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The Colorado Ultraviolet Transit Experiment: Integration, Testing, and Lessons Learned on a NASA Astrophysics CubeSat

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ABSTRACT

The past few years of space mission development have seen an increase in the use of small satellites as platforms for dedicated astrophysical research; they offer unique capabilities for time-domain science and complementary advantages over large shared resource facilities like the Hubble Space Telescope, including: (1) low cost and relatively quick development timelines; (2) observing strategies dedicated to niche but important science questions; and (3) ample opportunity for students and early career scientists and engineers to be involved on the front lines of space mission development. The Colorado Ultraviolet Transit Experiment ($CUTE$) is a NASA-supported 6U CubeSat assembled and tested at the Laboratory for Atmospheric and Space Physics within the University of Colorado Boulder. It is designed to observe the evolving atmospheres on short-period exoplanets with a dedicated science mission unachievable by current and planned future space missions. $CUTE$ operates with a bandpass of $\sim$2487 − 3376 Å and an average spectral resolution element of 3.9 Å. The mission launched in September of 2021 and is in the process of conducting transit spectroscopy of approximately one dozen short-period exoplanets during its primary mission. This proceeding describes the overall $CUTE$ satellite program, including the mission development integration and testing, anticipated science return, and lessons learned to improve both universities' and commercial companies' ability to create and collaborate on successful academically and research-focused small satellite missions. While CubeSats are becoming increasingly accessible and utilized for scientific research and student education, $CUTE$ serves as an example that university small satellite programs have specific needs to successfully and efficiently achieve both scientific and educational elements. These include (1) a minimum threshold of commercial-off-the-shelf product quality, performance, and support; (2) specific and timely guidelines from launch service providers regarding launch readiness and delivery requirements; (3) and sufficient funding to provide multi-disciplinary engineering and program management support across the developmental life-cycle of the mission.

1 Introduction

Over the preceding two decades, exoplanet science has made great strides in identifying the occurrence, location, and orbital parameters of exoplanets, and has begun to extensively study their atmospheres in order to understand their diversity and evolution. An atmosphere can be characterized by transit spectroscopy, the process of studying the time-varying stellar spectrum as it is absorbed by a transiting planet's atmosphere. Photometric light curves (the star's brightness profile over time) created with broad photometric bandpasses in the optical and near-infrared (e.g., the objectives of Kepler,[1] TESS,[2] CHEOPS,[3] WASP,[4] KELT[5]) probe the opaque body of the planet and usually display transit depths of at most just a few tenths of a percent. Light curves created using tens of Å-wide bands isolating specific atoms and molecules tend to have larger transit depths; they trace the planet's atmosphere, can serve as a proxy for relative atmospheric abundances, and overall reveal a rich diversity of planetary compositions, dynamic features, and processes. In extreme cases atomic-transition light curves can have transit depths on the order of ten percent or more.[6]

Atmospheric escape, when the planet's atmosphere is driven outside of the planet's gravitational boundary via thermal, photochemical, or ionic interactions, is a fundamental process in planetary evolution. Relatively small rates of escape have been observed on planets within the solar system. Direct evidence of escaping exoplanet atmospheres is seen on planets undergoing hydrodynamic escape, a kind of thermal escape where stellar heat and wind inflates a exoplanet's atmosphere potentially past the exoplanet's gravitational Roche Lobe. The signal is evident in deep transit light curves of wavelengths which correspond to neutral and ionized atomic species at very high altitudes. To date, only a handful of exoplanets (out of the more than 5000 confirmed exoplanets) have shown evidence of hydrodynamic escape, and most current evidence comes from ultraviolet (UV) observations with the UV channels on the Cosmic Origins Spectrograph (COS)[7,8] and Space Telescope Imaging Spectrograph (STIS)[9–11] on the Hubble Space Telescope (*HST*), *HST*'s Wide Field Camera 3 Ultraviolet Imaging Spectrograph G280 Grism,[12,13] and The Neils Ghrels Swift Observatory's Ultraviolet UV/Optical Telescope UVOT.[14,15]

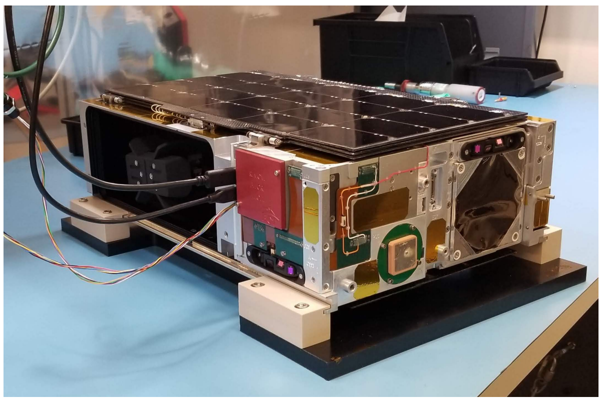

Figure 1: The *CUTE* spacecraft with solar panels stowed and charging cables attached, sitting in LASP laboratories.

The Colorado Ultraviolet Transit Experiment (*CUTE*) (Figure 1) was developed to utilize UV observations to characterize atmospheric properties. The first NASA grant-funded CubeSat for UV/Optical/IR astrophysics and the first dedicated spectroscopic exoplanet mission, *CUTE* was designed to measure the near-ultraviolet (NUV) transmission spectra of ∼10 short-period exoplanets around nearby stars to characterize their atmospheric shape, size, and composition. The *CUTE* CubeSat is part of a larger trend to utilize small spacecraft as follow-up and monitoring missions for discoveries made with large shared-resource facilities like the HST and the James Webb Space Telescope (JWST).

CUTE was developed at the Laboratory for Atmospheric and Space Physics in the University of Colorado, Boulder. Over the course of four years, more than 20 early career students, scientists and engineers had a hand in helping *CUTE* become flight ready and operate in space. Parsons Corporation, contracting for the US Space Force, served as the Launch Service Provider (LSP). *CUTE* launched out of Vandenberg Space Force Base on September 27th, 2021 as a secondary payload on the Landsat 9 launch. A thorough overview of the *CUTE* mission is provided in France et al 2022 (ApJ, in-prep). This proceeding is concerned with the integration and testing (I&T) procedure of the flight payload and spacecraft with notes about lessons learned; it is organized as follows: Section 2.1 provides and overview of the instrument design; Section 2.2 describes the spacecraft bus; Section 3 details the integration and environmental testing for both the spacecraft as a whole and the optical system as it related to the spacecraft; Section 4 provides a summary of the delivery and first ground station contact post-launch; Section 6 concludes.

2 Spacecraft and Instrument Description

The *CUTE* mission comprises a near-ultraviolet telescope and spectrograph integrated into a Blue Canyon Technologies (BCT) XB1 6U spacecraft bus, shown as a CAD model in Figure 3. The instrument and spacecraft are each given an overview in this section.

2.1 Instrument Description

The *CUTE* instrument, shown in Figure 2, is a rectangular Cassegrain telescope and a compact, low-resolution near-ultraviolet spectrograph (R $\sim$ 750, $\lambda \sim 2487 - 3376$ Å). The primary mirror is 206 mm × 84 mm; the secondary mirror and spectrograph are coupled together through a hub mounted off of the primary mirror central aperture. A bistable shutter was installed at the entrance to the spectrograph. It was powered with a fail-safe such that it would automatically close if the instrument ever lost power in order to prevent stray sunlight from entering the spectrograph and damaging the detector.

With the shutter open, light from the secondary mirror bounces off of a fold mirror towards the Cassegrain focus, located at the center of a slit. Light is then is diffracted off a holographically ruled diffraction grating from JY-Horiba, focused by a cylindrical fold mirror, and the spectra are recorded on an e2v CCD42-10 UV-enhanced CCD with a 515 × 2048 array of 13.5 μm pixels.[16] The slit is 18′ tall in projection with three different widths (120″, 60″, and 30″), has a reflective substrate, and is mounted at a 45° angle at the Cassegrain focus. Any light that strikes the slit's substrate is directed down a slitjaw tunnel and exits through a small aperture in the spacecraft's baseplate; that aperture was used during instrument testing in conjunction with an aspect camera and was covered with a closeout panel before delivery to the LSP. A baffle is epoxied inside the spectrograph to mitigate stray light from reaching the detector. A thermal stackup consisting of a thermo-electric cooler (TEC), copper heatsink, and a copper strap couples the detector to a radiator panel on an external spacecraft surface.[17] A more detailed instrument description can be found in Egan et al. 2020.[18]

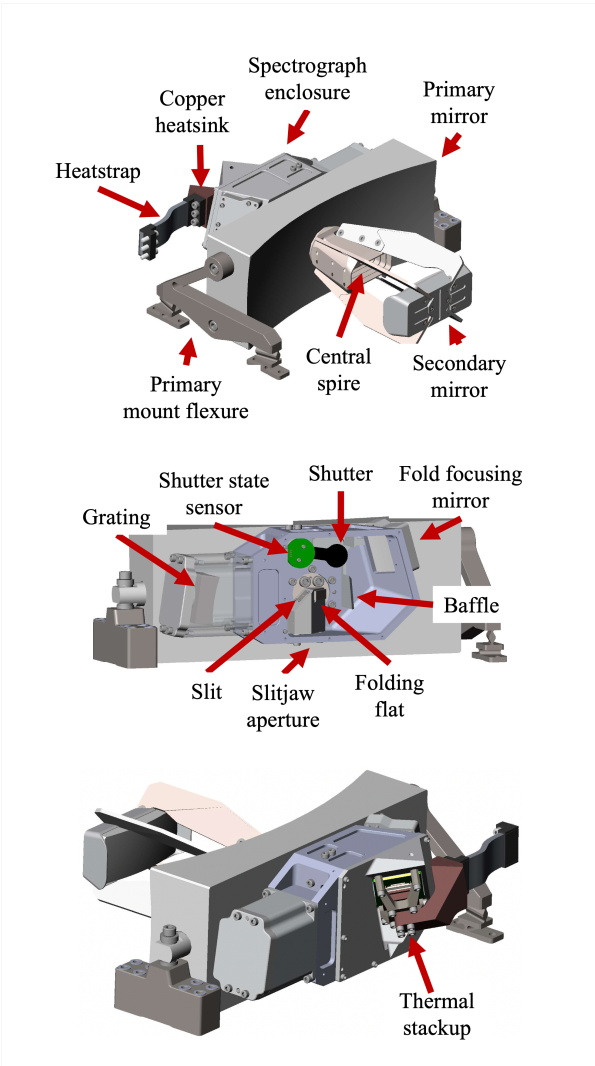

Figure 2: CAD rendering of the *CUTE* instrument. Top panel: Angled front view of the primary mirror, the secondary mirror cantilevered in front, the spectrograph on back, and the heatstrap coming off the spectrograph. Middle panel: Transparent rendering of the spectrograph to make internals visible. Bottom panel: Opaque view of the spectrograph on the pack of the primary mirror.

The telescope was manufactured by Nu-Tek Optical Corporation and was vibration tested before delivery to 14.1 G_{rms}, as standardized in NASA's Goddard Space Flight Center (GSFC) General Environmental Verification Standards (GEVS).

2.2 Spacecraft Description

The *CUTE* payload is hosted in an XB1 spacecraft bus provided by Blue Canyon Technologies (BCT), designed to be accommodated by a Planetary Systems Corporation (PSC) launch dispenser. At the time of the mission's proposal, PSC dispensers were one of the more common dispensers available; it was chosen in an attempt to maximize *CUTE*'s launch opportunities. Given the long lead time of the spacecraft bus and science payload hardware, compatibility with a specific dispenser had to be selected prior to manifest.

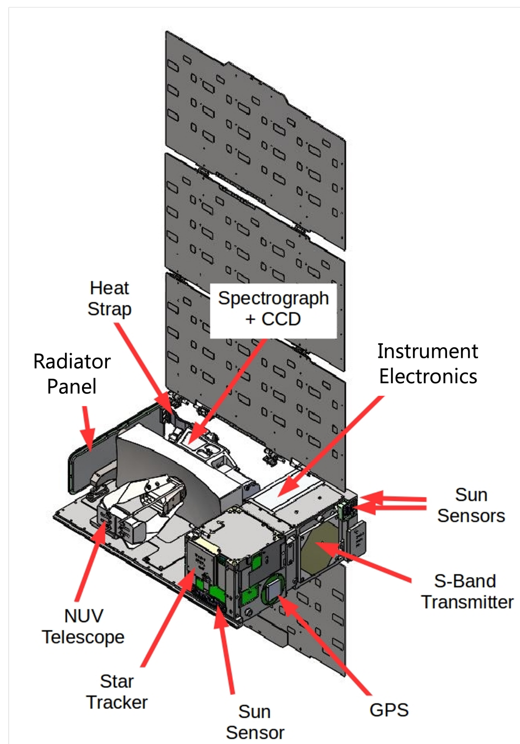

Figure 3: CAD rendering of the *CUTE* spacecraft. The top and side panels are removed to reveal the internals. Not pictured is the UHF antenna, which is located on the bottom of the spacecraft. Reaction wheels, star tracker, and batteries are located in the 2U avionics section.

The XB1 provides: power with 4 solar panels and 6 batteries; the attitude determination and control system (ADCS) with torque rods, reaction wheels, sun sensors, a GPS patch, a single star tracker offset from the telescope boresight by 10° in the pitch direction; and radio up and downlink capabilities with a SpaceQuest TRX-U and BCT S-band radios.

The solar panels are split 3:1 (Figure 3). A single solar panel is mounted on the bottom of the baseplate with the solar cells facing outward. When stowed it holds the UHF antenna flush to the baseplate and when released the UHF antenna simultaneously deploys. The three panel solar array section is mounted above the payload chamber and folds down in an accordion style so that, when stowed, the solar cells face outward. The solar-cell outward stowing scheme was chosen so the solar panels could charge the spacecraft in the event they did not deploy.

All bare external spacecraft surfaces were covered with reflective aluminized kapton tape to assist with spacecraft cooling.

3 Integration and Testing

CUTE underwent a series of component-level testing and spacecraft functional and environmental tests to ensure survival through launch and estimate performance in a space-like environment. Each of these tests is described in more detail below, but in general the order is as follows: component level testing of key science payload hardware (e.g., telescope focus, diffraction grating efficiency, CCD detector characterization), optical focusing and alignment to spacecraft; spacecraft functional performance; vibrational testing; post-vibrational optical measurements and alignment; thermal vacuum deployment and day-in-the-life (DITL) operational tests; and comprehensive performance testing (CPT) including end-to-end radio tests.

3.1 Optical focusing and alignment to spacecraft

The *CUTE* instrument was focused in the University of Colorado Long Tank Facilities[19] integration with the spacecraft. The fold mirror described in Section 2.1 focuses the spectrograph via three set screws and three adjustment screws. A Hg penray served as the light source and an Astronomical Research Cameras Gen III Controller[i] (sometimes called a Leach Controller) provided the readout for the CCD. Details of this focusing process can be found in Egan et al. 2020.[18] The final empirical pre-flight resolving power was R $\sim$ 1500.

After the instrument was focused it was integrated into the spacecraft and measured the star tracker/telescope boresight offset (Section 2.2). While it is nominally 10° in the spacecraft pitch direction, the offset can vary on the order of arcminutes in both pitch and yaw due to tolerances in telescope installment and launch vibration-induced shifts. We measured the offset to (1) measure the induced shift in alignment due to testing and launch vibration and (2) assist in adjusting pointing commands by the appropriate offset once in flight. The spacecraft was installed on a mounting plate with pitch and yaw actuation (Figure 4) and we positioned the spacecraft such that collimated light beam was (1) focused at the Cassegrain focus and (2) with in the star tracker field of view. The difference of those two measurements provides the offset. This test was repeated after the spacecraft underwent its vibrational test to capture any vibrational-induced changes in the offset, as well as to provide an estimate for the magnitude of shift we could expect due to launch. Pre-launch, the offset magnitude was about 39.6 arcminutes. After scanning the instrument across a bright calibration star, the offset magnitude was measured to be about 43.9 arcminutes, or about a 4.3 arcsecond change from pre-launch measurements.

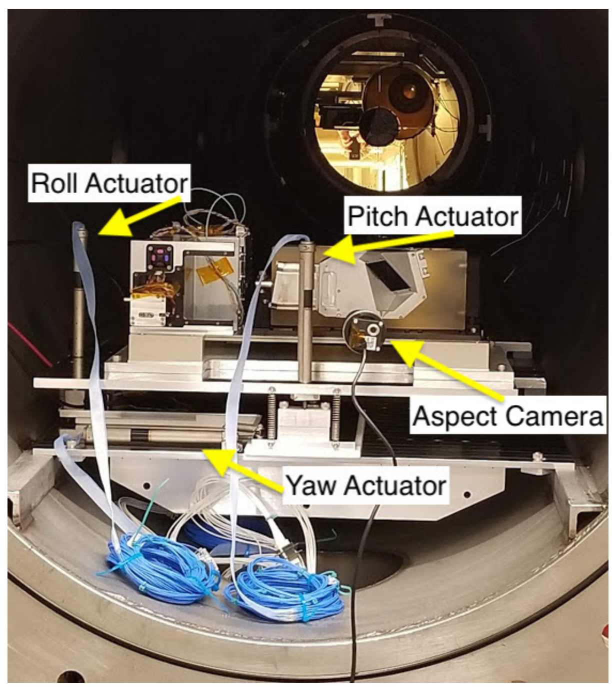

Figure 4: View of the telescope and XB1 2U avionics section mounted in the CU Long Tank. The mount plate has three actuators, labeled pitch, yaw, and roll. An aspect camera sits below the spectrograph to image the slit. The 2 foot diameter collimating mirror is seen in the back of the chamber.

[i]https://www.astro-cam.com/

3.2 Spacecraft Functional Testing

Spacecraft functional tests involve ensuring the spacecraft starts up correctly, can acquire GPS signal, set proper time, and enter the proper operating mode when required. We used COSMOS[ii] and a BCT-supplied Real-Time Dynamics Processor (RDP) to simulate the spacecraft in orbit and send commands to the XB1. OASIS-CC (Operations and Science Instrument Support - Command and Control) is a LASP-developed and maintained software used to decode and display telemetry and send commands to the spacecraft during both launch and I&T.[20] Comprehensive performance tests (CPTs) involved a few different tests designs. A baseline test included basic XB1 functionality and nominal currents, voltages, battery discharge rates, reaction wheel rates, and sun sensor functionality; a comprehensive test included the previous tests as well as long duration testing to ensure all safe-mode and spacecraft reset triggers fired as expected.

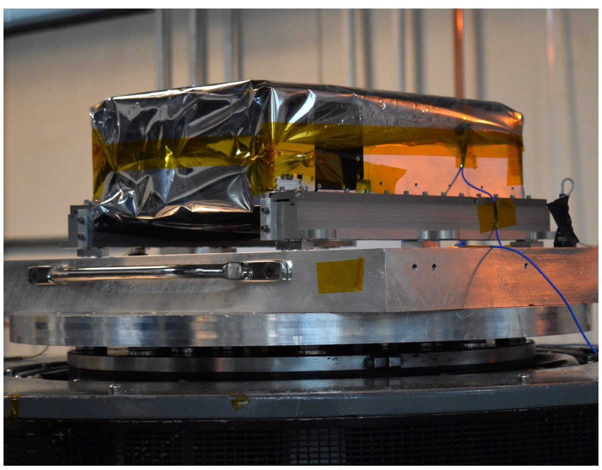

Figure 5: The *CUTE* Spacecraft on a vibration table at Element Material Technologies. The spacecraft was covered in anti-static bagging to mitigate damage to the spacecraft electronics.

The COVID-19 shutdowns induced a significant loss in personnel time in the lab. One consequence is that XB1 laboratory testing was delayed by about 12 months while essential mission personnel conducted other instrument testing and calibration activities. During the 12 month storage period, the XB1 batteries suffered chemical damage and required replacing. A work contract was set up in April 2021 in order to replace them.

3.3 Vibration Testing

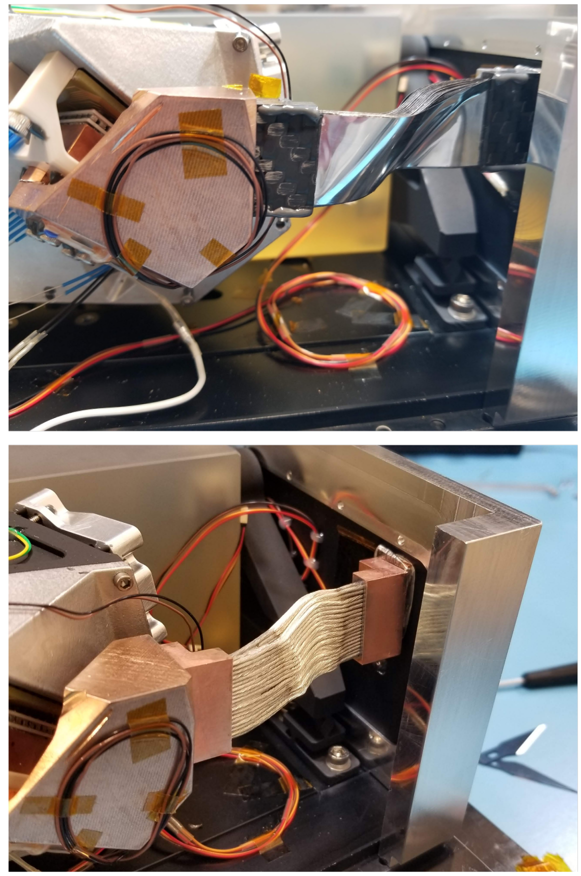

Figure 6: Top: The ThermalLynx heat strap, permanently twisted after the second vibration test. Bottom: The new heat strap made of 38 copper braids.

The original Interface Requirements Document (IRD) guidelines provided by the LSP stipulated a vibrational profile of half GEVS in all three axes. *CUTE* underwent vibrational testing at Element Material Technologies in Longmont, CO. We conducted the test by starting the power at -12dB, ramped up in power by 3dB until the highest level was reached, held that level for 60 seconds, and repeated in all three spacecraft axes (Figure 5). A post-vibrational functional and optical test was considered a success as the instrument did not display any significant changes in spectral resolution during post-vibrational and end-to-end optical testing; the spacecraft CPT passed nominally.

However, after the first vibrational test, NASA and the LSP determined that the original IRD vibrational test profile was incorrect and under-calculated. A new launch vehicle vibrational model

[ii] https://www.ball.com/aerospace/programs/commercial/cosmos

run by GSFC and the LSP required us to run a second vibrational test with higher levels in two of the three spacecraft axes. As these new requirements were levied on the instrument team less than three weeks prior to the payload delivery date to the LSP, a second full vibration test was quickly arranged. This introduced 10 more days into the schedule and resulted in delayed delivery to the launch site, in addition to some hardware damages that could not be fixed due to the schedule constraint.

During the second vibration test, the secondary mirror and spectrograph rotated within the primary mirror, an over-test risk the experiment team was concerned about. While this did not affect the optical performance, the rotation damaged the heatstrap by partially removing it from its housing, reducing the thermal conductivity to a level unsuitable to cool the CCD and thus rendering the thermal strap unusable (Figure 6). With no time to order a second heatstrap, we instead fabricated a new one out of two custom-machined copper end pieces in the same style as the ThermalLynx strap, and 38 silver-coated copper braids. A side by side comparison of each heatstrap is shown in Figure 6.

Including the launch itself, the spacecraft underwent vibration three times, with the telescope experiencing a fourth vibration due to the manufacturer's pre-delivery vibration test.

3.4 Thermal Vacuum Testing

Thermal vacuum testing involved two major events: solar panel deployment at hot, cold, and room temperatures, and payload operation during thermal cycling. Solar panel deployment occurred in the MOBI vacuum chamber within LASP facilities. We chose to test deployment at -15°C, 20°C, and 45°C. The XB1 deploys the solar panels 30 minutes after the deployment switch is released; the single solar panel is released first which subsequently frees the UHF antenna and allows it to beacon a state-of-health and identifying packet at 16 second intervals. About 5 seconds later, the three panel section deploys.

Thermal cycling was a two week test using COSMOS to simulate DITL spaceflight while in LASP's Bemco thermal vacuum chamber. UHF and S-band hats were placed over the antennas to allow for radio communication (Figure 7), and an uncollimated Hg penray was placed in front of the telescope to illuminate the instrument with in-band light. A solar array simulator was used to simulate day-side solar panel charging and night-side battery-driven operation. We practiced sending commands, receiving and decoding telemetry, and taking and downlinking CCD images.

The uncollimated light source did not produce a star-like spot but instead fully illuminated the slit, serving as an acceptable method to verify the shutter actuated properly.

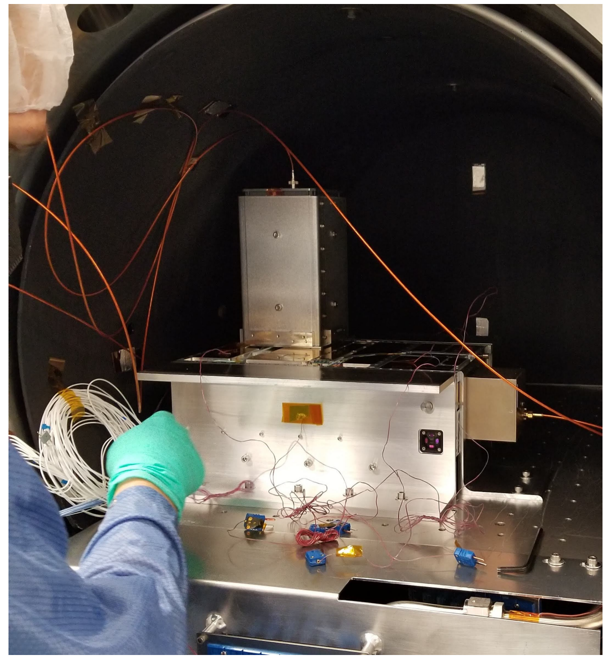

Figure 7: ***CUTE*** **installed in the Bemco thermal vacuum chamber at LASP. Hats are placed over the S-band and UHF antennas.**

Early in thermal cycling, the TEC failed. The schedule did not allow time to implement a fix the mission's active cooling plan was descoped to passive cooling, discussed in Section 4.

3.5 End-to-End Testing

Final end-to-end testing occurred within the last few days before delivery wherein we verified the spacecraft reaction wheel phasing and conducted an at-distance radio operational test. A single-axis air bearing and a heliostat were used to verify that the XB1's sunsensors could identify and lock up on the sun's location. *CUTE* was placed in two orientations to test out two of the three axes. The layout of hardware on the spacecraft's external surfaces prevented efficient testing of the third axis.

Outdoor radio tests were conducted at the Scenic Overlook on US 36 in Louisville, CO, just southwest of Boulder. A polycarbonate box housed *CUTE* and protected it from the environment for the few hour duration of the test. The box was oriented to point the S-band antenna at the LASP ground station (Figure 8). We conducted the baseline CPT test and downlinked a few images over the S-band antenna. The single solar panel deployed was enough to keep *CUTE* power-positive for the duration of the test, though we did periodically place a shade over the box to prevent spacecraft temperatures from rising above 45°C.

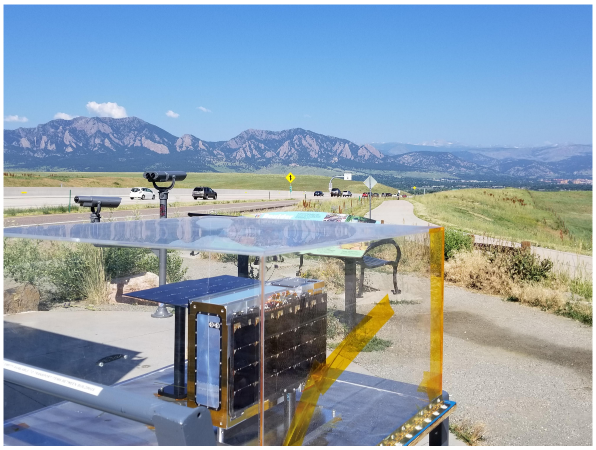

Figure 8: The outdoor radio test. ***CUTE*** **is mounted inside a polycarbonate box to protect it from dust and pollen. The single solar panel is deployed to free the UHF. The S-band antenna is aimed at the LASP ground station. The Flatirons are in the background.**

4 Delivery, Launch Summary, and Nominal In-flight Behavior

CUTE was delivered to Vandenberg Space Force Base on July 23rd, 2021 and integrated into a Planetary Systems Corporation dispenser (Figure 9). A few days before launch, *CUTE*'s lead electrical engineer (EE) worked with the SatNOGS community to schedule 6 hours of observations with the SatNOGS ground station network.[iii] The team's lead EE also worked with the founder of gr-satellites to establish a Grafana telemetry dashboard.[iv] Both of those tools were paramount establishing prompt communication with *CUTE* post-launch.

The launch occurred on September 27th at 11:11 am Pacific Time on an Atlas V 401 rocket carrying the NASA GSFC Landsat 9 mission.[v] *CUTE* was deployed about 2 hours after launch, and roughly 35 minutes after deployment, a ground station in Italy picked up *CUTE*'s beacons; telemetry graphs on the SatNOGS Grafana dashboard indicated nominal spacecraft health. A discussion thread about the Landsat 9 launch on Libre Space[vi] provided the *CUTE* operations team with the most accurate TLE at the time of our first contact: 8:30pm Mountain Time at the LASP Ground Station in Boulder Colorado. The TLE was further honed over the next few days. *CUTE*'s final orbit is a 10am/10pm sun-synchronous orbit with an average altitude of 553.8 km and an inclination of 97.6°; about half of the orbit is sun-side and half is eclipsed by Earth.

Commissioning activities took place over the next several months: The XB1 performance was mostly verified for the first few weeks and payload calibration followed. While detailed mission commissioning activities can be found in Suresh et al. 2022 (in prep), a few points are listed below.

In the first few months of operations, two spacecraft anomalies appeared: one to do with the radio and one with pointing. It was found that the UHF and S-band radios cannot simultaneously request data from the payload data buffer as this causes the spacecraft to transfer fill-frames only to the S-band link, rather than science data. As we were otherwise operating normally with indications that science observations were proceeding as planned, it took about three weeks to determine the cause of the fill-frames and that manually resetting the spacecraft also resets the buffer. After setting up a support contract with BCT to investigate, they confirmed that the radio buffer issue was a possibility and verified that the documentation provided to us did not describe this potential issue.

Occasionally in orbit, the spacecraft will experience a loss of attitude during spacecraft charging periods, likely owing to Earth occultation of the single star tracker. *CUTE* cannot begin to slew to the target until it regains attitude, usually as it comes out of eclipse. During this loss of attitude, the spacecraft can drift into non-optimal thermal orientations and heat the CCD up to 8°C higher than with stable attitude control. A support contract was initiated to diagnosis this problem, and it was determined that, when on the sun side, the star tracker is unable to view enough stars to determine its attitude. Changing the spacecraft orientation to place more stars in the tracker's field of view while maintaining the solar panels are pointed at the sun may reduce the number of attitude losses. The *CUTE* team is experimenting with this at the time of this proceeding's

[iii] https://community.libre.space/t/request-to-add-cute-to-the-satnogs-db/8446
[iv] https://dashboard.satnogs.org/d/XfQj4RD7z/cute
[v] https://www.usgs.gov/landsat-missions/landsat-9
[vi] https://community.libre.space/t/atlas-v-401-landsant-9-2021-09-27-18-12-utc/8454

publication.

Instrument commissioning revealed additional damage to the TEC electronics board, specifically to one of the three voltage buses. The damaged board caused the spacecraft to spontaneously reset within a few hours of being powered. An immediate fix was to not supply 12 V to the TEC board. However, the 12 V line also powers the shutter; with this unpowered, the shutter-closed fail-safe (Section 2.1) prevented the shutter from being opened. A workaround was devised to power the TEC board, open the shutter, and remove 12 V power from the board slowly, so as to drain the fail-safe capacitor of enough charge such that the shutter could not actuate when power was fully removed from the board. This successfully occurred during a 10 minute long daytime pass in November 2021 and the shutter is now permanently open in flight.

Figure 9: Two *CUTE* team members (left and center) place the *CUTE* spacecraft on the conveyor to be installed in the PSC canister in Vandenberg Space Force Base.

5 Lessons Learned

This section summarizes the lessons learned throughout the mission development and operation, as well as additional programmatic considerations future investigators may find useful in developing their own lower-cost, highly educational, and scientifically successful small satellite missions:

1. A minimum threshold of commercial-off-the-shelf product quality, performance, and support: The BCT spacecraft is performing nominally in space, but the several issues faced post bus delivery (battery damage, radio buffer, loss and/or revalidation of attitude) were unanticipated, undocumented, and accrued additional costs to correct. Future missions may want to consider the breadth of "warranty" services provided by spacecraft vendors to accommodate otherwise expensive support contracts required by unforeseen or undocumented hardware behavior.

2. Specific and timely guidelines from launch service providers: the last-minute change in vibration profile after *CUTE* had successfully passed the original requirement caused real damage to the payload without allowing sufficient time for repair. Small satellite missions are often inexpensive and run by small teams; LSPs should finalize mission readiness requirements early in the mission to ensure payload teams can finalize design and testing to meet requirements. If the small satellite is launching as a secondary payload, launch readiness requirements should be designed to levels that are no greater than "do no harm" to the primary launch payload.

3. Sufficient funding to provide multidisciplinary engineering and program management support across the development life-cycle of the mission: CubeSats require significantly more management full-time-equivalents (FTEs) than "true suborbital" (balloon/rocket) missions because the spacecraft bus, communications, operations, and all subsystems are managed by the experiment team rather than a program office.

4. The delivery of the spacecraft bus was delayed by approximately one year. This late delivery, in combination with time lost due to COVID, induced responsibility pile-up on members of the experiment team later in the mission. Staggering engineering hires in real-time with hardware delivery can introduce schedule, work-load, and budget flexibility in otherwise low-cost short-duration missions.

5. Coordination with SatNOGS has been essential in providing round-the-Earth monitoring of spacecraft health and early commissioning activities. We strongly recommend collaborating with this open-source ground station community.

6 Summary and Conclusion

The Colorado Ultraviolet Transit Experiment is a 6U CubeSat obtaining near-ultraviolet transit spectroscopy of gas giants around nearby bright stars. The mission was delivered approximately four years from the start of funding (including 16 months of pandemic-related impacts), launched on September 27th, 2021 out of Vandenberg Space Force Base, and is successfully undergoing its primary science mission.

This proceeding described the spacecraft and instrument design and the overall testing and integration process. We outlined the more serious changes to instrument performance that occurred during testing (including the loss of our active cooling system and telescope shutter), and our inability to address them due to schedule strain. These schedule losses were mainly due to COVID-19, occasional unplanned loss of personnel, and last-minute changes to testing requirements from the LSP.

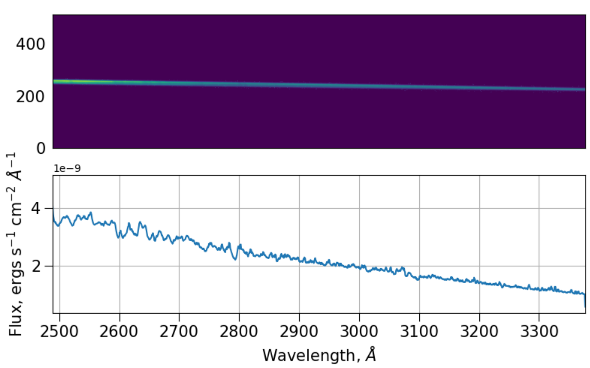

Figure 10: Top: A two-dimensional full frame (2048 x 515) CCD image of the spectrum of ζ Puppis. Bottom: One-dimensional flux-calibrated spectrum for ζ Puppis. Archival *HST* and *IUE* data were used for flux calibration.

However, the *CUTE* mission is an overall success, and a first-look two-dimensional CCD image and one-dimensional spectra for ζ Puppis, a *CUTE* calibration star, is shown in Figure 10. *CUTE* is part of NASA's suborbital program with an approach akin to the NASA Sounding Rocket Program; *CUTE* was able to produce a fully functional and scientifically capable satellite mission effectively on the budget of a sounding rocket payload. The suborbital program is also one wherein educational and training opportunities are paramount to a successful mission. The four years of mission development and current operations are replete with training opportunities and student involvement: Two PhD students, two postdoctoral researchers, an early-career PhD and now current P.I., two post-bachelors' engineers, and four undergraduates have spent *at least two years* on the mission. Six undergraduate students additionally contributed to various laboratory and science activities. *CUTE*'s operations team further included two graduate students and two undergraduate students. Over the course of the whole mission, *CUTE* has provided mentorship, training, and support for more than 20 students and early career researchers and engineers.

The *CUTE* CubeSat is a unique spacecraft among CubeSats with an instrument the first of its kind. The compact instrument design has been emulated by the SPRITE[21] mission and *CUTE*'s observing and scheduling strategy is being utilized by the Pandora[22] mission. We have acquired more than 1.2 Gb of science data since launch at the time of this publication. Finally, the mission's pre-launch activities' student involvement exhibits the rich opportunities CubeSats provide for educating the next generation of scientists and engineers.

Acknowledgments

CUTE was developed and operated with the support to two NASA/APRA awards to the Laboratory for Atmospheric and Space Physics at the University of Colorado Boulder, NNX17AI84G and 80NSSC21K1667. The *CUTE* team acknowledges the numerous invaluable discussions with colleagues about ultraviolet transit science and the potential to do science with small satellites. We extend much gratitude to the SatNOGS community for providing the antenna resources to hear *CUTE*'s beacon as fast as was possible, and for establishing a Grafana telemetry dashboard.

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