

Adapting to Change in Small Satellites, Lessons from the TacSat Program

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Abstract: The TacSat series of spacecraft have very short development times but also very challenging technical goals. To meet the ambitious requirements of these programs requires a systematic approach to change control that allows developmental payloads and subsystems to be integrated rapidly and correctly with the rest of the spacecraft. Often this approach balances documentation and consideration of design impacts of changes with the need for quick decision making and rapid accommodation of changes. MSI has been involved in TacSat-2, TacSat-3, and TacSat-4. The Roadrunner, a.k.a. TacSat-2 mission is being conducted by the Air Force Research Laboratory (AFRL) to demonstrate techniques and methodologies to dramatically shorten the development time required for small satellites. TacSat-II is scheduled for launch on November 13, 2006. MSI supplied the bus for TacSat-2 and supported I&T of the system at AFRL under Jackson & Tull. MSI was one of four bus contractors awarded a phase A study for TacSat-3 and is one of the members of the systems engineering team supporting early TacSat-4 development. In this paper we will discuss the specific techniques used on these programs to accommodate changes at various levels of development. We will discuss who the appropriate decision makers should be, how to communicate changes to the team, how changes are documented at different stages of development, and discuss some of the technical design details that allow change to be accommodated with minimum impact. In each case we will use examples from the TacSat and other programs to illustrate how such processes have evolved and the implications they have on program elements such as risk management, cost control, testing and configuration control. We will also present an update of the TacSat-2 mission status and show how various changes during the program lifetime affected the development of the mission from a bus contractor's viewpoint.

Introduction

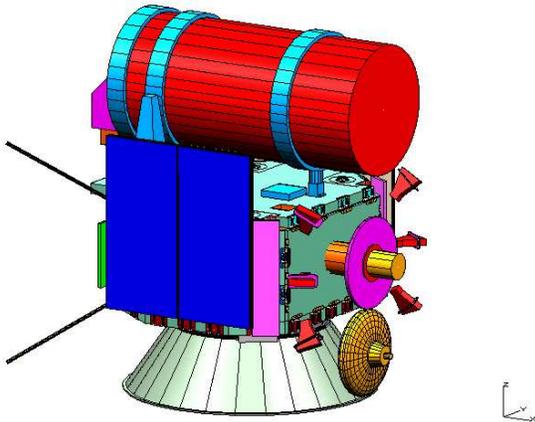


Figure 1 – TacSat-2 Initial Concept

The ability to quickly and correctly accommodate change is arguably the key aspect of success in any small satellite endeavor and the TacSat series has enabled MSI to distill a number of important lessons in this regard. As shown by Figure 1 above and Figure 2 below, the difference between concept and final product (MSI bus) delivered 12 months later can be dramatic.

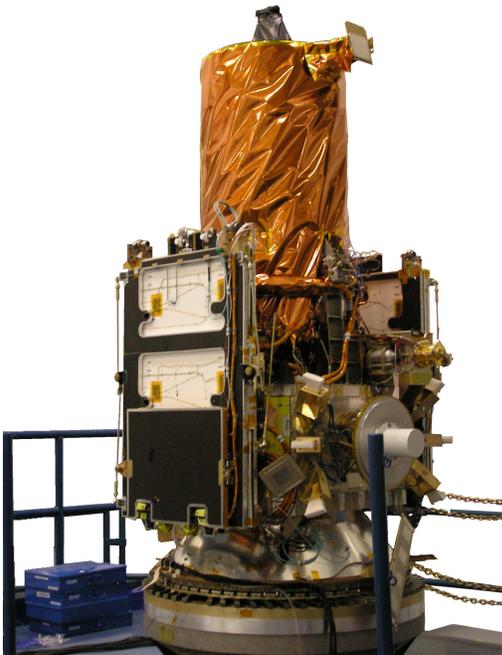


Figure 2 – TacSat-2 Final Space Vehicle

In many ways the ability to handle change faster is the principle attribute in allowing a small satellite project to compress schedules to 1-2 year developments instead of 10-15 years. The total number or severity of changes that a small satellite program encounters may be no more or less than a traditional satellite program, but in order to contain costs, these changes must be dealt with much quicker. Achieving this fast reaction to change without sacrificing quality is crucial to any company's survival in this market niche.

Laying the Foundation for Change

As with other aspects of life, the first step is admitting that we have a problem. In the author's experience across many companies and projects, there is a perception throughout our industry that small missions are immune from the need to plan for proper change control. Many people believe that because a mission happens so quickly it won't have time to change much. Others believe that small budgets and limited scope will reduce change control to a trivial task not worth consideration.

Some ideal small satellite missions are conducted with a single payload/purpose that are adequately funded, politically stable, and have secured a launch vehicle. For this subset of missions, it is reasonable for the team to expect a minimum number of changes, especially if the customer has a stated and proven dedication to minimizing change as a method of cost containment. For the vast majority of small satellite missions, however, all of these initial conditions are not met and thus the stage is set for a wide variety of changes to be accommodated.

Changes arise from the need to meet the challenges of integrating multiple payloads

or accomplishing multiple mission objectives. This is because increasing complexity reduces the ability of the designers to correctly anticipate all of the potential interactions and interfaces between systems. Even in missions that are ideal, some change will always occur simply due to the fact that as further design definition is produced for the various elements need to remain in synch which means a continuous evolution of design details during development. Additional changes arise from a severely cost or technically constrained mission. These additional changes arise because margins are typically the first line of defense containing the small developmental changes that always occur. In missions that are severely constrained the lack of margin means that small changes must be accommodated by continually re-optimizing the system to meet the stringent goals.

Now that we have established that changes are to be expected in small missions, the next step is ensuring that all major stakeholders agree on expectations for how to deal with the changes. For this we will consider the perspectives of the customer, the marketing department, management and the line engineer. Ground rules should be established early to determine what types of changes to expect and allow for, what aspects will remain inviolable, and what processes will be used to shepherd the changes.

Marketing can help set the stage for initial expectations of change. It is often tempting in proposals to ignore the cost of changes because many proposals are prepared in response to a point design request or a fixed set of requirements. Neglecting the dynamic nature of requirements is a common oversight at this stage. Pushing designs further toward the edge of the performance

envelope in order to win an award increases the risk of such changes later on, a fact which is also easy to forget at this stage. Proposal preparation teams would be well served to remember former AMSAT NA President Jan King's aphorism, "Performance, Price, or Schedule; pick any two to optimize and don't complain about the third." By now the small satellite industry has enough experience as a whole to be able to recognize what realistic expectations are and we best serve our future interests by being honest with customers even during the sales stage of the mission.

Once the marketing group adopts an appropriate stance to change, the customer and the management teams can have meaningful discussions on the ground rules for how to accommodate changes. This should include things such as prioritizing the various mission objectives to allow trades to be conducted. Customers and management must agree on the relative weighting to assign performance, price, schedule and risk in these trades. It also includes agreeing on the various strategies and processes to accommodate change and designating individuals to lead this process.

The other final component, the line engineer, must also buy into the concept of handling change rapidly and efficiently. This can be especially difficult for some engineers who are used to working on the larger traditional space programs where the pace of change is not nearly as challenging. It is important that team members accept that change is going to be part of the program. They should be prepared to redo analyses and designs as necessary to support shifts in requirements or new discoveries from other areas that drive change in their systems. It is also critical that they avoid dwelling on complaints about being forced

to change and instead step up to the challenge of meeting the new requirements. Attitudes toward accepting and dealing with change vary widely among people in general. For a small satellite mission to be successful in fostering good relationships among all participants, it is important to select team members that display a willingness to deal with change in a positive fashion.

Strategies for Success

In selecting the program's overall strategy for success, decision makers should consider how they wish to balance schedule, risk, budget, and performance parameters to achieve the mission objectives. The primary strategies for dealing with change can be categorized according to the various emphases they place on these competing objectives.

For example, on MSI's DSX mission, the mission timeline from initial development to launch is fairly long for a smallsat, approximately 6 years. To contain costs and accelerate payload definition, the program made an early decision to define and build the spacecraft bus first, then use that to define the interfaces to the payloads. This effectively removed the possibility that individual payload design details could drive changes of the bus. However, as illustrated in Figures 3 and 4, this strategy did not make the mission immune from changes due to the finalization of the payload manifest.

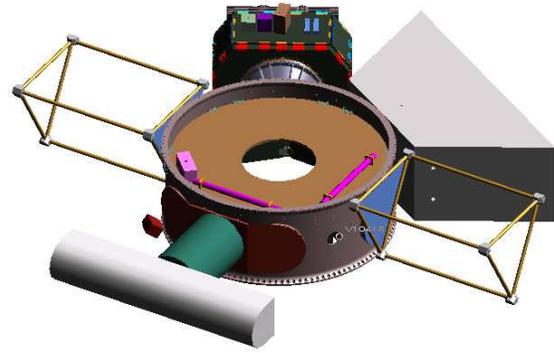


Figure 3 – DSX Stowed Configuration As Originally Proposed by MSI

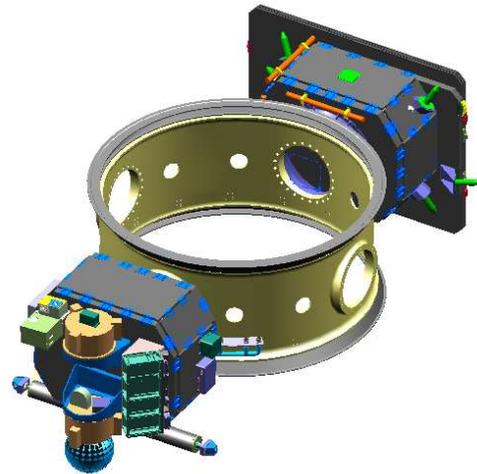


Figure 4 – DSX Stowed Configuration As of April 2006 (In Fabrication)

A similar set of ground rules was adopted for TacSat-2. This program decided early on to be “capabilities driven”, by which we mean that the program office would adjust the mission performance requirements to match the capabilities of the off-the-shelf hardware that we could acquire in time to support the mission. This allowed bus design and manufacturing to proceed immediately while payload development occurred in parallel, thereby shortening schedule and minimizing changes that would have budgetary impacts to the bus.

Another MSI mission is only documenting as built designs, eliminating the need to revise drawings and most other documents entirely. This approach is consistent with a customer that has a critical need for rapid delivery and low cost. The approach is only compatible with very simple missions with limited objectives that can be achieved with a very small development team. The small team is essential to maintaining a coordinated effort where written documentation is cut to the bone. In this case, it is possible to keep a handful of people coordinated via verbal instruction and e-mail if they are co-located. Any more than half a dozen members offers too many opportunities for miscommunication. The risk posture of the customer for this mission had a profound influence on the MSI approach. In this case the customer is familiar with high risk endeavors and was willing to accept this approach to achieve their cost and schedule targets.

One area of strategic decision making that can have a profound affect on the ease of accommodating changes later on is the selection of appropriate design margins for many key spacecraft elements. This process is largely dependent upon engineering judgment given the nature of the mission and what sorts of changes are expected during development. Categories for margins include overall mass, cg, peak power, orbit average power, spare switch lines, spare analog and digital I/O, processor memory and MFLOPS, etc. By providing adequate margins to accommodate potential changes, the design attains a level of flexibility that allows changes to be compartmentalized so that every minor alteration does not require an intensive systematic analysis and redesign. The difficulty lies in selecting the right level of margins, ideally just enough to cover the changes without wasting any capability. Margins that are too

conservative can lead to spiraling capability and cost. Margins that are too aggressive will lead to significant impacts for even minor changes. One pitfall in a capabilities driven mission is the natural tendency to keep adding payloads or objectives until all the capability is used up. It is important to remember that just because a mission decides to live within the capabilities of the spacecraft bus, it is still prudent to maintain a reasonable cushion on those capabilities as a hedge against later changes.

Flexibility can also be added into the architecture of the spacecraft by the use of several techniques. First, keeping the basic functionality of the spacecraft simple protects the core functions from becoming complex and interdependent. This allows a mission to achieve its primary objectives most reliably with less dependency upon secondary systems or secondary mission objectives. Implementing this philosophy is an exercise in the KISS principle and is applied to basic functions such as safe mode and primary payload accommodation.

Secondly, designing a generic baseline of capability allows a wider latitude in adjusting to major changes later on. For example, choosing a 3 axis stabilized ACS architecture that can point any body vector at any target provides significantly more robustness to changing mission needs than a gravity gradient or sun pointing only architecture would.

Thirdly, incorporating modular, flexible interfaces at key points prevents accommodation of changes from propagating throughout the entire design. Use of FPGA's to drive the digital data interfaces to payloads, for example, allows many aspects of the protocol and link layers between payloads and the bus to adapt with little impact to the rest of the system.

Similarly, a modular approach to software interfaces can dramatically reduce the effort to debug and finalize these interfaces in later stages of the project. Specifically, one may employ techniques like using a standard command and telemetry structure throughout software and only translating them to and from the specialized formats of the hardware elements on the last software modules (device drivers) that interface directly with the various hardware elements. This allows changes in the hardware interface to be made without have to propagate them throughout.

Finally and most importantly, flexibility in staff roles is an extremely powerful tool in successfully accommodating change. By selecting team members who possess a variety of skills across multiple disciplines and across all stages of development, there are far fewer individuals involved, exponentially reducing the communication effort involved in adjusting to changes.

Also, these individuals can continue to play key roles throughout the program life cycle, eliminating hand-off's to new personnel and retaining the tribal knowledge gained early in the process. This allows them to evaluate late breaking changes with the full contextual knowledge of how the system was designed in the beginning and lets them take full advantage of the system capabilities to accommodate such changes.

Process Mechanics

The change process follows the sequence of first being initiated by someone on the team, then being evaluated, a decision made, and finally documentation and implementation. This process as typically implemented at MSI is graphically represented in Figure 5.

In the first part of the process changes in traditional programs are initiated typically by the customer through the contract requirements or through the engineering

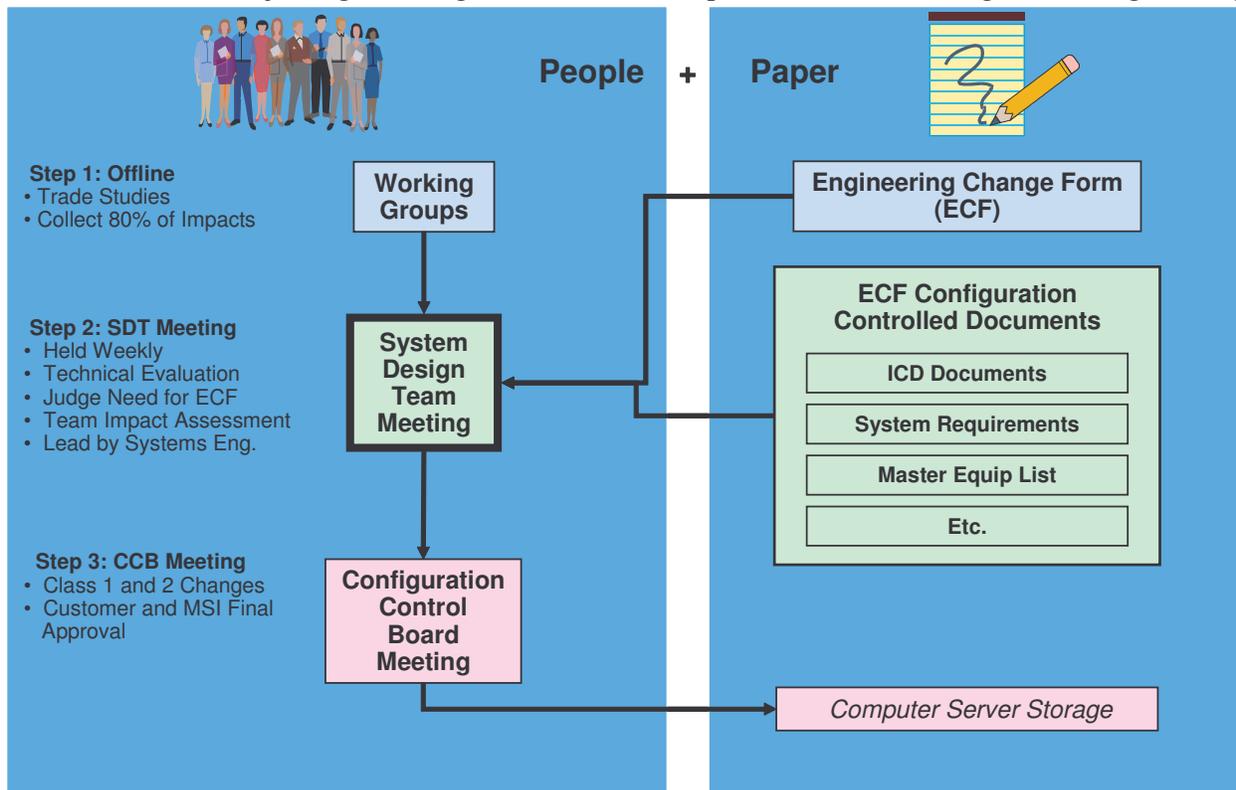


Figure 5 – MSI Typical Change Process

team as they adapt to developing design

details. In many small satellite missions, the need for quick reaction to change requires a less formal relationship with the customer that allows the bus contractor to begin working on change impacts without waiting for contract documentation. This should be negotiated up front to allow maximum flexibility to work to the customer's direction. Two keys enablers of success are less specific statements of work and adequate funding margin to cover the anticipated changes. The underlying requirement that makes this relationship possible is trust, built on a foundation of past performance and mutual dedication to the program's success. If these elements are lacking then the customer driven change process will be limited to the speed at which contracts are renegotiated, typically an order of magnitude slower or more.

Design initiated changes in all programs need to be formally evaluated for their impacts across all subsystems and mission elements prior to approval being given to implement the change. In smaller satellite missions, the small size of the team makes this process more streamlined since fewer individuals are involved in making the decisions and evaluating the impacts. Communication in these small groups can often be less formal and are easier to arrange. The other factor working in favor of small missions is that the short time scale of development means that communications don't have to persist for 5, 10 or 15 years, so they can be documented less rigorously.

For the TacSat-2 mission many of the changes in the design and implementation of the mission were documented via e-mail instead of with formal change paper. Formal change paper, listing "was" and "now" details and collecting impacts was reserved for changes which altered the interface between organizations including

ICD's or requirements. Another successful strategy used was to delegate authority for change control to individual payload or subsystem leads if the change did not affect any team members outside that particular organization. This system works well only when all the subsystem leads make sure to involve systems engineering at the bus or program level as appropriate whenever there is a question about possible impacts outside their subsystem or payload.

At the subsystem level, design changes are tracked on a redline record sheet for structures, on a change log for power and mass budgets, in the Microsoft CVS system for software (ground, test, and flight), and in the change log for the harness wire diagrams for harnessing. For thermal, the lead engineer documented the current state of his design and kept it up to date with any new information as soon as he received it. The format used for this was a comprehensive CDR quality PowerPoint presentation. This had the added benefits of making the current state of his subsystem immediately understandable to anyone on the program and eliminated the need to specifically prepare other materials for any of the normal design reviews.

At the bus system level, a log was kept of all bus changes driven by external factors. This log listed the authorizing entity in the program organization, the nature of the change, effective date, and top level impacts to the bus. In addition, all system level documents such as the requirements and the ICD's contained a version or change log to describe the differences in each updated release. These documents, when changed, also had an associated change record as described earlier. Changes affecting cost, schedule, or deliverables still needed to be

approved by the full change board including customer representatives and negotiated with a contract modification. For each of these changes each subsystem was polled for impacts. For the major changes a full impact study was conducted to formally evaluate how to best implement the change and trade the various options. Cost, schedule, risk and technical performance in each subsystem would be evaluated for these trades with detailed impacts provided to assist in the justification of proposed cost increases. These formal studies were reserved for major questions such as the potential addition of new payloads, consideration of different launch vehicles, or major configuration changes in the spacecraft affecting multiple systems. On TacSat-2 there were only seven instances of changes that were evaluated in this systematic way.

All other changes were handled informally by the engineering team by just involving the particular groups affected by the technical change. Due to collocation of all the bus subsystem leads, this coordination of bus only design changes frequently took the form of simply walking down the hallway and gathering all the stakeholders for a quick stand up meeting to decide minor issues or to at least determine a lead for a particular change topic and assign action items to support coming to a decision.

The net effect of this delegation of change control authority to lower levels where appropriate was to greatly streamline the process and allow the engineering team to keep up with the fast pace of development. It also resulted in a system that did not automatically push a large amount of detail information to the top level of management, but still kept that information available when needed.

Once the program moved into payload integration and test, all design documents were copied onto a master CVS server at the site of I&T. This central repository was updated with changes on an almost daily basis and this became the gold standard for finding current information about any aspect of the spacecraft or mission.

After a change decision had been made and documented, responsibility for implementing the change would be delegated back to the subsystem or payload lead(s) responsible for impacted areas. Progress on implementation of major changes was reported as part of the regular weekly status meetings.

TacSat-2 Update

TacSat-2 has successfully completed system thermal vacuum testing and vibration and shock testing. Payload integration is complete and all major system test milestones should be complete by the time of the publication of this paper. The mission is manifested for a November 13, 2006 launch aboard a Minotaur I launch from the Virginia Spaceport. As of the submission of this paper, all but a dozen or so open issues have been successfully dealt with and closed. The team is currently preparing for launch and mission operations. Some initial simulations of operations have been run and more rehearsals are scheduled in preparation for the launch.

The journey from initial mission concept pictured in Figure 1 has seen the addition of several payloads, the deletion of some, a major configuration change to the mounting of our primary instrument, a change of orbit, and a change of launch vehicle. Throughout this process, the techniques described in this paper have been used to keep the bus portion

of the work on schedule and ensure mission success with a minimum of rework.

Conclusions

Changes need to be accommodated on a rapid time scale for small satellites to be successful. Recognizing this fact and planning for it at the beginning of a project can greatly improve the chances of staying on budget and on schedule. Setting clear groundrules and processes for handling change early can save considerable expense and difficulty later in the project. Specific recommendations include keeping the statements of work general enough to avoid renegotiation for smaller changes, adequately funding efforts to include a management reserve to deal with the changes, keeping adequate system margins on technical resources such as mass, power, I/O interfaces, etc. The process of dealing with changes when they occur can also be streamlined by delegating authority to deal with compartmentalized changes at the subsystem level, relying on less formal communications such as e-mail and design descriptions instead of formal change paper for the less serious changes, and making sure to institute general documentation practices that are easy to keep up to date and still capture the important steps in a design's evolution.