United States Government Accountability Office

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Report to Congressional Committees

May 2006

SPACE ACQUISITIONS

DOD Needs Additional Knowledge as it Embarks on a New Approach for Transformational Satellite Communications System

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Accountability * Integrity * Reliability

Highlights

Highlights of GAO-06-537, a report to congressional committees

May 2006

SPACE ACQUISITIONS

DOD Needs Additional Knowledge as it Embarks on a New Approach for Transformational Satellite Communications System

Why GAO Did This Study

The Department of Defense (DOD) wants to create a networked force where soldiers and systems are able to operate together seamlessly. To help facilitate this transformation, DOD began the Transformational Satellite Communications System (TSAT) program in January 2004. We reported in 2003 that TSAT was about to begin without sufficiently mature technology. In this report, at your request, we followed up with an assessment of (1) how the TSAT program is progressing, and (2) whether the program is using an acquisition approach that will provide the knowledge needed to enter product development.

What GAO Recommends

We are recommending that, before entering product development, DOD: (1) reassess the value of TSAT in broader context of other DOD investments, using updated knowledge on likely cost, schedule, technology, and initial capability; (2) update requirements in coordination with the TSAT user community; (3) demonstrate the maturity of all critical technologies; and (4) establish new cost, schedule, and performance goals. In commenting on the report, DOD agreed with the recommendations.

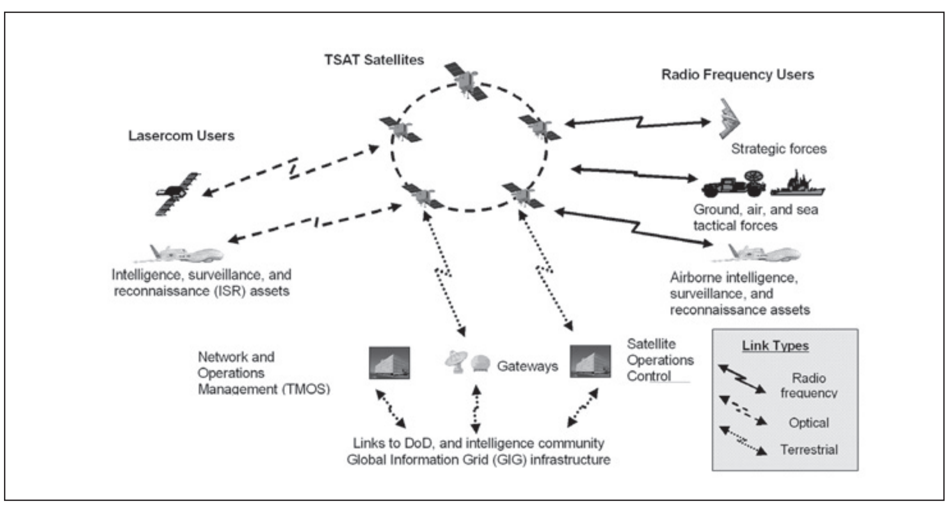
www.gao.gov/cgi-bin/getrpt?GAO-06-537.

To view the full product, including the scope and methodology, click on the link above. For more information, contact Mike Sullivan at (202) 512-4841 or sullivanm@gao.gov.

What GAO Found

The Department of Defense is not meeting original cost, schedule, and performance goals established for the TSAT program. When the program was initiated in 2004, DOD estimated TSAT's total acquisition cost to be $15.5 billion and that it would launch the first satellite in April 2011. TSAT's current formal cost estimate is nearly $16 billion and the initial launch date has slipped to September 2014—a delay of over three years. Furthermore, while the performance goal of the full five-satellite constellation has not changed, the initial delivery of capability will be less than what DOD originally planned. After DOD established initial goals for TSAT, Congress twice reduced the program's funding due to concerns about technology maturity and the aggressiveness of the acquisition schedule. DOD developed the initial goals before it had sufficient knowledge about critical TSAT technologies.

DOD is taking positive steps to lower risk in the TSAT program so it can enter the product development phase with greater chance of success. However, as DOD prepares to implement a new incremental development approach for the program, it faces gaps in knowledge that could hamper its success. An incremental development will mean reduced capabilities in the initial satellites and more advanced capabilities in the remaining satellites. Given this change, it will be important for DOD to update requirements in coordination with the TSAT user community. While senior DOD officials have agreed to these reduced capabilities to get the first satellite launched in 2014, DOD has yet to reevaluate its investment in TSAT in light of other DOD investments using the knowledge it has now gained. Using this new knowledge, DOD could be in a better position to set more realistic goals, before entering product development.



Source: Air Force.

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Abbreviations

ABL	Airborne Laser
ACTS	Advanced Communications Technology Satellite
AEHF	Advanced Extremely High Frequency
AISR	airborne intelligence, surveillance, and reconnaissance
ALEX	Airborne Lasercom Experiment
CDR	critical design review
DBRA	dynamic bandwidth and resource allocation
DOD	Department of Defense
DT&E	developmental test and evaluation
EHF	extremely high frequency
GIG	Global Information Grid
HAIPE	High Assurance Internet Protocol Encryptor
IP	Internet protocol
LES	Lincoln Experimental Satellite
LITE	Laser Intersatellite Transmission Experiment
MDR	medium data rate
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NGPR	next generation processor router
OSVS	Optical Standards Validations Suite
RF	radio frequency
SHF	super high frequency
SISR	space intelligence, surveillance, and reconnaissance
TCA	Transformational Communications Architecture
TMOS	TSAT Mission Operations System
TRANSEC	transmission security
TRL	technology readiness level
TSAT	Transformation Satellite Communications System
TSOC	TSAT Satellite Operations Center
TSOE	TSAT Satellite Operations Element
XDR+	extended data rate plus

GAO
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United States Government Accountability Office
Washington, DC 20548

May 24, 2006

The Honorable Jeff Sessions
Chairman,
Subcommittee on Strategic Forces
Committee on Armed Services
United States Senate

The Honorable Ted Stevens
Chairman,
Subcommittee on Defense
Committee on Appropriations
United States Senate

The Department of Defense (DOD) is seeking to transform its communication systems to achieve a networked force where soldiers and systems are able to operate together seamlessly. To help facilitate this transformation, DOD started a new program in January 2004—the Transformational Satellite Communications System (TSAT)—with an estimated cost of $15.5 billion. Plans call for TSAT to serve as the backbone for DOD's future communications system and to provide critical support to weapons systems. A key role envisioned for TSAT is to transfer information from DOD's planned ground-based Global Information Grid (GIG), a complex set of programs and initiatives intended to provide users with an Internet-like capability for sharing information among military and national security users around the world. Through the use of advanced technologies, TSAT is slated to transfer higher volumes of information to users at a faster rate than current systems, and allow interface with other U.S. national security agencies' satellite-based communications.

At your request, we followed up our earlier work and assessed (1) the TSAT program's progress toward its cost, schedule, and performance goals, and (2) whether the program's acquisition approach will provide the knowledge needed to enter product development.

To conduct our work, we interviewed DOD officials in the National Security Space Office, Office of the Director for Program Analysis and Evaluation, Office of the Under Secretary of the Air Force, Space and Missile Systems Center, and officials from the Massachusetts Institute of Technology (MIT) Lincoln Laboratory and the Aerospace Corporation. We reviewed and analyzed DOD documents related to capabilities, schedule, funding, and technology development efforts, and GAO studies that discuss acquisition problems and associated challenges, including our decade long body of work on best practices in weapon system development. We conducted our review from August 2005 to March 2006 in accordance with generally accepted government auditing standards. For more on our scope and methodology, see appendix I.

Results in Brief

DOD is not meeting original cost, schedule, and performance goals established for the TSAT program. When the program was initiated in 2004, DOD estimated TSAT's total acquisition cost to be $15.5 billion and that it would launch the first satellite in April 2011. TSAT's current official cost estimate is nearly $16 billion, and the initial launch date has slipped to September 2014—a delay of over 3 years. Furthermore, DOD has changed the TSAT program to an incremental development approach and under this approach, the initial delivery of capability will be less than what DOD originally planned but the performance goal of the full five-satellite constellation has not changed. After DOD established initial goals for TSAT, Congress reduced the program's funding in fiscal years 2005 and 2006 because of concerns about the maturity of critical technologies and an aggressive acquisition schedule. DOD developed the original goals before it had sufficient knowledge about critical TSAT technologies, rendering the goals unreliable. In early 2004, when DOD initiated the TSAT acquisition, only one of seven critical technologies was mature.

DOD is taking positive steps to lower risk in the TSAT program before entering the product development phase but as DOD prepares to implement a new incremental development approach for the program, it faces gaps in knowledge that could hamper the program's success. To lower risk, DOD has separated technology development efforts from product development and is conducting detailed reviews of the TSAT program at critical milestones. Second, DOD has reduced program complexity and is incorporating software development best practices for the software-intensive ground network that is to interface with DOD's other planned ground networks, such as GIG, to deliver enhanced capabilities. Third, DOD plans to demonstrate critical technologies' maturity during key integration tests in fiscal year 2007, before initiating product development. Despite these efforts, DOD could improve the likelihood of program success by gaining additional knowledge. In 2006, DOD directed the TSAT program to follow an incremental development approach—a strategy that calls for reduced capabilities in the initial satellites and more advanced capabilities in the remaining satellites. This approach will likely reduce risks by introducing less new content and technology in the first two satellites. In light of this change, it will be important for DOD to update requirements in coordination with the TSAT user community. While senior DOD officials have agreed to reduced capabilities up front to increase the confidence in launching the first satellite in 2014, DOD has yet to justify the TSAT investment in light of other DOD investments using the knowledge it has now gained. Using this new knowledge, DOD could be in a better position to establish realistic goals for the TSAT program before initiating product development.

To improve DOD's transition to transformational communications and gain the additional knowledge needed before initiating TSAT product development efforts, we are recommending that DOD (1) reassess the value of TSAT in the broader context of other DOD investments, using updated knowledge on likely cost, schedule, technology, and initial capability; (2) update requirements in coordination with the TSAT user community; (3) demonstrate the maturity of all critical technologies; and (4) establish new cost, schedule, and performance goals. In written comments on a draft of this report, DOD concurred with our recommendations, and we have incorporated detailed comments where appropriate (DOD's letter is reprinted in app. II).

Background

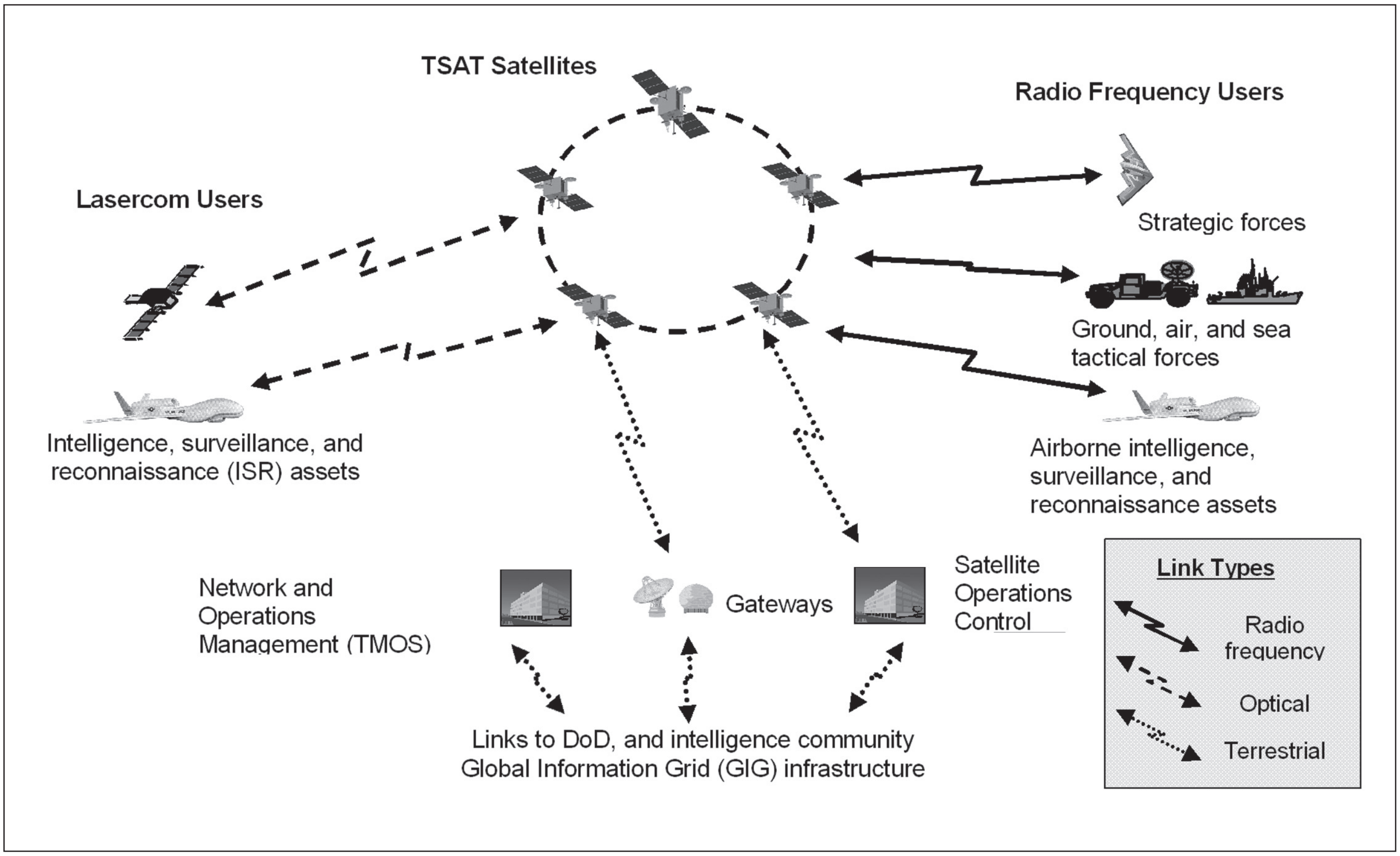
Present and evolving threats highlight the need to design, operate, and defend military communication networks to ensure continuity of joint operations. However, current systems lack the connectivity, capacity, interoperability, control, adaptability, availability, and coverage to support military action. To address these shortcomings, DOD is moving toward network-centric communication systems to facilitate critical communication. A key system in this concept is TSAT—one of DOD's most complex and expensive space programs involving the integration of multiple, complex technologies never before integrated in a single space system.

As early as 2001, DOD had developed a new Transformation Communications Architecture (TCA) to guide the implementation of emerging communications technologies. The TCA is an element of a broader global information network or grid, DOD's overarching vision to provide authorized users with a secure and interconnected information environment. The performance parameters for the GIG define the fundamental requirements for the systems to be interconnected through the TCA. The TCA is designed to realize the benefits of an Internet protocol (IP) environment, as it will provide instant accessibility to the military and intelligence communities. The goal of the TCA is to provide accessibility to all users while removing communications constraints related to capacity, control, and responsiveness. It is composed of elements in ground stations, aboard tactical vehicles, and in space.

TSAT is the space-based network component of the TCA that is expected to provide survivable, jam-resistant, global, secure, and general purpose radio frequency and laser cross-links with air and other space systems. Some of the satellite technologies TSAT will employ have been evolving for over 25 years. TSAT is building on these heritage technologies in three primary areas: onboard signal processing for protection and connectivity, networking, and space laser communication. Through these advanced technologies, TSAT will improve communications to DOD, intelligence community, and homeland defense users by transmitting large amounts of data at a faster rate. Further, TSAT is designed to vastly improve satellite communications by extending the GIG to users without ground connections and making it possible for users to travel with small terminals and communicate while on the move.

The TSAT system will consist of a five-satellite constellation (with a sixth satellite for backup), the TSAT satellite operations element (TSOE) which includes a primary TSAT satellite operations center (TSOC) for on-orbit satellite control, a backup TSOC, and a set of transportable units, a TSAT Mission Operations System (TMOS) to provide network management, and ground gateways (see fig. 1).

Figure 1: TSAT System Elements



Source: Air Force.

DOD has awarded four TSAT contracts through separate bidding processes. In 2003 DOD awarded a contract to Booz Allen Hamilton for overall systems engineering and integration. DOD also awarded two separate contracts to competing contractor teams—Lockheed Martin Space Systems/Northrop Grumman Space Technology and Boeing Satellite Systems—to conduct risk reduction efforts and present development plans for the TSAT satellites. DOD expects to award a contract to one of these contractor teams in 2007 to design and build the satellites. Finally, in January 2006 DOD awarded a $2 billion contract to Lockheed Martin Integrated Systems and Solutions to develop TMOS and the overall network architecture. This network development contractor is responsible for negotiating the interfaces between the TSAT network and the space segment, user terminals, and other external networks.

Recently, DOD changed the TSAT acquisition strategy to an incremental development approach. This approach establishes time-phased development of new products in increments. The first increment incorporates technology that is already mature or can be matured quickly. As new technologies become mature, they are incorporated into subsequent increments so that the product's capability evolves over time. This approach also reduces risks by introducing less new content and technology into a design and development effort, an approach intended to enable developers to deliver a series of interim capabilities to the customer more quickly. As such, incremental development is considered a best practice for successful DOD and commercial development programs because it allows these programs to make cost and schedule estimates that are based on mature technologies. Recognizing the benefits of evolving space systems, DOD included the incremental development of space systems in its revised National Security Space acquisition policy.

DOD Not Meeting Original TSAT Goals

DOD is not meeting its original cost, schedule, and performance goals for the TSAT program. TSAT's cost has increased by over $420 million, the planned launch date for the first satellite has slipped more than 3 years, and the satellites will be less capable than originally planned. Since DOD established initial goals for the program, Congress has twice reduced the program's annual budget and directed DOD to spend more time developing and proving critical technologies. DOD developed the initial goals with limited knowledge, when almost all of the critical technologies had yet to be proven to work as intended. As a result, the goals were developed without a high level of reliability.

Initial Goals for TSAT Were Based on Limited Knowledge

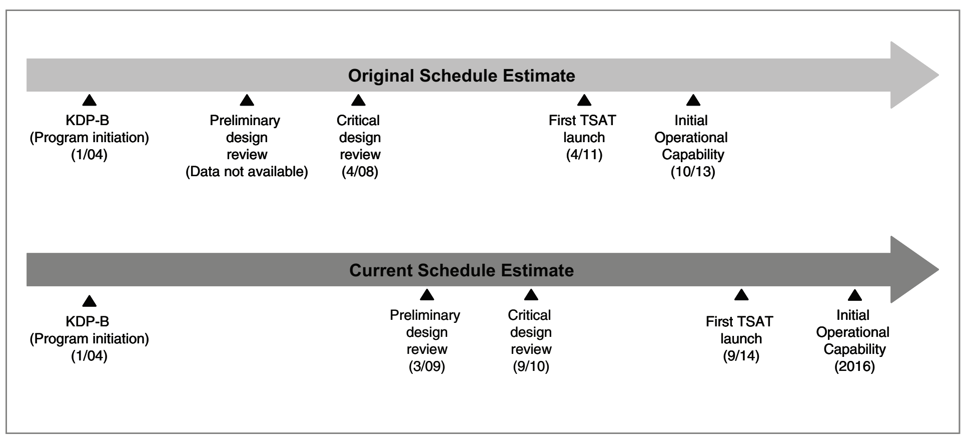
When DOD started the TSAT program in January 2004, it estimated the total acquisition cost to be about $15.5 billion. TSAT's acquisition cost had increased to nearly $16 billion by the end of 2004.[1] DOD also originally scheduled critical design review (CDR) for April 2008 and the first TSAT satellite launch in April 2011. CDR is now scheduled for September 2010 and the first launch in September 2014—delays of approximately 29 and 41 months, respectively. In addition, DOD recently changed its TSAT acquisition strategy to an incremental approach by deciding to build the first two satellites with fewer capabilities and delaying the more advanced

[1] At the time of this report, the 2005 end-of-year cost data and a new program baseline were unavailable.

capabilities for the later satellites in the program. While the initial two satellites will not perform as originally planned, the full five-satellite system will still meet the original user requirements, according to program officials.

According to program officials, the original goals for TSAT have been revised several times as a result of reductions in program funding. After DOD set its initial goals for TSAT, Congress twice funded the program at levels below DOD's request (in fiscal years 2005 and 2006) because of concerns about the state of technical maturity for key subsystems and an aggressive schedule for acquisition. During this time, Congress also directed the program to focus on the challenges of integrating the technologies needed for the system. Figure 2 shows the changes to key milestones dates in TSAT's acquisition schedules. The program recently was directed to develop a new total acquisition cost estimate at a higher level of confidence—which could further increase the amount of funding requested in the near term for the program.[2] However, as of April 2006, DOD had yet to develop this new estimate.

Figure 2: Changes to Key Milestones in TSAT's Acquisition Schedule



Source: Air Force (data); GAO (presentation).

[2] DOD originally estimated the TSAT program cost using a 50 percent confidence level, which meant that the program had a 50 percent chance of being completed under or over budget. DOD is changing to an 80 percent confidence level in its next estimate which should result in a higher, more accurate, program cost estimate.

When DOD established initial goals for the TSAT program, it lacked sufficient knowledge about key critical technologies. Our past work has shown that a knowledge-based model leads to better acquisition outcomes.[3] This model can be broken down into three cumulative knowledge points for technology maturity, design maturity, and production maturity. At the first knowledge point, a match is made between a customer's requirements and the product developer's available resources in terms of technical knowledge, time, money, and capacity. We have also reported that starting a complex program like TSAT with immature technologies can lead to poor program performance and outcomes.

In early December 2003, we reported that the Air Force would have difficulty establishing goals when starting the TSAT program because critical technologies were underdeveloped and early design studies had not been started.[4] At that time, we recommended that the Air Force delay the start of the TSAT program until technologies had been demonstrated to be at an acceptable level of maturity and to consider alternative investments to TSAT. One month later DOD started the program with only one of the seven critical technologies mature, and could not have known with any certainty what resources would be needed to eventually meet users' requirements, despite having confidence in its technology development schedule.

For the TSAT program, the Next Generation Processor Router (NGPR) and laser communications are the highest-risk areas. Program officials reported that three of the critical technologies in the NGPR are involved with the transmission of data: (1) packet processing payloads, (2) dynamic bandwidth and resource allocation (DBRA), and (3) protected bandwidth efficient modulation using high data rates. The use of these Internet-like processes will provide unprecedented connectivity for all TSAT users by moving from an older circuit-based network (similar to telephone) to the newer IP-based network (similar to the Internet). Additionally, DOD continues to develop the technologies that are needed for laser

[3] See GAO, Defense Acquisitions: Space-Based Radar Effort Needs Additional Knowledge before Starting Development, GAO-04-759 (Washington, D.C.: July 23, 2004).

[4] See GAO, Space Acquisitions: Committing Prematurely to the Transformational Satellite Program Elevates Risks for Poor Cost, Schedule, and Performance Outcomes, GAO-04-71R (Washington, D.C.: Dec. 4, 2003).

communications. Table 1 identifies the level of maturity of TSAT critical technologies at program start and their expected maturity dates.

Table 1: Technology Readiness Levels of TSAT Critical Technologies

Critical technology	TRL level at development start[a]	TRL level as of March 2006	Expected maturity date[b]
Communication-on-the move antenna	4	6	N/A
Packet Processing Payload	6	6	N/A
Bandwidth Efficient Modulation (XDR+)	3	5	2007
Dynamic Bandwidth Resource Allocation (DBRA)	3	5	2007
Information Assurance – TRANSEC	3	6	N/A
Information Assurance – HAIPE	4	6	N/A
Single-Access Lasercom	5	5	2007
Multi-Access Lasercom[c]			
Narrow field of view			
Wide field of view	2	2	to be determined

Source: Air Force (data); GAO (analysis).

N/A: not applicable

[a]TRL levels might vary in maturity among the viable suppliers.

[b]These dates might vary depending on the viable supplier and refer to the original acquisition approach; they could be different for an incremental approach, as resources are restructured.

[c]Multi-Access Lasercom is shown here for context only. The TSAT program is being restructured and this technology is no longer part of the baseline TSAT program.

To minimize the potential for technology development problems after the start of product development, DOD uses an analytical tool to assess technology maturity. This tool associates technology readiness levels (TRL) with different levels of demonstrated performance, ranging from paper studies to actual application of the technology in its final form. For TSAT, the space segment contractors are using a series of events to demonstrate and integrate the critical technologies into subsystems and then testing to determine the extent the components function properly together. The maturity levels of the critical technologies for TSAT currently range from TRL 5 to 6, with the remaining technologies needing integration testing to demonstrate maturity. (See app. VI for a description of the TRL levels.)

According to program officials, these technologies will be demonstrated at TRL 6 when key integration tests are completed in fiscal year 2007. The two main tests facing the program are the second series of integration testing on the Next Generation Processor Router and Optical Standards Validation Suite (NGPR-2 and OSVS-2). Program officials said that the program is using these independent tests to reduce risk by uncovering technical problems before awarding the space segment contract for the design and assembly of the satellites. The results of the tests are to be assessed at the second interim program review before DOD makes a decision to enter the product development phase of the program. At the time of this report, results from the first series of integration tests were unavailable.

DOD Taking Steps to Lower Program Risk but Additional Knowledge Needed Before Product Development

DOD is taking positive steps to lower TSAT program risk, but additional knowledge is needed before entering product development. DOD is separating its technology development efforts from product development, continuing to conduct program reviews before making key decisions, reducing program complexity by staggering the awards on its ground and space segment contracts, and incorporating knowledge-based metrics in software development. Additionally, DOD is reducing risks in technology development efforts by leveraging decades of knowledge on heritage systems and using independent integration tests to demonstrate the maturity of critical technologies. Despite these efforts, DOD faces gaps in knowledge that could hamper successful outcomes. As DOD implements an incremental approach for the TSAT program, it has yet to justify the TSAT investment in light of other DOD investments using the knowledge it has now gained.

Efforts Under-Way Reduce Program Risk

DOD is reducing TSAT program risk in the following ways:

- *Separating technology and product development*—DOD is separating technology development from product development and plans to prove that all critical technologies will work as intended before the TSAT program enters product development in 2007. In the past, DOD has not successfully implemented acquisition best practices in its space programs to reduce risks and increase the likelihood of better outcomes, particularly in some of its larger and more complex programs. We previously reported that DOD could curb its tendency to over-promise the capabilities of a new system and to rely on immature technologies in part by separating technology development from product development (system integration and system demonstration).[5] According to program officials, the TSAT program will not start building the TSAT system until all critical technologies needed for the system to satisfy user requirements are mature, ensuring a clear demarcation between the two phases of system development. This approach better enables decision makers to determine if a match exists between TSAT requirements and available resources (time, technology, capacity, and funding).

- *Conducting program reviews*—DOD plans to continue conducting reviews of the TSAT program at key milestones to reduce program risk. DOD's space acquisition policy requires that program managers hold milestone reviews or independent program assessments as a program is nearing key decision points. Following this guidance, the TSAT program's acquisition schedule requires the program manager to assess program knowledge at specific points. The next major milestone is scheduled for the fourth quarter of fiscal year 2007, when the program will hold an interim program review to assess the program's readiness to proceed into the product development phase. Importantly, this review will include an assessment of the maturity levels of the critical technologies. Part of this review will involve the use of independent cost estimators as a way to develop an unbiased, consistent, and objective total cost estimate for the program.

- *Reducing ground and space segment complexity*—DOD has lessened the likelihood of problems in development by reducing the complexity of the program. Specifically, according to program officials, the contract for ground-based network operations was awarded before the space segment contract so that the competing space segment contractors could work toward a stable and more mature network design. In January 2006, DOD awarded a TMOS contract worth $2 billion to Lockheed Martin Integrated Systems and Solutions to start developing the overall network architecture and TMOS. Awarding this contract first will allow the competing space contractors to focus their satellite designs on a single architecture and mission operations system, thereby reducing program complexity.

[5] See GAO, *Defense Acquisitions: Improvements Needed In Space Systems Acquisition Policy to Optimize Growing Investment in Space*, GAO-04-253T (Washington D.C.: July 12, 2005); and GAO, *Military Space Operations: Planning, Funding, and Acquisition Challenges Facing Efforts to Strengthen Space Control*, GAO-02-738 (Washington, D.C.: Sept. 23, 2002).

- *Incorporating software best-practices*—Our review of the development plans for the software-intensive TMOS segment that is to interface with other networks like the GIG shows that DOD is also incorporating best practices in this area to mitigate program risks. Our previous work has identified and reported on three fundamental management strategies that are best practices for software development: (1) implementing an evolutionary approach, (2) following disciplined development processes, and (3) collecting and analyzing meaningful metrics to measure progress.[6] First, the evolutionary approach includes setting requirements, establishing a stable design, writing code, and testing. Second, successful acquisitions require that developers demonstrate they have acquired the right knowledge before proceeding to the next development phase. Finally, metrics such as costs, schedule, size of a project, performance requirements, testing, defects, and quality provide evidence that the developer has acquired appropriate knowledge in moving from one phase to another. Although DOD's software acquisition plans may incorporate these best practices, the potential for cost and schedule increases because of unforeseen software complexity is inherent in the development of a large quantity of software, as is needed for TSAT. To manage this risk, program officials stated that extensive and fully funded mitigation plans are in place and that the network contractor will be held to the best practices through program oversight and reporting.

Heritage Technologies and Independent Tests Reduce Program Risk

To reduce risk while developing the critical technologies for TSAT, DOD is leveraging decades of existing knowledge from heritage systems. For TSAT to be successful, DOD will have to integrate technologies that have been proven to work in other space systems, but now must be integrated into a single communication system. Officials at MIT's Lincoln Laboratory, who are responsible for the independent testing and verification of TSAT technologies, stated that there are no fundamental discoveries or breakthroughs involved with developing TSAT. Rather, the enabling technologies build upon architectures and technologies developed across decades of space programs or experiments. However, officials at the Aerospace Corporation who are working closely with the TSAT program stated that there are risks involved in using heritage technologies—primarily integration risks—because the technologies must still be tested

[6] See GAO, *Defense Acquisitions: Stronger Management Practices Are Needed to Improve DOD's Software-Intensive Weapon Acquisitions*, GAO-04-393 (Washington, D.C.: Mar. 1, 2004).

and evaluated to determine if they will work together as intended. The three main TSAT enabling technologies are onboard signal processing, networking, and laser communications. See table 2 below for a list of the critical technologies and a description of their purposes.

Table 2: TSAT Critical Technologies and Their Purposes

Critical technology	Purpose
Communication-on-the move antenna	Provide satellite to ground link using a 1-foot antenna for mobile assets.
Packet Processing Payload	Convert incoming analog radio signals into an Internet-like packet of digital data and then interpret the header on the data and pick the correct Internet-like address that is to receive the data packet.
Bandwidth Efficient Modulation (extended data rate plus: XDR+)	Provide a set of radio frequency waveforms to transfer data from the satellite.
Dynamic Bandwidth and Resource Allocation	Algorithm used to choose which radio frequency waveform (XDR+) to use, depending on what speed the data need to be sent; determined by such factors as environmental conditions on the ground (e.g., urban, desert, trees, etc.).
Information Assurance (transmission security: TRANSEC)	TRANSEC algorithms and keys that provide transmitted signal cover to avoid detection, identification, and exploitation (such as traffic analyses.)
Information Assurance (high-assurance IP encryptor: HAIPE)	Inline Network Encryptor devices to protect user data.
Single-access lasercom	Use of a single telescope, optical module, high-power optical power amplifier, and modem to transport data along a laser carrier from one location to another.

Source: Air Force (data); GAO (presentation).

TSAT is building upon the onboard signal processing developments in military satellite communications that started in the mid-1970s. These developments initially focused on providing highly robust communications, but over time have evolved to increased capacity and bandwidth, as well as enhanced efficiency. For example, the Lincoln Experimental Satellites (LES) 8 and 9, Milstar I and II, and Advanced Extremely High Frequency (AEHF) system have verified the onboard processing capabilities that will be used in TSAT.

According to officials at the Lincoln Laboratory, much of the required technology for the network services for TSAT comes directly from the ground-based Internet. Further, TSAT is building on the successful achievements of previous space programs like DOD's Milstar and AEHF satellites, the National Aeronautics and Space Administration's (NASA) Advanced Communications Technology Satellite (ACTS), and the Spaceway and Astrolink satellites from the commercial sector.[7] In addition to space-based signal processing, the TSAT satellites will use packet routing in space, faster data transmission, and Internet-like data transmission formats to produce the networking capability to extend worldwide network services to the user.

TSAT will use high-rate laser communications to connect TSAT satellites into a global network and to provide readout from other space- and air-borne intelligence, surveillance, and reconnaissance (SISR/AISR) assets. According to Lincoln Laboratory officials, many of the needed components for TSAT's laser communications are versions from commercial optical networking. A series of three systems developed by Lincoln Laboratory (Lincoln Experimental Satellites (LES) 8 and 9, Laser Intersatellite Transmission Experiment (LITE) and LITE-2, and GeoLITE) have and continue to demonstrate laser capabilities needed for TSAT. Moreover, recent programs like Lincoln Laboratory's Airborne Lasercom Experiment (ALEX) are providing knowledge about how TSAT's laser communications can be used to support AISR assets, and DOD's Airborne Laser (ABL) is helping scientist to characterize certain limits of laser capabilities in atmospheric conditions, according to the officials. Appendixes III through V further highlight the history of the technology heritage being applied to TSAT.

Remaining Gaps in Knowledge Could Hamper Successful Outcomes

Despite these positive steps to lower program risks, DOD faces gaps in knowledge, as it begins to implement its new development approach, that could impede TSAT's success. In 2006, DOD directed the program to follow an incremental development approach, changing the contents of the program. Under this approach, the program will deliver less capability in the first two satellites, and then more advanced capabilities as technologies mature and are incorporated into the remaining satellites. DOD has not fully assessed the value of the TSAT investment in light of major changes to the program.

[7] Although the Astrolink system was never launched, the first payload was essentially complete before the launch was canceled.

Historically, many new development programs in DOD have sought to quickly gain the latest capabilities,[8] but because the technologies were not mature enough to make such leaps, programs were often in development for years while engineers continued to develop and mature the needed technologies. This increased both the time and cost required to develop the systems. An incremental approach, on the other hand, reduces risks by introducing less new content and technology into a design and development effort. The incremental approach for TSAT allows more time for the development of higher-performing capabilities, thereby potentially increasing the level of confidence in the launch date of the first satellite, planned for 2014. High-level DOD officials have agreed to these reduced capabilities up front, so the TSAT program now plans to deliver satellites that meet user requirements in an evolutionary manner.

Notwithstanding the approval for the revised TSAT program from senior DOD officials, DOD has yet to justify the TSAT investment in light of other DOD investments using the knowledge it has now gained on cost, schedule, and initial capabilities to be delivered. For example, TSAT's cost estimate has increased and the initial satellites will be less capable than originally expected. Furthermore, it is imperative, given the recent changes to the program, that DOD work with the TSAT user community to update requirements to ensure the timely delivery of promised capabilities. Finally, it does not appear that DOD has completely addressed all the unknowns concerning the relationship between TSAT and two of DOD's other expensive and complex systems, namely the GIG and Space Radar. For example, work still remains in finalizing the requirements for these systems and understanding how the incrementally developed TSAT will satisfy the needs.

Conclusions

DOD has taken action to put itself in position to prove out critical technologies before initiating satellite development—an approach not typically seen in DOD's space programs. DOD has taken further action to reduce program risk by changing to an incremental development approach. While this approach will reduce the capability of the first two satellites, it is a positive step in reducing program risk because the program will gain additional technical knowledge before integrating the more advanced technologies into the satellites. Even though DOD is taking

[8] See GAO, *Missile Defense: Knowledge-Based Practices Are Being Adopted, but Risks Remain*, GAO-03-441 (Washington, D.C.: Apr. 30, 2003).

such positive steps, TSAT is still expected to be one of the most ambitious, expensive, and complex space systems ever built. TSAT is being designed to transform military communication using Internet-like and laser capabilities—key integrations risks. Other weapon systems are to interface with it and will be highly dependent on it for their own success. While DOD is planning to undertake new systems, such as TSAT, broader analyses of the nation's fiscal future indicate that spending for weapon systems may need to be reduced, rather than increased, given the constrained fiscal environment. Given these challenges and fiscal realities, it is prudent for DOD to reexamine the value and progress of TSAT before committing to building the full constellation of communication satellites.

Recommendations for Executive Action

To improve DOD's transition to transformational communications by gaining the additional knowledge it needs before TSAT enters product development, we recommend that the Secretary of Defense direct the Under Secretary of the Air Force to take the following four actions:

- Reassess the value of TSAT in the broader context of other DOD investments, using updated knowledge on likely cost, schedule, technology, and initial capability;
- Update requirements in coordination with the TSAT user community;
- Prove that all critical technologies will work as intended; and
- Establish new cost, schedule, and performance goals for the program once the above knowledge has been gained.

Agency Comments

We provided a draft of this report to DOD for review and comment. DOD concurred with our recommendations and provided detail comments, which we have incorporated where appropriate. DOD's letter is reprinted as appendix II.

We plan to provide copies of this report to the Secretary of Defense, the Secretary of the Air Force, and interested congressional committees. We will also provide copies to others on request. In addition, the report will be available on the GAO website at http://www.gao.gov.

If you or your staff has any questions concerning this report, please contact me at (202) 512-4841 or sullivanm@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. Key contributors to the report are Arthur Gallegos, Assistant Director, Tony Beckham, Noah B. Bleicher, G. Martin Campbell, Sharron Candon, Claire Cyrnak, Maria Durant, and Hai V. Tran.

Michael J. Sullivan
Director, Acquisition and Sourcing Management

Appendix I: Scope and Methodology

To assess the Department of Defense's (DOD) progress toward achieving cost, schedule and performance goals for the Transformational Satellite Communications System (TSAT), we collected and reviewed (1) budget and expenditure plans, (2) acquisition planning documents, and (3) technology and readiness information to determine if the program was meeting its original goals. We compared changes in cost and schedule to original estimates and evaluated DOD's plans for maturing the critical technologies against best practice standards to determine if they will sufficiently mature when DOD plans to start product development. We discussed this information with DOD officials in the Office of the Secretary of Defense, Program Analysis and Evaluation, Crystal City, Virginia; National Security Space Office, Chantilly, Virginia; Space and Missiles Systems Center, Los Angeles Air Force Base, California; and with officials at the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, Boston, Massachusetts; and the Aerospace Corporation, El Segundo, California.

To determine if the TSAT program is using an acquisition approach that will provide the knowledge it needs to proceed to product development, we collected and reviewed documents that described the TSAT program's plans to build knowledge and to mitigate risks. We reviewed detailed documents related to capabilities, schedule, funding, and technology development for the revised acquisition strategy. We considered DOD's current knowledge-building activities against DOD and GAO studies that discuss acquisition problems and associated challenges with acquisition programs—including work on best practices in weapon system development that we have conducted over the past decade. We analyzed the extent to which the TSAT program is using a knowledge-based approach to technology and product development. To do this, we focused on the whether the new acquisition approach will meet user requirements and match those needs to resources. We discussed DOD plans and efforts to meet user's needs with DOD officials in the Military Satellite Communication Joint Program Office, Los Angeles Air Force Base, California; Directorate of Space Acquisition, Office of the Under Secretary of the Air Force, Arlington, Virginia; and Office of the Assistant Secretary of Defense (Networks and Information Integration), Arlington, Virginia.

We performed our work from August 2005 through March 2006 in accordance with generally accepted government auditing standards.

Appendix II: Comments from the Department of Defense

OFFICE OF THE ASSISTANT SECRETARY OF DEFENSE
6000 DEFENSE PENTAGON
WASHINGTON, DC 20301-6000

May 16, 2006

NETWORKS AND INFORMATION INTEGRATION

Michael J. Sullivan
Director, Acquisition and Sourcing Management
U. S. Government Accountability Office
Washington, D.C. 20548

Dear Mr. Sullivan,

Thank you for the opportunity to respond to the Government Accountability Office (GAO) draft report, GAO-06-537, "DOD Needs Additional Knowledge as it Embarks on a New Approach for Transformational Satellite Communications (TSAT) System," dated April 24, 2006 (GAO Code 120478). The attached enclosure addresses some specific comments and observations made in the report. Below is our response to the GAO recommendations.

The Department agrees with all four GAO recommendations. The GAO report and recommendations are consistent with the measures taken by the Department to restructure the TSAT Program subsequent to the department-wide review during the 2005 Quadrennial Defense Review (QDR). The lower risk Block strategy that resulted from the QDR assessment and close scrutiny of TSAT is consistent with the GAO review and recommendations, and in a broad sense, uses the GAO knowledge point model continually along the life of a program.

As part of the TSAT program requirements and acquisition oversight, and in preparation for the next acquisition Key Decision Point (KDP), the DoD will update requirements in coordination with the TSAT user community, demonstrate the maturity of all critical technologies, and establish new cost, schedule, and performance goals—GAO recommendations two, three and four respectively. These measures are an inherent part of the requirements of National Security Space Acquisition Policy 03-01.

With regards to GAO's first recommendation, to "*reassess the value of TSAT using updated knowledge on likely cost, schedule, technology and initial capability*," the Department completed a thorough assessment as part of 2005 QDR. The QDR deliberative processes that resulted in the TSAT Block Build approach reasserted the value of TSAT. The block strategy was vetted through and ultimately approved by all DoD stakeholders including all Services, the Combatant Commanders, and the Intelligence Community. It included a thorough review of military satellite communications capability with particular emphasis on the TSAT program and leveraged multiple, independent, in-depth reviews. The QDR assessed the TSAT program in terms of cost, schedule, risk and capabilities and validated the restructured program as the best way to meet warfighter requirements. Another in-depth review will be accomplished prior to KDP-B, currently scheduled for September 2007. In addition to the in-depth program assessment, the KDP-B decision will incorporate the knowledge gained from the System Design Review, completion of technology maturity, and incorporate any other new knowledge gained post-QDR before establishing the program baseline.

One of the findings during QDR and a key element of the Block strategy included rescinding the January 2004 KDP decision to enter into the Preliminary Design Phase (Phase B). Although the TSAT program continues to proceed according to plan, when viewed in conjunction with the 2004 revised space acquisition framework, which is consistent with the GAO knowledge point model, TSAT's current activities fall squarely within the Concept Development phase (Phase A). This adjustment included rescinding the previously established baseline. The new baseline will be established once the appropriate knowledge is gained per space acquisition policy.

A final comment regarding the GAO report merits visibility. The overall system performance goals of TSAT were not changed during the restructure and new block strategy. Although the initial two satellites (Block 1) may have less capability, the latter satellites (Block 2) will have more capability, for an overall constellation that meets the original warfighter requirements. Block 1 should not be viewed as a stand alone system; Block 1 is a stepping stone to the full TSAT capability that reduces program risk while increasing delivery schedule confidence. TSAT is still meeting the performance goals as originally set, and the Block strategy will include continual involvement of the user community.

Thank you for the opportunity to respond to the GAO draft report. We look forward to working with you again.

Sincerely,

Ronald C. Jost
Deputy Assistant Secretary of Defense
(C3, Space and Spectrum)

Enclosure:
As stated

GAO Draft Report 06-537

"DOD Needs Additional Knowledge as it Embarks on a New Approach for Transformational Satellite Communications System" (U)

DEPARTMENT OF DEFENSE DETAILED COMMENTS (U)

(U) The following is a detailed review of the GAO report on TSAT, with specific explanations of DoD's concerns.

1. (U) Highlights, paragraph 1, and Results in Brief, paragraph 3, state: "*We are recommending that DOD: (1) reassess the value of TSAT using updated knowledge on likely cost, schedule, technology, and initial capability;...*" And Recommendations, paragraph 1, states: "*...we recommend that the Secretary of Defense direct the Under Secretary of the Air Force to: Reassess the value of TSAT using updated knowledge on likely cost, schedule, technology, and initial capability;...*"

(U) DOD seniors scrutinized the TSAT program during the 2005 Quadrennial Defense Review (QDR). They reassessed TSAT's value using the latest cost, schedule, and technology data. QDR membership included the Deputy Secretary of Defense and Service Vice Chiefs (who also serve on the Joint Requirements Oversight Council). Additionally, the TSAT Users Forum, with all COCOMS and Services represented, accepted the block TSAT acquisition approach. The TSAT Program Office and the TSAT Users Forum are now performing detailed trades to settle on the specific performance capabilities of the block TSATs.

2. (U) What GAO Found, paragraph 1, and Results in Brief, page 2, paragraph 1, both state: "*The Department is not meeting original cost, schedule and performance goals...*" and DOD Not Meeting Original TSAT Goals, page 5, paragraph 1, states, "*DOD is not meeting its original cost, schedule, and performance goals for the TSAT program.*"

(U) As noted on Page 6, "*After DOD set its initial goals for TSAT, Congress twice funded the program at levels below DOD's request...because of concerns about the state of technical maturity for key subsystems and an aggressive schedule for acquisition.*" Per Congressional direction, the TSAT Program Office lengthened the TSAT schedule. As a direct result, program completion costs increased. The Program Office also completed studies on cost, schedule, and performance goals during the fall of 2005. Mr. Thomas Young and Gen (ret) Tom Moorman, who served on the 2003 Young Panel to assess the "Acquisition of National Security Space Programs" also completed an independent assessment of the program and provided constructive feedback. Congressional guidance and these analyses led the Program Office to baseline the QDR-approved block build cost, schedule, and incremental performance goals. With respect to the performance goals, the full, five-satellite constellation's goals have not changed; they remain the same as originally captured in the warfighter's Key Performance Parameters.

3. (U) What GAO Found, paragraph 2, states: *"...DOD has yet to reevaluate its investment in light of the knowledge it has now gained."* Results in Brief, paragraph 2, states: "*...DOD has yet to justify the TSAT investment in light of the knowledge it has now gained.*" And DOD Taking Steps to Lower Program Risk but Additional Knowledge Needed Before Product Development, page 9, paragraph 1, states: "*As DOD implements an incremental approach for the TSAT program, it has yet to justify the TSAT investment in light of the knowledge it has now gained.*" And Remaining Gaps in Knowledge Could Hamper Successful Outcomes, page 13, paragraph 3, states: *"DOD has not fully assessed the value of the TSAT investment in light of major changes to the program."*

(U) As stated in (1) above, DOD reevaluated its investment in TSAT during the fall 2005 QDR process. That said, we acknowledge we will incorporate additional knowledge gained through continued technology development. For example, this will include the findings collected during the Optical Standards Validation Suite Demonstration 2 (OSVS-2) and Next Generation Processor Router Demonstration 2 (NGPR-2), scheduled to run from November 2006 through February 2007.

4. (U) DOD Not Meeting Original TSAT Goals, page 5, paragraph 1, states: "*DOD developed the initial goals with limited knowledge, when almost all of the critical technologies had yet to be proven to work as intended. As a result, the goals were unreliable.*" And Initial Goals for TSAT Were Based on Limited Knowledge, page 7, paragraph 2, states: "*...DOD started the program with only one of the seven critical technologies mature...*"

(U) The original TSAT goals were not unreliable; they were developed based on the confident expectation that the critical technologies would mature on a reasonable schedule. As previously noted, Page 6 of the GAO report states, "*After DOD set its initial goals for TSAT, Congress twice funded the program at levels below DOD's request...because of concerns about the state of technical maturity for key subsystems and an aggressive schedule for acquisition.*" Within the program's Congressionally-directed budget reductions, the driving TSAT technologies continue to make solid progress. In traditional space acquisitions, critical technologies are expected to achieve Technical Readiness Level (TRL) 6 by system preliminary design review (FY09 for TSAT). For the TSAT program, all critical technologies are currently at no less than TRL 5, and all are projected to be at TRL 6 by system design review in FY07, nearly two years ahead of typical programs.

5. (U) Initial Goals for TSAT Were Based on Limited Knowledge, page 6, paragraph 1, states: "*The program recently was directed to develop a new total acquisition cost estimate at a higher level of confidence—which could further increase the estimated cost to complete the program.*"

(U) While the use of a higher confidence cost estimate does increase the estimated cost of a program, it is important to note that use of such an estimate has no negative impact on *actual* cost of the program. In fact, use of a higher confidence cost estimate, as recommended to Congress by the Young Panel, is aimed at *decreasing* actual program cost, risk, and schedule by affording DOD the flexibility to proactively address potential and incipient problems through a priori planning for the timely application of management reserve.

6. (U) Remaining Gaps in Knowledge Could Hamper Successful Outcomes, page 14, paragraph 2, states: "*Finally, it does not appear that DoD has completely addressed important questions about how DoD's other systems and programs, including such expensive and complex systems as the GIG and Space Radar, will be affected by an initially less capable TSAT system.*"

(U) The TSAT block build approach still meets all user Key Performance Parameters. It is true that there are unknowns concerning the relationship between TSAT and the terrestrial portion of the GIG and TSAT and Space Radar; as one would expect with programs at the early stages of development. However, the issues that exist now are the same ones that existed prior to the TSAT block build restructure. Both the GIG and Space Radar are still working through their requirements, to better establish their communications needs. In each program, the TSAT community is completely engaged, participating in forums such as the GIG Net Centric Implementation Documents development activities, the Transformational Communications Architecture version 2.0 update, and a National Security Space Office (NSSO)-led study of Space Radar communications solutions. Work remains in fleshing out the requirements and understanding how the TSAT block build contributes towards their satisfaction. The TSAT MJPO remains committed to supporting these efforts, and OASD/NII is engaged to ensure this cross program communication remains robust.

Appendix III: Onboard Signal Processing Technology Heritage

Time frame	Program title	Purpose/mission	Relevance to TSAT
Mid-1970s	Lincoln Experimental Satellites (LES) 8 and 9	First satellites to use onboard signal processing, spread spectrum techniques (frequency hopping) to demonstrate protected military satellite communications, and radio frequency (RF) crosslink capability.	Onboard signal processing; spread spectrum satellite communications; and satellite-to-satellite crosslinks.
Mid-Late 1980s	Fleet Satellite Communications System (FLTSATCOM) EHF Packages: FEP	Built by MIT Lincoln Laboratory and hosted on the operational FLTSATCOM satellites 7 and 8 (built by TRW). These packages provided the first satellite communications at extremely high frequency (EHF) on the uplink and super high frequency (SHF) on the downlink.	Multichannel onboard signal processing; EHF/SHF spread spectrum satellite communications; and onboard control for circuit switching.
Early 1990s	Milstar I	Satellites provided the first strategic/tactical operational satellite using the EHF/SHF. Satellites also provided narrower spot beam coverage and electronically agile beam coverage to provide enhanced service to small, dispersed user terminals.	Combined strategic/tactical service at EHF, narrow beam antenna coverage, electronically steered antenna coverage; and intersatellite crosslinks.
Late 1990s	Milstar II	Satellites provided enhanced capacity and protection through the addition of a medium data rate (MDR) payload through narrow spot beam antennas. Satellite capacity was more than 10 times greater than Milstar I.	Extension of EHF waveform to higher rates. improved protection via active antenna discrimination (nulling).
2005	Advanced EHF (AEHF)	The Advanced EHF (AEHF) system provides a further increase in the capability of EHF satellite communications by increasing both the total satellite throughput by another factor of 10 and by increasing the data rate available to individual terminals. The extended data rate (XDR) waveform supports data rates from 75 to 8,192,000 bytes per second for individual terminals.	Binary bandwidth efficient waveforms for EHF, improved support for small terminals, and onboard processing technologies for increased satellite throughput.

Source: MIT Lincoln Laboratory.

Appendix IV: Networking Technology Heritage

Time frame	Program title	Purpose/mission	Relevance to TSAT
1980s	Milstar and AEHF	The Milstar satellites were the first satellite payloads to use onboard processing and onboard switching of user signals. The AEHF system further developed space-based signal processing technology, providing more capacity and higher data rates.	Space-based signal processing; quickly reconfigurable circuit setup, teardown, and switching; packet-over-circuit transmission to/from geosynchronous orbit
1990s	NASA Advanced Communications Technology Satellite (ACTS)	This satellite produced many important studies of networking protocol behavior (such as Transmission Control Protocol/Internet Protocol: TCP/IP) in a combined space and terrestrial environment.	Provided performance measurements for IP, and increased the class payload processing rate to more than 100 megabytes per second.
2000s	Spaceway and Astrolink	These are the first satellites designed to perform packet switching in space. The Astrolink system was never launched because of a sudden market downturn in the telecommunications industry. However, the first payload was essentially completed before market conditions caused cancellation of the deployment. The first Spaceway satellite is now onorbit and operational, and launch of the second is planned in the near future.	Lessons include how to build packet processing and routing hardware and software for use in space in the gigabytes per second data rate class.

Source: MIT Lincoln Laboratory.

Appendix V: Lasercom Technology Heritage

Time frame	Program title	Purpose/mission	Relevance to TSAT
1975	Lincoln Experimental Satellites (LES) 8 and 9	The LES-8/9 satellites built by Lincoln Laboratory in the mid-1970's were originally slated to use lasercom crosslinks. The development of these crosslinks was impaired by the lack of an industry base for the necessary optical components and was abandoned in favor of RF links.	Development of a fiber-based architecture, and use of space-qualified commercial fiber-optic components.
1980s-1990s	LITE and LITE-2	The LITE lasercom terminal developed by Lincoln Laboratory was able to capitalize on commercial parts to leverage its large-scale production processes. In the early 1990s, as commercial fiber optic components became available, the LITE-2 terminal was developed. It used a new fiber-based architecture with remote optics. The ability to remote the telescope and other free space optics from the High Power Optical Amplifier and modem dramatically simplifies spacecraft integration.	Telescope, optical module, fiber-based high power optical amplifier, modem, and high-rate lasercom.
Late 1990s	GeoLITE	Built in the late 1990's by Lincoln Laboratory and flown aboard a Northrop-Grumman (TRW) satellite. The GeoLITE experiment (launched in 2001) used the fiber-based architecture developed under the LITE-2 program. The lasercom payload continues to send telemetry from critical subsystems that provide insight into the lifetime of optical components in space.	Same as in LITE and LITE-2, demonstrating all of the capabilities needed for the TSAT mission.
2000s	Airborne Lasercom Experiment (ALEX)	ALEX, built by Lincoln Laboratory, successfully demonstrated the capabilities necessary for air-space lasercom.	While ALEX focused on the airborne terminal, it demonstrated an understanding of the channel that is relevant to TSAT lasercom AISR support.
2000s	Airborne Laser (ABL) program	The ABL program has performed numerous experiments characterizing the propagation of optical wavefronts through various airborne environments. These data are relevant to the TSAT Air-Space link.	Atmospheric and airborne platform boundary characterizations.

Source: MIT Lincoln Laboratory.

Appendix VI: Technology Readiness Levels

Technology Readiness Level	Description	Hardware/Software	Demonstration Environment
1. Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.	None (Paper studies and analysis)	None
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.	None (Paper studies and analysis)	None
3. Analytical and experimental critical function and/ or characteristic proof of concept.	Active research and development is 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.	Analytical studies and demonstration of nonscale individual components (pieces of subsystem).	Lab
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.	Low fidelity breadboard. Integration of nonscale components to show pieces will work together. Not fully functional or form or fit but representative of technically feasible approach suitable for flight articles.	Lab
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.	High fidelity breadboard. Functionally equivalent but not necessarily form and/or fit (size weight, materials, etc.). Should be approaching appropriate scale. May include integration of several components with reasonably realistic support elements/ subsystems to demonstrate functionality.	Lab demonstrating functionality but not form and fit. May include flight demonstrating breadboard in surrogate aircraft. Technology ready for detailed design studies.
6. System/ subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond the breadboard tested for 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 simulated operational environment.	Prototype—Should be very close to form, fit and function. Probably includes the integration of many new components and realistic supporting elements/subsystems if needed to demonstrate full functionality of the subsystem.	High-fidelity lab demonstration or limited/ restricted flight demonstration for a relevant environment. Integration of technology is well defined.

Technology Readiness Level	Description	Hardware/Software	Demonstration 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 in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.	Prototype. Should be form, fit and function integrated with other key supporting elements/ subsystems to demonstrate full functionality of subsystem.	Flight demonstration in representative operational environment such as flying test bed or demonstrator aircraft. Technology is well substantiated with test data.
8. Actual system completed and “flight 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.	Flight qualified hardware	DT&E in the actual system application
9. Actual system “flight 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.	Actual system in final form	OT&E in operational mission conditions

Source: GAO and its analysis of National Aeronautics and Space Administration data.

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