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Closing the Deep Space Communications Link with Commercial Assets

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ABSTRACT

Growing commercial and governmental interest in lunar and asteroid resource extraction, as well as continuing interest in deep space scientific missions, means an increase in demand for deep space communications systems. Jet Propulsion Laboratory's MarCo demonstrated the viability and usefulness of cubesats as relay stations for deep space communications. Given their relatively low cost of construction and launch, cubesats can decrease the cost of building deep space communication systems. This has the potential to make it feasible for a group without a large budget, such as a university cubesat team, to build such a system. However, while minimizing the cost of the satellite is important, it is only one part of the communications link. The ground station is the other. The cost of accessing the Deep Space Network puts it out of reach for most operations that are not NASA programs, including our student-designed and built University of Colorado Earth Escape Explorer (CU-E^3) 6U cubesat. This means that a project such as ours has to look at options provided by commercial ground station services.

As a competitor in the NASA Cubequest Challenge Deep Space Derby, the CU-E^3 team's goal is to demonstrate it is possible to build a deep space communications system that is small, powerful, and (relatively) low cost. This means not just the hardware on the satellite but also the ground station. On the satellite side, we have developed custom hardware to interface with an AstroDev Li-2 radio for C-band uplink. For downlink, we will be using an X-band radio developed for low earth applications at the University of Colorado Boulder under the NASA Small Satellite Technology Development program. For ground station services, we will be partnering with a commercial provider, ATLAS.

This paper describes the architecture of the CU-E^3 communications system, the challenges of developing a communications system small enough to fit in a 6U cubesat yet powerful enough for deep space, and the process we used to research and partner with a commercial ground station service to help us fulfill our mission.

BACKGROUND

University of Colorado Earth Escape Explorer (CU-E^3) is a student-designed and built 6U cubesat competing in the Deep Space Derby segment of NASA's Cubequest Challenge. The competition includes prizes in four categories: best burst data rate, largest aggregate data volume sustained over time, spacecraft longevity, and farthest communication distance from earth. The competition begins when spacecraft attain a distance of four million kilometers from Earth, and will continue for one year after that time.

Goals of the competition include opening deep space exploration to non-government entities and developing technologies to enable deep space communications from small spacecraft.

Prize	Award- 1st / 2nd Place	Floor Value	Condition
Best Burst Data Rate	$225k / $25k	One 1024-bit data block	Highest error-free blocks in any 30-minute window
Largest Aggregate Data Volume Sustained Over Time	$675k / $75k	One thousand 1024-bit data blocks	Highest error-free blocks in any 28-day window
Spacecraft Longevity	$225k / $25k	28 days	Elapsed days between the first, and very last, receptions of 1024-bit data blocks
Farthest Communication Distance From Earth	$225k / $25k	4,000,000 km	At least one 1024-bit data block

Figure 1: Categories and Prizes in the Deep Space Derby Segment of the Cubequest Challenge

Student staffing for CU-E^3 is provided primarily by students enrolled in a two-semester graduate projects course sponsored by the University of Colorado Boulder Aerospace Engineering Sciences program. After completing graduate projects, some students continue to work on the project as an independent study, while others continue as volunteers. Most students are completing master's degrees in either aerospace or electrical engineering. There are also a few upper level undergraduate students from both aerospace and electrical engineering participating.

From January 2018 to the present, the CU-E^3 communications team has been composed of electrical engineering undergraduate and graduate students.

CU-E^3's project budget has been a combination of ground tournament winnings (~$80,000), crowdfunding (~$2,000), and donations of money, services, and hardware from corporate sponsors (Blue Canyon Technologies, ATLAS, First RF, RT Logic, and Northrop Grumman).

CU-E^3 OVERVIEW

CU-E^3 is a 6U cubesat with no propulsion system. Reaction wheels provide attitude and pointing control. Deployables include three solar arrays, a primary feedhorn antenna paired with a reflect array for signal amplification, and a secondary feedhorn antenna. The solar panels provide power to the spacecraft and enable the cubesat to utilize solar radiation pressure to desaturate the reaction wheels.

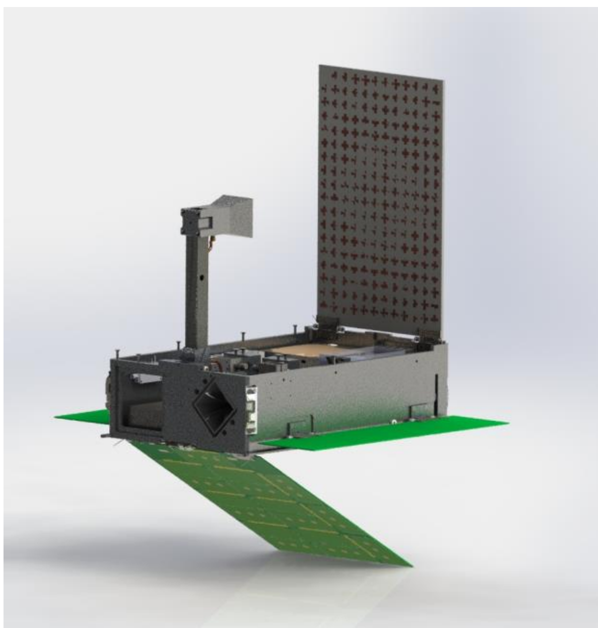

Figure 2: Model of CU-E^3 cubesat with primary feedhorn/reflect array and solar cells deployed

CU-E^3 won a ride to space on SLS-EM1 by finishing in the top three in ground tournament four of the NASA Cubequest Challenge. SLS-EM1 will have five "bus stops" where cubesats can be deployed. Our cubesat will be getting off at the last one, bus stop 5, and coasting. Once we reach a distance of four million kilometers from earth (as determined by the Deep Space Network), the competition will begin. We will generate random data according to NASA's specification and transmit it to our ground station. From there, we will transfer it to NASA, where a committee will review the transmitted data for errors and determine if it meets the threshold for any of the prize categories.

CHALLENGES OF DEEP SPACE COMMUNICATION

The farther away you are from Earth, the weaker your transmitted signal becomes. To overcome this, deep space missions have used large antennas mounted to large spacecraft. Then Jet Propulsion Laboratory's MarCo cubesat demonstrated it was possible to downsize the spacecraft and still close the deep space communications link.

On the ground side, NASA-funded deep space missions have relied on the Deep Space Network (DSN). DSN has high gain antennas at three points on the globe with approximately 120 degrees of separation from each other. This means deep space missions using DSN are in view of at least one antenna at all times.

However, there are two problems with DSN for non-governmental missions. The first is cost. Compatibility testing alone runs in the range of $40,000 to $50,000, Then there is an additional cost for aperture time once the mission is underway.

The second problem is demand. The increasing sophistication of scientific instruments on deep space missions has led to an increase in demand for DSN's services. According to JPL's Office of the Chief Scientist and Chief Technologist, "NASA estimates that the deep space communications capability will need to grow by nearly a factor of 10 each of the next three decades."[1]

CU-E^3 is addressing the spacecraft side of the problem by using a high power amplifier in conjunction with a reflect array to amplify the transmitted signal.

For the ground station side of the problem, CU-E^3 is partnering with a commercial provider, ATLAS. While ATLAS does not have the same level of coverage as the Deep Space Network, it does have access to a worldwide network of antennas with the capability to transmit to and receive signals from deep space. Our communications window will be limited to the time when our ground station is in view. For our current launch date and ground station antenna in Brewster, Washington, we estimate the communications window to be approximately six hours at the beginning of the mission. That time will change over the course of the mission. Additionally, if the launch date changes, our trajectory will change, and that will affect the length of the communications window. Finally, it is also possible that the ground station will change. We are currently in discussions with ATLAS about other antenna possibilities. Balancing all these factors to produce a communications plan for the mission will be a critical part of the mission going forward.

In addition to the limitations on transmit time imposed by the communications window, there are two other technical factors limiting our transmit time:

1) heat dissipation from the transmitter and high power amplifier. We currently estimate we can transmit continuously for approximately four hours.

2) desaturation of the reaction wheels. The reaction wheel desaturation maneuver means we need to orient the satellite in a way that directs the antenna away from the earth. The goal is to perform reaction wheel desaturation during the hours when we cannot contact Earth.

Since these limitations mean CU-E^3 would not be able to communicate with Earth 24 hours a day, the reduced ground station coverage is an acceptable trade-off for the significantly reduced cost of aperture time.

CU-E^3 COMMUNICATIONS SYSTEM

Overview

To minimize costs and to provide learning opportunities for students on the project, the CU-E^3 transmit and receive chains are a combination of student-developed hardware and commercial off the shelf (COTS) parts.

Uplink is C band (5182 MHz), while downlink will be X band (8447.6 MHz).

Due to the distances at which CU-E^3 will be operating, initially we had planned to use BPSK for both uplink and downlink to maximize the accuracy of data transfer. However, due to difficulty getting our Lithium 2 to demodulate a BPSK signal, we are now looking at using GMSK for uplink, while still using BPSK for downlink.

Receive chain

The CU-E3 receive chain consists of four pieces: a C band patch array antenna, low noise amplifier, downmixer board, an Astrodev Lithium 2 radio, and the XB1 central avionics unit (CAU). Power connections to some components in the chain are routed through an expansion board.

The patch array antenna is student-designed. It receives C band signals at a frequency of 5182 MHz and provides amplification of approximately 9.8 dB. The low noise amplifier (LNA) is a Pasternack PE15A1010 which amplifies the incoming signal by up to 39 dB with a noise figure of 0.9 dB. The receive downmixer board is another student-designed and built part. It downconverts the received signal to an intermediate frequency of 420 MHz that is within the acceptable range for the Lithium 2 radio. The Lithium 2 radio converts the analog signal to digital form and demodulates it, then sends a bitstream to a Blue Canyon Technologies XB1 CAU for further processing.

Power to the low noise amplifier and Lithium are provided via an expansion board. The phase lock loop voltage controlled oscillator on the receive downmixer board is programmed by the XB1.

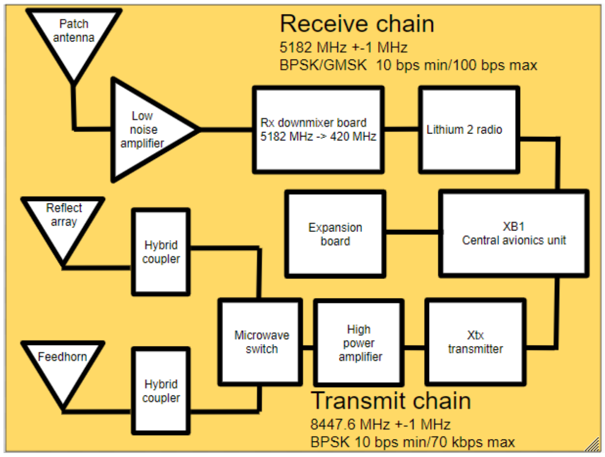

Figure 3: CU-E^3 Communications System Block Diagram

Transmit chain

Like the receive chain, the CU-E^3 transmit chain is a combination of student-designed and COTS parts. The transmit chain consists of the XB1, an Xtx transmitter, a high power amplifier, a microwave switch, two hybrid couplers, a primary feedhorn antenna/reflect array, and a secondary feedhorn antenna.

The XB1 generates a random bitstream according to the competition specifications provided to us by NASA.

The Xtx transmitter from Blue Canyon Technologies is an X-band radio developed for low earth applications at the University of Colorado Boulder under the NASA Small Satellite Technology Development program. It will transmit a signal at 8447.6 MHz with an accuracy of plus or minus 1 Mhz. Recent testing suggests even greater accuracy, with frequency drift of less than 10 kHz over its operating temperature range of -20 C to 50 C.

The high power amplifier was developed and built by students. It amplifies the signal by approximately 30 dB, up to a signal power level of approximately +35 dB (3 W).

The DowKey 401T-420832A-ROHS microwave switch directs the signal either to the primary feedhorn and reflect array or to the secondary feedhorn.

The Anaren 1E0018-3 hybrid couplers create a circularly polarized signal which is then sent to an antenna for transmission.

The secondary feedhorn has a measured gain of 12.8 dB. It will be used for initial commissioning of the satellite, pre-competition, at distances less than four million kilometers. The primary feedhorn with reflect array has a measured gain of 22.3 dB. It will be set up prior to reaching the competition distance of 4 million kilometers, and then used for the competition transmissions.

The expansion board provides data and power connections for the Xtx. It also provides power connections and thermistor output for temperature monitoring of the high power amplifier, and power and control switching for the microwave switch.

CHALLENGES AND LESSONS LEARNED

Staffing and turnover represent a significant challenge for the project. Because students are often on the project for only one or two semesters, and are not around to train in their successors, maintaining continuity between semesters is difficult. The project has attempted to address this by requiring students to write documentation as part of their coursework. However, documentation quality varies, and even when documentation is well-written, understanding it often requires incoming students to have a level of knowledge they do not yet possess.

Additionally, finding students to work on the communications subsystem of CU-E^3 poses a particular challenge. While CU Boulder does have a strong program in radio frequency (RF) engineering, most of the students in that program are PhD students who are committed to projects in the electrical engineering department. Hence they are not available to work on CU-E^3.

A related problem is making a match between what the project needs to have done (for example, antenna design and digital communications) and skills that students available to work on the project have. Because CU Boulder's electrical engineering program does not specialize in digital communications, students must learn "on the job" while working on CU-E3's communications system. A high level of self-motivation and willingness to seek out resources is required.

Yet another staffing challenge is related to certain tasks "falling through the cracks" and not being anyone's responsibility. One example is Altium parts libraries. We were using libraries originally developed for another cubesat mission, QB50. Some parts had footprints which did not match the package specified (for example, a 1k 0402 resistor had an 0603 pcb footprint). This made it impossible to automatically generate a bill of materials to populate the high power amplifier board. The person working on that in spring 2019 had to generate the bill of materials manually. Due to the pressure to complete the high power amplifier board in time for testing at the Deep Space Network, he did not have time to fix the library. When we talked with the board's designer about the problem, he said he knew about it, and also said he had not had time to fix the parts library. The pressure to get a design completed, and the fact that the project has not had enough human resources to appoint a librarian for PCB design files, has led to a situation where people know that a problem exists, but no one has time to fix it.

Some technical challenges have been created or exacerbated by budget and/or staffing problems. For example, the team looked at purchasing a C-band patch array antenna. Such components typically cost several thousand dollars, and the project did not have the budget for that purchase. Consequently, that part became part of the student-designed hardware. After eighteen months of development, the team found that the students' design was too thick to be manufactured. This necessitated a redesign after the original students involved in the antenna project had left. This caused a significant delay in the production and testing of that part.

Challenges that are more purely technical include adapting hardware originally designed for low earth or near earth orbit to function in deep space. An example of this is the Lithium 2 radio that is part of CU-E^3's receive chain. The Lithium had been used on other CU Boulder cubesat missions, but with a GMSK modulation scheme suitable for low earth to near earth orbit. With a firmware update, the Lithium theoretically supports BPSK. However, after a semester and a half of trying, the communications team was unable to get it to demodulate a BPSK signal. At the distances we are operating at, switching from BPSK to GMSK may increase bit error rates from one in a million to one in a thousand, posing a risk to successfully commanding the satellite.

CU-E^3 GROUND SYSTEMS SUPPORT RESEARCH PROCESS

Many, perhaps most, satellite missions have a single ground system which provides telemetry, command, and ranging services. CU-E^3 is different in that we will be using two separate ground systems. The NASA competition we are participating in requires that we use the Deep Space Network for ranging. For budget reasons, we needed to find another provider for telemetry and command services.

The team conducted research on potential ground station partners at the 2017 SmallSat conference. After team member John Sobtzak presented a poster on the CU-E^3 communications system at the conference, the team was approached by the University of Alaska Fairbanks about working with them for ground station support. CU-E^3 also talked with ATLAS Space Operations at SmallSat, and had follow-up conversations with them via email.

ATLAS buys time on antennas around the world, and serves as an aperture time broker service. Antennas in the ATLAS network have transmit and receive capabilities at various frequencies, including the C-band uplink and X-band downlink capability that CU-E^3 needs for its mission. Users access the antenna network using ATLAS's Freedom™ platform.

ATLAS is also developing a second service, the LINKS™ electronically steered array system. This system achieves the power provided by a 70 m parabolic dish antenna. The LINKS™ system is the basis of the Interplanetary Satellite Communications Network (ISCN), which can track and communicate with satellites operating up to 18 million kilometers from earth using VHF, UHF, S, and X band frequencies.[2]

Ultimately, CU-E^3 selected ATLAS for telemetry and commanding. ATLAS has the necessary technical capabilities and was willing to donate aperture time in return for the possibility of receiving a portion of any prize winnings.

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- NASA
- Northrop Grumman
- RTLogic/Kratos Defense
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- Jordan Klepper, RTLogic/Kratos Defense

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