

Tactical Satellite 3: Requirements Development for Responsive Space Missions

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ABSTRACT

The Department of Defense is embarking on a broad initiative to make its space programs more responsive. There are many different views of responsive space, but common tenets include no cost and schedule growth within space programs, and space capabilities delivered directly to the operational and tactical warfighter within a theater of war. The Tactical Satellite 3 (TacSat-3) mission success criteria are unique integration of program management objectives of cost and schedule and technical objectives. TacSat-3 will demonstrate a Hyperspectral Imaging capability direct to the tactical warfighter within 10 minutes of a collection opportunity. Central to providing this capability direct to the warfighter is fielding it in a responsive manner. Responsiveness demands a program structure and system design where cost and schedule are primary over mission performance to some minimum level. To be successful, the TacSat-3 program has developed requirements and mission success criteria which intimately link the cost and schedule to all aspects of requirements. The fundamental basis is the development of mission success criteria which are measurable, but allow for sufficient flexibility to meet aggressive cost and schedule constraints. Several examples of requirements trades are given.

The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

1.0 Introduction

Numerous Department of Defense (DoD) studies show implementing a responsive satellite capability provides for significant military utility to augment or surge current space capabilities. The TacSat concept explores the capability/technological maturity of small, low-cost satellites with the most prominent efforts currently being conducted within the Science and Technology (S&T) Program. In addition to providing for ongoing innovation and demonstration in this important technology area, these S&T efforts also help mitigate technology risk and establish a concept of operations (CONOP) for future acquisitions.

TacSat efforts underway by the Air Force Research Laboratory and the Naval Research Laboratory are focused on demonstrating small (<500kg), operationally responsive, low-cost satellite and launch capabilities to support warfighter. TacSat S&T efforts comprise four elements; (1) coordinated DoD-wide effort to address core S&T shortfalls and barriers to realizing ORS, (2) robust effort using space demonstrations as test beds to validate and refine S&T, CONOPs, and military utility of TacSat-like satellite systems, (3) Warfighter demonstrations using TacSat to refine operational views for deployment of TacSat-like capabilities and to determine their military utility, and (4) acquisition strategy to ensure rapid transition of S&T efforts, demonstrations, and warfighter experimentation if deemed cost-effective in meeting warfighter needs.

AFRL's Space Vehicles Directorate is leading the Tactical Satellite 3 (TacSat-3) team and partners include Space and Missiles Center Detachment 12, the Army Space Battle Laboratory, the Air Force Space Warfare Center, and the DoD Office of Force Transformation. TacSat-3 demonstration features a low cost plug and play modular bus and low cost militarily significant payloads - a Raytheon developed Hyperspectral imager and secondary payload data exfiltration provided by the Office of Naval Research. The key objectives are rapid launch and on-orbit checkout, theater commanding, and near-real time theater data integration. Although third in the series, the TacSat-3 is the first of the tactical satellite demonstrations to have gone through a formal payload selection process with Air Force Space Command (AFSPC) and Combatant Commands (COCOMs). Users identified capability gaps/shortfalls and ultimately a general officer team made the final payload selection decision. A building block for Operationally Responsive Space, TacSat-3 will demonstrate a Hyperspectral imaging capability direct to the tactical warfighter within 10 minutes of a collection opportunity.

TacSat-3 will demonstrate evolutionary steps and traceability towards objective system goals for the capabilities and processes including rapid response to a user defined need for target detection and identification. It will also feature a rapid development of the space vehicle and integrated payload and spacecraft bus by using components and processes developed by the Operationally Responsive Space modular bus. The mission provides traceability for a rapid deployment from call-up for launch to theater control within 7 days and responsive delivery of decision-quality information to operational and tactical commanders by enabling tactical tasking and data delivery.

A key component for the responsive space initiative is to leverage plug and play technologies to develop a fully modular bus. Funded by the DoD Office of Force Transformation, TacSat-3 will focus on the first generation of modular bus technologies. Goals of the modular bus are compliant with standard interfaces and modular subsystems. Additional objectives are a flexible data bus, plug and play switch fabric, modular solar arrays, scalable power and a system adaptable to all orbits. Four contractor teams will develop a preliminary design. One team will be selected to fabricate the actual TacSat-3 modular bus with schedule objectives of 10 months following task award.

Design constraints established for the TacSat-3 program include a total program cost to be less than \$50M, to fit on a low cost responsive space booster and a satellite weight of less than 400 kilogram with a development and test time for payload and modular bus of less than 18 months. The TacSat-3 CONOPS

breaks old paradigms and gives COCOMs first realistic opportunity for responsive, dedicated space capabilities at the operational and tactical level. The TacSat-3 spacecraft will collect and process images and then downlink material ID text and geolocation or downlink full data image using a Common Data Link. An in-theater tactical ground station will have the capability to uplink tasking to spacecraft and will receive full data image. The TacSat HSI payload will conduct spectral reconnaissance and surveillance fused with high resolution imaging. Depending on how rapidly TacSat HSI spectral products are generated, the system may be able to cue other sensors or respond to tip-offs or cues from other assets.

To determine when 'good enough' is reached you must be able to measure 'enough'. The systems engineering principle of bounding the entire set of requirements on the system must be established early, and fixed early. This requirements management philosophy must open the trade space enough to allow for design trades to optimize the cost and schedule for the program while sub-optimizing the performance. Additionally, the requirements must be developed sufficiently to be able to verify the design and track its performance against measurable quantities. These principles are being applied to the TacSat-3 program.

2.0 TacSat-3 Mission Overview and Objectives Development

The Tactical Satellite initiative is a broad initiative across all the main space DoD science and technology centers. This includes the Naval Research Laboratory, the Air Force Research laboratory, the Defense Advanced Research Projects Agency, the Army Space and Missile Defense Center, and the USAF Space and Missile Systems Center. The focus is on the operational and tactical needs of today's and tomorrow's warfighter. With this focus in mind, the Air Force Space Command led a task force to investigate the needs for space products direct to the operational and tactical level within a theater. This process intimately involved all the Combatant Commands across the United States military. A list of needed capabilities was produced, and the science and technology community responded with a list of potential missions to fill or augment these needs.

These potential missions have strict criteria to meet before even being considered for approval. They must meet the science and technology objectives, directly address a Combatant Command's needs, and just as importantly they must realistically be able to demonstrate a level of capability within 18 months of the Authority to Proceed and meet the strict cost goals of the program. TacSat-3 was born of this process. This was extremely important process for developing the major stakeholder's ownership of the TacSat-3 mission. It formed the basis for developing the TacSat-3 mission objectives.

2.1. TacSat-3 Mission Objectives Development

From the TacSat-3 mission selection process, a set of constraints for the mission and a set of mission objectives were established. However, these constraints and objectives were not written down, or articulated to the entire TacSat-3 team. There were several challenges in the definition of these objectives as well as achieving a level of consensus on the right wording of these objectives. These challenges were met with three main elements key to any mission objective definition: firm backing of top level personnel (most notably the Senior Space Experimentalist), a common vision of the end product, and finally frank, open and honest communication among the team members.

Having top level support is essential to the development of mission objectives. Someone with enough power to influence budgeting and direction must be able to accurately communicate the vision for the program. This vision is then used as the litmus test for evaluating the effectiveness of the objectives. It also helps to have a sounding board by which to break possible disagreements in the direction the objectives should take. Often it was asked: what would the Senior Space Experimentalist say?

Along with a top level person to articulate vision and guide mission objective development, having a common understanding of the vision of the end product should not be understated. Each member of the TacSat-3 team came to the table with specific, differing perspectives. These perspectives aided in the

definition of the mission objectives by ensuring all possible angles were covered. Another fundamental benefit is the sense of ownership each participant now has within the mission. This sense of ownership allows for common ground to be found when tough problems, and facilitates honest communication between team members. A common understanding of team goals is well understood to produce success: “Goals serve to focus team member activity on specific tasks and motivate members toward a similar endpoint.”²

These tenets were used in the TacSat-3 Mission Objectives development process. Ultimately, a small group developed draft versions of the mission objectives. These objectives were presented by the entire government team, and comments were provided over the course of several weeks. This was one of the first products produced by the entire TacSat-3 government team. The objectives were subsequently briefed to all levels of management in a working group type of format with the culmination briefing to the Senior Space Experimentalist. Upon revision and acceptance, by the Senior Space Experimentalist the objectives were reviewed by the major stakeholders. In this case, the largest stakeholder, the United States Army, represented the fielded warfighter (the primary user of TacSat-3 products).

2.2. TacSat-3 Mission Objectives

There are fundamental concepts represented in the TacSat-3 mission objectives (shown in Table 1) which meet the Responsive Space objectives. Fundamentally, to be responsive the program must deliver within cost and schedule first, and then focus on providing a minimal militarily significant level of performance direct to the warfighter. This must be accomplished within the TacSat paradigm as a demonstration, not a fully fielded system. However, the demonstration must provide realistic traceability to an operational system.

Table 1. TacSat-3 Mission Objectives

TacSat-3 will demonstrate traceability for:	
Hyperspectral Imaging Products	Rapid response to a user defined need for target detection and identification
Next Generation Plug & Play Capability	Rapid development of the space vehicle – integrated payload and spacecraft bus – by using components and processes developed by the Operationally Responsive Space Modular Bus Program
Enable Rapid Launch within 7 days from Alert Status	Rapid deployment from alert status for launch to theater control within 7 days
Responsive Theater Communications	Responsive delivery of decision-quality information to operational and tactical commanders by enabling tactical tasking and data delivery
Low Cost Implementation Of An Objective System	Deliver fieldable capability within reasonable cost constraints which may only require minor modifications to achieve an objective system capability

2.2.1 Traceability Paradox

The fundamental root to the TacSat-3 mission objectives includes the word traceability. The ultimate objective is to demonstrate an end to end capability with minimal technology development required for

acquisition of an ‘objective’ system. However, to prove the responsive space tenets of operating within cost and schedule there may be items requiring some development. This allows the program to meet objectives within limited schedule and cost by limiting the development required under the demonstration program. The ultimate assumption with traceability is the amount of ‘reasonable’ development required to field an objective system.

Traceability, however, is a nebulous term upon which many stakeholder and team members have different definitions and points of view. Traceability implies a level of requirements to be met, but does not necessarily define the requirements which must meet the traceability standard. Traceability must be quantified. The key component to meeting this challenge is defining specific measurable mission success criteria discussed below.

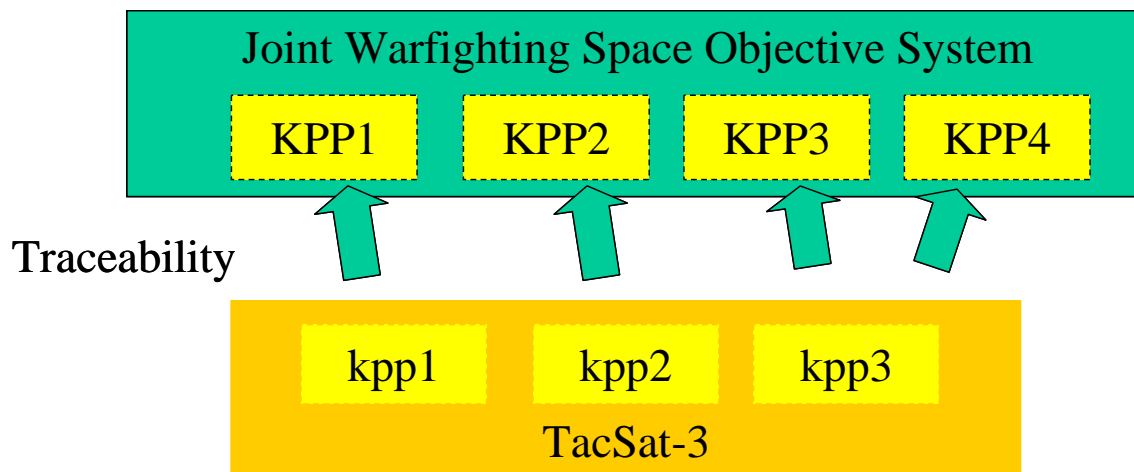


Figure 1. Traceability Illustration of Key Performance Parameters Mapping into Objective System

2.2.2 Traceability Example

The mission objective of enabling launch within seven days from alert status is a prime example of how traceability will be utilized. Nominally the goal for the objective system is to integrate a space vehicle within two days from modular components, integrate the space vehicle to the launch vehicle within two days, launch the combined vehicle in two days, and once on orbit the space vehicle would be operational within a day of launch. Performing these feats without significant infrastructure and streamlined processes is impossible in today’s environment. Therefore, TacSat-3 will show traceability to performing this type of responsive space operation.

The use of traceability in a space demonstration allows the objective system designers the benefits of documented pitfalls to avoid and early identification of potential design deficiencies. For this part of the mission, the lessons learned outweigh any actual results. In practice, the plan during the launch phase of the mission is to institute a ‘stop watch’ plan. The process will be as streamlined as possible, and if a delay is encountered (from the objective 7 day plan) the circumstances will be documented for review at a later time. In a delay, the ‘stop watch’ will be stopped, the issue addressed, and ultimately the stop watch will be restarted upon resumption of activity. In this case, the key performance parameter of time as aggregated over the entire stop watch plan will be mapped into the mission objectives and an ultimate objective system.

2.2.3 Cost and Schedule Component to Mission Objectives

A key aspect of the TacSat-3 mission objectives is the inclusion of a low cost implementation of an

objective system. To achieve this, TacSat-3 must stay within cost and schedule. Elevating the program constraints to the same level as performance objectives puts them on the same footing within the system trades. The philosophy drives a significant amount of design decisions. Ultimately, there is a minimum set of performance parameters which must be attained even within the cost and schedule constraints. This set has been defined as the mission success criteria.

3.0 TacSat-3 Mission Success Criteria

Mission Success Criteria provide a critical link between the mission objectives and the lower level design requirements. They are similar to Buede's objectives hierarchy which he defines as "a hierarchical representation of the major performance, cost, and schedule characteristics that the stakeholders will use to determine their satisfaction with the system."¹ The distinctions are blending them with lower level requirements to pull out very specific and measurable key performance parameters. Furthermore these performance parameters must have distinct threshold criteria. It was also deemed necessary to put these in terms of success and failure for the mission, to add to a clear demarcation between acceptable and unacceptable. The success criteria are divided among the main mission objectives shown in Table 1.

Fundamentally, TacSat-3 will demonstrate providing Hyperspectral Imaging products directly to the warfighter with data latency no greater than 10 minutes. TacSat-3 must also accomplish this demonstration within a maximum total cost and a very tight schedule. Mission success is directly linked to cost and schedule. Failing either will have the same impact as an on-orbit failure. Of course, there may be outside factors such as funding instability, process impediments, contractual arrangements, etc...

Metrics within the Mission Success Criteria come in a variety of forms, from analysis derived key performance parameters, to cost metrics, to simple binary, 'did it happen or not', and time metrics for schedules. Each metric had to be tailored to the intent of the mission objective to which it was mapped.

3.1. Hyperspectral Imagery & Data Delivery Direct to Tactical Warfighter

The primary capability the TacSat-3 mission will provide is quality Hyperspectral Imagery products. These products have distinct and quantifiable characteristics which are defined by analysis. The specific criterion reads: "Demonstrate tactically significant Hyperspectral Imagery collection and processing sufficient to meet militarily relevant detection thresholds." These thresholds are defined in specific quantitative terms. The criterion is then directly mapped to a portion of the system which may include a specific sensor or a portion of the entire system. This allows for incremental measurement of success.

Another increment in measuring success is the criterion for data latency from collection to delivery. The criterion is worded as: "For a single-pass opportunity, the time period from a specified target collect to delivery of a processed product to the warfighter level must occur within 10 minutes (Threshold: 30 minutes)" There are a few key elements in this criterion. First, it states the conditions upon which success is measured. Next, it defines the measurement points, and finally the metrics to be measured. All of the success criteria have similar structure.

3.2. Modular Bus Demonstration & Rapid Launch

A key component of providing for the responsive space initiative is to leverage plug and play technologies to develop a fully modular bus. TacSat-3 will focus on the first generation of modular bus technologies. This situation of proving a new technology concept lends itself to establishing a binary, yes or no success criterion. The specific criterion is worded as: "Demonstrate common Plug & Play electrical and software interfaces between bus components and between the bus and payload." This criterion will be verified upon a functional space vehicle being built, tested and flown.

Modular bus development is a key technology to proving the rapid launch capability. There are four

success criteria which directly relate to specific phases in the deployment and launch process:

- Demonstrate traceability to support deploying the spacecraft from an alert status to integration with launch vehicle within 2 days (Threshold: two days)
- Demonstrate traceability to support performing launch vehicle processes from spacecraft/launch vehicle integration to spacecraft separation on-orbit within 4 days (Threshold: six days)
- The launch vehicle must deliver spacecraft to an orbit altitude providing at least 12 months of orbital lifetime (Threshold: six months)
- Perform spacecraft checkout and payload functional checkout with overlap to complete initial checkout and attain readiness for theater tasking in 1 day (Threshold: two days)

Specifying traceability in a success criterion establishes the product which must be evaluated. In this case, an after action report is required. The report must show the required actions to meet the threshold metrics within the criterion. Additionally, if a success criterion applies to only a distinct part of the overall system, it is specifically defined in the criterion. This is shown in the launch vehicle criterion. If a specific system is not defined; it is implied as a measure against the entire system.

3.3. Responsive Space Development

A key aspect of responsive space is directly linking the program cost and schedule constraints to mission success. There are two criterion which address this mission objective: “Zero cost growth from the baseline cost presented by TacSat-3 Program Management” and “Meet the following development schedule goals : ARTEMIS [primary HSI sensor] sensor development – 15 months from contract ramp-up, modular bus development – 10 months from Task 2 award [a specific contractual date] and space vehicle integration and testing – three months.” Schedule and cost are integrally linked, but more importantly mission success and failure is tied to programmatic constraints.

The schedule criterion has specific metrics tied to periods in the schedule upon which the TacSat-3 program management have definite control. External forces may influence schedule which may not necessarily be under program control. Programmatic success criteria must be written within the sphere of control the program has.

Another success criterion is related to cost, but crosses between technical design and programmatic concern. This criterion is “Demonstrate traceability to a total cost per launched spacecraft for an objective system of \$20 Million or less.” This criterion has definite impacts upon the system design. It precludes unique, one-of-a-kind solutions. It necessitates the design to be as simple as possible. The total cost number assumes all elements of the system, and is viewed as aggressive. Aggressive numbers without traceability would immediately doom a design and program to failure. However, to change paradigms, the metrics must be sufficiently aggressive to encourage innovation.

3.4. Capabilities-based Risk & Reliability

The axiom states: “Nothing is more expensive than failure.” This may tend organizations to set a near impossible (from a feasibility point of view) risk averse atmosphere. For responsive space missions, this axiom still holds true, but risk must be managed smartly. As a demonstration, the mission can be designed in a paradigm spelled out in DOD-Hdbk-343 as a Class D satellite: “Class D is defined as a higher-risk, minimum-cost effort. The characteristics for Class D usually involve some combination of the following features: medium to low national prestige, short life, low complexity, small size, single string designs, simple interfaces, hard failure modes, no flight spares, lowest cost, short schedule, and a noncritical launch schedule. Vehicle and experiment retrievability or in-orbit maintenance may or may not be possible.”³ This class of satellite is useful for demonstrations to allow for cost and schedule constraints. However, this paradigm is not inconsistent with fast, inexpensive responsive space missions. With low cost missions (including launch costs) and the ability to rapidly launch these systems, more risk

is acceptable.

Defining risk and reliability has been a challenge for the TacSat-3 program. Consensus has been achieved to look at it as a percentage of capability at the end of life. A risk management philosophy will be spelled out in the risk management plan for the program. The success criterion which directly addresses risk is: “Provide operational lifetime of 12 months (goal); six months (threshold) with 80% mission capability effectiveness. This effectiveness level is measured against the Success Criteria thresholds.”

3.5. Relationship to Lower Level Requirements

Lower level requirements must be derived from the Mission Success Criteria. TacSat-3 has specifically linked the mission design requirements with the Success Criteria. These requirements are extremely important to verify the system design, but they must be used in the proper context. If a design trade is constrained by the lower level requirements, but not constrained within the Success Criteria the lower level requirements must be changed. This is a guiding principle throughout the TacSat-3 design, and has been used to good effect.

4.0 Design Example – Using Responsive Space Mission Success Criteria

A prime example of balancing design requirements against the Mission Success Criteria is the design trade for a cover on the Hyperspectral Imager (ARTEMIS). There are two main dimensions to this design trade. A cover provides some specific capabilities to the payload, but has a significant impact on the system as whole. These capabilities must be balanced against the mission success criteria.

4.1. Cover Capabilities Trades

The baseline ARTEMIS design does not include a cover for the optics. This cover would be mounted on the end of the telescope barrel, and must be actuated with a duty cycle every orbit. It would provide contamination protection during space vehicle integration and test, and during the launch environment. There are specific concerns of atomic oxygen degradation of the optical surfaces after the payload fairing on the launch vehicle is ejected. Atomic oxygen degradation would also occur during the lifetime of the space vehicle on orbit. A cover would minimize this degradation. A cover would also protect the optics from possible damage from solar energy deposited directly onto optical surfaces. This would have an impact on the performance of the sensor, but could potentially damage certain components. Another benefit to a cover would be to allow for dark current collection on the focal plane arrays to enhance the usefulness of the ARTEMIS data.

Even with these benefits, inclusion of a cover has impacts onto the system. The first impact would be to the cost and schedule for the entire program. The added impacts of designing a cover, designing structural and cabling accommodations on the ARTEMIS payload, testing of the cover and integration of the cover significantly increases to the total space vehicle costs against other options. It would have a schedule impact, as well. Another impact would be the added complexity to the bus command and data handling software, as well as introducing a failure mode in the spacecraft which would end the primary mission (the cover mechanism failing closed).

The alternatives were varied, but can be categorized into two distinct categories: risk acceptance and other design considerations. The risk acceptance required the program to look into the severity and probability of several risks detailed above. Chief among these were the contamination, atomic oxygen degradation, and solar damage risks. Other design considerations were modifications to the launch window timing (during flight not having the sun enter the ARTEMIS Field of View during launch post payload fairing separation), increasing the robustness of the fault protection software on the spacecraft bus, and orienting the nominal flight orientation of the spacecraft away from pointing the telescope boresight in the ram

direction of flight.

4.2. Mapping Impacts to Success Criteria

This design trade was a major test of trading lower level design requirements against Mission Success criteria. Each of the capabilities provided by the cover directly mapped to Mission Success Criteria, as well as the impacts to the system. The benefits of protecting against contamination, atomic oxygen degradation and to an extent solar thermal energy protection directly related to the Hyperspectral Imaging Mission Success Criterion. However, expert opinion and some analysis showed this risk to be manageable, and did not exceed the metrics put forth in this Success Criterion.

The more important impact was an increase in the system's total baseline cost and schedule. This would mean the cover option automatically failed two main mission success criteria. This mission success failure is unacceptable in the program. Therefore a cover is not part of the TacSat-3 baseline. This is consistent with most design trades performed in most engineering projects. The nuance is trading perceived risk against acknowledged mission failure. Each design trade must look at the entire system impacts and be evaluated against the Mission Success Criteria. Other design trades were considered which did not increase program cost and schedule and provided a reduction in risk. This result is not surprising, but shows the utility of having program constraints a part of the mission success criteria.

5.0 Summary

TacSat-3 is a responsive space mission with a focus to provide a full capability direct to the warfighter, while meeting the cost and schedule portion of the responsive space paradigm. Crucial to the success of the TacSat-3 mission are well defined mission objectives coupled with measurable and feasible mission success criteria. All design information and trades must be traceable to these success criteria. The TacSat-3 mission addresses operational responsive space needs and provides an HSI payload provides military utility to theatre commanders. The tactical satellite demonstration program provides a streamlined acquisition model for operational system. TacSat-3 mission addresses needs for operational responsive space and has strong support from Air Force and DoD leadership.

6.0 References

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²Ancona D., Kochan, Scully, Van Maanen, Westney, *Managing for the Future: Organizational Behavior and Processes*, 2nd Ed., South-Western College Publishing, Cincinnati, 1999, M-3, pp. 18.

³DOD-Hdbk-343, "Design, Construction, And Testing Requirements for One of a Kind Space Equipment", <http://snebulos.mit.edu/projects/reference/MIL-STD/MIL-HDBK-343.pdf>, 1 Feb 1986, pp. 8.