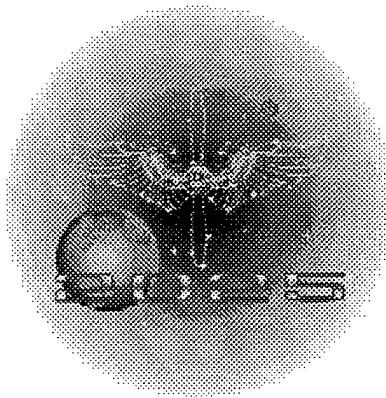


**SPACENET:  
On-Orbit Support in 2025**



A Research Paper  
Presented To

Air Force *2025*

by

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August 1996

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## **Disclaimer**

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## *Executive Summary*

In 2025, on-orbit support will be vital to employing space assets as an instrument of national power. Four areas of on-orbit support need to be developed over the next three decades to ensure that the US maintains space dominance. These four key areas together form the Spacenet 2025 system. This white paper examines these four areas in the context of supporting space assets, not the particular missions the satellites may accomplish.

First, support to the war fighters will be the priority of the military space program. The theater commander requires reliable, timely support from space to utilize all war fighting assets. This space support includes communications, navigation, weather, missile launch warning, and data transfer. Although intelligence is not addressed in this report, on-orbit support provides sufficient processing, storage, and transmission capability to fully support the intelligence architecture. In essence, the war fighters in the field will not need to worry about overloading voice or data channels—the required capacity will be available continuously.

Second, the satellite command, control, and communication (C<sup>3</sup>) system must be responsive enough to position satellites in the correct orbits to support the theater commander. This requires: C<sup>3</sup> systems to control satellites over the horizon from the ground control station; automatic, redundant switching to ensure that a particular satellite receives the correct commands; and flexible, secure, and mobile ground stations. Satellite autonomy is the ultimate goal, however, when required, ground control is minimized.

Third, satellite design is critical. Improved design lowers cost, increases flexibility, and enhances survivability. Key design considerations include satellite size, longevity, power and propulsion requirements, radiation-hardened electronics, satellite autonomy, and satellite disposal. Quantum leaps in information systems technology will lead the design environment, but adapting system capabilities to operate in space is a major stepping stone to achieve Spacenet 2025 capabilities.

Finally, space assets must be survivable in a hostile space environment and immediately replaceable if destroyed. Satellite security employs both passive and active defenses to counter manmade and environmental threats such as space debris, antisatellite (ASAT) systems, or meteorites.

These four areas of on-orbit support are the pillars of the Spacenet 2025 system. This “internet in space” depends on the four pillars to provide timely data and support to war fighters worldwide, seamless C<sup>3</sup>, and carefully designed satellites that are survivable and secure. The Spacenet 2025 system synergistically builds capabilities so the whole Spacenet 2025 system is greater than the sum of its parts. Spacenet 2025 may become the ultimate force enhancement and projection system, ensuring that the US remains the world’s sole superpower throughout the 21st century.

# Chapter 1

## Introduction

Alfred T. Mahan recognized the importance of lines-of-communication (LOC) in the vastness of the earth's oceans. One of the Navy's missions was to protect merchants traveling those sea LOCs. Additionally, "The government by its policy can favor the natural growth of a people's industries and its tendencies to seek adventure and gain by way of the sea."<sup>1</sup>

US airpower and space power doctrine should follow a policy favoring the natural growth of space industries and promoting the security and safety of these commercial ventures. Research and development, policies, and guidance of a large-scale satellite C<sup>3</sup> backbone system, used by both commercial and military sectors, will enhance the safety of the LOC for spaceborne platforms.

In 2025, space operations will be a vital instrument of national power. On-orbit support will help determine the effectiveness and efficiency of space operations. This paper describes the desired operating methods of on-orbit support to ensure the US remains the dominant space power in 2025 and beyond. Specifically, the scope of on-orbit support in this paper begins with satellite release from the launch vehicle and ends with satellite disposal at mission termination. Launch operations and specific missions of space assets are the subjects of other papers in the 2025 research project and are referenced in this paper but are not specifically addressed there.

Two assumptions form the essential basis of this report. First, the US will be a dominant world power in 2025. Second, space assets and operations will increase in importance both militarily and commercially. In fact, commercial enterprises will lead the development of some space technology. As DOD continues

downsizing, virtual presence from space will replace troops as the vehicle for forward presence. On-orbit support is the enabling function for the global awareness necessary to maintain US space dominance.

Four pillars describe the Spacenet 2025 on-orbit system. The first pillar is the war fighter's requirements. The second pillar is command, control, and communications (C<sup>3</sup>) of space assets—the method of satisfying the customer. Spacecraft design is third with a focus on satellite size, service life, power and propulsion requirements, radiation-hardened electronics, autonomy, and satellite disposal. The final pillar is satellite security in the context of manmade and environmental hazards.

The end-state goal is for on-orbit support to be transparent to the user: responsive, effective, and unobtrusive. The Spacenet 2025 system will meet the challenge.

#### Notes

<sup>1</sup> Alfred T. Mahan, *The Influence of Sea Power Upon History* (New York: Dover Publications Inc., 1987), 82.

## Chapter 2

### Required Capability

The roles of the US military in 2025 will likely span the entire conceivable spectrum, from internal security and deterrence of major conflict to military operations other than war. The alternate futures of 2025 may find the advancement and growth of technology either constrained or exponential.<sup>1</sup> Even with constrained growth in 2025, technological advancements in the next 30 years will be significant. If the US military hopes to remain the world's premier deterrent and fighting force in 2025, it must take advantage of technological advancements to improve on-orbit support.

In 2025, war fighters will operate in an information rich-environment. Both commercial and military sources will provide this abundant information and adversaries will probably exploit the commercial information opportunities. This trend is readily visible today with the commercial sale of 10-meter resolution imagery from the French system probatoire d'observation de la terre (SPOT) satellites, the explosion in commercial communications ventures, and worldwide commercial use of global positioning system (GPS) navigation signals.

Space will be the medium of choice for information collection and dissemination in 2025. The unique capabilities to operate freely at any point above the earth, communicate with other satellites and ground personnel "over the horizon" (using satellite crosslinking), and near simultaneous dissemination of information to numerous users make space systems the premier force-enhancement capability.

If space force enhancement data is widely available commercially, will there be "parity" between nation-states or groups with enough money to buy and exploit this data? Absolutely not—the key will be to quickly gather huge masses of information, assimilate it, and act accordingly.

On-orbit support is a key requirement to deliver the core competency of space dominance. Within on-orbit support, four areas provide the basis for investigating required capabilities for satellites in 2025: support to the war fighter, C<sup>3</sup>, satellite design, and satellite security.

To support the war fighter of 2025, satellite systems must tighten the US's observe, orient, decide, and act (OODA) loop (fig. 2-1) to stay well ahead of the adversary's capabilities.<sup>2</sup> This does not mean simply supplying truckloads of data to whomever has time to read it; the war fighters of 2025 need information that is critical to the particular mission and they need it at the optimum time. In a high technology environment the dangers of information overload are real. Information overload must therefore be avoided.

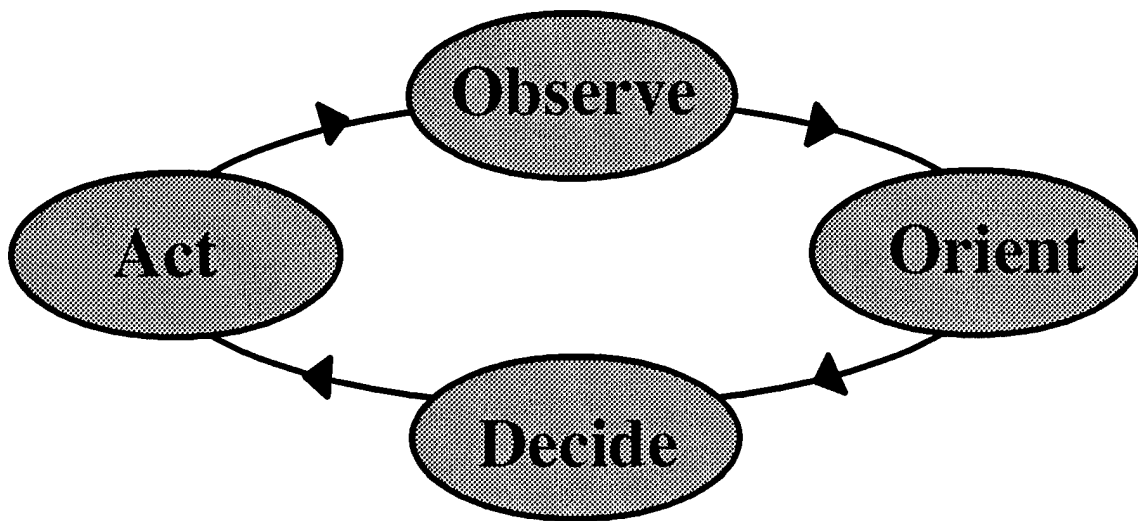


Figure 2-1. Observe, Orient, Decide, and Act (OODA) Loop

Satellite C<sup>3</sup> is another required capability. C<sup>3</sup> must be simple, cost-effective, and robust. Communication from earth-to-space or earth-to-earth using satellites is another key to "tightening" the OODA

loop. Additionally, increased weapon lethality and miniaturization necessitates the designing of more survivable satellite C<sup>3</sup> systems.

Satellite design is another key link to achieving space dominance. Space systems must be smaller, more cost-effective, and more responsive to the customer's needs. Today's limitations of propulsion fuel and satellite electrical power and the susceptibility of electronic components to space radiation, satellite autonomy, and satellite disposal require revolutionary directions to fully "operationalize space." Solutions to these satellite limitations should also drive costs down so that more money can be spent on the "shooters," rather than their supporting platforms in space.

Given the criticality of space support to the war fighters of 2025, the proliferation of commercial satellites, and other nations playing the "space game," satellites become increasingly high-value targets. Satellites in 2025 must employ inherent countermeasures to ensure US space dominance. The solution is not to give satellites armor like M-1 tanks, but to employ active and passive countermeasures where they make sense. If all else fails, plan for attrition—and for recovery of lost capabilities with timely satellite replacement.

On-orbit support is the linchpin to maintaining US space dominance in the 21st century. Aggressive developments in war fighter support from space, satellite C<sup>3</sup>, design, and security will form the building blocks of the Spacenet 2025 system to meet the requirements and solidify US space dominance in 2025 and beyond.

#### Notes

<sup>1</sup> Air Force 2025. Alternate Futures white paper. 2025 database, (Maxwell AFB, Ala.: Air War College/2025, 1996).

<sup>2</sup> 1Lt Gary L. Vincent, "In the Loop in Command and Control," *Airpower Journal*, Summer 1992, 17-18.

## Chapter 3

### System Description

A coming information revolution and its impact on the battlefield is a popular topic for military theorists today. Many considerate it a revolution in military affairs (RMA)<sup>1</sup> while others simply consider it an evolutionary change that exploits information with technology. Whether the emerging information systems are revolutionary or evolutionary is a subject for debate. What is not debatable is the fact that war fighters and peacekeepers of the future will operate in an information-rich environment and must possess the technical means to obtain and exploit information in near real-time.<sup>2</sup> One Chinese defense expert described future wars this way: "In hi-tech warfare, tactical effectiveness no longer depends on the size of forces or the extent of firepower and motorized forces. It depends more on the control systems over the war theater and the efficiency in utilizing information from the theater."<sup>3</sup>

#### The War fighter's Requirements

The need for accurate information is critical to war fighters and peacekeepers. War fighters must obtain accurate information faster and immediately employ it with decisive results. Accurate information helps penetrate the fog of war and decreases the risk. Fighting and winning in 2025 will hinge upon accurate and timely assimilation of vital information from space. War fighters will operate in an information-rich environment as countless terabits ( $10^{12}$ ) of information will flood the theater of operation. Some of this information will be critical and some of it useless. The key will be separating the "wheat from the chaff" quickly to facilitate a "good" decision.

The availability of data from both commercial and military sectors can and will place information in the hands of adversaries, potentially disrupting or denying US objectives. This data will serve as a catalyst, allowing adversaries to shrink their OODA loop.

In 2025, the amount of observed data may reach parity between opposing forces, making the “observe” step of the OODA loop a “dead heat.” However, through exploitation of the “orient” step (via on-orbit and in-theater processing), the US OODA loop can tighten well inside that of any potential adversary (fig. 3-1). With the critical information identified first, US war fighters can “decide” and “act” well before adversaries can remove the “chaff.”

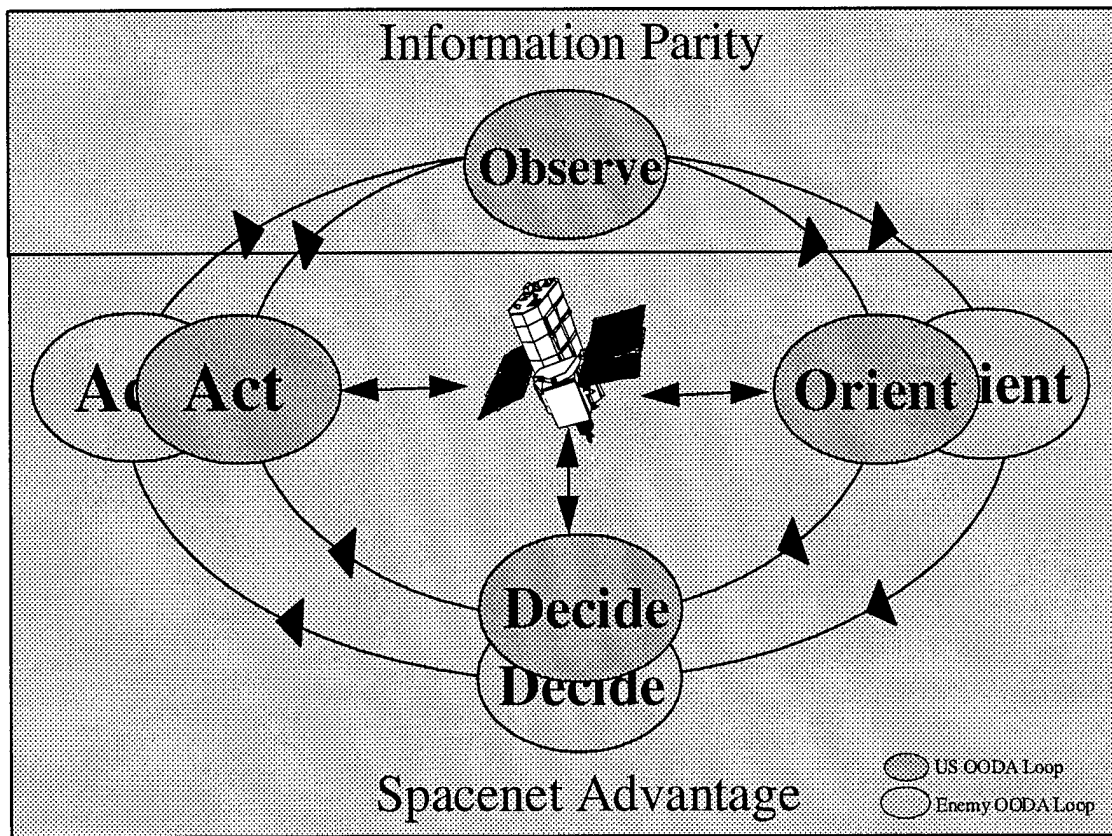


Photo from Microsoft Clipart Gallery © 1995 with courtesy from Microsoft Corporation

**Figure 3-1. The Impact of Spacenet on the US OODA loop**

History has shown even the most accurate information is useless if not given to the war fighter in a timely manner (just-in-time) or on-demand. A prime example of accurate intelligence with negligible results was the SCUD hunting missions during Operation DESERT STORM. In all, coalition forces launched 2,493 sorties<sup>4</sup> against an estimated 225 SCUD transporter-erector-launchers (TEL).<sup>5</sup> To date, there is no evidence

that any TELs were destroyed. Evidence confirms the destruction of decoys, trucks, and objects with SCUD-like signatures despite the fact that space-based assets immediately detected launches of Iraqi SCUD missiles.<sup>6</sup> Within minutes of a detected launch, theater commanders were notified and an aircraft was scrambled or diverted to the missile launch site. By the time the alert had been processed and communicated to the personnel, the TEL had vacated the launch site. Authorities estimate that an Iraqi missile crew could launch, drive off, and conceal a TEL in five minutes.<sup>7</sup> In future battles involving chemical, biological, and nuclear weapons, these minutes could be the difference between victory and defeat. In 2025, time-critical information will have to travel the shortest possible distance, directly from the satellite to the war fighter.

A war fighting commander's goal for information is to have it in the right hands at the right time, on-demand. Delays for processing are unacceptable. In 2025, war fighters will rely heavily on preprocessed, archived data, and rapid dissemination of new or custom information.

### **On-Orbit Processing**

The keys to controlling information are the quantum increases in the speed and capacity of information-processing systems and the ability to move processing and correlation functions into space. Equally important is the integration of hardware, software, and information from the commercial sector.<sup>8</sup> On-orbit processing of data and the resulting rapid distribution of critical information to the individual war fighter, just-in-time or on-demand, is a vital step in maintaining land, air, and space dominance. As technology advances, the feasibility of automating data collection, fusion, and distribution becomes a reality. Recent events, such as the bombing of the World Trade Center in New York City and the federal building in Oklahoma City, show some of the vulnerabilities of fixed ground facilities. Satellite control facilities may be better protected, but are only somewhat less vulnerable. The combination of technological advances and vulnerabilities will necessitate dispersing many information processing functions to the next high ground—space.

In order to increase the speed of dissemination, information from space-based assets must be available to all levels of friendly combatants. Every war fighter, from the joint force commander (JFC) to the soldier in the field, must have access to critical information on-demand and in near real time. Advances in computer processing speed, artificial intelligence software, data storage, and power supplies will enable on-orbit

processing. Direct links from the satellite sensor to a cockpit, a foxhole, or a warhead are a necessity in 2025.

Exploitation of information at the lower levels will require user-friendly, battlefield savvy systems that allow the company commander, the squad leader, the pilot, or the officer at the helm to access and assimilate critical information quickly. These man-portable systems will interface directly with on-orbit assets and with mobile theater control centers. Predetermined information requirements based on the need-to-know will allow in-theater and on-orbit archiving and updating of pre-packaged, fused information. Wide bandwidth transmissions that allow two-way communications are a necessity. Additionally, the user must have the option to request modified data in near real time as the battlefield situation changes, enabling operations well within the enemy's OODA loop.<sup>9</sup> Several emerging technologies will make on-orbit processing feasible.

### **Artificial Intelligence**

The heart of any processing system is the software. There will be a fundamental shift from programming computer actions to allowing computers to serve as a thinking agent, anticipating needs based on preprogrammed criteria and real-time inputs from the war fighter. These new programs or "software agents" are a major step toward artificial intelligence.<sup>10</sup> 2025 software will adapt and evolve just as organisms mutate in order to adjust to environmental changes.<sup>11</sup> Individual war fighters will be data-linked to a space-based processing center and their every action will be recorded by software agents. These agents will use these real-time inputs to analyze, anticipate, and predict what the war fighter will need. The software agents will then coordinate in cyberspace with spaceborne collectors and ground-archived data-processing nodes to prepare a fused information package for the war fighter. Time-sensitive information will be pushed to the war fighter. The software agents will also have the ability to update archived data to ensure "freshness."

### **Archiving Data**

Information-processing in space will require tremendous leaps in the storage capacity of "hard drives," not to mention a reduction in their weight. Just 10 years ago, a 10-megabyte personal computer hard drive

cost approximately \$2,500; today, 100 times more memory costs less than \$300. Today's research indicates that the future of information storage is in optical systems. Budding technologies such as holographic data storage systems (HDSS) will exponentially increase the ability to archive and retrieve data. HDSS has several key features that make it ideal for space and field applications: it is lightweight, has tremendous capacity for storage, allows exponential increases in throughput, and has no moving parts.<sup>12</sup> HDSS offers the possibility of storing trillions of bits of information on a disk the size of a small coin.<sup>13</sup> The system employs lasers and an optical data-storage medium. These high-capacity, high-bandwidth storage devices can be accessed in parallel, achieving throughput rates approaching one gigabyte per second<sup>14</sup>—or maybe—better by 2025.<sup>15</sup> With this storage capacity on-orbit and in-theater, archived information is available when needed by the war fighter.

### **Data Compression**

To further multiply the value of HDSS, new technologies in data compression are being researched. For example, imagery products require a large amount of storage space and are ideal for compression. When imagery is decompressed, however, it loses resolution relative to the amount of compression it underwent. Fractal compression research offers high compression rates and high resolution after decompression. This new technology converts imagery to mathematical equations and then looks for redundancy in the equations.<sup>16</sup> By noting these mathematical similarities, the data is then compressed and decompressed accurately. Initial compression rates from 20:1 to 50:1 are possible with no appreciable loss of resolution.<sup>17</sup> Fractal compression has one additional benefit; imagery will update itself as it skews, moves, or rotates.<sup>18</sup> This will enable near real time detailed video updates.

### **Command, Control, and Communications**

The missions of air power and space power in 2025 will still be to win wars. The primary reason for maintaining a military establishment will remain the same as it is today: to protect vital interests and provide security. To maintain air and space dominance over the next three decades of shrinking budgets, the *New*

*World Vistas* Study recommends the military outsource capabilities that are not considered core competencies.

Telecommunication is one area the *New World Vistas* Study recommended for commercial outsourcing.<sup>19</sup> Military telecommunication using commercial systems is a trend underway today. AFSPC currently leases commercial communications satellites, aptly named Leased Satellite Communications System (LEASAT) by their owner, Hughes Communications.<sup>20</sup> AFSPC uses LEASAT to transmit satellite command and control (C<sup>2</sup>) information, along with mission data, from remote satellite tracking stations to the satellite control facilities at Falcon AFB, Colorado, and Onizuka AFS, California. Army Special Forces units will begin operational use of commercial mobile satellite communications technology starting in 1997.<sup>21</sup> The Navy uses commercial communications satellites such as International Maritime Satellite Organization (INMARSAT)<sup>22</sup> for communications with ships at sea. As this trend grows, it will affect communications on earth and in space.

Communications systems will be a vital force multiplier for war fighters. The fiber-optic backbones that MCI, Sprint, and AT&T are installing in the 1990s have "advantages for heavy-volume point-to-point traffic, whereas satellites will continue to be cost-effective for multipoint and thin route services."<sup>23</sup> Translated into military terms, terrestrial communications work well in-garrison, but satellites provide less expensive communication to fast-moving mobile units.

Communication satellites currently provide a significant portion of DOD communications. Additionally, the 1996 draft *Air Force Executive Guidance* assumes that "US reliance on space-based capabilities will continue to increase" and "the number of national and non-national entities utilizing space-based assets to gain advantage will increase."<sup>24</sup>

### **Spacenet—The Internet Deploys to Space**

Given the trend towards using space-based commercial telecommunications and its impact on the war fighter, the Air Force should maximize use of commercial systems to meet military requirements. To focus the research and development required, the Air Force should encourage the development of Spacenet, a

generic spacecraft command, control, and communications (C<sup>3</sup>) system to meet C<sup>3</sup> needs and enhance interoperability in 2025.

One component of spacenet is a backbone communications system that allows scaleable, survivable, and flexible response to user needs. The concept of operations for the backbone is similar to that of orbiting internet nodes. Orbiting communications spacenet nodes—switches in space—transmit information packages to other communications switches. Multiple orbiting switches route packets efficiently by tracking the different paths available to the final destination. Paths to destinations can be through other orbiting switches or terrestrial communications links. The network of orbiting switches expands easily—new switches identify themselves to switches already in the network, and their address is passed throughout the network. As orbiting switches degrade or “die,” operating switches detect the failure and route packets around the problem switch. Packets receive appropriate priorities for transmission based on priority tables uploaded by ground controllers.

Spacenet strongly supports the principles of command, control, communications, and computers (C<sup>4</sup>) (table 1).<sup>25</sup> The backbone communications system is flexible enough for spacecraft C<sup>2</sup> and transfer of mission data into and from space. The system must have sufficient capacity to take control of all essential space assets during a contingency.

**Table 1**  
**C<sup>4</sup> Principles and Criteria versus Spacenet**

C <sup>4</sup> Principles and Criteria	Spacenet Support for the Principles
Interoperable	A backbone communications system, providing interoperable space and terrestrial communications
Flexible	Communication anywhere in the solar system; expanding as humanity's reach expands
Responsive	A reliable and redundant method of communication
Mobile	Available anywhere in the solar system (as the Spacenet is expanded) through mobile terminals
Disciplined	Provides control methods to prioritize communications
Survivable	Multiple interconnected nodes allow graceful degradation if nodes fail
Sustainable	Financed primarily through commercial ventures

The analogy of an internet in space extends beyond technology into the concept of operations. The internet was originally developed as a military system, called the Advanced Research Project Agency

Network (ARPANET) for survivable communications in a nuclear environment. Spacenet provides a survivable communications architecture for space systems. The internet has grown because of commercial use; it is more cost-effective to hook into internet than to lay dedicated data-communications lines. Spacenet will grow with commercial use because it will be more cost-effective for commercial entities to hook into a large, flexible C<sup>3</sup> system for spacecraft rather than build another C<sup>3</sup> system. The military benefits from the commercial growth of spacenet because the larger system provides more communications capacity and has more survivable nodes. Similarly, the military utility of spacenet will grow through commercial additions. Table 2 compares today's internet with the 2025 Spacenet.

**Table 2**  
**Similarities of Terrestrial Internet and Spacenet**

Similarity	1996 Internet	2025 Spacenet
Military Use	Originally developed by DARPA for Cold War communication	Developed for cost-effective, survivable, mobile communications solar system- wide
Commercial Use	Commercial terrestrial information transfer	Commercial solar system-wide information transfer
Hub/Spoke Architecture	Easily expanded, using industry standard protocols	Architecture allows expansion with new nodes to add capacity or reach other parts of solar system
Concern with Results, not Technologies	1996 user does not need to know internet communications architecture—it just works	2025 user does not need to know spacenet architecture

A fundamental question to answer is: why have an internet in space? The terrestrial internet can reach most locations on earth that have telephone access. However, the terrestrial internet system does not extend out to space assets. Current US space operators communicate with space assets through a limited number of fixed, vulnerable ground antennas.

Another reason for spacenet is that the world of 2025 may need to support remote information users in the air and in space. Just like the transoceanic telephone system communicates on Earth, space-based users will need a communication system to send information to or get information from the earth. Several of the 2025 systems, including those proposed in the *Counterair* paper and the *Unmanned Aerial Vehicle* paper, call for using a space-based C<sup>3</sup> system. Spacenet fills the C<sup>3</sup> void as an inexpensive, standardized system for providing communications to a multitude of terrestrial, airborne, and space-based military systems.

Spacenet complements the terrestrial communications system as a more cost-effective alternative to provide connectivity for remote and mobile users. "Fiberoptic costs per circuit-mile are high for low utilization but decline rapidly as the number of circuits increases; satellite costs per circuit-mile are lower at low utilization but decline more slowly."<sup>26</sup>

### **Advances Required for Spacenet**

The operational environment in 2025 could pose a number of obstacles that a robust space-based C<sup>3</sup> system must overcome. Current technologies must grow to meet the requirements of the 2025 operational environment. Emerging systems must mature and improve.

Tables 3 and 4 compare the increase in data throughput of terrestrial versus space-based telecommunications transmissions media. In 1996, terrestrial telecommunications transmission capabilities have out-stripped the capabilities of satellite systems. In 2025, satellites may still only carry a fraction of the total solar system's telecommunications traffic, but that fraction must provide more throughput than possible today.

*SPACECAST 2020* proposed that information needs in the future will be driven by user demand, pulling information from the source when needed as opposed to pushing information at a constant rate. Users will require high data transfer rates to support demand for large quantities of information. Current technologies do not support the data rate required by future users. In 2025, a mixture of extremely high-frequency (EHF) broadcast radio communications and high-bandwidth pinpoint laser communications will meet the need for higher data transfer rates.

**Table 3**  
**Throughput for 1996 Satellite Systems**

Satellite	Throughput Rate
MILSTAR II Satellite	49MB/sec <sup>a</sup>
Defense Satellite Communication System	100MB/sec <sup>b</sup>
Advanced Communication Technology Satellite	220MB/sec <sup>c</sup>
Tracking and Data Relay Satellite	300MB/sec <sup>c</sup>

<sup>a</sup> Capt Michael L. Figurski, Milstar Engineer, 4th Space Operations Squadron, telephone interview by Maj Carl Block, 23 February 1996.

<sup>b</sup> 1Lt John Giles, Squadron Defense Satellite Communication System Engineer, 3rd Space Operations Squadron, telephone interview by Maj Carl Block, 23 February 1996.

<sup>c</sup> Andrew Wilson, ed., *Jane's Space Directory, Eleventh Edition 1995-1996* (Alexandria, Va.: Jane's Information Group, 1995), 361.

**Table 4**  
**Throughput for 1996 Terrestrial Communication Systems**

System	Throughput Rate
Fiber Distributed Data Interface	100 MB/sec
Asynchronous Transfer Mode	622 MB/sec
Fiber Channel	1064 MB/sec
Fiber Distributed Data Interface Follow On	1250 MB/sec

**Source:** Nathaniel I. Durlach and Anne S. Mavor, eds., *Virtual Reality Scientific and Technological Challenges* (Washington, D.C.: National Academy Press, 1995), 366.

Current radio-based communications systems interfere with each other if not closely coordinated. For example, the super high-frequency (SHF) Air Force satellite control network uplink and downlink frequencies are protected by the Federal Communication Commission (FCC) in the US, but these frequencies are allocated to commercial satellite systems in Europe.<sup>27</sup> The EHF band is relatively empty compared to the clogged SHF communications band. Moving to EHF reduces the interference problem for the short term. However, when EHF frequencies become standard, interference may affect EHF bands as well.

The US currently has only three antennas used to control deep space satellites.<sup>28</sup> These antennas are barely able to support current deep space projects; they will certainly be unable to support the large number

of future satellites which will be used in other parts of the solar system. These deep-space satellites may come as commercial asteroid mining ventures or military satellites patrolling the solar system.<sup>29</sup> Moreover, if a planetary defense system is developed, the current C<sup>3</sup> system clearly cannot support it. Future requirements demand an upgrade to the current satellite communications backbone. The current satellite C<sup>3</sup> infrastructure will not meet future demands of satellites in earth orbit or beyond.

The satellite communications backbone must be capable of handling large fleet operations from the post-launch phase through satellite disposal. The system must provide for C<sup>2</sup> of the spacecraft, in addition to transmission of mission data back to the user. Additional capacity could be used to transfer information packets from one terrestrial user to another. The backbone needs to operate with spacecraft in earth orbit or orbiting elsewhere in the solar system. Depending on deployment, the backbone will allow C<sup>2</sup> of spacecraft anywhere in the solar system.

Fiscal reality is a limiting factor—therefore the system needs to be scaleable. Pieces of the system should fit into an interoperable architecture that allows incremental increases in the communications backbone. This allows implementation to meet the needs of the users and remain within budget. At the same time, it provides a framework for growth to ensure that previous investment is not lost when demands expand (the system can grow with the demand).

The system will operate with both commercial and military satellites, allowing cost sharing to minimize overall expense and encourage commercial development. Economies of scale will reduce the cost of common components. Opening the system to commercial users also makes upgrades less expensive since many users share the costs.

### **Advances in Earth-to-Space Communication Links**

As the requirement to move more data through satellite communication channels increases, communication links will change from the current SHF frequency band to the higher EHF frequency band for communications between satellites and earth. In 1996, the DOD has two Military Strategic and Tactical Relay (MILSTAR) satellites using an EHF uplink and an SHF downlink.<sup>30</sup> EHF frequencies provide several benefits to both commercial and military customers (table 5).

Laser communication systems are a poor choice for communications between satellites and individual earth stations because of the laser signal attenuation caused by clouds or fogbanks. However, a number of spatially distributed earth stations, connected by high-speed terrestrial datalinks, could allow for laser communications between satellites and earth. "With three to five sites, 99 to 99.9 percent probability of a cloud- and fog-free line of sight to at least one station is possible."<sup>31</sup>

**Table 5**  
**EHF System Advantages**

Factor	Advantages To General Users	Specific Military Advantages
Small Antenna	Mobility	Inconspicuous
Highly Directional Signal	Decreased susceptibility to interference	Low probability of intercept
Large Available Frequency Range	Increased data throughput	Low probability of intercept and decreased susceptibility to jamming

**Source:** N. E. Feldman and Sharlene Katz, *Earth to Satellite Communications above 8 GHz, Features of Importance to the Military(U)* (Washington, D.C.: Defense Communications Agency, 1977), 46-47. (Secret) Information Extracted is UNCLASSIFIED.

#### **Advances in Satellite-to-Satellite Cross-links**

Relay satellites will become the norm for satellite control. By using relay satellites, the controller is not required to have the target satellite in view. NASA currently operates Tracking and Data Relay System (TDRS) satellites to demonstrate this concept. TDRS allows NASA to maintain communication with the space shuttle when it is out of view of the main NASA ground antennas. A more advanced constellation of relay satellites will allow users of spacenet anywhere in the world, or in the solar system, to contact an operational satellite. The relay satellite can then cross-link the signal to any other relay satellite to deliver the message to the intended operational satellite anywhere in the solar system (fig. 3-2). The constellation may use a packet-switching technology to ensure that appropriate signals are relayed to the correct satellites. A constellation of relay satellites provides for graceful degradation if one or more of the relay satellites fail, avoiding a single point of failure. Network control software distributed to each relay satellite will allow the network to adjust automatically to outages, rerouting information around degraded satellites and maintaining a constant level of service to operational satellites.

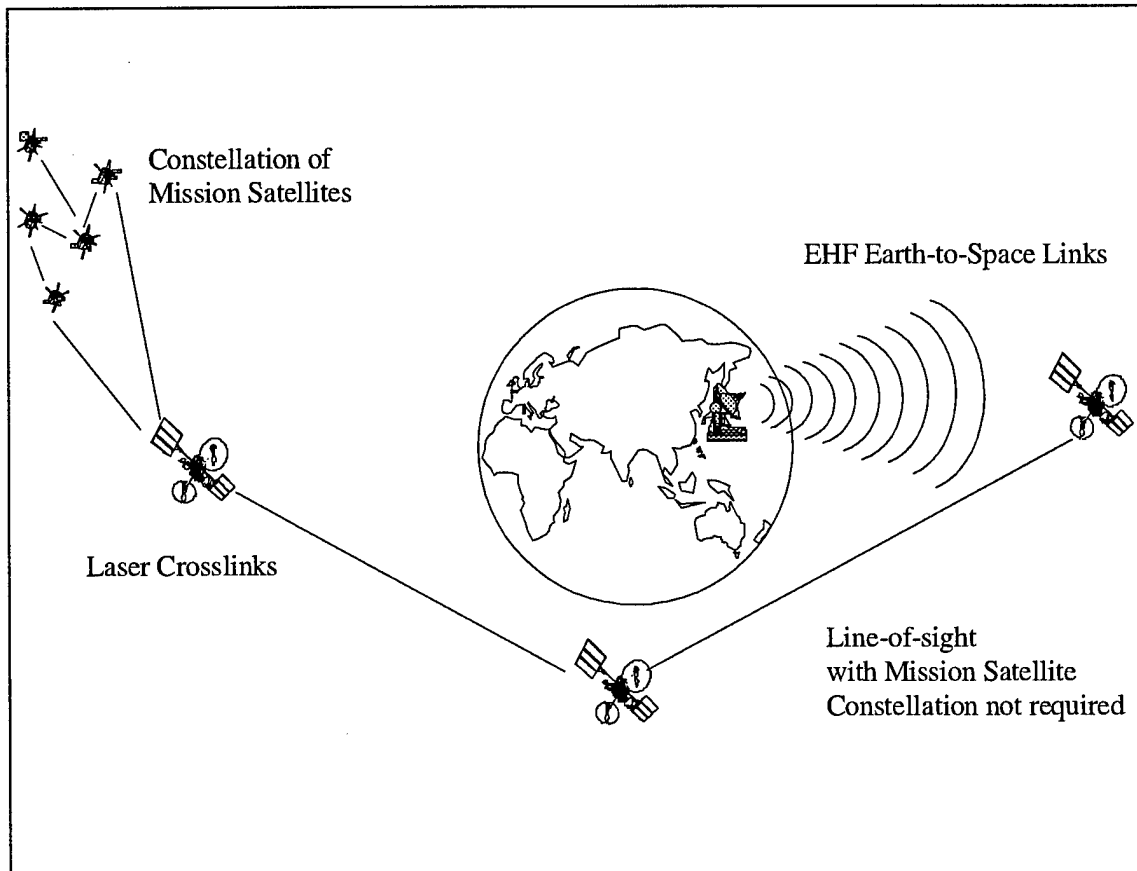


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**Figure 3-2. Spacenet Telecommunications Links**

To minimize costs of launching and maintaining large numbers of satellites, standardized communications packages will be developed to interface with the spacenet. A limited number of models of standard communications packages will meet the requirements of large and small satellites. Limited models of the standard communications package allow simple, standardized interfaces between satellites. A simple, standardized interface makes troubleshooting easier as well.

The standard configuration package will use lasers for satellite cross-links. The communications laser will automatically evaluate the satellite system's orbital geometry and redirect information to the best satellite. For emergencies, the standard package will include an EHF radio transceiver to communicate directly with earth stations. The system also includes an emergency beacon to alert satellite controllers of a system failure.

Hardware and software onboard the standard communication package will provide automatic reconfiguration services, depending on the needs of the satellite. Communications automatically travel

through the appropriate transceiver--laser or radio--depending on final destination. Intelligent materials will facilitate some hardware changes required to meet the on-orbit needs of the satellite's communications package.

Lasers will provide high-bandwidth communications capability between vehicles in space. Lasers have high data throughput and small transceivers. Since lasers provide line-of-sight communication, their signals will be difficult for an enemy to intercept.<sup>32</sup> The Air Force's Defense Support Program experimented with laser crosslinking between satellites in the 1980s. Unfortunately, the experiment failed because laser aiming techniques were immature. Subsequent systems such as the Air Force MILSTAR and GPS satellites use radio cross-links between spacecraft.<sup>33</sup>

Accuracy of laser aiming will improve with time, allowing laser communication between satellites by 2025. The Phillips Laboratory is working on phased arrays of laser diodes to steer lasers electronically. An experimental phased array is flying on the technology for autonomous operational survivability (TAOS) satellite today. However, improvements in aiming are required because the experimental package has a limited steering angle.<sup>34</sup>

The commercial market has been busy tackling the problem of stable spaceborne laser-aiming platforms. The Thermo Trex Corporation of San Diego, California, has introduced a new system called Lasercom.<sup>35</sup> Lasercom uses laser transceivers approximately the size of a bread box to communicate between satellites. Thermo Trex claims to have solved the problem of aiming spaceborne lasers by using beacons. The company plans to launch Lasercom onboard a military satellite in 1997.

In a system trying to avoid detection by enemies, beacons are clearly unacceptable. However, given the probable advances in phased array, laser-aiming technology and microscopic machinery,<sup>36</sup> sufficiently stabilized platforms and laser-aiming systems should be feasible without using beacons by 2025.

Laser communication between satellites on orbit presents a number of opportunities. Lasers provide higher data throughput than today's radio frequency satellite cross-links. Lasers are directional and can aim at the intended receiver without fear of intercept. Wayward signals (known as side lobes) produced by radio-frequency antennas on today's satellites would be eliminated. Laser communications are easily manipulated by optical computers which are immune to electro magnetic pulse (EMP) effects.

Higher frequency lasers can increase available bandwidth for transmitting information in 2025. Future satellite communication systems will use visible light lasers. However, moving towards ultraviolet or possibly even X-ray lasers will increase the data transmission capability of the communications package.

X-ray lasers present special opportunities that warrant the extra effort to achieve this technology by 2025. X-ray lasers were first demonstrated at the Lawrence Livermore Laboratory in 1984. First-generation X-ray lasers were room-sized or larger. Slowly, the size of X-ray lasers is decreasing. Jorege Rocca, a physicist at Colorado State University at Fort Collins, Colorado, reports building an experimental table-sized soft X-ray laser in 1994.<sup>37</sup> Given the trend of electronics miniaturization combined with more sophisticated power supplies, there may be an operational X-ray laser small enough to fit on a satellite by 2025.

High-frequency lasers are ideal for satellite C<sup>3</sup> because of the vast increase in data-throughput on a single channel versus SHF band communication channels. A visible light laser has the potential for a thousandfold increase in data transfer capability over SHF communications. An X-ray laser has the potential for a millionfold increase over the communications capability of visible light lasers, giving the X-ray laser a billionfold increase over 1995 satellite communications capabilities (table 3-6).

Economies of scale ensure that standard communication packages will be less expensive than the custom communication packages used today. Some small moves towards standardization are now occurring. The International Telecommunications Union, a committee of the United Nations, allocates the frequencies used by satellites<sup>38</sup> in earth-to-space communications. Additionally, the Air Force Satellite Control Network uses standard communications channels for satellite communications.

However, more than just frequency standardization is required. To make systems less expensive and take advantage of economies of scale, hardware must also be standardized. As satellites move towards increasingly reusable parts, the communications package will become more standardized.

**Table 6**  
**Data Capabilities at Various Frequencies**

Common Name	1995 Communications Use	Theoretical Maximum Data Transfer Capacity	Approximate Frequency Range
Ultra High Frequency	– Satellite Communication – Terrestrial Microwave	$1.5 \times 10^9$ BPS	$300 \times 10^6 - 3 \times 10^9$
Super High Frequency	– Satellite Communications	$15 \times 10^9$ BPS	$3 \times 10^9 - 30 \times 10^9$
Extremely High Frequency	– Satellite Communications	$150 \times 10^9$ BPS	$30 \times 10^9 - 300 \times 10^9$
Infrared Radiation	– Experimental	$150 \times 10^{12}$ BPS	$300 \times 10^9 - 3 \times 10^{14}$
Visible Light	– Fiber Optic Communication	$400 \times 10^{12}$ BPS	$3 \times 10^{14} - 8 \times 10^{14}$
Ultraviolet Light	– Experimental	$15 \times 10^{15}$ BPS	$8 \times 10^{14} - 3 \times 10^{16}$
Soft X-rays	– Experimental	$1 \times 10^{18}$ BPS	$3 \times 10^{16} - 2 \times 10^{18}$
Hard X-rays	– Not Used	$12 \times 10^{18}$ BPS	$2 \times 10^{18} - 2.5 \times 10^{19}$

**Sources:** Ovid W. Eschbach and Mott Souders, eds., *Handbook of Engineering Fundamentals* (New York: John Wiley & Sons, 1975), 1057.  
William Stallings, *Data and Computer Communications* (New York: Macmillan Publishing Company, 1988), 43.

One method of standardizing communications packages may be the combined use of micro-miniature machines<sup>39</sup> with intelligent materials to automatically adapt standard antennas to specific needs. Micro-miniature machines and intelligent materials can modify the physical properties of an antenna as needed for different frequencies or different transmission characteristics. Satellites requiring wide-beam broadcasting or a narrow pinpoint beam for data security can use the same antenna design.

Modification of antennas and optical lenses on-orbit to conform to the needs of the communication package requires the capability to build and modify on-orbit materials without human intervention. Intelligent

materials offer the hope of building modifiable materials to meet the changing needs of systems. In 1995, NASA used electroactive materials to modify the optics on the Hubble space telescope.<sup>40</sup> Future advances should allow intelligent materials to be more useful in self-repair of on-orbit systems.

In those areas where intelligent materials are not sufficient or appropriate to modify equipment on-orbit, self-assembling materials built into the original communications package may provide the capability to regenerate damaged systems or create new systems. Self-assembly techniques were used in 1995 to build crystal semiconductor memories in an experimental environment.<sup>41</sup> Advances in self-assembly technology may allow on-orbit repair or replacement of degraded systems without human intervention.

Communication system repair could use self-assembling materials to refurbish parts on orbit. Self-assembling materials could continuously repair systems on-orbit, keeping the system fully mission capable. Should catastrophic system failure occur beyond the repair capabilities of the self-assembling materials, the system is replaced using black-box technology, where the entire system is simply pulled out and replaced.<sup>42</sup>

### **Driving Satellite C<sup>2</sup> into the 22d Century**

The trend towards a multitude of satellites clogging earth orbits continues. Commercial communications entities will launch over 100 satellites before the turn of the century: Motorola plans to achieve initial operational capability of its Iridium<sup>®</sup> system with 66 satellites in 1997;<sup>43</sup> TRW launches the first of a 12-satellite constellation Odyssey<sup>®</sup> system in 1998;<sup>44</sup> Loral plans to complete its GLOBALSTAR<sup>®</sup> system with 48 satellites in 1999.<sup>45</sup> As the new century starts, the Teledesic Corporation plans to launch a constellation of 840 small satellites to transmit video starting in 2001.<sup>46</sup> These large constellations of satellites push the current state of the art in satellite C<sup>2</sup>. Survivable mobile C<sup>2</sup> nodes with simple-to-use three-dimensional (3D) interfaces could greatly improve satellite control.

As a military system, spacenet must be survivable throughout the spectrum of conflict. The space and ground segments need to be survivable, since one is useless without the other. To enhance survivability of ground controllers, the system should not require line-of-sight communication with a mission satellite. Any uplinks or downlinks should have electromagnetic signatures that avoid disclosing the location of the ground controller or the mission satellite.

Survivable ground stations in 2025 will be mobile—both on and off the planet. To enhance mobility, systems must be small. This requires the computer used in the ground station to be small. It also requires a portable antenna to communicate with the satellite. The small mobile ground station should require a minimum of setup time to ensure all necessary operations begin immediately upon deployment.

To ensure maximum flexibility, the small mobile ground stations should not tie satellite controllers to large groups of satellite engineers. They should instead allow independent ground-control operations. The knowledge necessary to perform the satellite control mission will be resident in the mobile C<sup>2</sup> computer, avoiding the need to contact engineers to make decisions about satellites.

Software will replace the team of satellite controllers, orbital analysts, and engineers. The vast majority of routine operations will occur without human intervention. Human intervention is only needed for nonroutine operations and anomaly resolution. Artificial intelligence software will also aid nonroutine operations and anomaly resolution.

Breakthroughs in artificial intelligence software combined with vast databases of information will help model the knowledge required to fulfill the nonintervention requirement. Improvements in knowledge representation, along with vast amounts of encoded knowledge, will make these capabilities possible.

The world of computer science has continually progressed towards larger databases. The primary technical constraint is storage media capacity. Capacity is growing at an exponential rate and is continuing to grow—more and more data can fit in the same space. In the 1980s, magnetic storage media was common. In the 1990s, light-based storage using CD-ROMs is the trend in some terrestrial computers. The DOD is testing space-qualified optical disks on the STEP M3 (space test experiments platform) satellite and on STP-1 (space test payload 1) aboard the space shuttle.<sup>47</sup> In the future, budding optical technologies such as holographic data storage systems may provide even greater storage capacity<sup>48</sup> in both terrestrial and space-based C<sup>4</sup> systems.

Knowledge representation has vexed computer scientists for years and continues to be a major constraint to fielding operational artificial intelligence systems. However, new schema's for knowledge representation are continuing to grow in strength. Formal computer methods such as "Z" improve the ability to model reality.<sup>49</sup> Trainable computer neural networks offer new methods of gathering and storing knowledge. Optical computers, combined with neural network technology (fig. 3-3), promise to provide

extremely fast knowledge-base searches by exploiting the vast numbers of parallel interconnections that an optical computer could support.<sup>50</sup>

## Laser Communication Optical Computers

### Major Advantages:

- High data throughput
- Protection from EMP
- Exploits interconnectivity of neural networks

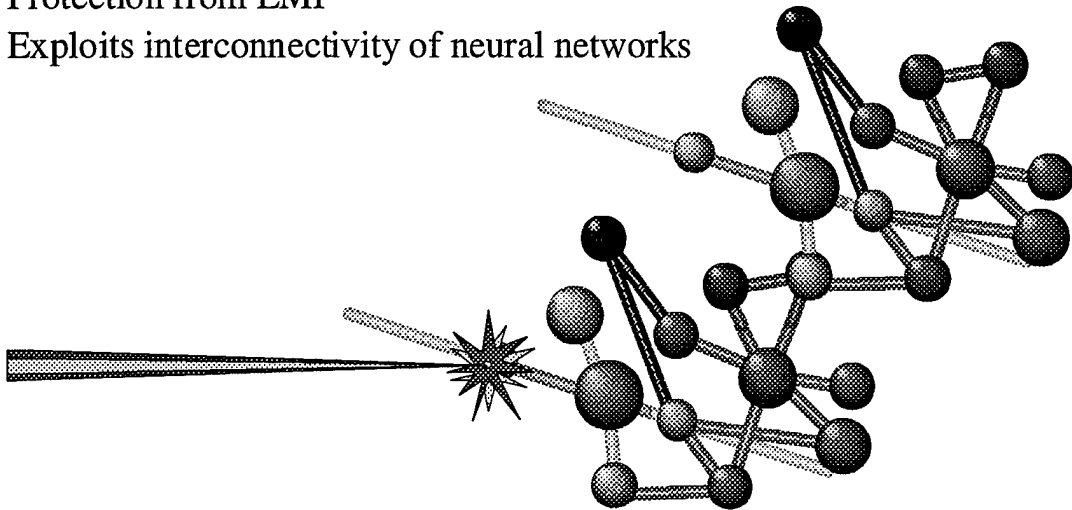


Photo from Microsoft Clipart Gallery © 1995 with courtesy from Microsoft Corporation.

**Figure 3-3. Combining Laser Communication and Optical Computers**

To enhance portability, antennas for contacting the satellite will be tiny. This will allow ease of transportation, rapid setup, and increased concealment in a hostile environment. To further enhance autonomous operations, antennas should not rely on off-site orbital analysts (engineers) to provide satellite location data for antenna pointing. The portable ground station will maintain its own information for pointing to the satellite.

Antenna size is a function of the wavelength of the signal, antenna gain, and aperture efficiency (fig. 3-4).<sup>51</sup> Advances in several engineering disciplines will combine to make antennas smaller. The antenna size required to transmit to a satellite will decrease with higher frequencies and smaller wavelengths. Advances in signal processing electronics will permit lower gain requirements, also decreasing antenna size. Finally, as new antennas are designed, relative antenna efficiency will increase.

Antenna area	=	$G\lambda^2/4\eta\pi$
G	=	Antenna gain
$\lambda$	=	Wavelength
$\eta$	=	Aperture efficiency

Source: Timothy Pratt and Charles W. Bostian, *Satellite Communications* (New York: Jon Wiley & Sons, 1986), 81.

**Figure 3-4. Calculation for Area of an Antenna**

The system must be seamless and transparent to the end users to allow them to concentrate on the mission. User interfaces must be intuitive, requiring a minimum of operator training to cut costs and implementation times.

User interfaces for C<sup>2</sup> of satellite systems are constantly improving. In the early 1980s, the Air Force fielded the satellite C<sup>2</sup> software system based entirely on mainframe technology using character displays. The Air Force upgraded it in the late 1980s to more advanced mainframe technology, but it still used character displays. The Air Force intends to move to a graphic computer interface in 2000 with the introduction of the Common Telemetry Tracking and Commanding System (CTT&C).<sup>52</sup> To control large constellations of satellites in 2025, it will be beneficial to have a 3D display of satellite locations, orbits, and the targets for mission packages.

Commercial companies built primitive, yet realistic 3D computer displays in 1995. GTE Corporation advertised the Collaborative Three Dimensional System (C-3D) for teleconferencing. An article in *Signal* magazine stated the system makes people "at distant locations appear to be in the same room, seated at the end of the conference table. When a ball was tossed by one of the distant users, it seemed so realistic that the editor involved reached to catch it."<sup>53</sup>

More advanced 3D displays are in research and development. Autostereoscopic displays require no viewing aids such as 3D glasses or head-mounted displays. Autostereoscopic displays offer the possibility of operationalizing 3D displays in future scenarios, since no more equipment is required beyond a display monitor. Texas Instruments is working on 3D autostereoscopic displays using "slice stacking" technology. In the same manner that a spinning line of lights looks like a plane, a rotating plane of lights appears as a 3D image. Texas Instruments is using vibrating micromechanical mirrors to produce this effect.<sup>54</sup> Massachusetts

Institute of Technology has created holographic 3D computer displays in the laboratory.<sup>55</sup> The University of Washington's Human Interface Technology Laboratory is working on technology to paint a 3D image on a person's retina using microlaser technology.<sup>56</sup>

Given the growth in computer technology expected in the next 30 years, advanced 3D computer displays should be common by 2025. The commercial market will push the technology for these displays. Already, the entertainment industry is interested in the technology for telecomputer and interactive video games in the home.<sup>57</sup> The trend toward home use will help decrease 3D display costs.

### **Satellite Design**

Satellite design directly affects the simplicity or complexity of on-orbit support requirements. Design philosophies for space systems in 2025 should simplify or minimize on-orbit support requirements and ensure the space system does not create debris problems on-orbit once it is defunct.

Design goals in 2025 may move toward distributed small microsatellite (microsat) systems, reusable microsat systems, or disposable microsat systems, as well as retaining some large, maximum longevity space systems.

Space systems should be almost entirely autonomous for both mission (payload) execution and C<sup>2</sup>. The war fighter should have a pull system and get only the data needed, when needed, and in a format quickly assimilated. The war fighting environment of 2025 will be more complex for the battlefield commander, so the US must avoid the biggest risk to future combatants—information overload.<sup>58</sup> Today's space operations mission control complex is staffed with several hundred operations and engineering support personnel. Space systems in 2025 must be able to "fly" with minimum human intervention.

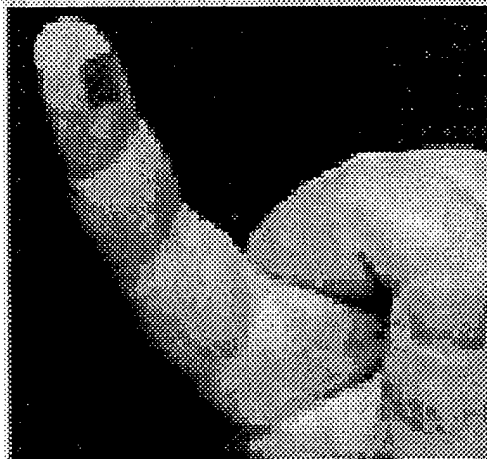
Finally, proliferation of space systems in 2025 requires investigation of disposal issues—what to do with space systems when they no longer function.

### **Microsatellites**

Current space system design practices focus on maximum longevity to avoid costly replacement of the space system as well as associated launch costs. Redundancy of critical components or subsystems

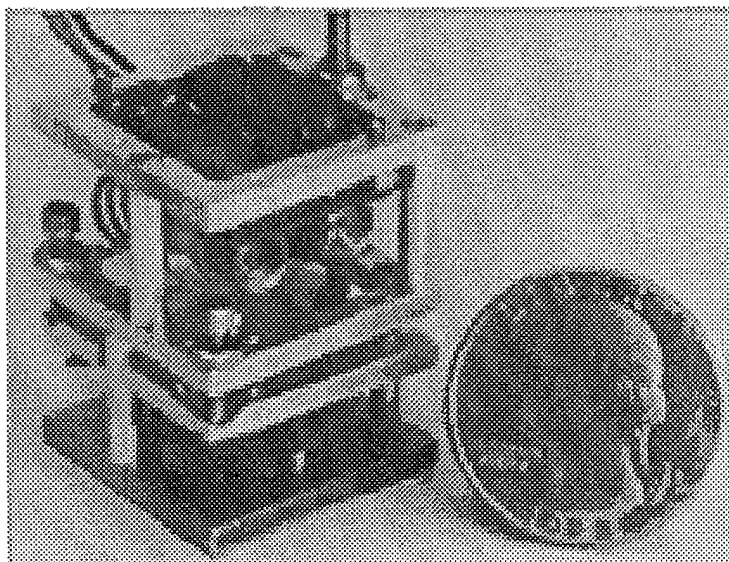
minimizes the chances of “single point failures.” New smallsat designs for single- or dual-purpose satellites are several hundred pounds with a body the size of a three-foot cube. Advancements in electronics and miniaturization have sparked concept work on microsats—approximately shoebox-size and weighing between 20 and 30 pounds.<sup>59</sup>

The Micro-Devices Laboratory within NASA’s Jet Propulsion Laboratory (JPL) has focused on developing miniaturized space instruments (figs. 3-5 and 3-6).



**Source:** NASA JPL, New Millennium Program Brochure, Internet Address: <http://nmp.jpl.nasa.gov/About/Brochure/Graphics/page-2.gif>.

**Figure 3-5. Camera On A Chip**



**Source:** NASA, JPL New Millennium Program Brochure, Internet Address: <http://nmp.jpl.nasa.gov/About/Brochure/Graphics/page-2.gif>.

**Figure 3-6. Microseismometer**

Engineers at JPL are also working on ways to reduce spacecraft to the size of a frisbee.<sup>60</sup> In early 1995, NASA launched its *New Millennium Program* at JPL. *New Millennium* envisions a 21st century program of affordable, frequently launched missions where numerous small and "micro" spacecraft will travel outward in armadas to study the earth, the solar system, and beyond.<sup>61</sup> Throughout the galaxy, these probes will feed information back to earth via telecommunication links to create a "virtual human presence" throughout the universe.<sup>62</sup>

At this time, the technology to produce microsats is not mature, mission capabilities are limited, and production is expensive. Within the next 30 years, miniature electronic components should be tested and demonstrated in space environments, driving microsat costs down to thousands of dollars, compared to today's tens of millions of dollars or even much higher for many DOD satellites. With miniaturization, the new features of today's systems like crosslinking, autonomous operation, and reprogrammable onboard computers will help bring systems of microsats to reality. It should be feasible for a commander to order the immediate launch of microsats to cover a theater to perform communications, weather, surveillance, and reconnaissance missions.

Distributed systems of on-orbit microsats in 2025 could deliver seamless mission capabilities to the war fighters.

True distributed satellite systems increase performance at a rate which is faster than linear with the number of systems deployed. For example, a single satellite can perform processing tasks for a large number of special purpose satellites if an on-board communication link is smaller or lighter than a dedicated processor. A central processor reduces the processing requirements of individual satellites in the constellation.<sup>63</sup>

Operators "in theater" may be able to "task" the microsats' payloads to gather and deliver mission data directly to the war fighters. The more ambitious goal is total control of the microsats and their payloads in-theater (sufficiently behind the forward battle area), providing maximum responsiveness to the war fighters without the "armies of engineers" of today's systems.

### **Reusable Microsatellites**

By 2025, an alternate power source for space systems may be possible, thereby eliminating the solar arrays and associated hardware. The satellites would be much "cleaner" on the exterior, making it possible

to shield enough of the satellite from heat in order to facilitate reentry into the earth's atmosphere. This will make recovery possible and facilitate building and operating reusable satellites that can be launched for a tactical purpose. When the mission is complete, the satellite flies or parachutes to earth or is recovered by a transatmospheric vehicle and returned to earth for subsequent reuse.

### **Disposable Microsatellites**

Very-low-cost and launch-on-need tactical microsats could be employed to support a theater commander for a limited amount of time—possibly only several months. These disposable microsats are exclusively owned and controlled by the theater commander. When the commander's mission is complete, the microsats are simply discarded.

### **Multimission, Maximum Longevity Satellites**

Some large, multimission satellites with maximum longevity may still be necessary in 2025. The factors limiting space system longevity are electrical power, propulsion fuel, and radiation hardening of internal electronic components. Evolutionary improvements continue in each of these technologies. Any improvements will benefit both multimission, maximum longevity satellites and microsats.

**Spacecraft Power.** Current satellite components are electrically powered by solar cells or from storage devices like batteries when sunlight is blocked from the solar cells. Solar array size and efficiency, battery capacity, and the amount of power required by the satellites are the limiting factors. Today's silicon solar cells provide 11 to 12 percent efficiency, but development is underway on gallium arsenide cells with up to 20 percent efficiency.<sup>64</sup> Battery technology has moved from nickel-cadmium to nickel-hydrogen. According to *New World Vistas*, previously hard applications become easy and new applications become possible if power is not an issue.

Revolutionary improvement is required to make a leap to fully capable microsats in 2025. Possible revolutionary solutions are nuclear power,<sup>65</sup> laser power beaming, or electrodynamic tether systems.<sup>66</sup> Nuclear-powered satellites have been demonstrated, but political and environmental unpopularity have limited research and development. A laser power beaming system would employ a space- or ground-based

high-power laser system to propagate a laser beam to a satellite's collection and conversion device. One possible system would use solar array-like devices to collect the laser beam and convert it to electrical power.<sup>67</sup> The Tethered Satellite System aboard space shuttle mission STS-75 was intended to demonstrate electrodynamic system technology using a 20.7-km-long tether to generate approximately 5,000 volts.<sup>68</sup> The tether broke while deploying the satellite—the capability remains untested.

**Spacecraft Propulsion.** Propulsion fuel is another limiting factor for space systems because it is used to maintain proper satellite orbit and to reposition the spacecraft for mission purposes. A propulsion system with minimal or no expendable fuels is the goal. Possible solutions are electric, nuclear, or laser propulsion, satellite refueling, or a space “tug.”

Arcjets, plasma engines, and ion engines are three possible electric propulsion technologies.<sup>69</sup> These technologies could provide high energy with much less weight than current systems.

A nuclear propulsion system could, theoretically, more than double the specific impulse energy output of today's current liquid propulsion systems using a solid-core thermal reactor engine with liquid hydrogen propellant.<sup>70</sup> Once again however, research and development has been limited because nuclear propulsion systems are politically and environmentally unpopular.

A laser propulsion system may use a ground, airborne, or orbiting laser to transmit energy through an optical window on a spacecraft to heat a fluid—like a hydrogen/cesium mixture, for example.<sup>71</sup>

Another possible solution for spacecraft propulsion is on-orbit refueling via another satellite or transatmospheric vehicle.<sup>72</sup>

Figure 3-7 depicts another solution—moving the satellite with a “space tug.”<sup>73</sup> The Tethered Satellite System aboard space shuttle mission STS-75 was also intended to demonstrate this “Space Tug” concept.

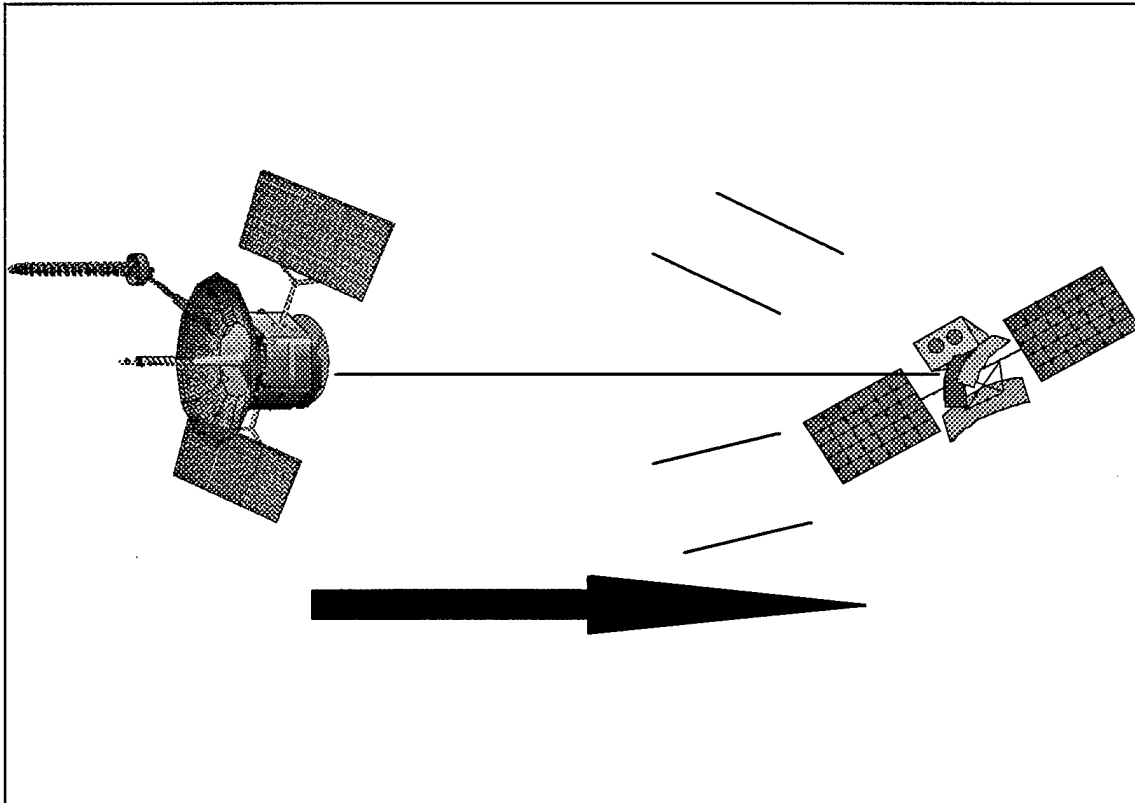


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**Figure 3-7. Space "Tug"**

### **Radiation-Hardened Electronics**

Miniaturized electronic components contain more and more circuitry in smaller areas on silicon chips, making the chips more vulnerable to single event upsets, latchups, and degradation due to "total dose" (long-term exposure) radiation from the natural space environment or from nuclear counterspace threats.

The level of natural radiation a spacecraft endures depends on its orbit. Low earth orbit (LEO) systems encounter relatively little, geosynchronous (GEO) systems encounter somewhat more, and medium orbit systems like the NAVSTAR GPS satellites are exposed to significant radiation because they orbit at 10,900 miles—in the heart of the Van Allen radiation belts.

Radiation hardening of spacecraft electronics—particularly random access memory (RAM)—is a limiting technology for computing power in medium- to high-orbit systems today. Current preventive measures include shielding the electronics with tantalum, aluminum, or lead.<sup>74</sup> More elaborate silicon-on-sapphire semiconductor technology that is upset-resistant is in development.

There are only a handful of companies in the world that manufacture these "space-qualified" or "Class S" parts to meet DOD specifications because the business base is very small and the parts are very difficult and expensive to manufacture. Chips for these purposes do not double their speed and capacity each 18 months like chips for personal computers. The largest RAM chips flying in an Air Force satellite today are 16-kilobyte (k) chips in the MILSTAR spacecraft.<sup>75</sup> GPS Block II replenishment satellites will contain 64k chips. Some Hughes commercial communication satellites in high orbits today contain "commercial grade" 64k chips.<sup>76</sup> A commercial grade chip is not tested as rigorously and specifications are not as strict as for DOD Class S parts. Motorola's Iridium spacecraft (in a very low earth orbit) will reportedly attempt to use one-megabyte commercial RAM chips.<sup>77</sup>

Until recently, DOD and NASA missions drove the advancement of space electronic technology. The explosion of commercial space use now drives the state of the art. Two things must be considered, however. First, some DOD space missions like GPS require medium orbits with high inherent radiation. Commercial ventures are unlikely to drive solutions as quickly for these missions. Second, commercial satellites are not designed to withstand radiation from hostile counterspace threats like ASAT weapons. Future DOD space systems must have a "countermeasure"—systems either designed to withstand the radiation threat or planned for satellite attrition and timely replenishment.

Space systems in 2025 must operate with minimal  $C^2$  from much smaller operations crews. The *New World Vistas* team recommended automation to reduce the number of people involved in launch and mission control by at least a factor of ten.<sup>78</sup> Automation of some tasks like satellite thruster firings, attitude adjustments, and health and status monitoring can reduce operations crew size and minimize requirements for  $C^2$ . Autonomous operation designs will also allow 2025 space systems to continue seamless mission support to the war fighters if ground control capability is interrupted. The current NAVSTAR GPS Block II replenishment spacecraft requirement is to operate for 180 days without ground control while still maintaining mission requirements for navigation and timing accuracy. Crosslinking and GPS-augmented guidance should allow 2025 space systems to perform a preprogrammed mission independently for several years. NASA's JPL predicts that future satellites will have extraordinary navigational precision.

Imagine a basketball shot from Washington, D.C., toward a hoop in Moscow, Russia—with the ball passing straight through the hoop, not even touching the rim. This accuracy is

equivalent to NASA launching a basketball-sized satellite to rendezvous with a speeding comet.<sup>79</sup>

One key technology to enable ambitious automation and autonomy goals is onboard computing power. These autonomy goals require larger onboard volatile and nonvolatile memory to increase overall computing power.

Fiber optic or light-based computing technology could dramatically improve computing power for earth and space applications in 2025. Computers perform two basic functions: switching and communications. Optics do a good job with communication functions and are widely employed today for high-data-rate terrestrial communications. Switching functions however, generally require some material or device to facilitate photon-to-photon interaction.

The switching function in today's electronic computers works because electrons are massive, charged particles that are easily manipulated with electric fields—thus the electronic transistor. The challenge of using optics for the computer switching function stems from the fact that photons are massless and chargeless so there is a difficult asymmetry in their properties and switching uses.<sup>80</sup>

Nonlinear optical materials may offer some possibilities.<sup>81</sup> One of the most promising approaches uses a device known as a self-electrooptical effect device (SEED).<sup>82</sup> The interim step to optical computing in 2025 is using optical preprocessing modules to operate in conjunction with existing electronic hardware—in effect, doing the communication portion of computing with optics and the switching portion with electronics. This interim approach can provide performance improvements over today's entirely electronic approach.<sup>83</sup>

Further, more simple and efficient software designs should employ commercial techniques to minimize costs and increase commonality with other space systems. *New World Vistas* recommended the Air Force drop the mandatory use of the Ada programming language and stop development of compilers and rely on commercial solutions.<sup>84</sup>

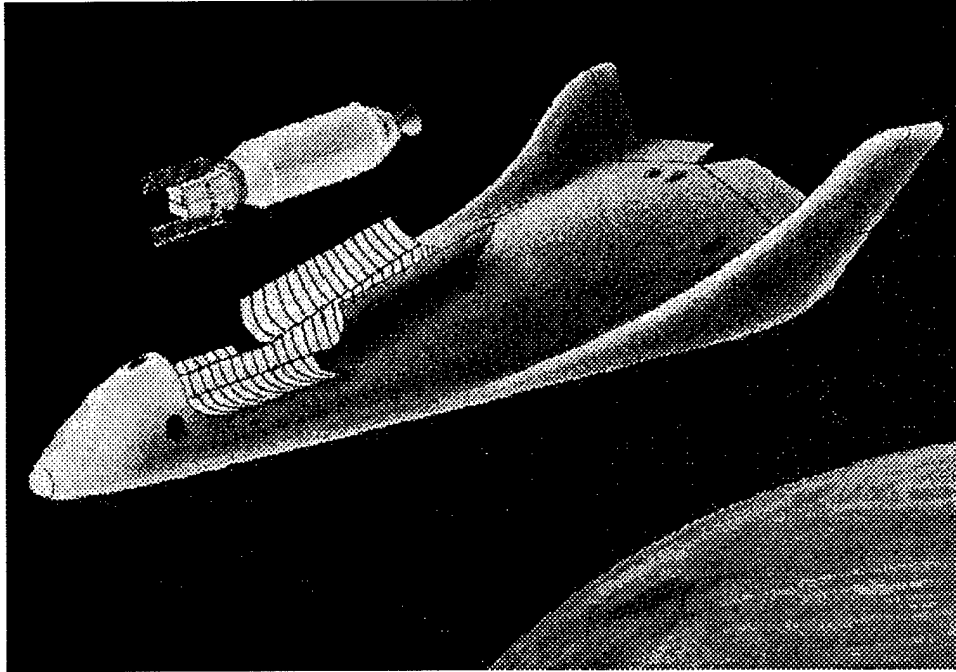
Space system reliability must be improved as well. Current space systems undergo significant factory and prelaunch testing to meet reliability requirements. They rely heavily on redundant systems to reduce risk of the most serious “single point” failures—that is, if a critical component is lost, the mission capability is lost. Space systems in 2025 should employ more robust designs, maximum use of common and commercial components, and improved manufacturing methods to ensure the highest possible reliability from piece-parts up through the component and subsystem levels. Improved fault detection methods will also improve

autonomy and automation. Onboard computers should be able to precisely trace most problems to the root cause and correct or compensate for them, ensuring minimum mission downtime and optimum system longevity. In 2025, electron “tagging” methods may be employed to determine precisely where errant commands came from or what caused a component to malfunction.<sup>85</sup>

### **Satellite Disposal**

If space system disposal issues continue to languish, debris strikes will be a serious issue in 2025 and beyond. Space systems fielded in 2025 should have a disposal scheme inherent in the design. Depending on the orbiting altitude of the space system, several options are feasible. LEO satellites can be maneuvered or allowed to naturally reenter the earth’s atmosphere and burn up—smaller space systems have little to no chance of any debris surviving reentry. GEO space systems can be sent away from earth by using a final allocation of fuel. Medium-orbit satellites like GPS orbit at 10,900 miles and present a greater challenge; propulsion fuel requirements to reenter the atmosphere and burn-in or jettison to outer space could be prohibitive without refueling or using a space “tug.” Environmental concerns for outer space—or for “political correctness”—may prohibit the burn-in or jettison options.

A potential solution is a “spacecraft compactor” vehicle,<sup>86</sup> possibly a transatmospheric vehicle adaptation (fig. 3-8).



**Source:** Lockheed Martin Missiles and Space Corporation. Public Affairs Office, Internet, 5 April 1995.  
Available from: <http://www.lmsc.lockheed.com/newsbureau/photos/shuttle1.jpeg>

**Figure 3-8. "Spacecraft Compactor"**

This remotely controlled spacecraft compactor could orbit the Earth, maneuver, and retrieve defunct hardware or other "space junk." The compactor must contain hardware designed to avoid debris breaking loose, and it should compact the hardware to maximize onboard capacity. The contained, compacted blocks may then be jettisoned to outer space, burned into the earth's atmosphere, or returned to earth for subsequent recovery and disposal.

Necessary for this capability are affordable spacelift to get the spacecraft compactor into space, a very strong, lightweight containing structure to hold the debris, and a propulsion system that is either refuelable or uses onboard "unexpendable" sources like nuclear power. Another concept would use an adapted transatmospheric vehicle.

### **Satellite Security**

Successful military operations in 2025 will rely heavily on space-based systems to provide timely and accurate information on demand. These systems will enable planners, operational commanders, and personnel in the field to access critical information for making the "right" decisions. These "right" decisions

will allow operations tempo control through a broad spectrum of operations from war to military operations other than war. Technologically advanced systems such as spacenet, GPS, MILSTAR, and other satellites allow the exploitation of gathering and dissemination of information via space-based systems. Utilization of these spaced-based assets will drive new military doctrine designed to best exploit these capabilities. As reliance on these systems increases, it will become more important to protect them from hostile intent and to regenerate the system or the capability if satellites are destroyed.

Information collection and dissemination by space-based systems (satellites) will become a vital center of gravity and a high priority target for adversaries. US national security will depend on keeping the space lines of communication open. As the military continues to compensate for numerical superiority with technology, information collected by satellites will increase in importance. Hence, satellites are a vital force multiplier in the information age and beyond. Uninterrupted, timely, and accurate information is critical to the war fighter and planner of future campaigns and operations.

The US's commercial and military space-based systems' target value increases proportionally as the military's dependence on information from space increases. In the future, the military will rely increasingly on commercial systems to collect and disseminate information to aid in operational planning and execution. The proposed satellite defense systems utilize a variety of countermeasures to protect these vital space-based assets.

Defensive systems will be employed on all satellites to ensure that information on demand is not interrupted by incidental or intentional force. Since both commercial and military systems are vulnerable to a variety of threats, cooperation between these two sectors will be mutually beneficial in many ways. First, standardization will increase interoperability between systems. This will facilitate connectivity to and from information transfer media by establishing common coding, equipment, and procedures. Second, standardized designs will ensure that satellites fit onto launch vehicles without costly modification to the launch system or the satellite itself. Finally, standardized defense systems will ensure uninterrupted information flow which translates into profit for the commercial sector and security for the military sector. Defensive system funding for research and development and employment will be the responsibility of the military.

## Limiting Factors

International law places many restrictions on the use of space-based weapon systems, whether intended for defensive or offensive purposes. There are two options to ensure that satellite defensive system designs are lawful. First, systems may operate within the intent of the existing laws by limiting the lethality of the weapons employed. For example, systems would not utilize weapons of mass destruction to negate a threat. Second, current laws, treaties, and agreements may be amended by the signatories to allow deployment of space-based weapon systems. The US must move cautiously, since other nations may use these amendments to deploy previously prohibited systems to counter the US advantage in space. Amendments should not promote the proliferation of weapons or ignite a space arms race.

Public opinion regarding nuclear-powered vehicles launched into space will have a significant impact on the type of security technologies employed. If capsules containing nuclear materials cannot be designed to maintain integrity in the event of catastrophic failure, significantly improved satellite propulsion and power systems will be extremely limited. Propulsion and electrical power systems are key to many satellite defensive capabilities.

Economics will determine the types and to what extent defensive systems will be employed. The assumption is that it is more cost-effective to employ small single- or dual-mission satellites than large multimission satellites. These large satellites with defensive system capabilities are not cost-effective for a number of reasons. With launch costs approaching approximately \$20,000 per kilogram,<sup>87</sup> they are far too heavy to be launched economically. Also, if one of the onboard systems fails or is destroyed, there are two options; replace the capability by launching an identical multimission satellite or do without the capability. The latter could have a catastrophic impact on military operations and readiness—it is simply unacceptable.

The principles of mass, economy of force, and simplicity are the foundation for a viable defensive strategy regardless of the medium—land, sea, air, or space. These principles can be exercised in deploying microsat constellations of single- or dual-purpose satellites, which could be launched at substantial savings. The redundancy provided by numerous constellations of single-purpose satellites would ensure no loss or degradation in capability if a single satellite is destroyed. Since readiness and operational capabilities would not be degraded or compromised, it would decrease the urgency to replace the satellite. The satellite will be replaced as soon as practical.

Cost-effectiveness will be further enhanced by the ability to build and deploy replacement systems quickly, economically, and en masse. Advances in miniaturization and development of durable materials will enable the production of small, lightweight satellites that are more economical to launch. Prompt replacement of obsolete or disabled satellites is vital to sustain defensive system capabilities.

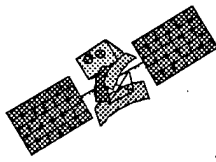
Simplicity of design has at least three distinct advantages. First, fabrication and construction costs are kept at a minimum since cost per item is driven down by volume. Given budgetary constraints and swings in funding, it is not economically feasible to manufacture large, complicated, easy-to-detect systems that are vulnerable to destruction. The second advantage is speed of production. Simple, standardized systems require minimum production time. Plug-and-play technology already exists and is incorporated into many of today's satellites. As next-generation hardware becomes available, it is simply plugged into existing bays with no need for structural modifications. Third, simple can be made small. Miniaturization of components is practical only if they contain few moving parts and complex structures.

### **Roles and Missions**

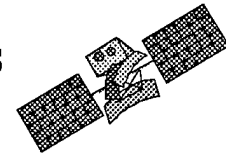
The objective of satellite security is to employ a space-based defensive system that is reliable, economically feasible, and timely to produce, maintain, and deploy in the quantities necessary to protect US space lines of communication. A successful security system ensures uninterrupted, timely, and accurate information from space.

Satellite security in 2025 will depend on a robust defense system with roles and missions having foundation in today's operational philosophies. Air Force Manual (AFM) 1-1, *Basic Aerospace Doctrine of the United States Air Force*, was the primary source for establishing strategies for satellite security: specifically, the Principles of War;<sup>88</sup> Roles and Typical Missions of Aerospace Power,<sup>89</sup> and the Tenets of Aerospace Power.<sup>90</sup>

The defensive system supports several roles and missions (fig. 3-9). The counterspace mission will ensure the friendly use of space by employing interdiction to disable or destroy threats. The defensive systems will be supported by spacelift for launch and by on-orbit support for sustainment or replenishment.



## Supporting Roles & Missions

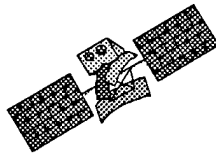


### ROLES

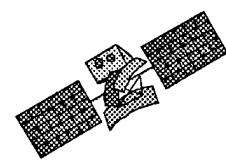
Space Control  
Force Application

### MISSIONS

Counterspace  
Interdiction



## Supported Roles & Missions



### ROLES

Force Enhancement  
Force Support

### MISSIONS

Spacelift  
On-Orbit Support

Source: AFM 1-1, *Basic Aerospace Doctrine of the United States Air Force*; vol. 1, March 1992, 7.  
Photo from Microsoft Clipart Gallery © 1995 with courtesy from Microsoft Corporation.

Figure 3-9. Roles and Typical Missions of Aerospace Power

### Defensive Philosophy

Given the vastness of space and the multitude of threats, no defensive system can be devised to make satellites invincible. The proposed satellite defense system will not counter 100 percent of all threats, but will reduce the system's vulnerability. It is more cost-effective and operationally feasible to replace damaged satellites than it is to expend limited budgetary funds in an attempt to make them "invincible."<sup>91</sup> A multimission satellite with operational mission systems and equipment coupled with a vast array of offensive systems is economically impractical. "Single- or dual-purpose satellites must be the rule rather than the exception."<sup>92</sup> However, this does not preclude incorporating some defensive capabilities like shielding, detection, and maneuver into each satellite.

Space-based systems, by their nature, are protected against all but the most technologically advanced or economically "well-off" states capable of deploying or purchasing ASAT systems. To date, only Russia has pursued ASAT technology. However, it is prudent to assume that ASAT technology is available on the open market. As states or groups hostile to the US increase their treasuries through the sale of petroleum, arms, or advanced technologies, they will be in a position to purchase ASAT capability by the year 2025.

Strategies and systems described in this section are designed to counter manmade and environmental threats that interfere with the operation and transmission of data to and from satellites. Since their potential for destroying space-based systems is approximately equal, both threats were given equal weight when countermeasures were developed. Countermeasures were intentionally designed to overlap in order to provide redundancy and ensure effectiveness.

Since space debris and radiation are potential threats to all satellites, defensive systems should not exacerbate the problem. Countermeasures employed will not add to the amount of debris or radiation clouds already in space. Offensive weaponry will employ systems that eliminate debris from the environment and will not employ nuclear detonations with lingering radiation. To do this, the systems will totally vaporize the object or deflect it into a trajectory that will cause it to burn up in the atmosphere.

The ability to employ OODA loop logic will be a vital software capability. Software programs will perform threat analysis and will take appropriate countermeasures autonomously. This capability will rely on "artificial life"<sup>93</sup> software programs that react to a dynamic environment with the appropriate force or action. This defensive capability will be incorporated into all satellites regardless of intended purpose. Satellites will use their unique capabilities to negate the threat and reduce satellite vulnerability.

Once a threat is detected, OODA loop logic will direct passive and/or active defense mechanisms onboard the satellite to counter the threat. The appropriate countermeasures may be maneuver, activation of shields, or manipulation of satellite exterior surfaces. On ASAT platforms, offensive countermeasures such as activation of directed energy (DE) or kinetic energy weapons will be initiated by artificial life software programs. Passive identification friend-or-foe systems (encrypted) will hasten detection of friendly satellites.

Survivability will be enhanced by designing energy-absorbent materials into the exterior surfaces of the satellites. These materials will serve two purposes: (1) defense and (2) power regeneration. Energy (solar,

laser, radar) will be absorbed by the external materials and converted into energy to power the satellite's operating defensive systems. If not needed immediately, the energy would be stored in batteries for later use.

## **Threats**

Satellites face two potential threats in space: (1) environmental (meteors, asteroids) and (2) man-made (space debris, offensive weapons). Approximately 2 million kg of man-made material orbits within 2,000 km of earth.<sup>94</sup> Add to this another 200 kg of meteoroid mass the same distance from earth and the probability of damage from impact is high.<sup>95</sup>

**Environmental Threat.** Environmental threats include solid debris resulting from the disintegration or decomposition of celestial or man-made materials. Countermeasures will have to nullify the effect of kinetic energy expended from particles traversing space and impacting the satellite. Projectiles traveling through space reach ultra-high velocities, making even the smallest particle a potential threat to satellites. Tiny particles act like sandpaper eroding external surfaces whereas larger particles are capable of totally destroying a satellite.

Radiation from any source—environmental or man-made—also poses a significant threat. Unlike kinetic energy damage, the effects of radiation are not always instantaneous. Like corrosion, radiation decomposes material in space, erodes surfaces, and undermines the integrity of the structures. The insidious nature of this erosion makes degradation difficult to detect until the damage is severe.

**Manmade Threats.** This category includes deliberate actions taken against a space-based system for the purpose of disabling or degrading the satellite. Typically, these threats are designed to destroy or disable instantaneously. Their targets will have to be replaced. DE weapons are one example of a man-made threat employed to inflict an instantaneous effect or an insidious effect. Regardless of the speed with which they act, these threats must be countered. Any loss or delay in information transfer to the end-user will impose serious consequences on operational capabilities.

## Countermeasures

To ensure optimum effectiveness, defensive strategies will be developed to exploit the synergistic effect of passive and active defense mechanisms. Most satellites will employ predominantly passive systems with the exception of the ability to maneuver—an active measure. Utilization of these strategies will facilitate simplicity of design and allow for a smaller physical cross-section, which in itself provides a defense mechanism. Passive defense can provide great benefits due to the amount of energy saved from not having to maneuver or activate offensive systems.

Using the single-purpose design philosophy, offensive strategies will be executed only by hunter killer (HK) and decoy satellites. These HKs are designed to employ offensive systems and their only function is constellation defense. Decoy satellites which morph the physical attributes of other satellites will be deployed to add a degree of deception to the overall defensive system.

**Passive Defense.** This concept relies on three strategies for all satellites: low detectability, shielding, and ultra high orbits. These strategies are incorporated into the structural design of the satellite and are primarily defensive in nature—they require no energy expenditure from the satellite itself. The strategy is to reduce vulnerability, not eliminate the threat.

*Low Detectability.* Visibility equals death. Low satellite detectability may be achieved via three technologies: (1) energy absorbent materials, (2) non-reflective surface design (also referred to as energy diffusion design), and (3) energy refracting and/or reflecting material. Each technology is designed to defeat a specific detection medium (acoustic, energy, or optic sensor). These materials will double as a component of the satellite's energy conversion system, which will convert hostile energy into a potential satellite power source.

**Shielding.** This strategy will provide some defense against kinetic energy and radiation threats. Defense against kinetic energy threats will take the form of "reactive armor" designed to absorb and dissipate the inertia of projectiles traveling at ultra-high velocities. Behind the reactive armor, the satellite's external structures and surfaces will be set at acute angles to deflect projectiles should they penetrate the reactive armor. Because of the ultra-high velocity of objects traversing space, it is impractical to defend against all kinetic energy threats. Total protection would make satellites too cumbersome and expensive.

*Ultra High Orbits.* These orbits enhance defense and operational capability. Defense is enhanced, since satellites are simply out of reach of most ASAT systems. If an ASAT system is employed, it will have to travel great distances to maneuver into an offensive position. While the ASAT travels this extra distance, the satellite may activate defensive countermeasures or move out of the threat area. These orbits enhance operational capabilities by providing a better vantage point for some information collection.

**Active Defense.** This strategy will employ distributed satellite systems, detection, maneuver, deception, decoys, and HK satellites. In keeping with the single-purpose philosophy, only Decoy and HK satellites will possess an offensive capability.

*Distributed Satellites.*<sup>96</sup> This strategy uses several constellations of single-purpose satellites. Each constellation will work together to provide operational support and defense from specialized systems. Constellations will be deployed in a defensive formation similar to that used by the Navy's carrier battle groups. Each constellation is comprised of several mission satellites surrounded by HK and decoy satellites to provide fire support to counter threats (fig. 3-10).

Numerous constellations provide redundant capabilities and make it impossible for an adversary to totally incapacitate a specific capability. This redundancy will ensure continuous information transmission if one constellation is permanently or temporarily disabled.

*Detection.* Mission, decoy, and HK satellites will possess detection capabilities to identify hostile threats in space or on the ground. Space-based threats will be identified as friend or foe through use of transponders fitted to all friendly commercial and military satellites. Ground threats, identified after initiation of hostile action, will be targeted and destroyed or temporarily incapacitated by utilizing onboard systems. Detection systems would utilize laser radar (LIDAR)<sup>97</sup> to detect changes in atmospheric conditions or IR sensors to detect heat signatures from hostile platforms. Once a hostile threat is detected, each satellite takes the appropriate action based on capabilities. For example, mission satellites maneuver, decoy and HK satellites take offensive action.

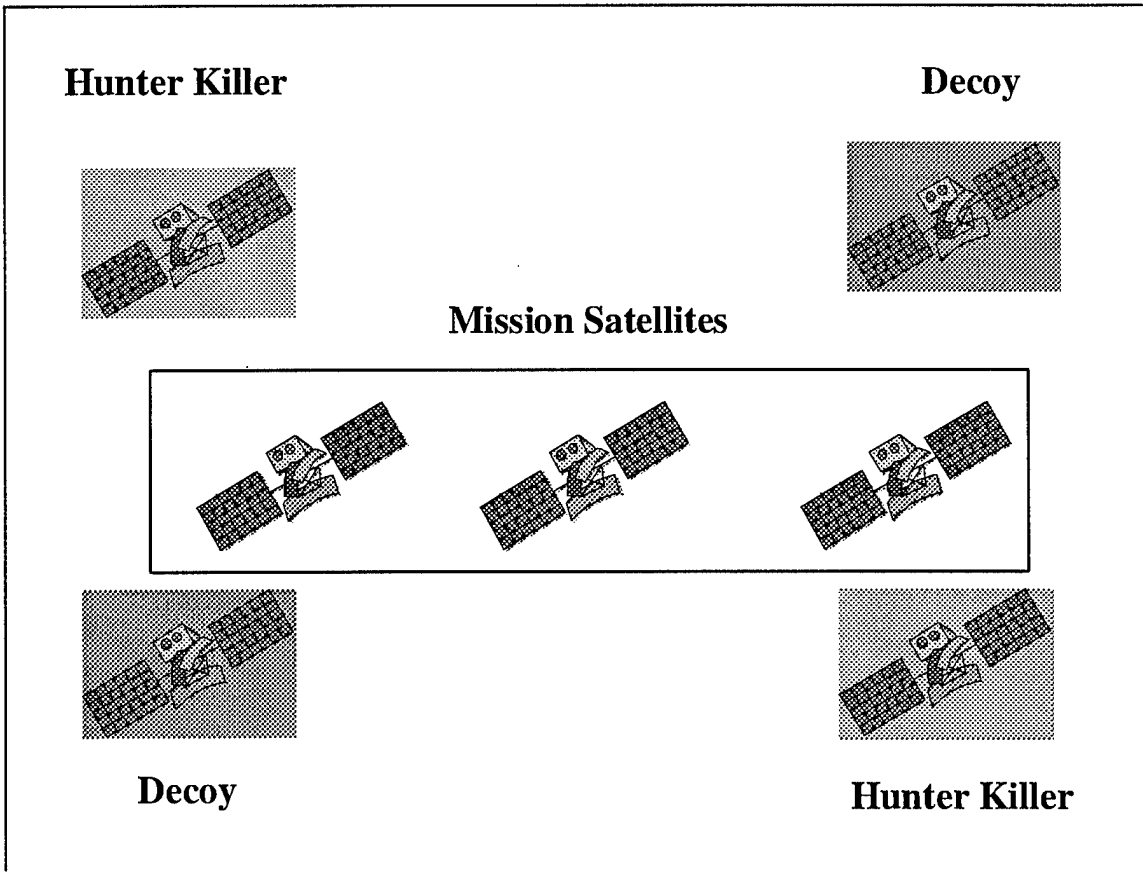


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**Figure 3-10. Typical Satellite Constellation**

*Maneuver.* This strategy includes nonstandard or irregular elliptical orbits. Maneuvers will be programmed into the artificial life software options available in the OODA loop process. Nonstandard orbits will make the targeting equation more difficult by eliminating satellite orbit predictability. Satellites will possess limited capability to maneuver over vast distances. Added weight and size of propulsion systems increase the cost of production and launch.

*Deception.* All satellites will be designed to look similar, regardless of function. Solar panels provide electricity on mission satellites and will also function as threat detection antennas on decoy and HK satellites. It will be difficult for sensors to detect the differences in satellite function, thus complicating an adversary's targeting problem. To eliminate or impede a capability, it will be necessary to target the entire constellation. This will be time-consuming and may require more assets than the adversary is willing to expend.

Another idea for deception is to design satellites that look like asteroids or space debris. Synthetic surfaces could be designed to act as functioning surfaces for the collection or transmission of data.

A projected virtual image (VI) capability can be incorporated into decoy and HK satellites. This system will project a holographic image into space to deceive optical sensors. Once a hostile weapons platform takes action, the VI projecting satellite will target and destroy it with one of its weapons.

**Decoy Satellites.** Decoys will look similar to mission satellites, but instead will possess the ability to maneuver and impact (ram) hostile platforms. They will be fitted with detection and propulsion systems to facilitate their mission.

**HK Satellites.** HKs will be the fighter escort of the satellite system. They will be deployed specifically as an offensive weapon platform employing DE weapons (these include speed-of-light weapons, high-power microwaves, and laser). These satellites will identify hostile platforms (in space or on the ground) and destroy or disable them.

Figure 3-11 shows each type of satellite in a constellation—and its capabilities. Each satellite in the constellation provides functions so the “whole” spacenet constellation is more capable and secure than the sum of the parts. The spacenet satellite security system will ensure that uninterrupted, timely, and accurate information is delivered to the war fighter without fail.

### Summary

The four pillars of the spacenet 2025 system are support to the war fighter, C<sup>3</sup>, satellite design, and satellite security. Each pillar contributes synergistically to the spacenet system capabilities. The spacenet system ensures that the US maintains space dominance well into the next century. The next chapter will outline the spacenet concept of operations and show how each pillar fits into the system. A notional scenario will show some of the routine spacenet uses and capabilities in 2025 and beyond.

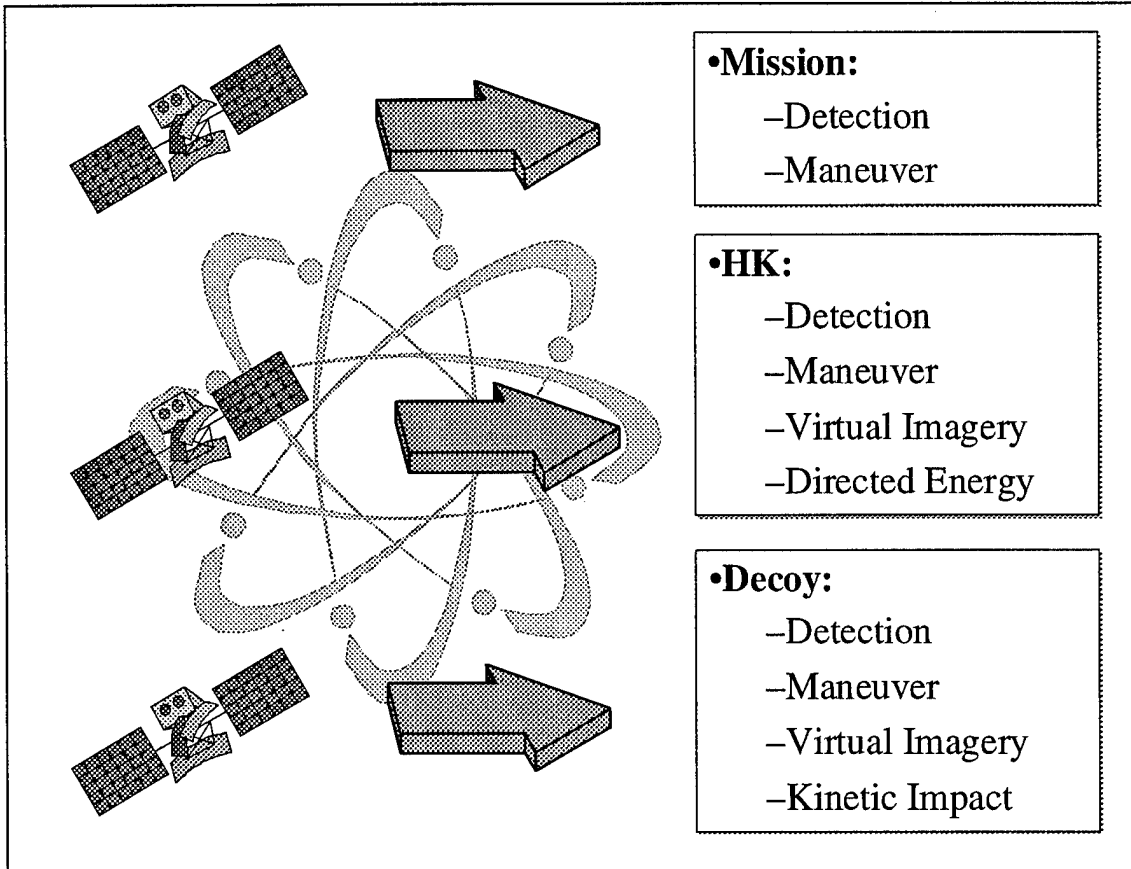


Photo from Microsoft Clipart Gallery © 1995 with courtesy from Microsoft Corporation.

**Figure 3-11. Typical Satellite Defensive Capabilities**

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## Chapter 4

### Concept of Operations

As a potential crisis is identified, a theater commander requests space support for an area of responsibility (AOR). Space support in 2025 will include a few large, national, multimission platforms that collect information from the AOR and distribute processed data through centralized channels. Priority and control of these national assets remains with the National Command Authority (NCA).

The majority of space support comes from large numbers of microsats in distributed constellations. Some microsat systems continuously orbit the earth as part of established space support. Existing systems provide immediate force enhancement and force multiplier support, but do not adequately provide the “eyes and ears” for the theater commander in 2025. However, more constellations of reusable and disposable microsats are launched within four hours of the execute order. These systems provide tailored, optimized support to the commander and forces. These assets and the operators are “owned” by the theater commander and are fully responsive to the needs of the forces in the AOR. Constellations are a robust mix of single- and dual-purpose satellites performing communication, navigation, weather, reconnaissance, and defensive missions.

The combat satellite operators near the AOR will deploy from their garrison to remote locations. Once in place, they will command satellites into position to facilitate force support in an impending deployment or conflict. Satellite operators easily carry their equipment with them on the deployment and require almost no additional logistics infrastructure to move their equipment—in some cases, it is stuffed in a side pocket of their rucksack. This portability is a result of extraordinary miniaturization of electronics and the ability to process and distribute force enhancement data from space in 2025.

Upon reaching their locations, the satellite operators immediately set up small C<sup>2</sup> systems, gain control of assigned satellites, and begin employment activities necessary to meet the information needs of the theater commander. Coordination with orbital analysts is not necessary since each small ground-control station immediately and automatically tracks the correct satellite. Anomalous conditions on the satellite are brought to the attention of the operator along with a list of recommended options to fix the anomaly—the operators do not need to refer to any engineers to solve most problems.

Satellite operators are difficult for the adversary to detect because their transmitters emit very narrow directional signals. In addition, the adversary has difficulty searching for the satellite operators, since they are not required to be anywhere near the AOR or the commanded satellite. If the enemy should get lucky and detect one of the satellite operators, the operator immediately grabs the portable equipment and moves to another location. If the operator is neutralized there is no emergency—the satellite continues its mission autonomously until another fully-trained and capable operator takes over.

Operators control some microsats dedicated to the theater or military operation—control is not shared with other users and satellites may be reconfigured or maneuvered to support the theater commander. However, other operators are responsible for transmitting mission requirements for national multimission assets to the respective control center to satisfy the theater commander's requests. The commander gets immediate feedback when support will be delivered.

Operators anywhere on earth or in space directly uplink signals to spacenet and the signals are routed between orbiting assets to the intended satellite. Spacenet is a seamless, "invisible" system because it operates with reliability and efficiency that even terrestrial utility companies try to emulate in 2025. Extraordinary amounts of data are exchanged nearly instantaneously through laser cross-links between space systems.

The commander's forces in the AOR easily "pull" the data they need from the space systems. Artificial intelligence and "smart" software ensure that the tank drivers, infantry, sailors, pilots, and commanders in 2025 get the data they need—without the reams of accompanying "chaff." Enemy forces have access to much of the same information through commercial means, but the US OODA loop is tighter, enabling reactions well inside enemy capabilities and maintaining military superiority.

The satellites themselves are a mixture of technological masterpieces (a few national, multimission systems) and many small, cost-effective, and reusable or disposable microsat systems. These small, cost-effective, 30-pound spacecraft of 2025 parallel the unexciting but highly efficient six-dollar pocket calculators of the 1990s. The space systems of 2025 do not suffer from limits of electrical power and propulsion fuel like space systems of the 1990s—nuclear power and electric propulsion eliminated such limitations. Further, optical computers onboard the spacecraft are highly resistant to radiation and provide colossal computing power and data throughput. This computing power enables maximum satellite autonomy. Preprogrammed missions require no human intervention from start to finish unless changes are required. “Standardized” changes are commanded using macros—and more elaborate one-of-a-kind changes take a few more keystrokes from the operator.

In 2025, “space-capable” adversaries cannot negate US space forces. Microsat constellations provide inherent defensive capabilities. A constellation may include several operational, single mission microsats, two HKs and two decoy microsats. Both passive and active defenses are employed through low detectability, shielding, autonomy, detection, maneuver, deception, and HK offensive systems. When an adversary takes out a few US microsats, an execute order is issued for a four-hour response launch for replenishment microsats.

At the end of the conflict the large, multimission satellites continue their mission of global awareness and global presence. The distributed microsat systems continue normal operations. The cost-effective, single mission reusable satellites launched specifically for this operation are de-orbited to their recovery base in the Mojave Desert where they will be refurbished and prepared for the next operation.

Satellites reaching the end of their service life, particularly the “disposables,” are later collected by an orbiting “spacecraft compactor.” This transatmospheric vehicle (adapted to a cleanup mission) collects defunct hardware, compacts it into small, dense cubes, and jettisons them deep into space.

## Chapter 5

### Investigation Recommendations

The effectiveness of the spacenet 2025 system is best examined by “grading” it against measures of merit relevant to the alternate futures of 2025. The spacenet 2025 system is highly effective, according to the measures of merit. Next, the paths to achieve the key technologies of the system are outlined. These require an *evolution* of space systems and related technologies with some technological *revolutions* as springboards to evolution at the system level. The spacenet system is achievable within 30 years.

#### Measures of Merit

Examination of measures of merit for the spacenet 2025 system proves its military value in the alternate future worlds. Starting with the three tenets of Air and Space Superiority—awareness, reach, and power—the AFIT operational analysis team and the 2025 white paper teams derived over 100 force qualities and associated measures of merit to evaluate the 2025 white paper concepts. When the spacenet 2025 system was analyzed against all force qualities, the results showed 29 measures of merit from nine categories as valid measurements for this system

1. Ground Survival
2. Identify
3. Integrate
4. Monitor
5. Plan
6. Decide
7. Communicate
8. Space Survival
9. Maintenance in Space

## Ground Survival

First, the ground survival category measures performance of the ground portion of the spacenet 2025 system—specifically the small, portable C<sup>3</sup> devices used to operate the satellites.

**Detection.** Spacenet 2025 will use small, mobile communications devices in the field to communicate through spacenet for C<sup>2</sup> of spacenet satellites. The mobile terminals should be as small as today's handheld cellular phones. Focused beam EHF signals minimize the probability of signal intercept. Large frequency ranges available in the EHF band allow spread spectrum communications to make signals blend in with everyday radio-frequency background noise. Packaged switched technology enables burst communications—minimizing the time of radio transmissions, reducing the probability of detection.

**Countermeasures.** EHF communications can use very small antennas, possibly only inches in diameter. Miniaturization of electronics should yield handheld space communication devices by 2025. These communications devices allow instant mobility, minimizing the probability that the user will be hit by an adversary if detected.

**System of Systems.** Spacenet accommodates many simultaneous users, giving “spatial distribution” so it is impossible to hit all system users. The war fighter in the field has multiple paths to transmit or receive information, since transceivers can be distributed anywhere in theater or the world. Loss of as many as 10 percent of the satellite C2 nodes should not impact the spacenet system since multiple nodes can be spatially distributed anywhere on the earth. Further, the small, portable communication devices are relatively inexpensive and easily replaced. If some field devices are neutralized, replacements are easily deployed.

## Identify

The identify category measures spacenet's ability to accurately recognize situations of interest to the war fighters, including possible natural or man-made threats against spacenet.

**Tempo.** Spacenet 2025 provides global coverage for the war fighter. With “eyes and ears” and efficient data processing in space, war fighters receive critical information from spacenet on demand. Spacenet 2025 provides the earliest possible sensing, detection, and data delivery to maximize war fighters' operations tempo. Indications and warnings delivered by the spacenet system allow the war fighter to

anticipate some enemy actions in advance. Further, spacenet can detect, identify and engage hostile ASAT systems before they can attack.

**Traceability.** Spacenet uses package-switched digital technology to transfer information between satellites and users. Package-switched technology provides an address of both the intended recipient and the original sender with each package that flows through the spacenet system. These addresses give users the ability to trace all information through the spacenet system.

**Accuracy.** Spacenet systems will be highly accurate. Increased multispectral sensing capabilities and onboard computing power will enable spacenet to correlate data with great certainty. This correlated data could be force enhancement data for war fighters or information about hostile threats to the spacenet system itself. Spacenet will use onboard databases and intelligent software to compare real-time data with stored threat information to maximize accuracy of processed information.

**Resolution.** Technological advances in multispectral sensing will improve resolution to levels not possible today. Miniaturized, distributed spacenet systems in low earth orbit can collect multiple data sets and synthetically combine them to improve resolution and fidelity. An example is multiple missile warning systems detecting an event, exchanging information through cross-links, and computing the solution for improved geolocation. These same sensor and computing advances will also provide enhanced resolution in identifying counterspace threats.

## **Integrate**

Next, the integrate category measures spacenet's ability to integrate data into a coherent picture to support the war fighter and help negate threats against the spacenet.

**Battle Space View.** Co-orbiting spacenet systems will provide excellent overview of any battlespace area on or near the earth. Large numbers of microsattellites in LEO can provide continuous coverage of an AOR. When proximity to the AOR is not critical, a few satellites in geosynchronous orbit can "see" the entire earth and space theater out to 22,000 miles. Spacenet is designed to be modular, and is easily expanded to cover different AORs as priorities change.

**Tempo.** Spacenet 2025 provides global coverage for the war fighter. With significant data processing using intelligent onboard software, spacenet will rapidly integrate data in the least possible time and transmit

it to the users on demand. With unparalleled coverage of the earth from space, the spacenet system integrates and provides critical data to war fighters in advance of hostile enemy actions, maximizing the operations tempo.

**Correlation.** Using onboard databases and knowledge modeling, spacenet satellites and their accompanying defensive satellites will have access to historical information about missions, targets, and threats. Spacenet will make maximum use of historical data to correlate and process "raw" or real-time data and communicate the conclusions to the war fighters that need the data. The onboard computers "know" who needs particular data, and they filter information to avoid overload.

### **Monitor**

The monitor category measures the ability of the spacenet system "owners" to track and control spacenet resources.

**Resources.** The spacenet is a self-monitoring system. Spacenet communication nodes keep track of other nodes and terrestrial users to route communications traffic via the most efficient means, routing traffic around degraded or destroyed nodes. Further, the spacenet system can provide health and status data of any satellite in the system to the appropriate ground controllers worldwide. The spacenet system ensures the theater commander and individual ground controllers know the status of all theater space resources. The spacenet system does its own battle damage assessment. If a spacenet satellite or ground terminal is "alive," the users will know it; appropriate operators are immediately notified if an asset is "killed."

**Forces.** Spacenet can track satellite controllers on the ground by locating controllers when they contact the spacenet. Protocols can "poll" the spacenet to ensure that in-theater controllers "check in" at selected times. Thus, we know that they are still alive and controlling their space assets. If a controller has not checked in, a replacement controller deploys immediately.

### **Plan**

Next, the plan category measures how spacenet prepares for upcoming situations.

**Effective.** The goal of spacenet is to provide timely, global, and secure communication of force enhancement data to war fighters on the earth, in the air, or in space. War fighters identify the targets and use the spacenet system to get the information needed about the targets. Spacenet system priorities will be set at the appropriate levels. Theater commanders set priorities for spacenet assets they "own" (like the tactical, disposable microsats). National authorities establish priorities between theaters for shared spacenet systems. The "internet in space" feature of the spacenet system ensures instant connectivity and maximum flexibility to change goals, targets, or priorities.

**Efficient.** The spacenet system is efficient in many aspects, ensuring reduced operations costs and minimum logistics support. Common spacecraft components ensure maximum connectivity at the lowest cost. People, aircraft, unmanned aerial vehicles, or other satellites can use small lightweight communications devices for standardized communication with the spacenet and other systems that communicate with the spacenet. Nuclear systems, laser power beaming, or electrodynamic tether systems may provide cost-effective, efficient power for spacenet satellites. Nuclear or electric propulsion systems provide a nearly unexpendable energy source to maneuver spacenet satellites. Inexpensive, disposable microsats may provide optimum support for short, tactical missions.

## **Decide**

The decide category measures spacenet's capability to use information to make a decision and the overall quality of the decision made.

**Decision Basis.** The spacenet system uses optical devices to store the information needed by onboard computer systems for decisions. Optical systems will store orders of magnitude more data than today's electronic systems, providing a solid foundation for the decision-making software. Optical storage could come in the form of holographic data storage. Knowledge for decisions could be represented in advanced formal data models such as "Z."

**Quality.** To avoid information overload, it is important for the spacenet to make high-quality decisions about traffic routing, data delivery to users, spacenet defense, and autonomous operations. Artificial intelligence will help ensure high-quality decisions. Genetic algorithms can adapt themselves to changing situations to improve their actions. Neural networks perform pattern-matching to choose optimal courses of

action for a given situation. Highly capable computers onboard spacenet satellites enable complex calculations to ensure the highest quality decisions.

### **Communicate**

The communicate category measures spacenet's communication abilities.

**Capacity.** Spacenet is partly a communications system. Spacenet provides communication capacity to terrestrial, aerial, and space-based users. Those users could be people, autonomous sensors, or unmanned vehicles. System capacity depends on the communications medium in 2025, and on data compression improvements. Spacenet will transfer data at 400 gigabits per second for a single visible light laser (expected not later than 2010). If technology moves beyond visible light lasers by 2025, data transfer rates could exceed 15 terabits per second for ultraviolet lasers, or 1,000 terabits per second for soft X-ray lasers. Each of these data throughput rates may improve from 20 to 50 times, through use of advanced data compression schemes such as fractal compression.

**Connectivity and Interoperability.** The spacenet digital communications scheme will connect to many standard systems. Spacenet must connect to many systems since it will use both civilian and military space-based communication nodes. Spacenet also provides connectivity to users without direct spacenet transceivers through terrestrial internet compatibility.

**Security.** Spacenet will ensure that unauthorized users cannot tamper with its internal configuration. Improved data encryption units and authorization codes will protect vital information. This security also prevents tampering with onboard packet routing information, prioritization, and defensive tracking and targeting information. Spacenet must also protect "friendly" communications and data from unauthorized users. Small encryption units on authorized military spacenet transceivers provide this security. Cryptographic key codes will change regularly to deny enemy use of "captured" spacenet transceivers. Encryption protects satellite cross-links, uplinks, and downlinks. Laser cross-links take advantage of laser pinpoint accuracy to minimize probability of signal intercept. EHF uplinks and downlinks provide narrow footprints on the earth, making it more difficult to intercept signals. Spread-spectrum, short-burst transmissions also make spacenet uplinks and downlinks difficult for unauthorized receivers to detect and record.

**Data Accuracy.** The communications channel provided by spacenet should follow commercial standards for data accuracy. Advanced error correction encoding or error detection and retransmission technology ensures data accuracy.

**User Friendliness and Human Interaction.** The Spacenet 2025 system will use 3D computer displays to ease the human-computer interaction.

## **Space Survival**

The space survival category measures spacenet's survivability in the harsh space environment.

**System of Systems.** Spacenet consists of many different orbiting communications, mission, and defensive satellites. The distributed design of the system ensures that the spacenet will still be able to accomplish the mission and route communications traffic to other nodes if some of the satellites fail. Ultimately, the user will nearly always get the data desired.

**Countermeasures.** The satellite security section defines active and passive countermeasures available in spacenet to counter threats to individual satellites and the system as a whole. The system is able to counter both natural and manmade kinetic and radiation threats.

*Detectable.* The satellite security section defines three possible low-detectability technologies incorporated into military spacenet satellites: energy diffusion surfaces, energy-absorbent materials, and energy-refracting or -reflecting materials. Each technology defeats a specific detection medium. To keep costs low, civilian spacenet satellites will not use low-detectable materials.

*Vulnerability.* Spacenet is primarily many small, distributed microsattellites, each providing an independent mission, communications, or defensive function. A weapon or a natural object impact could destroy these satellites because they are small. The relatively low cost and easy replacement of spacenet microsattellites offsets this vulnerability.

## **Maintenance**

Finally, maintenance in space measures the maintenance aspects of the spacenet system.

**Maintenance Footprint.** Spacenet has no need for separate system maintenance in space. Spacecraft are self-maintained by well-designed systems. These systems use intelligent materials and some microminiature machines for small-scale subsystem repair. If an entire satellite fails, the spacenet system knows to bypass it until a replacement satellite arrives. When they break, the relatively inexpensive microsattellites are “thrown away” and replaced. “Unexpendable” propulsion sources minimize any refueling or space “tug” requirements. The spacenet 2025 maintenance footprint should approach zero.

**Reliability.** Spacenet satellites will have a high mission capability rate from simplicity and the ongoing self-maintenance scheme of each subsystem provided by microminiature machines and intelligent materials. Onboard computers and autonomy ensure maximum mission availability. Satellite designs in 2025 minimize satellite failures caused by the harsh space environment.

**Security.** To avoid tampering with the internal system functions of spacenet, security measures and procedures protect each spacenet satellite from the time it leaves the factory until launch. Once on orbit, active and passive security systems ensure continuous protection against enemy threats—both physical and signal-intercept threats.

**Storage Volume.** Spacenet microsattellites are small and made of common parts. The common parts make the satellites quick to assemble. This avoids the need to have a large number of spacenet satellites built and awaiting launch. Should a spacenet satellite fail, a replacement will be assembled in a few hours from the common parts and launched into orbit the same day. Since the satellites are small, they will not take up much room if stored, nor will they occupy significant space in the launch vehicle payload fairing.

### **Timelines for Development**

Future timelines described in this section were developed using the Horizon mission methodology. The Horizon mission methodology starts with a given end-state, then describes those changes that must occur to achieve the end state. The methodology works back from the future to the present, until it describes the current generation of technologies.

Improved war fighter support begins with today’s initiatives, like Technical Exploitation of National Capabilities (TENCAP), to connect the “sensor to the shooter.” Evolution of these systems, combined with

some revolutionary improvements in information processing and storage and intelligent software for use on earth and in space, will lead to a highly efficient user-pulled system in 2025. The key to success is to ensure a continuous partnership between the users and the war fighters in the development process from requirement identification to demonstration, validation, and production.

Improved C<sup>3</sup> for the spacenet 2025 system also requires a stepped approach. First is today's initiative to minimize on-site personnel at satellite remote tracking stations, resulting in unmanned, global, fixed satellite command and control. The next step requires miniaturization of electronics and computing power to enable these same systems to become portable. High-rate, robust earth-to-space and space-to-space data transfer must evolve in parallel. Laser cross-links and other technologies co-developed by the commercial and military communities will make the spacenet a reality by 2025.

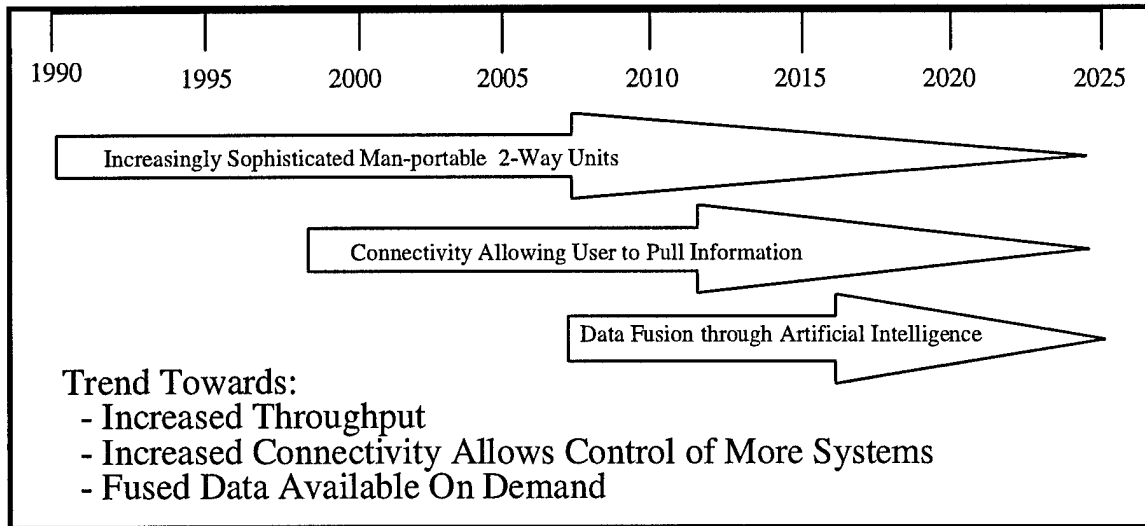
The road to microsat constellations in 2025 begins with today's miniaturization initiatives by DOD, commercial entities, and NASA's New Millennium program. There is probably one generation of "medium sized" 500-700-pound satellites between now and the 20-to-30-pound microsats of 2025. Revolutionary leaps in spacecraft power, propulsion, and computing power are required, along with evolutionary growth in autonomy capabilities, to implement the spacenet 2025 system. Leadership by the commercial space world and integration of capabilities into military uses is also vital.

The world of 2025 may include several "space-capable" nation-states. To ensure that the US maintains space dominance, countermeasures must minimize the perceived natural and hostile threats to US space assets. A defensive strategy could include passive and active defensive measures and fast, cost-effective satellite replenishment.

The general progression to spacenet 2025 starts with today's "demonstration systems" like Clementine and TAOS, that are proving the concepts of autonomy, miniaturization, and simplicity. The US should aggressively lead a forum to share "lessons learned" between military, civil (NASA), and commercial space programs. Once proven, the "medium-sized" satellites will replace today's large, multimission platforms. These "medium" systems open the door for the spacenet 2025 system of microsats that ensures US control of space throughout the 21st century.

## Serving the War Fighter

The true measure of spacenet is its ability to get critical information to and from the war fighter in near real time. This information may come in human-readable form, or machine-readable form for controlling devices such as unmanned aerial vehicles or sensor systems. This real-time information capability will require the development, refinement, and integration of numerous systems with the spacenet (fig. 5-1).

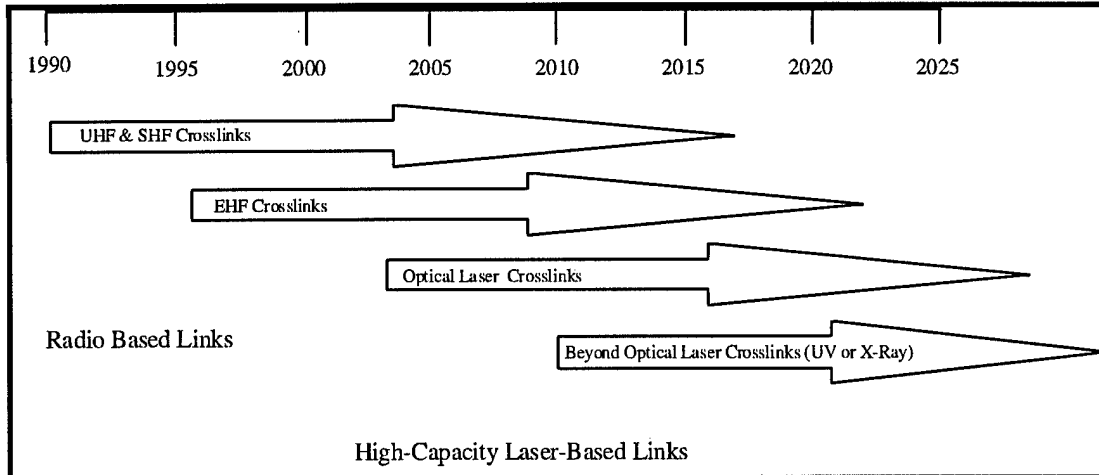


**Figure 5-1. Advances in Fielded C<sup>3</sup> Systems**

Although portable satellite communications systems exist now, they will continue to become more transportable while providing more throughput. Connectivity will increase as more systems adopt standard protocols for data transmission. This will occur as space communications become more commercialized. Finally, as the information explosion grows, consumers will demand improved methods to avoid drowning in a sea of data. Data-fusion technologies will grow, dependent upon increases in artificial intelligence.

## Communication Systems Development

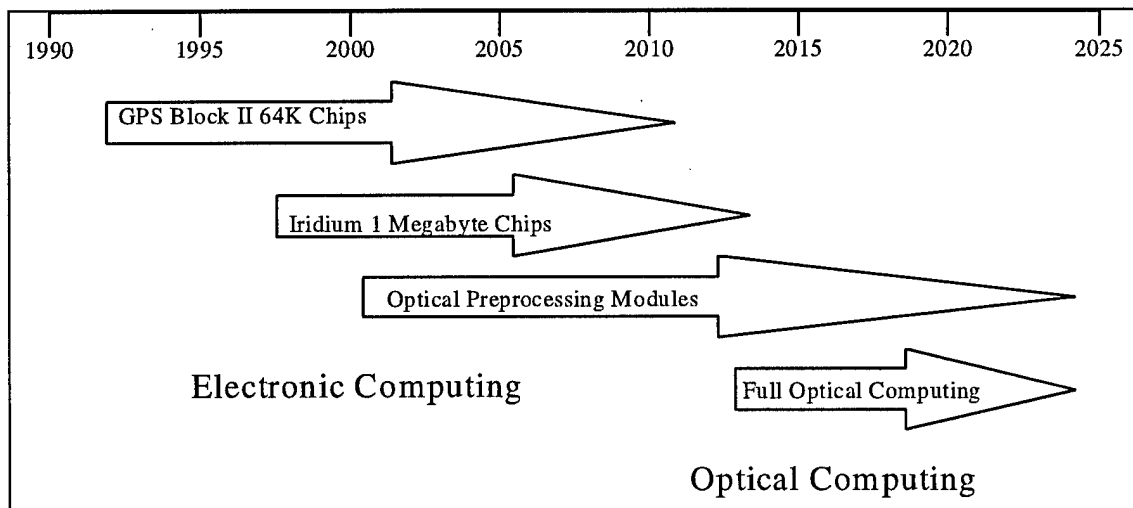
In 2025, high-speed cross-links between satellites will be used to interconnect mobile and remote forces (fig. 5-2). The move towards satellite cross-links, already started in 1996, needs to continue for satellites to provide communications capabilities needed in 2025. Moving towards higher frequencies will come naturally as the commercial satellite market provides more throughput.



**Figure 5-2. Technological Advances in Satellite Cross-linking**

### Space-Qualified Computer Development

Several systems outlined earlier require advances in computer processing and storage. Commercial computer and satellite markets will push these advances. As the commercial satellite market grows, more-capable space-qualified computers will emerge (fig. 5-3). As communications technologies increase in speed, space-qualified systems will become faster, driving towards optical computing technology.



**Figure 5-3. Advances in Satellite Computer Technology**

### Common Subsystems Development

In 2025, satellites will use common subsystems, making them less expensive than those of 1996 (fig. 5-4). Common systems are just starting in the commercial space industry, with the Hughes standard satellite bus "series 600." Given a standardized bus, standardized subsystems such as power, propulsion, and attitude control are the next step. The final step is to make components from different manufacturers standardized in much the same manner as interchangeable personal computer components today.

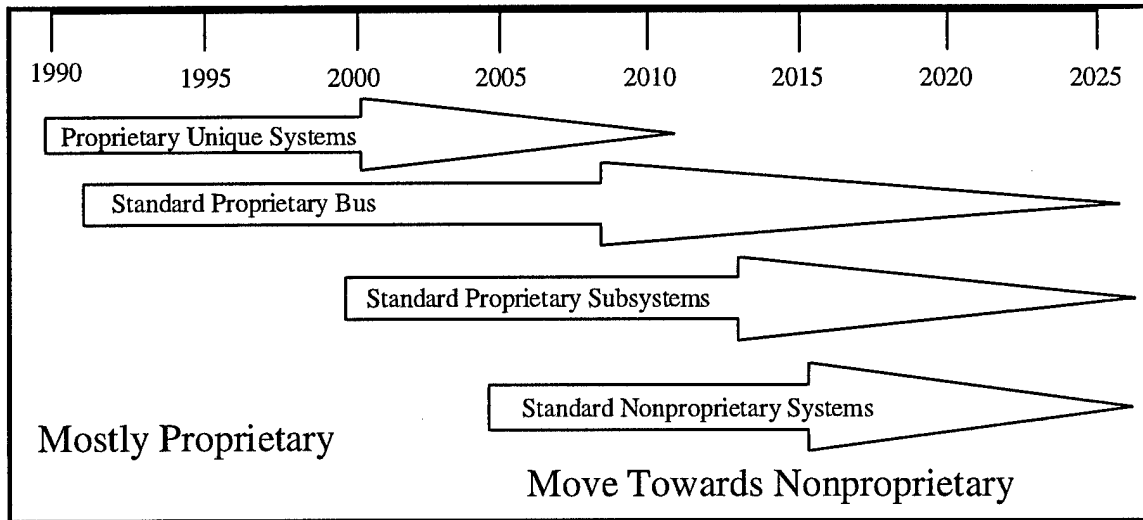


Figure 5-4. Timeline for System Standardization

### Defensive Systems Development

Active and passive satellite defenses will increase the survivability of a satellite system in 2025 (fig. 5-5). As more and more civilian satellites are launched, civilians will protect their investments by making their satellites more survivable in the natural space environment. The military will need to pursue defenses against man-made attacks.

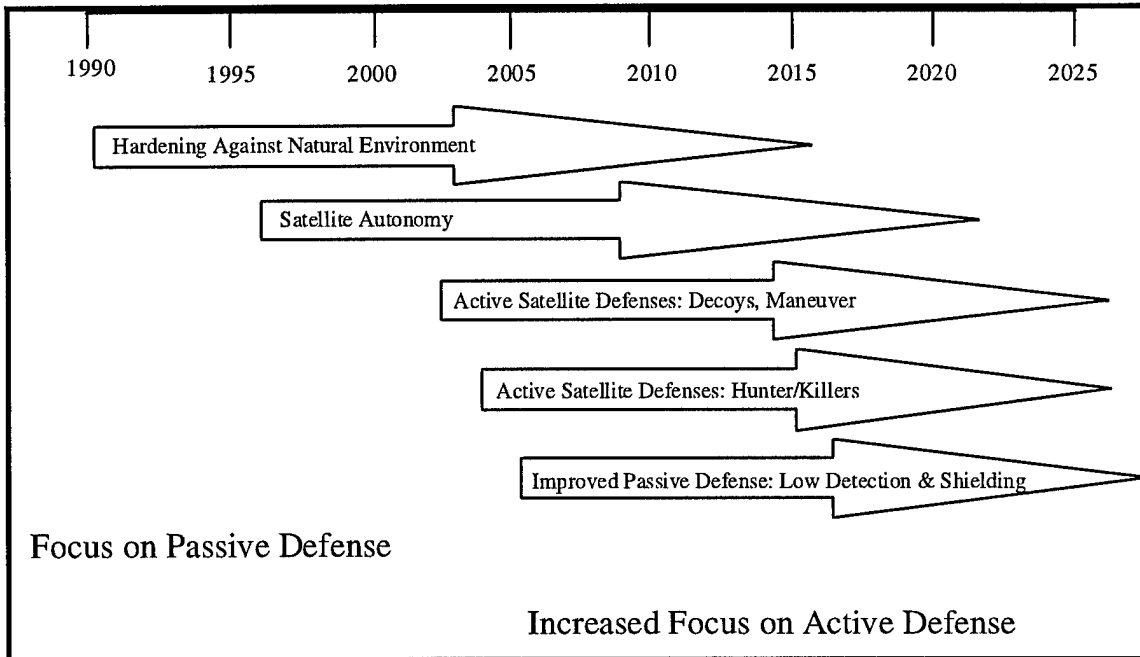


Figure 5-5. Advances in Satellite Defensive Systems

### Recommendations

Government and the commercial sector must leap forward harmoniously to maximize synergy and continue on course to achieve the common long-term goals: US economic prosperity and continued US space dominance throughout the next century.

Three categories of recommendations are worth consideration. First, the commercial sector should lead advancement in some technologies. These will be evolutionary and natural progressions, and they should directly enhance growth and profitability in the commercial sector.

Second, the Air Force/US Government should provide incentives in some technology areas that are not necessarily in the commercial evolutionary path or that may involve high risks and DOD-unique requirements. The Air Force should fund technology programs in this category to reduce risk, and they should provide incentives to the commercial sector to “take over.”

Finally, technologies that the Air Force/US Government should lead are very broad-based activities requiring overarching leadership—at least to get started. The US Government should lead the spacenet C<sup>3</sup> system architecture development just as it did in the early days of the internet. Other technologies in the final category are most clearly DOD-unique requirements or high-risk, and expensive development programs.

Technologies the Air Force should expect the commercial sector to lead:

1. Telecommunications
2. Computers and data storage (both terrestrial and spaceborne)
3. Software and artificial intelligence
4. Miniaturization (electrical and mechanical)
5. Common/standard space subsystems and components

Technologies the Air Force/US Government should provide incentives for:

1. Radiation-hardened electronics
2. High-bandwidth communication capabilities (laser cross-links)

Technologies the Air Force/US Government should lead:

1. Space-based, common C<sup>3</sup> system
2. Satellite defensive measures (active and passive)
3. Revolutionary propulsion (nuclear, electric, laser)

### Conclusions

The spacenet system meets or exceeds the applicable measures of merit relevant to the alternate futures of 2025. The paths are feasible to achieve the key technologies of the spacenet 2025 system. These paths require an *evolution* of some technologies and some technological *revolutions* as catalysts to lead the system evolution. Three categories of recommendations suggest ideas that the Air Force should consider to stay on track to achieve the spacenet system by 2025.

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