potential weapons effects, from nonlethal to hard target kill . . . these improvements will result in increasingly discrete and precise capabilities, selected to achieve optimum results and applicable to both combat and other operations."[3]

The *New World Vistas* team predicts "space-control and projection of force from space technologies will become as important [as global observation and global situational awareness] in the twenty-first century as global technology for utilization of space becomes more available to many countries of the world."[4] Achieving these desirable capabilities will not be easy and it will not happen overnight. We must begin work now if we wish to be ready for the world of 2025.

Directed-Energy Weapons

Directed-energy weapons operating at or near the speed of light offer the greatest opportunity for sudden, precise attacks across the spectrum of force against a wide range of targets. Reliable, effective directed-energy weapons will not be possible without compact, high-capacity power supplies. Today's solar power technology is insufficient—too much time would be required between shots to regenerate the system's energy reserves. Large, light-weight space structures of particular kinds are also critical. Laser space-strike systems require large, light-weight, optically smooth adaptive mirrors capable of correcting beam aberrations.

Current sources of directed energy also require further research. Highpower, solid-state, and diode lasers must be investigated because of their inherent efficiency advantages, their ability to operate without bulky chemical fuels, their potential for operation at shorter wavelengths, and because diode lasers can operate in phased arrays (obvious advantages in pointing and beam combining).

Finally, further work is required in directed-energy beam propagation. The impressive success of modern low-power adaptive optics techniques must be extended to high-power beams if laser space-strike systems are to reach their full potential.

Projectile Weapons

The approaches mentioned in this paper involving long-range ballistic missiles are already possible—the only thing lacking is the will to proceed. Two technologies are desirable to enhance the effectiveness of such weapons: high-speed (submicrosecond) fusing and high-speed dispersal techniques for submunitions in the terminal phase.

The destructive interaction of hypervelocity projectiles with targets has been investigated by the US military and NASA. These investigations must continue, particularly with regard to hydrodynamic penetrators, if we are to understand how to configure and direct hypervelocity projectiles to achieve optimum effect. Terminal guidance techniques must be improved to enable the use of kinetic-energy weapons as true precision-guided weapons.

Space Sortie

The main challenges here lie in propulsion technology (both air breathing and for space) and aerodynamic design for reliable hypersonic flight. Light-weight, high-endurance propulsion systems are needed to operate transatmospheric vehicles (TAVs) for long-range sorties. Light-weight, high temperature materials and high-capacity cooling systems must be developed to form the "skin and bones" of the TAV.

General Considerations

Space-strike weapon systems will not be possible without reliable, affordable access to space. The investigation recommendations of the AF *2025* Space Lift white paper are therefore seconded without reservation in this paper. All the space operations missions—space control, force enhancement, force application, and space support—depend on access to space.[5]

A blind marksman is a contradiction in terms. The space-strike weapon systems of 2025 will depend heavily on America's global information network.(see appendix B). In this regard, the following areas of study are as critical for this white paper as they are for the surveillance and reconnaissance and information operations white papers: advanced sensors; data fusion techniques; miniaturization (nanotechnologies and MEMS); secure, reliable, wideband communications; reliable distributed networks (particularly distributed networks of small satellites); advanced, high-speed, high-capacity computers; and the combination of hardware and software technologies which will enable true "artificial intelligence."

The areas recommended for further investigation in this paper must be pursued in full cooperation with industry wherever possible. The days of "fat" defense budgets are long gone—they will not come again in our time. Civilian (domestic and foreign) research dollars will determine the main areas where technology will advance in the twenty-first century. The US military must keep its collective eye on the "main chance," directing its precious and limited research funds where they will have the greatest effect. Anything less would be irresponsible.

[1] Quoted in Lt Col Charles M. Westenhoff, USAF, compiler. *Military Air Power-The CADRE Digest of Air Power Opinions and Thoughts*, Airpower Research Institute, Air University Press, Maxwell AFB, Ala. October, 1990, 90.

[2] "Joint Planning Document FY 1998-2003," 15 December 1995, Vol. 4 (Future Capabilities) 2.

[3] "Joint Vision 2010 - America's Military: Shaping the Future," a publication of the Joint Staff provided to AF ***2025*** by AF/XOXS, January 1996, 4.

[4] USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century,* summary volume (Washington, D.C.: USAF Scientific Advisory Board, 15 December 1995), 60.

[5] Lt Col Henry. Baird, et al., "Spacelift - Integration of Aerospace Core Competencies," AF ***2025*** study (Maxwell AFB, Ala.: Air War College, 1996).

Appendix A

Global Presence

Global presence includes a full range of potential activities ranging from the physical interaction of military forces and targets to the "virtual interaction" between information systems envisioned by the "information warriors." We will explore the idea of global presence by discussing the strengths and weaknesses of the space systems which could yield "global space presence" in 2025. Key technologies will ultimately be identified that link global space presence to a global space-strike capability and to the integrated network of sensors, communications, and information processing required to collect data from any (and every) area of the planet and convert it into information and knowledge in a suitably short time frame. Along the way, we will emphasize the important synergy and interconnectedness between military and commercial space systems in 2025.

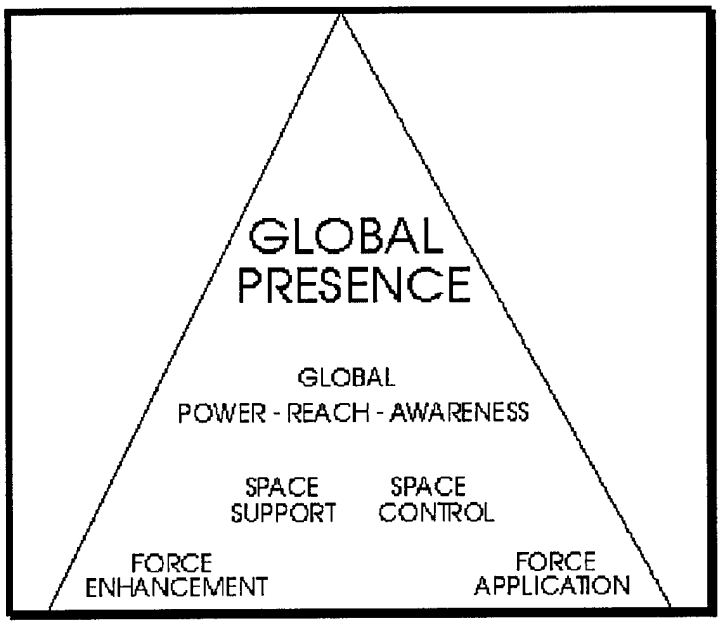


Figure A-1. Space Operations Missions

Some Important Definitions

Global space presence means providing military space capability, including non-belligerent applications and/or leveraging of information, to deter or compel an actor or affect a situation.[1] Through global space reach and global space power, multiplied by global space awareness and backed up by sustainment and readiness, the Air Force can provide an unmatched power projection capability to America's joint force in 2025.[2]

Global space reach includes those activities conducted from space that improve the operational effectiveness of military forces operating in all mediums (space, air, land, sea, subsurface).

Global space power involves the application of the full spectrum of force, physical and virtual, from space on demand to an adversary's means of pursuing the conflict.

Global space awareness is achieved through the integrated, worldwide acquisition, transmission, storage, and processing of information through space to enhance the employment of all military forces.

Readiness and sustainment means providing the ability to mount and support continuous military operations.[3]

Global space presence is a vital capability that can only be achieved by a nation with global space reach, global space power, global space awareness, and a robust readiness and sustainment system. By 2025, a nation that hopes to reap the benefits of great power status must possess global space presence.

In 1996, military space operations are organized to perform four core missions.[4] These mission areas are equally critical to the future success of US military operations at all levels—strategic, operational, and tactical. Space operations have already impacted the combat arms and the combat support elements of all branches of the US military through space reconnaissance, surveillance, and communication. The four core missions focus on enabling or supporting terrestrial (land, sea, air, and subsurface) military operations with assets operating from space (force enhancement); providing freedom of access to and operation in space for friendly forces while denying enemy access (space-control); applying force, both physical and virtual, to terrestrial military targets with weapon systems operating from space (force application); and conducting launch support and on-orbit military command and control for crucial military space assets (space support). Since these mission areas overlap, actual military space operations are broader than any one mission area.[5]

Notes

[1] Gen Ronald E. Fogleman, USAF, and Dr Sheila E. Widnall, *Global Presence 1995* (Washington, DC: HQ USAF, pamphlet, 1995), 3.

[2] Air Force Doctrine Document 1, Air Force Basic Doctrine, first draft, 15 August 1995, 3.

[3] Ibid., 3. Adapted from the discussion documented here.

[4] AF Manual 1-1, *Basic Aerospace Doctrine of the United States Air Force*, vol. 2, Essay L (Washington, D.C.: HQ USAF, March 1992), 103–111. The missions listed in this paper were adapted from this essay.

[5] Maj Thomas A. Torgerson, USAF, "Global Power Through Tactical Flexibly Deployable Space Units," (Maxwell AFB, Ala.: Air University Press, Research Report AU-ARI-93-6, June 1994), 4.

Appendix B

The System of Systems

All the systems of the force application system-of-systems must be integrated with all the other systems that interface with it. On board (guidance, maneuvering) and off board (surveillance, some processing) systems all work together as a distributed system-of-systems.

SAT/BDA

The surveillance, acquisition, and tracking/battle damage assessment(SAT/BDA) requirements fall into the general mission category of force enhancement. The impact of cost constraints and rapidly developing technologies on the Defense Department is moving the initiative in these areas toward the commercial sector. The global positioning system (GPS) is a prominent modern example, with commercial units being bought by the thousands to support Operation Desert Storm. It is very likely, therefore, that a significant amount of surveillance, acquisition, and tracking and battle damage assessment will depend on commercial concepts or commercial assets by 2025. This will be an important factor in two ways. First, a great amount of equipment will be available "off the shelf," and not just in America. Given their high cost, satellite assets will probably be shared, and not always by allies. Who will be in control?

One of the biggest questions in a multinational world, with multinational corporations, is whether we will have access to the information we need. If we do not wish to build duplicate military systems, we must in some way assure ourselves of access to commercial assets while retaining the capability to block an opponent's access. This might be done through treaties or binding business arrangements, but most likely we

will need some built-in capability to literally seize control of the necessary portions of shared commercial satellite assets.

The global information network (GIN) of 2025 is the obvious and probably the only affordable place to perform most of the SAT/BDA function. If the military's relatively limited (a matter of funding, not ingenuity) computers, sensors, and dedicated communications are not linked to the GIN, it will be impossible to assemble an accurate "digital picture of the battlefield" in real time. Linkage to the GIN will also provide ready access to rich sources of information unavailable to the modern war fighter. From the perspective of a space-strike weapon system, the availability of multiple views in many sensory bands of each target is an irresistible advantage. This suggests most SAT/BDA functions in 2025 will be performed "off platform" for space-strike weapon systems, making the development of secure, jam-resistant communication links a top priority. Two possibilities have been suggested in this regard: redundant radio frequency (RF) links in many frequency bands, possibly including spread spectrum techniques, and ultrawideband optical communications.[1]

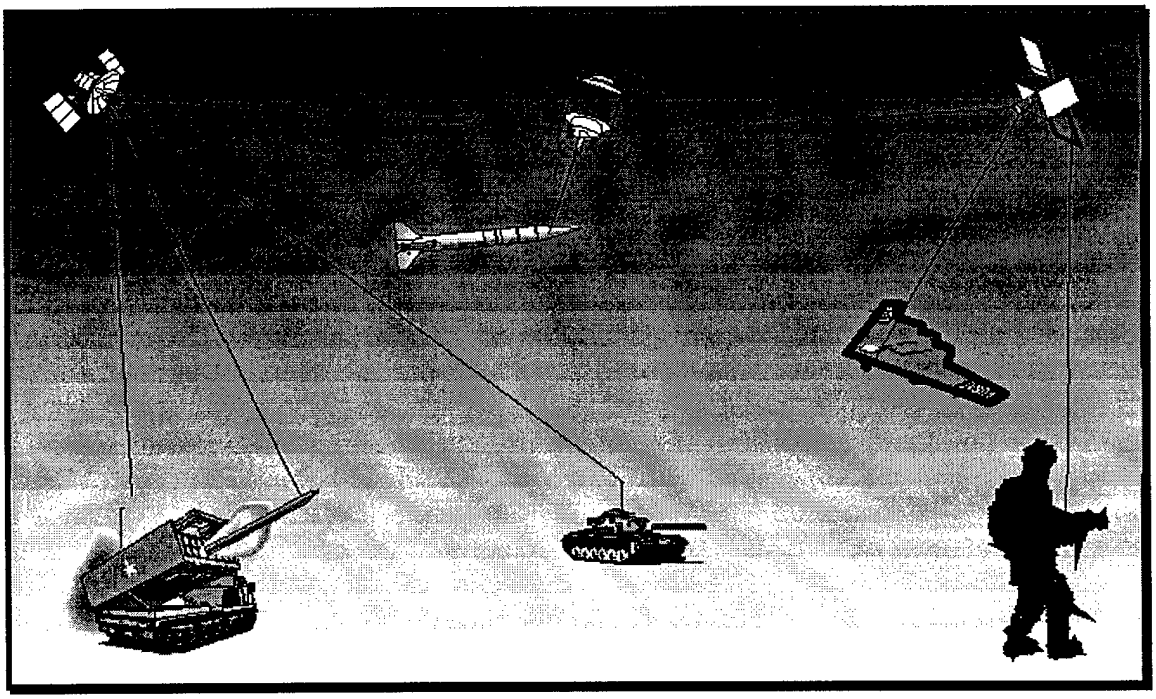


Figure B-2. Battlespace Awareness

Surveillance

Surveillance can be defined as "systematic observation of aerospace, surface, or subsurface areas, places, persons or things by visual, electronic, photographic or other means."[2] The requirement for this information seems critical today, but in the much faster world of 2025, real-time information will be an absolute imperative. The most survivable and effective way of obtaining real-time surveillance in 2025 will involve networking and fusing sensory data from a wide variety of military, civil, commercial, and even foreign (allied) assets. This exciting possibility awaits technical advances in wideband communications, wide-area networks, data fusion, and above all a far greater number of fielded sensors. That industry is already moving into the area of high-resolution remote sensing (and especially satellite remote sensing) is obvious from the many recent announcements of commercial satellite imaging systems with a spatial resolution approaching one meter.[3]

In 2025, surveillance systems operating from space will provide the war fighter with indispensable real-time, accurate, preprocessed information. Satellite systems will provide wide spectrum coverage, including visual, infrared, RF, and active radar, for fusing with air-, sea-, and land-based networks of distributed sensors.[4] Fusion and dissemination of surveillance data will be handled by a distributed, wide-area network of computers (probably based on microprocessors in a parallel architecture) linked by the communications system described below in the section on "utilities." The war fighter and his weapon systems, whether air-, sea-, land-, or space-based, will be able to access this information on demand, probably in a graphically oriented format. The ***Spacecast 2020*** study is correct in its claim that "a system and architecture must exist to provide a high resolution 'picture' of objects in space, in the air, on the surface, and below the surface—be they concealed, mobile or stationary, animate or inanimate."[5] The real challenge will not be the collection of sufficient data, but its processing into useful, easily digested forms. This will be an ever greater challenge as the amount of types of available information grows between now and 2025.

Acquisition and Targeting

Today "sensors, computers, and communications jointly comprise the essence of targeting."[6] America's main investment in these systems will be commercial by 2025, with a "sprinkling" of important, well-

protected (hardening, stealth, CONUS basing, deception), military-only or military-priority assets. This dispersion of assets will be an advantage, since properly designed, distributed systems are much more survivable than centralized, dedicated systems, and because it may be impossible to determine which portion of which physical asset is being used by the military at any one time. Surveillance and acquisition functions can and should, therefore, be provided by "off platform" distributed systems.

Targeting is a more complex and specialized function. By 2025, automated target acquisition and identification will finally be a reality. The necessary databases and specialized information processing assets can be made available through the GIN, which will also be linked to any specialized military sensor data that might be required to deal with particularly difficult targets. Automated target acquisition and identification is the subject of intense research today, and many promising approaches are being investigated on conventional supercomputers and clever, proprietary combinations of electronic and optical computers.[7] Commercial satellite remote-sensing systems are already in development with spatial resolutions good enough to identify aircraft, surface ships, land mines, and most smaller vehicles.[8] The results of the primarily off platform acquisition and targeting functions will then be handed off to the weapon platform, which will provide the tracking and force-application functions.

The Spacecast 2020 special study discusses a similar approach. "With appropriate algorithms and beam selection, it is conceivable that the entire sensor constellation could be available for collection all the time. Fusing of the reflected data from a single "taste" [speaking metaphorically] would take place on a central platform, probably in geosynchronous orbit."[9] By 2025, there will be no need for a vulnerable, central collection platform. With the continual miniaturization of computers and electronics, improved network hardware and software, and redundant wideband communication links (both optical and RF) these data collection and fusion can and should be shared among a variety of platforms, space and earth-based.[10] This approach has the enormous advantage of eliminating critical nodes in the US military information system.

Battle Damage Assessment

"BDA has historically been a task of considerable difficulty because the wide range of munitions utilized, the target types attacked and the modes of attack have precluded the application of any single, reliable method."[11] This problem is further complicated by our current strategy of pursuing parallel strategic attacks. By 2025, the solution to this problem will be evident in the "digital picture of the battlefield" assembled from the fused input of myriad sensors of many different types linked wirelessly to the GIN. The very system needed to survey and acquire targets will be used to assess battle damage. The advantages are obvious: cost effectiveness through elimination of redundant sensors and communications, nearly instant assessment of the need for restrike, and economy of force by avoiding the expenditure of unnecessary strikes. Additionally, accomplishing BDA through the GIN would provide instant, automatic feedback to the logistics system of the number and nature of resources expended.[12]

Utilities

During Operation Desert Storm, American and allied forces relied heavily upon space-based systems for navigation, weather information, secure communications and surveillance support. These and other space assets played a key role in the successful prosecution of the Gulf War. The reliance of the American military on these systems will only grow with time.

The quantity and quality of information that can be gained from the vantage of space enhances the power of existing terrestrial forces, both conventional and unconventional, by providing more and better information ever more rapidly. This rapid movement of information, no matter what the source, will become increasingly essential to all aspects of military operations. The near-real-time capability in communication, navigation, and weather sensing offered by the proper utilization of space assets and the opportunities they present make these functions critical to the successful military exploitation of space. No space-strike weapon system can operate without the information provided by communications, navigation, and weather systems. That is why these functions are called "utilities" in this paper.

Communications

The US military has become more and more dependent on radio frequency (RF) communications since World War II. Currently, worldwide military communications depend on several constellations of RF communications satellites, including the high-frequency (HF) and ultrahigh frequency (UHF) Defense Satellite Communications System (DSCS); the UHF, superhigh frequency (SHF), and extremely high-frequency (EHF) Fleet Satellite Communications (FLTSATCOM) and Ultrahigh Frequency Follow-On (UFO) Systems; and the secure, jam-resistant UHF, SHF, and EHF capable Milstar System.[13] Submarine cables, fiber-optic lines, and microwave radio can compete with satellite communication systems only for geographically fixed, wideband service. Satellites are unchallenged in the area of wideband transmissions to mobile terminals, which is precisely the area of greatest need for the military.

During Operation Desert Storm, even the United States's apparently robust satellite communications architecture was overwhelmed—the coalition was forced to lease time on the INTELSAT and SKYNET systems, although the total capability was still "grossly inadequate." The total requirement for voice, data, and video links for the Gulf War ("only" a major regional contingency) was staggering. The worldwide network assembled for Operation Desert Storm involved practically every type of commercial, strategic, and tactical telecommunication equipment available. Unsurprisingly, network management and control was "a sub-optimized, manual process—improvised on the spot and under enormous pressure for instant results." It is now generally agreed that "a mix of military and commercial networks is the only way to provide adequate communications support in the future."[14]

The most likely military communications architecture in 2025 is a shared commercial satellite communications system. This system will be based on a large constellation (hundreds or thousands) of small satellites in low earth orbit. Each satellite will be cross-linked to every other satellite with a mixture of truly wideband solid-state laser communication links (digital data rates in excess of 10 gigabytes/second) and high-speed RF back-up links (60 Ghz or greater). Most downlinks will still involve RF technology, since it is simple and inexpensive, but the most demanding traffic will have to be handled optically. Ground stations will be simple and easily relocatable, since each satellite will carry its own formidable computer brain to manage the communications traffic redundantly (the inevitable consequence of the explosion in computer processing speed and capacity). Ground line communications will be nearly nonexistent (too expensive),

except for emergency back-up systems and a few ultrasecure, jam-resistant communication systems (based on optical fiber as the only way to handle the load). In the world of 2025, every person could contact anyone, anywhere, at any time, if properly equipped.

Navigation

The Navstar GPS satellite navigation system currently provides reliable three-dimensional position information with an accuracy and precision of 16 meters and time with an accuracy of 0.1 microseconds (uncorrupted version).[15] Whenever enough satellites are in view, GPS can even provide velocity and acceleration information. Combined with inexpensive commercial receivers, GPS navigation was critical to the success of coalition forces in the Gulf War. This information is good enough to pilot cruise missiles hundreds of miles to large targets and to provide targeting coordinates for modern PGMs. It is not good enough for many of the space-strike weapons described earlier in this paper, which require extreme time and position accuracies (a few nanoseconds in time, centimeters in position) to be fully effective.

The ***Spacecast 2020*** special study recognized the need for an improved navigation system in their Super GPS white paper.[16] In 2025, such a system will be owned and controlled by civilian organizations—the Federal Aviation Agency is assuming greater control over the existing GPS constellation every day. The most likely candidates for control of the Super GPS system of 2025 are the Federal Aviation Agency (or more likely an internationalized successor) and one or more international commercial concerns. The system, based on a larger constellation of small satellites in LEO for increased coverage and on-orbit redundancy, will certainly be more accurate and precise. It is difficult to predict where the constantly evolving commercial demand for three-dimensional positioning information will be in 2025, but it is probably safe to forecast performance measured in feet (large fractions of a meter). Military demands in excess of this will be handled either by small military-owned payloads on the commercial satellites or by a small military-funded augmentation to the commercial constellation.

Weather

Military commanders have always needed timely, accurate weather information to mount successful campaigns. This need will be even more urgent in 2025, when optimal use of all forces will require real-time information on all battlefield conditions. Additionally, space-strike weapons need a mixture of space weather data and battlefield environmental data to be effective. Space-based HPMW beams can be disrupted by intense solar winds. Space-strike lasers are dispersed by water clouds and battlefield dust and smoke. Hypervelocity kinetic energy weapons must have good information concerning the state of the atmosphere to reach the proper spot on the target.

Industry is developing smaller and higher performance remote sensors with every passing day.[17] Commercial demand and commercial funding is already out stripping the military's capabilities (everyone needs to know about the weather). The National Oceanic and Atmospheric Administration is already taking charge of what were once military-controlled weather satellites.[18] These trends strongly suggest that long before 2025, weather-related remote sensing will be entirely controlled by industry. The commercially controlled weather monitoring and prediction system in 2025 will probably depend on a sophisticated suite of ultraminiaturized electronics and sensors operating as a secondary payload on a LEO satellite communications constellation, thereby taking advantage of existing down and cross-links. A few small weather satellites will still be parked at geosynchronous earth orbit (GEO) to take advantage of its larger-scale view of earth and to monitor "space weather" at a distance from the less-placid LEO environment. While most requirements for weather-related information in a military theater of operations will be handled by this mix of LEO and GEO weather satellites, some detailed weapon system requirements for data on surface conditions will still have to be handled by a network of ground-based sensors connected to the global information network.

Notes

[1] ***2025*** concept, no. 900522, "Space-Based AI-Driven Intelligence Master Mind," ***2025*** concepts database (Maxwell AFB, AL: Air War College/***2025***, 1996); ***2025*** concept, no. 900283, "Information Supremacy," ***2025*** concepts database (Maxwell AFB, AL: Air War College/***2025***, 1996); ***2025*** concept, no. 900335, "Worldwide Military Cellular Phone System," ***2025*** concepts database (Maxwell AFB, AL: Air

War College/***2025***, 1996); ***2025*** concept, no. 900585, "Global Location & Secure Comm," ***2025*** concepts database (Maxwell AFB, AL: Air War College/***2025***, 1996).

[2] Data Fusion Lexicon, Data Fusion Sub-Panel of the Joint Directors of Laboratories, "Technical Panel for C^3," 11.

[3] Maj James G. Lee, USAF, "Counterspace Operations for Information Dominance" (Maxwell AFB, Ala.: Air University Press, October 1994), 14–16.

[4] ***2025*** concept, no. 900414, "Artificial Intelligence: A New Aircrew Member in Tomorrow's Combat," ***2025*** concepts database (Maxwell AFB, AL: Air War College/***2025***, 1996); ***2025*** concept, no. 900263, "The All Seeing Warrior," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[5] Spacecast 2020 study, "Global Surveillance, Reconnaissance, and Targeting System"(Maxwell AFB, Ala.: Air University Press, 1994).

[6] Briefing by Dr Lowell Wood at Air War College, subject: Special Projects at Lawrence Livermore National Laboratory, 27 October 1993, slide 7.

[7] Information obtained from senior industry personnel under the promise of nonattribution.

[8] Maj James G. Lee, USAF, "Counterspace Operations for Information Dominance" (Maxwell AFB, Ala.: Air University Press, October 1994), 15. See Table 5.

[9] Spacecast 2020 Study, "Global Surveillance, Reconnaissance, and Targeting System," Maxwell AFB, AL: Air University Press, 1994.

[10] ***2025*** concept, no. 900370, "Molecular Manufacturing and Nanotechnology," ***2025*** concepts database (Maxwell AFB, AL: Air War College/***2025***, 1996); ***2025*** concept, no. 900518, "Electronic Grid - Throwaway Sensors," ***2025*** concepts database (Maxwell AFB, AL: Air War College/***2025***, 1996); ***2025*** concept, no. 200023, "Surveillance Swarm," ***2025*** concepts database (Maxwell AFB, AL: Air War College/***2025***, 1996); ***2025*** concept, no. 900231, "Gnat Robot Threat Detectors," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[11] Carlo Kopp, "Air Warfare Applications of Laser Remote Sensing" (Fairbairn, Australia: Air Power Studies Centre), 3.

[12] ***2025*** concept, no. 900672, "Integrated Logistical Battlespace Sustainment," ***2025*** concepts database (Maxwell AFB, Ala.: Air War College/***2025***, 1996).

[13] Kimberly M. Walker, USAF, "Space Operations Training Course - Chapter 9: Introduction to Communications Satellites" (Peterson AFB, Colo.: 1994), 134–148.

[14] Alan Campan, *The First Information War*, AFCEA International Press, 1994; 18, 21.

[15] Capt Kimberly M. Walker, Capt, USAF and Capt Tery L. Donelson, Space Operations Training Course - Chap 10: Navstar Global Positioning System" (Peterson AFB, Colo.: 1994), 152.

[16] ***Spacecast 2020,*** "Operational Analysis" (Maxwell AFB, Ala.: Air University Press, 1994), 35.

[17] Sarah L Cain, "Eyes in the Sky: Satellite Imagery Blasts Off," *Photonics Spectra,* October 1995. 90.

[18] Conversations with Air Force Colonel Chuck Thompson, Air War College Space Chair, December 4 1995.

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