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The Small Payload Access to Space Experiment (SPASE): Using Non-Traditional Aerospace Technology to Enable a New Generation of Low-Cost Missions

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Abstract. Launching on STS-108 *Endeavour* in late 2001, the Small Payload Access to Space Experiment (SPASE) demonstrates a number of new technologies, efficient ways to conduct a nanospacecraft development program, and how to take such a spacecraft through the Shuttle Hitchhiker safety and integration process. This paper describes the essential "lessons learned" in each of these areas. Commercial solar panels, batteries, imagers, photocells, integrated circuits, and manufacturing techniques are used throughout the vehicle, bringing the low cost and high manufacturing reliability of these products into the space realm. Core personnel carried the program from conception through proposal, requirements definition, design, development, integration, test, and delivery, making the whole program significantly more efficient. Shuttle safety issues were addressed from the beginning and continually throughout the program, as part of (not added to) the development effort. The information learned throughout this process, and the new doors opened by this demonstration – such as the first use of Lithium-Ion batteries in a Shuttle payload – help make space utilization more efficient, more affordable, and easier for future missions. AeroAstro's Bitsy nanospacecraft kernel will be flight-proven by the SPASE mission.

Introduction

The SPASE program began in Spring 1998 with a partnership between AeroAstro and NASA Marshall Space Flight Center (MSFC) Science Directorate (SD). MSFC SD wanted an inexpensive way to perform free-flying microgravity crystal growth experiments; AeroAstro wanted to demonstrate its Bitsy nanospacecraft kernel.

The SPASE mission was proposed in September 1998 to the X-34 Future-X program as a way to reduce the cost of access to space, by developing and demonstrating a vehicle that could perform a useful science / technology mission for under $2M including launch. The program was awarded in December of that same year. Contract negotiations began in mid to late 1999, and the contract was signed in January 2000.

Technical development of AeroAstro's portion of the satellite (Bitsy – providing power management, voltage regulation, commanding and telemetry, data storage, batteries, and radios) and SD's portion (the Microgravity Crystal Growth Demonstration, or MCGD, containing the crystal growth cell, illumination, camera, and interface electronics) began at that point, along with development of the shared components (solar panels, specified by AeroAstro but mounted to MCGD, and passive magnetic attitude control system, with parts mounted in both units).

Flight unit integration lasted from late Winter through late Spring of 2001, and at time of this paper's writing, the spacecraft is in environmental test, performing well after mass properties, vibration, and all five cycles of thermal/vacuum testing. Integration with the Shuttle Hitchhiker is expected on July 30, 2001. This timeline itself demonstrates one important lesson: proposal and contracting took approximately the same amount of time (~18 months) as the technical program.

While the core SPASE team was small, the personnel and organizations involved were ultimately extensive. The primary contributors to the program included:

- MSFC Space Transportation Directorate, providing funding and program management for all aspects of the program except the MCGD
- MSFC Science Directorate, providing the MCGD payload and science analysis
- MSFC Engineering Directorate, providing test facilities and support personnel
- AeroAstro, the prime contractor for the spacecraft, providing the Bitsy spacecraft kernel and ultimately responsible for the mission
- University of Alabama at Huntsville, providing the ground station facility and spacecraft operators
- Payload Systems Incorporated, providing Shuttle safety support, and authoring the majority of the Shuttle safety package
- NASA Goddard Space Flight Center (GSFC), providing the Hitchhiker ride into space and extensive safety support
- NASA Johnson Space Flight Center (JSC), providing final Shuttle safety review and particular assistance in battery issues
- Team Encounter, providing funding for a CMOS imager experiment to assist in the development of a new star tracker
- Kyocera Solar Corporation, providing the solar panels and the process for creating them that has the advantages of commercial manufacture with the resilience required for space

The spacecraft itself is 56.6 cm tall, 43.2 cm in diameter, fitting comfortably inside a Hitchhiker can. It will be ejected by a Pallet Ejection System (PES) from a cross-bay bridge on STS-108, scheduled for launch on November 29, 2001 for a Space Station servicing mission. SPASE will be deployed near the end of the Shuttle mission into a Station altitude and inclination orbit.

Figure 1. SPASE Demonstration Vehicle.

The photograph in Figure 1 shows the SPASE Demonstration Vehicle flight hardware during mass properties testing. The Shuttle Hitchhiker Palette Ejection System interface is visible at one end of the spacecraft, as are two of the six commercial terrestrial solar panels.

Visible in the following picture (Figure 2) are the internal Bitsy electronics. The radio stack, an S-band transmitter/receiver using FM uplink and BPSK downlink, is in the left corner. The Lithium-Ion battery pack is in the bottom corner, with charging and managing electronics visible on top of the battery enclosure. The large electronics board spanning the width of the Bitsy box is the Bitsy-SX[*] Power/Command/Telemetry board.

Figure 2. Bitsy Internal Electronics.

The NASA Marshall Microgravity Crystal Growth Demonstration canister is shown in Figure 3. A commercial camera is mounted inside of a hexagonal support structure, and is focused on a sugar water solution in which a crystal will grow on orbit. The experiment is thermally isolated as much as possible to maintain a suitable sample temperature.

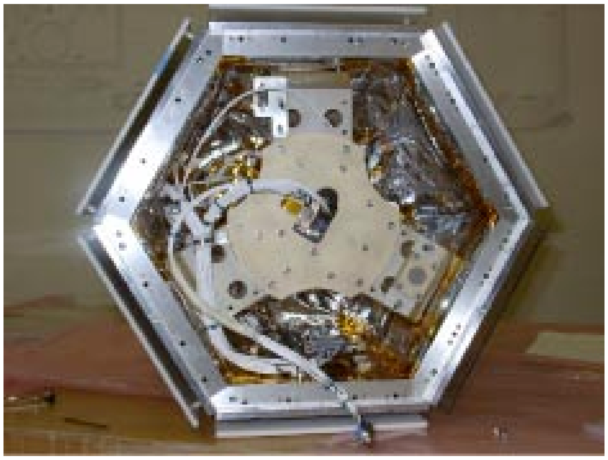

Figure 3. NASA Marshall MCGD.

This paper will explore "lessons learned" in three realms:

- The Recurrent Lessons, items which remain true for all programs but are reviewed to highlight their importance
- Technology Lessons, specific things learned about the various technologies being demonstrated on this vehicle
- Shuttle Lessons, focusing on the effort of Shuttle safety approval.

Recurrent Lessons

Integrate Early

Any two pieces of equipment, however well designed and however well-defined the interface, will have at least one anomaly when they are integrated for the first time. Often and hopefully these issues are small and easily resolved, but they will occur, and sometimes they will be significant and require nontrivial modification to one or both items. This applies to both electrical and mechanical interfaces. Therefore, integrate early to learn sooner rather than later what needs to be fixed.

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[*] The Bitsy product line has three versions: 1) SX, the core electronics providing power, commanding, and telemetry functions; 2) DX, the SX with an automotive-electronics computer; and 3) LX, a product in conceptual design that will incorporate recent advances in miniaturized technology such as micro momentum wheels.

To integrate early, something in subsystem development has to be shortened (assuming the product delivery time is fixed). A shortening of the design effort is good if it encourages simplification in the design, but bad if it induces a rush to production. A shortening of the subsystem test effort is good if it focuses those tests on subsystem behaviors that cannot be tested once integrated, but bad if it produces subsystems that "mostly work" and have to be extensively modified later.

Simplicity Breeds Robustness

A single straightforward, easily tested system is worth four cross-redundant complex ones. It may not be glamorous or exciting to build simple systems, but simple systems work, and in the space industry the device *must work*.

On the SPASE battery system, we inherited a design which used a microcontroller to program the charger. There is a version of the charger IC which does not require a microcontroller, but the battery pack vendor chose features over simplicity, and used the microcontroller. We have had no end of problems with this design.

Conversely, the communications system is a bytewise UART-based protocol, with no phase-locked-loop clock recovery in the receiver, no packetization of the downlink data, and a single 5-byte command structure that controls all spacecraft functions. This reduces our bandwidth efficiency, increases our bit error rate, and forces the ground station software to piece together the bits of an interrupted downlink, but it works, and works well. In space, "optimal" should have a very clear meaning: one optimizes for robustness, and let "performance" (a term which certainly only has meaning when the device works) fall where it may.

Schedule Conservatively

It is alright to be pleasantly surprised when things go well and faster than anticipated. It is not alright to have things go poorly and then run out of time to correct them. There are clear warning signs that a program is walking down the wrong path.

The first warning sign is a knowledge at the beginning of the program that getting to the end in time is going to be difficult – at the beginning, one should think that there is just a little too much time. The perception of "just a little too much time" at the beginning generally corresponds to an accurate prediction of the actual time something will take. Another warning sign is the presumption that something (usually a test) is going to go well. This has two problems: one, it encourages too little time to be scheduled for the test; and two, it discourages a sense of urgency to perform that test, and delays it.

On SPASE we were concerned that the digital electronics and the power system would be difficult to integrate. We were pleasantly surprised at how easy it was. We were however not concerned about the system's performance at temperature, since we were expecting a quite benign temperature regime of -7 to $+35^{o}$C. As a result we did not take early opportunities to temperature-cycle the electronics, and when we did get to it, had a number of issues to address, and no time to do so. The total number of issues we encountered in the digital/power integration far exceeded the four problems we had at temperature; but the latter problems had far greater impact because we did not schedule time to deal with them.

A final note on scheduling is the fairly obvious, but still critically important, statement: do not add new hardware near the end of the program. As with the timing perception above, the sense that "We could have done more" generally reflects that the program has done exactly the right amount. Resist the urge to trade current schedule advantage for a new and untested feature.

Test to Break Things, Not Show They Work

This is an overstatement but a valuable one. Thorough testing – by which is meant many hours of using a system in the manner in which it will be used operationally – is critical for a device that is going to spend its operational life far out of reach of repairing hands. "Thorough", however, is a nebulous word easily twisted to mean "I tried each thing once and it worked". The testing attitude is critically important, and for design testing – not workmanship – the attitude should be "What can I do to make this device misbehave?" Each power line may have worked when it was turned on. But what if they were all turned on at once? The current limit may work, turning a line off when it pulls too many amps. But what if the device pulled the maximum number of amps, continuously, not crossing the limit? Can the system sustain that? Are the analog telemetry signals affected? How about the combination: all the power lines turning on at once, all of them pulling the maximum amount of power. Will the system support that? It may be alright if it does not. But the very act of trying it will teach you more about your system, lessons you want to learn on the ground.

There is another approach to testing which says to characterize every parameter of a system, quantitatively. This is certainly informative but it does not encourage the useful attitude above. It often inspires a false confidence because the parameters you check are already the ones you designed for; the "What can I do to break it?" attitude encourages thinking about aspects of the system not directly related to specific performance parameters.

Have a Small, Highly Communicative Team with a Leader

It is a highly desired but never attained goal to have all interfaces, and performance characteristics, and system architectures defined completely at the beginning of a program, then letting the designers go off and build their well-specified systems. The fact of any development is that there are new things learned on a daily basis which affect, change, or obviate yesterday's specification. This is not to be avoided; it is to be understood and incorporated into the development flow. Any changes should be communicated with the team, not formally (which can discourage communication), but by simply contacting the people involved and discussing the change with them. In order to make sure that a change made in one realm does not conflict with a change made in another, the team should have a leader who is always kept informed of these developments. This only works if the team is small and interactive enough to allow such spontaneous communication without grinding the program to a halt or overwhelming the leader with information.

Technology Lessons

Commercial Solar Panels Are Good

Space solar panels have three issues which distinguish them from terrestrial solar panels: one, they see severe thermal shock at orbit dawn / orbit dusk, stressing solder connections and material bonding; two, they encounter more ultraviolet and ionic radiation; and three, they must survive launch stresses[*]. As a result, space solar panels are traditionally handmade, with careful attention paid to

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[*] There is an issue of performance – cells optimized for higher wavelengths, and the increasing use of multijunction cells in spacecraft – but that is a distinction in degree rather than in kind; terrestrial panel manufacturers care about performance too.

interconnect strain relief, and with individual glass panes placed over each cell because glass is resilient to ultraviolet radiation and helps block ions. The result is a labor-intensive, costly process that cannot take advantage of automated manufacturing techniques or quantity testing.

Kyocera Solar Corporation expressed confidence that they could manufacture panels using a variant of their usual process that would satisfy the three requirements for space use, while still taking advantage of the highly refined and reliable automated manufacturing process they use for manufacturing commercial units. They worked extensively with AeroAstro to develop a series of prototype panels, and with the cooperation of NASA Marshall under a Space Act Agreement, the panels were tested and the process refined to produce exactly what Kyocera promised. Panels built under this refined process are now set to fly on SPASE, and should answer the one remaining question, of performance in a LEO radiation environment.

The lessons learned here are both programmatic and technical. Programmatically, having a vendor like Kyocera who is interested and excited about the project makes enormous difference both in the ease of the interaction and in the quality of the product delivered. Vendors whom we had to convince to work with us turned out immeasurably worse. Technically, the panels are superlatively easy to work with, being covered in Tefzel® (a durable and protective Teflon laminate) instead of glass, and show a very respectable 12-14% efficiency. This is one of the most exciting technologies being demonstrated on SPASE.

Lithium-Ion Batteries Are Good

This is the other singular technology that is most notable on SPASE. To explore the lessons learned, a distinction must first be made: the battery cells, manufactured by vendors such as Maxell or SAFT or Sony or a host of others, are robust, reliable, safe, and inspire great confidence. The battery electronics, designed in-house or delivered by a vendor, can be finicky and must handle the high power flowing through them in any configuration. The electronics must be able to switch directly from high-current charge to high-current discharge and back. More strongly, the electronics must be more than able to handle such extreme conditions: they must be overdesigned, able to handle conditions far more extreme than the ones actually expected.

Lithium-Ion battery circuits, to assuage safety concerns (which are actually now handled within the cell anyway), traditionally incorporate a pack manager in addition to a charger. This manager disables charge, or discharge, or both, if it detects a problematic situation in the battery cells: overvoltage, undervoltage, overcurrent, overtemperature, undertemperature, or cell mismatch. The difficulty is that if it misinterprets any of these conditions as existing when it does not, it can become caught in an unrecoverable mode, with the battery turned off and no way to get it back. AeroAstro's observation is that a cell management circuit does not add to the safety features already present in modern Lithium-Ion cells, and decreases overall pack reliability.

To reiterate the earlier statement, the Lithium-Ion cells themselves are excellent, their manufacturing process refined through billions of cellular telephones and laptop computers and camcorders and the like. The future use of Lithium-Ion in spacecraft, with energy densities well over 100 Watt-hours per kilogram, is a given, and SPASE is a pathfinder for this development in the industry.

Industrial Electronics Are Good

The aerospace industry lives with the legacy of a time when integrated circuits were in their infancy and careful parts testing and selection, including, usually, custom part development, was essential. This has long since become untrue but the legacy lives on. Modern industrial-grade electronics are practically indestructible, and the fact of mass production means that their quality far exceeds any custom-built device. In an effort to understand why parts remains such a concern in space industry circles, AeroAstro began investigating reports of part failures, and found without exception that each case investigated was one where the part was misapplied or the systemic behavior misunderstood; that is to say, the fault was with the circuit design, not the circuit components. In fact, during Bitsy prototyping, electronic components were often subjected to conditions far outside their stated tolerances, as is usual during debugging; yet almost every time, even these abused parts kept working.

The issue of radiation is often presented as a reason why terrestrial electronics are inappropriate for space. This conception continues despite the many spacecraft using industrial electronics, even in high-radiation orbits, without problem. Certainly there are missions and situations which call for radiation-hardened or radiation-tolerant parts, but the majority of modern missions – in Low-Earth Orbit for 3 years or less – do not. It is worth noting that humans are less tolerant to radiation than any semiconductor by approximately one order of magnitude, and they have been living in LEO for quite some time.

CMOS Imagers Are Promising and Worth More Effort

Team Encounter funded the addition of a CMOS camera to the SPASE vehicle as part of a star tracker development for their extrasolar Encounter spacecraft. The advantages of CMOS imagers over others (particularly CCDs) are that CMOS has significantly lower power requirements – lower voltage, more tolerance to noise, lower total power consumption – and an easier interface, and especially useful for star trackers, they can perform massively parallel two-dimensional computations on the imager plane: particularly, the imager itself can identify all star loci in a single step. The tradeoff is that CMOS is significantly less light-sensitive than CCD technology. The advantages of CMOS warrants continued development into a useful star tracker, and the CMOS camera flying on SPASE will characterize the current state of technology in this application.

Passive ACS Systems Are Easy to Design, but Just as Difficult to Test as Active Ones

SPASE uses four hysteresis rods and one permanent magnet to reduce rotational accelerations and help the side-mounted solar panels point generally at the Sun. The hysteresis rods are soft-magnetic material which resist a change of orientation within a magnetic field, and require no power. The permanent magnet is mounted at the top end of the spacecraft inside MCGD, and the hysteresis rods are at the bottom end on each of Bitsy's four walls, to prevent the former from magnetizing the latter. The design is simple, efficient, and performs the required function of keeping the crystal growth chamber (mounted near the center of gravity of the vehicle) in a microgravity acceleration environment.

The difficulty lay in the characterization of the magnet and the rods to ensure they would perform the required job. The forces involved are so miniscule that they are easily overwhelmed by gravity or the mechanical and material characteristics of the test apparatus. The forces (as predicted) are more than adequate in space, where the contravening forces – gravity gradient, solar pressure – are similarly small. But they are "lost in the noise" on the ground, at least for a reasonable budget. SPASE relies on the simplicity-into-robustness argument in the extreme for the ACS system, as it is simple in the extreme. However, thorough and realistic ACS testing remains, for this simple system as well as for complex ones, one of the most significant difficulties of spacecraft manufacture.

Miniaturization Can Make for a Spacecraft That Is Both Very Easy and Very Hard to Assemble

For SPASE, the single Bitsy box housed the subsystems that required six boxes on AeroAstro's previous spacecraft: power management, batteries, command and data handling, telemetry and control, radios, and payload interface. And AeroAstro's previous spacecraft themselves had fewer boxes than was typical. This miniaturization pays off not only in having fewer units to assemble, but in the fact that the result system is quite small and easily managed by a single person. Thus disassembly of the spacecraft to get at a subsystem took a single person a fraction of an hour, instead of a team of people most of a day.

The negative consequence of this is that all of the radio, and power, and payload, and telemetry cabling, that used to be spread out across a vehicle the size of an oil drum, is now tucked into a space the size of a pie box. This makes both mounting and routing a difficult process that generally requires either small fingers or a clever tool. This lesson will certainly be applied in AeroAstro's future Bitsy-based spacecraft.

Shuttle Lessons

Communicate Extensively with Shuttle Safety People

A design decision explained early will have a smoother ride through the safety process than the same decision explained at the formal safety package presentation. Conversely, when choosing between two otherwise equal design options, discussing it with the relevant Hitchhiker or Shuttle safety person can eliminate a great amount of difficulty. Selecting separation switches, setting the radio transmission power level, placing electrolyte-absorbent material around the battery cells, and any number of other issues were rendered easily solved at the design stage instead of having to be addressed post-manufacture because the matter was raised with the Hitchhiker safety team. There is also the significant – arguably more significant – factor that by communicating frequently with the NASA safety team, a sense of mutual trust and understanding is fostered, making the formal document approval more straightforward because the reviewers are already familiar with both the design and the designers.

It Is Vital to Know the Opinions of the Particular Safety People Involved

The Shuttle safety process is certainly replete with specification documents, and clarification documents, and inter-center agreements to recognize each other's documents. The commonly held belief is that these documents fully specify the requirements that must be met by a Shuttle payload. The fact, however, is that there is a great amount left open to interpretation, and it is of course only the interpretation of the people approving your safety plan that matters. For instance, there is a limit, expressed in Volts per meter, defining how strong a radio transmitter can be before it is considered a hazard. What is not expressed is where this limit applies. At the outer envelope of the payload? At the nearest device that can be affected by the transmission? At some nominal distance, such as one meter? Each of these possibilities were presented by various Shuttle safety personnel at various times. As above, the important thing is to communicate the system design to the safety team, and solicit the opinion and advice of the individual responsible for approving this aspect of your safety plan.

Simple Does Not Equal Easy

No matter how simple the design, no matter how straightforward the approach, you will still need to explain it to the safety team just as thoroughly, and justify it just as solidly, as if it were thoroughly intricate and complex. Certainly a simple design is easier to explain than a complex one; but the scrutiny will be the same on both. Once again, the key is communication with the safety team.

Involve Someone who Already Knows Their Way around the System

AeroAstro hired Payload Systems Inc., who has assisted with the integration of a number of Shuttle payloads – assisting particularly in the safety process – to help take the SPASE design and convert it into a safety package that would look familiar, understandable, and complete to the safety review team. PSI knew or got to know many of the personalities involved with the Shuttle safety process, both the Goddard Hitchhiker team and the Johnson Shuttle team. This was very valuable both in knowing whom to ask when a particular question arose, and in determining the best way of expressing the safety aspects of the SPASE mission in a way acceptable to both the Goddard team and the Johnson team. It is important to remember, however, that by involving another organization in this process, that organization must be kept informed of new developments in the spacecraft design, both in order to incorporate this information into the safety package, and to highlight any safety implications of the new design.

Conclusion

The SPASE mission demonstrates a number of exciting new technologies to reduce the cost of access to space. In conducting this program, many technological and programmatic lessons were learned, which can benefit other missions of its type, and will benefit AeroAstro's Bitsy nanospacecraft kernel and Bitsy-based spacecraft. Since the idea of Bitsy is to create a kernel of spacecraft functions that can be used across a broad variety of missions, the benefit of the SPASE program is not only in the increased experience of the team involved, but in the reproducible Bitsy product itself.