Integration and Testing of a Cryogenic Receiver for the Exoplanet Climate Infrared TElescope (EXCITE)

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ABSTRACT

The EXoplanet Climate Infrared TElescope (EXCITE) is an instrument designed to measure spectroscopic phase curves of extrasolar hot Jupiters from a long duration balloon platform. EXCITE will fly a moderate resolution spectrometer housed inside of a cryogenic receiver actively cooled by two linear pulse tube cryocoolers. Here we provide the current status of the design and performance of the cryogenic receiver, its heat rejection mechanism, and associated control electronics. A recirculating methanol fluid loop rejects heat from the cryocoolers and transports it to sky-facing radiator panels mounted to the gondola. The cryocoolers are controlled by drive electronics with active vibration reduction functionality to minimize the impact of vibrations on pointing stability. We discuss the thermal and vibrational performance of the cryogenic receiver during ground-based pointing tests in its 2023 field campaign in Ft. Sumner, NM and present its current status as EXCITE prepares for its 2024 test flight campaign.

Keywords: exoplanets, spectroscopy, atmopsheres, cryogenics, balloon-borne instrumentation, heat dissipation, vibration control

1. INTRODUCTION

The Exoplanet Climate Infrared TElescope (EXCITE) is a NASA-funded purpose-built balloon-borne instrument designed to perform phase-resolved spectroscopy on the atmospheres of extrasolar giant planets (EGPs, or "hot Jupiters").[1] These measurements consist of continuous spectroscopic observations of transiting exoplanets as they complete full orbits around their host stars, a resource-intensive process with scientifically rich results. Phase curve observations can provide insight into the atmospheric composition and energy distribution of exoplanets,

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as well as how that composition changes as a function of pressure and altitude.[3] When performed over a wide enough spectral band, they can also constrain these measurements for a planet's temperature. However, such measurements require excellent photometric stability over long observations, up to 1-3 days even for planets with short orbital periods. To achieve this, EXCITE will fly a spectrograph with resolving power $R \approx 50$ in the 0.8 - 3.5 μm band. EXCITE will observe from a stratospheric long duration balloon (LDB) platform deployed from Earth's poles. This observing platform is ideally suited for phase curve measurements. Many short period EGPs are continuously observable from EXCITE's platform, and importantly EXCITE's wide spectral band includes the peak of the planets' thermal emission spectra. Flying from above 99.9% of Erth's atmosphere, EXCITE avoids the atmospheric contamination which limits near-infrared (NIR) observations from lower altitudes.

In the following sections we will discuss the design and performance of the EXCITE cryostat and present results from the 2023 field campaign which indicate that is meets the thermal and vibrational requirements of the instrument.

2. PAYLOAD DESCRIPTION

EXCITE's science instrument (Figure 1) consists of a semi-custom Ritchey-Chrétien telescope built by Officina Stellare with a 0.5 meter diameter primary mirror and a carbon fiber baffle, and a cryogenic receiver mounted to its backplate. The instrument is housed in a gondola built by StarSpec Technologies. The gondola consists of three nested frames which rotate on nearly-orthogonal axes. The EXCITE gondola has been designed to give the telescope a pointing range of $\pm$ 50° in azimuth anti-sun and 20 - 60° in elevation, allowing it to continuously view its targets when flown near the poles.[1] This gondola design, telescope, and pointing system are based on those used for the Super-pressure Balloon-borne Imaging Telescope (Super-BIT), which achieved 0.05 arcsecond pointing stability over 90 minute integration times.[4]

EXCITE's spectrograph is housed in a cryogenic receiver which is mounted to the telescope via a "transfer box", which was generatively designed to minimize mass, maximize stiffness, and account for the thermal expansion coefficient mismatch between the aluminum cryostat and the carbon fiber back plate of the telescope. Light which passes through the telescope is directed by a piezo-actuated tip/tilt mirror to an ambient temperature dichroic, where it is split into a transmitted component (0.6-0.8 μm) and a reflected component (0.8-4 μm). The transmitted component is used by the fine guidance system to adjust the tip/tilt mirror, while the reflected component passes into a two-channel prism-based spectrometer.[11] The spectrometer utilizes a Teledyne HAWAII-2RG (H2RG) detector read out by an ASIC for Control And Digitization of Imagers for Astronomy (ACADIA) controller.

3. CRYOSTAT DESCRIPTION

The EXCITE cryogenic receiver consists of a dual-stage cryostat containing the spectrograph, H2RG detector, and ACADIA readout electronics. The first stage cools the spectrometer and ACADIA readout electronics to $\sim$ 100 K, and the second stage cools the detector to $\sim$ 50 K. A diagram of the cryostat is shown in Figure 2.

Both stages of the cryostat are cooled by Thales LPT9310 linear pulse tube mechanical cryocoolers. These cryocoolers have space flight heritage,[6] and EXCITE will be the first experiment to use them on a balloon platform. By using these cryocoolers instead of liquid or solid cryogens, EXCITE is able to reduce the mass and volume of the cryogenic receiver. Considering the amount of cryogen that would be required to keep the EXCITE cryostat at operating temperature during its prospective $\sim$ 3 week long science flight, the benefits of using mechanical cryocoolers are significant. Linear pulse tube cryocoolers also have fewer moving parts and export weaker vibrations than other cryocooler technologies such as Stirling cycle cryocoolers, which is an essential consideration given EXCITE's pointing requirements. The cryocoolers are rigidly mounted to the top plate of the cryostat by aluminum brackets which also act as heat exchangers, pictured in Figure 2. Two redundant fluid loops run through the brackets to dissipate heat from the cryocooler compressors and necks via forced convection. In flight configuration, methanol is pumped through the fluid loop and exchanges heat with aluminum panels which will radiate heat to the sky. This scheme is described further in Section 5. During lab testing when radiative cooling is not feasible, water is pumped through the fluid loops and cooled by a water chiller to facilitate convective cooling.

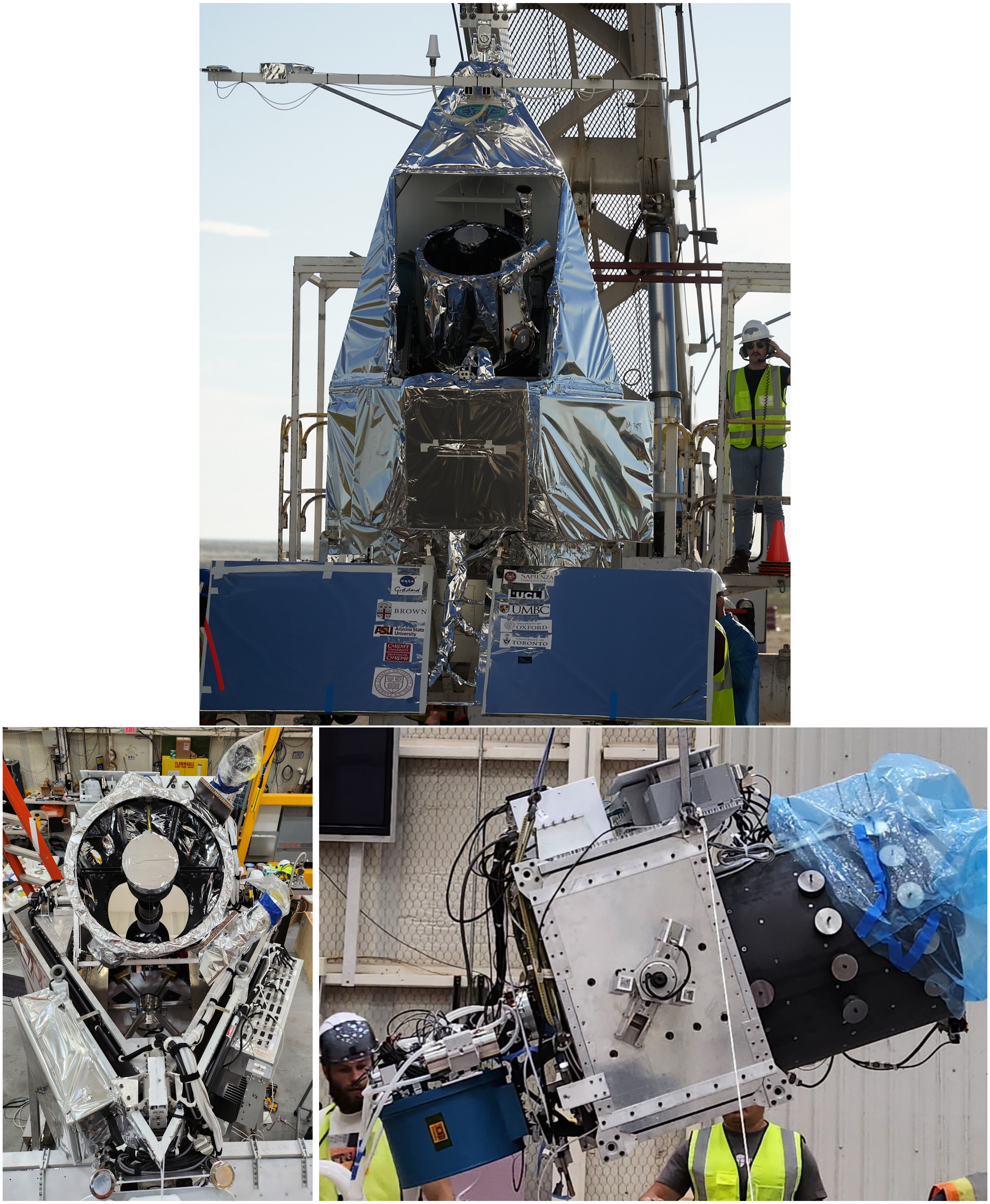

Figure 1. Images of the EXCITE payload during the 2023 campaign. Top: fully assembled payload suspended from launch vehicle. Bottom left: top-down view of partially assembled gondola with the instrument mounted in the three nesting frames. The inner frame, which holds the instrument, controls the pitch. The middle frame holds the inner frame and controls the roll. The outer frame holds the middle frame and rotates in azimuth via a pivot at the top of the gondola; its motion is controlled by a reaction wheel, which is visible below the telescope in the image. Bottom right: cryogenic receiver mounted to back of the telescope while inner frame is suspended during assembly.

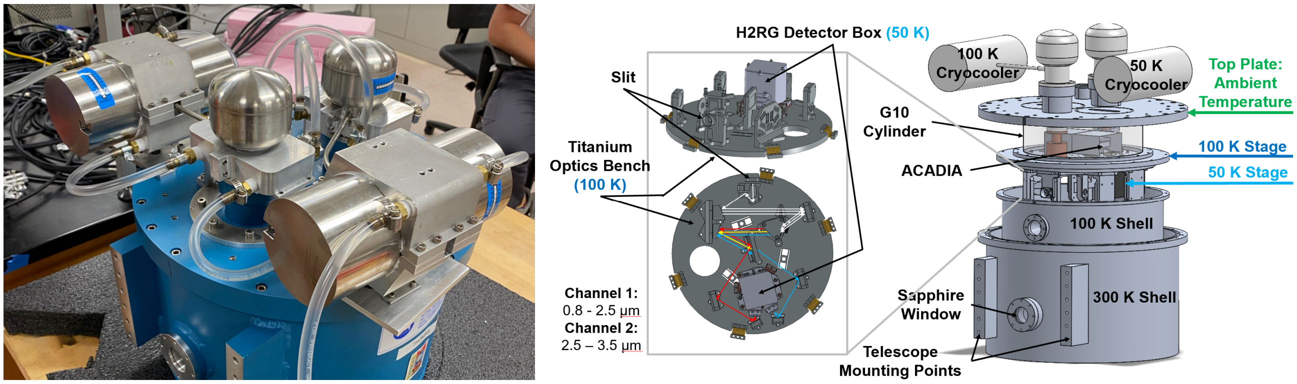

Figure 2. Image of closed cryostat (left) and diagram of cryostat and spectrometer (right). Both cryocooler compressors are held in place by aluminum heat exchangers, which are discussed along with their accompanying cooling fluid loop in Section 5.

Light enters the spectrograph via a sapphire window in the external shell of the cryostat and a light guide in the 100 K shell. The spectrograph design and status are discussed in the presentation at this conference, "Assembly, integration, and laboratory testing of the EXCITE spectrograph".[11] Both the inside of the 100 K shell and the light guide are painted with a low outgassing, high thermal absorptivity black polyurethane coating to mitigate stray light and set the spectrographs's blackbody temperature. The cold plate is attached to the top plate of the cryostat by a rigid G10 cylinder, thus isolating it thermally and maintaining mechanical stability. The ACADIA electronics read out the detector via a feedthrough electronics flange in the cold plate, which thermally anchors the cable and minimizes its thermal gradient. Both the ACADIA and the detector are independently temperature controlled to stabilize their operating temperatures. This process is discussed further in Section 4.

The performance of the EXCITE cryostat relies on minimizing the convective, conductive, and radiative heat loads between the ambient temperature shell and the cold stages, and maximizing conductive heat transfer between the cold stages and the cryocooler cold tips. The convective heat load is minimized by pumping the cryostat down to vacuum pressures prior to cooling. Once the cryostat is cooled, connection to the pump is closed off via a block valve and the cryostat holds its pressure. Cryopumping is facilitated by an activated charcoal trap which is mounted to the detector stage. When cooled below $\sim$ 77 K, the charcoal is designed to adsorb the majority of residual gasses inside the cryostat, keeping the pressure low. Multi-layered insulation (MLI) is used to cover as many surfaces within the cryostat as possible to reduce radiative heat load. Conductive heat load is minimized by choosing materials with low thermal conductance for components which must connect a cold stage to ambient temperature. This includes using a G10 cylinder to mount the cold plate to the ambient temperature top plate, and using low thermal conductance wire for all wiring inside the cryostat. Additionally, the detector stage is thermally isolated from the $\sim$ 100 K spectrograph via Kevlar suspensions. These efforts keep the thermal load on the cryocoolers low enough to reach our thermal requirements during flight.

To maximize thermal conductance where desired, cold surfaces within the cryostat were manufactured from aluminum whenever possible. This also ensures matching coefficients of thermal expansion. The optics bench holding the spectrograph is constructed from titanium, which has a low coefficient of thermal expansion and helps minimize changes to the optical path due to temperature changes. To account for the mismatch in thermal expansion coefficients between the aluminum cold plate and the optics bench, flexure mounts are used to attach the two surfaces. To improve thermal conductivity, nine copper straps consisting of ten layers of copper foil each were attached to the optics bench and aluminum cold plate at various points around its circumference (Figure 3).

Flexible copper straps connect the 100 K and 50 K cryocooler cold tips to the spectrograph cold plate and detector mounting plate, respectively (Figure 3). Each strap consists of two oxygen-free high thermal conductivity (OFHC) copper blocks with six grooves fitted for flexible copper braids, which are clamped into the grooves by a copper plate and brazed into place to ensure even thermal contact. The length of flexible braid between the

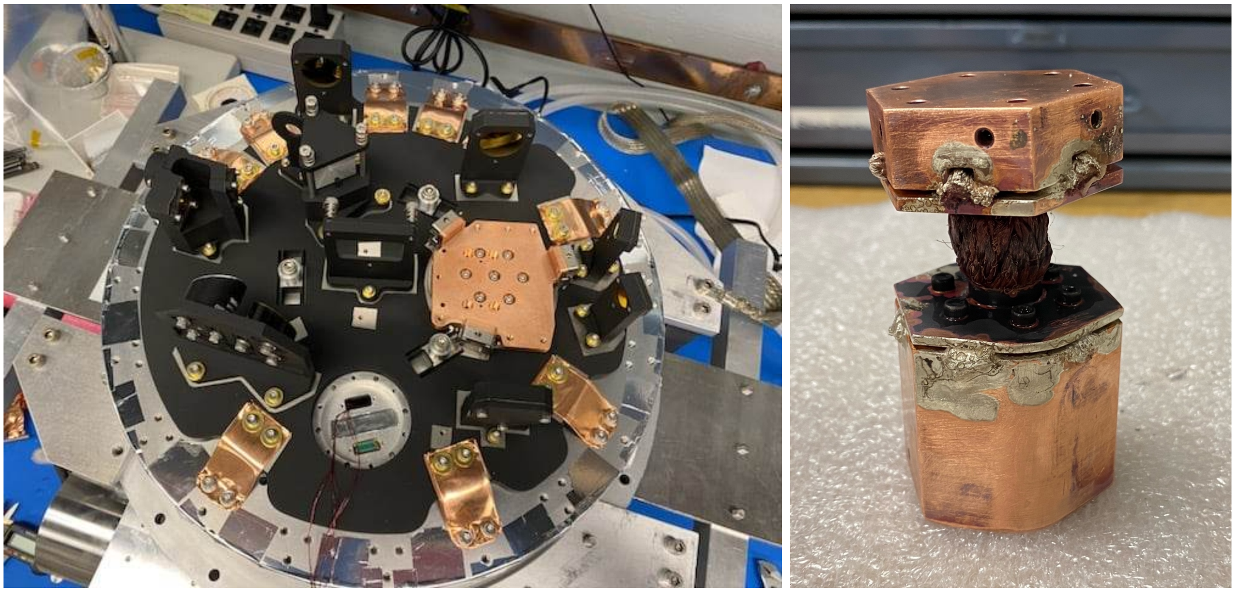

Figure 3. Images of the copper straps used to bridge thermal interfaces within the EXCITE cryostat. The titanium optics bench and aluminum cold plate are thermally connected via nine copper straps consisting of ten layers of copper foil each (left). These straps are flexible enough to accommodate mismatched thermal expansion. The 100 K cryocooler cold tip is attached to the aluminum cold plate via a flexible copper thermal strap (right) consisting of two blocks of copper with a length of flexible copper braids connecting them. This strap allows relieves strain due to differential thermal expansion while maintaining a thermal gradient of ~ 10 K between the cold tip and cold plate. The strap connecting the 50 K cold tip and detector plate is nearly identical, the only difference being the length of flexible braid between the two blocks. The thermal gradient across the 50 K strap is ~ 3 K.

two blocks minimizes the potential strain due to mismatched thermal expansion between the two surfaces. A sheet of indium foil between the aluminum cold plate and the 100 K thermal strap is used to reduce thermal resistance at this interface.

In laboratory and field tests, the cryostat was able to hold the detector stage below 65 K and the spectrograph stage below 140 K with significant margin, meeting the instrument's thermal requirements. Even while running the cryocoolers at well below their maximum power, we can achieve temperatures as low as 58 K on the detector stage and 116 K on the spectrograph optics bench.

4. CRYOGENIC CONTROL ELECTRONICS

The EXCITE cryostat is monitored and controlled by a science computer box (SCB) which interfaces with the gondola power system, internal and external thermometers and heaters, the flight network, and two cryocooler drive controllers built by West Coast Solutions. A diagram of the SCB and associated cryogenic control devices is shown in Figure 4.

The main computer in the SCB is the Cryogenic Control Computer (CCC), which is a PC/104 stack consisting of a CPU and an analog to digital (A/D) I/O board. The CCC runs continuous software which collects data from the cryogenic control devices, sorts it into a telemetry frame, and sends it along the flight network via Ethernet to be logged and processed by ground computers. It also listens for commands sent from the ground computers over the network, receives and processes them, and gives instructions to the relevant control devices. The A/D I/O board is mainly used to read sixteen platinum resistance temperature detectors (RTDs) which are mounted to key external components of the cryogenic control system. A series of DC/DC converters are used to regulate the nominal 48 V DC power provided by the gondola power system and convert it to the appropriate voltages for the cryogenic control devices. Two high power capacity DC/DC converters handle the power for the cryocooler drive electronics.

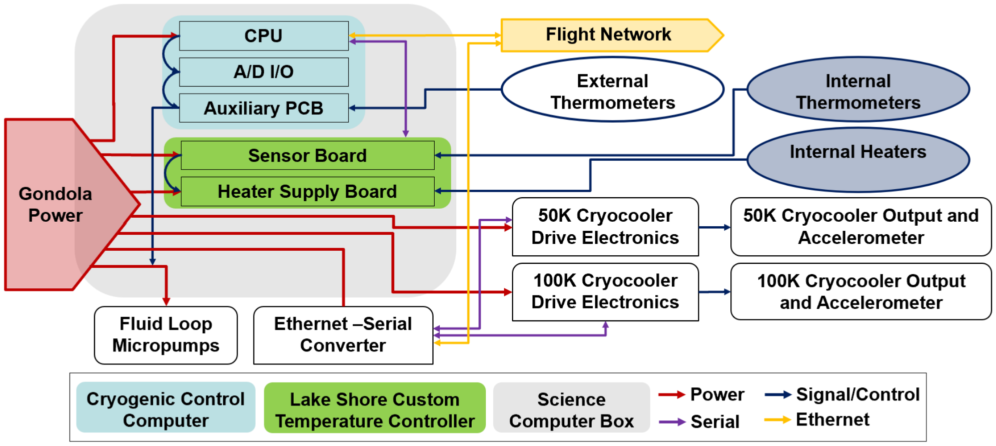

Figure 4. Diagram of the connections between the Science Computer Box (SCB) and other cryogenic control devices.

The SCB also houses a modified Lake Shore temperature controller which has been designed to function in an extended temperature vacuum environment. This device reads eight silicon diode thermometers which are mounted in key locations inside the cryogenic receiver, allowing us to remotely monitor its performance in real time. We also use two of the heater outputs on the Lake Shore temperature controller and its PID loop functionality to stabilize the temperatures of the ACADIA controller and the detector stage. With this, we are able to maintain mK-level thermal stability of these components.

The SCB interfaces with two West Coast Solutions cryocooler drive controllers. These devices feature both passive and active vibration control, and allow the cryocooler pistons to be locked for shipping and termination of the payload. We discuss the implementation and testing of the vibration control in Section 6.

5. CRYOCOOLER HEAT DISSIPATION

Each LPT-9310 cryocooler is expected to dissipate about 150 W of heat, evenly split between the neck supporting the bulb and the compressor,[7] for a total of about 300 W of heat dissipated by the cryogenic receiver. The operating skin temperature range of the cryocoolers is -40 to 71° C, however their ideal temperature is 20° C. During lab-based performance tests, we observed a decrease in cooling power as the skin temperature of the cryocooler increased past 20° C (Figure 5).

To dissipate heat and keep the cryocooler skin temperatures within operational limits during flight, two redundant methanol fluid loops run through aluminum heat sinks which are mounted to the neck and compressor of each cryocooler. Each loop then runs through copper tubing embedded in aluminum heat exchangers on the back of two 1 m^2 aluminum radiator panels which are mounted on the front of the gondola such that they will face away from the sun during flight (Figure 6). The panels are coated with silver Teflon tape to maximize reflectance in the visible range while maintaining high infrared emissivity. The methanol returns to a reservoir after being cooled by the radiator panels, and is pumped back through the loop by a magnetic drive gear pump. The methanol fluid loops effectively dissipated heat in thermal vacuum chamber tests at NASA Goddard Space Flight Center (GSFC) and in ground testing during EXCITE's 2023 campaign at Columbia Scientific Balloon Facility (CSBF) in Ft Sumner, New Mexico.

6. VIBRATION MANAGEMENT

EXCITE requires subarcsecond pointing stability over the course of 1-3 day long continuous observations. In order to achieve this, the exported vibrations of the cryocoolers and fluid pumps must be adequately controlled. The West Coast Solutions cryocooler drive electronics have the ability to passively and actively mitigate exported vibrations from the cryocoolers. To minimize crosstalk between both coolers, we operated them at 45 Hz and 49 Hz respectively, a small step away from their ideal operating frequency of 47 Hz. We noted no degradation

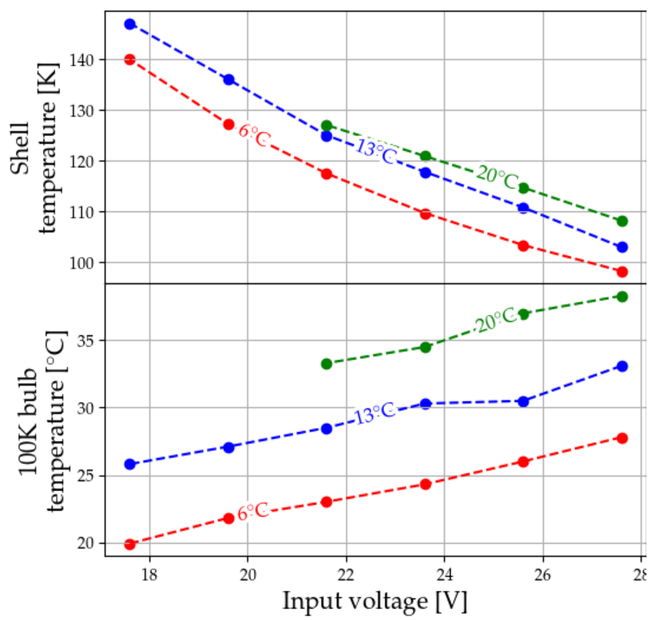

Figure 5. Plot of the temperature of the 100 K shell of the cryostat at various drive voltages during a lab test where chilled water at controlled temperatures was run through the fluid loop instead of methanol. When the fluid loop is chilled to 6° C the bulb temperature stays below 30° C at maximum drive voltage (28 V_{RMS}) and the shell temperature dips below 100 K. However when the water is only chilled to 20° C the bulb temperature rises close to 40° C at maximum drive voltage and the minimum shell temperature rises about 10 K. While the minimum temperature is still well below the flight requirement of 140 K, this change indicates a correlation between the effectiveness of heat dissipation and cryocooler performance which may be more pronounced in stratospheric conditions.

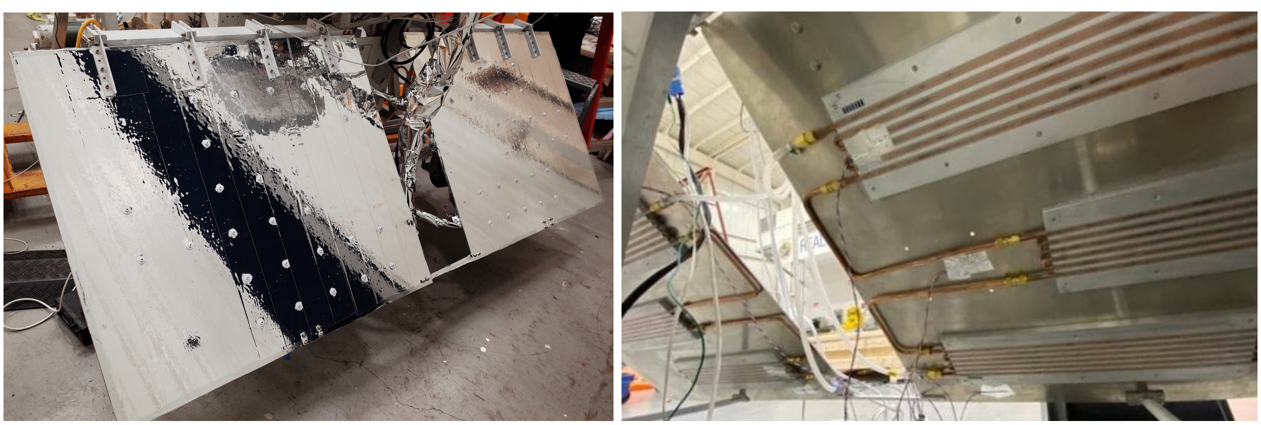

Figure 6. Image of the sky-facing side of the radiator panels (left) coated with silver Teflon tape, and the reverse side showing the aluminum heat sinks with copper tubing (right) which allow the methanol fluid loop to transfer heat to the panels.

in performance. We integrated and tested this system during the 2023 field campaign at CSBF in Ft Sumner, New Mexico and observed significant decreases in the exported vibrations read by the accelerometers in the first three harmonics (Figure 7). Vibrations in the fundamental and third harmonic were typically reduced by at least a factor of five, and in the second harmonic by a factor of ten. Simultaneous ground-based pointing tests also demonstrated that the instrument was able to achieve the desired pointing stability – these results are further detailed in the presentation at this conference, "The EXoplanet Climate Infrared TElescope (EXCITE): Gondola Pointing & Stabilization Qualification".[10]

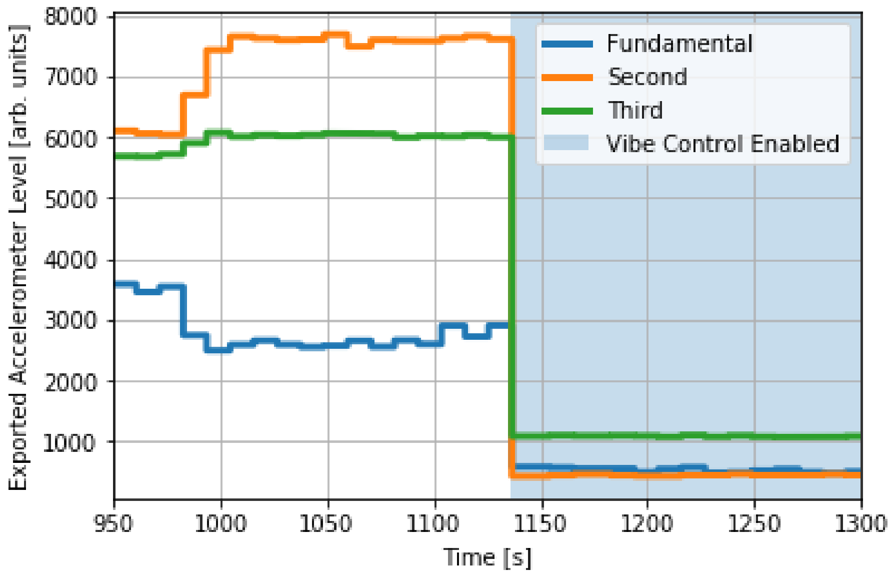

Figure 7. A plot of the exported accelerometer levels of the 50 K cryocooler in the first three harmonics before and after active vibration control was enabled on the cryocooler drive electronics. Vibration levels in the fundamental and third harmonic were reduced by a factor of five, and by a factor of ten in the second harmonic. With vibe control enabled, EXCITE is able to achieve gyro noise-limited stability.

During the upcoming 2024 CSBF campaign, EXCITE will further characterize and quantify the performance of the cryogenic system and the effect of the vibration reduction scheme on pointing stability, both during ground-based tests and a prospective test flight.

7. CONCLUSION

During the 2023 CSBF campaign, we integrated and tested the complete cryogenic system. In ground-based field tests, the cryostat maintained internal temperatures and pressures required for science operations. The 100 K spectrograph stage remained below 140 K, which is the temperature at which the spectrograph's thermal background is comparable to the signal form a dim science target. The detector stage remained below its operating temperature of 65 K, and in future tests we plan to further control this stage to achieve mK stability. During operation of the cryocoolers, the methanol fluid loop was pumped through the heat sink mounts and did not experience leaks or other mechanical issues. We have yet to have an opportunity to test the effectiveness of the radiative cooling of this system, but plan to do so in our upcoming 2024 campaign.

As described in Section 6, the cryocooler vibration reduction scheme showed promising results in field tests, both when the payload was stationary on the ground and conducting pointing tests while suspended by crane. We plan to directly quantify the effects of vibration reduction on total payload vibrations and pointing stability during our North American test flight.

After the 2023 campaign, many improvements were made to the cryogenic control electronics to make them more robust for flight. Much of the thermal wiring inside the cryostat was made more modular, as was the wiring inside the SCB. Increased functionality has been added to the CCC software to allow more complete communication with the devices necessary to control the cryogenic system.

We are looking forward to evaluating these improvements upon reintegration of the instrument during EXCITE's upcoming 2024 campaign and prospective North American test flight.

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