SMALL SATELLITE MECHANICAL DESIGN EXPERIENCE

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Abstract

The design approach used and the experience gained in the building of four small satellite payloads is explained. Specific recommendations are made and the lessons learned on the SAMPEX program are detailed.

Background

The Special Payloads Division, formerly the Sounding Rocket Division, has a long heritage of designing and building scientific payloads for a variety of launch vehicles. After years of building sounding rocket, balloon, and high altitude aircraft payloads, the division took on the design of Spartan, Get Away Special, and Hitchhiker payloads for the Space Shuttle.

After designing, building and flying Pegsat, the first Pegasus payload, the Special Payloads Division with help from other Engineering Directorate Divisions was chosen to build the SMall EXplorer (SMEX) series spacecraft. The first of these, SAMPEX, was launched on a Scout rocket in July 1992. The second,FAST, is undergoing Engineering Test Unit (ETU) development for launch in Summer 94. The third, SWAS, is scheduled to fly in Fall 95. Four more are in a phase A/B study for launch in the 97-98 time frame.

The goal of the SMEX program is to produce small, cheap, satellites in a short time frame.

Design drivers/requirements

The drivers for mechanical design are a combination of the science requirements, spacecraft subsystems, the launch vehicle constraints and the physical realities of space flight. The science requirements determine the instrument component, the attitude control system, the data system, the power system, and the desired orbit.
The launch vehicle imposes weight and volume constraints as well as launch loads and operational requirements. The space environment imposes a severe thermal and radiation environment that is orbit dependent. The instruments and other on board components have structural and thermal limits that must not be exceeded. There also are special instrument requirements for field of view and magnetic and optical cleanliness.

Accommodating the desired science requirements of these missions for launch on a small launch vehicle has demanded custom mechanical designs. So far each of the four small satellites we have designed, PEGSAT, SAMPEX, FAST, and SWAS have had a unique structure and mechanical subsystem.

Tight budgets and schedules as well as minimal weight are design drivers.

It is important early on to pin down the true design requirements.

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The lead engineer

Our approach to the design has been to assign a lead mechanical engineer to the project as soon as possible, and have him/or her do the initial layouts to propose a possible design and get the necessary inputs and comments from the other leads. Giving all the subsystem lead engineers authority as well as responsibility allows them to operate as a team and achieve the necessary iterations to a final design. The design process is necessarily a highly iterative one.

Peer reviews both formal and informal should be frequently held to encourage innovative thinking not just to make sure that the design only uses existing ("flight proven") techniques.

The lead mechanical engineer is responsible for his budget and scheduling as well as the design, analysis, drawings, fabrication, assembly and qualification of the hardware. It is a lot of responsibility to reside in one individual, but he/or she does have branch support and the spacecraft are small enough for this to be possible. This placement of the responsibility in a few individuals across the subsystems is what makes it possible for the small satellite to be **" -faster -better -cheaper "**

This is a people oriented **team** approach. The subsystem leads operate outside of their boxes on the "org" chart. A parallel systems engineering approach develops among the subsystem leads that complements the roll of the project systems engineer in preventing items from falling between the cracks of organization and becoming real problems.

Keeping the team of lead engineers intact from design through integration, test and launch is vital.

Design considerations

The basic design principle is to minimize the load path from the mass of the spacecraft to the launch vehicle interface while providing the instruments with the required field of view, thermal environment, and the other subsystems required.

Thermal

In a small satellite everything except appendages tends to run at the same temperature, which simplifies the thermal/mechanical design. However thermal considerations are still a major influence on the design and must not be an afterthought. Blanketing, radiator panels, and battery or experiment isolation are more difficult than on a larger spacecraft.

Ground service equipment

Proper attention must be paid to ground service equipment during design; not as an afterthought.

Areas of concern are:

Turnover fixtures,
Test fixtures,
Lifting rigs,
Lifting points on the spacecraft,
Dollies,
Battery cooling,
Access to vital spots on spacecraft,
Shipping containers,
Clean room accommodation,

Mechanisms

If you must use mechanisms, make them simple, reliable, and easy to test in one "g". Don't make them overly complicated striving for "redundancy". It is very difficult to increase the reliability of a mechanism by making it more complicated. Allow for thermal blankets on the structure as well as the mechanism. Don't make heaters and blankets an afterthought. Don't make connectors and wiring an afterthought either. Go through a thorough test program. Operate the mechanism in several orientations to prove that gravity is not helping too much and be wary of "g" negation systems.

Other design considerations

Allow for the cable harness that connects the boxes and provide for its mounting. Visualize it as at least a garden hose. Before the advent of computer busses as interfaces we used fire hose to mock up a satellite harness. Also allow for connectors and the minimum bend radius of the cable.

Analysis

After the initial design layout is made a simple analysis is run, often by hand, to check the initial assumptions on the primary load path. Later on a simple finite element model is made and the frequencies are checked and structure is examined to reduce weight and increase margins if necessary. Eventually a complete model of the final design will be made to run a coupled loads analysis with the launch vehicle. Even this model need not be too detailed. After all this is supposed to be a finite not infinite element analysis.

Fracture analysis is not necessary, but is used on pieces that are not subject to strength testing to comply with the structural reliability requirements. All subsystems mechanical designs, including experiments and electronics boxes, should be reviewed by a mechanical engineer and have at least cursory or "back of the envelope" stress calculations. Finally everything should be subject to thorough testing with plainly stated goals and enough analysis to know what levels are really being tested to.

Testing

Building a mechanical Engineering Test Unit (ETU) has proven to be essential to maintaining the tight schedule that these small satellites are built on.

The ETU is used to run mechanical fit and interface verification checks. These fit checks are run with the launch vehicle and every other piece of hardware as early as possible and every time there is the possibility of a design change. A high fidelity ETU frees the flight unit to continue integration while these important checks are made. It also allows lifting and other handling schemes to be worked out and practiced without endangering the flight unit. The ETU is also subject to thorough loads and vibration testing and a modal survey to qualify the structure. If there are mechanisms, they are subject to these tests and a thermal vacuum test as well as deployment tests.

Testing is not limited to GSFC facilities but is preformed at Wallops Is. Langley or anywhere else that makes sense.

Documentation

The earlier that Interface Control Documents and drawings can be agreed to, the better. Less cost will accrue to program and life will actually be made easier. Having said that; minimize documentation to what is actually needed. Lead engineers in close contact can dramatically reduce the formal paper flow while still maintaing the communication necessary.

Control and minimize changes

Avoid requirement creep...we often try to go the extra mile for the experimenter and incur the extra month, pound and dollar. Avoid unnecessary changes but quickly accommodate the necessary ones and pray the project has the wisdom to differentiate between them.

Conclusion

If a small satellite is going to be "**faster -better -cheaper**" it is going to be, as Dr. Len Fisk said on 1/25/89...
"A grown-up sounding rocket, not a scaled down great observatory"

Specific SAMPEX lessons learned[1]

Interface verification

Fit check everything as early as possible. We fit checked most of the SAMPEX components on the ETU structure early in development. There were a few problems but there was plenty of time to correct them. There were a number of items not checked due to the unavailability of the components.

During flight unit integration the majority of items that were not fit checked on the ETU didn't fit properly. Some required only quick "file to fit" modifications but one required complete redesign of an instrument housing and significant rework of the spacecraft structure with significant cost and schedule impact.

All these items had ICD drawings. The problem was that either the hardware didn't match the drawings or that changes made in one side of the interface were not followed up and incorporated into the other side.

GSE and test fixtures also need to be fit checked. We had our mass properties test fixture available several weeks before the test. When we were ready to run the test we discovered the fixture didn't fit on the mass properties table. This was due to the drawing being misread. If we would have fit checked the fixture as soon as it was available we could have discovered the problem and fixed it long before we went to test saving ourselves one more aggravating delay.

LESSON LEARNED: People make honest mistakes and ICD drawings aren't always correct or complete. Fit checks are the only way to verify the interface and the earlier they are done the easier it is to correct problems.

Control and Minimize Changes

The HILT instrument was integrated and then removed for some rework including adding heaters and thermostats. When we went to reinstall HILT it wouldn't fit properly. The wire bundle for the heaters and thermostats was causing an interference problem which required rerouting of the wiring.

In another incident, after we had performed the vehicle heat-shield fit check we added a small air conditioning tube to cool the spacecraft battery on the launch pad. When we went to install the heat-shield there was interference with the air conditioning tube and we had to cut it off on the pad to allow heat-shield installation.

LESSON LEARNED: Don't change anything after fit checks are completed. If a change can't be avoided make sure the change is communicated explicitly and incorporated into the other affected interfaces. Then recheck the interface.

Mechanical Design Lessons

SAMPEX Antenna Problem

The structure of the SAMPEX antenna consisted of a fiberglass tube into which a fiberglass plug was bonded to form the base. In this plug was installed a heli-coil insert by which a #10-32 screw was used to attach the antenna to its mounting bracket.

Both antennas were mounted to their respective brackets with high strength (160 KSI) #10-32 screws and torqued to 55 in-lbs. This was the standard torque value we used for this type screw. The spacecraft then went through complete vibration and thermal vacuum testing without incident (regarding the antennas). The antennas were then removed for component level checkouts.

Upon reinstallation of the antennas a "pop" was heard during torquing of the upper antenna. The antenna was removed and a crack was discovered running across the base plug. The lower antenna was later removed and it was found to be cracked also.

The root cause of the problem was that there was no mechanical engineering involvement in the detailed design of the antenna. This led to the following specific problems which in combination caused the cracking:

1. The torque of 55 in-lb was not needed for this specific application. This torque provided a pre-load of over 1000 lbs. to hold on antenna that weighed less than a quarter of a pound.

2. The fibers in the base plug were unidirectional. The high stress from the screw pre-load was applied perpendicular to the fibers. With no fibers to carry the load the matrix simply cracked.

3. The mating surface was not flat. The base plug was slightly recessed into the antenna tube and there were small bumps formed by the epoxy adhesive. These high spots created a bending load on the base plug when the screw was torqued.

To correct this problem we first machined the base of the antennas flat, then pressed fit the antennas into a aluminum base cap. The pressed on base cap put the base plug into compression preventing any further cracking. We also reduced the screw torque to 15 in-lb. These antennas were requalified by component level vibration testing.

LESSONS LEARNED:

1. All mechanical designs should be reviewed by a mechanical engineer and have at least cursory or "back of the envelope" stress calculations.

2. Use the appropriate screw torque for the given application.

3. Make sure the fibers carry the load when using composite material especially when machining fiberglass parts from stock material. Make sure the fibers run in the correct direction(s).

4. Specify flatness for critical mating surfaces.

Tolerancing and Clearances

Don't make tolerances and clearances tighter than needed. In a despin test failure, an out of spec cable ball wedged in its release slot where there was only .007 inch nominal clearance. There was no need to have the clearance this tight and a small variance caused a failure. In another case we ran a battery air conditioning tube close the edge of an 8 inch square opening in the vehicle heat-shield. Due to normal variations and tolerance buildup the tube ran too close to the heat-shield and had to be cut off on the pad. We could have run the tube 2 inches from the edge of the opening and had plenty of margin for error.

Wire Harness Considerations

Allow adequate space for wiring harness, define routing concept early in design stage. Allow space for mating and securing connector fasteners, and for harness strain relief. Consider harness tiedown methods.

Thermal Considerations

Define thermal limits for mechanisms as early as possible. We had designed and built our ETU solar array mechanism before we had a firm worst case cold temperature. This temperature turned out to be much colder than we had anticipated. We had to add heaters and numerous thermal isolators to enable the mechanism to work at the cold limit.

Review with the thermal engineer early on the mounting of thermally sensitive components such as batteries to provide proper mounting and heat paths for these components. Also review heater, thermostat and thermistor locations to allow ample space for them.

Blanketing

Allow ample time in the schedule for thermal blanket fitting and installation. Allow for blanket thickness in mechanical design especially around mechanisms. Blankets can be 1/4 inch thick or more. Don't make blankets an afterthought.

Mechanical ETU Program

An ETU of the structure and mechanical systems proved invaluable in the development of SAMPEX. It allowed early fit checks with ETU components where several discrepancies were discovered and corrected when there was still plenty of time in the schedule.

The ETU allowed structural qualification and model verification to be completed early. Also vibration test response data from the ETU was used for component level testing.

The ETU allows testing in parallel with the flight unit development. We were able to run solar array deployment and yo-yo despin tests on the ETU without impacting the flight schedule.

The ETU was great for showing people what the spacecraft actually looked like, and working out details of the flight unit design such as for harness routing and thermal blanket details.

The ETU allows performing tests that may be too risky to be performed on flight hardware. For example during despin testing a failed cable release caused the cable and weight to wrap around the ETU. This could have severely damaged the flight spacecraft but was incidental to the ETU.

We also exercised all our lifting and turnover equipment on the ETU before it was used on the flight spacecraft.

Testing Lessons

Design mechanisms so that they can function in a one "g" environment if possible, but take into account any deflections in the one "g" that will not be present in zero "g". The SAMPEX solar arrays were designed to operate in one "g" and this enabled easy testing both ambient and in thermal vacuum.

Put ETU hardware through the toughest testing. The SAMPEX ETU electronic boxes were only put through random vibration. Flight boxes were put through random, shock, and sine burst vibration testing. We should have put the ETU boxes through the tougher testing first to uncover any potential problems. Then the flight boxes could have been put through less stringent acceptance level tests. The same thing happened in EMI where ETU boxes were not EMI tested at the component level. The flight boxes were EMI tested when in actuality it was too late to do anything about problems that came up.

Spin Balance Lessons

We were able to balance the spacecraft with a filled unbaffled fluid tank with its centerline mounted on the spin axis, but this made the process a lot slower.

Design in a place to mount balance weights. Ideally, the upper and lower circular balance planes should be as far apart as possible. Using a continuous circle avoids having to split the weights to fit at discreet points which requires greater total weight to achieve balance and takes more iterations.

Design weights so that small amounts can be added or removed without disturbing the entire weight. We had weight stacks which had to be completely removed to adjust the weight. The slight misalignment from removing and reinstalling the weight stacks was enough to disturb the balance. Stick on weights for the final trimming would be a good idea.

Bring raw material to make weights to spin balance. We brought precut plates that we intended to stack to attain the proper weight. In one case we needed more weight than anticipated and had to rig up a huge, ugly, bolted together weight stack. If we had had material to cut new weights we could have done a faster, more structurally sound and aesthetic job.

Balance is very sensitive; ounces, even grams of mass added or removed can throw the balance out of spec. For this reason spin balance should be performed as late as possible in the schedule to minimize the potential for changes which could affect the balance.

Despin Testing

A yo-yo despin system will not despin to the predicted final spin rate if tested in air. If the final spin rate is critical, the system must be tested in vacuum. We tested our system in air and were unable to attain our target spin rate of 0 ± 3 rpm. In vacuum we easily met this goal. Although the tests in air did prove valuable in testing the function of the mechanism where some problems were uncovered.

Miscellaneous Lessons

Provide two sets of GSE such as lifting slings and dollies, if the cost is not prohibitive. This way one is available to use while the other is out being proof tested and inspected or is with the ETU for off site testing.

Pyro actuators are long lead items. Order them early and get plenty of spares for functional testing. On our ETU we ran one ambient and four thermal vacuum solar array deployments, and five yo-yo despin deployments. We also ran two solar array deployments in thermal vacuum on the flight spacecraft. That's a total of twelve pyro activated test deployments and more pyros than that fired.

Management/Operational Lessons

Provide contingency time in schedule. We had virtually no contingency in the schedule during SAMPEX I&T. This meant that any small glitch or delay threw the entire schedule into disarray and made it very difficult for people to plan work especially on nights and weekends. This was very aggravating for people who were already on the verge of burnout. Problems and delays are to be expected and contingency should be provided in the schedule to reduce the continuous reshuffling of the schedule.

Most operational problems were caused by lack of communication and lack of clearly defined responsibilities for tasks not clearly under a specific subsystem. We had some of our most aggravating days performing what seemed like simple tasks.

For example to ship the spacecraft to building 7 and get it set up in the thermal vacuum chamber was fraught with problems. The truck driver was told the wrong time to be there, no one in building 7 is expecting us, there is no crane operator ready, no lifting procedure, no one knows what clean room suits to wear, etc. etc.

Find problems early. Problems found early are easy to fix. Problems found late in the game cause many late nights and gray hairs. Do whatever is possible to uncover problems early. Fit check everything, even if only a box enclosure is available. Test ETU hardware rigorously.

Do tasks in parallel as much as possible. This is why ETU hardware is so valuable. It allows testing off line without affecting the flight spacecraft flow, saving valuable time. When you rush you make mistakes. When we were performing our last thermal vacuum test of the solar array we rushed to get the ETU ready for test and forgot to include some thermal isolators.

This caused the test to fail. Luckily this was on the ETU and did not affect the flight spacecraft schedule, but we did have to work another weekend to fix the problem and pay for additional time in the thermal vacuum chamber. All because we were in too big of a hurry.

Travel

Travel pays for itself. We traveled to Max Plank Institute in Munich Germany three times to discuss the HILT instrument design and work out interface details. Although these trips were highly enjoyable, each trip uncovered significant problems that we were able to resolve early on. It is doubtful these problems would have been uncovered until the instrument was delivered for integration had we not traveled to Germany, talked with the engineers and seen the actual hardware.

The same was true with the LEICA instrument which was developed at the University of Maryland. Since Maryland is within easy driving distance we were able to work closely with LEICA engineers to resolve all problems.

On the other hand, we (mechanical group) never traveled to the west coast or saw the MAST/PET instrument until it was delivered for integration. The instrument was to be assembled from parts on the shelf to old specifications which were supposedly well defined. The actual instrument, when it arrived, violated its ICD and would not fit in the spacecraft structure. The structural integrity of the instrument enclosure was also questionable. To make a long story short it cost us $17,000 to modify the spacecraft structure and redesign and rebuild the instrument enclosure. Add to that several weeks of civil service manpower, Swales analysis and the cost of vibration testing of the instrument and we could have paid for more than a few trips to the west coast.

1. SAMPEX Lessons Learned: Mechanical Subsystem
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