

Finding the Shape of Space

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Abstract

The US National Space Policy specifically addresses the preservation of, and freedom of action in, space. In order for the policy to succeed, would-be attackers must believe that the United States will detect and attribute their actions. Today's space surveillance network cannot detect either the newest and smallest satellites, nor can it detect small particles of space debris. It therefore cannot monitor or attribute the actions of small satellites, nor can it guarantee the safety of our existing space assets. As new technologies enable packaging increased capabilities into ever smaller space-faring packages, by 2030 our inability to detect small objects in space will become a critical capability shortfall in preserving the United States' freedom to operate in space.

An inability to monitor small satellites and space objects could diminish our military instrument of national power and the ability to conduct diplomacy. To properly engage foreign powers using the political instrument of national power, our diplomats must also know what space objects are doing, their intentions, and who owns them.

The Air Force must make decisions today regarding technology investment to ensure that the United States possesses comprehensive space situational awareness (SSA) in the future. This monograph is concerned with the direction space technologies will take over the next 20–30 years. Specifically, this research takes a purposeful look at accelerating technological change as it relates to US space capabilities instrumental to improving SSA and other key space initiatives.

Preface

This volume contains research produced by the Center for Strategy and Technology (CSAT). CSAT's purpose is to engage in long-term strategic thinking about technology and its implications for US national security. Air War College (AWC) and Air Command and Staff College (ACSC) students authored these research papers under CSAT's *Blue Horizons* study. The *Blue Horizons* program began in 2006 when the Air Staff tasked Air University to start a series of long-range studies looking approximately 20–30 years into the future to provide a vision for what the Air Force must do today to prepare for the challenges of the 2025–40 time frame. Future studies guide Air Force investments in people, training, education, and technology. However, long-range planning is difficult. While there are several future planning methodologies, the future is difficult to discern with clarity.¹ Further, the pressures of current operations and everyday activity often leave little time for reflective thought or funding for concepts that will not materialize for decades.

The *Blue Horizons* study answers questions similar to those addressed in the 1996 *Air Force 2025* study: What are the emerging technologies that will shape the US Air Force and the conflict arena in which it must operate in 20–30 years? What could air, space, and cyberspace power look like? Who will have access to emerging technologies that can make a difference? How soon will these important technological achievements become fielded systems?

To answer these questions, AWC faculty and approximately 45 AWC and ACSC students each year research future systems and technological concepts. The faculty and students worked closely with subject matter experts from the Air Force Research Laboratory, the Defense Advanced Research Projects Agency, the Department of Energy National Laboratories, major universities and businesses, and other government agencies. In addition to producing research reports, the cadre of officers became conversant in emerging technologies. These officers are entrusted with the ability to assess systems in directed energy, biotechnology, nanotechnology, and cyber technologies as well as understand the implications for the future of the US Air Force.

The *Blue Horizons* studies serve as an input for the development of Title X war games, strategic planning guidance, Quadrennial Defense Review scenarios, and the development of service requirements. The *Blue Horizons* program study topics are chosen by the Air Force chief of staff and the Air Force deputy chief of staff for plans and programs. CSAT runs the program.

Note

1. Norman Dalkey, *Delphi Method: An Experimental Study of Group Opinion*, RAND Report RM-5888-PR (Santa Monica, CA: RAND, June 1969); Peter Schwartz, *Art of the Long View* (New York: Doubleday Publishing Group, 1991); and Peter Schwartz, *Inevitable Surprises* (New York: Gotham Books, 2003). There are several accredited future studies programs in more than 20 universities (e.g., University of Houston).

Chapter 1

Introduction

*Lt Col Christopher C. Shannon
Maj Tosha N. Meredith*

The past 50 years of space exploration and exploitation have been instrumental to US economic, political, and national security. Our space capabilities are national assets that constitute joint, inter-agency, and national interests. The United States relies on space for its security and well-being more than any other country. Our lives reflect increased satellite services to our homes, schools, businesses, and hospitals. Services come in the form of global communications, television broadcasts, weather forecasting, vehicle navigation, computer synchronization, communications, and electric power grids. Further, space systems are integral to collecting information on potential adversaries' capabilities, monitoring treaties and agreements, and supporting military operations worldwide. This dependence is economically and militarily beneficial, but it also increases vulnerabilities and challenges.

Gen Kevin P. Chilton, previous commander of Air Force Space Command, highlighted a concern about the US Air Force space mission during a media roundtable on 14 September 2006: "I don't want to ever answer that phone and not be in a position to say we know what's going on and this is what we think we need to do. The first steps in doing that—and you'll find this in any domain that you operate in, whether it be land, sea, or air—is to understand the environment, understand what is up there, and what the capabilities are of the things that are up there. What we call this in military jargon is situational awareness."¹ Secretary of the Air Force Michael Donley made similar comments during the Air Force Association's Global War Symposium in Los Angeles on 21 November 2008. He noted that the increase of objects in Earth's orbit requires us to "enhance our capabilities to track these items and to assess their purpose and, when necessary, their intent."² China influenced the secretary's thinking and reminded the whole world of the reality of potential threats when its antisatellite (ASAT) weapon tests debunked the myth of uncontested space.

A purposeful look at accelerating technological change as it relates to US space capabilities is instrumental to improving space situational awareness (SSA) and other key space initiatives. These space initiatives include, but are not limited to, improved responsive space access, satellite operations, and air and space capability integration to deliver combined effects. Further, the initiatives include resource realignment to sustain existing space surveillance capabilities and to improve war-fighter access to the nation's full

spectrum of space capabilities. Based on these initiatives, Air War College (AWC) and Air Command and Staff College (ACSC) space research students investigated space topics exploring the accelerating change over the next 20–30 years to make recommendations useful to the Air Force.

The *Blue Horizons* researchers are integral to an effort initiated by the Air Force chief of staff to accomplish long-range technological and strategic assessments that make “taking the long view” a standard part of Air Force strategic planning, investment, and capability decisions. Students explored space-related technologies with high potential for the Air Force in 2025–40. These researchers paid special attention to the potential for commercial and governmental activities that generate technological and operational surprises and disruptive change. The results took the form of technology forecasts of concepts of operations for emerging technologies and original technology ideas. The students concluded that the ability to respond to aggressive technological change is paramount to the United States’ maintaining its space superiority advantage.

This volume offers four research papers that consider the implications of accelerated technological change related to the US space mission in 2025–40. Each researcher formulated a series of questions relative to his or her section of this monograph. Researchers traveled to conduct interviews with senior members of the Department of State, the national intelligence agencies, and the Department of Defense (DOD). In addition, members traveled to various countries to study their respective locations.

In chapter 2, Lt Col Scott Scheppers articulates the advantages and importance of SSA through a technology known as full motion video (FMV). He discusses the use of Google Earth’s FMV data application and how the United States could potentially benefit from implementing a similar technology. “Google Earth Tube,” a virtual environment that provides an extraordinary amount of information to whoever accesses it, sets the stage for improved surveillance. Space-based persistent surveillance, in the form of FMV, arguably offers the most efficient payoff for the United States. Colonel Schepers briefly examines trends in airborne FMV and focuses on technology issues the space community must resolve in order to make satellite FMV a reality. He also analyzes the wide-ranging implications of satellite FMV for US national security. His research findings suggest that when realized, FMV from space will provide the United States unprecedented situational awareness and insight regarding global activities. Specific to the military, FMV is poised to make significant contributions to help track mobile targets, provide unambiguous warning, aid in SSA, and network human activity.

Chapter 3, written by Lt Col Dustin Ziegler, ties Colonel Schepers’s FMV and SSA research to a specific concept—distributed real-time awareness global network in space (DRAGNETS). While discussing DRAGNETS, Colonel Ziegler paints a picture of how

constellations of thousands of miniaturized satellites working together provide a flexible SSA architecture. He addresses the importance of SSA and suggests that the United States has a tremendous investment in space for the military, intelligence, scientific, and commercial sectors. Furthermore, he suggests that the lack of persistent situational awareness of the space operational environment, which ensures freedom of action, is one of the United States' vulnerabilities. The DRAGNETS research focuses on real-time data gathering and capabilities with a direct focus on the possibilities in 2025. More specifically, Colonel Ziegler's research suggests that the DRAGNETS concept is an approach that departs from the traditional paradigm of large and specialized space-based surveillance satellites.

Colonel Ziegler identifies the realities of the United States' dependence on space today and in the future while highlighting the threat environment and existing SSA gaps. The discussion then transitions to a detailed description of DRAGNETS at an operational concept level and delves into the technological advances required and the feasibility of these advances. Specifically this section focuses on the role of nanoscale technology as an essential enabler for DRAGNETS, describing focus areas for further development. His research findings suggest that there is a compelling need to fill capability gaps in the future US SSA architecture. The expense and difficulty of populating strategic locations on Earth's surface with new ground-based space surveillance assets, coupled with the difficulty of producing large, complex satellites within budgetary and schedule constraints, require strategists to think about the problem in a different way.

Building on the discussions about SSA, Maj Brian McDonald follows up with research on scramjet technology in chapter 4. The purpose of his research is to explore scramjets as an alternative to rockets to meet the space access capability gap projected for 2030. A panel of propulsion and space access experts, convened specifically for the scramjet research, predicted a moderate likelihood that 20 or more nations would own ASAT technologies in 2030. Major McDonald's research clarifies the expectations of scramjet-enabled space access in 2030 by applying two rigorous technology forecasting methods. The first method employs the Delphi process by interviewing and questioning a panel of 12 diverse propulsion and space access professionals. The second method employs an Air Force-sanctioned war game, set in 2030, which provides the framework for a student-led replay that pits a notional scramjet-enabled launch system against a near-peer competitor. Major McDonald's research findings forecast that a US scramjet-enabled space launch system by 2030 is within reach although the schedule risk is high. Further, the Delphi panel forecasts a better-than-moderate likelihood of having disruptive capabilities such as turnaround times of

24 hours or less and omniazimuthal launch from any site at any time by 2030.

The final chapter looks at the possibilities of designing space systems using carbon nanotubes (CNT). In this chapter, Maj David Menke investigates CNTs' attributes, utility, and probability of availability for 2030's space access, SSA systems, and more. CNTs represent a specific nanotechnology with several key attributes, including high strength and low weight. CNTs offer the military an exponential advantage in structures and component materials related to space system size, weight, and power (SWaP) constraints. Further, CNTs provide the opportunity to shift to smaller systems to improve access to space and to protect space systems, from both a space environment and an ASAT threat perspective. The purpose of this research is to provide a CNT technology forecast for 2030. Major Menke's research findings suggest that the United States must embrace a new, smaller satellite design paradigm in which it leverages nanotechnology to continue to increase US satellite technological advantage and to field more capable systems for a lower cost.

In the end, the authors, both individually and collectively, conclude that there will be a need for improved and untapped space access technology. This need encompasses a change in political thought and direction. The United States must dedicate the necessary resources to meeting the SSA need. US national security depends on it. This dependence, coupled with the growing threats of actors seeking to deny the use of this medium, creates vulnerabilities the United States cannot currently address. The studies presented in this monograph offer a wide range of plausible scenarios and potential solutions for space-based deterrence designed for the United States. Though not all-encompassing, the contents of this research may become a reality in the very near future. The United States must take action on maintaining space dominance, or it will encounter challenges from adversaries that could prove devastating if not addressed well in advance.

Notes

1. Gen Kevin P. Chilton, commander, Air Force Space Command, "AFSPC/CC Media Roundtable," Air Force Space Command, 14 September 2006, accessed 30 July 2010, <http://www.afspc.af.mil/library/speeches/speech.asp?id=325>.

2. SMSgt Matt Proietti, "Secretary Donley: U.S. Can Retain Space Leadership Role," *Air Force News*, 24 November 2008, accessed 30 July 2010, <http://www.af.mil/news/story.asp?id=123125341>.

Chapter 2

Google Earth Tube

Prospects for Full Motion Video from Space

Lt Col Scott J. Scheppers

The US National Space Policy says that the “United States will: preserve its freedom of action in space; dissuade or deter others from impeding those rights [and] take those actions necessary to protect its space capabilities.”¹ In order for this deterrence policy to succeed, would-be attackers must believe that the United States will detect and attribute their actions. Today’s space surveillance network (SSN) cannot detect the newest, smallest satellites and therefore cannot monitor or attribute the actions of small satellites. By 2030 this capability gap will widen. Small satellites will proliferate as they become cheaper and available to more actors. To preserve space superiority, the United States must arm the diplomatic instrument of national power with knowledge beyond what is in space. Diplomats must also know what space objects are doing, who owns them, and what their intentions are. The Air Force must decide today to develop the technologies to provide comprehensive space situational knowledge.

In the following research, the advantages and importance of SSA through a technology known as full motion video (FMV) are highlighted. Also discussed is the use of Google Earth’s FMV data application and how the United States could potentially benefit from implementing a similar technology.

Introduction

It’s only a matter of time. Persistent ISR is going to be absolutely no different than GPS. Never, ever, did we have a discussion on who ought to own GPS, who ought to control GPS, it’s just there.

—Gen Lance Smith
Commander, US Joint Forces Command, 2007

As the United States adapts to fight irregular warfare, the requirement for persistent intelligence, surveillance, and reconnaissance (ISR) continues to skyrocket. Specifically, the advantages of FMV, popularized by the Predator remotely piloted aircraft (RPA), have allowed commanders to track, target, and kill individuals in the insurgent battlespace. General Smith thought the service argu-

ment “strange” because it failed to account for the future of persistent ISR, which he believes would become ubiquitous.²

In comparison to FMV, still-shot imagery is commonplace. Anyone with a computer can access imagery of almost any point on Earth using commercially available computer software like Google Earth. Google Earth markets its software application’s ability to let the user “fly anywhere on Earth to view satellite imagery, maps, terrain, 3-D buildings, from galaxies in outer space to the canyons of the oceans.”³ Google Earth regularly incorporates new geospatial data into its application via selectable layers. In July 2008, Google Earth incorporated a layer which allows users to choose from 4,500 worldwide webcams showing images usually no older than 30 minutes.⁴ The webcams are placed in geographic areas of interest such as a landmark, beach, or tall building. In the future, the spatial frequency and availability of these sources will increase.

Technology currently exists to enable an FMV data layer in Google Earth’s application. The variety of web-based programs allows users to watch live events digitally on network-based devices including televisions, computers, and personal digital assistants. Existing video streaming technology coupled with FMV provides the opportunity for “Google Earth Tube,” a virtual environment that provides an extraordinary amount of information to whoever accesses it. As with Google Earth, FMV sources for Google Earth Tube will include stationary, airborne, and satellite sensors. While developments in airborne FMV provide US forces a significant advantage and the prospects for near-space sensors offer unique advantages of their own, this chapter focuses on similar space technologies.

Space-based persistent surveillance, in the form of FMV, arguably offers the most challenges and perhaps the most efficient payoff. By 2035 technology improvements will allow persistent ISR in the form of FMV from satellites—possibly changing the way the United States operates militarily. This chapter briefly examines trends in airborne FMV and then focuses on technology issues the space community must resolve in order to make satellite FMV a reality. It also analyzes the wide-ranging implications of satellite FMV for US national security.

Airborne Full Motion Video

The success of FMV systems like the MQ-1 Predator and the MQ-9 Reaper in Iraq and Afghanistan has increased demand for these and similar systems. Maj Gen Paul Dettmer, the Air Force’s assistant deputy chief of staff for ISR, described the demand as “insatiable” and “exponential” over the course of the last seven years.⁵ In response to operational requirements, Secretary of Defense Robert Gates accelerated deployment of systems to support the global war on terrorism. As of May 2008, the Air Force was two years ahead of its original RPA deployment timeline with 24 RPA

combat air patrols supporting the war on terrorism.⁶ In addition to accelerated Air Force RPA deployments, new FMV systems are in production. The DOD is outfitting 51 Beech King Air aircraft with MQ-9 Reaper-like FMV sensors to augment the ISR capability in Iraq and Afghanistan.⁷ Additional ISR platforms allow increased, persistent FMV for coalition forces, but there are other means to expand this capability.

Improved FMV sensors, specifically addressing area coverage shortfalls, bring increased capability. A 2007 Government Accountability Office report noted that repeated tasking of surveillance assets are required to obtain a complete view of an area due to the “soda straw” field of view of the Predator RPA.⁸ Responding to this requirement and a specific need identified by the US Marine Corps, the US Air Force Research Laboratory (AFRL) and the Los Alamos National Labs developed the Angel Fire sensor for the Marine Corps in 2005. The sensor design allows for near-real-time, wide-field-of-view coverage of sufficient resolution to identify dismounted personnel.⁹ The near-real-time term accounts for the delay introduced by automated data processing or network transmission usually measured in single-digit seconds.¹⁰

In the summer of 2006, the US Army developed and fielded a similar system called Constant Hawk.¹¹ The primary difference between the systems is employment options. The Marine Corps uses Angel Fire for near-real-time situational awareness, and the Army uses Constant Hawk for forensic change-detection analysis, investigating events after they occur.¹²

The key advantage of these systems is the area covered. While an RPA such as the MQ-1 or MQ-9 provides high resolution of a city block, Angel Fire and Constant Hawk provide high resolution coverage of an entire city. Furthermore, Angel Fire can simultaneously provide imagery to multiple analysts. Any analyst on the ground with access to the Angel Fire imagery server can view FMV within a 10-second latency period from when the sensor took the image.¹³ Imagery analysts can simultaneously access data of unique areas of interest in the same FMV stream independently of each other.¹⁴ The Air Force is pursuing a similar wide-area collection capability for its RPA FMV sensors.¹⁵ When fielded, the wide-area airborne surveillance sensor developed for the Reaper RPA provides 30 times the area coverage of the current sensor.¹⁶

The Defense Advanced Research Projects Agency (DARPA) is exploring concepts that provide even more area coverage. The autonomous real-time ground ubiquitous surveillance-imaging system (ARGUS-IS) will provide 50 “Reaper-like” steerable beams over a 27-square-kilometer (km) area using the DARPA-developed A-160 Hummingbird helicopter as its aerial platform.¹⁷ Operating in near space, airships hold the promise of providing an even larger footprint of coverage.

In the future, users operating in the realm of terrestrial systems like Angel Fire, ARGUS-IS, or an airship in near space will have persistent ISR in the form of FMV available to them at all times. This persistent ISR is “just there,” said General Smith.¹⁸ Airspace access limits these systems. To be effective, most of these systems fly through contested battlespace; thus, air superiority is essential. With regard to areas in which air superiority is fleeting or unattainable, the United States will likely not risk the loss of these unique systems or provoke adversaries by flying an FMV system over another country’s sovereign airspace. Achieving persistent FMV capability through spacial resolution is a step toward solving the challenge with air superiority.

Spatial Resolution: How Much Is Enough?

In 1960 the United States began an effort to look at Earth from space with its troubled missile defense alarm system (MIDAS).¹⁹ The MIDAS concept places an infrared sensor on board a telescope flying in low Earth orbit (LEO) to provide the United States early warning of intercontinental ballistic missile launches from the Soviet Union. Because of the use of LEO, MIDAS required 24 satellites to ensure adequate dwell time over the Soviet Union. In short order, scientists evaluating the system were concerned that the poor spectral resolution of the telescope would produce too many false alarms caused by the sun reflecting off clouds.²⁰ As a result, the Air Force cancelled the program in 1960 after placing fewer than a dozen MIDAS satellites in orbit.²¹

In 1966 Program 461 replaced MIDAS with a more capable infrared telescope; however, the DOD cancelled the program almost immediately because of the expense of the large number of satellites required in LEO. Instead, a high-level scientific committee recognized that a large, powerful telescope in geosynchronous Earth orbit (GEO) could image as much area as 12 similar satellites in LEO. Thus design on the Defense Support Program began.²²

The first Defense Support Program satellite launched in November 1970; 23 satellites later, this highly successful program, upgraded multiple times, continues to operate today. Defense Support Program satellites use a 6,000-pixel focal-plane array (upgraded from the original 2,000 pixels) to monitor ballistic missile launch and large-scale infrared events throughout the world.²³ While useful for detecting intense sources of heat across large portions of Earth, the satellites’ low resolution makes them of little value for the targeting and surveillance of conventional force and counterinsurgent activities required for maneuver and irregular warfare, respectively.²⁴

Image quality affects its utility. The national image interpretability rating scale (NIIRS) is the tool most commonly used to rate image quality. It uses 10 levels (0–9) to communicate the usefulness

of imagery to analysts, manage tasking and dissemination for collection managers, and assist in design and assessment of imaging systems.²⁵ Designed by the intelligence community, the original scale helped analysts identify military equipment. The 10 NIIRS levels are associated with the ability of trained imagery analysts to meet specific interpretive tasks. The higher the NIIRS rating, the more detail seen in the image. For instance, a NIIRS level of seven allows an analyst to identify individual railroad ties while a lower level of five reveals only the railroad tracks.²⁶ Recognizing the increasing reliance and applicability of imagery to civilian and environmental applications, the imagery resolution assessments and reporting standards committee released a civilian version of the scale in 1996.²⁷

A NIIRS rating accounts for multiple variables associated with an image; the most important is the ground sample distance (GSD). The GSD is a key criterion by which engineers design optical systems; therefore, it is necessary to relate the usefulness of an image to GSD. GSD is the minimum observable distance between two objects, which is necessary to distinguish them as distinct and separate. A NIIRS six rating equates to a GSD of .4 to .75 meters. According to NIIRS six criteria, a trained imagery analyst should be able to identify automobiles, detect livestock, and see foot trails through tall grass.²⁸ The FMV sensor on Angel Fire has a designed GSD of .5 meters in order to track dismounted individuals in an urban environment.²⁹ A FMV sensor of .5-meter GSD should provide sufficient resolution to support the targeting and surveillance requirements necessary to monitor most human activity—observation is fundamental to irregular warfare.

Given the requirements for targeting and surveillance, the design and engineering budgets examined in this chapter assume an ideal resolution of .5 meters. This assumption also recognizes the ability to conduct surveillance versus maneuver warfare activity. For instance, tracking mobile missiles will not require as much spatial resolution but is still useful and desired for military applications.

Optics

The following equation calculates GSD from an imaging satellite, where h is the satellite's altitude, λ is the operating wavelength of the electromagnetic spectrum, and D is the diameter of the primary antenna or aperture:³⁰

$$\text{Equation 1.1} \quad GSD = h \left[\frac{1.22\lambda}{D} \right]$$

This equation shows that, given a fixed wavelength of light, the only variables to adjust resolution are altitude and the diameter of the imaging sensor's primary mirror. Higher resolutions are more

easily achieved in LEO because of the sensor's proximity to Earth, which is the location for most commercial imaging satellites.

Low Earth Orbit (LEO) Approach

The launch of Space Imaging Corporation's IKONOS satellite in September 1999 marked the first time resolution imagery of less than one meter was available from a licensed commercial vendor.³¹ The vendor placed the satellite in a 700 km altitude orbit while using a primary mirror of .7 meters, allowing it to achieve .82-meter resolution.³² Since the exploration of the .82-meter resolution, US companies launched three additional commercial imaging satellites.³³ The most recent, GeoEye-1, has a 1.1-meter primary mirror diameter, giving it .41-meter resolution from a LEO of 682 km altitude.³⁴ Using corresponding NIIRS values, these resolutions allow skilled analysts to distinguish between trucks and cars as well as detect the presence of individuals.³⁵ The drawback, inherent to satellites in LEO, is the limited field of view and revisit time. GeoEye, GeoEye-1's owner, advertises the capability to image a 15 km x 15 km swath width with a revisit time over the same location in just under three days.³⁶

GeoEye-1 and most commercial imaging satellites are in a sun-synchronous polar orbit ensuring global coverage. The satellites cross the equator at the same local time each day. This orbit is not optimal for revisit time over a specific target. Modeling such a circular LEO at 500 km altitude reduces imaging revisit time approximately to five hours for any target at 33 degrees north latitude—the same latitude as Baghdad, Iraq.³⁷ A snapshot of the same location every five hours, regardless of resolution, is far from the ability to stare continuously at the same spot on Earth. As with the LEO MIDAS early warning system in the 1960s, the only way to improve dwell time or increase the revisit rate over a particular location is to increase the number of satellites operating in LEO.

Iridium Satellite LLC's operation is one example of improving dwell time in LEO by increasing the number of operating satellites. With 66 LEO cross-linked communication satellites operating as a single network, Iridium owns the largest commercial satellite constellation in the world.³⁸ Communication satellites in LEO have almost four times the average access to ground targets during a given pass because of generous field-of-view requirements limited only by line of sight.³⁹ This means the satellite can fulfill its mission as soon as it achieves line of sight, generally once it rises five or 10 degrees over the horizon.

The constraints on imagery satellites are much more severe. To avoid atmospheric degradation, imagery satellites must typically image no further than 30–45 degrees from nadir—the point on Earth directly below the satellite.⁴⁰ The smaller field of view for imagery satellites means it would require more than 66 imagery satel-

lites operating as a single constellation to provide persistent access and coverage of any target. In a 500 km, 41-degree inclination orbit, optimized for a target at the latitude of Baghdad, 186 imagery satellites provide persistent imaging access to any target at Baghdad's latitude.⁴¹ This orbit provides no access to targets in latitudes higher than Baghdad's.

Ideally, a satellite constellation will have access to any target on the globe. The only orbit capable of providing this access is the sun-synchronous polar orbit. One such orbit requires 2,379 satellites to maintain persistent imaging access to any target on Earth.⁴² This type of constellation is impractical and cost-prohibitive under the current construct used for building and launching satellites into orbit. Such a constellation requires a change in thinking from complex, highly capable satellites to small, affordable—albeit likely less capable—systems.

A small, simple, modular satellite is what Pumpkin Incorporated envisioned when it invented its ultracompact CubeSat design. Measuring 10 centimeters (cm) x 10 cm x (.5, 10, 15, 20, and 30) cm, the CubeSat serves as a satellite bus for Pumpkin's miniature imaging spacecraft (MISC).⁴³ The MISC is a turnkey imaging spacecraft designed to provide multispectral imagery with a 7.5-meter GSD from an altitude of 540 km.⁴⁴

This medium-resolution satellite would not suit military operations with a requirement to track individuals. The mirror diameter required for .5-meter resolution is obtained by substituting 600 km, a nominal LEO, into equation 1.1, simplifying it to the following:

$$\text{Equation 1.2} \quad GSD \text{ LEO (600km)} \cong \frac{366}{D}$$

The corresponding graph (see fig. 2.1) reflects significant resolution gains with mirror diameter increases up to approximately .65 meters.⁴⁵ This happens to be close to the diameter required to achieve .5-meter resolution from a nominal 600 km LEO. Therefore, expanding the MISC design 10-fold would give it a large enough mirror diameter to achieve .5-meter resolution. For reference, the graph also includes hypothetical GSD, given current mirror diameters of representative US commercial space imaging spacecraft (IKONOS, GeoEye-1) and the Hubble Space Telescope.

Achieving persistent FMV from LEO satellites requires hundreds of satellites for imaging access. The satellite's ability to disseminate information also requires complex communications architecture. For FMV to be of optimum value, users need access to the video in near real time. To facilitate near-real-time FMV in LEO, satellites need to constantly off-load data to the ground either through a ground station in their communications footprint or relay satellite architecture. This proposed architecture is feasible; however, it adds significant cost and complexity to an already overly ambitious approach. The FMV strategy in 2035 may compare to 2008 when

the United States opted to build relatively large numbers of less sophisticated RPA FMV ISR platforms versus continued investment in an expensive, limited number of ISR imaging platforms like the U-2. The alternative to large numbers of satellites in LEO is to opt for a smaller number of satellites in a higher altitude orbit.

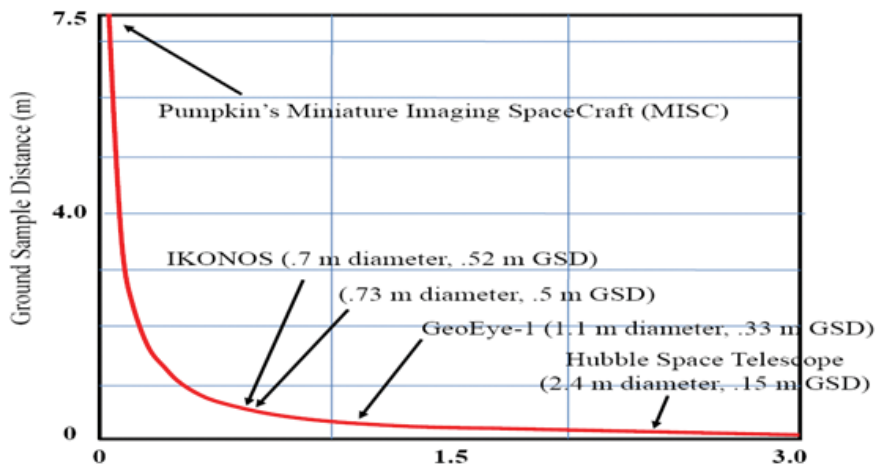


Figure 2.1. GSD versus telescope mirror diameter (nominal 600 km altitude LEO)

Geosynchronous Earth Orbit (GEO) Approach

A satellite in GEO eliminates revisit rate and field-of-view operation limitations inherent in LEO imaging satellites. Satellites in GEO match the rotation of Earth and maintain continuous access over the same field of view on Earth. The high altitude allows the satellite a theoretical field of view approximately 33 percent of Earth's surface.⁴⁶ While revisit and field-of-view considerations favor surveillance, the high altitude reduces resolution with current mirror technology.

Primary mirrors presently used on LEO imaging satellites are not large enough to provide the resolution necessary for precision targeting considerations. Using the same primary mirror size on IKONOS and GeoEye-1 satellites in a GEO computes to a resolution of 36.4 meters and 22.4 meters, respectively, a fact that demonstrates the loss in resolution. At these resolutions, an analyst would find it challenging to distinguish between airfield taxiways and runways or detect a medium-sized port facility.⁴⁷ Therefore, GEO satellites require much larger diameter primary mirrors to achieve the resolution of existing LEO systems.

Solving equation 1.1 by substituting 42,164 km for h , a satellite at geosynchronous altitude, and 500 nanometers (nm) for λ ,

as a wavelength at the center of the visible spectrum, the equation simplifies to

$$\text{Equation 1.3} \quad GSD \text{ GEO (42,164 km)} \cong \frac{25.72}{D}$$

Figure 2.2 depicts a graph of equation 1.3 showing GSD versus diameter of the primary mirror in GEO.⁴⁸ Significant gains in resolution correspond to increased mirror diameters up through approximately 26 meters. At this point, increases in mirror diameter offer diminishing improvements in resolution.

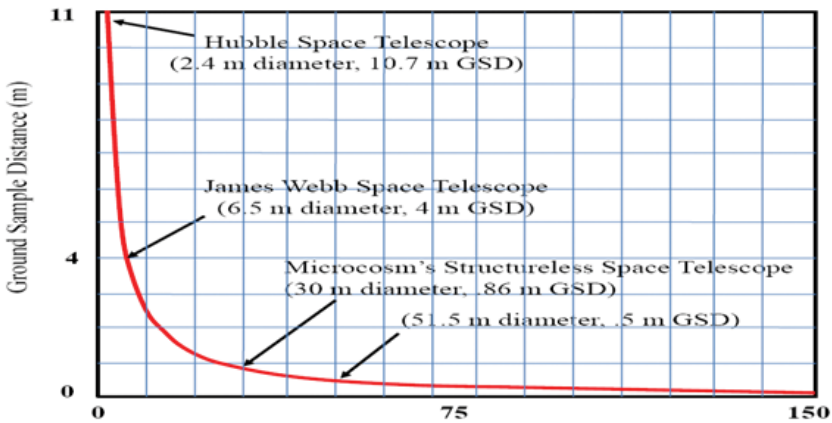


Figure 2.2. GSD versus telescope mirror diameter (nominal 42,164 km altitude GEO)

Having been used in ground observatory telescopes since the beginning of the twentieth century, large-diameter mirrors are not unique. The Mount Wilson Observatory's 1.5-meter mirror in 1908, the 2.5-meter Hooker in 1917, and the Hale telescope's five-meter mirror in 1948 were the earliest large-diameter monolithic mirrors.⁴⁹ Improvements in mirror construction keep pace with the increasingly exacting polishing requirements necessary for larger mirror diameters. Currently, there are nine eight-meter-class mirrors operating in telescopes around the world.⁵⁰ Terrestrial-based large mirrors are relatively easy to transport on Earth; however, placing large mirrors into orbit for space or Earth observation introduces significant challenges.

The biggest challenge of placing large mirrors into orbit is the mass and volume constraint associated with space launch vehicles.⁵¹ Technological developments reducing mirror mass coupled with complex packaging to decrease the mirror's volume in the launch vehicle address the payload problems. In addition, improved space launch vehicle lift capability will allow the launch of

heavier and larger mirrors. The ability to place larger mirrors in orbit in the future will improve the resolution of satellites in GEO.

New materials and construction techniques have allowed engineers to produce larger-diameter mirrors at lower areal density. The complete mass of the mirror divided by its surface area equates to the areal density. Mirrors on most ground-based large telescopes have an average areal density of between 300 to 500 kilogram (kg)/meter squared (m^2).⁵² In the late 1970s engineers started constructing the 2.4-meter primary mirror of the Hubble Space Telescope using Corning's ultra low expansion glass with an areal density of 180 kg/m^2 .⁵³ This massive mirror, with a closed core structure, weighed 828 kg.⁵⁴ Hubble's scheduled replacement, the James Webb Space Telescope (JWST), projected for launch in 2013, will carry a 6.5-meter primary mirror with an areal density of 26 kg/m^2 .⁵⁵ Use of the metal beryllium with an open-back, folding design allows the weight of this mirror, more than seven times larger than Hubble's, to be less than half that of the Hubble mirror.⁵⁶

Ongoing experiments for space telescopes use nanolaminates and active mirror designs, an approach used on many ground-based telescopes to compensate for atmospheric turbulence. These technologies hold promise for reducing areal densities to the 5 kg/m^2 range.⁵⁷ In the Mirror Technology Roadmap, the National Aeronautics and Space Administration (NASA) estimates that mirror areal density will be less than 1 kg/m^2 by 2030.⁵⁸ Figure 2.3 shows the downward trend for areal density, reflecting both increased mirror diameters and corresponding decreases in the mirror weight. Reduction in areal density allows more mirror to be launched; at the same time, it pushes the limit on launch vehicle volumes.

The volume of current launch-vehicle shrouds also limits the size of mirrors. Simply put, any mirror with a diameter larger than that of its respective launch vehicle shroud will not fit on the current inventory of space launch vehicles. The space shuttle launched the

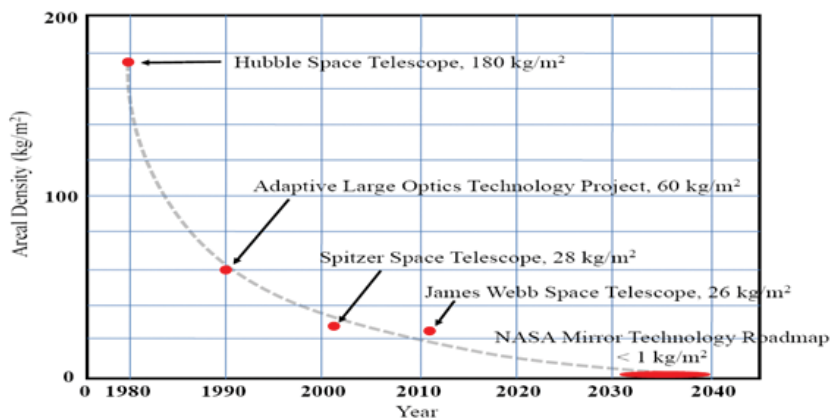


Figure 2.3. Areal density of telescope mirrors

Hubble Space Telescope's 2.4-meter-diameter monolithic mirror, which easily fit into the shuttle's 4.6-meter-diameter payload bay.⁵⁹

Currently, the world's largest-diameter launch vehicle shroud is the five-meter one on the Boeing Delta IV rocket.⁶⁰ The European Space Agency's Ariane V, scheduled to carry the JWST into orbit in 2013, has a shroud diameter of 4.57 meters. The 6.5-meter telescope mirror of the JWST will fit into the Ariane V only with innovative packaging, creating collapsible structures on the telescope wherever possible.⁶¹ Instead of a single, monolithic structure, the 6.5-meter-diameter mirror is a series of 18 separate mirrors designed to fold and stack to fit on the Ariane V. Once in space, the segmented mirror unfolds to create one large mirror.⁶²

Segmented mirrors offer potential for much larger apertures but also increase technological risk in deployment, phasing, and control system requirements.⁶³ Active mirror design mitigates some risks associated with segmentation but also adds complexities. Active mirrors use actuators to deform the mirror's shape to account for environmental factors such as gravity and wind.⁶⁴ An emphasis on reducing mirror mass and volume is one path to launch large-diameter mirrors with higher resolutions into GEO. The alternative path is increasing the lift capability of space launch vehicles to carry oversized or larger payloads.

The Ares V, NASA's potential next-generation heavy-lift space launch vehicle, will provide substantially more lift capability than current systems. In comparison to the Delta IV, the Ares V lifts approximately eight times more mass and twice the volume (see table 2.1).⁶⁵

The Ares V system could open new possibilities for the rapid deployment of large-aperture space telescopes. The increased diameter of the payload shroud (10 meters) allows launches of larger monolithic mirrors because of their simple design, reducing technological risk and the associated cost of segmented-mirror-designed apertures.

Table 2.1. Comparison of Delta IV and Ares V space launch capability

Category	Mass (kg)	Cost (\$ millions)
Large satellite	>1,000	100–2,000
Medium satellite	500–1,000	50–100
Minisatellite	100–500	10–50
Microsatellite (microsat)	10–100	2–10
Nanosatellite (nanosat)	1–10	0.2–2
Picosatellite (picosat)	0.1–1	0.02–0.2
Femtosatellite (femtosat)	<0.1	0.0001–.02

NASA's Marshall Space Flight Center recently modeled the successful launch and deployment of an eight-meter monolithic-mirror space telescope into a Sun-Earth L2 orbit, well beyond that needed for GEO.⁶⁶ An eight-meter monolithic mirror staring at Earth from GEO provides a resolution of approximately three meters. The Ares V shroud would allow even larger segmented-mirror designs. NASA is currently exploring 16- to 24-meter segmented-mirror telescope concepts, with the potential of providing 1.6- to 1.1-meter resolution.⁶⁷ Segmented-mirror apertures will continue to outpace the growth of launch vehicle payload shrouds. As this occurs, structureless approaches or designs assembled in space will supplant deployable space mirror concepts.

Structureless Telescopes

Structureless telescopes include all key elements of normal telescopes (primary and secondary mirror, focal plane array) but lack the physical structure holding these components together. Ivan Bekey, a recognized space technologist of Bekey Designs Inc., said this powerful new principle “replaces structures with information” and capitalizes on the fundamental attributes of space in which mass is costly and information and processing are less expensive.⁶⁸ Structureless telescopes replace precision-manufactured structures and complex deployment systems with computer software to control the relative position of key components such as the primary, secondary, and tertiary mirrors along with the bus support structure housing the focal plane and communications antenna. Using advanced software, the central computer can control several separate telescope components, each independently orbiting in space, that act as a single, large system.

A structureless approach has numerous advantages. The modular approach allows economical expansion or replacement of independent components in space. Detached elements allow incorporation of modest technical requirements, avoiding complexities associated with deployable, attached systems. Additionally, because individual components can be launched separately into space, the system is mass insensitive, which may result in decreased cost and risk. For this reason, there is no fundamental limit to the size of a space telescope. The telescope can grow or shrink over time and change with differing payloads, depending on user requirements.⁶⁹

A structureless design also has hurdles to overcome. Most important, the concept is radically “nontraditional” and requires thorough reviewing, testing, and user acceptance. Because of the number of free-flying components, structureless designs will include more bus components, resulting in higher initial overhead costs compared to a single, smaller system like the one based on the Hubble Space Telescope design. Finally, slew rates—the tele-

scope's ability to point at different targets in the field of view, with a large-aperture structureless design—are likely slower than a structured system due to the free-floating nature of the components.⁷⁰ Various designs for structureless systems already exist.

Bekey created a design with a piezoelectric biomorph material serving as the primary mirror. A piezoelectric membrane, capable of changing shapes when an electric field is applied, is a lightweight, thin film that folds up for launch. In May 2000 Sandia Labs announced breakthroughs in its research using piezoelectric materials weighing less than 1 kg/m^2 in large-aperture space mirrors.⁷¹ Once in orbit, lasers continuously scan the surface of the material, taking precise measurements to determine the shape of the antenna. An electron beam then shapes the material, making periodic optical corrections. Bekey's concept includes an additional corrective stage consisting of a liquid crystal modulator to account for minor imperfections remaining from the electron-gun-shaping effort. Published designs include a 25-meter primary mirror affording approximately a one-meter GSD; however, Bekey describes potential for 100- to 300-meter telescopes that would provide resolutions of .25 to .09 meters, respectively.⁷²

Photon sieves, an alternative primary optic using a lightweight, thin film, are a variation of the Fresnel zone plate, which consists of concentric alternating opaque and transparent circular zones maintained on a single plane. Diffracting a chosen wavelength of light around the opaque zones and converging to a focal point where an image is created require sizing of circular zones (see fig. 2.4).⁷³ Fresnel zones are created two ways: (1) printing out opaque circles on a clear substrate (in this case, transmission and thickness properties of the substrate are critical because of the diffractive properties of light),⁷⁴ and (2) physically removing circular rings from an opaque substrate. This removal creates the problem of unsupported rings, which are difficult to maintain in the same plane. Ribs can be added to hold the rings in place; however, this

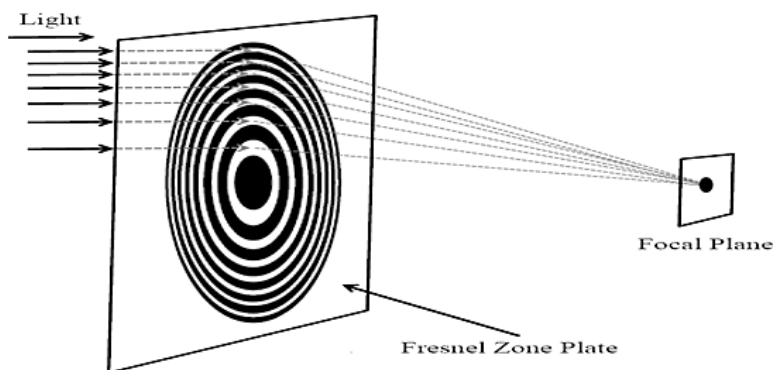


Figure 2.4. Fresnel zone plate

still creates difficulties when trying to pull the optic flat.⁷⁵ A photon sieve overcomes both obstacles.

Many holes are located on the transparent circular zones in a photon sieve. The holes are sized to match their diameter with the thickness of the transparent zone (see fig. 2.5). This maintains the optical characteristics of the original Fresnel zone lens. Also, the holes are not connected; therefore, the substrate retains its structural integrity and can be pulled flat—a critical capability needed for space deployment.⁷⁶ Dr. Geoff Andersen, an Air Force Academy physicist, has researched photon sieves extensively.

In the laboratory, Dr. Andersen has shown the ability to achieve diffraction-limited performance from a .1-meter photon sieve with 10 million holes.⁷⁷ A diffraction-limited observation is limited only by the optical power of the instrument and unaffected by factors such as lens material impurities or atmospheric turbulence.⁷⁸ The .1-meter photon sieve is just the beginning of the academy's research.

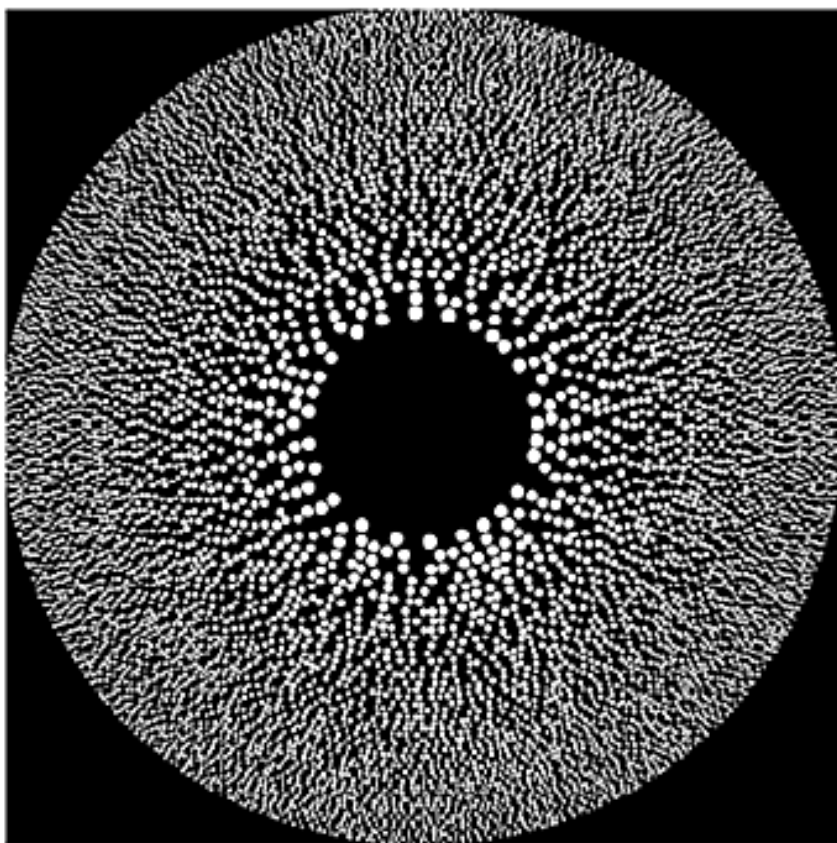


Figure 2.5. Photon sieve developed by Dr. Geoff Andersen. (Reprinted from Geoff Andersen and Drew Tullson, "Photon Sieve Telescope" [Colorado Springs, CO: US Air Force Academy, Department of Physics, 2008].)

“Our next step is to construct and test a larger-diameter photon sieve in the laboratory,” said Dr. Andersen, who is also testing an experimental payload in space on board FalconSat VI.⁷⁹ He adds that electron lithography makes precise hole construction in the membrane relatively easy. He envisions photon sieves in the future approaching up to 100 meters in diameter for use in space telescopes.⁸⁰ Regardless of the type of primary optic, keeping relative positions of structureless satellite components in space is critical and accomplished in a variety of ways.

Bekey proposed a tethered design to reduce the need for propulsion for the various independent structureless components. The design would have small anchor masses five to 50 kilometers apart, straddling a GEO that holds the figure sensor, focal plane assembly, and electron beam generator in line (see fig. 2.6).⁸¹

The calculated total weight of both the tethered and untethered 25-meter piezoelectric material design is 260 kg, while a 100-meter design has an estimated weight of 1,800 kg. By comparison, the JWST design, when extrapolated to 100 meters, would weigh more than 200,000 kg.⁸² Smaller-aperture mirrors incorporated using interferometry allow even larger telescopes.

Interferometry uses a cluster of smaller apertures to simulate a larger one. Because portions of the primary aperture are in effect “empty,” the reduction of mass occurs without a significant sacrifice in resolution. Bekey estimates that a 250-meter sparse-aperture design using a piezoelectric membrane covering only 10 percent of the area of a filled aperture would weigh 1,600 kg. He thoroughly validated the sparse design of Microcosm, Inc.⁸³

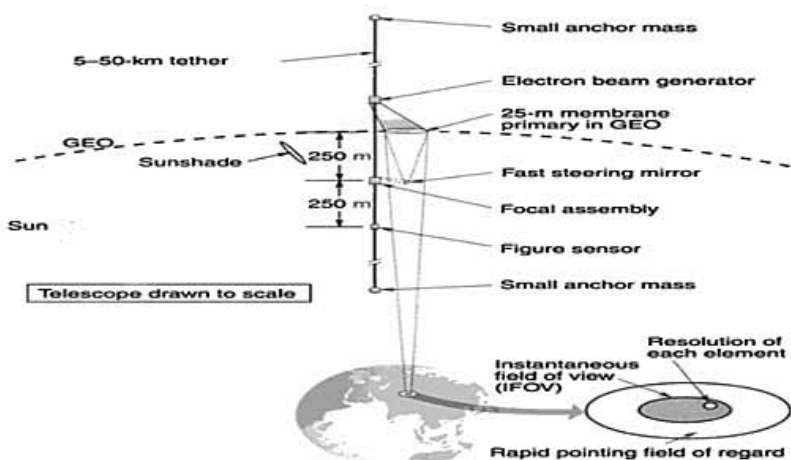


Figure 2.6. Ivan Bekey’s concept for a tethered long-dwell imager. (Reprinted from Ivan Bekey, *Advance Space System Concepts and Technologies: 2010–2030+* [El Segundo, CA: Aerospace Press, 2003], 28–29.)

In 2004 Microcosm presented a structureless space telescope design to the Universities Space Research Association as part of a NASA Institute of Advanced Concepts contract. Microcosm specializes in reducing space mission costs and has worked with the Air Force for various projects.⁸⁴ Instead of a piezoelectric membrane or photon sieve, Microcosm's approach reduced risk by using conventional lightweight-mirror technology. The concept included 88 two-meter mirrors free-floating beside each other in hexagonal patterns with the center of each mirror three meters apart (see fig. 2.7). A series of control lasers surrounds the mirror array, providing near-continuous "light pressure" on control tabs connected to each mirror segment, thus ensuring proper alignment and altitude.⁸⁵

The smaller mirror segments connect to produce the equivalent of a 30-meter-diameter primary mirror. Microcosm estimates that its design provides simultaneous one-meter resolution video (30 frames per second [fps]) of approximately 10 20 km x 20 km areas in the satellite footprint, depending on the number and size of secondary and tertiary mirrors.⁸⁶

According to Dr. Richard Van Allen, Microcosm project manager, the limiting factor for resolution is not the size of the primary mirror but the size of secondary mirrors. "Monolithic mirror sizes needed for secondary and tertiary mirrors must fit in current launch vehicle shrouds," said Dr. Van Allen. Although current technology limits resolution, large-segmented mirrors and increased launch-shroud diameters (as with Ares V) should allow Microcosm's design to achieve better resolutions in the future.⁸⁷ Dr. Van Allen acknowledges this but also notes that deployable

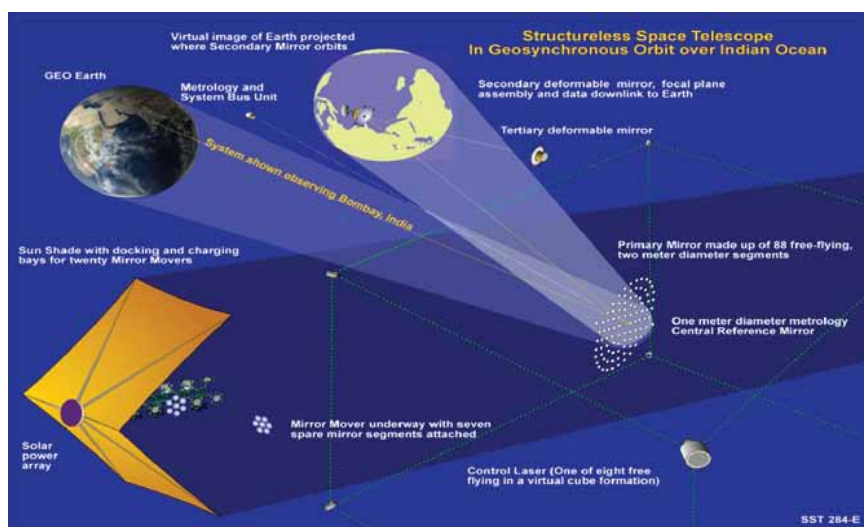


Figure 2.7. Microcosm Inc.'s structureless space telescope concept. (Reprinted from Microcosm Inc., "Structureless Space Telescope [SST]: Low Cost, Low Risk, Unblinking Vigilance from Space" [Hawthorne, CA: Microcosm, November 2008].)

mechanisms mean increased risk, something Microcosm is working to mitigate as it prepares its design for launch within the next decade. “Our system has no deployable optics or optical bench, giving us very good reason to believe it will function as planned at low cost. If funded, we could have a system operating in GEO in 2018,” Dr. Van Allen said.⁸⁸ In addition to the scalability, Microcosm also highlights the flexibility and modularity of its design.

“As technology improves, our telescope will also improve, allowing the system to grow over time,” Dr. Van Allen notes. He further adds, “Focal plane arrays, onboard computers, or laser controllers can be swapped to provide additional coverage, see into a new spectral region, or improve onboard processing or primary mirror responsiveness.”⁸⁹ In a similar manner, this flexibility makes the system fault-tolerant. Operators can replace damaged components in space without having to write off the entire system as a loss. An alternative to launching components that form either traditional or structureless designs is to build systems, once in orbit.

Other Approaches

Constructing a near-flawless membrane in orbit removes the need for adaptive material and electronics associated with a piezoelectric membrane, Bekey said. Taking advantage of the near-zero-gravity environment in space provides the ability to create almost perfect spheres with extremely smooth surfaces. One method inflates a large, balloon-like film and attaches a separate inflated torus. The torus is then cut away, exposing the concave side of the spherical membrane. The result is an aluminized or coated reflective material, which creates a near-spherical reflector of arbitrary size.⁹⁰

An alternative process, which precisely shapes rings to form a thin membrane, consists of stretching molten glass and adding pressure while using an expanded iris. Researchers at the University of Alabama–Huntsville Center for Applied Optics demonstrated the feasibility of this process using a small test bed. The researchers believe it holds promise for the manufacture of large, high-quality spherical mirrors in space.⁹¹ In addition to mirror fabrication, engineers have researched construction of entire optical structures in space.

Massachusetts Institute of Technology (MIT) researchers investigated the feasibility of two concepts for on-orbit assembly of a 30-meter-diameter segmented mirror. Both methods use space tugs to transport hexagonal-shaped mirrors from a vertical stack into position on the primary mirror assembly. The difference between the methods is in how the tugs exert the force and torque to move the mirror segments. The first method uses propellant, and the second uses an electromagnetic base. Both were effective at assembly. The advantage of the propellant-based tug was that it

assembled the mirror two to three-and-a-half times quicker than the electromagnetic tug. This, however, requires increased mass for propellant; if the process requires reconfiguration, the electromagnetic tug is more desirable.⁹²

Mirrors are the key technology needed for high-resolution FMV from space. The laws of physics dictate that the greater the distance from an object, the larger the diameter of the mirror required for maintaining the same resolution. Another important technology for useful FMV from space is data processing. This technology presents its own challenges; however, in general, it is more forgiving with continued gains in computer processing following Moore's law (computers of the future will be more powerful and quickly become less expensive as newer, more powerful computers are built).

FMV Processing

As a rule, FMV takes up more digital storage space and requires more computer processing than traditional satellite imagery. The increased storage and processing requirements are a direct result of the method and rate at which images are collected.

Current commercial imaging satellites in LEO use a push-broom imaging process (see fig. 2.8). In this process, a linear array of sensors collects a one-dimensional image (essentially a line), and the sensor moves across its target. As the satellite moves in a direction perpendicular to the linear array, it produces a series of one-dimensional images. After a given time, the one-dimensional line images are pieced together using a time-difference-of-arrival technique, resulting in a two-dimensional image.⁹³ It typically takes less than a minute to construct one image using the push-broom imaging process. The time delay to construct the image, coupled with the required forward motion of the sensor, makes linear arrays impractical for FMV imaging satellites.

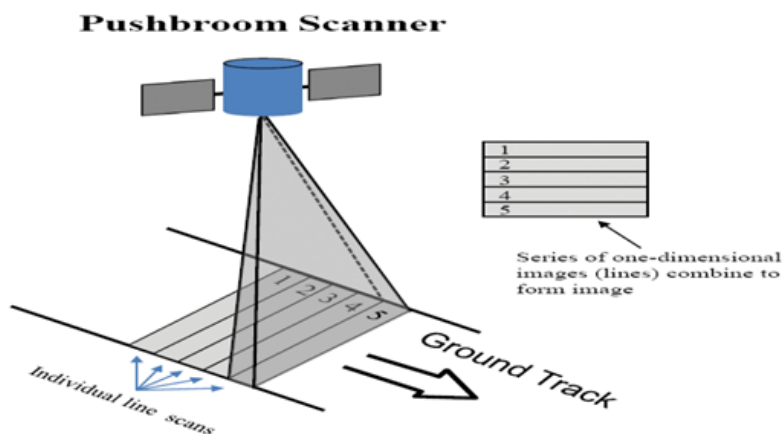


Figure 2.8. Push-broom imaging process

The best option for the focal-plane sensing array on an FMV satellite is a two-dimensional array using a complementary metal oxide semiconductor (CMOS) integrated circuit design. The alternative to a CMOS array is a charged coupled device (CCD), a more mature technology that has provided better image quality in the past. Technology advancements in the last 10 years put CMOS sensors on par with CCD image quality.⁹⁴ With comparable imagery quality, there are other important reasons to use a CMOS array. Unlike CCD, CMOS circuits are not sensitive to the high radiation environment encountered in space.⁹⁵ In addition, CMOS-based sensor designs offer miniaturization with reduced power and cost versus the CCD.⁹⁶ Speed is possibly the biggest reason to use a CMOS sensor instead of a CCD. CCDs use serial ports while CMOSs use parallel ports. A CMOS sensor can image at very high speeds, an important capability for an FMV sensor.⁹⁷

Unlike push-broom linear arrays, two-dimensional sensors capture an entire image during one dwell period (usually measured in milliseconds). This is how digital cameras capture images, and these sensors are found in digital cameras, cell phones, and other image and video capture devices. Scientists have incorporated two-dimensional arrays on satellites. The Hubble Space Telescope and Cassini Spacecraft (designed to explore Saturn) both incorporated two-dimensional arrays in their imaging subsystems.⁹⁸ Notably, both Hubble and Cassini Spacecraft designs incorporate CCD technology instead of CMOS. Both were designed before recent advances in CMOS technology; for their applications, slower CCD imaging speeds are more than satisfactory.

The number of pixels in a two-dimensional sensor array varies, and more pixels equates to more data. High-end cell phones like the T-Mobile G1 and Apple iPhone 3G have 2 million and 3.2 million pixels, respectively, which are normally described in terms of megapixels. Airborne surveillance platforms use sensor arrays approaching 100 megapixels. The Hubble Space Telescope and Cassini Spacecraft both use 1024 x 1024 pixel arrays.⁹⁹ The one-megapixel design on multimillion-dollar spacecraft is smaller than the one on most digital cameras and many cell phones. Microcosm's structureless design calls for a focal plane array sensor of 400 megapixels, which is 400 times larger than the arrays in use on Hubble and Cassini. The number of pixels on a two-dimensional array is an important factor affecting the amount of data generated. Another key factor is the frame rate of the sensor.

Video is simply a number of still images taken per unit of time. The higher the frame rate, the more data required to process, store, and transmit. The Advanced Television System Committee (ATSC) standard frame rate ranges between 24 and 60 fps for television in the United States.¹⁰⁰ A generally accepted frame rate for video applications is 30 fps, the historical analog standard for US television.¹⁰¹

The type of event under surveillance should determine the frame rate. Staring at a fast event, like a satellite in LEO or an Air Force exercise involving high-speed aircraft, will likely require a higher frame rate than tracking relatively slow insurgents on foot in an urban environment. A November 2008 joint Defense Science Board/Intelligence Science Board report on sensor integration cautions against oversampling with FMV surveillance sensors. The report recommends limiting the frame rate to “1.5 to 2 times the maximum frequency defining the event.”¹⁰² Using this method, Angel Fire engineers achieved sufficient temporal resolution at rates much less than 30 fps for current counterinsurgency operations in Iraq.

Angel Fire currently scans at a rate of one fps. The sensor uses a 66-megapixel array allocating eight bits per pixel, which equates to about 66 megabytes of data generated every second on board the aircraft. Joint Photographic Experts Group image compression techniques, using a 6:1 ratio, compresses the data to about 10 megabytes.¹⁰³ By comparison, the current Microcosm design for its structureless telescope calls for a frame rate of 30 fps using a 400-megapixel array with eight bits per pixel. This creates 12 gigabytes of data per second before compression. Use of an identical compression ratio as Angel Fire can reduce the frame rate to two gigabytes of data per second.¹⁰⁴ This data rate is 200 times the data Angel Fire currently processes per second.

Angel Fire engineers encountered a similar dilemma when they used a frame rate of 30 fps. Through consultation with the Marine Corps, the engineers determined that by reducing the data rate to 1 fps, the possibility exists to maintain the utility. Microcosm could benefit from the same reduction in frame rate. If sampled at 1 fps, Microcosm could reduce the raw image file to 400 megabytes per second. With compression, it could further reduce the file size to 67 megabytes per second. Microcosm is currently pursuing the capability to handle the data requirement generated with 30 fps.

Space Micro Inc., a company specializing in space microelectronics, sensors, and computers, is working on the onboard data processing for Microcosm’s structureless space telescope. Space Micro has experience in high-performance space computers, working for several companies and government entities such as NASA, the Missile Defense Agency, and AFRL.¹⁰⁵ Space Micro engineers have already demonstrated the ability to process four gigabytes of data per second by compressing data using a 15:1 ratio, resulting in an output of 266 megabytes per second.¹⁰⁶ Microcosm’s design could handle 10 fps by using today’s technology, potentially a high enough sample rate to observe high-speed events with sufficient frequency to capture almost any activity of interest.

The amount of FMV data collected by sensors for processing will likely increase in the future. This increase is the result of larger two-dimensional pixel arrays and requirements for imagery in different spectral regions. Improvements in image compression will

partially offset this increase, and Angel Fire engineers are already benefiting. The engineers plan to incorporate an improved compression algorithm that nearly triples the amount of compressed data. The algorithm, with a 15:1 ratio, is the same type of algorithm that Space Micro is incorporating for Microcosm's design. This allows the engineers to increase the size of Angel Fire's pixel array from 66 to 96 megapixels. It also allows the engineers to increase the number of bits per pixel to 12 while maintaining approximately the same amount of output data per second.

Experimental sensing techniques show promise for significantly reducing the amount of data a sensor needs to collect to achieve high-resolution images. Researchers at Rice University have demonstrated a compressive sensing technique that produces an image equivalent to five megapixels compressed to 50,000 pixels.¹⁰⁷ This equates to a 100:1 compression ratio. With these improved compression ratios and sensing techniques, faster computer processors will likely be the biggest factor driving manageable rates of data output. This will be critical to meet projected finite, high-demand satellite communications bandwidth.

Satellite Communications

High bandwidth required of an FMV satellite will be met by an anticipated extensive deployment of laser-based communications architecture. Laser-based communication in space is currently in limited use.

In November 2001 the European Space Agency's ARTEMIS satellite effectively relayed data at 50 megabits per second using a laser data link between a SPOT 4 imagery satellite and its mission ground station located in Toulouse, France. The ARTEMIS relay was operating at 31,000 km altitude while the SPOT 4 imager operated at 832 km altitude.¹⁰⁸ The ability to communicate via laser between two satellites that are moving extremely fast in relative motion to one another overcomes a key technical challenge for using laser communications between satellites.¹⁰⁹ The United States also demonstrated laser communications in 2001 when the National Reconnaissance Office's (NRO) GeoLITE experimental spacecraft exchanged data with another US government spacecraft through laser cross-links.¹¹⁰ The GeoLITE demonstration was a precursor to the Air Force's transformational satellite (TSAT) project.

The TSAT project was originally going to consist of five geosynchronous communications satellites using laser links to communicate with one another, airborne systems, and forces on the ground. According to the Air Force program office, the purpose of the TSAT design is to "enable real-time and persistent worldwide connectivity to ISR assets thereby providing increased situational awareness and targeting information to the warfighter."¹¹¹ Originally slated for 36.3 gigabits per second, the TSAT total bandwidth optimization

occurred through existing Internet protocols use. The program was cancelled in April 2009.

John Young, the undersecretary of defense for acquisition, technology, and logistics, directed the Air Force to restructure the TSAT program in December 2008. He called on the service to plan for TSAT initial operating capability in 2019 without the laser cross-links.¹¹² Although laser cross-links will not be on the first phase of the TSAT spacecraft, Air Force Space and Missile System Center program managers believe the system's second deployment phase will include them.¹¹³ With or without the laser cross-links, communications satellites probably will have significantly increased capability by 2035. As a rule, communications satellite bandwidth trends show orders-of-magnitude increases approximately every 10 years (see fig. 2.9).

Although engineers project communications bandwidth to increase substantially in the future, demand will likely outpace availability.¹¹⁴ A FMV constellation in LEO requires TSAT-like communications architecture. However, the FMV geosynchronous option may not require any relay capability.

Geosynchronous FMV imaging satellites could communicate data directly to any ground station in their footprint. Three geosynchronous satellites could cover most of Earth (sans the north and

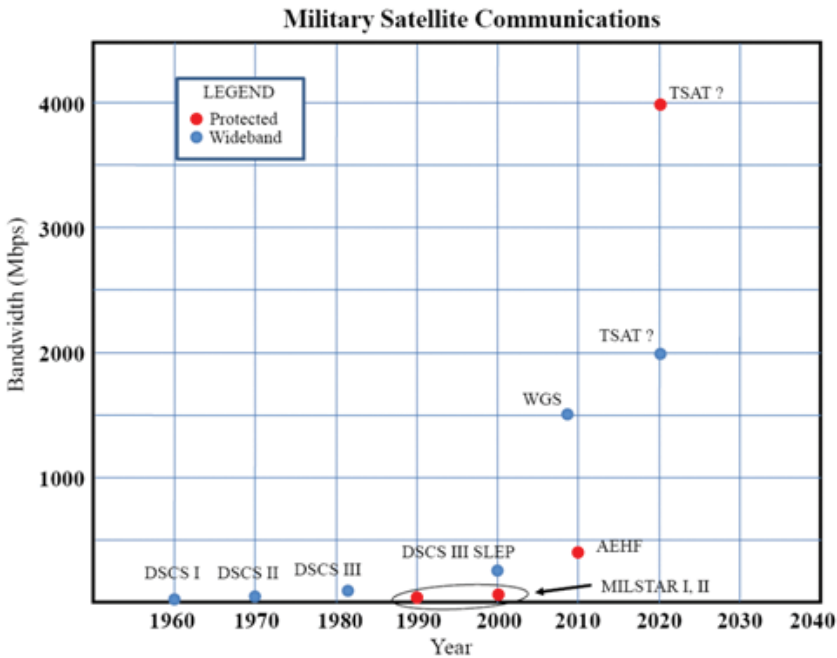


Figure 2.9. Military satellite communications bandwidth trends. (Reprinted from Brig Gen Ellen Pawlikowski, "MILSATCOM Briefing to the National Defense Industrial Association" [Los Angeles Air Force Base, CA: Space and Missile Systems Center, 17 April 2007].)

south polar regions above 85 degrees latitude). Three separate ground stations dispersed on Earth are required, each operating in their respective satellite's footprint. Assuming the imaging satellite communicates with the ground station via laser, it is possible to transfer gigabits of data per second to the ground station bypassing any relay satellite.¹¹⁵ Once the ground station receives the data, a terrestrial fiber backbone could move it to nearly any analyst or customer who requires it.

An advantage of FMV is the usefulness of the data to untrained imagery exploiters. Initial exploitation is possible by almost anyone watching the video feed. However, there is much to learn from FMV by trained imagery analysts. The tools to help analysts exploit FMV are the focus of the next section.

FMV Exploitation

Exploitation capabilities often take a secondary role to sensor and platform development. The lead paragraph in the executive summary of the Defense Science Board's November 2008 study titled "Integrating Sensor-Collected Intelligence" describes how the rapid proliferation of sensors has overwhelmed the ISR architecture. The report specifically mentions huge backlogs of imagery that analysts will never review.¹¹⁶ This backlog of data calls into question the ISR community's approach to exploitation. Current FMV exploitation methods warrant investigation.

The Air Force exploitation of FMV has changed very little in the last decade. Operation Allied Force was the first major operation in which the Air Force used and exploited FMV data from the Predator RPA. For exploitation, six imagery analysts and one imagery mission supervisor exploit one Predator RPA FMV feed. One of the six analysts is assigned a 10-minute window and is responsible for FMV exploitation. As events happen in near real time, the imagery analyst types a description of observed activity into various shared and monitored chat rooms around the world. Once the 10-minute window is over, a different analyst is delegated near-real-time exploitation duties. Meanwhile, the analyst who just finished this responsibility reviews the previously recorded 10 minutes via a media device. If activity warrants formal reporting, the analyst and supervisor write, review, validate, and enter an imagery report into the national intelligence database. The analyst then waits for his or her next near-real-time reporting window.¹¹⁷

After 10 years, the process is essentially unchanged. In the past, engineers recorded data to videocassette; currently, FMV exploitation teams use digital video recorders. In addition, imagery analysts anticipate incorporating speech recognition software, which will automatically translate their verbal cues into text for chat rooms.¹¹⁸ The large area collection of Angel Fire creates additional issues for the Marine Corps.

Angel Fire's 4 km x 4 km image views data every second and uses one sensor to meet the needs of multiple users. Although effective for multiple users, exploitation is not efficient. Each user exploits his or her designated area of interest, providing situational awareness to relevant parties; however, analysts do not review the majority of data in temporal or spatial dimensions.¹¹⁹ Reviewing the unchecked data may have helped save lives in some instances. For example, in order to provide warning of impending harm (like an insurgent planting an improvised explosive device), the analyst must exploit the right area at the right time and report results in a timely manner. Failure in any one of these areas could prove fatal.

Forensics review of the data is useful to track and capture insurgents after an event, but the goal must be to prevent the attack instead of mitigate consequences in an attack's aftermath. The Marine Corps does not have the necessary number of analysts to provide comprehensive exploitation of the entire collection. With the projected explosion of wide-area collectors, the intelligence community's ISR exploitation capability will continue to fall behind without changes. Without tangible solutions, automated exploitation and long-term research remain the best option.

Automated imagery exploitation has been an unfulfilled promise for several years. Engineers have shown exceptional success in the laboratory using controlled, synthetic data. However, the results are poor when researchers run complex, real-world data in the algorithms.¹²⁰ Most automated target-recognition technology is associated with primarily synthetic aperture radar and imagery. Although purely automated systems have not met expectations in an operational environment, technology aimed at assisting, rather than replacing, the imagery analyst has demonstrated success.

Automatic change detection is an example of a software algorithm that aids an imagery analyst. A National Geospatial Intelligence Agency imagery analyst can choose to have a computer application screen all images pending exploitation of targets in their account. An account is a target set, such as North Korean ballistic missiles, that the imagery analyst is assigned to for an extended period in order to develop expertise. The software screens the image queue, pending exploitation with previously exploited imagery. The software program flags images reflecting significant change to previously exploited images for the analyst. In this manner, the analyst makes effective use of time by focusing initial effort on targets that may have more intelligence value based on computer-predicted target activity.¹²¹ Researchers at MIT are applying change detection to FMV.

MIT's approach takes individual frames of two videos in order to achieve initial spatial registration, after which the software outputs a new video stream where differences in pixels differentiate and manipulate the two streams.¹²² Researchers highlight the ability of the algorithm to handle large-scale differences between images;

however, videos must follow spatially similar trajectories.¹²³ This technique might not work using airborne FMV but appears compatible with FMV from a geosynchronous satellite where the spatial trajectory is essentially static with respect to surveilled objects. DARPA is leading a different FMV exploitation effort that assists analysts in tracking targets.

The goal of the video verification of identity (VIVID) program is to track multiple targets—stationary and moving. The sensor’s capability is the limiting factor for tracking and determining targets. After receiving input from an analyst about a target of interest, VIVID takes over and rapidly slews from target to target, collecting a few frames on each observation.¹²⁴ VIVID’s key objective is to maintain track on targets in dense environments with multiple “confusers” or occlusions. For example, VIVID intends to track individual vehicles in dense traffic in an urban environment where multiple buildings occlude the target vehicle.¹²⁵ The VIVID program is currently conducting technology and system demonstrations.

By the time a space-based platform produces FMV, imagery analysts should be able to capitalize on existing exploitation technology developed in support of a multitude of fielded airborne FMV sensors. Exploitation tools, at least in the near term, will continue to emphasize reducing analyst workload; however, these tools will not completely replace the human element. In the future, analysts will likely be able to select the degree of automated exploitation to assist them.¹²⁶ Despite the fact that current FMV exploitation completely depends on human elements, the anticipated increase in volume of FMV will force a change in the way the ISR community approaches this problem.

Analysis

At the current pace of technological development, the United States will be capable of fielding a medium-to-high-resolution, FMV-capable space architecture in the 2020–35 timeframe. Unlike the Global Positioning System (GPS), a space-based FMV system will not be omnipresent, as General Smith predicted.¹²⁷ However, a space-based system will provide FMV of nearly any location on Earth in a matter of minutes. This is technologically possible from either LEO or GEO—the latter is the better choice.

What Is the Optimum Orbit?

GEO allows a less complex, more cost-effective option for space-based FMV. A LEO space-based FMV architecture could require 2,379 satellites to maintain persistent access to any location on the surface of Earth.¹²⁸ Such a constellation would require a communications relay architecture with staggering, and possibly unattainable, bandwidth requirements based on projected future com-

munications capabilities in that timeframe. In addition, the cost of multiple satellites far surpasses the cost of a similar capability in GEO. Using current cost estimates, the price for one Pumpkin Inc. MISC CubeSat imaging satellite is \$294,000.¹²⁹ Thus, it would cost approximately \$700 million for the satellite architecture required. This number is deceptively low because of the simple, less capable nature of the MISC satellite. The actual number would likely be much higher after factoring in increased functionality of the satellite (spatial and temporal resolution), coupled with its associated communications architecture. The recently launched, state-of-the-art LEO imager GeoEye-1 cost \$502 million.¹³⁰ Using this as the baseline for LEO architecture puts the total cost of an FMV constellation at approximately \$1.2 trillion, without the additional cost of a complex space-based communications architecture. In comparison, Microcosm Inc. estimates that it could field its structureless telescope to geosynchronous for \$2.7 billion, factoring in two launch failures. NASA estimates the JWST will cost approximately \$4.5 billion by the 2013 launch date.¹³¹ GEO requires three satellites to provide the same coverage as the 2,379-satellite LEO constellation, with an approximate cost of about \$10 to \$15 billion. Assuming that GEO is ideal for an FMV satellite, a segmented mirror or monolithic mirror design—the latter of which users must launch with a new-generation space launch vehicle—is capable of field placement around 2020.

A segmented mirror design, capitalizing on JWST technology, is a viable option for an FMV imager. The telescope would incorporate a 6.5-meter segmented mirror capable of four-meter resolution from GEO. Users could mitigate risk associated with this concept by using lessons learned from JWST's design and operation. A comparable monolithic mirror reduces risk considerably but requires substantially more lift to achieve orbit because of mass and payload diameter considerations. If NASA's new heavy-lift space launch vehicle, the Ares V, proceeds on schedule with its first test launch in 2018, an eight-monolithic option will provide more resolution (three-meter GSD) carrying less risk than a design modeled after the JWST. Neither of these options will approach the .5-meter resolution needed to track individuals. Resolution of .5 meters requires a structureless approach.

The technology for a structureless design will mature well before 2035; however, US government authorities will likely opt for more traditional, proven approaches. Microcosm estimates that it can begin operation of a one-meter resolution structureless telescope in nine years.¹³² This is unlikely to occur for two reasons. First, recent acquisition problems with the Air Force's TSAT and the NRO's Future Imagery Architecture programs have created a risk-averse approach to nearly all space-related programs. Second, the current state of the US economy means there could be less money for research, development, and deployment of nontraditional, un-

proven technology. These pressures and the perceived high risk of a structureless system will likely overshadow advantages a structureless design provides.

By 2035 structureless demonstrations in LEO and GEO will be successful enough to deploy a system. An advantage of the structureless design is its ability to expand and incorporate new technology. Designs for 2035 should be of sufficient size to achieve .5-meter resolution. Once fielded, high-resolution, space-based FMV gives unprecedented advantages over airborne FMV sensors.

Advantages of Space-Based FMV over Airborne FMV

The advantages of space-based FMV versus aerial FMV sensors are relatively typical when relating advantages of satellites over their airborne counterparts. First, space-based systems usually overcome the tyranny of distance by allowing access to areas otherwise denied to aerial sensors. As with current imaging satellites, an FMV system could routinely observe activity deep within a country's border and is not limited to activity on Earth's surface. Space-based FMV will also observe activity in air and space. Subsequent sections in this research address groundbreaking implications of observing activity via the space-based FMV.

Related to access, a geosynchronous space-based FMV sensor could image anywhere activity is happening within its field of view in minutes or even seconds. The same holds true for airborne FMV sensors. The difference is that the field of view for a space-based sensor is approximately one-third of the planet. Current wide field-of-view airborne sensors may be capable of constant dwell over one-third of a large city.

Another advantage of space-based FMV is that it is continuous. Current aerial systems have reduced on-station duration because of fuel and crew limitations. Mission durations for remotely piloted aerial sensors continue to climb, and near-space airships will have long durations regarding rival space-based sensors; however, airships will be the exception. Most terrestrial-based FMV sensors will have limited duration. In contrast, a space-based sensor will retain its utility long after aerial systems return to base or redeploy upon completion of an operation.

Disadvantages of Space-Based FMV Compared to Airborne FMV

The disadvantages of space-based sensors when compared to their airborne equivalents are cost and complexity. The cost of one advanced space telescope ranges from \$2.5 to \$4.5 billion. A Reaper RPA consisting of four airframes with sensors costs \$69 million.¹³³ Adding extensively to the cost of satellites is their complexity.

The satellite components' unique nature and the harsh space environment in which they operate drive a more complex design of

each independent subsystem. In addition, once launched it is highly unlikely that there will be an opportunity to fix the spacecraft once in orbit (the Hubble Space Telescope being the exception). This forces greater redundancy of critical satellite components and a more rigorous and time-consuming system integration and testing process. Lastly, due to the scarcity of space assets, users try to exhaust satellite capability by levying too many requirements on a system. This is likely what Gen James Cartwright, vice-chairman of the Joint Chiefs of Staff, was referring to when he questioned the risk associated with fielding laser cross-link technologies on the first TSAT spacecraft, something for which the Air Force was pushing.¹³⁴

Mission Areas Where Space-Based FMV Is a “Game Changer”

FMV from space will provide the United States unprecedented insight and information pertaining to difficult problem sets that are, in many cases, unattainable by any other source. The ability to track mobile targets, provide unambiguous warning, enhance SSA, and network an individual’s behavior patterns in otherwise denied areas are all problems that FMV from space may help solve.

Tracking Mobile Targets. FMV from space allows monitoring of any type of surface-based mobile target. Using exploitation technology developed through DARPA’s VIVID program, an analyst can tag a moving target, and VIVID will independently track its movement. The implications are significant, especially with target sets of theater ballistic missiles and mobile surface-to-air missile systems. Knowing the location of these threats at all times eliminates the adversary’s perceived survivability advantage of having a mobile weapon system. In the case of mobile surface-to-air missiles, the growing lethality of these threats makes engaging them on the move all the more desirable. FMV from space makes it possible to track moving targets.

Providing Improved Warning. The US intelligence community has failed, at times, to provide adequate warning of events with potentially catastrophic consequences. The Korean War, China’s entry into the Korean War, the Iraqi invasion of Kuwait, and the 1998 Indian nuclear test are all examples of the intelligence community’s failure to provide ample warning.¹³⁵ FMV has the potential to eliminate much of the ambiguity surrounding these types of events. Ultimately, deciding whether or not to issue a warning is an analyst’s call. For an analyst, in the absence of signals or human intelligence, an imagery snapshot conjures up multiple opinions with regard to intent—a picture is worth a thousand words. FMV alone cannot eliminate the margin of error in an analyst’s assessment; however, it does provide important spatial fidelity to help reduce uncertainty.

Enhancing Space Situational Awareness. SSA refers to the understanding of what objects are in space and what capabilities those objects have.¹³⁶ SSA is increasingly important in the wake of China's January 2007 ASAT test that destroyed a weather satellite in LEO. Microcosm Inc. markets its 30-meter telescope as capable of tracking objects as small as one meter in LEO as the objects traverse against Earth or space background.¹³⁷

Ground-based telescopes operating as part of the Air Force's SSN already provide good resolution on objects in LEO.¹³⁸ SSA is most difficult for objects in GEO; however, placing a large telescope in GEO would assist the United States in obtaining SSA. An enclosed telescope, able to slew its mirror and focal plane in unison, is better suited for this type of surveillance mission than a structureless telescope whose mirror remains in a relatively static orientation toward Earth for this type of surveillance mission. Three FMV imagers evenly separated in GEO would provide high-resolution FMV of geosynchronous satellite deployment or space activity in their field of view.

Networking Human Activity. The insatiable demand for persistent FMV in the ongoing operations in Iraq and Afghanistan is due, in large part, to the ability of current sensors to track hostile individuals operating in the battlespace and threatening the United States and coalition forces. The hunt for Abu Musab al-Zarqawi, the Jordanian-born terrorist who operated in Iraq, demonstrates the value of FMV tracking of human activity and networks. US forces spent weeks tracking and monitoring the movements of Sheik Abd al-Rahman, Zarqawi's spiritual advisor, often using FMV sensors. After some time, intelligence analysts were able to predict when Rahman would meet Zarqawi. These and other crucial sources of intelligence led to Zarqawi's death when coalition Airmen bombed the house where he was hiding.¹³⁹

Space-based FMV will provide fidelity into human networks not acquired via other sources. For instance, if a 50-meter structureless telescope were operating today from GEO over Asia, the United States would have close to an unblinking eye on significant portions of the Federally Administered Tribal Areas of Pakistan, where the US intelligence community believes key members of al-Qaeda are hiding. Over time, analysts would develop a very accurate spatial depiction of human patterns of behavior. This spatial depiction, in conjunction with other intelligence, could aid in identifying suspicious individuals and targets and thus in directing a strike or raid. Alternatively, spatial depiction could even serve as a recruitment tool.

Possible Counters to Space-Based FMV

As with any tactic, adversaries will adopt countertactics to negate or mitigate a US advantage. China recognizes the importance of countering the US surveillance and reconnaissance capability.

China's deputy chief of staff of the Jinan Military Region's 54th Group Army stressed that failure to evade enemy sensors spells doom on today's battlefield since "detection means destruction."¹⁴⁰ Many adversaries regularly practice passive countertactics today and, in all likelihood, have plans for using active countertactics against US space systems when needed. Wide field-of-view space-based FMV in 2035 will give adversaries little sanctuary from observation. To counter the increase in spatial frequency and areas that the United States will collect, adversaries will have to increase the frequency and areas where they practice countermeasures.

Controlling the weather is a tactic that could counter the FMV sensors. For example, in a hypothetical 2035 scenario, China is preparing for a large-scale exercise in which it intends to test several new weapon systems. It doesn't want the United States to observe events on the ground or in the air. To conceal the activity, China saturates the upper atmosphere with silver iodide crystals, forming a layer of cirrus clouds that effectively prevents, or significantly reduces, observation from space. This scenario is not far-fetched. China leads the world in its efforts to control the weather. Bill Woodley, a scientist who ran several cloud-seeding experiments for the National Oceanic and Atmospheric Administration, calls China the "epicenter of all weather modification activity."¹⁴¹ "They're training young scientists and pilots; they've just gone crazy over there," adds Woodley. He notes that Beijing employs 32,000 people nationwide in its Weather Modification Office and invests \$100 million annually in the program.¹⁴²

An alternative to using clouds for concealment is to operate underground. Many adversaries have already moved many of their most sensitive military programs underground. A joint 2001 DOD and Department of Energy report to Congress assessed that more than 10,000 underground targets exist worldwide with more than 1,400 known to shelter or suspected of sheltering weapons of mass destruction, ballistic missiles, or command facilities.¹⁴³ In the future, less sensitive activities will likely take place underground as the proliferation and improvements of high-tech tunneling equipment will make this feasible. Many companies around the world are competing to improve tunneling machines.¹⁴⁴ In the early 1970s, boring machines could tunnel approximately 180 meters per month in hard rock. Today, 120 boring machines are in operation around the world, and many regularly tunnel more than 1,200 meters per month.¹⁴⁵ Altering the weather and large-scale tunneling are likely to remain within the domain of states with significant resources. Insurgents with fewer resources have other means to counter space-based FMV.

Similar to how the DOD teaches US service members to counter potential terrorist-surveillance activity, insurgents could complicate US spatial-networking analysis by randomizing their normal patterns of behavior. Varying the time and location of meetings and

activities obscures an analyst's ability to predict an individual's behavior. Unlike maneuver warfare where mobile targets such as missiles, trucks, and tanks are relatively easy to track, mobile insurgents operating in an occluded urban environment are difficult to track. Instead of entering into a game of hide-and-seek with the United States, adversaries may choose to engage in active counter-measures using asymmetric means.

The cyberdomain offers multiple opportunities to degrade the United States' ability to collect space-based FMV. Adversaries could attempt to insert a virus into the satellite's command and control network or jam either the satellite's antenna receiver or the ground station terminal. Employing a high-powered microwave or high-powered laser against the satellite may be a more blatant adversary approach. Due to satellites' distance from Earth, efforts to target them in GEO cause complications with energy weapons, resulting in loss of Earth-based system coherence. High-powered lasers and microwaves originating from satellites would be more successful against geosynchronous targets.¹⁴⁶ While these approaches focus directly on the space-based system, attacking telecommunications networks that indirectly support the space system's operation could have a detrimental effect on satellite operations and information dissemination. Cyberattacks provide varying opportunities which, coupled with the associated plausible deniability, make this an attractive option to counter satellite FMV capabilities.

Who Is in Control?

Using a combination of stationary, airborne, near-space, and satellite sensors, FMV could be ubiquitous over a localized area of operations by 2035. In this case, the primary users will likely be the military, operating with air superiority gained by military force or host government acquiescence. US military services probably will not argue over operation of the system because the primary users have established a precedent where the NRO flies the nation's reconnaissance satellites. In addition, control over collection tasking will likely be a nonissue among functional components as persistent FMV data will be everywhere in the area of operations. This is similar to how Angel Fire operates in Iraq today, albeit with a much larger footprint. Ubiquitous FMV on a global scale, however, will not be feasible. As a result, demand for space-based FMV will exceed availability of the asset.

Control over the tasking of space-based FMV will likely manifest itself in competition among various government departments and agencies rather than the DOD services. For example, the Department of the Treasury, which owns the Secret Service, may insist that an FMV satellite maintain stare on the president at all times during a state trip to East Asia. FMV could provide enhanced situational awareness of the area surrounding the president at all

times, which helps the Secret Service fulfill its protection mission. At the same time, the Department of Energy may attempt to monitor potential aircraft delivery of nuclear weapons components between North Korea and a Middle Eastern country. The ability to watch an aircraft loading and unloading could provide insight into the cargo. Meanwhile, the DOD could require coverage of an ongoing North Korean army training event in the winter.

The list of requirements will surely be exhaustive and never met completely by projected space-based FMV capability. The competition amongst US government entities for space-based FMV in 2035 could parallel the situation in 2009 in which the functional components are sorting airborne FMV priorities in Iraq and Afghanistan.

Conclusion

By 2035, after decades of becoming accustomed to the spatial and temporal fidelity provided by FMV from airborne and possibly near-space airships, the United States will count space as a new source for FMV data. Alone, space-based FMV will not be omnipresent but will provide tremendous payoffs in its ability to allow the United States to stare at any spot on Earth's surface. Satellite FMV should be possible because of technological innovations associated with large-diameter mirrors, image-compression algorithms and processing, and satellite communications. Automated target tracking and identification exploitation tools could improve the utility of FMV data.

The ability to launch large-diameter mirrors into space is the single most important technology enabling FMV from a satellite. Communication and cost are key factors making GEO the optimum operating location for an FMV satellite, but because of the distance from Earth, decreased resolution is the tradeoff. To achieve useful resolutions on par with modern RPA and airborne FMV data, mirrors on satellites in GEO will need to be more than 50 meters in diameter. NASA's Ares V heavy space launch vehicle, projected for initial launch in 2018, will fit only an eight-meter monolithic mirror; therefore, users desiring RPA-comparable FMV resolutions must develop different approaches. Today's structureless telescope designs, which use interferometry or membranes as their primary optic, hold promise for mirrors as large as 100 meters in diameter. These would provide FMV with resolutions comparable to those of current state-of-the-art commercial imagery satellites.

The large amount of data generated in an FMV satellite, dictated by the frame rate of the sensor, could range between .5 and 12 gigabytes of data per second. Using the newest image-compression algorithms, faster processors, working in parallel if necessary, should allow data reduction by a factor of 15. Anticipated extensive deployment of laser-based communication links is projected to carry data rates in the gigabits-per-second range. Although US

communications requirements will likely outpace bandwidth availability in 2035, FMV satellites in GEO should be unaffected. Analysts will be able to communicate via dedicated organic links with their respective ground station.

Taking full advantage of FMV data from satellites and other sources requires improved automated exploitation tools to assist human analysts. Currently, the US ISR architecture is overwhelming its analytic capability. In the near term, improved FMV sensors covering more area will worsen the problem. Automated exploitation tools have long been an unfulfilled promise, yet they offer the most potential to help the intelligence community keep pace with collection.

When realized, FMV from space will provide the United States unprecedented situational awareness and insight regarding global activities. Specific to the military, FMV is poised to make significant contributions to help track mobile targets, provide unambiguous warning, aid in SSA, and network human activity. In response, adversary countermeasures will increase in frequency and area coverage to mitigate or negate improvements in the United States' FMV capability.

The demand for space-based FMV will outstrip the capability of sensors to collect. The large quantity of theater-based FMV assets may make ubiquitous FMV a reality in an area with ongoing combat operations. This could eliminate interservice battles over taskings. Competition for target coverage with the FMV satellite will cause services to prioritize taskings through vetting procedures using current national collection-management processes. This will not be the case at departmental and agency levels in the US government.

The implications of space-based FMV will be profound. Incorporation of a space-based FMV data set into a user-friendly application like Google Earth could help the nation and its military maintain an advantage across multiple domains throughout the spectrum of conflict. By 2035 system deployment is likely. This will ensure that the nation maintains its unmatched technical collection capability.

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Chapter 3

Persistent Space Situational Awareness

Distributed Real-Time Awareness Global Network in Space

Lt Col Dustin P. Ziegler

The United States needs to move beyond SSA toward space situational knowledge. The nation's leaders must know not only what is in space, but also what the objects are doing, their intentions, and who owns them. In chapter 2, Colonel Scheppers provided an overview of the benefits of FMV in space. He postulated that when realized, FMV from space will provide the United States unprecedented situational awareness and insight regarding global activities. Specific to the military, FMV is poised to make significant contributions to help track mobile targets, provide unambiguous warning, aid in SSA, and network human activity. One possible solution for persistent SSA is distributed real-time awareness global network in space (DRAGNETS).

Introduction

Gen Lance Lord, former Air Force Space Command (AFSPC) commander, defined SSA in simple terms: "The foundation of Space Superiority is Space Situation Awareness, which means having a complete understanding of what is happening in space."¹ "It is no longer sufficient to simply know where a satellite is in space. We must know what the satellite is capable of doing, what it is being used for and what it may be used for in the future," he said in a 2005 *High Frontier* article.²

The United States has a tremendous investment in space for the military, intelligence, scientific, and commercial sectors. US space capabilities influence everything the country does. Nevertheless, the lack of persistent situational awareness of the space operational environment, ensuring freedom of action, is one of the United States' vulnerabilities. As former AFSPC commander Gen Kevin Chilton stated in a 2006 media roundtable event at Peterson AFB, Colorado, "We have been really good in the past at counting what's up there and keeping track of what's up there. I maintain it's time that we move beyond cataloging to be able to identify what's up there and understand what its mission is and then ultimately determine intent."³ General Chilton's vision was to gather this information within an object's first orbit. Real-time data gathering in space may benefit the United States and its allies. The United States must determine the capabilities for persistent, responsive, and adaptive systems.

This research focuses on real-time data gathering and capabilities with a direct focus on the possibilities in 2025. More specifically, this research suggests the DRAGNETS concept as an approach that departs from the traditional paradigm mind-set of large and specialized space-based surveillance satellites. For the purposes of this research, the term *concept* is defined as a theoretically and scientifically possible future system. Additionally, DRAGNETS is defined as a concept that refers to a set of technologies which make up a system providing the ability to gather real-time data. Further, DRAGNETS will provide global network awareness for the military, intelligence, and civilian sectors by utilizing a suite of technologies and melding them into a potential system.

Conversely, this research considers an interconnected network of small centimeter-scale femtosats (spacecraft one-centimeter [cm] squared and less than 0.1 kg) proliferated throughout a variety of orbital regimes, in which each femtosat is a sensing node contributing to a greater common operational picture. In addition to providing indications and warnings, these nodes can form constellation clusters with enhanced aggregate capabilities to collect more detailed information on objects or events of interest, share that information throughout the network, and give commanders in the space operational environment immediate situational awareness. The idea of using clusters of small satellites in missions traditionally relegated to large, complex, monolithic spacecraft is not new.⁴ What is unique about the DRAGNETS concept is the aggressive focus on miniaturization of the elements and their use in an adaptive, global SSA constellation.

The United States has a compelling need for DRAGNETS. This research identifies the realities of the United States' dependence on space today and in the future, while highlighting the threat environment and existing SSA gaps. With this context, the discussion transitions to a detailed description of DRAGNETS at an operational concept level and investigates the technological advances required and the feasibility of these advances. Specifically, the section focuses on the role of nanoscale technology as an essential enabler for DRAGNETS, describing focus areas for further development. In addition, it explores the influence of global nanoscale-technology market trends and public perception on the development pace to provide a snapshot of the Air Force strategic planning environment. The research concludes with near-term, midterm, and long-term investment strategy recommendations. Examining the context, which drives the need for a DRAGNETS capability, provides the foundation for this research.

Background: A Story of Compelling Need

The United States' dependence on space is increasing drastically. To say the United States is dependent on space is a tremen-

dous understatement. The prevalence of telecommunications and navigation services used by the government and private sectors speaks volumes to the already high and growing importance of this medium in every aspect of life. If there is any question, one need only recall May 1998 when PanAmSat Corporation's *Galaxy 4* satellite failed, resulting in pager-service loss to 40 to 45 million pager customers as well as service loss to many automated teller and credit card processing machines and television stations.⁵ More recently, Lt Gen David McKiernan, the combined forces land component commander in Operation Iraqi Freedom, stated that space capabilities "allowed me to talk via tactical satellite communications and other means across a battle-space of hundreds of miles. It allowed us to make decisions and then execute those decisions faster than any opponent."⁶ Gen James Cartwright, the US Strategic Command commander, that emphasized in a 2005 statement before the Senate Strategic Forces Subcommittee on Space Policy that "the US economy, our quality of life, and our nation's defense are all linked to our freedom of action in space."⁷ However, the United States is not alone in its space dependence or the vulnerabilities that this dependence creates.

Europe, Russia, China, Japan, and a few other countries have long been cohabitants of the United States in space. The trend of space occupation is spreading as international cooperation and transnational commercial ventures provide access to nontraditional partners like Southeast Asia and Africa. Some of these state actors recognize the United States' dependence on space and see inherent strategic vulnerabilities and potential threats. Defense Intelligence Agency director Lt Gen Michael Maples said before the Senate Select Committee on Intelligence, "Several countries continue to develop capabilities that have the potential to threaten US space assets, and some have already deployed systems with inherent ASAT capabilities."⁸ In an emphatic coincidence, China launched an ASAT missile that destroyed its *Fengyun-1C* weather satellite during a technology demonstration on the same day that General Maples testified.⁹

Additionally, the 2001 Space Commission Report identified microsattelites and nanosatellites (10–100 kg) as a growing threat to US space assets. According to the Space Commission Report, miniaturized platforms could be "placed on an interception course and programmed to home on a satellite . . . [to] fly alongside a target until commanded to disrupt, disable, or destroy the target."¹⁰ Determining how to detect these special threats in advance is a critical element for the United States. Prior to detecting the special threats, the United States must identify and assess SSA capability gaps.

The existing SSN consists of about 30 ground-based sensors around the world and the orbiting midcourse space experiment. Together these networks provide most of the US SSA capabilities, which are limited to counting and cataloging space objects. Key SSA

coverage gaps result from limited ground-sensor fields of view, weather-dependent optical sensors, a lack of high-resolution data (particularly at geosynchronous orbits), and an inability to perform high-fidelity wide-area searches for small objects.¹¹ In an *Aviation Week* article, Jefferson Morris wrote that AFSPC's future programs plan contains only one space-based SSA initiative over the next 25 years for coverage of high-interest objects: an orbiting telescope known as the space based surveillance system.¹² Even considering this additional SSA system, a capability gap still exists for handling the threats identified by General Maples and the Space Commission.

In the strategic planning calculus for future space requirements, the combination of a growing US dependence on space, increasing vulnerabilities to the United States' space assets, and the existing situational awareness gap leads to a compelling need for a robust SSA architecture. The DRAGNETS concept represents a new way of approaching the challenge to enhance the SSA architecture. Prior to the United States' launching such architecture, the DRAGNETS concept warrants further exploration.

DRAGNETS Concept

Progress in nanoscale technology may result in putting SSA capabilities into smaller satellites. Subsequently, this may enable constellations of LEO and GEO femtosats operating as interconnected sensing nodes on one network. A part of this network, the femtosat is a spacecraft one centimeter squared and less than 0.1 kg.¹³ These nodes respond to objects of interest such as foreign satellites, co-orbital ASAT threats, or anomalous debris by condensing into localized clusters of femtosats to perform higher-fidelity characterization while cueing other assets for further investigation. This network provides high temporal and spatial resolution situational awareness of the space environment to support missions such as space object surveillance and identification, debris field mapping, technical intelligence collection, and space weather monitoring. The benefits of distributed small-satellite networks extend beyond the missions they enable.

In addition to the characteristics mentioned, the distributed femtosat concept has several practical advantages. Because of the small size and simple structure, relative to traditional spacecraft, femtosats lend themselves to rapid, low-cost mass production analogous to microelectronics fabrication today. Testing femtosats, the size of sugar cubes, is easier from a process and logistics perspective than testing today's medium-class 2,500 kg satellite. One must consider the launch options in support of SSA.

At 10 grams (g) per femtosat, a constellation of 250,000 femtosats has the same launch mass as a medium-class satellite. That constellation could place clusters of 10 femtosats spaced every 1.7 km at a 600 km LEO altitude. Alternatively, the constellation could

use excess launch vehicle capacity on military, intelligence, NASA, or commercial missions. Finally, replacing individual femtosats or replacing the whole cluster may accomplish the replenishment and upgrade of the constellation capability. The exploration of DRAGNETS capabilities and advantages lends itself to a more detailed observation at the inner workings of the DRAGNETS concept.

DRAGNETS Elements

The DRAGNETS concept consists of three elements: the femtosats, constellation, and command and control (C2). The femtosats fly in *wolf packs* as needed to surround an object and investigate it from multiple perspectives. The femtosats and their clusters are part of a constellation operating in a particular orbital regime, perhaps a specific altitude at a given orbital inclination, with multiple constellations needed to cover the full spectrum of missions. The architecture requires a few relay satellites to forward data streams to the ground stations and command uploads back to the femtosats. Finally, the C2 element includes the relay satellites, the unmanned remote ground stations, and the manned ground control center, all elements for an effective concept of operations.

The following hypothetical scenario provides an example of how DRAGNETS supports the future space war fighter:

Country X launches a medium-sized 2,500 kg satellite into LEO as part of a well-publicized science mission. By all accounts in the open press, the satellite has a commercial remote-sensing payload and a suite of antennas for space weather analysis. As soon as the satellite drops into its LEO insertion point, a nearby DRAGNETS cluster detects the satellite with a combination of visible and infrared cameras as well as sensitive magnetometers and begins to monitor the spacecraft.

Fifteen minutes after launch, the small upper-stage engine stops and separates along with the payload adapter from the satellite. A few minutes later when the satellite, spent upper stage, and payload adapter are out of view of the SSN ground assets, three small eight-inch cube objects separate from the payload adapter and drift away. The DRAGNETS cluster observes the covert microcraft dispensing and relays the information immediately, passing along video, still images, and motion vectors. With access to a networked ground database of all known orbiting objects with current orbital elements, the DRAGNETS constellation autonomously determines (over the next few minutes) that the three microcraft are entering separate co-orbital tracks with three high-value DOD satellites and cues the appropriate clusters to monitor the microcraft. The constellation sends out a priority message as an alert to all DOD and national satellites on the network and transmits the information to ground, allowing cueing of the high-frequency, narrow-spot-beam SSN S-band radars. With this information, the operations director and key decision makers have visibility into these events within minutes, rather than waiting for several orbits to pass to build statistical evidence of the anomalous objects from ground sensors.

Meanwhile, a US femtosat cluster moves to within 1 km of a microcraft and begins a focused interrogation of the object. Several femtosats maneuver into position to obtain different simultaneous views with visible and infrared sensors, both active and passive. Additional data collectors could provide other high-value information on the objects using novel collection methods. The microcraft orbital altitude is beneath the cluster, so as the microcraft moves

away, the next cluster in the track begins surveillance. At the same time, a space based surveillance system satellite has been cued to the microcraft position and heading to bring its specialized telescopes to bear.

This scenario does not address specific operational details; however, it does provide an overview of how the DRAGNETS concept would operate as part of an integrated SSA architecture. To take advantage of a distributed situational awareness approach, one must reduce functions in size or combine them within multifunction subsystems, while improving the capacity. Improving SSA functions and capabilities leads to advances in nanoscale technology, prompting a discussion of this emerging field and its impact on DRAGNETS.

The Role of Nanoscale Technology

The ability to package SSA tools into small satellites in the future will depend on how well the United States miniaturizes and integrates satellite functions. Conventional satellite design processes classify these functions into eight critical subsystems: propulsion, attitude determination and control system, communications, command and data handling, thermal, power, structures, and payloads.¹⁴ Key to the reduction in size, weight, and power for these subsystems is a class of technologies known as nanoscale technology. It is first necessary to define nanoscale technology to understand how it will enable the femtosat concept.

Nano refers to the size or scale of the scientific phenomena applied to create nanotechnologies. More specifically, nano refers to length scales of one billionth of a meter, about the size of a molecule. The nanoparticles that form nanotechnologies range in dimensions from a few to several hundred nanometers (nm). By comparison, a red blood cell is 6,000 nm. Subsequently, *nanoscale technology* is a broad umbrella term referring to nanoscale science applications in which the materials have unique characteristics. For example, carbon nanotubes, discovered in 1991, are a special carbon form that has “100 times the strength of steel, conducts heat better than a diamond [itself one of the best thermal conductors in the world], and carries electricity better than copper.” Nanoscale technology enables the DRAGNETS concept at each level, from the femtosat components to the constellations and their C2.¹⁵

Application to DRAGNETS

At the femtosat level, the most important benefit from nanoscale technology is the significant reduction in size, weight, and power requirements for each function. In 2025 these functions may potentially coexist in multirole subsystems such as cameras, which are dual-use star trackers for attitude determination, or reconfigurable elements such as laser transceivers, which tune to different

frequencies appropriate for either laser imaging or communications tasks. As computational speed grows, satellite autonomy will improve and more onboard data processing will occur, thereby placing less demand on the communications architecture for raw data transmission. These computational advances also have implications at the constellation level.

Femtosat constellations should operate with a degree of self-awareness supported by the nanoscale technology-enabled processing power and networking technologies projected over the next two decades. Without intervention from the ground, the system should monitor its own health, identifying failing femtosat elements. The constellation should perform corrective measures, signal to ground for instructions, or deactivate and remove the faulty elements. The architecture should respond to external events by adapting to focus more attention on the event while passing along all relevant information to different constellation regions, other satellites on the network, and the ground C2 nodes. This complex architecture would overwhelm today's C2 capabilities; however, the US ground segment in 2025 may reap the benefits of nanoscale technology.

As stated in the National Nanotechnology Initiative (NNI) report *Nanotechnology in Space Exploration*, there will be a critical need "to transition the present mission operations paradigm of many humans per vehicle to many vehicles per human."¹⁶ Recall the problem's scope: tens or hundreds of thousands of femtosats per constellation monitoring and adapting, some providing event reporting, whereas others are streaming environmental measurements, debris characterization data, and so forth. Although the substantial onboard computing described will alleviate some challenges, there will be vast improvements in the control system's ability to handle the workload. Computational power and orders-of-magnitude-higher data-storage densities connect with new techniques for interaction between human and machine, resulting in a more efficient ground element with only a few people operating the constellation.

Discussing the four key functional nanoscale technology applications most likely to affect DRAGNETS (propulsion, sensors, power, and data processing) is an important component for analyzing DRAGNETS capabilities. The following sections address current trends in nanoscale technology in these four areas, providing snapshots of technological advances and the prospects for evolution to a DRAGNETS application.

Propulsion

The femtosat's propulsion subsystem will rely on nontraditional approaches to meet requirements for attitude control or to modify their orbits. Future femtosats will use a nanoscale technology

variant of electric propulsion because of the inherent system energy efficiencies, referred to as specific impulse (I_{sp}).¹⁷ One promising technology for high-efficiency operation on larger satellite systems is the field effect emission propulsion (FEEP) thruster.

A FEEP thruster operates through the interaction of electromagnetic fields generated by an accelerating grid and a liquid or solid substance from which ions or electrons are extracted. In a FEEP, an extractor grid forms an electrostatic potential that pulls ions and electrons from the surface of the working solid or fluid. Individual components are measured in microns and can be produced in varying sized arrays, up to a few centimeters in dimension using standard semiconductor fabrication techniques. Liquid indium FEEPs have demonstrated I_{sp} values as high as 10,000 seconds and thrust efficiencies of more than 90 percent (over 90 percent of the input energy converts into propulsive energy). By comparison the most common chemical combustion thrusters in use today perform with an I_{sp} of 300–400 seconds.¹⁸ The challenge with FEEP thrusters is that although they are efficient at low-thrust operation, the power requirements needed to achieve high thrust levels for quick-reaction adjustments are impractical for a femosat.

Researchers at the University of Michigan are investigating a FEEP-like thruster that uses carbon nanotube rods floating in a host fluid in lieu of pulling the ions from that fluid's surface. The advantage is lower electric field levels, leading to lower power levels, and the CNT rod size can be tuned for variable thrust levels. This tuning allows on-orbit throttling for low-thrust formation flying or station keeping or high-thrust orbit adjustments. The concept is at a technology readiness level (TRL) of two to three, based on limited component-level testing performed to date, while the more mature FEEP has been assessed at a TRL of four to five. (For an explanation of TRLs, see appendix 3.A.1.) It is clear that several areas will require focus to meet femosat propulsion challenges.¹⁹

Bridging the application gap to get the propulsion system smaller requires advances in the development and integration of nanoscale thrust sources with a robust focus on modeling and simulation to understand how these devices operate. Based on progress to date in this area, the underlying technologies described will likely mature to a TRL of six to seven within the next five years. A variable-thrust nanopropulsion system ready for integration into a prototype vehicle should appear in 10 years. Nevertheless, the Air Force should provide motivation for further subsystem miniaturization. Another area expected to benefit from the *smaller is better* trend is the sensor subsystem.

Sensors

Sensors influence several functions in the femosat, from camera systems that collect images of other objects, to star trackers

and sun sensors that determine the spacecraft attitude. By 2025 nanoscale technology will enable revolutionary improvements in sensor capability density, a figure of merit describing the data-collecting power per unit volume of a system. This section not only details progress to date in miniaturizing imaging cameras and attitude-determination sensors but also presents a path toward the DRAGNETS vision.

Since DRAGNETS depicts other space objects, progress in nano-enabled imaging technologies is of particular interest. The idea of collecting centimeter-class resolution images in low-light eclipse environments from several kilometers away using small sensors is challenging. Collecting enough light in an aperture for small sensors presents challenges; however, technologies such as Planet 82's single-carrier modulated photo detector (SMPD) may provide stepping stones in the right direction. Based on the company's research, the SMPD sensor is 2,000 times more sensitive and takes up half the area of a conventional CCD. The SMPD sensor is also smaller than the complementary metal oxide semiconductor sensors found in space-based imaging systems. Planet 82 currently markets this technology in the cell phone, security, and camcorder industries.²⁰ Japanese electronics provider Sharp also announced a miniaturized camera for mobile phones using mainstream technologies packaged in a 5.5 x 5.5 x 2.4 millimeter volume.²¹

Quantum dots (QD) are another class of nanoscale photonic technology with applications for sensing. As a passive detector, QDs offer low susceptibility to self-generated thermal noise. Another advantage is QDs' selective tunability to specific light wavelengths.²² Based on this property, they are efficient laser sources when paired with corresponding QD detectors in laser detection and ranging imaging systems. Attitude-determination sensors benefit from these sensitivity enhancements as well, but a more significant payoff is reducing the need for spacecraft resources and surface area in favor of mission payloads.

A 2002 Air Force Science and Technology Board report suggests that trends toward system-on-a-chip (SOC) implementations will allow more efficient packaging of attitude-determination functions. The report noted that "possible examples of spacecraft SOCs include sun and horizon sensors, inertial measurement units composed of microelectromechanical systems accelerometers and rate gyros, GPS receivers for navigation and attitude determination," among others.²³ Recent nanotechnology developments pave the way toward miniaturization of these functions. In 2005 the Technical Institute of Denmark's Department of Micro- and Nanotechnology reported on the development and test of a chip-based, two-axis sun sensor measuring less than a centimeter across. NASA's Jet Propulsion Laboratory has fielded a similar-sized device.²⁴ However, attitude-determination sensors will need to shrink at least another two orders of magnitude (submillimeter) for DRAGNETS. A demon-

stration of Air Force interest in this technology through small amounts of funding may spur research and development into the next generation of miniaturized sensors. These components need energy to operate, and the power subsystem will require its own advances.

Power

Power is the satellite's lifeblood, and striking the proper balance in devoting satellite volume and surface area to power collection versus mission capability is a delicate process. There are two ways to address this issue. The first method is to develop power-efficient subsystems. Nanotechnologies will make packaging more efficient, reducing the need for loss-prone interconnects and improving electrical signal transmission by eliminating parasitic heat losses. The second is to develop novel power-generation and storage technology to increase the materials' specific powers. Both approaches are important; the following paragraphs focus on the latter.

In a typical satellite, the solar arrays and batteries play critical roles in power generation and power storage. Future power-generation techniques will either gather power from the environment (for example, solar) or use stored power from fuel cells or radioisotope-based devices. Companies such as Evident Technologies and Konarka are developing QD-based solar cells with the ability not only to improve visible-light conversion but also to trap and convert infrared photons, taking advantage of a significant portion of the solar spectrum.²⁵ Another miniaturized concept is alpha-voltaic cells with radioisotopes that emit high-energy radiation into a semiconductor medium to convert the radiated particle's kinetic energy into a current, offering greater than 90 percent conversion efficiencies and decade-long component lifetimes.²⁶ Once energy exists in the form of electrical current, it must be stored for later use and for regulation of its distribution throughout the satellite.

Storage mechanisms are either batteries, operating on electrochemical processes, or capacitors, storing energy by maintaining a voltage between separated electrodes. Batteries in the femtosat application leverage nanostructures such as nanofiber electrodes and self-assembled nanowells for the energy-storage medium.²⁷ Supercapacitors are a promising alternative to batteries. The latest generation is under development at a laboratory benchtop level, incorporating the ubiquitous CNT as an electrode material and enabling energy densities eight times higher than the best capacitors available today.²⁸ Supercapacitor specific energies are lower than those of batteries, but have more discharge cycles with less degradation. Additionally, charge times measure in seconds versus minutes or hours for equivalent-sized batteries, and they are well suited for rapid surge discharge applications. Researchers expect commercial supercapacitors based on CNTs within five years.²⁹

The power technologies mentioned are building blocks toward the performance that DRAGNETS will demand. Significant momentum already exists to move these technologies along, and Air Force future investments should be in the area of integrating these devices into femtosat vehicles using SOC principles. Once power is available, the data-processing function can leverage that power.

Data Processing

If electrical power is the satellite's lifeblood, then the data-processing system is its brain. As satellite systems become more complex and demand more onboard number crunching, the processor speed and efficiency become limitations. The commercial market drives the technology in this field, but whether the application is commercial or military, nanotechnologies will influence computing in the next decade. Processor speed and data-signal distances are inversely proportional, so nanoscale devices will harvest gains in computing power.

In 2002 the Quantum Information Science and Technology (QIST) expert panel convened a quantum computing (QC) workshop in La Jolla, California, to establish a working road map for QC technologies with a 2012 target horizon. The panel identified nine different technologies for further development and highlighted QDs as a promising technique for miniaturized QC applications.³⁰ The QC advantage is a result of quantum superposition in which all possible outcomes of a given calculation with given inputs are determined simultaneously. Charlotte Barbier of the University of Virginia said, "Because of this, a quantum computer has the potential to be 10^6 times more powerful than current supercomputers."³¹ The QIST panel estimates that an integrated, all-electronic quantum computer capable of handling simple problems should be available by 2012.³² The DRAGNETS ground control system requires less miniaturization, which widens the trade space for meeting the data-processing requirements and other computationally intensive C2 functions.

Since basic constellation management is through onboard processing, the majority of ground-processing work focuses on mission data consolidation, interpretation, trend analysis, and archiving as well as product dissemination and flight software upgrades. To accomplish these tasks, one should emphasize increasing the processor speed and reducing the data-transmission latencies. A bottleneck in ground-processing architectures today is throughput—moving data between points that need it to perform their functions, such as from memory to processor. The challenge for nanoscale technology is reducing signal mismatches and transmission losses at the junctures between devices and shortening the distance signals need to travel between operations. Work remains, but the payoffs hold significant potential.

The foregoing discussion suggests that the femtosats' performance in a DRAGNETS architecture is possible only with significant technology advances. However, one must determine if there is a concerted scientific effort to move research in the right direction. Additionally, one must give attention to the required capital to support the necessary research. Perhaps global market trends in nanotechnology will shed light on these issues.

Nanotechnology Market Trends

Nanotechnology is not a new concept. CNTs have existed for 15 years, and research identified their predecessors, buckyballs, approximately two decades ago. Nevertheless, since 2000 the concept has gained momentum as promising research across many fields. In the foreword to the book *Nano-Hype*, Dr. Mihail Roco, former nanotechnology senior advisor to the National Science Foundation, underscored this point: "While nanotechnology may be oversold in the short term in some areas, its overall implications seem to be underestimated in the long term."³³

The Bush administration recognized the growing potential and importance of this technology class across a wide range of disciplines when it established the NNI in 2001. The NNI facilitates public and private-sector research and development into nanotechnologies.³⁴ Two years later, Congress enacted and President Bush signed Public Law 108-153, the *Twenty-First Century Nanotechnology Research and Development Act*, formally establishing the national nanotechnology program.³⁵ In the 2006 State of the Union address, the president featured nanotechnology as a cornerstone focus area for the President's American Competitiveness Initiative.³⁶ Moreover, the United States supported its commitments with resources as well. Since its inception in 2001, NNI program funding increased from \$464 million to over \$1.3 billion in 2006.³⁷ However, the United States is not alone in its nanotechnology interests.

In June 2005 Matthew Nordan from Lux Research, Inc., one of the nanotechnology market's most consulted analysis sources, testified before Congress that 2004 global nanotech expenditures topped \$8.6 billion. Nordan projected that "new, emerging nanotechnology applications will affect nearly every type of manufactured goods over the next ten years, becoming incorporated into 15 percent of global manufacturing output totaling \$2.6 trillion in 2014." Nordan also explained before the Research Subcommittee of the House Committee on Science that US dominance of the field is giving way to more aggressive foreign investment.³⁸

At present, the United States leads in absolute investment, nanotechnology-related patents issued, corporate research and development spending, and scientific publications; however, the United States currently lags behind several other countries in total investment relative to purchasing power.³⁹ An August 2005 *Foreign Direct*

Investment article described strong US competition from European and Asian countries. The article also highlighted some signs of cooperation, such as recent research agreements between China's Zhejiang University and California's International Institute of Nanotechnology.⁴⁰ These signs point to tremendous growth in the nanotechnology market in the coming decade—fertile ground indeed for the advances required to make DRAGNETS a reality. It is important to note, however, that progress in these breakthrough technologies comes with the requirement for due diligence with respect to environmental and public safety concerns.

When new technologies appear on the public stage in their infancy, there is a natural human tendency toward mistrust. If a given technology moves faster than the public's ability to accept it, a backlash may dampen development. In the past, negative perceptions toward pasteurized milk, nuclear power, and irradiated meats led to their slow acceptance, and today genetically modified foods face a similar uphill battle.⁴¹ To identify these concerns up front, the Bush administration made environmental, safety, and health analysis a key NNI program element from the beginning.

In 2006 the nanoscale science, engineering, and technology (NSET) subcommittee to the President's Council on National Science and Technology published a report from its Nanotechnology Environmental and Health Implications working group detailing the research areas required to “enable sound risk assessment and risk management decision making.”⁴² The report provided guidance to researchers, producers, and users of nanotechnologies about knowledge gaps of the impact of these technologies on health. It asks questions such as “What are the risks of exposure for the worker, the consumer, the public, and the environment?”; and “What are the effects of inhaling, swallowing, or absorbing nanoengineered substances?” NSET plans to incorporate input from “citizen and industry groups, academia, and other research entities . . . through workshops, public hearings, and other means.” Recent studies indicate that balanced information on risks and benefits mitigates public mistrust.⁴³

The Woodrow Wilson International Center for Scholars and the Pew Charitable Trusts cosponsor the Project on Emerging Nanotechnologies to explore nanotechnology's societal aspects. In September 2005 the organization published “Informed Public Perceptions of Nanotechnology and Trust in Government” to highlight what Americans understand about nanotechnology, its applications, and the proper way to manage its risks. The key findings led to a strong desire for public input in the decision-making process, particularly with billions of dollars in government expenditures at stake. The report also identified a desire for government regulation of the technology; however, respondents voiced mistrust of existing federal regulation approaches, citing corporate influence over Congress and the White House as problematic. In general, those sur-

veyed were suspicious of the tendency for industry to forge ahead with product development and marketing before adequate testing. The importance of keeping the public informed and putting the proper controls in place to ensure responsible technology development should not be underestimated.⁴⁴

Public nanotechnology perceptions will not change Air Force strategic planning, but science and technology managers should expect to see the aforementioned controls applied through the federal acquisition process. Although the technologies are new, the importance of environmental, health, and safety concerns is not. Environmental impact assessments will be required, and Occupational Safety and Health Administration regulations will still apply, tailored to the specific needs driven by nanotechnologies. Public awareness of nanotechnology's benefits will broaden as nanotechnologies begin to impact consumer products and health care. A positive outlook toward these applications could spur stronger growth, benefiting the DRAGNETS concept.

Limitations

Any move toward incorporating DRAGNETS-like capabilities into future SSA architecture demands a discussion of limitations. Two key areas requiring resolution beyond the basics of developing the enabling nanotechnologies are radiation survivability and debris management. Radiation survivability is significant in light of the electronic component importance in the femtosat design. Debris management deals with what happens to hundreds of thousands of metal cubes when they reach the end of their lives.

Radiation Hardness

In contrast to what intuition implies about the vacuum of space, the space environment bombards the upper atmosphere and the satellites above it with a continual energetic-particle stream. High-energy free electrons can become embedded in spacecraft surfaces and components, leading to sparks in sensitive equipment. Even higher-energy particles such as those from solar flares can cause single-event upsets, manifesting temporary or permanent component malfunctions. The extent to which a component is resistant to or shielded from these effects is its radiation hardness. Conventional techniques for hardening against energetic electrons and protons often involve shielding with aluminum or other absorbing materials. Though this approach is impractical in the DRAGNETS concept, it is worth exploring whether nanocomponent properties offer inherent radiation hardness.

Nanoscale technology may offer solutions to challenges with radiation hardness. One approach cited by the Air Force Science and Technology Board uses vacuum integrated circuits, a modern twist

on vacuum tube technology. These devices pull current from a cathode by applying an electric field, a process known as field emission. Nanomaterials can be used to make long-lasting cathodes for integrated circuits to operate in “extreme temperature and radiation environments.”⁴⁵ Another helpful phenomenon is QD- and CNT-based-devices radiation resistance. According to a paper published at the 2004 International Energy Conversion Engineering Conference, “QD/CNT-based photovoltaic devices have the potential to be as many as five orders of magnitude more resistant to radiation damage” than conventional electronic devices.⁴⁶ Nevertheless, unless the satellite is made entirely of QDs and vacuum microelectronics, questions remain concerning space-radiation effects on nanoelectronics.

The End-of-Life Conundrum: Femtolitter

The second key issue is how to deal with the orbital debris resulting from failed femtosats. When thousands of these 10-gram sugar-cube-sized satellites die at an altitude of 600 km, they become uncontrolled micrometeorites with the same kinetic energy as a small car traveling 45 miles per hour.⁴⁷ A fail-safe approach to eliminating this problem is necessary if DRAGNETS becomes a practical solution for SSA. The obvious choice is to provide some means for end-of-life deorbit for LEO constellations and storage orbits for geosynchronous femtosats.

To ensure end-of-life disposal, the propulsion method must act mechanically or use a separate dedicated power source triggered by a sustained power loss. Vaporizing liquid and digital microthrusters (see fig. 3.1) provide small and simple thrust sources for miniaturized applications.⁴⁸ These thrusters run on minute propellant micropackages that ignite or vaporize by applying a small heat source. The thrusters are ideal for use following a catastrophic system failure. The residual challenge is how to tell the femtosat the direction in which to thrust if it is dead. Solving the radiation hardness and end-of-life disposal limitations of the DRAGNETS architecture is an essential step in attaining a distributed situational awareness capability vision.



Figure 3.1. Northrop Grumman prototype of a digital microthruster array. (David Lewis, “MEMS/Micropropulsion,” Northrop Grumman Corp., <http://www.st.northropgrumman.com/capabilities/space propulsion/technologies/micropropulsion.html>.)

Recommendations

There is a compelling need to fill capability gaps in the United States' future SSA architecture. The expense and difficulty of populating strategic locations on Earth's surface with new ground-based space surveillance assets coupled with the difficulty of producing large, complex satellites within budgetary and schedule constraints require strategists to think about the problem in a different way.⁴⁹ DRAGNETS offers one approach—harnessing the power of *small* to address large problems. To make DRAGNETS a reality in 2025, the Air Force should phase its investment strategy in light of fiscal and technical constraints as well as the current worldwide momentum toward nanoscale technology development. The following sections provide recommendations on areas the Air Force should *lead* and those it should *leverage*, looking ahead to the near term (2008–14), the midterm (2014–20), and the far term (2020–25).

Near Term (2008–14)

The first recommendation is to develop an overarching nanoscale technology road map within the Air Force technology enterprise. This would enable the various science and technology elements (AFRL, the Air Force Office of Scientific Research, AFIT, and the Air Force Academy) to compare their investment strategies and provide strong traceability from the DOD to the NNI, which funds the DOD at \$350 million per year.⁵⁰ On the development side, the Air Force should leverage commercial and academic basic research at the component level, taking full advantage of small business innovation research and small business technology-transfer opportunities to capture the leading-edge ingenuity while continuing similar efforts at the research laboratories. Beyond academia, the Air Force and commercial sectors can benefit from manufacturing. The Air Force must ensure robust and level funding of nanoscale-production technology within AFRL's manufacturing technologies program to provide stable, long-term partnering incentives. Modeling and simulation (M&S) will also be a critical need. Strong leadership and investment in a coordinated M&S effort will pay dividends down the road through better understanding of how to use these technologies in applications of interest to the Air Force.

Midterm (2014–20)

In the midterm the Air Force should plan to emphasize application efforts, leading the demonstration of femtosat subsystem performance in key areas such as forming images from ultrasmall, nano-enabled cameras at low-light levels; hosting flight software packages on quantum-computing test beds; and integrating nano-enabled attitude control and propulsion systems. Constellation

management and cooperative multivehicle SSA operations should be demonstrated on orbit using larger, mature nanosatellite platforms such as the CubeSat satellite bus.⁵¹ By 2020 the Air Force should have integrated femtosat subsystems, flown test articles to demonstrate functionality, and established opportunities for early operational assessments. In parallel the Air Force should leverage advances in nanoscale technology-based supercomputing and artificial intelligence with an eye toward fielding efficient ground control architectures.

Far Term (2020–25)

The final stage of DRAGNETS investment planning will drive an Air Force-led, on-orbit, distributed femtosat-constellation demonstration. Important accomplishments will include simulating autonomous investigation of an uncooperative space object, sharing information with other constellation members, cueing other space-based and ground-based SSA assets, sending out test alerts to satellites with self-defense capabilities, and relaying data in near real time. The culmination of this development stage will be operational assessment activities leading to a TRL of seven rather than the TRL of six traditionally identified for transition to an acquisition program. This will reduce technology risks that plague many of today's programs.⁵²

Areas for Further Research

Since this research focuses on the role of nanoscale technology in clearing the technical hurdles, a few key areas require further research. In particular, an integrated, self-managed femtosat constellation will rely on advances in artificial intelligence for decision making across a wide range of operational scenarios. Further investigation will provide an assessment of the risks and requirements of implementing autonomous operations in distributed satellite networks. The femtosats also will need an adaptive communications approach to share information with the other constellation members, other accessible satellite platforms, and the ground segment. Microsoft sponsors work in this area for terrestrial, wireless, self-managed networks, and IBM funds research in autonomic computing.⁵³ Collectively, these efforts are a springboard for further analysis of the communications challenge.

Conclusion

The United States depends on space. That dependence, coupled with the growing threat of actors seeking to deny the use of space, creates vulnerabilities the United States cannot currently address. The DRAGNETS concept, composed of constellations of thousands

of miniaturized femtosats, is a new way of viewing SSA. Furthermore, DRAGNETS represents the natural convergence of the trend toward distributed, networked military solutions and the capabilities that nanoscale technology will enable over the next 20 years. This convergence holds cost benefits, too.

Once DRAGNETS transitions to acquisition, the concept will realize cost savings. The satellite-on-a-chip implementation lends itself to mass-production efficiencies that allow femtosat constellation production in a fraction of the time it takes to build a large satellite. Additionally, testing can be streamlined from today's one-year-long process by using cost-effective facilities. Finally, launch options for a distributed system are flexible, from single-launch insertion of entire constellations to incremental buildups using space-available services. To get to this point, the United States must shepherd market enthusiasm and public trust.

Although technology leaps must occur, global market momentum is positive. The US NNI and other publicly and privately funded efforts have contributed billions in research dollars toward basic science and applications. The rest of the world continues to match the United States' enthusiasm. To maintain that momentum, the United States needs to ensure public confidence in its stewardship of this new technology. Although this requires additional health and safety measures, the advantages of public support outweigh the overhead.

To make DRAGNETS a viable part of an integrated SSA architecture, the Air Force needs to phase its goals and investments. The first phase is for AFRL to lead an Air Force effort to establish and shepherd an overarching nanoscale-technology road map. In 2008–14, investments should focus on leveraging small-business innovation while leading the charge in manufacturing and M&S technologies. The second phase, to be implemented by 2020, will require the Air Force to lead the integration and demonstration of femtosat-class spacecraft, make significant progress in constellation behavior and self-management research, and bring computational advances into the ground stations to realize significant efficiencies in ground control and data handling. Finally, in the third phase, the Air Force must target demonstrations of femtosat prototype constellations at both LEO and GEO to prove the capabilities in an operational environment by 2025. In taking these measures, the Air Force will put the right tools in the hands of combatant commanders to preserve freedom of action in space.

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Chapter 4

Toward Breaking the Rocket Monopoly on Space

Scramjet-Enabled Space Access in 2030

Maj Brian C. McDonald

In chapter 2 of this paper, Colonel Scheppers, emphasized the importance of a comprehensive SSA architecture to US national security. Colonel Ziegler conceptualized that architecture in chapter 3 by proposing a system called DRAGNETS. While diplomats exercise their power, armed with real-time information from space, the Air Force must be ready to access space when called upon to respond to an issue or to dispatch and maintain the space intelligence architecture. Once it is aware of a space access requirement, can the Air Force quickly respond and achieve any orbit, regardless of launch time or coordinates? Can it initiate a semicovert response? Projecting today's rocket technology into scenarios for 2030 suggests a capability gap with desired response time, orbital access, and concealment. This chapter explores scramjets as an alternative to rockets to meet the space access capability gap projected for 2030.

Foreshadows of the Need for Dominant Space Access

This year, the 50th anniversary of Sputnik, we had another significant emotional event when the Chinese demonstrated that, indeed, space is not a sanctuary.

—Gen Kevin P. Chilton
Former Commander, Air Force Space Command

Three extraordinary events in the last five years reminded the United States of its reliance on, and the precariousness of, the space-based advantage it enjoys. In March 2003 the United States invaded Iraq based, in part, on intelligence that included satellite imagery purportedly showing Iraq's concealment of weapons of mass destruction (WMD). In January 2007 China demonstrated its ability and willingness to destroy orbiting satellites with a successful ASAT test on its own weather satellite. In December 2007 Chinese space ambitions generated further apprehension when an unidentified blogger posted a picture of an unacknowledged, reusable subscale space plane.¹ These captivating events foreshadow the US space requirements and threats in 2030 and, therefore, serve as

vignettes for considering desirable, futuristic space capabilities—the most fundamental category being space access.

Not only do the aforementioned events predict requirements and potential threats in years to come, but also they demonstrate the capability gap that exists for US SSA, with respect to desired response time, orbital access, and concealment. Subsequently, the purpose of this research is to forecast the condition of US scramjet-enabled space access in 2030 to aid Air Force planners and strategic decision makers. Scramjets dominate hypersonic propulsion and enjoy resurgent interest by the Air Force. However, scramjet selection for this spacelift forecast does not assume it is the optimal alternative to today's rocket-only paradigm, nor does it suggest that the scramjet is the best hypersonic propulsion method that uses atmospheric oxygen. Rather, the goal of this forecast is to examine the likelihood of maturing a promising propulsion idea that, if realized, would represent a transformational shift in US space access.

Overview

For as long as the United States remains the global superpower, international legitimacy of United States–initiated aggression will depend on reliable intelligence. Did gaps in or the predictability of US satellite coverage of Iraqi weapon storage facilities contribute to an inaccurate assessment of the Iraqi WMD situation? A 2004 US Senate investigation revealed major intelligence flaws in Secretary of State Colin Powell's speech to the United Nations before the Iraq invasion. The Senate committee could not corroborate that Iraq had a national-level biological weapons denial-and-deception program in 2002.² In light of this intelligence failure, the ability to place small turnkey satellites into specific orbits to collect time-sensitive and uncompromised imagery may prevent national future embarrassment. This would be a breakthrough space-access capability for the intelligence community and decision makers of 2030.

Potential adversaries will seek exploitable US vulnerabilities. The United States' disproportionate reliance on space-based assets, both commercially and militarily, may create a high-value target. Within one year, the Chinese revealed two systems under development that could degrade US space use during a conflict. In response to the ASAT system demonstration and the Chinese system development, Gen J. E. Cartwright, then commander of United States Strategic Command, testified, "Space is now a contested domain where, without adjustments to our strategy, we may not be able to count on unfettered access to space-based systems should others persist in their course of developing counterspace weapons."³ Indeed, with demonstrated ASAT weaponry proliferating beyond the Cold War superpowers, how safe will the US orbiting fleet be in 22 years? A panel of propulsion and space access experts (see

appendix C), convened specifically for this research, predicted a moderate likelihood that 20 or more nations would own ASAT technologies in 2030.

When the photograph of the Chinese space plane *Shenlong* went public, the same panel of experts said it as a significant event. Five years prior, a Chinese Academy of Sciences member said, “China’s spaceplane should be able to go in and out of the atmosphere and would serve as a ‘space combat weapons platform.’”⁴ China’s sudden, open confirmation regarding progress toward this goal made the *Shenlong* photograph newsworthy. With foreign ASAT technologies and combat space planes on the horizon, the ability to covertly orbit spare satellites prior to attack or quickly reconstitute satellite constellations after an attack would ensure US space-based capabilities. This rapid, flexible, and covert access to space could deter or overcome a potential space attack by future adversaries.

The Promise of Supersonic Combustion Ramjets

Rocket propulsion has monopolized the spacelift market for the last 50 years and posted an awe-inspiring space achievement list. The United States must determine if gradual improvements in rocketry over the next 22 years are adequate to maintain space dominance and if a transformational change is necessary. Rocketry’s ability to deliver much more capability for the demanding spacelift requirements anticipated in 2030 is questionable. According to George Paul Sutton and Oscar Biblarz, “Since the state of the art is relatively mature today, the design and development of a truly novel [rocket] engine does not happen often.”⁵ Conversely, the untapped promise of air-breathing hypersonics, powered by scramjet engines for space launch, presents an opportunity for the United States.⁶ Air breathers open a new design favorable to futuristic space access capabilities like turnaround times measured in hours, omniazimuthal launch, and discreet operations. Nevertheless, the technical and economic challenges to make scramjet-enabled spacelift a reality in 2030 beg the questions “Can the United States do it?” and “Is it worth it?”

This research attempts to answer the questions by clarifying the expectations of scramjet-enabled space access in 2030. This chapter applies two rigorous technology-forecasting methods. First, a panel of 12 diverse propulsion and space access professionals forms predictions and provides expert commentary in accordance with the Delphi method, a systematic process designed to elicit group judgment. Rocket proponents and scramjet advocates acknowledge, “While performance uncertainties for an integrated air-breathing launch system exist, air-breathing systems have been shown to be less sensitive to these uncertainties than rocket-based systems performing the same missions.”⁷ Second, an Air Force-sanctioned war game, set in 2030, provides the framework for a student-led

replay that pits a notional scramjet-enabled launch system against a near-peer competitor. Compared with those of future conventional rocket systems, the air-breather's forecast capabilities are intriguing. For these reasons and others, scramjet propulsion in a combined-cycle application for air-breathing space launch may be a more promising way to maintain US space dominance in 2030.

Futures Research Methodologies

Most people (including technical planners) imagine the future to be a more or less “linear extrapolation” from the present. This leads them to conceive future space systems as being similar in form and function as today’s systems but having, for example, larger versions of chemically fueled rockets for launch.

—Ivan Bekey

The Delphi futures research methodology, coupled with war gaming, yielded a forecast for scramjet-enabled spacelift likelihood, prevalence, form, function, and employment. This information offers Air Force leadership a plausible vision and path to that vision, so that improved long-term planning and investment strategies can be made.

The Delphi Method

RAND Corporation conceived the Delphi method in the 1950s as a systematic way to approach consensus among a group of experts on topics requiring expert judgment.⁸ Judgments on the likelihood and desirability of a means to achieve a future end state are accommodated. Theodore J. Gordon said that the premise is that “experts, particularly when they agree, are more likely than non-experts to be correct about questions in their field.” The author assembled a diverse and credentialed panel, for the “key to a successful Delphi study lies in the selection of participants.” The demographics of the final 12-member panel were diverse by expertise (air-breathing propulsion, rocket propulsion, and other fields) and by employment (two from NASA, four from the DOD, two from industry, one from academia, and three self-employed or consultants). Eight members of the Delphi panel held a doctorate in aeronautical engineering, mechanical engineering, or physics. The average panelist’s experience was 32 years, and three-quarters of the group reported being a senior member or fellow of one or more professional societies. Furthermore, the same 12 panelists responded to all three rounds of questionnaires—no attrition. Appendix C contains additional panelist information.⁹

War-Gaming the Future

The Delphi questionnaires included questions on scramjet-propulsion implementation that bridged the Delphi method to the subsequent war-gaming research methodology. The Delphi panel helped develop feasible scramjet-enabled spacelift concepts that offered the most favorable design space for achieving the three futuristic benchmark capabilities: (1) turnaround in 24 hours or less; (2) any LEO from anywhere at any time; and (3) semicovert launch. This exercise is not system design but gives necessary form to the technology for game play. One of the three initial vehicle concepts was war gamed. The resultant system was a two-stage-to-orbit (TSTO), air-breathing space launch system composed of two reusable air and space vehicles capable of injecting payloads into LEO. Coincidentally, this vehicle concept had many similarities to those endorsed by the 2000 Air Force Scientific Advisory Board.¹⁰

War gaming placed the conceptual attributes and capabilities into a 2030 war scenario, providing a forum to explore the military advantages of the benchmark capabilities, as provided by an air breather, in the context of a challenging future space environment. Since the players were military officers with various career experiences, the war game elicited professional judgments on potential launch concepts of operations (CONOPS) different from those of advanced rockets, such as evolved expendable launch vehicles (EELV).¹¹ This war-fighter perspective was the war game's key research contribution.

In summary, the Delphi study and the war game provided complementary means to forecast scramjet-enabled space access in 2030. Synthesized expert judgment clarified what may be accomplished by 2030 as well as the technical and nontechnical drivers for that future. This expert judgment fed the war-gaming effort by which military officers evaluated the promised air-breather capabilities and CONOPS. Through these methodologies, significant results emerged.

Launch Capabilities for a Demanding Future

The primary, compelling application of hypersonics for Air Force missions is space access. That is an enduring, critical mission requirement for the Air Force of today and even more so for the Air Force described in Vision 2020. Routine, reliable, flexible, and supportable space access is key to the aerospace force of the future.

—2000 Air Force Scientific Advisory Board

Operationally Responsive Spacelift

The Iraqi and Chinese events demonstrate how space assets and access to space are central to US military action and constitute a center of gravity. These events also signify an emerging environment in which the Air Force may need an improved launch system that provides more responsive and flexible, but less noticeable, access to space.

The DOD and the Air Force have begun to emphasize improved operationally responsive space (ORS) capabilities. The *Plan for Operationally Responsive Space*, published for Congress by the DOD in 2007, defines ORS as “assured space power focused on timely satisfaction of Joint Force commanders’ needs.” Initial requirements include “rapid launch capabilities along with . . . tactics, techniques, and procedures to ensure responsive space operations.” The plan also states that “strategic or long-term needs are not [ORS’s] primary focus.” Although this plan downgrades pursuit of technologies for 2030, it provides a baseline for technology developers to anticipate and pursue next-generation ORS capabilities.¹²

Space Access Capabilities for 2030

To mission-orient the space access technology forecast, this chapter defines three futuristic operationally responsive spacelift (ORS-L) capabilities. The capabilities result from extrapolating the 2001 mission needs statement-listed (MNS) capabilities and characteristics, cross-referencing them with technology trends. The first capability is a less-than-24-hour system turnaround time. Turnaround time within hours is a desirable goal in multiple sources.¹³ This also implies prompt launch readiness and high usage rates.

Launching to intercept any LEO independent of launch coordinates or launch time is the second capability. Today experts restrict most payloads to “launch windows” because of the orbital mechanics of ballistic trajectories originating at fixed locations on Earth’s surface. One source declared, “The potential exists for a single launch site for all orbital inclinations.”¹⁴ Inherent in this capability is tremendous mission flexibility. It also facilitates a high launch rate and all-weather operations.

The third capability is semicovert liftoff and ascent, an idea rarely discussed but critical to understanding discreet missions and improving survivability in a hostile space environment. How clandestine are spy satellites if the United States launches them from well-known, fixed spaceports?

These three capabilities, which may help avoid a prewar intelligence debacle and deter foreign space attacks, serve as benchmarks for futuristic space access performance and facilitate assessment of air-breathing hypersonics as a promising launch technology.

Scramjet-Powered Hypersonics

You will reach the point in the distant future when you won't even think of opposing air in the air. It will be moving too fast. You'll fight them at the launching site or you won't fight them.

—Maj Gen Orvil A. Anderson

Hypersonics

Before covering scramjet propulsion basics and use for space access, one must first clarify the term *hypersonics*. With many recent scramjet engine demonstrations, hypersonics is often used to refer to air-breathing systems that fly at speeds over Mach 5. Mach 5 is the hypersonic flight threshold, but linking air-breathing propulsion to flight in this regime detracts from six decades of experience. As recently as 2004, the first vehicle with air-breathing power, NASA's X-43A, was able to sustain hypersonic flight.¹⁵ Its scramjet operated for about 10 seconds. In 1949 a two-stage, liquid-fueled rocket made the first hypersonic flight.¹⁶ The later space age of intercontinental ballistic missiles (ICBM), manned reentry capsules, and space shuttles required a growing understanding of hypersonics. To date only rocket propulsion has provided operational capability in this flight regime.

The fundamental difference that distinguishes air-breathing space-launch systems from rockets is atmospheric oxygen use for combustion. This requires a technical mastery of the hypersonic regime beyond that required for rockets, which use onboard oxidizers. To maximize outside oxygen use, air-breathing space-launch systems must fly a launch profile that lingers in the atmosphere.¹⁷ Atmospheric acceleration beyond Mach 5 exposes the vehicle to hypersonic flows. At these speeds there is tremendous heat flux into the vehicle, as well as strong shock waves and turbulent flow that increase pressure and drag. Conventional rockets also experience these conditions, but for less time as they take a more direct route to orbit. By making use of harsh flight conditions, air breathers benefit from small carried-oxidizer weights, aerodynamic lift, efficient orbital plane changes, and trajectory flexibility.¹⁸ If air breathers are to operate in this harsh environment and achieve these gains, their subsystems must be integrated. Integration of the powerplant with the vehicle is the sine qua non of air-breathing hypersonic performance (see appendix B).

Scramjets and Combined-Cycle Engines

The scramjet engine fills a critical need for an air-breathing hypersonic vehicle. The first two letters of its name stand for its defining characteristic: supersonic combustion. Fuel injection, ignition,

and heat release all occur in an airflow that exceeds Mach 1. This allows the scramjet to produce efficient thrust at higher speeds. The irony of a scramjet-powered launch vehicle is that the scramjet cannot operate much below Mach 5 or much above the oxygen-rich atmosphere. In other words, a scramjet cannot power a launch system alone, so the complete powerplant is a combined-cycle engine.

Combined-cycle engines consist of multiple types of propulsion—air-breathing (for example, turbojet, ramjet, and scramjet) and non-air-breathing (for example, rockets)—to operate across the launch profile from ground to space. Each propulsion method has an optimal operating envelope quantified by specific impulse—an efficiency metric analogous to automobile miles per gallon (see fig. 4.1). Like gas mileage, a higher I_{sp} is better.

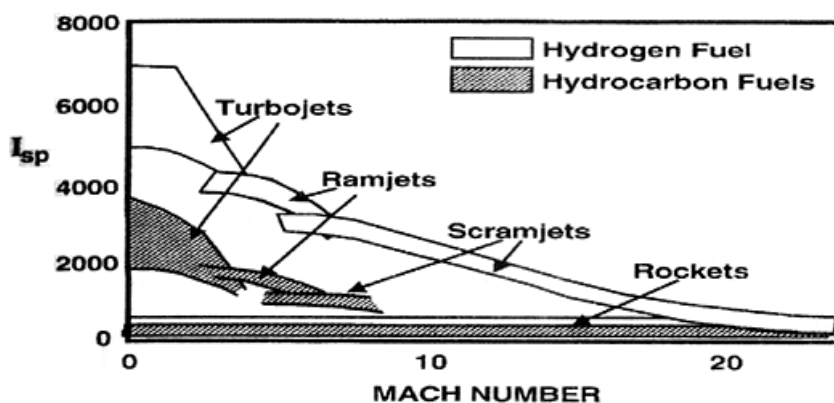


Figure 4.1. Propulsion operating envelopes. (Reprinted from Lourdes Maurice, Tim Edwards, and John Griffiths, “Chapter 12: Liquid Hydrocarbon Fuels for Hypersonic Propulsion,” in *Progress in Astronautics and Aeronautics*, vol. 189, *Scramjet Propulsion*, ed. E. T. Curran and S. N. B. Murthy [Reston, VA: American Institute of Aeronautics and Astronautics, 2000], 761, fig. 1.)

System designers combine propulsion methods to meet mission requirements and produce required thrust. For example, a turbine-based combined-cycle (TBCC) engine sequentially employs four kinds of propulsion. First, the turbojet operates up to Mach 3 where its thrust efficiency begins to drop sharply. Second, the ramjet, devoid of inefficient turbomachinery but still with subsonic combustor through-flow, uses shockwave compression to reach Mach 5 efficiently. Third, the scramjet, which permits supersonic combustor through-flow, takes over until rocket propulsion, the fourth kind, is required. Similarly, a rocket-based combined-cycle engine employs ramjet, scramjet, and rocket propulsion, but in a different sequence than the TBCC. For both combined-cycle engines, the scramjet is the air-breathing workhorse. Furthermore, “the performance of an air-breathing vehicle is improved over a rocket-powered vehicle by extending the useful operation of the

scramjet engine to as high a flight speed as possible.”¹⁹ The desired system capabilities determine which combined-cycle engine is most appropriate. The system also determines the appropriate measure for employing the combined-cycle engine.

Technical Challenges

Research provides a plethora of documentation for the technical challenges and progress of scramjet propulsion and air-breathing hypersonics. US research dates back to NASA’s predecessor in the late 1940s, and substantial Air Force investment began in the mid-1950s.²⁰ Since then, national commitment to air-breathing hypersonics has ebbed and flowed.

By the 1960s the maturity of advanced air-breathing technology caused a redirection of thought toward complex, reusable TSTO vehicles that have air-breathing first stages (with combinations of turbojets, turboramjets, or ramjets/scramjets) and rocket-boosted second stages. The economic realities of the 1970s dictated using semiexpendable approaches, typified by the space shuttle. In the 1980s the potential of the advanced air-breathing scramjet led to the abortive national aerospace plane (NASP) and horizontal take-off and landing concepts for air-breathing single-stage-to-orbit (SSTO) vehicles, using complex propulsion systems.²¹

Despite this tumultuous history, the knowledge pool has been maturing for 60 years. This decade could qualify as another upswing in air-breathing hypersonics research, characterized by the historic X-43A test flight.²² Within the last four years, separate government and industry committees conducted a comprehensive study of the most advanced technologies in hypersonics. A report produced by the National Research Council in 2004, *Evaluation of the National Aerospace Initiative* (NAI), documented an effort to assess the state of two of the three NAI pillars—hypersonics and access to space.²³ Critical areas that require technical advancement were identified, prioritized, and discussed. One year later, the National Institute of Aerospace followed with an even broader report, “Responding to the Call: Aviation Plan for American Leadership,” that decried America’s declining leadership in aeronautics.²⁴ The report devoted one portion to hypersonics, which detailed the status and priority of technical challenges. Both reports included technical-maturity forecasting, with the “Aviation Plan” focusing on a five-year time span and the NAI looking to 2025.

This research defers to those reports for in-depth assessment of the foundational technologies. (Appendix B contains a selection of National Research Council evaluations of NAI-defined technology areas.) In contrast to the technology taxonomy found in those two sources, this research effort focuses on system-level attributes named by the Delphi panel. The panel identifies key enablers of plausible capabilities and CONOPS desirable for Air Force space ac-

cess in 2030. This research contains a section that explains which key enabling system attributes the expert panelists identified, ranks their relative importance, and assesses present-day investments.

The Expectations

Men are to be guided only by their self-interests.

—Thomas Carlyle

What can the Air Force expect from air-breathing access to space in 2030? This research's results produced a plausible answer to this broad question through the two lenses (1) feasibility—likelihood and prevalence; and (2) capability—form, function, and employment. The results include some numeric predictions backed by the identification and extensive discussion of key underlying issues. As expected, differences of opinion were common among Delphi panelists and war gamers, and within the literature. These differences coalesced into prorocket and pro-air-breather camps. For example, one Delphi panelist argued, "Progress in space transportation can be made only if existing chemical rocket engines are supplemented with, or replaced by, revolutionary modes of propulsion." Another rebutted, "The claim that scramjets and air-breathing propulsion will enhance launch flexibility versus rockets is not consistent with the laws of physics or engineering." Dissensus is valuable because it prompts long-term planners to consider future requirements and the options to fulfill those. This research will quote arguments from both sides yet focus on the degree to which scramjets promise a transformational space access capability by 2030.²⁵

Feasibility

When one forecasts the state of an immature or nonexistent technology, the first result should be the likelihood of its existence. If emergence is likely, prevalence is the next logical result. Delphi questions targeted both aspects by asking what percentage of US spacelift launches will and should include an acceleration phase powered by scramjet propulsion. This wording forced panelists to commit to a numeric value to compare with their peers' values and to provide insight into scramjet's prevalence in 2030 across government and commercial users (see fig. 4.2).

The panel predicted that 22 percent of spacelift launches could be enabled by scramjet propulsion by 2030. Essentially, this predication equates to approximately two out of every 10 spacelift launches. To put this percentage in context, historically the space shuttle accounted for 20 percent of US orbital launches in each decade since the 1980s.²⁶ Though this percentage appears to be numerically insignificant, this metric indicates a potential emer-

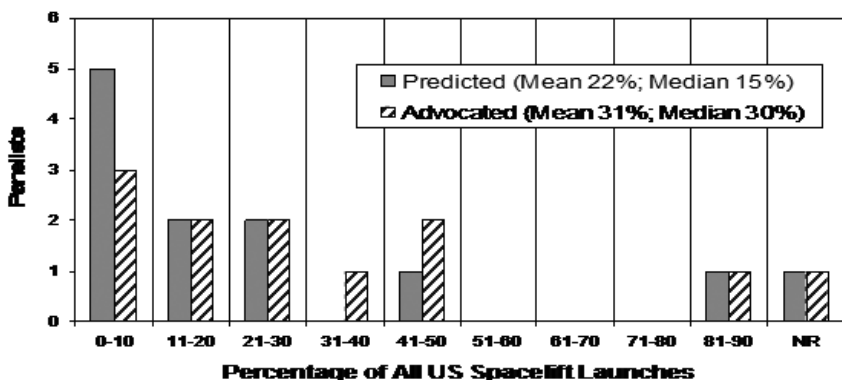


Figure 4.2. US spacelift launches in 2030 powered by scramjets

gence of an air-breathing space launch system by 2030. It must be noted that 30 percent of the panelists predicted that no scramjet-enabled launches will occur. Furthermore, one panelist, who refused to answer, indicated considerable skepticism. Perhaps this skepticism correlates with schedule risk, as discussed later in the research. In one panelist's words, "2030 is much closer than anyone can imagine."²⁷

The metric reached approximately 30 percent of spacelift launches being enabled by scramjet propulsion when the panel was asked for the desired percentage. The increase from predicted to advocated could potentially imply that there is a belief that the United States may ignore air-breathing space access if not significantly influenced, either politically or otherwise. Subsequent panelist debate on technical and economic influences helped explain this likelihood and prevalence forecast.

Technical Influences. After 60 years of research, the technical challenges are known and their solutions are beyond basic research. In this sense, it is justifiable to have some timeline optimism. The more divisive technical issues that cloud the path to future employment demonstrate how difficult those challenges are to solve. If the challenges are solved, one must determine if the resultant air-breathing launch system will deliver what is currently promised.

In 2000 the Air Force Scientific Advisory Board said, "Hypersonics is beyond the point where primary questions involve technological feasibility. Rather, questions now primarily involve investment and resource issues, and issues of operational need."²⁸ Anchoring this position's far end, one panelist considered technology-based pessimism a "story of deception and untruths."²⁹ To explain what has thwarted prior attempts to develop air-breathing launch capability, this group cited political interference and poor leadership. In the wake of these destructive forces is a scrap heap of prematurely canceled experimental and demonstrator vehicle concepts such as the McDonnell Mach 12 Cruiser, X-30 NASP, and X-43B. Moderates in this group acknowledged the technical challenges ahead

but suggested that 22 years of concerted effort is enough time to produce an operational system. In this group's eyes, if nontechnical influences (for example, management, funding, politics, and so forth) nurture technical progress and do not interfere with it, the United States may break the rocket monopoly on space by 2030.

Those who rebut this group point to the technical challenges that a reusable, air-breathing space launch system must overcome. Never before has a launch system had to operate extensively in the extreme temperatures and pressures of the hypersonic regime without structural degradation to fulfill its biggest promises—rapid reusability. One panelist warned against attempting this feat when he stated, “Trying to leap to an operational capability by 2030 is fraught with risk, and to be successful would require multiple technology breakthroughs.”³⁰ Although the panel questioned the term *breakthroughs*, technical advancement in key areas was viewed as difficult.

Four of the five enabling system attributes (full reusability, combined-cycle propulsion, high-temperature materials, and damage-tolerant materials) ranked as the most difficult to achieve. To underestimate these technical challenges would add to the long list of failed programs. To this group, overcoming these challenges requires significant, steady, and long-term investment—likely past 2030.

A similar debate raged at the system level with regard to scalability, design tradeoffs, and test vehicles. These issues relate to how well the air breather's design can move from demonstration to operation. “Scalability ensures that component technologies will be developed and flight-tested in environments relevant to the operational end system.”³¹ Mimicking the hypersonic environment requires tremendous energy, and it remains impractical to test combined-cycle engines and hypersonic vehicles at full-scale size or duration. Therefore, the ability to scale up from a tested model is essential to maturing an air-breathing launch system. Some foresaw accurate computational fluid-dynamics models bridging the gap between subscale experimental data and complex full-scale flows, while others emphasized the scaling difficulty: “The most challenging technology development still remaining . . . will be the 10-fold scale increase and systems integration required to develop an operational reusable launch system.”³²

Experts also disagree on how the air-breathing vehicle attributes will affect design tradeoffs. This debate shakes the foundation of the air-breathing pulpit because it calls into question the achievable performance even if experts solve the basic technical challenges. In simple terms, the issue is whether the multiple propulsion cycles employed by an air breather to optimize I_{sp} and reduce its propellant weight fraction will more than offset the accompanying increased structural weight fraction and aerodynamic drag. Past efforts to tip the balance in favor of the air breather led to

fragile structural margins (as with NASP) or large engines because of low thrust-to-weight ratios (as with TBCC engines). Nonetheless, advancements in lightweight materials and turbojet performance may tip the scale in the near future. Furthermore, in response to the common quip that air-breathing benefits are theoretical, a fully reusable rocket-only system is also theoretical. “Since neither system currently exists, both have uncertainties in weight and performance. The best bet is to go with the system with the least sensitivity to those uncertainties, which is the air-breathing system.”³³

The recent upswing in planned scramjet flight demonstrators was one forecast driver that positively resonated across the Delphi panel. Some optimistic panelists asserted that near-term scramjet demonstration programs are developing the necessary propulsion technologies, aircraft-like operations, and integration of turbo-, ram-, and scramjets. As one panelist noted, “These vehicles and their follow-on operational systems before 2020 will lead to the development of operationally responsive spacelift vehicles before 2030.”³⁴

The major program lineup includes the record-setting NASA X-43A, the soon-to-fly Air Force/DARPA X-51A scramjet-waverider, DARPA’s Force Application and Launch from the continental United States (Falcon) HTV-2, the ongoing Air Force/Australian Hypersonic Flight International Research Experimentation (HIFire), and the Air Force/DARPA Blackswift TBCC-powered vehicle (Falcon HTV-3X). Some panelists remained skeptical that these programs would carry through to an operational system by 2030, saying that “such technologies fall well short of demonstrating the potential for scramjet-based access to space.” Nonetheless, Delphi commentary agreed that US investment in incremental, diverse flight-testing is the best way to resolve technical concerns for or against scramjets.³⁵

In summary, the Delphi study showed that technical influences support a future in which a first-generation, scramjet-enabled launch system provides a small portion of the US spacelift capacity in 2030 as long as the associated technologies approach theoretical performance. When asked about the recent advances in air-breathing hypersonics, Air Force historian Richard Hallion said, “This is like 1937 with the jet engine, which appeared in ’39 or it’s like 1944 in supersonic flight, which we achieved in 1947.”³⁶ Nonetheless, if practical performance does not meet expectations, excitement and support will fade.

Economic Influences. In contrast to the technical influences, the Delphi panel viewed economic influences as greater impediments to realizing scramjet-enabled launch by 2030. Within this broad topic, system costs and funding sources dominated the debate on how money would shape the air breather’s future.

The Air Force Scientific Advisory Board said that “the development of a hypersonic TSTO launch capability would require a massive effort that has been estimated at \$15 to \$25 billion over 15 to 20 years after a decision to proceed.”³⁷ Identifying the resources for

funding an additional \$1 billion per year is challenging. Subsequently, the Air Force is beginning its surge to modernize and recapitalize the aircraft fleet, facing the need to replace many satellite constellations past their design lives, and rolling out its near- to midterm space launch solution—the EELV fleet. To probe the effect of one potential instigator of budgetary change, the Delphi study's second round asked panelists to quantify the effect of emerging foreign ASAT and other counterspace technologies on US funding for space access as well as any resultant change in scramjet propulsion investment. The average panel response expected a slight increase in both areas. Explanatory comments were split but slanted toward a perception that more funding should be spent on space access; however, leadership may be content, right or wrong, with the rocket-only solution.

Even if air-breathing hypersonics are funded at \$1 billion per year, it is difficult to protect their funding streams. Panelists said that “there has been a continuous, albeit fragmented and cyclical, [hypersonic air-breathing propulsion] development effort for decades that will continue.”³⁸ A cyclical funding profile is not conducive to developing a new technology, which several panelists blamed, in part, on other programs plundering hypersonics. At the time of this research, the highest-profile contenders for space launch dollars included the shuttle replacement program and the EELV program. Pres. George W. Bush also called for a return to the moon and a manned mission to Mars. On 15 April 2010 Pres. Barack Obama expressed a desire for Americans to continue to explore ventures to the moon and Mars; however, he also stated that because Americans have already been to the moon, the United States should embrace a space strategy that seeks to move beyond our past accomplishments, perhaps towards other areas of space exploration.³⁹ Given the approximately \$6 billion advanced-capabilities funding allocated to NASA over the next five years, it is unlikely that air-breathing hypersonics will receive sufficient funding, as the cost of developing this technology is very high. NASA's existing programs all have a stake in rockets, and according to the panel, this will likely drive funding for the foreseeable future.⁴⁰

Reduced cost per pound of payload to orbit is the economic promise that the pro-air-breather camp believes may help the technology rise above the rest. It is common knowledge that this recurring cost is sensitive to launch rate. An order-of-magnitude increase in the launch rate results in an order-of-magnitude drop in cost per pound of payload. One panelist provided a figure that showed 3,000 launches per year, equating to \$100 per pound.⁴¹ The United States averages fewer than 200 launches per year using predominantly expendable rocket propulsion across all launch platforms.⁴² The assertion is that a reusable, air-breathing hypersonic launch system operating like an aircraft offers the highest potential to increase the US launch rate by at least an order of

magnitude. Even if air breathers realize this recurring cost reduction, opponents argue that this will do little to offset the system life-cycle cost. One panelist responded with a financial analysis, explaining that the interest cost on a \$15 billion or greater investment would far outpace even the most optimistic recurring cost savings an air breather could provide.⁴³ In short, the selling point of the first of these systems is not its ability to pay for itself through reduced cost to orbit.

In the end, the pro-air-breather camp had few analytical counterarguments to defend new launch technology development for economic gain. Nevertheless, this did not seem to dampen their 2030 capability forecasts because, in their minds, economic justifications take a backseat to need. “Cost will not be the primary driver for development of the scramjet-aided space access technology. Flexibility in deploying assets will drive the need for this technology. The DOD’s need is operationally responsive spacelift. Rocket-engine propulsion cannot meet this need. Air-breathing propulsion on the first stage of a TSTO system can meet this need,” the panelists said. These responses diverted the debate to the second predominant lens—capability—that shed light on what the Air Force can expect from air-breathing space access in 2030.⁴⁴

Capability

The two central questions posed at the beginning of this chapter were, “Can the United States do it?” and “Is it worth it?” The research results presented thus far on technical and economic feasibility forecast how likely it is that the United States can support scramjet technology. The remaining results address the question “Is it worth it?” To a mission-focused Air Force, the expected payoffs and their likelihoods are equally important. Therefore, this futures research also examined the systems’ likelihoods of achieving each of the three benchmark space-access capabilities and the key enabling system attributes. Panelists based forecasts on and argued for whichever system attributes they believed were most favorable to capability achievement in 2030. The split between rocket-only and scramjet proponents was evident, based on a 10-point scale from impossible (0) to certain (10). The value *five* was described as a “moderate likelihood.”

Turnaround Time Less than 24 Hours. The first of the three notional benchmarks for futuristic space access performance, extrapolated from the 2001 MNS, is a less-than-24-hour recovery-to-launch turnaround time. The author asked the Delphi panel to forecast the likelihood of the United States’ operating a launch system with this capability in 2030 (fig. 4.3).

The group statistics indicate a better-than-moderate likelihood of achieving this capability. The figure also shows the mean skewed toward the lower end. The most pessimistic panelist said that “this

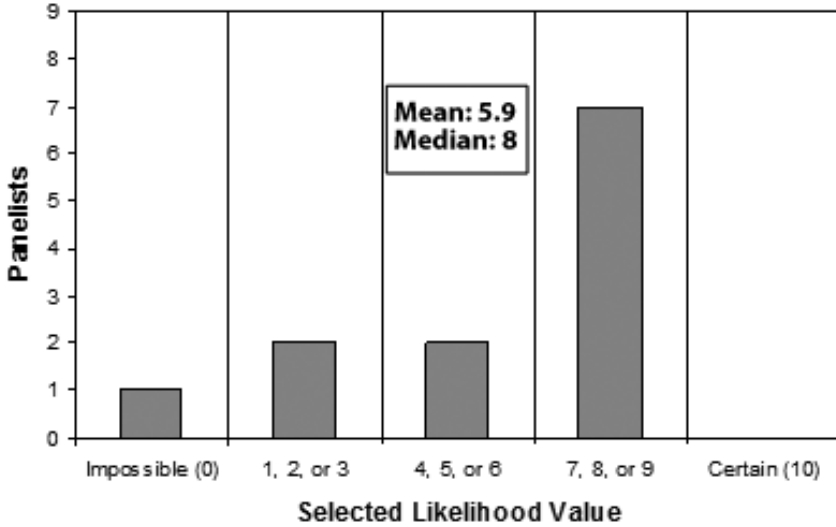


Figure 4.3. Forecast of rapid launch turnaround in 2030

capability requires recovery, inspection, repair, replacement, re-configuration, and reprogramming technologies that are beyond our technical and financial reach before 2030.” The next two lowest values came from panelists who assigned different values to different system characteristics. In these cases, the Delphi moderator included only the lowest value to report a conservative forecast. Specifically, one panelist was more pessimistic about rapid turnaround of the upper stage of a TSTO system (value of two) than the first stage (value of seven). Another advocated an all-rocket-enabled system (value of nine) while condemning a scramjet-enabled system (value of one). In the end, the panel marginalized this individual’s viewpoint by rank-ordering rocket-only propulsion as the least enabling attribute, ranking combined-cycle propulsion four places higher.⁴⁵

Of the 14 system attributes described by panelists as key enablers for rapid turnaround, the top five, beginning with the most enabling, were (1) fully reusable; (2) made from damage-tolerant materials and structures; (3) multistaged; (4) equipped with advanced vehicle-health monitoring; and (5) capable of advanced maintenance techniques. Reusability and damage tolerance are the first and fifth most difficult to achieve. Regarding reusability, one panelist responded, “Pursuing reusable technology has proven to be a dramatic drain on both intellectual and financial resources with no commensurate return.” This aligned with the perceived task difficulty but ran contrary to the majority view on its potential for future launch systems. To paraphrase this majority view: full reusability is essential to breakthrough utility. When a launch system operates like an aircraft, orders-of-magnitude launch-rate increases become realistic. Regarding damage tolerance, this attri-

bute is critical to driving down per-sortie maintenance while providing design benefits. “Deserving of more attention is the reduction of uncertainty in predicting failure of advanced materials toward reducing required safety factors. Structural overdesign has a major negative impact on air-breathing system viability,” a panelist said. Furthermore, when asked which enabling attributes were not being addressed commensurate with their difficulty level, four panelists cited damage-tolerant materials and structures; five cited fully reusable systems.⁴⁶

Any LEO—From Anywhere, at Anytime. The second of the three futuristic space access capabilities is launching to intercept any LEO independent of launch coordinates or launch time. This is the epitome of a responsive and flexible spacelift system. Figure 4.4 shows the predicted likelihood of achievement in 2030.

Of the three capabilities examined, the panel was most optimistic about this one forecast. The pro-air-breather camp asserted that this capability is, in all practicality, exclusive to scramjet-enabled launch systems: “This is the key benefit of air-breathing launch vehicles, especially for the military. This should be the focus of their assessment versus other systems.”⁴⁷ Another panelist said, “Hybrid or reusable TSTO launch vehicles with chemical-rocket engines on both stages do not provide ORS-L because they cannot provide all-azimuth launch capability.”⁴⁸

Unlike a TBCC-powered first stage, chemical rockets cannot be refueled at low speeds to allow loiter, cruise, or both prior to initiating the launch profile. TBCC engines received attention during this debate because of the allure of true aircraft-like operations, provided by the venerable turbojet. However, turbojets are also notorious for their low thrust-to-weight ratios and marginal performance

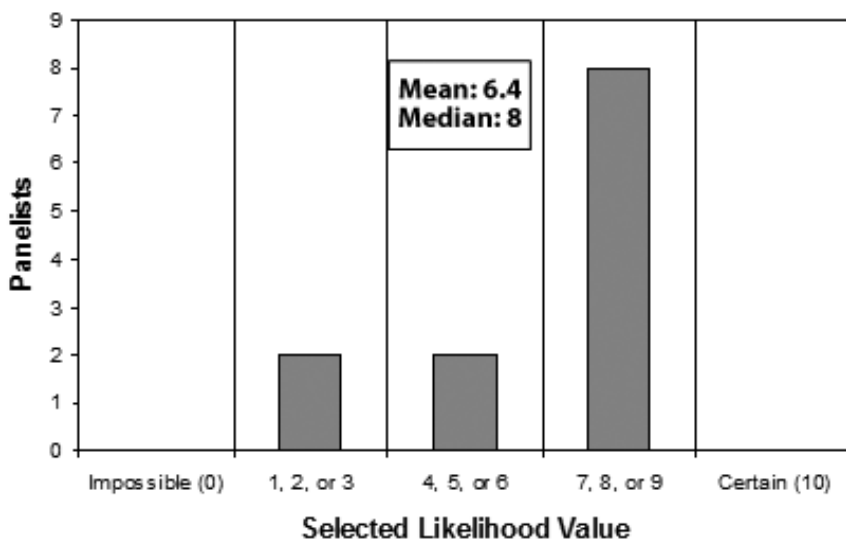


Figure 4.4. Forecast of intercepting any LEO in 2030

at high Mach. The pro-rocket camp rebutted the use of large conventional rocket systems or of an air collection and enrichment system to supply liquefied atmospheric oxygen to the rocket engine to provide this capability. Conversely, the RAND Corporation's 2006 *National Security Space Launch Report* supported the air-breathing argument: "A requirement for an all-azimuth launch to insert payloads into any orbital plane would benefit greatly from the development of systems with hypersonic air-breathing propulsion."⁴⁹

As with the turnaround-time capability, the Delphi study inquired about key enabling system attributes for achieving any LEO from anywhere at any time. The top five enablers were (1) all-weather operations; (2) staging (two or more); (3) combined-cycle propulsion; (4) aerodynamic maneuver during launch; and (5) efficient cruise or self-ferry. Four of the five enablers paint a clear scramjet-enabled launch system picture. The most obvious, combined-cycle propulsion's high rank, is not rocket-only. Aerodynamic maneuver and efficient cruise use lift-generating surfaces that conventional rockets lack. A rocket-powered space plane, a concept endorsed by one panelist, could have these surfaces; however, a rocket would be inefficient during low-Mach cruise. Finally, the fixed rocket-launch sites make them vulnerable to local weather conditions. An air-breathing launch system, which operates from runways and performs long-duration cruise and loiter combinations to select the desired orbit inclination, can avoid severe weather. The United States must pay a price to acquire these attributes.

Of the top five most-difficult-to-achieve attributes, combined-cycle propulsion placed second, and all-weather placed fourth. Furthermore, the panel placed both in the top-three list of attributes not being addressed by the space access community, commensurate with their difficulty level. In the words of one panelist, "The price to have this capability should be paid."⁵⁰

Semicovert Liftoff and Ascent. The third futuristic space-access capability is semicovert liftoff and ascent to obscure the launch, final payload inclination, mission purpose, or all three. Some panelists acknowledged that there could be a covert benefit from an indeterminate launch location. "[Semicovert] launch will require the first stage of a launch vehicle to appear like a conventional aircraft so that the launch vehicle can exit the identified launch area and enter an area where the acceleration phase cannot be observed."⁵¹ Regardless of the panel's position on the covert benefit from an indeterminate launch location, it was clear that any country with space-surveillance capability in 2030 would observe the launch profile. Free to presume any favorable system attributes, the panel predicted it to be unlikely that the United States would possess a semicovert liftoff-and-ascent system in 2030 (see fig.4.5).⁵²

If there is a compelling need for less obvious launch operations than those in existence today, air-breathing launch systems are

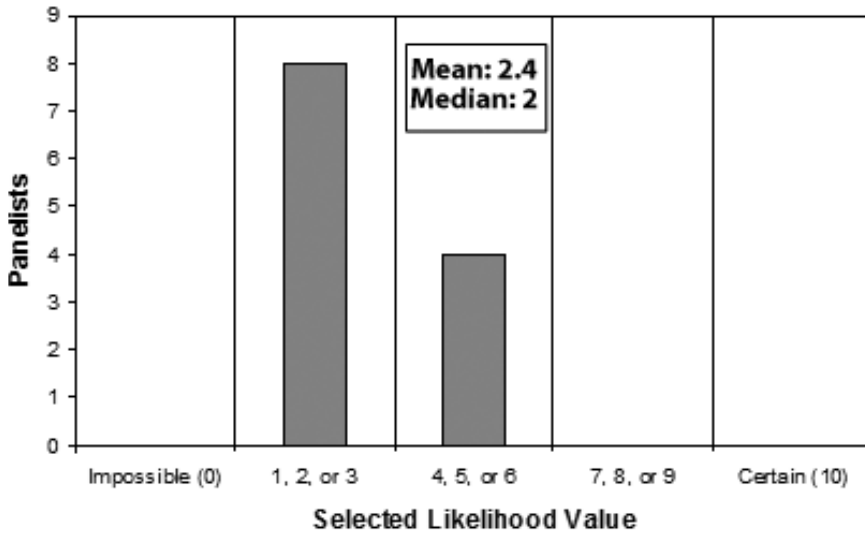


Figure 4.5. Forecast of semicover launch in 2030. The figure presents a mean of 2.4 and a median of two. The panel breakdown for votes were five votes of “one,” two votes of “two,” one vote of “three,” three votes of “four,” and one vote of “five.”

the logical choice. The panel ranked the following five attributes as the most enabling out of 13 considered: (1) launch location flexibility; (2) cruise or self-ferry; (3) staging (two or more); (4) minimal vehicle size; and (5) combined-cycle propulsion. Cruise and combined-cycle propulsion are exclusive to air breathers. Minimal vehicle size does not require new engineering solutions. In fact, small vehicles lessen the scaling challenge faced by air-breathing launch systems. Launch location flexibility would be a clear break from today’s rocket-only paradigm. Reusable air breathers with TBCC engines that can originate from runways across the United States and fly to remote areas of Earth promise wider basing options. Rocket-only propulsion was again ranked as the least enabling.

The Delphi panel predicted a better-than-moderate likelihood of the United States’ having an operational system in 2030 that will be able to recover and launch again in less than 24 hours and reach any LEO whenever and from wherever the liftoff occurs. Semicover launch was forecast to be a bigger stretch, but some multipurpose attributes lend themselves to partially obtaining this idea. The panel selected an aircraft-like air-breathing system rather than a rocket-only system as the one that has the greatest propensity to deliver these three capabilities. The Delphi panel considered staging the most enabling attribute and the least difficult by a wide margin. Attempting another SSTO solution, at least within the next 22 years, would perilously ignore this wisdom. If ORS-L is important to far-term US national security, pursuit of an air breather to provide these types of space access capabilities is worth the United States’ time and treasure.

Concepts and Capabilities War Game

The final research phase collected midlevel Air Force officer judgments on potential employment of these three capabilities. The Delphi-recommended, air-breathing TSTO system was added to the US (blue team) spacelift arsenal and pitted against the motives and forces of a near-peer competitor (red team) with significant ASAT capabilities. The most pertinent red team action for evaluating the TSTO system was an attempt to degrade the blue team's space-based ballistic missile early warning capability immediately before launching an ICBM barrage. The assumption that the blue team could and would destroy any remaining ASAT or ICBM assets following an initial attack provided the motivation behind its attack, resembling a "space Pearl Harbor."

War gamers identified two CONOPS for the new TSTO system that made a discernable, positive impact when compared with use of EELV spacelift. First, postmove adjudication found that the TSTO system's rapid reconstitution capability had a potential deterrent effect. The red team realized that the effect of its space Pearl Harbor would be short term; the subsequent backlash cost outweighed the benefit. Nonetheless, war gamers pointed out that if an adversary could repeatedly target satellites, continued replacement would be a costly and losing proposition.

The second CONOPS used TSTO's precise orbit insertion and semicovert capabilities. Knowing the red team had a formidable ASAT capability and a motive to use it, the blue team used the TSTO system to preemptively replace its critical LEO satellites with decoys. The red team's inability to survey the globe for orbital launches or to identify, track, and target individual satellites in real time allowed the TSTO system to covertly and surgically place decoys in the published, predictable orbits. Meanwhile, the actual satellites maneuvered enough to avoid collateral damage from an ASAT hit on the decoy. A corollary to this would be to place spare satellites on orbit covertly to assume the workload of those destroyed. The war-gaming team also noted that even if the red team had a limited space surveillance capability, the TSTO system's high launch rate would allow plausible deniability of decoy placement. Of the two CONOPS evaluated, decoy or spare satellite placement was the more intriguing and effective in the eyes of those conducting the war game.

Conclusion and Recommendations

Though there has been a somewhat constant trend in funding for hypersonics in general, the future is uncertain for air-breathing hypersonics specifically. It is easier to keep falling back on what is familiar when technical challenges persist and budgetary pressures build. The United States is as much a rocket-based space

industry as it is an oil-based economy. The United States may fall behind if a transformational pursuit is delayed. Recent world events prove that space is becoming more important and less hospitable. This research forecast that a US scramjet-enabled space launch system by 2030 is not far-fetched, but the schedule risk is high. Since the pure economic case for an air breather is weak, the Air Force and other space users must have a compelling need for what this system promises. As one panelist stated, “If there are will and leadership to change the rocket paradigm for a new and desired capability, the vested interests can be controlled and redirected and money can be created to bring about the change by 2030.”⁵³

The panel of 12 propulsion and space-access experts predicted a better-than-moderate likelihood of having disruptive capabilities such as 24-hour-or-less turnaround times and omniazimuthal launch from any site at any time by 2030. The commentary by both the pro-air-breather and prorocket camps made it difficult to discern which system better delivers these futuristic capabilities. Nonetheless, when forced to rank the attributes, the conflicted panel chose combined-cycle propulsion over rocket-only propulsion. Panelist parochialism may have contributed to this choice, but rocket-only propulsion came in last in all three rankings. Highly ranked attributes such as aerodynamic maneuver during launch, efficient cruise, self-ferry, and launch-location flexibility called for charting a new course away from today’s conventional rockets. War gaming this system in a challenging 2030 scenario revealed that intriguing, air-breathing, space access CONOPS merit investment for far-term US national security.

Several recommendations may help the Air Force end the directionless, sinusoidal trend in the air-breathing hypersonics field. First, document far-term (beyond 2025) space access needs pertinent to US national security. Seven years after the Air Force Scientific Advisory Board cautioned that “both operational and technological feasibility has been left to the S&T [science and technology] community,” the DOD published the *Plan for Operationally Responsive Space*, which disregards long-term needs.⁵⁴ This also contradicted a 2006 RAND recommendation to Congress that read, “The US government should identify post-2020 National Security Space requirements so that key technologies and related industrial efforts can be identified and supported.”⁵⁵ Requirements definition is the foundational step in system acquisition; a poor definition may cause focus to wander. To have transformational capabilities by 2030, the United States must begin to focus now. The Air Force should take the lead in defining far-term space access requirements to ensure that future national security needs are met.

Second, protect near-term breathing hypersonic and scramjet-propulsion flight-test programs (X-51A, Falcon, HIFire, and Blackswift) from hasty curtailment. Six of the 12 panelists believe that the current portfolio of US demonstrators is the right near-term

mix to follow a stepping-stone approach to scramjet access to space. Three others believe that the portfolio does not reach far enough. Scramjet flight-test data are essential to correlating theory to practice. The most repeated argument presented by rocket-only proponents was that the air breather's performance is still theoretical. For example, one panelist wrote, "All of these responses [that support air-breathing hypersonics] assume a great amount of knowledge about the performance of hypersonic accelerators which is just not justified by the current state of knowledge. The performance values predicted today are probably the highest they will be and, as we learn more, the performance numbers will decrease and the system weights will increase."⁵⁶ The scramjet must be allowed to prove itself as a success or a disappointment.

Third, settle the technical debate on which kind of space launch system, air-breathing or rocket-only, offers the greater promise to meet the DOD's defined, far-term needs. Far from settling this debate, this research project highlighted the controversy that threatens to dilute investment in the best technical solution. This is not to say that one should stop in favor of the "winner." Rather, the intent is to establish a weighted effort to accelerate achievement of the desired space access capabilities. The Air Force's consideration of either solution should not be impeded because NASA was designated the lead agency for reusable launch vehicles and the DOD was designated the lead agency for expendable launch vehicles. Follow-through must be incremental, methodical, and depoliticized to the greatest extent possible.

Fourth, document the reasons for divergence from air-breathing hypersonics road maps. The DOD often heralds new technology road maps, but later allows them to collect dust as the course changes with new leadership and administrations. Most course changes are necessary and often for the greater good, but documenting the causes for those changes is valuable. Too little of this retrospective angle is available from decision makers and is often reported by a third party attempting to reconstruct the context. Exceptions include the periodic, comprehensive, and publicly documented evaluations of 1998 and 2004 by the National Research Council on the major hypersonics efforts. Continuation of these kinds of road map evaluations are important to documenting why the United States has or has not been able to maintain the course in air-breathing hypersonics.

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Chapter 5

Disruption in Space System Design Using Carbon Nanotubes

Maj David Suh Hoon Menke

Carbon nanotubes have potential technological benefits for the SSA systems presented in chapters 2, 3, and 4 of this monograph. Ideal SSA systems should consist of small, cheap, and resilient satellites. This final chapter investigates CNTs' attributes, utility, and probability of availability for space access systems in 2030, SSA systems, and more.

Introduction

The *2007 State of the Future* lists nanotechnologies as one of five emerging advancements that will have the most positive economic benefit over the next 25 years.¹ The CNT represents a specific nanotechnology with several key attributes, including high strength and low weight. CNTs offer the military an exponential advantage in structures and component materials related to SWaP constraints. CNT technology could potentially disrupt the current large-satellite paradigm. Further, CNTs provide the opportunity to shift to smaller systems to improve access to space and protect space systems, from both a space environment and an ASAT threat perspective.

There are three reasons for claiming CNTs, which allow a shift from the current large-satellite paradigm to a new small-satellite paradigm. First, CNTs enable miniaturization of existing capabilities into micro- (10–100 kg), nano- (1–10 kg), or pico-sized (0.1–1 kg) satellites, allowing the use of existing smaller and cheaper launch vehicles. Miniaturization capabilities will potentially present a significant paradigm shift. Current design methodology and launch vehicles do not motivate engineers to decrease system weight. The appropriateness of maximizing system capability during the design phase is not in question; however, continuing to build large structures increases the cost of a fielded system.

Second, CNTs lend themselves to counter potential ASAT threats. Smaller satellites are more difficult to target, and lighter systems leverage stronger materials to support ORS. The third reason for a CNT paradigm shift is that nanotube technology holds promise in providing improved radiation-hardening attributes. Future satellite design using CNTs may change the thinking about satellites and launch-vehicle size relative to future ASAT threats. Future systems can potentially incorporate CNTs into several distinct applications. This research does not address specific payload capabilities like sensors or communication systems that nanotechnol-

ogy may bring to the fight. Rather, it addresses the methods by which CNTs will potentially benefit future technology trends.

Carbon Nanotubes

“Since their discovery in 1991 by Sumio Iijima, CNTs have fascinated scientists with their extraordinary properties.”² Carbon forms strong bonds with carbon. These bonds can be in the form of graphite sheets (graphene), which can roll themselves onto each other to form tubes.³ Graphene tubes, when constructed with a diameter several nanometers in length, are called CNTs and can be described by their diameter or chirality (twist). CNT classifications include single-walled nanotubes (SWNT) and multiwalled nanotubes (MWNT). MWNTs are composed of concentric SWNTs.⁴

Carbon-based materials exist in a variety of shapes and forms—diamond, graphite, tubular, helical spring cone, and box structures—making them ideal for atomic-level building.⁵ CNTs can be “studied as well-defined engineering structures; and many properties can be discussed in traditional terms of moduli, stiffness, or compliance and geometric size and shape. Nanotubes, owing to their relative simplicity and atomically precise morphology, offer the opportunity to address the validity of different macroscopic models of fracture and mechanical response.”⁶ Based on theoretical and directed experimentation, the elastic modulus of CNTs is one-to-five TPa, which is six-to-10 times that of a carbon fiber.⁷

SWNTs and MWNTs are stronger and more flexible than other materials. CNTs are the strongest and most rigid material known to man.⁸ CNTs

- have strength-to-weight ratio 100–600 times greater than steel;
- elongate 20–30 percent yet rebound with no damage;
- are tolerant to buckling on compression and can recover with no damage;
- conduct heat three times better than pure diamond;
- can be a metal or a semiconductor;
- will not rust or corrode to 1,000° F;
- have the largest surface area of any material in quantity per a given volume;⁹
- are used for plumbing, pressure vessels, electronic circuit boards, container packages, batteries, antennas, deployment mechanics, optics, wiring, rocket cases, and muzzles, among other items;
- unlike composites, do not require matrix compounds such as resin;¹⁰ and
- have an estimated 100-fold weight reduction.¹¹

There are several differences between an SWNT and an MWNT. Unlike the MWNT, the SWNT can be made either metallic or semiconducting, depending upon its chirality.¹² SWNTs, however, are

more difficult to prepare and purify.¹³ For a comparison of SWNTs and MWNTs, see table 5.1.

Table 5.1. Comparison of CNTs

SWNTs	MWNTs
One layer of carbon	Many layers of carbon
Low defect density	High defect density
Good mechanical and electrical properties	Not as good as SWNTs in mechanical and electrical properties
Hard to prepare	Easy to prepare
Hard to purify	Easy to purify

Reprinted from Jie Liu, "Using TGA for Quick Evaluation of Few-Walled CNTs" (presentation, 2nd Joint Workshop on Measurement Issues in Single Wall Carbon Nanotubes: Purity and Dispersion Part II, National Institute of Standards and Technology, Gaithersburg, MD, 26 January 2005).

CNTs can be either semiconducting or metallic. This opens future possibilities for semiconductor-to-semiconductor and semiconductor-to-metal junctions.¹⁴ In addition, carbon lends itself to future bionanotechnology uses.¹⁵

Methodology

This research provides a CNT technology forecast for 2030 and is made through a trend analysis. The following metrics are considered: quantity of CNT production, achieved lengths, production cost, research and development investment, patents, and production methods.

Satellite Design

Space access provides the United States an asymmetric economic and military advantage. Citizens first realized the significance of the space domain with the launch of *Sputnik I* on 4 October 1957. Initial fears focused on the Soviets' ability to place nuclear weapons anywhere on the globe, uncontested. "In the space race, Sputnik galvanized the United States government and popular will at a level comparable to the Japanese bombing of Pearl Harbor 16 years earlier," said Everett C. Dolman.¹⁶ Most citizens, however, take space capabilities for granted and may not desire to address the security issues with respect to current and future threats until a space-like Pearl Harbor event occurs. Despite this lack of interest, the United States dominates both commercial and military space systems to include weather, communication, and navigation. Commercial satellites support everything from credit card transactions to digital radio and television.

The current and anticipated increase in satellite reliance drives the design of systems to support existing and emerging requirements. The importance of space systems requires careful strategic planning to ensure efficient allocation of space program dollars.

The US strategic vision should drive satellite system design and CONOPS. The balance of this section addresses SWaP and its influence on the existing large-satellite design paradigm and the potential new small-system paradigm shift that leverages CNTs.

Spacecraft design is a systematic and iterative process. Engineers design the spacecraft to meet specific mission requirements, driving considerations such as orbit and survivability.¹⁷ Therefore, SWaP dominates satellite design.¹⁸ Concerning size, there are limits on the total volume and specific lengths in each dimension, specifically in launch configuration. Payload fairings critically affect the satellite and are the “single most significant driver of spacecraft design.”¹⁹ Payload fairings encapsulate the satellite during launch.²⁰

Payload capability to support the mission shapes the power requirement.²¹ For example, the total desired bandwidth on a communication satellite defines the required power.²² The duration a satellite remains in eclipse, a condition in which the satellite lacks solar power, influences how much power-storage capacity (size and weight) its batteries must have.²³ Selected satellite orbit also influences power system design. All three components of SWaP affect system cost; these factors led to the large-satellite paradigm.

Military space systems tend to be larger, heavier, and more capable systems. For communication systems specifically, the military and commercial hunger for bandwidth drives large systems. Larger communication and data satellites are believed to be more efficient because these satellites use launch vehicles with the greatest cost-per-pound efficiencies, resulting in a maximization and utilization of diminishing geosynchronous orbital slots. Yet, while the military continues to field large systems, especially for missions in the low and medium Earth orbits, it fails to address other cost challenges and future threats. However, those may be addressed with the use and integration of the CNT technology.

Assured Access to Space

US space dominance requires secure space access, and CNTs may assure this access at a reasonable cost. The current strategy is to reduce launch costs while increasing reliability by focusing on the launch industry. Current designs and process paradigms have likely maximized chemical launch efficiency. There are several approaches to reducing cost. One approach is to increase the number of launches; however, expense and weight requirements prohibit increased launches. Another approach focuses on the satellite itself. Using CNTs will reduce SWaP consumption of satellites without reducing payload capability and will lower the cost concern. The alternative is to transition to a new space access paradigm such as hypersonic vehicles or a space elevator. Yet, even with these systems, CNTs are a key technology because of their ability to provide light and small satellite systems.²⁴

Lighter and Smaller Are Better. The first step toward allowing flexible launch options and responsive space is building lighter and smaller satellite systems. CNTs provide the potential to rely on smaller, less expensive launch systems. “While we continue to develop traditional satellite constellations, we also have an eye on the future with smaller, more tactical, responsive spacecraft,” General Chilton said at a congressional hearing. “As technology improves, we aim to pursue the development of smaller satellites, opening up the possibility of smaller classes of boosters. The Minotaur program and tactical satellites are perfect examples of this strategy.”²⁵

Smaller launch systems promise absolute cost savings. The paradigm of maximizing cost per pound is misleading. For example, larger vehicles provide economies of scale that, when compared with those of smaller vehicles, will yield a lower price per pound. This presumes that satellite weight is not constrained to a smaller launch vehicle during the design process. CNTs allow the use of smaller launch vehicles than would otherwise be required. This can reduce the launch weight requirements by up to 50 percent, which can allow the use of smaller and less expensive lift vehicles. A medium-sized CNT-based satellite could be launched on a Taurus at a cost of \$19 million, rather than on a Delta II costing approximately \$55 million.²⁶ For large satellites, the cost savings are also significant. A CNT-based satellite could be launched on an EELV, involving a price per launch of \$138–92 million versus a launch on a heavy EELV configuration for non-CNT-based systems whose launch costs can exceed \$250 million.²⁷

Responsive Is Better. CNTs will improve the physical interfaces between satellites and launch systems. Today’s satellite contractors leverage commercial satellite structures to satisfy military systems. Upon final integration, several adapters mate the launch vehicle to the satellite. This adds parasitic weight and reduces lift capability, increasing launch cost. For example, the Lockheed Atlas V launch vehicle incorporates two adapters, including a 272 kg booster interstage adapter and a 1,297 kg Centaur interstage adapter.²⁸ Systems built on the current large-system paradigm could use CNT launch vehicle adapters to reduce parasitic weight. The extreme strength of CNTs permits smaller load-bearing interfaces. In addition, with the current-carrying densities of CNTs, potentially 1,000 times greater than copper, miniaturized power and signal interfaces are possible.²⁹ Compact CNT wire bundles could carry high power loads.

An aspect of responsive space requires systems launched on demand to bring new capability or to replace damaged systems. CNTs’ ability to shrink size and weight and to standardize physical interfaces facilitates the ability to launch on multiple systems, increasing responsiveness. Within the current EELV paradigm, the implementation of lighter CNT launch adapters allows program managers to select smaller, less expensive launch vehicles. If EELV continues

its success, the Air Force could transition to multimanifested launches, reducing costs and increasing launch range throughput.

Protection of Space Assets

“The Outer Space Treaty was the product of Soviet and US agreement, which by Cold War standards was globally unanimous. As more nations use space, however, a multitude of standards of behavior will emerge,” said Matthew M. Schmunk and Michael R. Sheets.³⁰ The Chinese ASAT test on 11 January 2007 delivers clear evidence of the plausibility of overt kinetic force in space by other nations.³¹ This test shows that space is not a sanctuary and that future survivability of space systems requires new designs and tactics. Focusing on designs such as smaller satellites permits a peaceful means of countering the ASAT threat. Smaller systems are more difficult to track and target, and miniaturization allows distributed or fractionalized systems. Distributed systems provide faster and less expensive methods to recapitalize capabilities or replace attacked systems. The remainder of this section discusses CNT advantages by discussing their inherent size and protection capabilities.

Smaller Is Better

Smaller space systems provide two major advantages. Recall the constraints of SWaP—“as satellite size decreases, its power requirement decreases faster than its projected area. Smaller satellites typically do not need deployable solar panels.”³² Small systems that do not rely on large, complex deployable appendages decrease risk, such as immediate mission failure. Additionally, smaller satellites allow for less complex structural design because of short thermal and load paths.³³ Also, smaller systems require high-fidelity adversary SSA systems to track, catalog, and understand a satellite’s purpose. Smaller physical size and reduced infrared signatures are obvious tactics for decreased detection.

Carbon Nanotube Inherent Protections

Radiation hardening and directed-energy shielding are key attributes desired for critical satellite systems. CNTs’ inherent physical properties provide these two protections.

Radiation Hardening. “Essential for all small and microsattelites is the durability, the protection against radiation and other particles and the position in orbit.”³⁴ According to the Aerospace Corporation, the military levies radiation-hardening requirements to counter both natural and fabricated sources of radiation. Shielding can occur at the space vehicle skin, box enclosures, and internal components.³⁵ CNTs in structures and components provide inherent radiation shielding.

Commercial satellite-radiation hardening requirements focus on natural sources. Commercial industry measures risk differently and has significant opportunity costs when incorporating margins of protection. Requiring hardened specifications presents a problem involving military systems attempting to leverage commercial technological gains.

CNT structures provide inherent radiation hardening as an added benefit without additional cost. According to the Defense Threat Reduction Agency, the increased cost is only 1 percent to harden against the natural environment. To provide the next level of protection against high-altitude nuclear bursts adds an additional 2 percent to costs. Costs increase an additional 2-to-3 percent for the next two levels of protection.³⁶ If the cost of CNT production drops low enough, commercial satellites may use this new technology. Unlike CNTs, current radiation-hardening methods increase satellite weight and subsequently increase costs.

Directed-Energy Shielding. In addition to size and weight benefits, CNTs may provide protection from directed-energy (DE) attacks. Satellite surfaces constructed of CNTs, which maximize metallic behavior and exhibit reflective properties, could protect satellites from directed-energy weapons (DEW). In addition, the thermal conductivity of SWNTs is second only to epitaxial diamond.³⁷ As a result, CNTs could act as a heat sink by transmitting heat along their tube axis. Bundled CNTs placed perpendicularly to the satellite's external surfaces could remove heat generated from DEWs.³⁸ The combination of the reflective and heat transport layers "laminated" to a satellite's CNT structure could be the ultimate combination of increased strength, reduced weight, and improved DE protection.

Two obstacles prevent this use of CNTs. First, the fabrication process of constructing a homogenous material of only metallic CNTs is expensive.³⁹ Second, CNTs are not the Holy Grail for DE protection. This study addresses attacks against the satellite structure and not the payload, such as optics or feed horns.

Futures Research Methodology

A RAND report noted that "the rapid emergence of nanotechnology also gives rise to 'wildcard' nanotechnologies (that is technologies not expected to be widely available by 2020 but, if they are, will likely have broad and substantial effects). These wildcard nanotechnologies include applications of CNTs or semiconducting and metallic nanowires as individual (designed) functional elements in electronic circuits, and manufacturing using molecular or biological methods."⁴⁰ CNTs are a potential wildcard to consider, and extrapolation can assist with gauging its availability in 2030.

Extrapolation

CNTs have completed the scientific findings and laboratory feasibility stages of innovation by applying Joseph Martino's technological forecasting methodology.⁴¹ NanoComp's report of the ability to produce a three-foot-by-six-foot ultrathin nanotube cloth shows that CNTs are in the prototype innovation stage.⁴² The extrapolation and leading-indicators forecasting methods are therefore appropriate for a 2030 CNT technical forecast. Areas examined include CNT production quantity, quality, length, and cost. Production rates drive overall costs and the feasibility to meet future demand. Data uncovered did not provide a clear picture. Annual production rates are sporadic, depending upon the data analysis.

Variables include the production method, the wall structure (SWNTs or MWNTs), and the required purity. For example, in 2001 arc discharge could produce six grams per hour of SWNTs.⁴³ In 2007 NASA reported rates of 50 grams per hour using a helium arc-discharge method.⁴⁴ Another source reported in 2002–3 that SWNTs were being produced by the high pressure carbon monoxide (HiPCO) chemical vapor deposition (CVD) method at a rate of 0.5 grams per hour.⁴⁵ Yet in 2007–8 several vendors provided pricing for kilograms of SWNTs and metric tons of MWNTs.⁴⁶ The positive trend shows increasing quantities, but the quality of the nanotubes is also critical.

Quality of production is important because of the small scale (nanometer) of CNTs. This scale magnifies differences and changes the material properties. Important attributes include diameter, chirality, removal of contaminants, and SWNT and MWNT segregation. In 2006 Rice University pioneered an approach creating catalyst seeds cut from a single nanotube to obtain uniform diameters.⁴⁷ The purifying process to remove catalysts and other contaminants presents concerns. One production method uses water-soluble catalysts to eliminate damage from the use of acids to remove catalyzing materials.⁴⁸ Changes in temperature, adjustment of the catalyst, or the method itself affects the ratio of SWNT to MWNT produced. A positive qualitative trend exists concerning improving the purity, diameter, and SWNT/MWNT segregation of CNTs.⁴⁹

Constructing small satellite structures requires CNT lengths to be measured in meters. Fig. 5.1 shows that current lengths fall short of the required meter lengths. In April 2007 the University of Cincinnati achieved MWNT lengths of 12 millimeter (mm) and 18 mm. Despite the length barrier, the last two record lengths were grown vertically aligned, in bulk, on a four-inch-wide substrate.

Figure 5.2 extends the data in the previous figure using a power trend line to forecast 2030 CNT lengths. The trend shows that one-meter lengths for SWNTs and 1.5-meter lengths for MWNTs could be achieved by 2024, provided the trend continues.⁵⁰ In the

next decade, CNT lengths may approach the inflection point in which dramatic increase occurs.

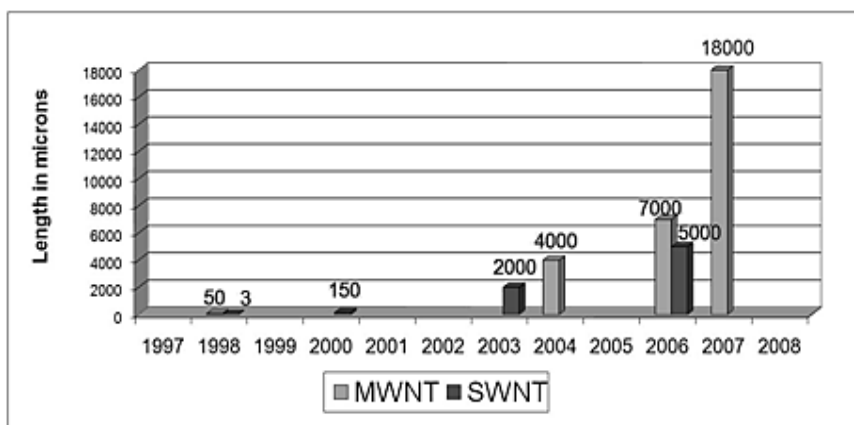


Figure 5.1. CNT achieved lengths. (Created by author, based on the following sources: Z. F. Ren et al., “Synthesis of Large Arrays of Well-Aligned Carbon Nanotubes on Glass,” *Science* 282, no. 5391 [6 November 1998]: 1105; Jian Chen et al., “Soluble Nanotubes,” *Science* 282, no. 5386 [2 October 1998]: 95–98; Philip Kim and Charles M. Lieber, “Nanotube Nanotweezers,” *Science* 286, no. 5447 [10 December 1999]: 2148; Shaoming Huang et al., “Ultralong, Well-Aligned Single-Walled Carbon Nanotube Architectures on Surfaces,” *Advanced Materials* 15, no. 19 [2 October 2003]: 1652; Zhiqiang Liang et al., “Solubilization of Single-Walled Carbon Nanotubes with Single-Stranded DNA Generated from Asymmetric PCR,” *International Journal of Molecular Sciences* 8, no. 7 [July 2007]: 710; and Wendy Beckman, “UC Researchers Shatter World Records with Length of Carbon Nanotube Arrays,” University of Cincinnati, 27 April 2007, accessed 16 March 2008, <http://www.uc.edu/news/NR.asp?id=5700>.)

Finally, it is important to trend production costs to predict return on investment and to evaluate opportunity costs. Specific SWNT and MWNT production costs should be reviewed (see fig. 5.3). SWNT production cost was \$1,000 per gram in 2000. By 2007 NASA’s helium arc discharge process cost \$67 per gram to produce SWNTs.⁵¹ As competition in the area of CNT production increases, looking at retail pricing is helpful in determining a trend. In December 2000 retail pricing listed SWNTs at \$1,500 per gram from BuckyUSA. For comparison, gold at the same time was \$10 per gram.⁵² BuckyUSA now lists SWNTs at \$150 per gram. The data points between the high and low ends of both retail and production costs came from various sources (see fig. 5.3 for the desired downward trend).

The addition of an exponential trend line displays extrapolated costs out to 2030 (see fig. 5.4). Figure 5.5 uses the same X-axis but zooms in on the Y-axis to show the potential cost per gram in the latter years. If the current trend continues, cost may drop below \$1 per gram.

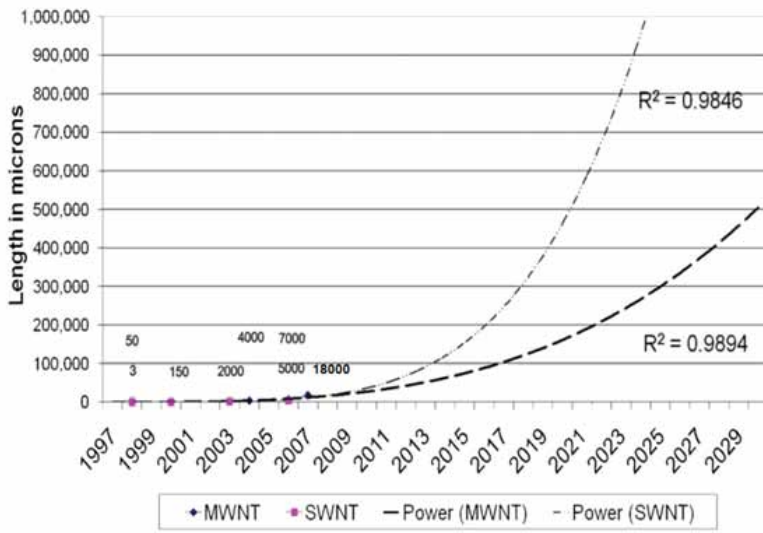


Figure 5.2. Power trend of CNT lengths. (Adapted from Wendy Beckman, “UC Researchers Shatter World Records with Length of Carbon Nanotube Arrays,” University of Cincinnati, 27 April 2007.)

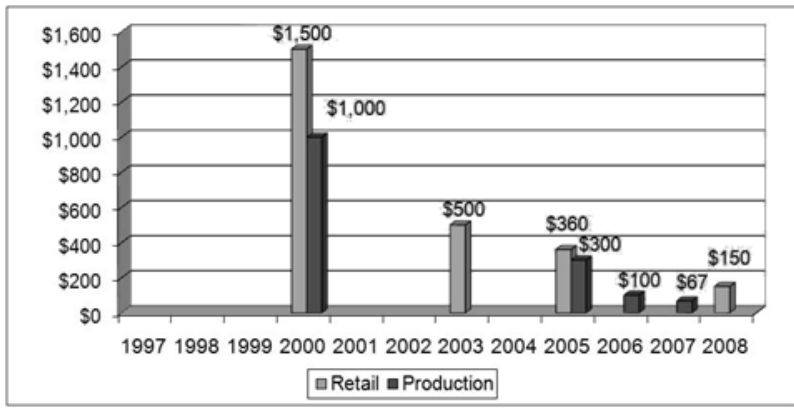


Figure 5.3. Historic CNT costs. (Created by author, based on displays of cost information found in the following: Philip G. Collins and Phaedon Avouris, “Nanotubes for Electronics,” *Scientific American*, December 2000, 67, http://www.crhc.uiuc.edu/ece497nc/fall01/papers/NTs_SciAm_2000.pdf; BNET, “Manufacturing High-Quality Carbon Nanotubes at Lower Cost,” *NASA Tech Briefs*, September 2004, http://findarticles.com/p/articles/mi_qa3957/is_200409/ai_n9437441; Michael Kanellos, “From Cars to Medicine, Nanotubes May Be Miracle Material,” *CNet News*, 20 October 2003, <http://www.news.com/2009-1008-5091267.html>; Harry Swan, “Workshop II: ‘Nanomaterials Surfaces and Layers’ Commercialising Carbon Nanotubes” [presentation, Nanotechnology Forum 2005], slide 24, http://www.nanotechnology.de/ntforum/download/17_Swan_Thomas_Swan&Co_Ltd.pdf; Jeannette Benavides, “Low-Cost Carbon Nanotubes (CNTs) from Coal,” NASA Director’s Discretionary Funds Report, 2, http://ddf.gsfc.nasa.gov/report/2005/pdfs/EN_Benavides.pdf; NASA Goddard Space Flight Center, “Producing Lower Cost Single-Walled CNTs without Metal Catalysts”; and BuckyUSA, “Price List,” 3 September 2007, 4, <http://www.buckyusa.com/price%20list.pdf>.)

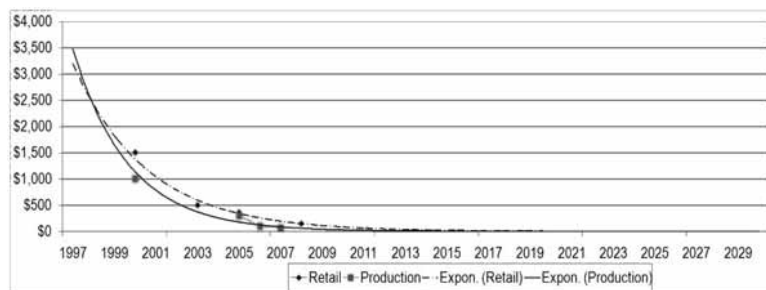


Figure 5.4. CNT cost projection. (Created by author, based on displays of cost information found in the following: Philip G. Collins and Phaedon Avouris, “Nanotubes for Electronics,” *Scientific American*, December 2000, 67, http://www.crc.uu.edu/ece497nc/fall01/papers/NTs_SciAm_2000.pdf; BNET, “Manufacturing High-Quality Carbon Nanotubes at Lower Cost,” *NASA Tech Briefs*, September 2004, http://findarticles.com/p/articles/mi_qa3957/is_200409/ai_n9437441; Michael Kanellos, “From Cars to Medicine, Nanotubes May Be Miracle Material,” *CNet News*, 20 October 2003, <http://www.news.com/2009-1008-5091267.html>; Harry Swan, “Workshop II: ‘Nanomaterials Surfaces and Layers’ Commercialising Carbon Nanotubes” [presentation, Nanotechnology Forum 2005], slide 24, http://www.nanotechnology.de/ntforum/download/17_Swan_Thomas_Swan&Co_Ltd.pdf; Jeannette Benavides, “Low-Cost Carbon Nanotubes (CNTs) from Coal,” NASA Director’s Discretionary Funds Report, 2, http://ddf.gsfc.nasa.gov/report/2005/pdfs/EN_Benavides.pdf; NASA Goddard Space Flight Center, “Producing Lower Cost Single-Walled CNTs without Metal Catalysts”; and BuckyUSA, “Price List,” 3 September 2007, 4, <http://www.buckyusa.com/price%20list.pdf>.)

Leading Indicators

Investment in nanotechnology, both foreign and domestic, provides an important leading indicator. From a domestic perspective, it provides insight into the national priority of the initiative. US investment for all nanotechnology in 2001 was \$464 million; by 2005 this amount had tripled to \$1.2 billion. By 2008 the figure had risen to \$1.4 billion.⁵³

A comparison of domestic and foreign investment shows that the United States provides about 25 percent of total global nanotechnology investment. The global trend projects a continuing US lead with Japan, China, and Europe as potential peers.⁵⁴

The second indicator, a lagging metric, is the number of nanotechnology patents. Patents provide an indication of return on investment of research and development dollars expended (see fig. 5.6).⁵⁵

The patents (ranging from 1997 to 2003) were sorted by date of submission, not the date of patent award. Patent submissions not awarded a patent were not considered. At first glance, it appears that patents peaked in 2003. Patent awards, however, can take several years. The final number of submissions validated by the US Patent and Trademark Office (USPTO), beginning in 2004, is unclear. Data reveal that the United States led in the total number of US patents through 2003, but it is too

early to analyze beyond that. There are two critical points to analyzing patents. First, the efficiency of the USPTO processing and the complexity of the patent submission may distort the data. Second, some companies prefer not to apply for patents. They would rather invoke security protocols such as nondisclosure agreements to protect CNT-related processes.⁵⁶

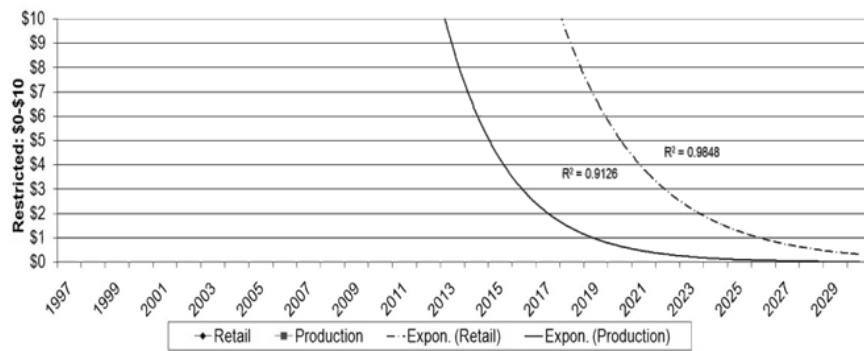


Figure 5.5. CNT cost projection, \$0–\$10 zoom. (Created by author, based on displays of cost information found in the following: Philip G. Collins and Phaedon Avouris, “Nanotubes for Electronics,” *Scientific American*, December 2000, 67, http://www.crhc.uiuc.edu/ece497nc/fall01/papers/NTs_SciAm_2000.pdf; BNET, “Manufacturing High-Quality Carbon Nanotubes at Lower Cost,” *NASA Tech Briefs*, September 2004, http://findarticles.com/p/articles/mi_qa3957/is_200409/ai_n9437441; Michael Kanellos, “From Cars to Medicine, Nanotubes May Be Miracle Material,” *CNet News*, 20 October 2003, <http://www.news.com/2009-1008-5091267.html>; Harry Swan, “Workshop II: ‘Nanomaterials Surfaces and Layers’ Commercialising Carbon Nanotubes” [presentation, Nanotechnology Forum 2005], slide 24, http://www.nanotechnology.de/ntforum/download/17_Swan_Thomas_Swan&Co_Ltd.pdf; Jeannette Benavides, “Low-Cost Carbon Nanotubes (CNTs) from Coal,” NASA Director’s Discretionary Funds Report, 2, http://ddf.gsfc.nasa.gov/report/2005/pdfs/EN_Benavides.pdf; NASA Goddard Space Flight Center, “Producing Lower Cost Single-Walled CNTs without Metal Catalysts”; and BuckyUSA, “Price List,” 3 September 2007, 4, <http://www.buckyusa.com/price%20list.pdf>.)

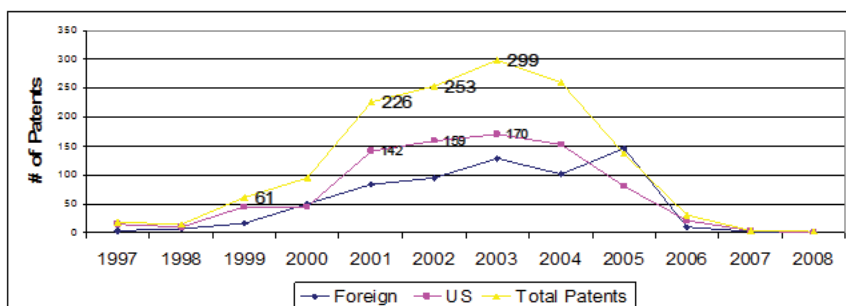


Figure 5.6. CNT patents by year. (Adapted from US Patent and Trademark Office website, <http://www.uspto.gov>.)

The final leading indicator considers the number of CNT production methods. With the discovery of new CNT production methods comes the potential for improvements in quality, quantity, and lower cost, resulting in confidence that a suitable production method will be discovered to support future space systems. The major CNT production methods include arc discharge, laser ablation, and variations of CVD. Arc discharge, the first method of production, uses a high current passed between graphite electrodes. The heat generated by the discharge sublimates the carbon, creating the CNTs. This method has a low yield of 30 percent by weight and produces both SWNT and MWNTs with lengths around 50 micrometers (μm), and diameters of 0.7–2.0 nm.

The second process, laser ablation, uses a pulsing laser to vaporize graphite. CNTs collect on a cool surface as the vapor condenses. This process yields about 70 percent and produces SWNTs. The expense of the laser makes this method more costly.⁵⁷ Laser ablation is done at lower temperatures of 1,200 Celsius (C) compared with the arc process at 2,000–3,000 C.⁵⁸

CVD, the third method of CNT production, dominates the industry. This process uses a substrate prepared with metal nanoparticles. The selection of nanoparticle size controls the diameter of CNTs produced. The substrate is heated and exposed to carbon-containing gas, and the reaction breaks the carbon into single atoms, which deposit at the edges of the nanoparticle catalyst. The carbon atoms continue to deposit and grow into the CNT.⁵⁹ This method occurs at 650–900 C. CVD offers the least expensive method of the three processes thus far.⁶⁰

CVD has variations in processing methods. One variation is plasma enhanced CVD (PECVD). This method introduces plasma and an electric field to force the CNT growth in the direction of the electric field, providing vertically aligned CNTs.⁶¹ The PECVD process permits controlled growth of CNTs. The DE section highlighted the potential application of these vertically aligned CNTs. On the downside, plasma CVD always produces MWNTs and carbon filaments.⁶³ This requires a purification and separation process if uncontaminated SWNTs are desired. Another variation, HiPCO, shows promise of continuous production of CNTs by using catalysts floating in the gas phase rather than fixed structures. This allows for continuous introduction of more catalysts for production of more CNTs.⁶³

Comparison of the three major CNT production methods shows that the CVD method leads because of its scalability; however, arc discharge may prove to be a dominating technology. Use of CNTs in satellite structures requires a version of CVD that produces higher-quality SWNTs, a more efficient version of arc discharge or laser ablation, or a new process. NASA has rediscovered and improved the arc discharge method, which will become the means of achieving

full-rate production of SWNTs to support future small-satellite structures. This assessment requires future expert validation.

In 2007 the National Nano Engineering Conference recognized NASA Goddard for its patented process of SWNT production that does not use a metal catalyst.⁶⁴ This process uses helium in its arc discharge method and yields 70 percent SWNTs compared with the original arc discharge yield of 30 to 50 percent. It has the potential to be more cost efficient by eliminating expensive metal catalysts and at least a one-step reduction in the purification process. According to NASA, “Unlike most current methods—which require expensive equipment (for example, a vacuum chamber), dangerous gases, and extensive technical knowledge to operate—NASA’s simple SWNT manufacturing process needs only an arc welder, a helium purge, an ice-water bath, and basic processing experience to begin production.” NASA indicates that integrating SWNTs into a polymer will create a fiberglass-type material stronger than steel but one-sixth the weight. NASA licensed this process to companies for production.⁶⁵

The Naval Research Lab has announced a method of production of MWNTs. Though not a SWNT production method, this new Navy process presents a significant leap in CNT production. First, it does not form CNTs from a carbon-containing gas. Rather, CNTs can be produced from thermal decomposition or from melting commercially available carbon-containing resins and adding metal salts. The carbonization of the material produces CNTs inside a solid carbon form. The Naval Research Lab claims that its solid-state process lends itself to large-scale production.⁶⁶ This new method of production could be modified to produce SWNTs.

Since their 1991 discovery, three methods of CNT production continue to dominate. The CVD process remains the preferred commercial method to produce MWNTs. Desire to lower cost continues to drive new variations of all three methods of production. The Naval Research Lab’s new method is a positive leading indicator. More developments indicate that CNT production could support satellite production in 2030.

Dual-Use Implications of Carbon Nanotubes

Funding required to develop military-desired CNT properties will not be driven by the commercial sector. However, the protections desired for military satellites have application in commercial space systems and also tremendous terrestrial utility.

Jim Oberg in *Space Power Theory* highlighted the shift from military to commercial investment in space activities. By 2010 only 10 percent of US space industry revenues will come from military sources, contrasting the situation in 1996 when the military provided half of the revenue.⁶⁷ Following Oberg’s publication in 1999, the satellite industry saw a reduction in satellite orders although

recovery has been seen in the last several years. From a commercial-satellite market perspective, the development of CNTs lacks priority. But the satellite industry emphasizes the benefits of space data and communication systems. Organizations such as the Satellite Industry Association point out that natural disasters such as hurricanes, tornados, or floods do not affect space systems.⁶⁸ If critical systems used by civilian first responders move to space, and if the global war on terrorism continues, systems must be able to protect themselves from threats such as high-altitude nuclear detonation.

It could be argued that in 25 to 30 years the need for stronger, lighter materials for terrestrial systems will rise. For example, Ford Motor Co. invests in nanotechnology to produce lighter car materials to improve safety and attain higher fuel-efficiency standards.⁶⁹ The drive for more efficient and lighter power cells may find CNT capacitors replacing nickel-metal hydride and lithium ion batteries. Also, the desire for alternative, cheaper, and greener power pushes solar cell technologies. Miniaturization of these power system components will enable smaller space satellites. Overall, industry will drive CNT space development as much as the military will.

Conclusion/Recommendation

The current paradigm drives the Air Force to produce larger and more capable satellite systems. This paradigm perpetuates the need for larger and more expensive launch systems. The United States must embrace a new, smaller satellite-design paradigm in which it leverages nanotechnology to continue to increase US satellite technological advantage and to field more capable systems for a lower cost.

Outlook of Carbon Nanotubes in 2030

Before CNTs are used in space structures and components, various technical challenges must be overcome. These challenges include issues with CNT length, quality, production quantities, and cost. This analysis shows that CNTs currently fall short of required meter lengths. Lengths of 12 mm and 18 mm for MWNT in late 2007 trend higher than the 50 μm produced in 1997.⁷⁰ If this power trend endures, lengths in meters could be achieved by 2030. A positive qualitative trend continues to improve the purity, diameter, and CNT segregation. Production quantities increase, but a year-end 2006 National Science Foundation-sponsored report reveals that Asia outpaces America in CNT production by a ratio of four to one. Costs have a downward trend ranging from \$1,500 per gram in 2000 to \$150 per gram in 2008.⁷¹ Similar to the length trend, if costs decrease exponentially, CNTs will drop below \$1 per gram by 2030.

What to Watch For

Several new CNT production techniques have been discovered, with a few enhancements of existing processes attempting to exploit all possible efficiencies. For example, the new NASA arc discharge method reduces or eliminates purification-process steps.⁷² CNT production development would change satellite design and employment. This could include smaller vehicles, leading to reduced signatures and launch-capability requirements, thus lowering costs and favoring distributed or fractionalized systems rather than single large satellites that present single points of failure. Additional direct military impacts include the space elevator concept, hypersonic vehicles, and future remotely piloted combat vehicles. Commercial benefits include transportation industry dividends by allowing drastic fuel-efficiency improvements. Additional areas of investigation specific to environment impacts such as health, disposal, and recycling must be accomplished.

The United States must be cognizant of global investments in CNTs. Inherent dangers loom if adversaries are the first to produce CNTs inexpensively, in large quantities, and as fabricating structures. The United States could face asymmetrical threats from foreign space systems launched faster and with technological advantages.

Targeted Investment to Enable Success

A RAND 2020 projection indicates uncertainty for military nanotechnologies, highlighting the need for coupling focused dollars into CNT research and development and leveraging the lucrative commercial CNT spin-offs. Vehicles with increased fuel efficiency resulting from exponential weight decreases could be built.⁷³ The demand for CNTs will continue the trend of increasing production and driving down costs.

The Air Force must focus research dollars in two areas: (1) determining CNT behavior in structures at the macroscale; and (2) determining required changes in satellite structure attributes based on CNT macroscale properties. These changes may include spar and stringer proportions such as length to thickness to maximize CNT properties. It may mean merging the payload component and the load-bearing structures. For example, CNTs used in circuit cards and component boxes could be attached to each other without being mounted to a separate frame or bus structure. This approach reduces weight and required satellite volume.

A reduction in the price of CNTs to below \$1 per gram in 2030 and the miniaturization of satellite payload capability would necessitate additional cost analysis. For instance, based on new system designs using CNTs, how much material would be needed for micro- (10–100 kg), nano- (1–10 kg), or pico-sized (0.1–1 kg) satellites? The weight provides the means to calculate material costs.

Nevertheless, new fabrication or structures processing may introduce additional satellite production costs that require further investigation.

Those who do not embrace change yet advocate staying the course with the current paradigm may argue that the expense of CNTs is too great. The previous pages highlight significant enhancements such as reduction in launch cost and defensive ASAT attributes that CNTs bring to the fight. CNTs also provide a means to disrupt the current paradigm of designing large-satellite and launch systems. The Air Force must pursue promising CNT research as an enabler for both space access and SSA in 2030.

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Appendix A

Technology Readiness Levels

Technology Readiness Level	Description
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Example might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3. Analytical and experimental critical function and/or characteristic proof of concept	Active research and development are initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory.
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
7. System prototype demonstration in an operational environment	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as an aircraft, a vehicle, or space. Examples include testing the prototype in a test-bed aircraft.

Technology Readiness Level	Description
8. Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system proven through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.

Reprinted from Department of Defense, *Defense Acquisition Guidebook*, 2006, table 10.5.2.1, accessed 17 March 2009, https://akss.dau.mil/dag/Guidebook/IG_c10.5.2.asp.

Appendix B

Status of Selected Space-Access Technologies

Major Technology Area (Criticality)	Constituent Technology	CML ^a /TRL ^b	Impact on Major Technology Area	Likelihood of Achievement in Time Frame
HIGH-SPEED/HYPERSONICS PILLAR				
Air-Breathing Propulsion (High)	Scramjet combustors	2.5/4–6	Extreme	Medium
	Engine control system	2.5/4–6	Significant	High
	Propulsion-airframe integration	2.5/3–6	Extreme	Medium
Engine Materials (High)	Cooled ceramic matrix composite panels	1.5/2–4	Extreme	Low
	Cowl lip	2.5/3–6	Extreme	Medium
	Seals	2/3–4	Extreme	Medium
Airframe Materials (High)	Leading edges	3/4–6	Extreme	Medium
	Thermal protection systems	2.5/3–6	Extreme	Medium
	Structure	3/3–6	Significant	High
ACCESS TO SPACE PILLAR				
Airframe Thermal Protection (High)	Materials	3/	Extreme	Medium
	Acreage surfaces	3/	Extreme	Low
Airframe Integrated Structures (High)	Highly integrated subsystems	3/	Significant	Medium
Propulsion Controls (High)	Health management	2/	Significant	Low
	Engine controls	4/	Significant	Medium
Vehicle Health (Medium)	Prognostics	2/	Significant	Low
Rapid Mission Response (Medium)	Launch and landing flexibility	2/	Significant	Medium

Adapted from National Research Council, Evaluation of the National Aerospace Initiative (Washington, DC: National Academies Press, 2004), 35–37, 61–80, tables 2-1, 3-1, 3-2, 3-3, 3-4, 3-5, and 3-6.

^a Current maturity level (CML)—roughly corresponds to DOD Science and Technology categories of (1) basic research, (2) applied research, (3) advanced development, (4) demonstration and validation, and (5) engineering and manufacturing development.

^b Technology readiness level (TRL). Scale used was an extension of the NASA TRL scale of one to nine.

Appendix C

Delphi Study Panelists

Dr. Kevin G. Bowcutt

Senior Technical Fellow and chief scientist of Hypersonics, Boeing Company–Phantom Works

PhD, Aerospace Engineering

MS, Aerospace Engineering

BS, Aerospace Engineering

Senior member, American Institute of Aeronautics and Astronautics

Visiting professor, Princeton University Mechanical and Aerospace Engineering Department

Twenty-five years of experience at Boeing. An internationally recognized expert in hypersonic aerodynamics, propulsion integration, and vehicle design and optimization. Technical lead for propulsion integration on the National Aerospace Plane (NASP) program.

Dr. Richard K. Cohn

Technical advisor/chief engineer, Liquid Rocket Engines Branch, Propulsion Directorate, Air Force Research Laboratory (AFRL)

PhD, Mechanical Engineering

MS, Engineering

BS, Mechanical Engineering

Cochair, Joint Army Navy NASA Air Force (JANNAF) Interagency Liquid Propulsion Subcommittee Technical Steering Group

Senior member, American Institute of Aeronautics and Astronautics

Seventeen years of experience in liquid rocket engine development and high-pressure, high-temperature flows

Prof. Paul A. Czysz

President, Hypertech Concepts LLC

Professor emeritus, Department of Aerospace and Mechanical Engineering, St. Louis University

BS, Aeronautical Engineering

McDonnell Douglas Corporation (MDC) Fellow

Associate Fellow, American Institute of Aeronautics and Astronautics

Chairman, Propulsion Committee of the International Astronautical Federation

Twenty-nine years of experience with the McDonnell Douglas Corporation. Served as the principal scientist for the NASP Program. Has authored or coauthored over 100 professional papers.

Mr. Jeff L. Drouhard

National Air and Space Intelligence Center

MS, Aerospace Engineering

BS, Mechanical Engineering

Twenty-two years of experience in technology development and assessment, focusing on advanced propulsion and hypersonic technologies

Dr. William H. Heiser

Professor emeritus, Department of Aeronautics, USAF Academy

PhD, Mechanical Engineering

MS, Mechanical Engineering

BS, Mechanical Engineering

Fellow, American Institute of Aeronautics and Astronautics

Fellow, American Society of Mechanical Engineers

Member, Aeronautics and Space Engineering Board of the National Academy of Engineering

Member, Office of Defense Research and Engineering Technical Area Review and Assessment Team

Fifty-two years in the research and development of propulsion and energy conversion technology. A balance of experience in business, government, and education.

Dr. Thomas A. Jackson

Deputy division chief for science, Aerospace Propulsion Division, Propulsion Directorate, AFRL

PhD, Mechanical Engineering

MS, Management of Technology

MS, Aerospace Engineering

BS, Aerospace Engineering

Chair, JANNAF Engine Testing and Validation Panel

Senior member, American Institute for Aeronautics and Astronautics

Member, American Society of Mechanical Engineers

Technical advisor for scramjet propulsion experimental research and former branch chief and researcher of lubricants, fuels, and combustion processes. Has authored over 15 major technical publications.

Dr. Unmeel Mehta

Division scientist, Space Technology Division, NASA Ames Research Center

PhD, Mechanical and Aerospace Engineering

MS, Mechanical and Aerospace Engineering

BS, Mechanical Engineering

Associate Fellow, American Institute of Aeronautics and Astronautics

Recipient of the NASP Gene Zara Award

Established the NASP Computational Fluid Dynamics Technical Support Team; provided direction and source-selection support for the NASP program; and served as a subject-matter expert on DARPA's HTV-3X effort under the Falcon Program. Has authored or coauthored 58 technical papers or reports.

Mr. Jess M. Sponable

Focus area lead for space access and long-range strike, Air Vehicles Directorate, AFRL

Program manager, AFRL Fully Reusable Access to Space Technology (FAST) Program

MS, Systems Management

MS, Astronautical Engineering

Twenty-year career as an Air Force officer with service in the NASP Program and as program manager, Delta Clipper-Experimental (DC-X) Program. Held various positions in the commercial and government sectors, including vice president of flight operations at Universal Space Lines.

Dr. Charles J. Trefny, Professional Engineer

Planner, Fundamental Aeronautics Program, NASA Glenn Research Center

Member, NASA Glenn Center Director's Research Advisory Board

PhD, Aerospace Engineering

MS, Mechanical Engineering

BS, Mechanical Engineering

Senior member, American Institute of Aeronautics and Astronautics

Member, American Society of Mechanical Engineers

Licensed professional engineer

Twenty-six years of experience at NASA Glenn Research Center working air-breathing and rocket propulsion. Has authored 34 technical publications.

Dr. David M. Van Wie

Director, Precision Engagement Transformation Center, Johns Hopkins Applied Physics Lab

Research faculty, Department of Mechanical Engineering, Johns Hopkins University

PhD, Aerospace Engineering

MS, Electrical Engineering

MS, Aerospace Engineering

BS, Aerospace Engineering

Member, Air Force Scientific Advisory Board

Member, National Academy of Science-National Research Council

Two-time recipient of NASP "Gene Zara Award"

Twenty-seven years of experience in the field of air and space vehicle design and development with emphasis on supersonic- and hypersonic-flight vehicles

Mr. Randy Volland

Vice president, Hypersonics, Aerospace and Clean Energy Technologies (ACENT) Laboratories LLC

MS, Fluid Mechanics and Thermal Sciences

BS, Mechanical Engineering

Associate Fellow, American Institute of Aeronautics and Astronautics

Twenty-four years of experience, 22 years at NASA Langley Research Center working hypersonics. Hyper-X Program (X-43A) Propulsion team lead and senior technical representative for X-43A Flights 2 and 3 Preparations.

Dr. James R. Wertz

President, Microcosm Inc.

Adjunct professor, Astronautics and Space Technology Division, University of Southern California

PhD, Physics

MS, Administration of Science and Technology

BS, Physics

Fellow, British Interplanetary Society

Fellow, American Institute of Aeronautics and Astronautics

Member, International Academy of Astronautics

Holds multiple patents for orbit and attitude control systems

Forty-two years of experience in orbit and attitude determination and control systems, satellite autonomy and sensor measurement theory, and space mission cost reduction. Editor and principal author of four reference texts on spacecraft control and mission analysis.

Abbreviations

ACSC	Air Command and Staff College
AES	aeromedical evacuation squadron
AFIT	Air Force Institute of Technology
AFRL	Air Force Research Laboratory
AFROTC	Air Force Reserve Officer Training Corps
AFSPC	Air Force Space Command
ARGUS-IS	autonomous real-time ground ubiquitous surveillance-imaging system
ASAT	antisatellite
ATSC	Advanced Television System Committee
AWC	Air War College
C	Celsius
C2	command and control
CCD	charged coupled device
cm	centimeter
CMOS	complementary metal-oxide semiconductor
CNT	carbon nanotube
CONOPS	concept of operations
CSAT	Center for Strategy and Technology
CVD	chemical vapor deposition
DARPA	Defense Advanced Research Projects Agency
DE	directed energy
DEW	directed-energy weapon
DOD	Department of Defense
DRAGNETS	distributed real-time awareness global network in space
EELV	evolved expendable launch vehicle
FAS	Federation of American Scientists
FEEP	field effect emission propulsion
FMV	full motion video
fps	frames per second
g	gram
GEO	geosynchronous Earth orbit
GPS	Global Positioning System
GSD	ground sample distance
HIFire	Hypersonic Flight International Research Experimentation
HiPCO	high-pressure carbon monoxide

ICBM	intercontinental ballistic missile
IMA	individual mobilization augmentee
IRARS	Imagery Resolution Assessments and Reporting Standards
I_{sp}	specific impulse
ISR	intelligence, surveillance, and reconnaissance
JWST	James Webb Space Telescope
kg	kilogram
km	kilometer
LEO	low Earth orbit
M&S	modeling and simulation
m ²	meter squared
μm	micrometer
MIDAS	missile defense alarm system
MILSATCOM	military satellite communications
MISC	miniature imaging spacecraft
MIT	Massachusetts Institute of Technology
mm	millimeter
MNS	mission needs statement
MWNT	multiwalled nanotubes
NAI	National Aerospace Initiative
NASA	National Aeronautics and Space Administration
NASP	national aerospace plane
NIIRS	national image interpretability rating scale
nm	nanometer
NNI	National Nanotechnology Initiative
NRO	National Reconnaissance Office
NSET	nanoscale science, engineering, and technology
ORS	operationally responsive space
ORS-L	operationally responsive spacelift
PECVD	plasma enhanced CVD
QC	quantum computing
QD	quantum dots
QIST	Quantum Information Science and Technology
RAF	Royal Air Force
RPA	remotely piloted aircraft
S&T	science and technology
SMPD	single-carrier modulated photo detector
SOC	system-on-a-chip

SPIE	International Society for Optical Engineering
SSA	space situational awareness
SSN	space surveillance network
STIS	Space Telescope Imaging Spectrograph
SWaP	size, weight, and power
SWNT	single-walled nanotubes
TBCC	turbine-based combined-cycle
TRL	technology readiness level
TSAT	transformational satellite
TSTO	two-stage-to-orbit
USMC	United States Marine Corps
USPTO	US Patent and Trademark Office
VIVID	video verification of identity
WMD	weapon of mass destruction

United States Air Force Center for Strategy and Technology

The United States Air Force (USAF) Center for Strategy and Technology (CSAT) was established at the Air War College in 1996. Its purpose is to engage in long-term strategic thinking about technology and its implications for US national security.

The center focuses on education, research, and publications that support the integration of technology into national strategy and policy. Its charter is to support faculty and student research; publish research through books, articles, and occasional papers; fund a regular program of guest speakers; and engage in collaborative research with United States and international academic institutions. As an outside funded activity, the center enjoys the support of institutions in the strategic, scientific, and technological communities.

An essential part of this program is to establish relationships with organizations in the Air Force, as well as other Department of Defense agencies, and identify potential topics for research projects. Research conducted under the auspices of the center is published as occasional papers and disseminated to senior military and political officials, think tanks, educational institutions, and other interested parties. Through these publications, the center hopes to promote the integration of technology and strategy in support of US national security objectives.

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