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Informing Large Space Science Missions from SmallSat/Class-D Mission Lessons Learned

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Abstract

The National Aeronautics and Space Administration (NASA) has flown successful large strategic flagship missions throughout the years in part because of development processes, procedures, and practices established from past successes and failures. This institutional knowledge, generated over time and embedded within both documents and people, has also meant that mission implementation has relied upon existing methods with a proven track record to manage risk within prescribed cost boundaries. As one looks, however, toward the future of sustainable space missions, particularly those that will use new mission architectures, lessons learned from the small satellite mission community offer potential paths to reduce risk, lessen costs, increase implementation speed, and manage complexity while leveraging new technology advances.

We summarize the outcomes from a NASA Science Mission Directorate (SMD)-led study that explored how optimal practices from small satellite (SmallSat) and Class-D missions could be applicable to large mission development. Over a period of 12 months, a broad team of NASA, academic, and industry experts consisting of project managers, chief engineers, standing review board members, program managers, and system engineers identified key findings compiled from over 240 interview comments from 37 interviewees. These participants have worked on Class A, B, C, D, and SmallSat missions that have flown throughout the solar system.

The team identified seven main findings that span the full mission lifecycle, covering team dynamics, team size, mission requirements, the use of commercial products, risk management, mission reviews, and documentation. While some of these findings demonstrated alignment with other prior studies, such as the NASA SMD Large Mission Study [1] and Psyche Independent Review Board Assessment report [2], the findings and recommended actions from this effort provide new insights given their genesis in the unique approaches that small missions have developed to ensure mission success under cost and schedule constraints. From this perspective and based on these observations we describe new strategies that were learned from the small mission approach that can be leveraged for large mission implementation.

Keywords: space science missions, project management, small spacecraft

1. Introduction

Small satellites have long played a role in NASA's space exploration effort, including Explorer 1 in 1958 the Apollo 15 Particle and Fields Subsatellite (PFS-1) deployed in 1971 [3], and relatively low-cost missions such as Mariner 4 and Clementine. By the beginning of the 21st century though, NASA science missions predominantly employed large satellites carrying complex, highly capable instruments to meet the agency's challenging science objectives and accepted the cost necessary for custom instruments and spacecraft buses.

In 1999, CubeSats (satellites using standardized 10x10x10 cm platforms) were invented by academia to provide a cost-effective method to enable student-led space exploration projects. The wider space community latched onto this new platform and its potential uses. The Ames Research Center launched NASA's first CubeSat—GeneSat—in 2006 and the Earth Science Technology Office launched the first CubeSat for NASA's Science Mission Directorate (SMD)—the Michigan Multipurpose Minisatellite (M-Cubed)—in 2011.

Following the success of these and other CubeSats in the community, the National Academies of Science, Engineering, and Medicine conducted a study to review the scientific potential and technological promise of CubeSats [4] to obtain science data that would align with the priorities identified in the 2014 NASA Science Plan [5].

In response to the National Academies' report, NASA created a strategic plan to coordinate the use of these small spacecraft across the Agency, adopting a definition of "SmallSat" to mean a spacecraft with a mass <500kg that can launch as a rideshare [6]. NASA's SMD created several processes to encourage broader use of smaller platforms for science and has subsequently developed well over 100 SmallSat missions, including CubeSats, to provide useful science data and/or demonstrate new technologies. SMD manages these small satellite missions differently than larger, traditional science satellites, primarily by employing reduced oversight and insight, heavier reliance on commercially available systems, and increased risk tolerance. NASA categorizes its missions into classes based on the risk tolerance expected for the mission, where a Class A designation is assigned to those missions that are of such significance that they cannot fail, down to Class D missions which are allowed to take risks with the expectation that success will be achieved at the fleet level instead of the individual level, thereby reducing costs to SMD [7]. Most of SMD's SmallSat missions have been designated as Class D. Now that SMD has significant experience successfully implementing these SmallSat Class D missions, the question arises as to whether lessons learned from small satellite practices can benefit NASA's larger science spacecraft missions.

To help answer that question, SMD interviewed dozens of project managers, program managers, scientists, and engineers with experience across the risk classification spectrum and convened a workshop to identify specific management practices used by SmallSat missions that could be applied to larger missions to reduce cost and schedule while maintaining quality. Note that not all SmallSat missions are successful, nor are they all managed exceptionally well. The workshop participants were asked to focus on what worked well on SmallSat missions, that is, to identify best practices that could be transferred to larger missions. The report from that workshop was published [8] and its key findings are summarized here.

2. Findings

Three dozen space mission experts convened for a two-day workshop to identify best practices employed by small spacecraft mission teams that could be applied to larger missions for potential cost savings. They found many. These findings are grouped along seven key themes: team dynamics, team size, mission requirements, the use of commercial products, risk management, mission reviews, and documentation. The findings are summarized below, including specific actions that could be enacted by larger missions to streamline management and reduce cost. In some cases, the recommendations could be broadly adopted by NASA across all mission classes.

In each case the findings refer to SmallSat missions that are managed as Class D; this notation is shortened to SmallSat for simplicity.

2.1 Small, Cross-Disciplinary Teams

Like the spacecraft themselves, SmallSat teams are small and this enables swift and open communication among team members and quick decision making. Additionally, their multidisciplinary composition enables system-wide awareness and understanding, which improves overall design and facilitates early identification of potential problems, especially those that cross system boundaries. Small teams foster checks and balances throughout the system and cultivate a sense of individual and collective accountability. SmallSat missions have substantial independence and accountability at the local level in decision making. Team members' influence does not stop at interface control documents.

In contrast, the culture in large missions is such that decisions tend to involve the project manager too often; decision making is diffused among multiple people, and much time is spent engaging multiple groups before arriving at decisions. Larger missions are very complex and involve specialized sub-teams whose interactions can become siloed, making it hard for team members to understand end-to-end processes and goals at the system and mission levels. Without constant communication among team members with big-picture perspectives, systems engineering can devolve into simply an accounting function.

Suggested actions that larger missions could adopt:

2.1.1 Promote fostering personal and collective senses of ownership, open communication, and system-wide awareness

An environment where everyone has a mindset of responsibility and system-wide awareness can ensure the success of the entire mission. A way to change the culture of large missions to provide big-picture thinking, without diluting attention to detail, would be to institute an environment akin to Stephen Covey's circles of control, influence, and concern [9]. In large missions, a cognizant engineer's circle of control ends with their responsibility to meet requirements within an interface control document, but it would be beneficial to encourage them to broaden their perspective to encompass other subsystems as their circle of influence, and the entire mission as their circle of concern, as is routinely done in small missions. Providing frequent opportunities for informal communication, coupled with this mindset, can go a long way toward unearthing opportunities and potential problems.

2.1.2 Transform decision-making culture

Based on the culture change above, sub-teams will have increased situational awareness; well-established, open communication channels; and increased trust with other sub-teams up and down the project management chain. Therefore, sub-teams can be empowered with greater decision-making authority, which should speed the decision-making process.

NASA Headquarters plays a role in establishing the decision-making culture for projects, and Headquarters representatives should educate missions early in the mission lifecycle that providing information in a timely manner about mission challenges will enable Headquarters to support decision makers if issues arise.

Larger missions should create communication channels among sub-teams to facilitate collaboration and to promote overall mission- and system-level awareness and contextual understanding (i.e., eliminate siloed communication, root out the "not my problem" attitude).

Larger missions should institute organizational practices that foster cross-communication among the sub-teams (e.g., encourage more frequent informal communications and esprit de corps activities).

Larger missions should promote the exchange of ideas and awareness in their team by encouraging members of sub-teams to participate in peer and/or tabletop reviews of other sub-teams. This practice allows for sub-teams to understand how subsystem changes could potentially affect one another.

2.2 Reduce the Standing Army

Small missions are effective at employing people on an as-needed basis rather than maintaining a standing army, defined as keeping all people needed for a mission on that mission from mission inception through launch and beyond. Large missions often use this standing army approach because it ensures ready access to knowledgeable personnel in case problems arise. Retaining only a small staff and recalling other subject matter experts on an as-needed basis, rather than keeping everyone on the payroll throughout the mission lifecycle, can very substantially reduce labor costs.

Suggested actions that larger missions could adopt:

2.2.1 Nimble workforce deployment

Large missions should deploy their workforce nimbly, acknowledging that this approach demands careful planning to ensure mission continuity without relying heavily on a fixed workforce.

2.3 Essential and Bottom-up Requirement Tailoring

NASA's SmallSat missions are guided by the Class D Mission Assurance Requirements (MAR) document that allows them to tailor their requirements using a bottom-up approach, only adding requirements that add value [10]. Large missions use an expansive MAR, often have a "checklist mentality," (i.e. tasks are executed without thinking through system-level ramifiations), and typically struggle to justify the removal of requirements.

Suggested actions that larger missions could adopt:

2.3.1 Encourage requirements tailoring

NASA should establish a lean Class C MAR like the SMD Class D MAR.

Training guidelines for Mission Assurance Managers (or equivalents) should be formulated. The Office of Safety and Mission Assurance and the NASA Office of the Chief Engineer should conduct presentations to educate all stakeholders (internal and external) on Class C MAR principles and significant departures from common practices.

NASA should feed lessons learned from small missions forward by developing suggestions for common tailoring of NPR 7120.5 [11] requirements for future Class C missions.

2.4 Commercial Off-the shelf (COTS) Product Usage

SmallSat missions effectively use COTS products and processes by designing around existing products and systems, which significantly reduces mission costs. Early in the design process, many SmallSat missions explained how they would reduce mission costs to embrace the Class D philosophy and have now demonstrated that COTS parts do not necessarily introduce unacceptable risks. Large missions can benefit from using COTS products and systems. When designing their systems, large missions often disregard existing commercial solutions or impose NASA requirements on commercially available systems.

Suggested actions that larger missions could adopt:

2.4.1 Identify methods to incentivize or promote the acceptance and utilization of COTS parts

The burden of proof should be on the large missions to justify why commercial products and processes aren't adopted.

Large missions should expend effort designing around the performance of COTS parts including selective redundant systems and/or spacecraft.

Large missions should encourage cost savings by eliminating adding margin on margins.

NASA should perform a technical, cost, management, and other factors study on design and test practices that build in margin on margin to determine the effect on total cost.

2.4.2 Team with vendors

Large missions should communicate with vendors to make sure that they clearly understand the needs and goals of the mission. If vendors allow NASA to examine their processes, NASA could then accept certain COTS parts and products as qualified and accept them "as is" without imposing NASA's processing and still getting acceptable results. Large missions should consider adding contractual language to require this insight.

Large missions should ensure vendors grasp which requirements are mission-critical to facilitate risk-based discussions and ensure product alignment with intended goals. The flow-down process for mission assurance requirements should be reviewed and included in contracts. "Blanket" flow down of requirements should be avoided by avoiding references to documents that contain requirements that are not directly pertinent to project needs.

2.4.3 Screen for vendors that are transparent and willing to work with NASA if an issue were to arise

2.4.4 Modify regulations and processes to focus on reliability goals

NASA should modify NPR 8705.4 Appendix D [12] to allow design architectures that meet the reliability goals instead of requiring a waiver for the use of Level 1, 2, or 3 parts as described in NPR 8705.4.

Large missions should be required to show that the design architecture would provide a verifiable approach to safely use COTS parts.

2.4.5 Parts documentation

NASA should relax the documentation requirement for parts that have been flown successfully multiple times in a relevant environment (e.g., NPR 8705.4 flowdown of embedded documents and MAR).

2.4.6 Preferred Parts List

NASA should establish a preferred parts list by tapping into expertise of other comparable missions and review this list on a regular basis.

2.4.7 Parts Environment Assessment Laboratory

NASA should establish a parts environment assessment lab within NASA to form trusted partners and a catalog of trusted parts.

2.5 Risk Management Practices

SmallSat missions managed under NPR 7120.8 [13] do not use formal risk management. Engineers on small missions conduct risk management as a matter of practice every day, rather than spending significant effort on risk management products. SmallSat missions leverage existing risk assessments and focus on understanding and mitigating operational mission risk. Large missions spend a significant amount of effort on risk management before designs are complete (developmental risks). Since risk management is tied to resource management, small missions cannot afford to eradicate all risks while large missions not only try to mitigate all risks but often overcompensate to provide margins on margins.

Suggested actions that larger missions could adopt:

2.5.1 Differentiate between developmental risk vs. operational mission risk

Large missions should employ simplified risk management tools until Critical Design Review (CDR) and levy fewer requirements for documenting developmental risk. Simply listing the design elements of concern and discussing the risks with a standing review board could be sufficient until Key Decision Point (KDP)-C as designated in NPR 7120.5.

Large missions should spend more effort solving problems instead of documenting potential risks.

2.5.2 Risk Assessment

Large missions should clearly assess risk mitigation activities (like test protocols) to assure that critical risks are addressed while eliminating unnecessary activities.

2.5.3 Open Culture

Large missions should establish open working relationships to build trust between mission teams and safety and mission assurance personnel. Mission leadership should establish team norms to ensure that teams have ongoing conversations about which risks require formal documentation and tracking vs. those that can be simply worked at the project level.

2.6 Small, Consistent, and Support-based Review Boards

SmallSat review boards are small, support-based, and remain with the project consistently; board members are experienced advisors focused on assisting the mission team. This consistent participation of reviewers leads to multiple layers of checks and balances and efficiency. Large mission reviewers focus on compliance, and board members are often specialists rather than generalists.

Suggested actions that larger missions could adopt:

2.6.1 Peer Review Practices.

Standing Review Boards (SRBs) for large missions should provide more informal expertise, including informal small group discussions outside of formal gate reviews.

2.6.2 Peer Review Trust

Large missions should work to build trust between their SRB and mission personnel.

As is the practice for SmallSats, large missions could recommend SRB members who are familiar with the mission team to facilitate open communication and who have good communication skills as well as technical expertise.

2.7 Identification and Combination of Critical Documentation

SmallSat missions identify and tailor documents that are truly needed and used. For example, one SmallSat mission used a six-page PowerPoint presentation instead of a 50-page document for its configuration management plan. Large missions create documentation that is oftentimes not referenced (i.e., the Systems Engineering Management Plan). Large mission teams may stop work to prepare significant documents for reviews. While all missions gain value from review preparation, but the small missions have determined how to identify and combine documentation preparation to minimize the overall cost/time impact to the mission lifecycle; large missions might be able to learn from these practices.

Suggested actions that larger missions could adopt:

2.7.1 Signatures

Large missions should tailor the document signature process to minimize the number of signatures required. For documents that require NASA Headquarters approval, the number of signatures should be reduced to only include the person who did the work, the backup, the supervisor, the responsible NASA official, and anyone else who is required to commit resources.

2.7.2 Reviews

Large missions should consider eliminating reviews such as the system integration review and replacing them with a series of small meetings that produce required products without the formal paperwork.

NASA should create a baseline template for barebones contract data requirements lists needed to support reviews.

Missions should track costs of review preparation to quantify the overall impact to mission lifecycle cost with the ultimate goal of motivating change.

2.7.3 Documents

NASA should study which documents SmallSats successfully eliminated, combined, or reduced, so that the set of documents required for large missions can be modified where appropriate.

3. Discussion

These findings and suggested actions for adoption by larger missions were reviewed by small groups of SMD program executives to assess them for realism and practicality. They concurred with every recommendation, finding them credibly scalable to larger missions and likely to provide benefits.

While the recommendations and discussion provided in this paper are specific to NASA, the authors believe the findings are relevant to other commercial and government organizations that are seeking to improve management processes for missions of all scales.

4. Conclusions

NASA's experiment to expand use of SmallSats for science was a success. These missions now routinely acquire high-quality science data at greatly reduced cost compared to bespoke larger missions. As documented in this report, there are numerous best practices and lessons learned from the agency's SmallSat experience that could be applied to improve the management of larger, Class A-C science missions. As NASA continues to maintain a healthy balance of large and small missions, these findings offer numerous ideas to reduce costs while maintaining the quality of all science missions.

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