Session 1302

The Spacecraft Design/Flight Experience at the Undergraduate Level

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On 30 September 2001, at 0240Z, the United States Naval Academy launched its own space program with the first successful flight of the USNA Small Satellite Program. USNA-1, Prototype Communications Satellite (PCSat) lifted off from Alaska Aerospace Development Corporation's Kodiak Launch Complex on Kodiak Island, AK aboard the National Aeronautics and Space Administration (NASA) Kodiak Star Athena I rocket. PCSat successfully separated from the payload upper deck (PUD) (the shelf that supported the satellites during flight) on schedule. First contact with PCSat took place 97 minutes after launch via portable ground equipment carried to Alaska by the PCSat launch support team.

With PCSat, USNA joins Weber State University and the United States Air Force Academy (USAFA) in the small group of purely undergraduate institutions that have enjoyed success with student-designed and built small satellites.

The PCSat development effort was an ambitious attempt to inject reality into the First Class (senior) design experience for Astronautics students. The Department of Aerospace Engineering requires Astronautics students to complete a spacecraft design course (EA470) during the spring semester of their First Class year. This course challenges the students to consolidate and focus all of the mathematical, scientific, and engineering skills acquired in the major on conceptualization and design of a workable spacecraft.

For many years, the design experience was limited to paper studies. The Astronautics faculty felt that this program could be improved by giving Midshipmen the opportunity to design, build and fly real satellites. The USNA Small Satellite Program (SSP) was created in 1998 for that purpose. The SSP actively pursues flight opportunities for miniature satellites designed, constructed, tested, and commanded or controlled by

Midshipmen. It provides funds for component purchase and construction, travel in support of testing and integration, coordination with DoD/NASA laboratories or universities for collaborative projects, and guides the Midshipmen through the DoD Space Experiment Review Board (SERB) flight selection process.

The satellite development process is a multi-semester effort requiring the contributions of Midshipmen from several consecutive graduating classes. The process begins in the spring semester with identification of the mission and determination of requirements, followed by development of the conceptual design. Students in subsequent classes take the satellite through feasibility study, final design, construction, testing, and launch platform integration. Each spring, students in the design class begin the process anew with a new satellite concept so that new projects are always germinating to take the place of those coming to completion and awaiting launch.

Our initial strategy called for building simple satellites containing little more than batteries for power, temperature sensors to provide elementary telemetry and transmitters to broadcast signals to the ground. We planned to advertise the existence of our satellite after completion of construction and flight qualification testing with the idea that another launch carrying less mass than full capacity would offer to take us along for free. In this scenario, our satellite would bolt onto the uppermost-stage rocket body and go into orbit with it rather than deploying as a free-flyer. This, we hoped, would minimize the engineering challenge and mission risk to the primary payload and make us more inviting to mission management.

Three challenges immediately stood out: we had no mission, no money, and no midshipmen signed up to work the project. To solve the problem of mission, we turned to the work of Jane Goodhue, a graduate of the class of 1997 whose First Class project had explored the concept of a small, inexpensive satellite to provide communications with the Naval Academy’s Yard Patrol (YP) boats when deployed along the Atlantic Coast during summer training cruises. Each summer the Naval Academy sends two squadrons of YPs on extended, multi-week cruises to give rising Third Class midshipmen (sophomores) at-sea experience. These 150-foot, diesel-powered craft are capable of operating at sea for up to five consecutive days.

The YPs have come to rely on cellular phones for communications with shore, but frequently find themselves operating far enough off shore to be out of cellular range. Goodhue’s satellite would provide additional capability during these times. Her concept called for the YPs to continuously broadcast their location in digital packet form on amateur radio frequencies. These broadcasts would be picked up by the satellite when passing overhead and immediately rebroadcast on those same frequencies (“bent-pipe” configuration) but to a much greater range. The Naval Academy would be able to receive these retransmissions when the satellite was simultaneously visible to both Annapolis and the YPs.

Goodhue’s work did not go past the concept development phase but it did provide a credible yet challenging project within the abilities of our students. To fulfill the requirements levied on satellites operating in the amateur radio bands, the mission was revised. At the suggestion of Robert Bruninga (W4APR), currently the chief engineer and operating officer of the USNA Satellite Ground Station (SGS), the satellite was envisioned as being an orbiting node on the Automatic Position Reporting System (APRS) providing digipeating service to amateurs worldwide. Mr Bruninga is the founder of APRS and is chiefly responsible for its development and growth over the past decade. He also served as the principal mentor of the midshipmen during development of the communications and power systems of PCSat.

The students following Goodhue on with the project would do a feasibility study, preliminary and final design, construction and testing, and flight integration.

Christopher Morgan of the class of 1999 volunteered to work on the project and was assigned to do a feasibility study of the new concept to determine what if any modifications to the Goodhue design were needed in order to have a viable spacecraft. Chris devoted the fall semester of 1998 to looking at the ground coverage and expected lifetime of the satellite assuming a typical space shuttle orbit, and also assessing the survivability of commercial non-space-rated components in that radiation and thermal environment. His assessment concluded that the proposed spacecraft had both an expected lifetime and adequate ground coverage great enough to make the mission worthwhile. Based on this assessment, we gave Chris clearance to proceed to the preliminary design phase in Spring 1999.

A major obstacle to satellite design and construction work at the undergraduate level is funding. The biggest needs in our experience fall into three areas: critical hardware, environmental testing, and travel. Commercial, non-space-rated parts can of course be used as much as possible, but budgeting must include the possibility that certain parts or components will be so critical to the mission that expensive space-rated hardware becomes mandatory. Any spacecraft produced will also have to pass rigorous environmental and flight certification testing that either has to be donated by capable facilities or for which reimbursement has to be made. This in turn calls for travel funds to send students and faculty to those facilities to perform the tests. And then, more travel funds are needed to courier the finished spacecraft to the launch site and integrate it onto the launch platform.

In the early days of PCSat, costs were low and could be absorbed in the USNA SGS expense account, but further funds would be needed to complete the project. LCDR David Myre, USN, put together a proposal to the Boeing Company for a five-year grant of $50,000 per year to the USNA Foundation to support the SSP. The proposed spending plan allocated $10,000 per year to equipment purchases; $15,000 per year to pay for environmental testing; $20,000 per year to hire knowledgeable and experienced personnel to supplement faculty instruction and to mentor students during all phases of the design, fabrication, and testing process; and $5,000 per year for travel and per diem for student trips to potential sponsors, partners, test facilities, regulatory authorities, conferences, and launch sites. Boeing accepted the proposal and presented the first check in May of 1999.

Inevitably, the biggest challenge is securing a launch. For USNA, the most direct route to spaceflight lay with the Department of Defense (DoD) Space Experiments Review Board (SERB). The SERB is convened annually under the authority of the Assistant Secretary of the Air Force for Acquisition (SAF/AQ), to examine all proposed DoD scientific space experiments and select those to be eligible for DoD-sponsored launch. This is a two-step process, requiring a proposed experiment first be reviewed by an independent service board and then, if accepted by that board, passed to the SERB. Within the Navy, that independent board is convened by the Naval Research Laboratory (NRL) Space Science Division.

Chris Morgan's development of PCSat was considered mature enough at the beginning of the 1999 spring semester to present to the SERB. He spent the month of January preparing a briefing advocating his project. Chris briefed PCSat to the Navy board at NRL in February of 1999. That board selected it and ranked it number 17 out of the 19 projects to be passed on to the 1999 SERB. PCSat was briefed to the DoD SERB in April 1999. The SERB accepted the project, rating PCSat 26 out of 40.

STP began actively looking for a ride for PCSat immediately after the announcement of the 1999 SERB list. Meanwhile, Chris Morgan graduated and a second team of midshipmen took over development of PCSat the following fall. The design team for academic year 2000 consisted of Erik Lundberg, Brian Scrabeck, Carlos Gomez, Lester Melanson, John Kollar, Travis Mattera, George Ortiz, and David Burroughs.

The AY2000 team took on the challenge of turning the Morgan-Goodhue design into hardware. The group divided up into four teams concentrating on the four critical areas of structure, communications, power, and thermal control. By the end of the spring semester, the team had developed a cube-and-shelf structural design with components stacked in layers above and below the shelf; a 24-volt battery-and-solar-panel electrical power supply; a dual redundant UHF and VHF transceiver design with separate VHF frequencies for North American and worldwide users; and command/control/telemetry circuits. The deployment system responsible for releasing the satellite from the spent upper stage rocket body and the antenna release mechanism were as yet unmet challenges.

The academic year 2001 design team included Robert Schwenzer, Laura Nolan, Steven Lawrence, Daniel Boutros, Daniel Sullivan, and Alex Gutweiler.

The search for a ride ended in the summer of 2000, when the NASA Athena I rocket originally intended for the Vegetation Canopy Lidar satellite became available. STP proposed to NASA that the rocket be reassigned to NASA's own Starshine III satellite with PCSat, Sapphire and the Air Force Research Laboratory's PicoSat going along as secondaries, and STP paying a proportionate share of the launch costs. NASA accepted the proposal, and that October all of the principal players met in Denver CO for the first Mission Integration Working Group (MIWG) meeting. The flight had to adhere to the original VCL launch date of 31 August 2001.

By this time, the design of PCSat had evolved into a cubic structure 25 pounds in weight and ten inches on a side with eight antennas, four six inches long and four 19 inches long, projecting from the centers of the edges of the top and bottom faces of a cubical structure. The antennas are sections of Stanley stainless steel tape measure.

Tape measure antennas have been used successfully on many satellites, are easy to manufacture and cheap to acquire. They are flexible enough to fold into the limited space underneath the rocket fairing, and spontaneously straighten when the satellite is deployed from the launch vehicle. Our design at that time called for the tape-measure antennas to be folded under with the free end clamped between the body of the spacecraft and the frame of the deployment system. When the satellite deployed from the rocket, the clamped ends would be freed and the antennas would automatically extend. This simple and reliable configuration guaranteed antenna deployment if the satellite successfully separated from the rocket.

This design was briefed to NASA and the Lockheed Martin launch services team at the first MIWG, and the first major crisis of the launch campaign hit when the group adjourned for a break at the conclusion of the briefing. Professional satellite engineers in the audience warned that in their experience tape measure antennas restrained at both ends for launch as intended for PCSat had never survived the launch environment. Vibrations from the rocket motors had always induced large sympathetic vibrations in the antennas that eventually tore them off at the mount.

This was a severe blow to the design effort. Several attempts to find a reconfiguration failed for one or more of the following reasons. Unrestrained tape measure antennas took up a lot of space within the rocket fairing and posed a danger to the other satellites present. Extendable rigid antennas were expensive, carried a significant risk of either deployment failure or premature deployment, and additionally required a major redesign of the satellite interior for proper mounting and operation. The antennas had to fit within a small region surrounding PCSat in order that they not touch any of the other satellites, or the streamlined shell housing them.

Thoroughly testing the antenna deployment scheme and conclusively demonstrating antenna survival in the launch environment was the only way of avoiding a risky and difficult total redesign of PCSat.

By December of 2000, construction of PCSat had progressed to full-scale working models of the frame and inner shelf. Mockups of the outer plates and antenna mounts were added to one of these models in such a way that the antennas could be tied down as they would be during flight. The NRL Naval Center for Space Technology (NCST) generously offered the use of their vibration tables for flight simulation, and testing took place during the week between Christmas and New Year’s Day. The NRL equipment shook the engineering model to twice the vibrational loads expected during launch. Visual observation, backed up by high-speed video recording of the test, showed no significant oscillation in the antennas. The antennas and mounts were free of any detectable damage or deterioration as a result of these tests.

All of the major design decisions for PCSat were made by the Midshipmen except for the design of the launch interface and separation mechanism. This was regarded as the most critical aspect of PCSat design because a failure here would jeopardize the success of Starshine III, the primary payload, as much as it would PCSat. At the time of the first MIWG, the PCSat design team and faculty advisors were tasked to capacity with communications, power, structure and thermal issues, and had not even begun to tackle this problem. This important issue had not been completely ignored, however. The launch interface for Sapphire had already been designed and constructed. An adaptation of the design had been used on Stanford's Opal satellite which flew on the Air Force Academy's JAWSat. The basic design was considered proven and reliable, so STP directed the use of the Sapphire/Opal design with minimal modifications to fit PCSat.

The PCSat design team considered this an acceptable approach. The Washington University Sapphire integration team agreed to build an exact duplicate of the Sapphire launch interface for PCSat use if USNA would supply the critical separation bolt. Here again, STP directed the use of the Model 9101 quick release bolt manufactured by NEA Electronics. This turned out to be the single most expensive component of PCSat. The SSP purchased six units for a total cost of $13,224.00, three for PCSat and three for Sapphire.

The launch interface and the actuators were delivered in mid-March, 2001. They were mounted on the mass model of PCSat, and then subjected to repeat vibration testing at NRL to demonstrate that the actuator and antenna restraint system would not fail in flight. These tests were uneventful.

The PCSat and Sapphire mass models were both then couriered to the Lockheed Martin Waterton Canyon Facility in Littleton CO for completion of critical fit checks and separation tests. For the separation tests, the mass models were fastened to pulley-and-counterweight systems configured to lift the model from the PUD after activation of the separation bolt. The separation test for PCSat failed.

Dissection of the actuator assembly on site discovered that the inner mechanism had been badly scored during the process of screwing the separation bolt into the base of the spacecraft. This prompted examination of the Sapphire bolt because it was identical to the one used on PCSat but had separated successfully. The same type of scoring existed on the Sapphire bolt, but much less extensive.

After involved discussions with the manufacturer of the actuator mechanism, it was decided to alter the assembly procedure in such a way that the separation bolt never turned within the bolt housing. The launch management team agreed to accept this new procedure if it could be demonstrated through testing that no scoring would take place and that separation would reliably occur. In addition, they requested that a repeat of the vibration tests to demonstrate that the scoring was not the result of stresses encountered then.

The PCSat and Sapphire mass models were returned to USNA and Washington University, respectively. Over the next month, the assembly procedure was modified, the vibration tests repeated, and a duplicate pulley-and-counterweight system built at the SGS. This second separation test was completely successful. The launch management team approved the use of the actuator mechanism with the modified assembly procedure on both Sapphire and PCSat.

The Midshipman design team continued the construction of the flight model, working right up to graduation. Two team members were lost to the project because of immediate training assignments. Four were fortunately detailed to the SGS as Ensigns to continue working on the project while awaiting initial training assignments. With the help of NRL technicians to complete critical electrical connections, PCSat was finished by late June of 2001. Vibration and thermal/vacuum testing of the flight model followed. Representatives of STP conducted their pre-ship review on 12 July and accepted the spacecraft for flight.

The satellite was delivered on 8 August. The satellite flew first class as cabin baggage: coach seats were too narrow to hold the shipping container. PCSat was integrated onto the PUD on 9 August. Launch was originally scheduled for 31 August but minor flaws in the launch vehicle that had to be corrected caused a delay. The launch was postponed to 15 September.

The 11 September World Trade Center and Pentagon attacks stopped all air travel. Critical launch personnel couldn’t get to Kodiak. Launch was postponed until 22 September. Four hours on the morning of 18 September were set aside for charging the batteries for flight. Charging finished at 1100 hrs local time and the fairing access door was closed for the last time.

The 22 September launch was aborted when a range tracking radar failed. Two days later, bad weather set in. Just as the weather began to clear up, the third largest solar flare ever recorded sent radiation in the space environment to unacceptable levels. Postponement of the launch stretched into a week. Weather looked likely to deteriorate again before the solar radiation levels died down.

A brief spell of fine weather looked imminent on 29 September. Radiation levels in space were falling rapidly enough to make an afternoon launch within the realm of possibility. The launch team decided to go ahead with the countdown, stopping at a predetermined point to monitor radiation levels. When and if they fell to safe levels, the countdown would resume.

Radiation levels fell as anticipated. The fine weather held. Kodiak Star lifted off at 1740 hrs local time and flew a flawless profile. Sapphire separated from the PUD 70 minutes after launch over the Indian Ocean off of the coast of Ethiopia. PCSat separated one minute later.

Both were designed to activate automatically on separation and begin broadcasting recognition signals. PCSat was heard almost immediately by an amateur radio operator in Qatar, although his data did not arrive at SGS via email until several hours later. Ninety-seven minutes after launch, PCSat completed its first orbit, passing over the Kodiak Launch Complex. The PCSat launch support team was waiting with a portable ground station listening for its recognition signals. The team acquired the PCSat signals at the same time that Lockheed reestablished contact with the telemetry module on the upper stage rocket body. We announced contact with PCSat simultaneously with their announcement that the telemetry module had recorded a successful separation.

The primary goal of the SSP had been to have a Midshipman-designed and constructed satellite separate successfully from the launch vehicle and operate in space. The 100% success criterion for PCSat was one verifiable transmission from the spacecraft on orbit. With the receipt of PCSat's recognition signals at Kodiak, 100% mission success had been achieved.

Since launch, PCSat has suffered nothing more than the failure of the solar panels on a minor face of the satellite. By using non-space-rated parts, we assumed a substantial risk that the satellite would not survive the first few months in space. Its durability so far is very encouraging, and its survival over the next few months will tell us whether those parts have the endurance for long-term use in space. The rechargeable batteries should be good for one to five years, and may survive many years longer. Radiation damage to the electronics is a concern, but does not appear to have happened yet. The working lifetime of the spacecraft is a wait-and-see measurement, but every working day is at this stage an extra accomplishment for the Midshipman design team.

Successfully leading undergraduate students through the satellite design, construction and flight experience has proven to be an ambitious undertaking. The effort demanded a staggering. amount of time from everyone involved.

Funding the effort and securing the launch were fairly straightforward tasks, given that USNA is a component of DoD and able to draw on its space-related resources and infrastructure, but even so, these two tasks were heavy management burdens for SSP personnel to shoulder in addition to normal faculty educational duties.

Students working on the project received three to six credit hours and had five to eight classroom hours per week on their schedules, depending on the scope of their responsibilities. Needless to say, they frequently devoted as much as twice this amount of time to the project. The students pursued the project as independent research under the direction of a student mission manager who reported to the SSP director. But progress was very slow until professional mentors could be identified among the faculty and staff and assigned to the student teams.

The lessons learned from PCSat distill down as follows:

1. Start out with a small simple design. The lighter the payload, the more likely someone will volunteer to fly it. The simpler it is, the safer and more reliable it will seem to the engineers who must decide whether to risk flying beside it. Get the funds, get the mission, get the personnel, and just build it, even if you don't expect to ever see it fly. Your students will benefit mightily from the experience, even if your satellite never leaves the campus.

2. For undergraduates working on such a project, strong faculty or other professional mentoring is essential. Mentors need to work side-by-side with the students (individually or as a subsystem team) to show them what to do and how to do it.

3. Identify alumni in government or industry space agencies who can act as intermediaries and broker donations of components, funds, or facilities.

4. It will take creative leadership on the part of someone in the institution - the more pigheaded, the better. It is a long, hard road.

Figure 1 The AY 2001 PCSat design team. From left: Daniel Boutros, Robert Schwenzer, Daniel Sullivan, Laura Nolan, Steven Lawrence, and Alex Gutweiler.

Figure 2 ENS Boutros and Schwenzer perform the final assembly of PCSat under the supervision of Robert Bruninga (CDR, USN Ret.), USNA Satellite Ground Station Operations Officer/Engineer.

Figure 3 ENS Boutros and Air Force Lt Col Billy R. Smith carry PCSat from the payload processing area to the payload integration area for mounting on the Athena I payload upper deck.

Figure 4 1740 hrs Alaska Daylight Savings Time, 29 September 2001. The NASA/Lockheed-Martin Athena I Kodiak Star mission lifts-off from Kodiak Launch Complex, Narrow Cape AK, carrying Sapphire (USNA-0) and PCSat (USNA-1) to an 800-km, 67 deg inclination, circular orbit.

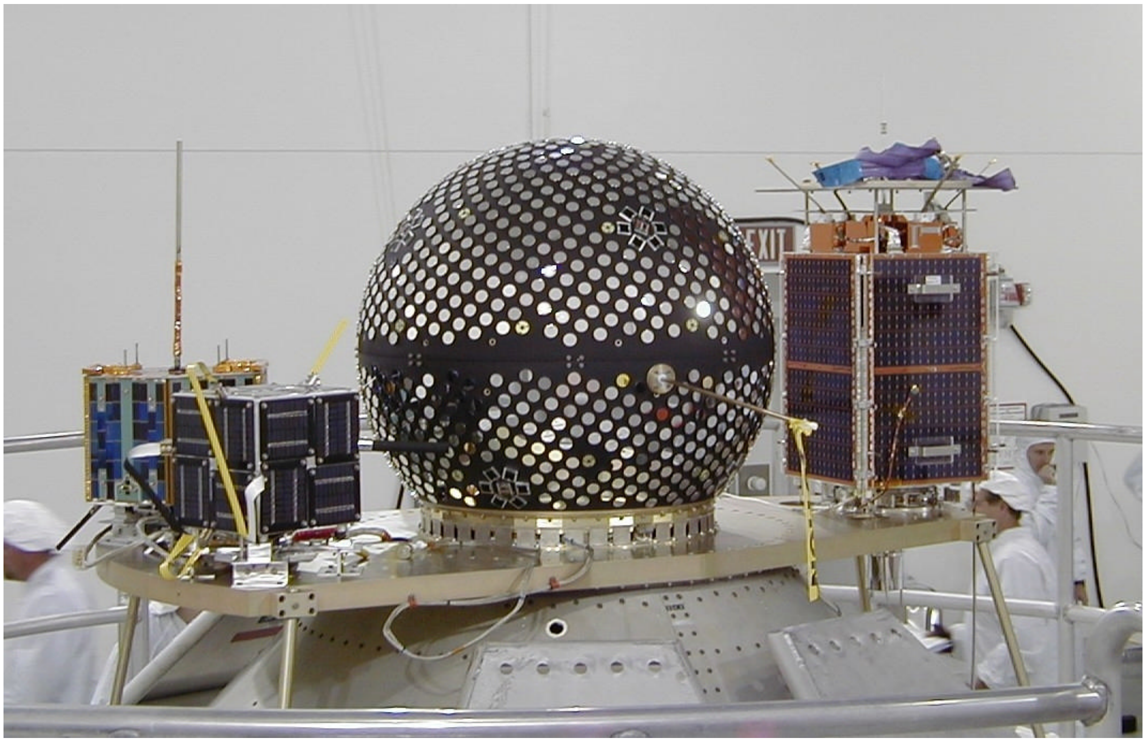

Figure 5 The four Kodiak Star spacecraft mounted on the payload upper deck. From the left: Sapphire, PCSat, Starshine III, and PicoSat.