THREE CORNER SAT: MISSION REVIEW AND LESSONS LEARNED

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Abstract

Three Corner Sat (3CS) was a joint collaboration among Arizona State University (ASU), the University of Colorado at Boulder (CU), and New Mexico State University (NMSU) as part of the University Nanosatellite Program sponsored by AFOSR, DARPA and NASA GSFC. Three Corner Sat consisted of two identical nano-satellites that were designed to demonstrate stereo imaging, innovative command and data handling, formation flying with RF communications, and MEMS micro-propulsion technology. This spacecraft was launched on December 21, 2004 aboard a Delta 4 Heavy as part of the Delta 4 Heavy Demo mission. The project demonstrates the feasibility of micro-satellites with regards responsive space and the capability of universities to deliver a flight worthy spacecraft.

This paper reviews the mission as well as discusses the lessons learned from this effort. With 3CS as a model, attention is also given to a university’s ability to contribute to the advancement of micro-satellites and the aerospace community as a whole.
Introduction

In this paper, the results of the Three Corner Sat program are discussed as well as the implications of the mission on future university micro-satellites to follow. A brief overview of the spacecraft and mission objectives will be given to start off. The rapid reconfiguration of the payload due to transition from Space Shuttle (STS) to the Delta IV Heavy will then be discussed followed by a summary of the program from delivery of the payload to post-launch. Finally, the lessons learned from the project and the overall benefits to the community will be considered.

3CS Overview

Three Corner Sat (3CS) is a collaborative effort among Arizona State University, University of Colorado-Boulder, and New Mexico State University. Sponsored under the University Nanosat Program through the Air Force Research Laboratory (AFRL), 3CS was originally designed as three micro-satellites (Ralphie, Petey, and Sparky) to be launched via the Space Shuttle (STS), and was eventually launched as two micro-satellites aboard the Delta IV Heavy.

Figure 1: 3CS in Final Flight Configuration

3CS was designed to accomplish several mission objectives: virtual formation flying, imaging, intersatellite communications, micropropulsion, autonomous communications, modular design, and student education. These mission objectives coincide with research interests of AFRL, the Jet Propulsion Laboratory, and NASA Goddard. The entire Nanosat-2 (NS2) payload also implemented an AFRL-developed Multi-Satellite Deployment System (MSDS) that utilized two innovative low-shock separation systems developed under contract with AFRL by Planetary Systems Corp. (PSC) and Starsys Research Corp. (SRC).

A detailed description of the spacecraft, design histories, and mission objectives are available among various pieces of literature [1-7].

From Shuttle to Delta IV Heavy

In mid 2003, the Air Force Space and Missile Systems Center commander (SMC/CC) tasked the Department of Defense Space Test Program (STP) with finding a payload that could be manifested on the Air Force Delta IV Heavy Launch Vehicle Demonstration (HLVD). In late 2003, the decision was made to pursue the Air Force Research Laboratory (AFRL) Nanosat-2/Three Corner Sat (NS2/3CS) satellite constellation [8]. As previously mentioned, the 3CS/NS2 payload was originally designed for flight aboard STS, and as a result had passed two phases of the shuttle review process. With no hope of a near-term launch due to the Columbia accident in January 2003, the 3CS team fell into a holding mode with the 3CS constellation being placed into storage at AFRL. The selection of 3CS to be flown aboard the Delta IV Heavy mission likely saved the program from being cancelled completely.

With a “GO” to pursue this launch opportunity, the 3CS team had to gear up for the reconfiguration of the 3CS constellation as well as the NS2 payload as a whole due to the transition of launch vehicles. With the decision being finalized at the end of January 2004, and a target launch date of July 3 2004, a delivery date to Boeing of mid-March of a fully tested and flight ready payload was required. The majority of the team that designed and built 3CS had graduated, taking with them intimate knowledge of the spacecraft. With only handful of university students, faculty, and staff, and the support of personnel from AFRL and STP, the 3CS/NS2 team had seven weeks to accomplish this task.

There were two aspects of the launch vehicle change the required the most attention and work. The first was the concern that fundamental frequency requirement of the Delta IV would not be met, since the only available space to mate the NS2 payload was the relatively thin aluminum skin of Demosat. The second change that had a large impact was the change in orbit. Three Corner Sat was designed for a LEO orbit on the order of the International Space Station (ISS). Aboard the Delta IV Heavy, the options were either a 28° inclination, 100 nmi x 135 nmi
parking orbit with low mission life (~0.5–2 days) or GTO, with its long life but undesired radiation environment. The decision was made to pursue separation into the LEO orbit. This change would impact our mission objectives as well as mission operations.

The following will describe the changes made specifically to the 3CS constellation prior to delivery to Boeing:

- Probably the largest aspect of the payload reconfiguration was the elimination of “Petey”, the top satellite in our original configuration (Fig. 2), leaving only two satellites on the flight payload (Fig. 1). This decision was made in order to meet the fundamental coupled frequency requirement. Since one of the objectives of the NS2 payload as a whole was to test the Lightband low-shock separation system, a 5 lb aluminum bulkhead was attached in place of “Petey”. Verification of Lightband separation would then be accomplished using both optical and radar tracking. The removal of the satellite also impacted the electrical ground support interfaces, requiring some modification and re-routing (Fig. 3).

- As a risk reduction activity, each of the nanosat power relay boards were modified to improve monitoring and verification of safety controls and inhibits (Fig. 4). This required the removal of a single side panel and the disassembly of the entire electrical power system (EPS) box. Verification leads were also added and routed to the exterior of the satellite.

- An issue that the team was aware of prior to the Delta IV Heavy opportunity was what appeared to be a faulty backup radio in the second satellite “Ralphie”. While the satellite was “open” and undergoing other modifications, this problem was explored. The problem was discovered in the internal wiring of the radio subsystem and was fixed as a result.

- The final version of the flight software had yet to be loaded prior to the new launch opportunity. Due to the new orbit and shorter mission lifetime, the software was modified in order to efficiently pursue the 3CS mission objectives. This new version was loaded and tested prior to delivery to Boeing.

- Various other modifications to the NS2 payload as a whole also took place during this period of time, but were not specific to 3CS.

In summary, the reconfiguration of the NS2/3CS required the complete de-mate and disassembly of nearly all hardware components including MSDS and the nanosats down to the subsystem.
box level. A team of eight personnel from AFRL and the universities performed the above tasks.

**Delivery Through Launch**

The reconfigured payload was delivered on time and under budget [8]. Mechanical mating of the payload to Demosat (Fig. 5) took place in mid-May and required only one day. A full functional test, battery charge, and final cleaning took place in conjunction with the mechanical mate

![Figure 5: NS2/3CS Mated to Demosat](image)

Now that the hardware had been delivered, ground station setup and testing as well as mission ops training required the full attention of the 3CS team. Originally, ground stations at the three universities would be adequate for the tracking of the orbiting spacecraft. Due to the new relatively low inclined orbit, the tracking station at CU would not be able to track the spacecraft at all, and the passes over the other two universities were limited. As a result, a mobile station was constructed to be located in Key West, Florida during the mission. The 3CS team also enlisted the help a station in San Juan, Puerto Rico, run by the Space Grant there.

The final ground station tracking setup consisted of ASU, NMSU, Key West, and Puerto Rico tracking the spacecraft, and sending the acquired data through the Internet to CU for analysis. A schematic of this setup is given below in figure 6.

![Figure 6: Ground Station Setup](image)

By mid-summer the launch date had slipped to mid-September, allowing for further training of the mission operations personnel at the various locations. Then again during the fall semester a series of launch slips due to the Florida hurricanes eventually moved the launch date to mid-December. This allowed for quite a few day-in-the-life training sessions to practice procedures and protocol as well as the continual testing of the ground stations. “Petey”, the third satellite no longer part of the payload, ended up serving as an extremely useful tool during the training sessions.

**Figure 6: Ground Station Setup**

**Long Time Coming**

After a long fall semester, and a couple launch scrubs, the Delta IV Heavy was finally thrust skyward on December 21, 2004. The 3CS team eagerly watched the launch vehicle via webcast, and prepared for nominal first contact, which was scheduled to occur several hours later.

Going by the latest two-line element set (TLE), which was the pre-launch estimate, the station began the first track along the path where the spacecraft should have nominally been located. None of the ground stations tracking received any sign of life. Nominally the team should have received an updated TLE prior to the first pass, and it ended up never being received, even following the first pass. Various attempts were made to track to satellites during the next scheduled passes using the pre-launch TLE, but were unsuccessful.

The team was eventually informed that there was a slight anomaly, and the s/c were separated at a far lower altitude than expected. The altitude that 3CS was said to have been separated at meant the s/c would have de-orbited 30 minutes after separation, long before the first expected pass. This was then confirmed to be the case, and at that point the team stepped down from the mission operations portion of 3CS. The final reports on the mission and explanation behind the low-altitude separation can be found via Ref. [9].
At this point, the Three Corner Sat adventure came to an end. Although most of the mission objectives never had the opportunity to be met, there are quite a few things that can be taken away from this mission.

Lessons Learned for University Programs

With micro-satellites becoming an increasingly viable opportunity for university students to design, build, and test their own spacecraft, university satellite programs are continually being developed on campuses around the world. Three Corner Sat is a program that experienced every aspect of satellite development, from concept to launch. With that experience comes many lessons that should be passed onto future programs.

Team Commitment, Communication and Attitude

An original goal of 3CS was to bring three schools together and incorporate each of their respective expertise to develop a successful mission and spacecraft. Rather than having each school build an individual satellite, each university was assigned subsystems that emphasized their past mission heritage.

The biggest challenges emerged when the subsystem teams were put in a position where interfacing and communication with other subsystems became necessary. This may seem familiar to situations in industry, but can produce extremely different results do to the culture of a university program, and college students in general. This requires much commitment and effort on the part of the students in order to avoid issues detrimental to the program as a whole. The program was able to focus on the team’s agenda as opposed to being focused on “exclusive” agendas. This led to a successful mission as opposed to a successful subsystem [10]. Another note on communication: students have also indicated that the familiarity obtained from face-to-face meetings between the universities allowed work to proceed more efficiently, and greatly improved unity among the team.

The central goals of all university programs include:

- Completing a mission within given specifications
- Making each mission useful to the scientific community
- Working as a unified team
- Student education and training

Theses goals are accomplished through the program environment. The key is the attitude in which it is administered by the advisor, industry interaction, and dedication of students involved on the project. Also, whether a multi- or single university project, an organized and efficient communication plan is essential. These are key reasons that 3CS was able to achieve its various successes.

Documentation/Configuration Management

Documentation often lacks the hands-on appeal hardware design and integration has on a student project, and often times as a result is neglected. It is also challenging for students to learn what type of information should be included on program documents. Regardless, the small successes of 3CS would not have been possible without it. Due to the lack of students with intimate knowledge of the satellites, documentation played a crucial role in the reconfiguration of the payload.

3CS followed a configuration management plan released by AFRL. The team took this plan and established the processes through which the plan was satisfied. Having a specific process for document release and control minimized communication errors among the schools and subsystems. Since documents were frequently transferred from one university to another, it was crucial that the most current revision was sent to avoid interface discrepancies. Detailed as-built and as-tested logs helped demonstrate system fidelity to our supervisors at AFRL, as well as those at Boeing. Using the guidelines provided by AFRL, students created templates and configuration management checklists each team member could use. Both the templates and checklists reduced the effort needed for proper documentation, allowing students to focus on more exciting aspects of the program.

One aspect the team attempted to improve upon is photographic documentation. This is perhaps a more informal part of configuration management, but the team learned that it is often the easiest way to communicate information regarding test configurations and hardware conditions. It does not replace the need for
detailed logs and procedures, but rather, enhances it. Another crucial aspect of documentation is a good centralized and organized location for all documentation, such as a server.

Configuration management is one of the most valuable lessons learned. Team members recognize that proper and thorough documentation is an important aspect of ensuring engineering quality and satisfying safety requirements.

Program Management vs. PI

The satellites were definitely the product of student efforts; however, active support from the principal investigators (PI) / advisors was a strong component of project success. The role of the PI’s included both financial support and mentorship when requested. Yet, the advisors understood and believe in student management as a fundamental principle of the team. Although the program became almost fully run by the students, when problems encountered during the project would arise, the PI facilitated discussions with students, but left final decisions on how to proceed up to the appropriate team leader, or program manager. This meant both the decision and the implementation of a solution to the particular challenge.

The feeling and stance that the advisors took with Three Corner Sat is that of educators, and not managers. The freedom to learn and even to make mistakes along the way was a crucial aspect of this project. Once they are made, they are not forgotten, and the experience is there to take into future projects and industry.

Student Turnover and the Common Thread

The most crucial issue with university programs is that of student turnover. Students graduate and move on, taking valuable knowledge of the respective project with them. To illustrate this reality, Table 1 below shows the turnover numbers over the entire project’s time span.

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<th>Table 1: Turnover Figures</th>
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<tr>
<td><strong>3CS Turnover Figures</strong></td>
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<tr>
<td>Total AFRL Program Managers</td>
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<td>Total 3CS Program Managers</td>
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<td>Total Subsystem Lead Changes</td>
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<td>Approximate Number of Students on 3CS at One Time</td>
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<td>Total Students on 3CS Team</td>
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The timing of the Delta IV Heavy opportunity was essential to the events that followed. There are two reasons the team was able to accomplish what they set out to do. The first reason is that there happened to be a handful (about 4) of students that had enough familiarity with the spacecraft to make the necessary technical modifications required. Six more months and these students would not have been available due to graduation. Were it not for these remaining team members, the reconfiguration effort would have failed [8]. The only way to address this is to get people involved early. On a university team, there needs to be an even distribution of class standings in order to provide continuity through projects.

The second reason for relative success was the program’s “common thread” members. These were not students, but university staff. If it were not for a NMSU staff member, and 2 CU staff members, the reconfiguration of the payload and the ground and mission ops segment of the mission would have struggled greatly. These members filled the gap between the PI’s and the students. Though the PI’s are relatively permanent, they usually do not acquire the intimate technical familiarity of the spacecraft or have the time that is required to bring the new students technically up to speed. On the other side there are the students that have the technical knowledge, but always see the need to want to graduate. This is a fine line because you do not want these members to take away from the experience of the students, but they need to be involved enough to gain that in depth knowledge in order to serve as the common thread through the entire project’s lifetime.
As previously mentioned, the “de-commissioned” satellite Petey played a very important role during the final months of the program. Being completely identical in all respects to the satellites mated to the rocket allowed for extremely thorough testing of ground stations and mission operation procedures. Petey ended up taking quite a tour through the southwest, being driven between AFRL Kirtland, NMSU, and ASU on various occasions. Even though the original plan was to build various sister sats to serve this purpose, the urgency to complete the task dropped rapidly after delivery of the flight hardware, and was never completed as a result. By the time the team realized the importance of fully functional replicas, pieces of hardware became discontinued or unavailable and students with the knowledge required to complete this task had graduated. Having Petey available truly saved the ground segment effort.

Due to a great lack of enthusiasm by students to build something over again after contributing so much effort into the flight hardware is difficult, but is so crucial to a program once hardware is delivered. It is the author’s opinion that the assembly of an exact functional s/c needs to be done in parallel with flight integration, not after completion of the flight unit. The idea should be to have two satellites, either of which could be delivered as the flight unit. I know this is a practice in some parts of industry, but it needs to be adopted by the universities.

Benefit to the Entire Community

So what does a university program, and more specifically 3CS, have to offer the community? Although the scientific objectives of 3CS were never given the opportunity to be met, the objective of education was surely met. Due to this program, many highly experienced, entry-level grads are now entering the workforce of the aerospace community.

Also, the rapid reconfiguration of the NS2 payload serves as a valuable baseline for the development of responsive space tools, methods and architectures. This idea of responsive space is an extremely hot topic across the entire community. The program achieved what few others have on a scant budget with low schedule and personnel resource margins: going from a mothballed mission to ready-to-fly on a new launch platform in a matter of weeks [8]. Through the use of flight heritage and COTS parts, modular design, and using small and lean organizational structures that were intimate with the mission objectives and design, the 3CS team was able to accomplish the reconfiguration task in an extremely “responsive” fashion.

The following describe aspects of the 3CS design and program structure that allowed for the relatively smooth and quick transition between launch vehicles:

- The modular design of the satellite’s structure allowed for easy access to all components of the spacecraft. All bolt patterns were standardized by the isogrid design, allowing for easy reconfiguration if components needed to be relocated or added. Also, do to its inherent abundance of routing locations, the open isogrid design also allowed for quick and efficient re-routing of electrical wiring.

- The relatively “lean” team of engineers that undertook the re-configuration of the constellation proved to be extremely advantageous. Complete knowledge of the spacecraft and necessary integration skills were fully available by the team of about 8 personnel. Though this is not feasible for projects on the order of a space telescope, small teams for small responsive missions are an efficient team structure.

- Three Corner Sat leaned heavily on commercial-off-the-shelf (COTS) or heritage components where possible instead of building hardware in-house, which played a large part in minimizing CM and QA requirements. This also helped offset inexperience and aspects of the spacecraft unfamiliar to the current team.

Although 3CS does not appear to be the most elegant of satellites, for a responsive mission a reduced capability is better than none at all. The capability of 3CS degraded as the program moved forward due to an increasing necessary response time. The trade between capability and responsiveness is the central issue at the heart of responsive space. With more missions evolving under the same, or stricter, temporal restrictions, experience and new ideas will bring the two sides of this trade closer together.
Conclusion

Although many of the original mission objectives were never given the opportunity to be met, there is much that can be taken from Three Corner Sat by the universities as well as the aerospace community as a whole. Three Corner Sat was able to successfully perform a radical mission reconfiguration in a matter of weeks, acquiring many lessons learned about university run satellite programs as well as getting a taste of how responsive space looks in real life.

References


