25 Alternative Spacecraft Designs

25.3 Alternative Systems Design: Small Spacecraft

25.3.6 SmallSat Mission Examples

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CRO (Chemical Release Observation) was sold as 3 identical shuttle-launched low Earth satellites each carrying a liquid which would be expelled into space vacuum for observation from Earth and space platforms. Total cost under 2 million dollars at 2011 price levels. The program manager can do some quick math: each person-year with overhead and other factors applied costs about $250,000 and probably 50% of program dollars are non-labor: e.g., parts, (typically 25%) travel, test facilities, operations support. Thus the labor budget is 4 people for a year. Or in the case of CRO, 6 people for 6 months and then 1 or 2 people working part time for the next year with additional occasional as needed support from the rest of the team. For 6 people to design and pretty much build a spacecraft in 6 months requires virtual elimination of travel, of formal reviews, of most classical documentation, of communication burden on the team, and a very simple spacecraft design.

The latter was achieved mainly because of two factors:

- The mission consisted of being a tank filled with a liquid capable of releasing its contents to space vacuum on command from the ground. While the initial architecture called for numerous ground commands, downlinking of telemetry and various scheduling functions, the final design responded to a wake-up command from the ground by downlinking data on a few voltages, temperatures and the tank pressure, and awaiting a single ground command to release the liquid payload. A 9600 baud 150 mW UHF radio link was more than sufficient
- Whereas initial design called for an active attitude control system to ensure release of the liquid along a known orientation relative to the spacecraft velocity vector, lacking the resources to even design such a system, a much simpler method was used. The shuttle's release of the spacecraft would be at an altitude low enough to aerodynamically stabilize it after deploying a simple drag device which also served as a corner cube radar reflector, ensuring that the spacecraft could be pinpointed for observation of the liquid release. The aerodynamic restoring force is passive, with no active control, requiring no sensors, no actuators, no software and very limited analysis, and very powerful, thus a limited analysis was able to demonstrate that most disturbance torques including magnetics and slosh of the liquid, were insignificant

Launching from the Get Away Special canister defined the spacecraft shape, a cylinder of about 50 cm height and diameter, and the design which came together in the first week or two was a cylindrical tank and above it a squat cylindrical service module for radios, batteries valves and actuation of the deployment device.

At which point it looked like even that small budget for 3 spacecraft might be unnecessary. We had indeed trimmed the specifications and the complications to an absolute minimum, and the resulting mission was simple. The plan was to steal designs for the radio and information management system from an earlier spacecraft, write a minimum of software to adapt them to this application, while purchasing some off the shelf tanks, integrate, test, and fly.

Even this absolutely minimal mission was capable of showing us how hard it is to do even very simple things. In fact, there are very few circular cylindrical tanks in existence, and none without hemispherical or at least curved end caps, and none of the diameter we wanted. We welded together aluminum tanks from cylindrical sections and flat end caps sealed with O-rings. But much later in the program discovered cavities in the welds which required complete disassembly of the spacecraft and fabrication of tanks from solid cylinders of aluminum, then the entire system had to be reassembled and re tested at the cost of significant time and money.

Murphy is even more subtle than that, and manifested in two even more unexpected ways.

NASA became concerned about two safety issues. One that the spacecraft would partially emerge from the cylindrical launch canister after its push from its ejection spring and result in the necessity of a spacewalk to either get it back in or release it before the Shuttle doors could be reclosed. The team was highly confident of the efficacy of a pinstriping of teflon rods running the length of the cylindrical structure that nearly touched the launch envelope walls. It was impossible for the spacecraft to be other than perfectly aligned, as a bullet in a rifle barrel. Still there was a concern about wobbling decaying the escape momentum, and eventually a series of complex tests had to be designed, built, and carried out to demonstrate that in every imaginable condition of the envelope clearance, spring and release mechanism, and spring force, the spacecraft would exit the launcher cleanly, completely, and along the cylindrical axis.

The other unforeseen issue was that the deployment mechanism, on board radios, or release valve would be triggered prematurely. The solutions for the three completely independent problems became independently redundant inhibits—devices to prevent deployment and actuation, 4 for each subsystem. Timer, radio command, sunlight on solar panels, and disconnect from the launch system. All of the associated electronics, including double sets of batteries, one to run the timers and permit prelaunch status verification (another function we had not envisioned) and a rechargeable set capable of doing the mission, fed from solar panels which would also confirm release, also originally not planned. We also had to add additional valves to ensure redundancy, requiring a mechanical redesign.

The result was that the one remaining engineer & manager that funding would permit on the mission (Rick Fleeter) carried the system through a second build and test, commuting between the home office in Virginia, test facilities in Los Angeles, and Shuttle safety meetings in Houston. The number of hours mounted way beyond those budgeted and hence many of them were not compensated.

Which highlighted a basic truth of almost all small spacecraft programs. A lot of responsibility falls on a small team, often on individuals. A big program may have a team of 10, 20, 30 engineers doing mechanical design. If one is ill or changes jobs or is called onto another project, the program is not strongly affected. Glitches can be absorbed. A team of 1 or 2 or 5 will have to work many months of long hours without the cushion of the big team along side them, and there is scant ability to offload work on others. A small mission is neither complex nor costly, but the focus on a small team puts pressures on the individuals not so often present in larger programs.

Terrestrial technology found a both unique and at the same time typical (of small spacecraft) role in CRO. Besides radar, it was required to observe the liquid release with optical telescopes which could not be accurately aimed solely based on radar data. The satellite, about a half meter in characteristic length, needed to be visible from more than 500 km away on Earth. Trade studies pointed to an on board strobe and looked, lacking space qualified strobe lights, at airline grade lamps, which proved much too large and power hungry for our service module which was less than 10 cm tall, providing at best a watt or two of power. We decided to use an off the shelf amateur photographic strobe, available for under $100 and highly reliable. At which point the necessary changes set in which were to cost at least 100 times more than the component.

The flash needed to repetitively fire autonomously instead of upon triggering by a switch on the host camera for which it was built. A circuit had to be designed, developed, and tested, which sensed when the unit was ready to flash and when a minimum time interval had expired, and then triggered the flash.

The product was originally built onto a cardboard circuit board mounted inside a plastic housing neither of which would withstand space environment nor launch vibration. The team carefully removed the circuit and the lamp from the housing, to which they were permanently affixed at the factory, since the philosophy of the consumer product was that it would be replaced rather than ever opened or repaired, and placed them, plus the new firing circuit, into a custom designed aluminum housing which was then potted with clear epoxy. A side benefit of encasing consumer electronics for space application in epoxy, besides mechanical support against vibration, is heat transport. Without an air environment for cooling, the consumer product would have immediately overheated. And by leaving a thin layer of epoxy over the lens of the lamp which was in fact the vacuum seal of the lamp itself, it was protected against the hazard of the lens fracturing.

Unable to find an historical precedent for optically tracking a satellite with a photographic strobe as the optical beacon, a new test was added to our already stressed budget. The flash was carried to a mountain top in California about 50 km from another mountain top where it would be observed via a small optical telescope. The flash team and the telescope team remained in contact via VHF radio, too distant and too remote from civilization for more readily available communications. The increased brightness resulting from being 10 times closer than spec was corrected with filters and telescope aperture, and over a few months the test was designed, built, and executed successfully. And unaffordably, from the point of view of the project, but fortunately the test was of interest to the customer who funded it and carried it out on their own account.

All the unexpected changes and problems resolved, the second Space Shuttle loss occurred on the flight before CRO's scheduled launch, requiring a very long stand down, not budgeted, and a subsequent rewriting of all STS safety requirements which forced yet another redesign of the spacecraft. The launched product was a shrunken version of the original with a second shell around it to add another inhibit to the possibility of premature chemical release. After all of these delays and changes none of the original team members remained at the developer, requiring reeducation of the team and some retesting.

From a technical point of view, the mission was a complete success, all 3 spacecraft launched perfectly from the Shuttle, stabilized aerodynamically, and accepted commands from the ground responding with telemetry of on board data. They released their liquid payload on command, and being nothing more than lightweight shells with drag in low Earth orbit, survived for a very short period of time thereafter before being evaporated on reentry. The budget was exceeded, however, by a factor of about 3, which is a significant, though not unusual, overrun in terms of percentage. But in raw dollars, it was insignificant compared with the funding for the end to end experiment.

Like most small missions, CRO was considered after the fact to have been, in fact, quite simple and not in any way remarkable. Its mission certainly did not have the sophistication of a major program, nor the performance. But the innovation, the ability to change course repeatedly, the flexibility to find and implement unique solutions plus the extreme productivity of the team, were nonetheless remarkable and at the same time typical of most small missions.

Other examples of small satellite missions include the GLOMR series of spherical data relay satellites built in the 1980s to retrieve telemetry from ocean buoys, storing data on board for downlink to a site on land for analysis. Previously, the job was done with aircraft overflight of the open North Atlantic which was costly, somewhat hazardous, and infrequent enough that many of the buoys drifted away and were lost forever.

The University of Surrey's early satellites provided similar store and forward and transponder missions, not so much for their own sake as to provide a first space experience for students and in national institutions charged with bringing space technology to their own sphere of application.

Quakesat was developed to measure small changes in Earth's magnetic field which might indicate an impending earthquake, requiring a dedicated low Earth orbiting satellite with relatively frequent revisit over potentially affected areas.

More modern small satellites like STP-SAT-1 executed missions begun with the ALEXIS spacecraft to provide a first flight for new instrumentation that might later be adapted to larger missions. With costs in the $10M range these are not CRO-class satellites built by a handful of people and tested by a team of one. They have 3-axis stabilization, multimegabit per second downlink, power budgets around 100 Watts with deployable solar panels and sometimes antennas, thousands or tens of thousands of lines of software, and relatively formal procedures, documentation, reviews, and design/production/test standards. Still, in comparison to major missions, they are relatively small, with teams around 40 people, have budgets 5% of bigger missions, are developed in an arc of two or three years, and require a different management style than much more complex space systems development.

Begun at Stanford and Cal Poly, a more recent set of missions has been addressed by CubeSats, which are 10 cm standardized cubic structures. By limiting the size, the complexity is almost automatically reduced, and they are typically developed by teams of 10 or 20 students over a program of a year or two. The cubes' missions, and spacecraft of similar dimension, include inspection of larger space systems, niche communications applications, demonstration of propulsion and attitude control systems at very small scale, and hosting science experiments, besides providing a hands-on education in space systems development.

Every successful small mission seems to later be considered to have been a special case, a particularly exigency, which happened to be addressable with a small, low cost spacecraft, but not considered to be a part of a growing trend in space engineering. But that is one peculiar and important niche of small space—to fill in these numerous small niches where an innovative solution must be found, not to provide 32 channels of wideband data relay from GEO or point a large telescope within arcseconds and download gigabits per second; but to discharge a small amount of liquid on command, to host a small telescope with a mission to stare for long periods of time at a single star, to frequently revisit a particular region on the globe.