Caerus – Concept through Flight in Eleven Months: A Story of Rapid Response and Lessons Learned

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On December 8th, 2010, USC's first cubesat rode into orbit on the SpaceX Falcon 9 Dragon mission. The cubesat was a joint venture between USC and Northrop Grumman. USC's portion is named "Caerus". This paper describes the requirements, design and implementation, test, flight and lessons learned of the vehicle. Particular attention is given to the deployable antenna, antenna sharing, beacon radio, main radio, store-and-forward software, a spacecraft state of health/state of flight system including MEMs gyroscopes, and mobile ground station dish with helical feed. Additional logistical hurdles we surmounted include: firewalls for ITAR and non-ITAR students, handling proprietary commercial information, RF spectrum licensing and coordination and finally, managing separate locations for: dish, commercial and academic mission control stations, commercial and academic and international beacon stations. The mission succeeded in attaining all Level One goals for Northrop Grumman NovaWorks. In all, it became a mission whose 11 month arc covered more aspects of spaceflight than most people are lucky enough to see in a career.

I. Introduction

We were tired but eager, having just completed our Critical Design Review. At the University of Southern California's Space Engineering Research Center (SERC), students and staff alike were hard at work on Aeneas — a cargo-tracking cubesat[1] scheduled to launch in 18 months. Although the SERC has had several successful land and air programs, this was to be our first *real* satellite, bringing with it all the visibility and high expectations associated with such an endeavor. As one would expect, the halls were abuzz with excited students and nervous managers, chiseling away at something that would surely make the USC history books, for better or worse.

That's when a call came from Northrop Grumman (NG).

It was the NovaWorks Advanced Concepts group, a section within NG responsible for cutting-edge research and development. They were in the process of developing their own cubesat to test some of their research and had secured a ride to space. They wanted us to design and build the communications subsystem for their cubesat and they needed it in 150 days.

The decision was difficult. Do we interrupt our first-ever satellite program to chase a closer target? Would the risk-reduction of flying our components outweigh the time lost in the schedule? Could we even accomplish a communications subsystem design and build in 5 months?

Ultimately, it is always better to rise to a challenge. Aeneas was put on hold and the engineers at USC's SERC swung their talents toward what would surely be one of the fastest satellite builds in history. Northrop's cubesat was named Mayflower, a reference to the risks and rewards that accompany bold action and innovative thinking. For our part, we named the communication subsystem Caerus. In Greek, it means "Opportunity."

II. Requirements and ConOps

NG's satellite was to be a "3U" Cubesat, meaning that it was comprised of three 10x10x10 centimeter Units. Two of the units would house NG's advanced technology, while the third was given to us for the communication subsystem. The initial requirements for the subsystem were to provide for Mayflower the following:

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- A store and forward system consisting of a last-in first-out buffer
- A radio system for data downlink and command uplink

These requirements were to be accomplished within the 1U volume and 1 kg mass restrictions. NG's section (the "main bus") would provide 10 W of power and 6 DOF attitude control. The initial meeting occurred in January, 2010, and the subsystem was to be delivered in May for final integration and environmental testing. Launch would occur in the Fall aboard SpaceX's Falcon 9 rocket to a low earth orbit.

The concept of operations was straightforward. After arriving on orbit, Mayflower would begin performing a series of tests. The detailed data from these tests would be given to Caerus for downlink to Earth. Caerus would store the information and retrieve it once a communication link was established. We would then downlink as much of the data as was possible while simultaneously uploading commands from NG to the satellite. From the particulars of our orbit, each pass would be 2 to 5 minutes of connection time.

Early analyses indicated that our radio system would need the following three items: a backup transmission of health and status, a deployable antenna shared between the primary and backup systems, and ground station software to organize the down-linked information. Further, once these systems were chosen, a host of derived requirements involving ITAR and proprietary data were in effect. Our primary radio and our international students were legally incompatible, and digital walls needed to be erected to separate the open amateur-class information from NG's encrypted proprietary data.

In addition to external requirements we saw an opportunity to risk-reduce portions of the Aeneas cubesat by incorporating them into Caerus. In particular, we wanted to verify the operation of our custom-designed Pluggable Processor Module (PPM). The PPM is slated to house the Flight Software of Aeneas, and by flying it on the Mayflower we would be able to test certain portions on orbit. Therefore, we imposed requirements on the communication subsystem to allow the PPM and a prototype flight software to self-test and communicate the results to the ground.

Finally, after the initial requirements were stated, a problem arose with the ground station hardware. A tracking antenna could not be secured by NG, so we took it upon ourselves to provide one.

III. Design and Implementation

The design of the store-and-forward system fell under two broad categories: computational resources and radio-related equipment. The processor, non-volatile storage and associated software were in the former category. The radios and antennas were in the latter. The overall system was intended to do the following:

- acquire messages from the Northrop Grumman flight processor,
- store the messages safely,
- retrieve them in a last-in, first-out order, and
- transmit them to a ground station over an encrypted link.

To achieve these goals, we used the subsystems and components described below.

A. Processor, Storage and Software

To coordinate the store and forward system, we used a PIC24 microprocessor: specifically the PIC24FJ256GA110. This 100-pin chip contains several hardware UARTs and SPI modules, used in communicating to the NG processor and flash storage, respectively. The PIC24 also supports up to 16 MIPS operation at 32 Mhz, using a Phase Lock Loop frequency multiplier on the internal 8 Mhz oscillator.

In terms of storage, the flash chip was the Atmel AT25DF641 64-megabit SPI Serial Flash Memory. Like many flash chips, it is addressable at the block level. In other words, the writing of individual bytes is allowed, but the smallest size that can be individually erased is a block (4 kilobytes). Communication with the chip was performed on an SPI line. For mission assurance, the SPI line was not shared with other components.

The software was programmed in ANSI C and compiled using the CCS PCD compiler. Although parts of the code have a long history dating back to the MSTI[2,3] spacecraft program, the portions of code dealing with C&DH were brand new. The software was meant to be as simple as possible — there were essentially only two programs running on it. The first program monitored the UART connecting the Caerus processor to the NG flight processor and recorded to flash any message packets it saw. As for the second program, any connection with the ground antenna would trigger it to retrieve the messages from flash and send them over the radio.

B. Radios: Primary Communications and Beacon

The primary communications radio was the MHX425 frequency hopping wireless modem by Microhard Inc. The MHX operates between 400 and 450 Mhz at rates between 19.2 and 230.4 kbps. The choice of this modem was a consensus between NovaWorks and the SERC, because both organizations had had prior experience with the device. NovaWorks had previously experimented with the MHX series, and the SERC was working with the modems on both a previous cubesat design as well as the current Aeneas design. Although Microhard has several variants, we opted for the 425 model for several reasons. First, the 425 modem performed well in the link budget analysis, shown in Figure 1. Second, its frequency of operation is close enough to that of the beacon to support a single antenna system, greatly simplifying the antenna design. Third, the included encryption received a Type 1 certification from the NSA, making it more than adequate to protect proprietary information on behalf of Northrop Grumman.

However, there were several downsides in choosing the MHX425. First, it is an ITAR-controlled device, which meant that we had to take extra precautions to ensure our foreign students did not come in to contact with the unit. Second, the specifics of the radio architecture were not easily scalable. The MHX425 operates as a master/slave pair, and in order to comply with FCC regulations we were forced to put the slave unit on orbit. This forced our master unit to the ground, which forbade simultaneous communications with adjacent ground stations. In other words, as a slave the satellite could only pay attention to a single ground station at any one time. From a risk and logistics perspective, this is less preferable than having the satellite broadcast be accessible with multiple redundant ground assets.

Final Link Budget — 350km

Item	Units	MHX425 Downlink	MHX425 Uplink	Stensat Downlink	Rcvr Sensitivity Downlink	Rcvr Sensitivity Uplink
Frequency	Mhz	437.0	437.0	437.0	437.0	437.0
Transmitter Power	Watts	1.0	10.0	1.0	1.0	10.0
Transmitter Power	dBW	0.0	10.0	0.0	0.0	10.0
Transmitter Line Loss	dB	-1.5	-1.5	-3.0	-1.5	-1.5
Transmit Antenna Beamwidth	deg	20.0	20.0	45.0	20.0	20.0
Peak Transmit Antenna Gain	dBi	-5.0	23.0	-5.0	-5.0	23.0
Transmit Antenna Pointing Error	deg	0.0	5.0	0.0	0.0	5.0
Transmit Antenna Pointing Loss	dB	0.0	-0.8	0.0	0.0	-0.8
Transmit Antenna Gain (net)	dBi	-5.0	22.3	-5.0	-5.0	22.3
EIRP	dBW	-6.5	30.8	-8.0	-6.5	30.8
Elevation Angle		15.0	15.0	15.0	15.0	15.0
Circular Orbit Altitude	km	350.0	350.0	350.0	350.0	350.0
Propagation Path Length (Slant Range)	km	1053.3	1053.3	1053.3	1053.3	1053.3
Space Loss	dB	-145.7	-145.7	-145.7	-145.7	-145.7
Propagation & Polarziation Loss	dB	-3.0	-3.0	-3.0	-3.0	-3.0
Peak Receive Antenna Gain	dBi	23.0	-5.0	12.0	23.0	-5.0
Receive Antenna Beamwidth	deg	20.0	20.0	45.0	20.0	20.0
Receive Antenna Pointing Error	deg	5.0	0.0	5.0	5.0	0.0
Receive Antenna Pointing Loss	dB	-0.8	0.0	-0.1	-0.8	0.0
Receive Antenna Gain (net)	dBi	22.3	-5.0	11.9	22.3	-5.0
Data Rate	bps	115200.0	115200.0	9600.0	-137.0	-137.0
Required Eb/No	dB	13.3	13.3	13.3		
Reciever Noise Temperature	K	300.0	300.0	30.0		
Antenna Noise Temperature	K	30.0	290.0	290.0		
System Noise Temperature	K	330.0	590.0	320.0		
Eb/No	dB	19.1	27.3	18.7		
Carrier to Noise Density Ratio	dB-Hz	69.7	77.9	58.5		
Bit Error Rate	N/A	0.0	0.0	0.0		
Implementation Loss	dB	-2.0	-2.0	-2.0	-2.0	-2.0
Link Margin	**dB**	**3.8**	**12.0**	**3.4**	**2.0**	**12.0**

User Input Value
From Figure in SMAD
Calculated Value

Figure 1. Link Budget for C&DH and Beacon Radios

The beacon was an addition that we suggested and thought imperative to mitigate risk for the mission. When we performed a survey of previous cubesat missions, we found a large number of satellites that were never heard from after launch. Part of this was due to difficulty in finding the satellites. Cubesat orbital information is not updated very often, and even when it is, it is sometimes difficult to pick out which cubesat is yours from amongst the group with which it launched. The lessons learned from these unfortunate failures was that having a beacon on the cubesat can help with both locating the satellite and diagnosing any additional failures.

Therefore, we purchased two radio beacons for evaluation: the Stensat, a one-watt, 1200/9600 baud AFSK device with flight heritage in Stanford's Genesat; and the Neon 1 by Astrodev, a 9600 baud GMSK device that was new to the market. Both beacons performed well under evaluation testing but for reasons of more universal accessibility, we chose the Stensat for flight.

The Stensat was our only backup in an otherwise single-string spacecraft. The beacon operated every 10 seconds for roughly 200 milliseconds, broadcasting a 240-byte packet. We filled the packet with as much information as we could, and published the details of our frequency and modulation so that amateurs around the world could find us and report anything they heard to our website. This proved to be quite valuable during the mission.

C. Antennas

With two radio systems aboard the spacecraft, we turn our attention to the antenna system that sends RF energy out for capture by the ground stations. There were several constraints within which we had to work. First, the geometry of our satellite forced us to build the antenna near the center of the spacecraft. Antennas tend to work better when they are mounted away from interfering metals or other objects. In a cubesat, this generally implies mounting the antenna off the end of the spacecraft rather than the middle. We did not have this luxury. Second, we were constrained from certain deployment angles due to extensive solar arrays. Many deployable whip antennas wrap around their host spacecraft, lying between the surface of the craft and the launch rails to which it is mounted during launch. When the solar arrays were stowed, they consumed all the available space between the surface of the satellite and these launch rails, which denied that space to us. Further, when the panels deployed, they were sensitive to any shading. The circuitry was such that a partially shaded panel might behave as if it were fully shaded.

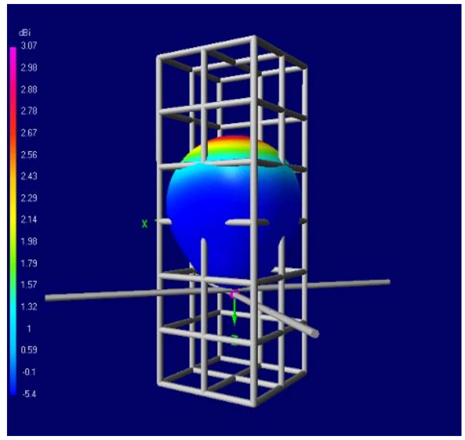

Figure 2. Diagonal Whip Placement

Under these constraints, we designed, constructed and tested a quad monopole antenna system which deployed at a 45 degree angle to the rectangular faces of the craft (see Figure 2). The design was very iterative. Concepts were bantered about and sketches were made and argued over. We constructed many models, first using 3D stereo lithography and then moving on to Delrin. Eventually, the body and rotor were hewn from flight-approved, RF transparent Vespel material. The body and rotor housed four deployable construction tape whip antennas. Throughout this whole process, one very dedicated grad student made countless trips to USC's Ultralab anechoic chamber in order to plot the gain of each iteration. The final result is the beautifully shaped +5 dBi radiation pattern shown in Figure 3.

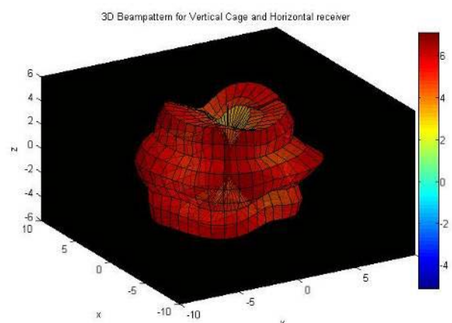

Figure 3. Quad Monopole RF Pattern

The quad monopole antenna was shared between the two radios. This coupling was made possible since the two operating frequencies were close: 437 and 437.6 MHz. However, the two radios were not operated simultaneously due to interference and power concerns. Instead, a multiplexer needed to be designed to both switch the antenna from the primary to the beacon and to feed the four whips in quadrature while maintaining an appropriate VSWR. We tasked a local aerospace company, Astronautical Development, LLC (AstroDev), with producing a switcher in a cubesat form factor. They produced an engineering model and two flight units, which were tested and used for flight.

Figure 4. Deployment Mechanism

Lastly, a deployable antenna requires a deployment mechanism. Through a similarly iterative process as the antenna, we discussed, designed and tested a "burn wire"-style system. In this system, a short, tightly stretched piece of nylon monofilament is surrounded by a nichrome wire. When energized, the nichrome wire melts the nylon, allowing the system to move. The deployment mechanism is shown in Figure 4. Once released, the quad whip antennas deploy naturally because they are stowed in such a way as to provide an ejection spring force.

D. Risk Reduction

One of the greatest ways to reduce risk in spacecraft is to use processes and components that have flown on previous missions. This is known as "legacy" or "flight heritage," and is an often-sought quality in spacecraft design.

There were two directions of heritage-based risk reduction on the Caerus mission: the present and the future. First, we reduced risk on Caerus by using heritage components wherever possible. For example, Pumpkin's Cubesat Kit, which we used, is filled with components that have flown on previous missions. Among these are the Flight Processor Motherboards (FPMs) and the chassis. In addition, although the Pluggable Processor Modules (PPMs) of that kit have flown with a different processor, the design of the PIC24-based PPM derives benefit from the common ancestry and ancillary components. Additional examples of heritage components include the deployment and remove-before-flight switches, the beacon, the antenna multiplexer switch and the stackable PC-104 style bus. The MHX425 radio had not flown in space yet but other variants of the radio, such as the MHX2400, had. Figure 5 shows the block diagram.

Looking to our future work on Aeneas, we sought to reduce risk in a second direction by using a common design between the two spacecraft and by flight-qualifying components (i.e., by flying additional parts on Caerus, we were able to certify them as having successful flight heritage for Aeneas.) An example of this is the PIC24 processor and our custom designed flight PPM with 3 single axis gyros. The PPM benefited greatly from this risk reduction due to its non-standard gyro mounting.

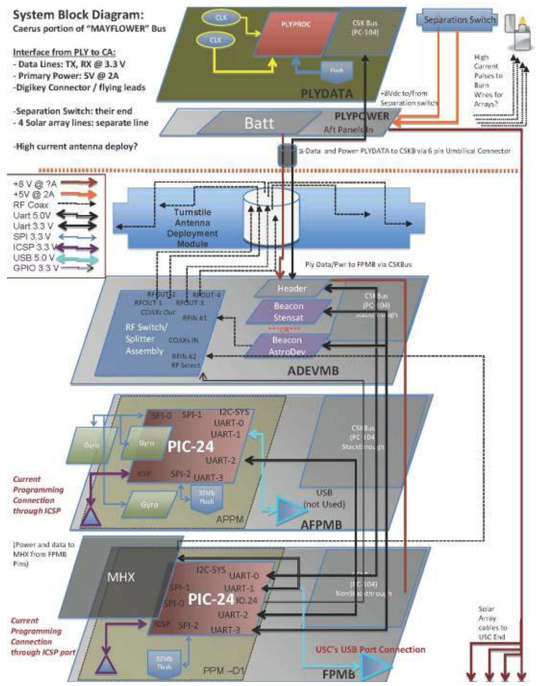

Figure 5. System Block Diagram

Our gyros were meant to be surface-mounted, and surface mounted components generally have low risk, as was the case with our Z axis gyro. However, the X and Y axis units were mounted vertically, normal to the plane of the circuit board. This was a non-standard attachment (see Figure 6) and it posed some concern. Although our PPM was not used for C&DH, the gyro data was collected and sent down via the beacon. By observing this data we were able to flight qualify this design for Aeneas. Both PPMs were hosted on two copies of the standard Pumpkin Flight Processor Motherboards (FPM) both in the bus stack which would be considered a bit odd or novel and did require a bit of thought to keep like functions from competing with each other.


Figure 6. Vertical Gyros (extreme top, bottom left)

Our design brought as much flight heritage to the subsystem as possible while also gaining some heritage for our future spacecraft.

E. Ground Operations

USC created a ground operations system using a mix of open source and custom software. The system enabled us to automate commanding, telemetry processing, and payload data distribution to Northrop Grumman. It consisted of multiple hardware and software pieces as well as a minimal operations crew, see Figure 7.

1. Ground Operations Software

At the center of the ground software was a suite named the Mission Server. The Mission Server actually consisted of several software components. One was the Mission Hub which listened for connections from the remote ground site. During a pass, the remote ground sites would connect to the Mission Hub and feed real time telemetry data. This data would be processed by the Mission Server and stored in a custom built MySQL database. Simultaneously, as applicable, commands would be automatically forwarded from the database to the remote ground sites and be sent to the spacecraft.

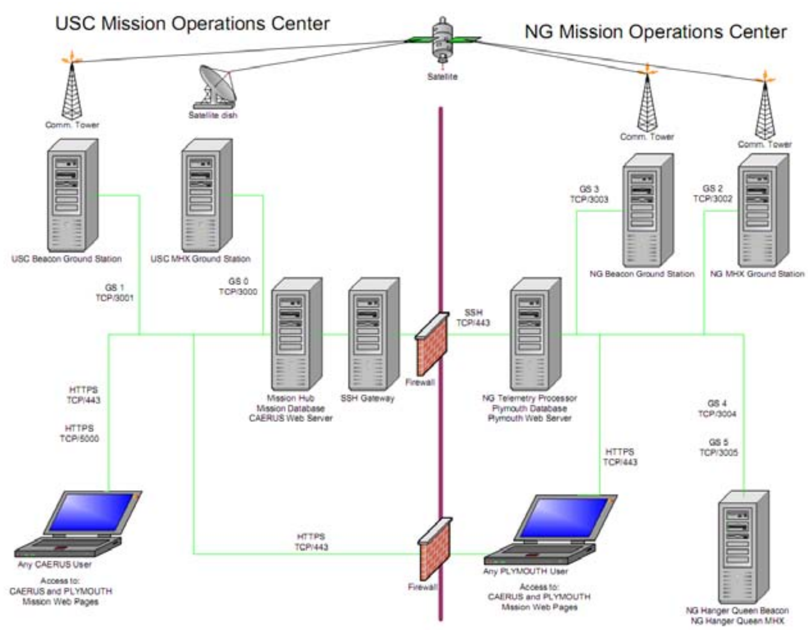

Figure 7. Mission Operations

Finally, an authorized user located anywhere on the internet could connect on a given TCP port to receive a real time feed of the raw bytes arriving from the spacecraft. This feature was especially useful during testing. The system was designed such that all these processes occurred automatically. The Mission Hub was written in Java and utilized a MySQL database backend. All data exchange with remote ground sites occurred over TCP.

The second major component of the Mission Server suite was an interactive web site for use by the Ground Operations utilizing this same database. It has the ability to display telemetry, both raw hex-encoded bytes as well as post processed telemetry with corresponding units. From this site, data could be downloaded, analyzed, and graphed. This web site, built primarily in PHP, was the primary vehicle for creating the command set for a given pass. Operators would use the web-based GUI to create a script for the satellite. The script could then be executed on the Engineering Model, located on earth in a clean tent, prior to sending to the on-orbit spacecraft. Finally, the web site included a Log Book which was used by the operations team as the primary repository for mission event recording.

Rounding out the Mission Server suite were various utilities such as Putty and Telnet to enable internet-based testing and operations. Finally, to ensure security, all connections outside the Mission Server computer where enclosed within an encrypted SSH session. Although this software supported a single spacecraft, it was built to support simultaneous missions. This is a source for future research.

Remote Ground Sites consisted of a standard laptop connected both to the Internet and to a radio receiver or transceiver. The software packaged installed on the laptops were open source applications solely to route the telemetry data received to the Mission Server and forward commands received from the Mission Server on to the radio and thus the spacecraft. First, each laptop had an SSH client running to create the secure sessions with the Mission Server. Then an application to convert a RS232 serial port into a TCP port was used so that in essence the radio was virtually connected to the Mission Server located back at the Mission Operations Center. Finally, the Remote Ground Site computers ran an instance of Amateur Radio software to control the Azimuth/Elevation rotators using TLE information. In practice, this last piece of software was often run on a separate laptop so that one operator could focus on verifying antenna pointing while another Operator verified good data flow with the Mission Server.

2. *Ground Operations Hardware*

For this mission, there were three remote ground sites. The first, considered the primary, was located in Playa Del Rey and operated the main communication link to the Microhard radio. This ground site had a tracking 3 meter dish with a custom feed helical feed. Because the frequencies were similar, this site could also receive beacon transmissions using the same dish and feed. The second ground site was located at USC's Main Campus near down town Los Angeles. This station provided primary beacon reception for the mission. An Azimuth/Elevation Yagi antenna and radio equipment were installed on the 7^{th} floor of one of the tallest buildings on campus. A difficulty of operating out of Los Angeles is line of sight. By placing the antenna on top of the building we were able to get visibility above 10 degrees elevation. The final ground station was located at Northrop Grumman's Space Park. It also consisted of a directional Yagi antenna and associated radio hardware. All these ground sites connected remotely to the Mission Server. The teams at the various ground sites as well as the Mission Operations Center (4 locations total) coordinated with a 4-way Skype video session.

F. Mobile Tracking Dish

One of the greatest challenges for the SERC team was the design and fabrication of the mobile satellite tracking dish. As a last-minute addition to the requirements, the dish posed a seemingly endless string of technical, financial and logistical issues.

The dish originated on an antenna farm in central California. After delivery to the USC campus in Los Angeles (requiring both new trailer tires and special driving permissions), the antenna was forcefully disassembled from its concrete base with a jackhammer. Bare metal stock was welded in the shape of an A-frame to the dish for azimuth and elevation control, while the controller itself was retrofitted for these modifications. We designed, constructed, tuned and tested a helical feed under vicious scheduling and technical constraints. All-in-all, it was a study in will over technology.

For operation, the antenna was towed to a SERC member's driveway in West Los Angeles. The controller was calibrated for the new location and operated from the garage. On the day of the mission, a SERC member had the truly heroic task of both monitoring the satellite and making sure his toddlers did not destroy any equipment. A collection of thumbnails, Figures 8-15, document the story.

Figures 8-15. The evolution of the ground antenna.
Top Row L-R, Purchase Fixed Dish, Ballast Removal, New Welded Mast and Az/El flange
Middle Row L-R, Az/El Rotator installation, A-Frame on Rotator, Az/El Operational Test
Bottom Row L-R, Completed Dish with Helical Feed, Ready for Transport, On Site Playa Del Rey

G. Amateur Radio Community

The mission also relied heavily on the generous contributions of the amateur radio community. Prior to the launch, we engaged the community by broadcasting radio and packet parameters via USC's website. After launch, the first beacons we received were forwarded from a community site! During the course of the mission, we received packets from radio operators around the world. These packets assisted us greatly in monitoring the satellite, and we are greatly indebted to these active amateurs.

IV. Test

As with any critical system, the Caerus communications package was exposed to a great deal of testing prior to delivery. The following pages describe the test environments and general results of the test program.

A. Store and Forward System Testing

In order to ensure mission success, we tested the store and forward system over a period of several weeks in increasingly harsh conditions. The tests were simple but effective at representing worst-case scenarios.

To understand the tests it helps to understand the software's function. Caerus' method of operation was to monitor a UART line for packets of data from the NG processor. To make things easier and avoid software integration bugs, our packet format was kept simple. The format was a two-byte sync code followed by 78 bytes of data. This data was not checked for corruption and the 80-byte packet size was fixed. The NG processor would parse all of its technical data into the 80-byte format, whether the data was a message, image or anything else.

We started testing by simply gauging the throughput of the system. One way to test this is to fake NG data. From previous projects, the SERC was in possession of several Rabbit microcontrollers. One of these was repurposed as a data generator. The microcontroller would produce any number of correctly-formatted packets with random characters as the data itself. Each packet was numbered, so the database on the receiving end could be compared to what was sent to determine if any packets had been lost. From these tests we were able to design and implement a hardware handshaking pin to control the flow of data between the processors.

Once we were confident in the data integrity under nominal conditions, it was time to test the performance under failure scenarios. We wanted to simulate as close as possible a worst-case scenario in terms of high data rates and frequent power failures. Toward this end, we employed another microcontroller called the Arduino. The Arduino is a hobby-class microcontroller programmable in C. In our test setup, this microcontroller was connected to relays for controlling the power to both the satellite and the ground station radio. The controller would manage the power to both devices in such a way as to simulate an actual mission. For example, the ground station radio was turned on every 90 minutes for 2.5 minutes to simulate an overhead mission pass. Turning on the radio in this way would enable the satellite to connect to it and downlink stored data. The controller also cut power to the satellite every hour for a few minutes to simulate a worst-case frequency for on-orbit power resets. This frequency of power loss could occur if the main bus (NG's section of the cubesat) was having difficulty maintaining solar-generated power.

Caerus passed these tests exceptionally well. The software was able to recover from every power loss and pick up where it left off. The data would correctly overwrite itself if the storage space became full, consistent with the concept of an overwriting Last-In, First-Out buffer. Lastly, when data was only partially transmitted due to a power failure, that data would be retransmitted on the next connection. Through several weeks of testing, the Caerus software did not lose a single packet unexpectedly.

B. Antenna and Radio Testing

There are essentially two parts to a communications link: the antennas, which send and receive electromagnetic energy to each other, and the radios, which interpret the signals from the antennas into meaningful data. A complete testing program needs to cover both.

Our system was comprised of two radios and three antennas. On the satellite is the Quad Monopole Antenna, described earlier and shared by both radios. On the ground are both the Yagi and 10-ft parabolic antennas, meant for the beacon and MHX links, respectively (though the parabolic dish could also serve as a backup for the beacon.) The table below shows which radios were to be used on which antennas.

Table 1. Radios and Antennas

Antenna/Radio	Satellite Quad Monopole	Ground Yagi	Ground 10 ft Dish
MHX425	Yes	No	Yes
Beacon	Yes	Yes	No (except as backup)

To fully isolate any problems in the system, we needed to test the antennas and radios separately. Ideally, we would subject each antenna to two different forms of testing:

- gain measurements using an RF network analyzer and anechoic chamber, and
- pointing tests using a far-field target.

We started with gain measurements of the three antennas. The quad monopole was the simplest. After spending much time and effort in the campus anechoic chamber, we were fairly confident that it could achieve 5 dBi under controlled conditions.

The 10-ft parabolic dish was next. There were multiple logistical issues with testing this antenna. First, it could not fit in our anechoic chamber, so we were forced to find an anechoic-like open space for testing. We requested the use of the USC football field, but that proved to be a futile endeavor. Further, the logistics of moving the dish denied other similarly appropriate spaces to us. Despite these challenges, we were able to adequately test it using a borrowed network analyzer and calibrated bilog antenna in a concrete alleyway between buildings near where the dish was constructed. The gain clocked in at roughly 20 dBi, which was near the expected value.

Last was the Yagi antenna. We did not find it necessary to measure the gain of this antenna due to its simple construction and ample margins. The purchase paperwork stated that the Yagi had a 16 dB gain. To verify this stated gain, we would have had to place a borrowed $60,000 network analyzer up a multistory ladder onto the roof. In lieu of taking that risk, we settled for a beacon test from campus to Griffith Observatory, 16 miles away. This test demonstrated acceptable signal strength. In addition, our campus beacon crew (made up of international students) went to work tracking and decoding several of the available amateur satellites and the International Space Station.

After verifying the gains to our satisfaction, we examined the pointing accuracy for the ground antennas. Both antennas were successful in tracking several amateur satellites. While these are not strict pointing tests, they indicated an acceptable level of accuracy in the pointing. Under the tight scheduling and logistical constraints, that would have to suffice.

Having tested the antennas fully, we turned our attention to the radios. Similar to the antennas, we would ideally test the radios in two different ways: environmental tests to observe performance under controlled conditions, and in-the-loop tests to measure gains and simulate the actual mission.

A critical legal issue impeded several of our tests. The MHX was ITAR-controlled, which meant we could not let it be seen by any foreign national. This rendered both our RF expert as well as all international students unavailable for radio testing. Because of this restriction, we were forced to test the MHX only through mission rehearsals where the ITAR-cleared team was available.

The beacon did not suffer from such a restriction, and two additional tests were performed on it before delivery. First the beacon was frozen in our office freezer with the temperature set at minimum. Thermocouples showed about 20° F and operation was tested. The unit powered up but the frequency did not allow for decoding of the AX.25 signal for several minutes. Eventually, internal heating rendered the signal decodable (likely by moving the frequency within tolerance). This was disconcerting but the unit was to be powered during flight and operated every 10 seconds. Therefore, we expected internal heating to keep it operational.

The second test was an in-the-loop functional check. We had performed this test many times successfully, but after Arathane coating (painting a conformal coat over all exposed pins), it failed the test. This was unexpected by both the beacon manufacturer and ourselves. Careful removal of the Arathane from a crystal input to one of the RF encoder chips brought back operation, and it was flown in this fashion.

With the standalone antenna subsystem testing completed, we awaited Mission Rehearsals for further system testing.

C. Ground Operations Testing

To verify the ground system would perform after launch, the team ran extensive tests to measure performance during mission-like conditions. Testing began by feeding large amounts of captured telemetry data (approximately 1Mb of raw data) from previous test sessions into a “remote” ground site located on one computer in the laboratory over the network to the Mission Server. This was done by bypassing the radio and feeding the data directly onto a serial port. Using the website, we verified that the data (tens of thousands of packets) had been stored correctly. Similar tests at the actual remote sites were then conducted using this captured telemetry, all with satisfactory results. Finally, we brought the engineering model cubesat (hanger queen) to the various remote ground sites to test the full system, end-to-end, including the radio equipment. By placing the cubesat near the antenna at each remote site, we could verify that the packets were being received and stored correctly in the database. We also tested that commands executed correctly when near the main ground station at Playa Del Rey, which contained the bidirectional MHX425 radio.

D. Environmental test

Environmental testing provided another opportunity for performance verification in mission-like conditions. Our spacecraft underwent two types of environmental testing: vibration and thermal-vacuum.

Vibration testing was performed in the launch configuration, which is to say in a P-POD cubesat launcher. The P-POD serves as the interface between our cubesat and the rocket. It is a heavy, metal, six-sided breadbox with a spring-loaded door on one end and a spring-loaded pusher plate on the other. There is a small amount of clearance between our satellite rails and the internal guides on which it rides. This clearance gives rise to complicated dynamic effects in a vibration environment, so it is important to test that the satellite will hold together when exposed to vibrations similar to a launch.

The vibration test was performed in each of the three vehicle axes. The shake environment for each axis was set to be similar to the environment expected on the Falcon 9 rocket at the position of the P-POD launcher, with a little extra as a safety margin. After each axis was shook, we used the communications system to verify nominal operation. In addition, the dynamic feedback from the shake table would have alerted us to any components shaking loose during the test. The spacecraft passed all vibration tests with no anomalies.

The next environmental test was a Thermal Vacuum (TVAC) test. TVAC tests are performed in a large metal cylinder, which is pumped to a vacuum and then heated and cooled according to a thermal profile. Our test profile was determined using the expected orbit and Northrop Grumman expertise. Before environmental tests began, our spacecraft was wrapped in multi-layer insulation, protecting the internal components from wild temperature swings and giving it the requisite space-vehicle look (Figure 16). During testing, we again used the vehicle's communication system to perform checkouts at various points in the profile. This was complicated slightly by the large, electromagnetic-blocking cylinder in which the test occurred, but by using two small whip antennas on both sides of the bulkhead we were able to communicate.

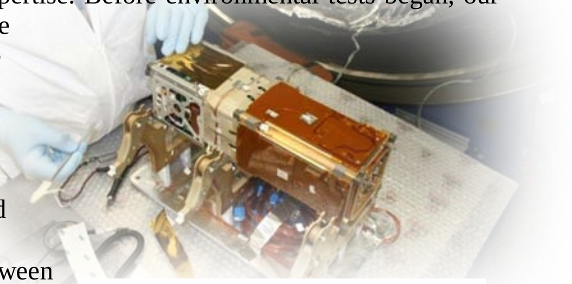

Figure 16. Satellite in TVAC

During the test, the beacon overheated and failed. Mismatches between the logic voltage levels of the processor and the beacon were to blame. We were expecting the failure, so the beacon was modified and the thermal vacuum test was repeated without incident.

During the repeated test, we were able to perform a power up and deployment following the coldest portion of the thermal profile. The chamber measured slight changes in the atmospheric composition, indicating to us that the nichrome melt wire performed the job. In addition, we had been monitoring radio transmissions using an amateur radio with an RF power meter. Following the deployment, the gain on the meter (indicating the received power) swung dramatically higher. This allowed us to verify antenna deployment without opening the chamber and breaking the vacuum seal.

E. Mission Rehearsals

Three mission rehearsals were planned for Mayflower, and each would follow a realistic timeline. The first mission rehearsal was performed in the final assembly lab, without public internet connections and without any ground antennas in the loop. After "launch" (i.e. powering the vehicle), we waited an appropriate amount of time before orbital parameters were released from the "launch provider." The orbital parameters, in the form of a Two Line Element set, were placed into tracking software. The software plotted the pass accesses – the times during which we expected the radios to connect. Because the main radios communicated via handshaking, we could simulate a pass by carefully powering and un-powering the ground radio according to the pass access schedule. To fool the spacecraft into believing it was in orbit, a GPS simulator was used as the ephemeris input. This test was successful, as data collected during the simulated passes was placed via private network into the databases as planned.

Figure 17. Satellite in Trunk

The second mission rehearsal was similar to the first, but included the ground antenna and public internet in the loop. The spacecraft and ground antenna were separated by ~100 feet, with the 10 ft antenna in a team member's driveway and the spacecraft in the trunk of another team member's car (Figure 17). During this test, we chose to keep the dish static (as opposed to tracking a fictitious object in the sky) in order to maintain the signal strength between the dish and the trunk satellite. In hindsight, this was an oversight and a false concern. At 100 ft, the signal strength between the 10 ft dish and the satellite was so strong that connection would occur even at severely oblique angles. Further, this proved to be a missed opportunity to test the tracking software, which worked well under perfect conditions but would freeze the computer if any bit of the TLE syntax was wrong. The beacon system was out of line of site but was checked with a second amateur radio and shown operational. The public internet was used to pipe data to both SERC and Northrop Grumman, and all systems worked as advertised.

A third mission rehearsal involving a long-range test of the primary communications radio was planned but never conducted. The plan was to conduct a mission rehearsal between the ground station dish in West Los Angeles and the satellite on Catalina Island. However, with only a short time remaining before delivery, the logistics of spacecraft portability and ground station dish movement proved to be insurmountable. The test was deemed impractical under the time constraints and the satellite was delivered. The lack of this third "long distance" test proved to be a critical omission.

V. Flight

The lead-up to the scheduled launch date was full of uncertainty and speculation. A shuttle mission was scheduled for launch just before us in late November 2010. As that launch was delayed, we expected to be delayed with it, and we wondered if our students would be on winter break for the launch. Surprisingly, we were moved ahead of the delayed shuttle to a December 6th date, then pushed back again at the last moment to December 8th. Even this final date was not confirmed until late the night before launch. None of this would matter except that our staff is mostly made of students with narrow time availability and daily launch slips created challenges with mission operations.

Launch was to occur at 6 am PST but was delayed two hours. Finally, when the time came, we watched the beautiful flight on a wide screen feed at a Northrop Grumman conference room. Then we immediately dispersed to our locations for the mission passes. The call came almost an hour early with the launch provider's ephemeris, and we scrambled to get the dish ready to track the first pass.

On the first pass, no contact was made with the main C&DH radio. However, beacon contacts were made from several locations around the world, indicating our satellite was alive. From the beacon data, we could tell the following positive results:

- The Caerus processor and clocks were functioning normally. (Indicated by regularly spaced beacons.)
- Satellite power was nominal, and no software bugs were resetting the satellite. (No increase in the reboot counter.)
- Communication to the NG processor was normal. (Indicated by markers in the flash memory showing that data was being stored.)
- The primary radio was powered and functional. (Indicated by the status bits.)

However, the following off-nominal conditions were also observed:

- The satellite was spinning slowly. (Indicated by gyro data.)
- The satellite was hotter than expected. (Indicated by gyro temperature data.)

Our primary radio link was not closing, but the beacon packets implied that the problem was not in space. The failure of the main radio link was either due to the ground antenna, the ground radio, or an unknown unknown. On the next 2 passes, similar results were observed. In addition to the off-nominal conditions shown, we began to observe power fluctuations that caused our satellite to reboot multiple times. On the last pass of the day, the main C&DH radio was switched to an amateur radio and a beacon was received with the ground dish, reproduced here.

KJ6FIX-1>CQ,TCPIP:
4341455255533B000200000C080A0210281E5B0000001000408B7C06008B75280008A6F154B02602
14C7C6D02AB9F80104100A040C17371E80AF8075FFAF80D780D2C0036C

This reception narrowed the suspect list greatly.

The following morning we attempted to diagnose our main C&DH radio. Since we had several MHXs on site, we decided to compare them. The radio's transmit strength was compared to other copies of the radio and the strongest transmitter among them was found. The new radio was quickly installed in the ground station dish, but by the first morning passes no more beacons were being heard. We surmised that the batteries had been exhausted, due to two reasons. First, the consistent roll indicated by the gyros had limited the solar power we could collect, starving our spacecraft of its recharging capability. Second the attitude control system was attempting to compensate for this roll by constantly firing the torque coils. Their operation is energy-intensive and without full recharge capability had likely drained the batteries. Although we expected the power system to conserve power and boot us occasionally, the chances of us receiving the 2 or 3 beacon packets before another shutdown were unlikely. By the end of the second day, our satellite was effectively dead.

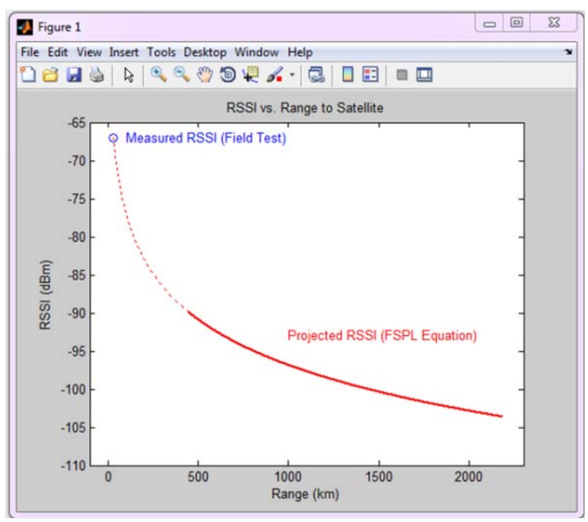

Figure 18. Free Space Path Loss Extrapolation

On the third day we were still trying to understand why the primary communication link did not close. The original and replacement radios were tested and the internal received strength signal indicator (RSSI) was monitored while completing the link between the dish and a backup build of the satellite 200 yards apart in the alley. In this test, we discovered that the original radio had 30 dB less sensitivity than the replacement. Whether due to damage or an inherent defect, this lack of sensitivity was the critical factor in our inability to close the link. It was a grave oversight that would have been easily caught by our third planned mission rehearsal test.

Some days later, before moving the mobile dish back to campus, we carried the backup satellite to Point Dume, 21 miles away from the mobile dish across the Santa Monica Bay. In a sort of reduced mission rehearsal test, we attempted to get the radios to talk to each other. The original radio was unable to close the link, while the replacement radio locked up with all three lights. RSSI information was taken as the dish was swept in one degree increments, confirming the operation and calibration direction of the dish. From the RSSI information an extrapolation was done to show the likely slant range of the link. It is shown in Figure 18. It indicates that with the undamaged radio, the link budget was sound.

VI. Lessons Learned

A. Extensive Testing

Extensive testing was the backbone of everything that worked on this mission. The point can not be made enough – everything we explicitly tested worked as planned.

We planned our testing to simulate the mission environment as much as practical. From the beginning we were to be a last-in-first-out buffer. Additionally we were viewed as a load that could be shed in power conservation situations. With this in mind we tested for weeks on end, using two additional microprocessors to simulate a torrent of data and worst-case power failures. This testing proved itself on orbit, as the beacon packets indicated the underlying system was performing nominally, even through power failures and reboots.

In addition, early low temperature testing in our office freezer may seem crude by the exacting standards of typical environmental tests, but it was able to identify problems on the beacon. The testing heightened the attention on that radio and allowed us to make contingency plans. When it finally failed in an actual thermal-vacuum test, we were ready with a solution.

Across all items, it was better to test than to analyze. And even across tests, it was better to test early and often (such as in our freezer test) than to wait for a more robust and official test. Without exception, the components we tested the most performed the best. The authors recommend all cubesat programs to have a robust test plan, to test early and often, and to perform low fidelity tests if high fidelity tests are unavailable or too far in the future.

B. Satellite Tracking

It is important not to leave the ground station work to the last minute. Tracking satellites with computer controlled Azimuth/Elevation rotors only works if they are calibrated to true North and leveled to zero elevation. This sounds simple with today's GPS and cell phone compasses, but when ground station work is left to the last minute, simple mistakes can creep in. In our case, the USC Campus tricked the students by 20 degrees off of true North, likely due to a combination of magnetic North and the non-Cartesian layout of Los Angeles. Many satellite programs naturally focus on their satellites and do not budget enough time for non-satellite work. The authors recommend this tendency to be actively avoided.

C. Mission Rehearsals

The mission rehearsals were extremely helpful in several ways, and the authors strongly recommend them.

First, they showed us how information would be passed on launch day. For example, Two Line Element set data is only updated once a day at best. Once it is received, it must be processed very quickly for use in planning passes and sending satellite commands. Further, if anything is wrong with the satellite, analyses and decisions must be made in a short 90 minutes. Mission rehearsals make viscerally real this period of time, and they are excellent training tools for students in how to be calm and productive under pressure.

Second, mission rehearsals exercise the end-to-end data plumbing within the system, which often goes unnoticed when one is in the weeds of coding and soldering. In our case, after testing the requested data was changed to better fit the link bandwidth.

Third, mission rehearsals exercise the hard-to-predict logistics. The second rehearsal from the site of the mobile ground station was instrumental in flushing out such things. For example, the link length to local routers, the wireless access away from buildings, the setup and takedown time of voice conference calls and other similar items was made easier through testing.

Lastly, mission rehearsals can catch problems that individual component tests cannot. In our case, a far-field mission rehearsal would have shown the low sensitivity of the ground radio and provided more data and successful uplink to the satellite.

D. Communication links

Do not underestimate what can be done to diagnose a mission with only an AX.25 beacon. Everything we know about what went right and what went wrong in our cubesat came from the beacon data. On Aeneas, we plan to exploit a similar link even further by rotating the information in the beacon packet. We expect to provide for large measures of mission success from this link alone, and recommend other cubesat programs to budget their missions similarly.

When testing a radio link, it is not enough to simply demonstrate the link across a room. The transmit power and receiver sensitivity must be measured, as well as the gains of all associated antennas. The authors recommend that two link budgets be created – one for orbit and one for a far-field test. After these are created, the far-field one can be verified experimentally. The difference between a link at several miles and a link to orbit is mostly due to free space path loss. By creating a link budget for a far-field test and then experimentally demonstrating it, the orbital link budget is much more believable.

Latest revision radios should be used or checked with the vendor as improvements usually happen over a time shorter than the life cycle of satellite design.

Wherever possible, the authors recommend pre-negotiating access to backup ground stations. In the rush of launch, these can go a long way in mitigating single point failures in the dish, ground radio, weather and related problems.

Contact lists were helpful but during a pass there is no time to find a number and call so an open speaker phone line proved even more useful. We had an open Skype line that was very helpful to ensure all were on the same page as the pass came up.

VII. Conclusion

It was a lot of work to design and deliver a communication subsystem in 5 months. Integration and environmental testing in another 5 months was equally difficult. Although it was a lot of work, the SERC team had a lot of fun. Further, the flight heritage gained by some of our components will make our upcoming Aeneas flight even better. Although the primary communication link failed, there was enough information between the beacon and the orbital data for NovaWorks to complete all Level One goals. We are proud to have assisted them in that endeavor, and congratulate them on their success. Finally, we feel privileged to give our students the experience of almost all aspects of a space flight design in such a short amount of time. By all accounts, we seized the opportunity that we were given and are better for it.

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