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A University Deep Space CubeSat Mission: Lessons Learned from the University of Colorado Boulder Earth Escape Explorer (CU-E^3)

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ABSTRACT

The University of Colorado Boulder Earth Escape Explorer (CU-E^3) CubeSat is a student designed and built CubeSat initially slated for launch into deep space on Artemis-1, the inaugural launch of the NASA Space Launch System (SLS). CU-E^3 was designed to compete in the Cube Quest Challenge's (CQC) Deep Space Derby for monetary prizes associated with deep space communication system performance, while also serving as a technology demonstration platform for a series of innovative university CubeSat technologies and practices, including a low-cost X-band CubeSat transmitter, an X-band reflectarray antenna, and the use of solar radiation pressure to control reaction wheel momentum build-up. An overview of the CU-E^3 project, including mission concept of operations, system architecture, and major component descriptions are provided. Emphasis is focused the challenges and lessons learned as a participant of the CQC with a student designed and built deep space CubeSat. These challenges include student turnover, limited commercial ground station capabilities and availability, deep space thermal environment, secondary payload safety procedures for the human space rated SLS, and deep space trajectory variance.

INTRODUCTION

The University of Colorado Boulder Earth Escape Explorer (CU-E^3) is a student-lead CubeSat mission focused on demonstrating novel deep space university CubeSat technologies, including a low-cost X-Band transmitter and reflectarray antenna. CU-E^3 was developed as one of the first academic deep space missions through the Cube Quest Challenge (CQC), a NASA funded competition that awarded CU-E^3 an Artemis-1 secondary payload position in 2016.

The CU-E^3 student team designing, testing, and assembling a deep space small satellite grappled with programmatic and design challenges related to both the deep space environment as well as a new human rated space launch vehicle. Challenges related to schedule, budget, and hardware failures resulted in an inability to meet the Artemis-1 secondary payload delivery date in late 2021.

This paper seeks to build from the experience of the CU-E^3 team to identify the challenges and lessons learned from a deep space secondary payload as well as citizen scientist/academic organizations participating in a NASA sponsored deep space competition. As activity in the CisLunar space and the number of deep space launches grows over the next decade, identifying deep space secondary payload challenges and solutions is critical for the long-term success of deep space small satellites.[1]

An overview of the Cube Quest Challenge and the CU-E^3 mission objectives, the mission concept of operations, and a brief description of the spacecraft design are provided as background for the identified challenges.

Cube Quest Challenge

The Cube Quest Challenge is a Centennial Challenges program funded by the NASA Space Technology Mission Directorate to support the development of novel deep space small satellite technologies by Academic and Citizen Scientist organizations.[2] The CQC consists of two phases: ground-tournaments and in-space derbies. The four ground tournaments primarily consisted of mission design reviews by NASA, industry, and department of defense experts with funding prizes for innovative technologies, robust mission design, and hardware development progress.[3] The fourth and final CQC ground tournament (GT4) selected one citizen scientist group, Team Miles, and two academic organizations, CisLunar Explorers from Cornell

University and CU-E3 from The University of Colorado Boulder, for Artemis-1 launch slots.[4,5]

The in-space portion of the CQC is split into the Lunar Derby and the Deep Space Derby, which CU-E3 was designed to compete in. The Lunar Derby is focused on the demonstration of propulsion and orbit determination technologies for lunar orbit insertion, while the Deep Space Derby is focused on communication system demonstration through the downlink of pseudorandom data at distances greater than three million kilometers from Earth. In addition to SLS Artemis-1 launch slots, the CQC reserved access to NASA's Deep Space Network (DSN) assets for several radiometric tracking passes for range verification of the three payloads selected at GT4.

Mission Overview

The CU-E3 mission design consists of four phases: Payload Transit, Commissioning, Competition, and Cruise. The mission concept of operations was designed to satisfy the single Cube Quest Challenge Deep Space Derby trajectory requirement of reaching 3 million km from Earth while also limiting mission complexity.

During the payload transit portion of the mission, CU-E3 was intended to be loaded onto the SLS directly below the Orion Spacecraft, launch on Artemis-1, and be deployed two days post launch directly before the Orion spacecraft completed a lunar flyby. CU-E3 would then enter the commissioning phase of the mission, starting to detumble and beacon, while utilizing the lunar gravity assist to enter a heliocentric orbit and reach range of 3 million km from Earth.

Once CU-E3 verified arrival at the Deep Space Derby start distance through radiometric tracking with the DSN, the competition phase of the mission would begin, with the spacecraft prioritizing downlinking the maximum volume of CQC pseudorandom data. After CU-E3 reached 10 million km from Earth, the cruise phase would begin, with CU-E3 focusing on demonstrating mission longevity and maximum communication distance prior to the mission ending one year post Artemis-1 launch.

Spacecraft Design

The CU-E3 spacecraft consists of a Blue Canyon Technologies (BCT) XB1 integrated Flight Computer, Attitude Determination and Control System (ADCS), and Electronic Power System (EPS), as well as uplink and downlink communication chains, as depicted in the system block diagram in Figure 1.[6]

The selection of the Commercial Off-The-Shelf (COTS) BCT XB1 was made to meet the aggressive initial SLS delivery date of 2018. By selecting a COTS CDH, ADCS, and EPS the CU-E3 team was able to primarily focus on the development of the communication system for the Cube Quest Challenge Deep Space Derby. The decision to not include a propulsion system was threefold: to allow the team to focus on development of the communications system, to reduce the quantity of applicable SLS hazard controls and safety requirements, and initial analysis indicated that CU-E3 would be able to leverage the SLS lunar flyby to meet all trajectory requirements.

The electronic power system consists of six Li-ion 18650 cells provided by the SLS secondary payload office, three solar panels designed and assembled at the University of Colorado Boulder, and two separate charging systems for pre-flight and on-orbit charging.[7]

For the communication system, CU-E3 sought to leverage University CubeSat flight heritage hardware for the uplink chain while demonstrating innovative CubeSat technologies for downlink. The uplink subsystem consists of a C-Band patch array antenna, a low noise amplifier, a downmixer and filtering PCB, and

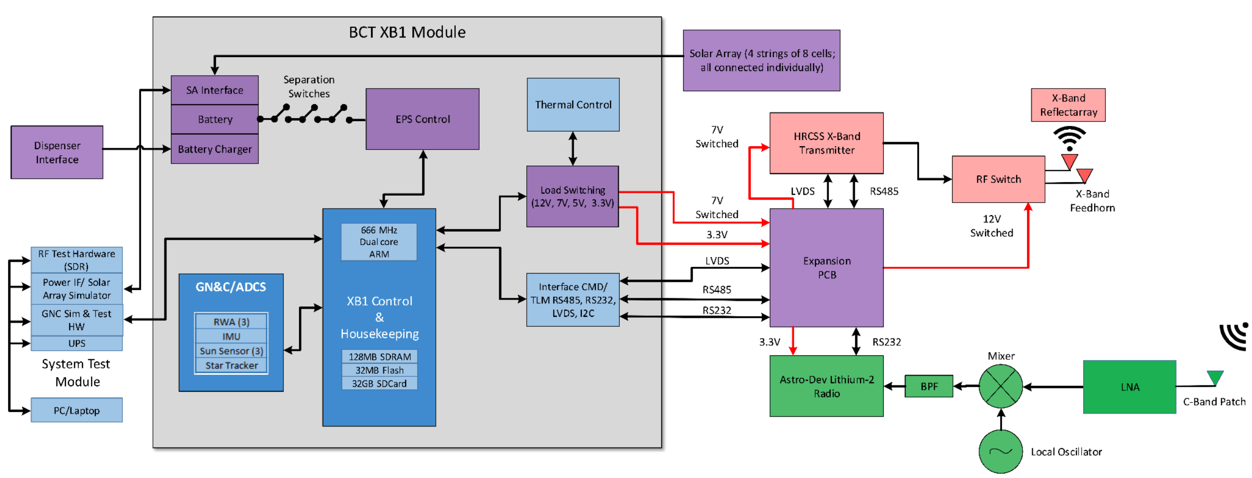

Figure 1: CU-E3 System Block Diagram. CDH and ADCS are identified in blue, EPS in purple, downlink communication chain in red, and uplink chain in green.

an Astrodev Li-2 Ultra High Frequency (UHF) transceiver. The downlink system consists of a low-cost Blue Cubed Bluefin X-Band transmitter, a medium beamwidth feedhorn antenna for initial beaconing and Earth location identification, and a high gain deployable reflectarray antenna system for low data rate communications at distances up to 350 million km from Earth.[8]

CHALLENGES AND LESSONS LEARNED

CU-E^3 encountered three primary categories of challenges: (1) Deep Space, focusing on the transition from low-earth orbit to the deep space environment, (2) the Space Launch System, related to the engineering and safety requirements of a new human rated space launch vehicle, and (3) Programmatic, focusing on schedule and budget challenges associated with the mission and the CubeQuest Challenge. The following sections describe the challenges encountered and solutions developed by the CU-E^3 team alongside suggestions for future deep space small satellites.

Deep Space

The deep space environment presents a series of challenges for small satellites and secondary payloads including trajectory complexity, vast and highly variable communication ranges, continuous solar illumination, limited magnetic field environment, and minimal Earth relative position knowledge post-deployment.[9] The CU-E^3 mission and spacecraft design sought to overcome four primary challenges associated with deep space operation: trajectory, post-deployment lost in space problem, reaction wheel saturation, and long-range RF communications.

A. Trajectory:

The primary mission defines the launch date, conditions, and initial trajectory for all secondary payloads, with orbital inclination and altitude as the principle launch constraints for Earth orbiting missions. However, the complexity of deep space trajectories for beyond earth orbit primary missions can result in significantly more varied trajectories for secondary payloads depending on launch date. Even for CU-E^3, a mission with a simple trajectory requirement of reaching 3 million km from Earth, Artemis-1 launch dates separated by only a week resulted in trajectories with maximum distances from Earth ranging from 10 to 100 million km and highly varied sun probe earth (SPE) angles, as shown in Figure 2. As the primary mission trajectory constraints were undefined for Artemis-1 secondary payloads, the potential trajectory variance was challenging to characterize.

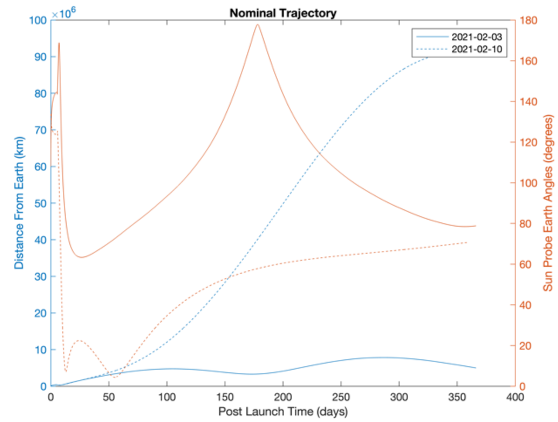

Figure 2: Nominal CU-E^3 trajectories for launch dates of 2021-02-03 and 2021-02-10. Different launch dates result in significant separation in maximum distance from Earth as well as SPE angle.

The central CU-E^3 trajectory lesson learned is that while orbit design can be a limited timespan activity for earth orbiting missions, deep space secondary payloads must retain trajectory team members throughout the mission lifetime to account for the potential impact of launch date changes. Additionally, geometry optimization for the relative pointing of antennas, solar panels, and science instruments is significantly more difficult for deep space missions than earth orbiting missions, increasing the value of independently steerable systems. Future deep space rideshare opportunities should consider communicating primary mission trajectory requirements to allow secondary payloads to derive trajectory bounds.

B. Lost-in Space Problem:

A follow up to the deep space trajectory challenge for beyond earth orbit small satellites is the lost in space problem, or the lack of absolute position and time knowledge post deployment. Without position and time knowledge, deep space satellites are typically unable to immediately identify the Earth or other targets for communication or plan trajectory maneuvers, with the difficulty of the challenge increasing as time between launch and deployment increases.

Post-deployment, the CU-E^3 spacecraft is designed to enter a lighthouse beaconing mode, rotating through the ecliptic plane with a large beamwidth antenna.[10] With repeated ground station passes tracking CU-E^3, the angular location of the spacecraft could be identified, allowing for initial commanding and commissioning of the spacecraft. For positioning, CU-E^3 tested methodologies for calculating range from RF power measurements, two-way time of flight measurements, and code-division multiple access ranging.[6] The CU-E^3 initial concept of operations can be leveraged by any mission with limited out of ecliptic plane motion and demonstrate the value of higher beamwidth, lower gain antennas even for deep space missions.

Future deep space rideshare vehicles should consider providing absolute time/position estimates immediately prior to deployment for use by the secondary payload or allowing secondary payloads to fly an ultra-low current real-time clock powered by a super capacitor or small battery. However, these solutions do provide additional safety hazards, with a portion of the payload being powered on while integrated into the launch vehicle. Other potential solutions center around the use of optical landmarks, such as Jupiter and its moons, for absolute position and time identification.[11]

C. Reaction Wheel Saturation:

Small satellites in Earth orbit leverage the Earth's magnetic field for attitude control as well as reaction wheel desaturation with permanent magnets and magneto torquers, respectively. The lack of a strong magnetic field in CisLunar or deep space greatly reduces the application of these technologies, driving deep space satellites to instead employ reaction wheels and propulsion systems for attitude control and desaturation. To overcome this challenge, missions have been investigating the use of Solar Radiation Pressure (SRP), in which the torque generated between the spacecraft center of pressure and center of mass is leveraged to reduce momentum buildup. SRP was first proven for small satellites by the MARCO mission, which leveraged both SRP and cold gas thrusters for reaction wheel desaturation.[12]

CU-E^3 is believed to be the first deep space small satellite spacecraft designed to desaturate its reaction wheels solely through the use of SRP. Future missions, and especially missions with extended transit times to final mission destination, can leverage SRP to retain additional delta-V for trajectory maneuvers to extend maximum target distance, open up missions to different deep space launch vehicles or primary mission trajectories, and extend mission lifetimes. To maximize the value of solar radiation pressure desaturation, the relative position of the center of pressure and center of mass must be a spacecraft design driver, and articulating deployables, such as solar arrays or antennas, provide the largest amount of flexibility for solar radiation pressure desaturation attitudes.

D. Communication

Deep space small satellite communication presents a series of challenges including vast and widely varying operating ranges, frequency licensing, and ground station capabilities and availability.

The communication distances and associated RF free space path loss for beyond earth orbit small satellites (> 350,000 km altitude) relative to Low Earth orbit (< 500 km altitude) small satellites drive deep space communication systems to operate at higher frequencies with larger gain antennas at lower data rates.[9] Additionally, widely varying spacecraft range throughout a deep space mission introduces complexities as the satellite and ground stations must adjust data rates, power output, and/or antenna gain to accommodate significant link budget changes as the free space path loss evolves throughout a mission. Finally, there are limited commercial ground stations with apertures and power amplifiers designed to support deep space satellites, and those that do exist are typically not licensed to support deep space small satellites.

Prior to CU-E^3, the majority of University of Colorado Boulder CubeSats operated in the Amateur radio UHF band, which has limited applicability in CisLunar or Deep Space due to the increased free space path loss. By developing a C-Band to UHF downmixing system and employing a flight heritage UHF transceiver, the CU-E^3 team was able to shift to a higher operating frequency while balancing hardware risk, development time, and deep space frequency licensing challenges. Additionally, the shift from UHF to C-Band allowed for high EIRP ground stations designed to support high data rate geostationary satellite communication to be utilized, reducing satellite uplink antenna gain requirements and licensing complications.[13]

The CU-E^3 mission is licensed to downlink in the Deep Space band at 8447.6 MHz through the Bluefin transmitter. Operating at X-band allowed for frequency licensing coordination with the JPL DSN, reduced signal wavelength and therefore antenna dimensions, and leveraged the reflectarray antenna and Bluefin low-cost X-Band transmitter initially developed at the University of Colorado Boulder. Future missions should continue to develop antennas that utilize the dispenser volume restricted to external components and deployables.

CU-E^3 partnered with ATLAS Space Operations for X-Band ground station support. Beyond the high frequency and high gain antenna systems necessary to support deep space link budgets, there were several software and concept of operations challenges to extend the commercial ground station capabilities to deep space. The pass planning software had to be updated to move from Two-Line Element driven passes to azimuth and elevation angle commands to ensure accurate tracking of CU-E^3 beyond Earth orbit. Additionally, extensive compatibility testing was required to optimize the software defined radio demodulator for a wide variety of data rates that are representative of communication from distances between 350,000 km to 100 million km. The number of commercial X-Band ground stations prepared to support deep space small satellites continues to grow, but future missions must be aware of the additional capabilities needed by commercial ground stations to support deep space missions.

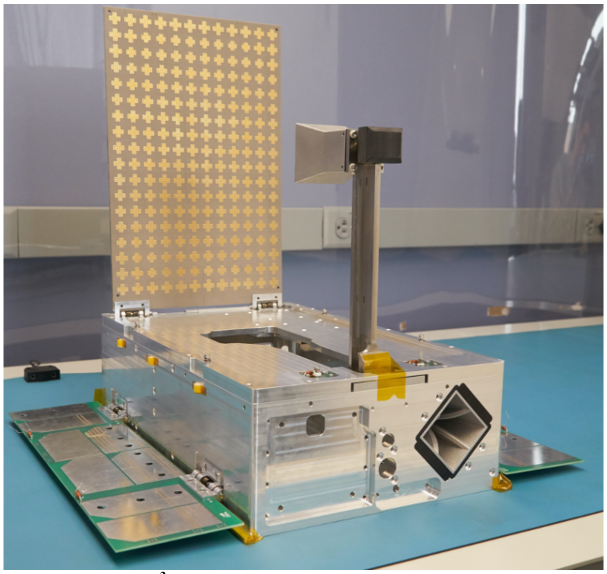

Figure 3: CU-E^3 Spacecraft with Deployed Reflectarray and Feedhorn Antenna System.

Space Launch System

The NASA Space Launch System is a new exploration class launch vehicle designed to provide deep space launch capabilities and transport astronauts to the Moon and Mars.[1] The SLS and the Artemis-1 mission represent one of the first secondary payload rideshare opportunities for small satellites to reach deep space. As one of the payloads originally manifested for Artemis-1, the CU-E^3 mission encountered several challenges related to the newly developed deep space launch vehicle as well as safety challenges related to being a secondary payload on a human-rated space launch vehicle.

A. New Deep Space Launch Vehicle:

Secondary payloads on deep space rideshare launch vehicles have significantly different launch experiences than earth orbiting SmallSats. These challenges include the widely varying trajectory and lost-in-space problems mentioned previously as well as environmental conditions within the launch vehicle itself.

The SLS was initially slated for launch in 2018 and has experienced schedule delays for a variety of reasons, including the COVID-19 pandemic, which further exacerbated the challenges related to deep space secondary payload trajectory design. The primary lesson learned by CU-E^3 is that deep space secondary payloads must be prepared for significant launch delays due to the limited number of launch opportunities, while also retaining team members to support system aliveness tests, dispenser integration, and trajectory design. With the structure of the CQC focused on in-space performance-based prizes, CU-E^3 found it difficult to retain funding and personnel throughout mission delays, indicating that for citizen scientist and academic organizations, additional front-loading of prizes/funding could be valuable.

The SLS has a secondary payload compartment capable of hosting up to 13 secondary payloads directly between the Orion spacecraft and the interim cryogenic propulsion stage (ICPS). Early in the mission design lifecycle, CU-E^3 made the decision to be deployed approximately 5 days post launch. However, eventual thermal analysis completed by NASA in 2020 indicated that the secondary payload storage areas could be exposed to extreme high and/or low temperatures well outside the survival temperature range of the CU-E^3 batteries. Because of this, CU-E^3 reduced the launch to deployment timespan down to two days while seeking to balance the ability to leverage the primary mission lunar gravity assist with the risks of potential lunar impact and thermal environments rendering the satellite damaged prior to deployment.

Future deep space launch vehicles with rideshare capabilities should consider incorporating environmental control capabilities into the secondary payload storage area to ensure payload survivability, as recommended by the Arizona State University Deep Space Summit participants.[9] Allowing secondary payloads to remain attached to the launch vehicle for extended periods will further shield payloads from the harsh space environment and allow missions to better leverage the primary mission trajectory to reduce overall propellant requirements. The reduction in propellant requirements can assist SmallSats to continually reduce the size of deep space small satellites, allowing for a greater number of systems to be deployed, and potentially pushing towards more highly distributed systems capable of high temporal and spatial resolution measurements as seen with swarms in the Earth atmosphere.

Due to the increased risk prevention posture of all human space rated hardware, it may not be reasonable for the SLS to support such an environmental control system.

B. Safety:

As a human-rated space vehicle designed to deliver astronauts and human space flight hardware to deep space, the SLS has an extremely low risk posture, which required Artemis-1 secondary payloads to complete a rigorous safety process consisting of hazard identification, hazard control development, and verification.

In general, most academic CubeSats face the largest challenges completing software development. However, the CU-E^3 team found the SLS safety process to require as much time as designing, testing, and integrating the entire spacecraft. CU-E^3 found that supporting simultaneous hardware development as well as safety verification required a large supplementary safety team headed by an experienced graduate student team member as students lack sufficient time to concurrently progress both spacecraft development and safety paperwork. It is important that future missions understand the complexity of the safety hazard identification, control development, and verification procedures to properly allocate budgetary and personnel resources.

Future deep space launch vehicles without the focus on human systems should consider reducing safety requirements relative to the SLS, which in turn would reduce the overall cost of deep space small satellites and significantly ease development complexity for citizen scientist and academic organizations.

Programmatic Challenges

Several programmatic challenges faced by the CU-E^3 project are discussed below. Note that the following is not an exhaustive list, but a selection of the most prominent challenges experienced.

CQC Challenges

A. Budget:

As previously stated, one of the goals of CQC was to see if groups outside of NASA could design, build, and fly a 6U CubeSat that could enter lunar orbit and/or provide error-free communications from deep space. As such, the selected projects did not receive any funding from NASA beyond what was awarded during the ground tournament stages of the competition, where CU-E^3 was awarded a total of approximately $80k. This lack of a funding base meant that CU-E^3 had to rely upon donated funds, components, and services to fulfill the mission requirements. Not being a paying customer meant a lack of priority/leverage over the entities donating to the project, which, in turn, did affect CU-E^3's ability to acquire components and technical information from the donating entities. In retrospect, the competition may be more suited for startup environments that had access to venture capital or other sources of funding than for academic teams. It is therefore proposed, for any future CQC competitions, that more of the prize money be allocated to teams during the ground tournament section(s) to help with the funding issues.

CU-E^3 did have extra space in its 6U form factor that could have been sold to an outside payload as a way to garner more funds for the project. However, with the original tight schedule of delivery and schedule slips given in increments of months, there was no time between 'expected' delivery dates to explore adding an outside payload. There was not enough time after an announced delivery slip for CU-E^3 to locate a paying customer, define all the interfaces of the proposed payload, update the CU-E^3 design to accommodate the payload, and to regenerate, resubmit, and receive all the necessary safety documents and approvals. These time constraints between the repeated shifting of the schedule precluded CU-E^3's ability to approach other sponsors about flying an auxiliary payload.

B. Schedule:

Additionally, to stay ahead of the shifting delivery dates CU-E^3 team members had to focus on tasks on the critical path that immediately precluded integration or delivery. As a result, it was difficult to recruit and train new team members as there was insufficient time and resources to complete the needed design tasks and get new people onboarded. However, this postponement of training of new members proved to be detrimental in the long run as the schedule continued to slip since the team was then not able to leverage one of the largest advantages of an academic CubeSat project, namely free student labor.

C. Safety Requirements:

As mentioned previously, the NASA safety requirements proved to be an exceptionally challenging part of the CQC. There was an enormous onus on the team just to navigate the SLS safety processes and list of deliverables that needed to be submitted. The amount of time and effort needed to meet all of the SLS safety requirements easily eclipsed the number of people-hours spent developing the satellite hardware.

An academic setting where student turnover is a constant made it even harder to get through the safety requirements. The knowledge and work needed to meet safety requirements reinforces that an environment where staff is consistent would be more successful. There was a CQC expectation that an academic team could successfully navigate and complete the unexpectedly vast NASA safety requirements. This expectation was found to be extremely difficult to meet by the CU-E^3 project.

Additionally, the safety requirements increased the difficulty of acquiring hardware through donations and partnerships. Hardware provided at reduced or no cost to academic organizations is typically accompanied by limited paperwork. Working to define the composition, design, and functions of donated hardware to meet safety requirements required additional time and dissuaded potential partners concerned about loss of intellectual property.

Academic Challenges

A. Student/Project Relationship:

How students participate on an academic project is challenging. There are several ways that students worked on CU-E^3 project. Some participated through enrollment in a class, others were volunteers, and a few key personnel were funded for their participation. All three of these methods have advantages and disadvantages from both the students' and academic institution point of view. For example, requiring the students to enroll in the associated class gives the academic side some leverage in terms of assignments that must be completed, grading, etc. However, the same arrangement allows the student to cut ties to the project cleanly after the semester's requirements have been met, which is often an abrupt parting of ways. Compensated help suffers from similar issues when funding runs out for the student. Volunteers can work well, especially if they are enthusiastic about the project. However, a significant percentage of volunteers leave the project as the semester progresses and other priorities arise, making volunteers an unreliable source of project help.

The challenge for the project becomes how to get student buy-in to the project such that they want to participate. Students participating through enrollment in a class must not see their efforts simply as a class with assigned deliverables, while volunteers must see project participation as a task worthy of their time. Therefore, it is up to the project to create a symbiotic relationship between the project and the students that benefits not only the project and current students, but future project team members as well.

B. Needed Skill Sets:

Another programmatic issue that occurred was the lack of certain, needed, skill sets among members of the project team. In the case of CU-E^3, the project is administered through the Aerospace Engineering department's Graduate Projects class, so finding certain aerospace engineering skills, such as orbital dynamics, project management, or systems engineering was not difficult. However, the CU-E^3 project required expertise in areas such as RF communications, for example, a skill set that is not easily found in the department. There was a similar issue when it came to finding participants with strong thermal analysis skills and expertise. These missing skill sets created a void in the required knowledge base for the satellite that needed to be filled, which in turn provided the opportunity to gain experience and new skills. However, it was often difficult for a student to take on an area well outside their major and comfort areas.

C. Continuity:

Continuity is always a challenge faced by projects when working with students in an academic setting. As students progress through their academic careers, they obtain working knowledge of a project. However, this expertise is not easily, or often, transferred to the next group of incoming students when the advanced students graduate and move on to industry. The result is a loss of the gained knowledge which often needs to be re-acquired by newer students, slowing down overall project progress.

Making it easy for incoming students to learn what has already been accomplished is important to avoid repeated work. It has been seen that if a new student is unable to figure out what the previous team has done the new student finds it easier to throw out existing work and redesign in a manner they understand. Thus, work gets repeated.

Several methods to preserve this knowledge across student changeover have been used, including students keeping a design notebook that can be examined and kept behind, students participating in mid- and end of semester reviews requiring them to summarize what they have learned and are working on. Reviews require the less experienced students to be present so the information can be passed on at these meetings. However, often these reviews are completed by the senior members of the team and knowledge is not disseminated to the newer team members.

Another knowledge retention method is to have students complete an end of semester report, akin to a term paper in other classes. The report needs to detail what they have accomplished and learned throughout the semester, the status of the system/subsystem when the semester started, i.e. need to study and understand what has been done already so they know where to pick up, what the student did during the semester to further their part of the design, and a summary of the system in its current state that is appropriately written targeting a newcomer as the audience.

None of the methods have been proven to be the ultimate solution, and a combination of these and other techniques may work the best. For CU-E^3 in particular, the safety requirements and process added an additional entry knowledge barrier for new team members.

D. Block/Wiring Diagrams:

One way that proved to be helpful in creating project/student symbiotic relationships and increase buy-in was for the students to understand the big picture of what they are working on. The tool that proved to be most helpful in this aspect was having updated system block diagrams, and later wiring diagrams available to team members. These diagrams allowed participants to not only see the big picture, but it also gave students a way to understand how their efforts would be used to complete the project and instilling in them a level of need and/or pride that helped to motivate their work.

The diagrams used in CU-E^3 started out as simple block diagrams showing the various subsystems and components that comprised the satellite, as shown in Figure 1. As the design and interfaces were further refined, the block diagram gave way to a more comprehensive wiring diagram, as shown in Figure 4. The wiring diagram not only allowed new students to see the whole satellite design, it also impressed upon them the amount of work and detail that had already been completed. Finally, the wiring diagram, shown below, was referenced often and proved to be indispensable during system integration as well as safety verification testing.

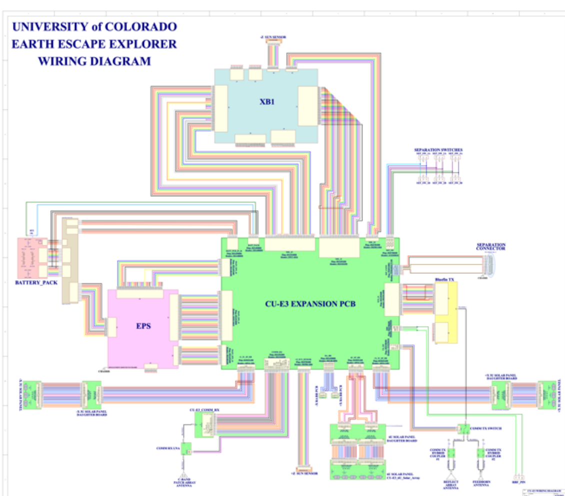

Figure 4: CU-E^3 System Wiring Diagram. Contains connector part numbers, pin and wire assignments, and voltage and current levels.

CONCLUSIONS

With the advancement of the NASA "Moon to Mars" plan and newly developed deep space launch vehicles, including the SLS, Falcon Heavy, and Firefly Alpha, small satellite lunar and deep space launch opportunities will continue to grow over the next decade. This paper worked to identify the opportunities and challenges associated with a deep space small satellite as well as citizen scientist/academic organizations participating in a NASA sponsored deep space competition.

Challenges identified included limited initial funding, widely varying trajectory and link budget characteristics, and safety requirements for a new human space rated launch vehicle. Solutions include high gain deployable reflectarray antennas, separate engineering and safety teams headed by experienced team members, and detailed system diagrams for onboarding student team members. Overall, the experiences, failures, and solutions identified by the CU-E^3 mission can be leveraged to ensure the success of the next generation of deep space small satellites.

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References

1. Robinson, Kimberly F., and George Norris. "NASA's Space Launch System: Deep-Space Delivery for Smallsats." *Annual AIAA Space and Astronautics Forum and Exposition 2017*. No. M17-6183. 2017.
2. Cockrell, Jim, et al. "NASA Cube Quest Challenge: Citizen Inventors Advance CubeSats into Deep Space on 2018 EM-1 Mission." 2016.
3. NASA Centennial Challenges in Collaboration with Ames Research Center. "Cube Quest Challenge Ground Tournaments, Deep Space Derby, and Lunar Derby Operations and Rules". 2020.
4. Hyde, Liz, and James J. Cockrell. "NASA's CubeQuest Challenge: Ground Tournament 4 Results and Technology." *Annual Conference on Small Satellites*. No. ARC-E-DAA-TN45532. 2017.
5. Zucherman, Aaron, et al. "Cislunar Explorers: Lessons Learned from the Development of an Interplanetary CubeSat." *34th AIAA/USU Conference on Small Satellites*. 2020.
6. Wallace, Brodie T., Scott E. Palo, and John Sobtzak. "The University of Colorado Boulder Earth Escape Explorer CubeSat: Mission Overview and Status." *AIAA SCITECH 2022 Forum*. 2022.
7. Dahir, A., Sandberg, A., & Mason, J. "Advancement, Testing and Validation of an Innovative SmallSat Solar Panel Fabrication Process". SmallSat Conference. 2017.
8. Palo, S., O'Connor, D., DeVito, E., Kohnert, R., Crum, G., & Altunc, S. (2014). "Expanding CubeSat

capabilities with a low cost transceiver”. SmallSat Conference. 2014

9. Aaron Zucherman, et al. “Interplanetary CubeSats: Summary of the Current Thinking, Approaches and Lessons Learned”. ASU Deep Space Summit. https://www.asudeepspacesummit.org/. 2022.

10. Dahir, A., et al. “Forgoing Time and State–The Challenge for CubeSats on Artemis-1”. Journal of Small Spacecraft, Vol. 10, No. 2, pp. 1049–1060. 2021.

11. Dahir, Andrew. *Lost in Space: Autonomous Deep Space Navigation*. Diss. University of Colorado at Boulder, 2020

12. Klesh, A., Baker, J., and Krajewski, J. "MarCO: Flight review and lessons learned." SmallSat Conference. 2019.

13. Withee, Sarah, et al. "Closing the deep space communications link with commercial assets." 2019.