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The Design and Development Status of the Cryogenic Receiver for the EXoplanet Climate Infrared TElescope (EXCITE)

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ABSTRACT

The EXoplanet Climate Infrared TElescope (EXCITE) is an instrument dedicated to measuring spectroscopic phase curves of extrasolar giant planets. EXCITE will carry a moderate resolution near-infrared spectrograph and will fly on a long duration balloon mission. We give an overview of the mechanical and thermal design and development status of the EXCITE cryogenic receiver. Active cooling for the EXCITE cryostat is provided by two linear pulse-tube cryocoolers. We discuss cryocooler thermal performance, integration of the spectrometer and detector, and the mounting scheme that attaches the cryostat to the backplate of the telescope. To reject heat power from the cryocoolers, gravity-assisted copper-methanol thermosyphons will maintain cryocooler temperatures within 20 °C of ambient temperature during operation. We discuss the results of preliminary thermal modeling of the thermosyphons as well as performance testing of a prototype built for in-lab verification.

Keywords: exoplanets, atmospheres, spectroscopy, phase curves, balloon-borne instrumentation, cryogenics

1. INTRODUCTION

EXCITE (EXoplanet Climate Infrared TElescope) is a NASA-funded balloon-borne experiment that will perform phase-resolved spectroscopy of transiting extrasolar giant planets (EGPs or "hot Jupiters") in an effort to characterize their atmospheric composition, dynamics, and thermal structure.[1,2] EXCITE will carry a moderate resolution spectrograph (resolving power $R \sim 50$) that will measure spectra during entire orbital periods across

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wavelengths 0.8–4 μm at stratospheric altitudes above 99.9% of Earth's atmosphere. By targeting bright, short-period EGPs, EXCITE will observe through the peak of their spectral energy distributions (SEDs) and break degeneracies between thermal emission and atmospheric features. Phase-resolved spectroscopy helps map the pressure-temperature profiles and chemical compositions in different atmospheric layers of an EGP as a function of planetary longitude. The EXCITE instrument will fly from a long duration balloon (LDB) and observe transiting EGPs continuously during their orbits. A complete overview of EXCITE is described in these proceedings by Nagler et al.[3]

2. PAYLOAD DESIGN

The EXCITE science payload consists of a semi-custom Ritchey-Chrétien telescope with a 0.5 meter diameter primary mirror from Officina Stellare housed inside a gondola constructed by StarSpec Technologies, Inc. The gondola, telescope, and pointing system are based on the design used for the Super-pressure Balloon-borne Imaging Telescope (SuperBIT), a balloon experiment which achieved 0.05 arcsecond pointing stability during 90 minute integration times.[4] When flown from near the poles, EXCITE's science targets are continuously observable with the instrument. Fig. 1 shows a CAD model of the EXCITE payload including the gondola, telescope, and cryogenic receiver. The cryogenic receiver is attached to the telescope through a "transfer box" optimized for low mass, high stiffness, and to match the coefficient of thermal expansion of the telescope back plate. The passband of the instrument is 0.6–4 μm. A piezo-actuated tip/tilt mirror receives the incident light from the telescope and points it towards an ambient temperature dichroic. The dichroic splits the incident beam into a transmitted component (0.6–0.8 μm) and reflected component (0.8–4 μm). The transmitted component is used by the fine guidance system, and the reflected component is directed towards the spectrometer. The spectrometer uses a Teledyne H2RG[*] HgCdTe detector and an ACADIA[†] controller.[5] An overview of the spectrometer is described in these proceedings by Bernard et al.[6] Fig. 2 shows the transfer box attaching the cryogenic receiver to the telescope as well as the tip/tilt stage and ambient temperature dichroic.

3. OVERVIEW OF THE CRYOGENIC RECEIVER

Fig. 3 shows the EXCITE cryostat and the two cryocoolers. EXCITE will be one of the first balloon-borne experiments to use the Thales LPT9310 cryocoolers. Compared to other cryocooler technologies like Stirling cycle coolers, pulse-tube coolers have fewer moving parts and generate weaker exported vibrations. From a preliminary analysis of the vibrations expected from these coolers, using both elastic and rigid body models, we expect no degradation to EXCITE's pointing stability. Each cryocooler has an expected drive frequency of 47 Hz and will be equipped with an accelerometer that enables active vibration reduction. Using cryocoolers instead of a liquid cryogen cooling system reduces the mass, volume, and complexity of the receiver at a moderate cost, making EXCITE a suitable platform for advancing the technology readiness of infrared space instrumentation while still meeting the baseline science goals. The resulting compact design minimizes the differences between SuperBIT and EXCITE, allowing EXCITE to leverage the SuperBIT platform's extensive flight heritage.

Fig. 4 shows an exploded view of the EXCITE cryogenic receiver. Light enters the cryostat through a sapphire window. There is a LPT9310 cryocooler dedicated to cooling the spectrometer to 100 K. The ACADIA controller is thermally stood off from the 100 K stage by G-10 fiberglass posts to self heat to a somewhat higher temperature; the ACADIA has its own thermal control system to maintain sub-Kelvin thermal stability. The other cryocooler cools the H2RG detector to 50 K. The estimated net heat loads on the 100 K and 50 K cryocoolers are 4.9 W and 0.06 W, respectively. A thermal performance study of the LPT9310 by Johnson et al. (2014) shows that the cryocoolers meet the estimated heat lift requirements.[7] At 20 °C, the expected ambient temperature during flight, they found that the LPT9310 can maintain a 100 K stage with a 9.5 W heat load and maintain a 50 K stage with a 1 W heat load.

[*]**H**AWAII (HgCdTe Astronomical Wide Area Infrared Imager), **2**048x2048, **R**: reference pixels, **G**: guide-window capabilities

[†]**A**SIC for **C**ontrol **A**nd **D**igitization of **I**magers for **A**stronomy

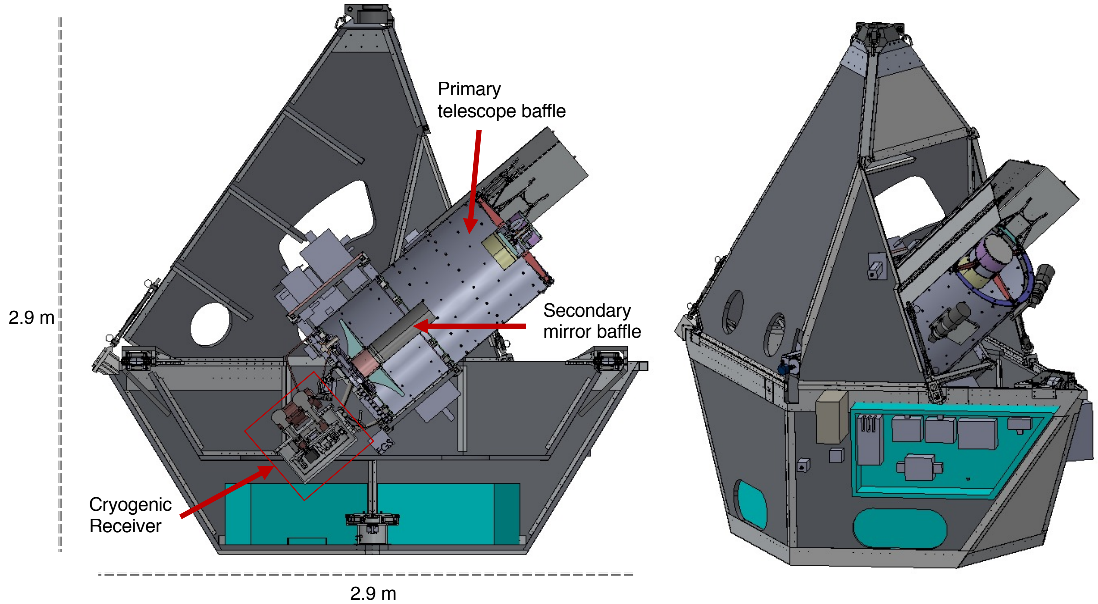

Figure 1. The EXCITE science payload. The gondola consists of three nested frames that control nearly-orthogonal axes. The science payload is supported by the inner frame, which achieves line-of-sight stability of < 1 arcsec RMS. Further improvements to the pointing stability are accomplished via a piezo-actuated tip/tilt mirror with feedback from a star camera, resulting in 50 mas RMS stability at the focal plane. The telescope azimuth range is ± 45 degrees anti-Sun, and its elevation range is 22–57 degrees.

4. THERMAL MANAGEMENT

There are two locations on the cryocoolers which require heat rejection: the necks and compressors. Fig. 4 shows these locations on the cryocoolers. A study on the heat rejection from the LPT9310 cryocoolers was done by Paine (2014) and shows that the fractional heat rejected by the cryocoolers as a function of input compressor power is roughly equal between these two locations.[8] The power dissipated at each of these locations is expected to be ~75 W for a total of ~300 W between the two coolers. The cryocoolers require an operating skin temperature between -40 and 71 °C. Typical allowable skin temperatures during flight are 0–40 °C. The EXCITE heat dissipation design uses gravity-assisted copper-methanol thermosyphons that transfer heat from evaporator ends, which are attached to the compressors and necks, to condenser ends, which are attached to aluminum radiator panels. The efficiency of this passive cooling system depends on the surface contact area at the evaporator ends and the radiating solid angle of the aluminum panels at the condenser ends. For in-lab use of the cryocoolers, a chilled water fluid loop is used.

Fig. 2 shows the telescope, transfer box, cryogenic receiver assembly with the heat dissipation system. The thermosyphons extend from the cryocoolers to cantilevered radiator panels at the end of the primary telescope baffle tube. Although the thermosyphons are gravity-assisted, higher elevation angles decrease the radiating solid angle of the condenser panels to the sky, so cryocooler skin temperatures are expected to increase. The elevation angle of the EXCITE instrument is limited to 22–57 degrees. Lower elevation angles are blocked by the gondola which is designed to avoid stray light from the ground entering the instrument, and higher elevation angles are blocked by the balloon. EXCITE uses thermosyphons modeled and built by Advanced Cooling Technologies, Inc. (ACT). ACT simulated the thermal performance of the thermosyphons inside the gondola structure and fabricated a prototype thermosyphon for lab verification. The simulations used an internal gondola emissivity of 0.2, a gondola temperature of 20 °C and radiator panel emissivity of 0.85. A heat load of 75 W was applied to the neck and compressor areas for each cryocooler, and the average skin temperature of the necks and compressors were calculated at different elevation angles. Fig. 5 shows these results using a preliminary design of the heat sinks at the evaporator ends. Updated heat sink designs are expected to lower the absolute temperatures by increasing the contact area with the evaporators and cryocooler compressors and necks.

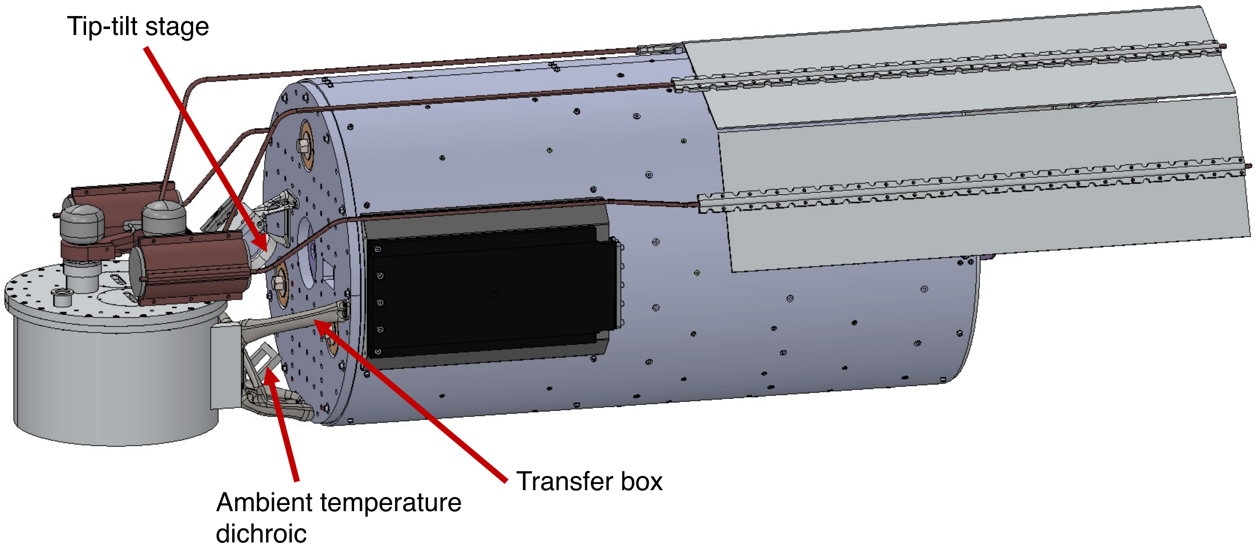

Figure 2. The EXCITE instrument showing the cryogenic receiver as it connects to the telescope. The receiver attaches to the back-plate of the telescope via a titanium "transfer box". The guide camera, which hangs below the ambient dichroic, and its baffles, are not shown. The black dovetail plates are for sliding the telescope into the gondola's inner frame.

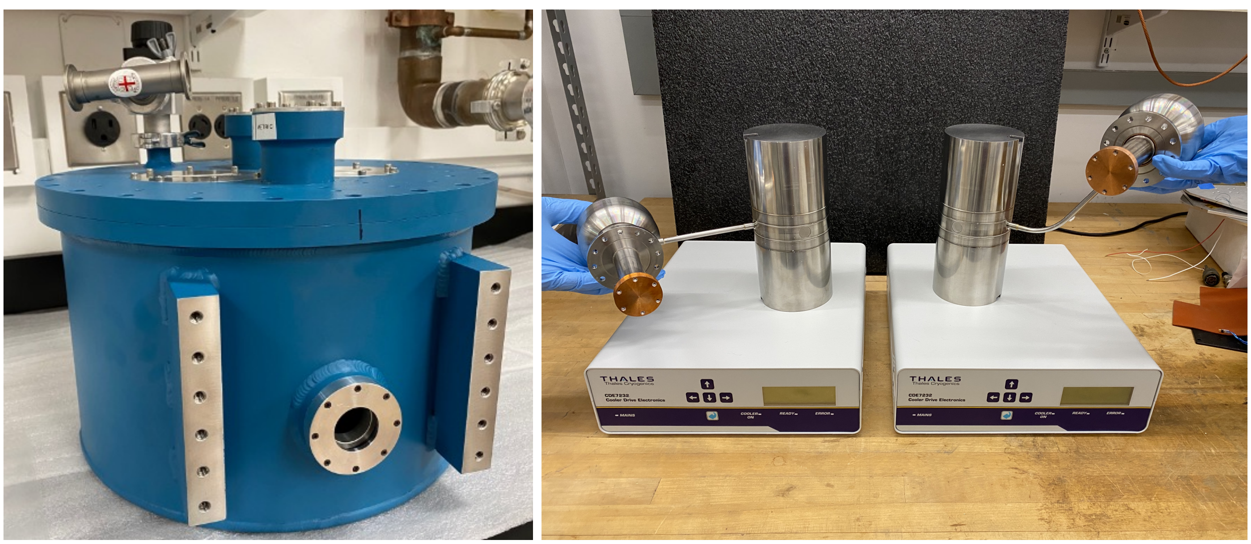

Figure 3. (Left) The outer shell of the EXCITE cryostat. (Right) The two LPT9310 cryocoolers placed on top of their cooler drive electronics boxes (Thales CDE2732).

A prototype thermosyphon was fabricated and tested and is shown in Fig. 6. The primary focus of the prototype testing was to show that thermal gradients across the thermosyphon are small and provide adequate heat transport. Because copper-methanol thermosyphons perform well over a wide range of temperatures, in-lab verification of low thermal gradients points to similar expected gradients during flight. The prototype is 218 cm long with an 8 mm inner diameter and has a representative bend to mimic the bend required to fit over the telescope backplate seen in Fig. 2. Fig. 7 shows the prototype thermal performance at elevation angles 60 and 20 degrees. The prototype was fastened inside a 7.6 cm long evaporator block at the lower end and a 5.1 cm long condenser block at the raised end. The in-flight thermosyphons will have a significantly longer condenser section and slightly longer evaporator section. A heat load of 75 W was applied to the evaporator with the

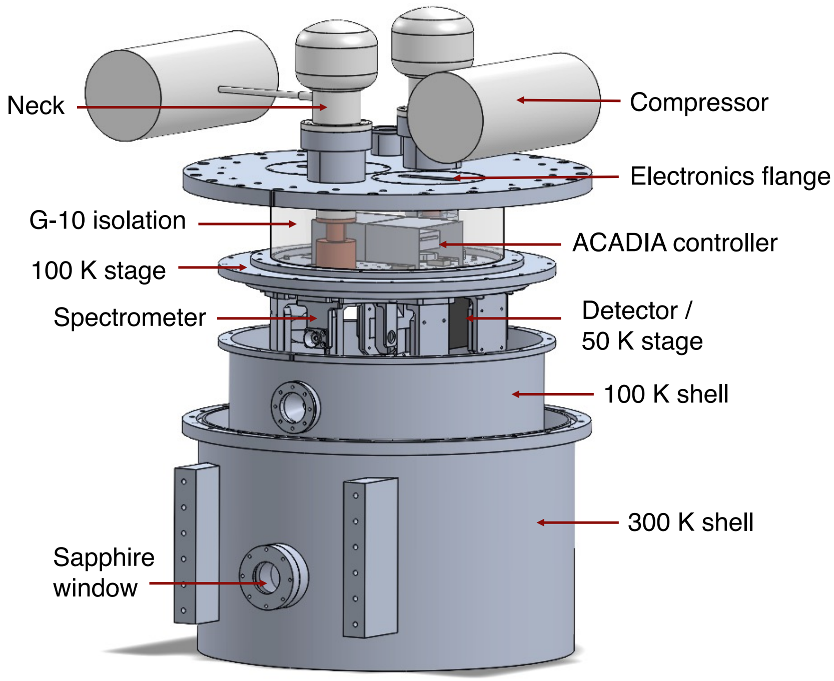

Figure 4. Exploded view of the EXCITE cryogenic receiver. The cooler on the left cools the spectrometer to 100 K and the cooler on the right cools the detector to 50 K.

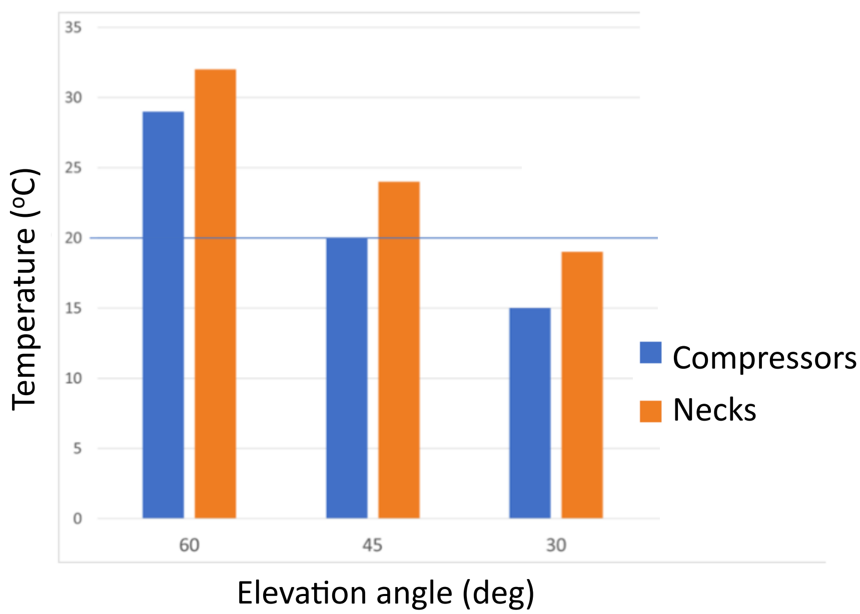

Figure 5. Simulated average temperatures of the cryocooler compressors and necks as a function of elevation angle.

condenser block attached to a fluid loop maintained at 10 °C. For both angles, the thermal gradient between the evaporator and condenser remained between 4 and 6 °C. The thermal gradients observed in the prototype agree with simulations and are sufficiently small to give confidence that this thermal dissipation solution will meet the EXCITE requirements. The absolute temperatures of the prototype during thermal testing in-lab are of secondary importance and depend on the details of the fluid loop chiller circuit (fluid, temperature, flow, etc.).

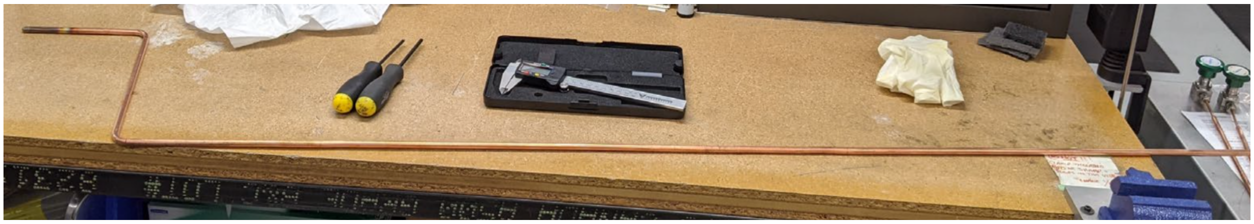

Figure 6. Copper-methanol prototype thermosyphon made by ACT.

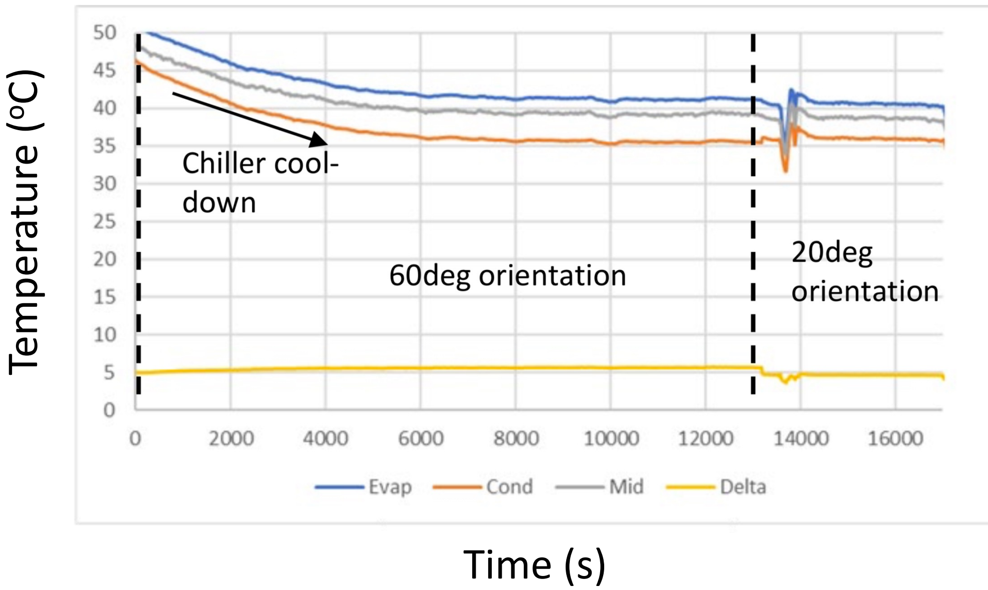

Figure 7. Thermal performance of the prototype thermosyphon. Temperatures were taken at the evaporator and condenser blocks and at a point midway between the evaporator and condenser. Some instabilities occurred shortly after switching to the 20 degree orientation. The yellow curve shows the temperature gradient between the evaporator and condenser.

5. SUMMARY

We designed and are testing a cryogenic system that will enable EXCITE to meet its science requirements. The system consists of a cryogenic receiver, two cryocoolers, and a heat-rejection scheme that utilizes thermosyphons and radiators. Together, this system can meet the temperature requirements of the detector and spectrometer without impacting the pointing performance or flight heritage of the SuperBIT platform.

The cryogenic receiver contains the readout electronics, spectrometer and an H2RG detector. The active cooling of the EXCITE cryogenic receiver is provided by two semi-custom pulse-tube cryocoolers. One cryocooler maintains a 100 K stage for thermal control of the spectrometer and readout electronics, the latter of which will be stood off and heated to a slightly higher temperature. The second cryocooler is dedicated to keeping the detector cooled to 50 K. A characterization study of the LPT9310 cryocoolers showed that they can meet the EXCITE heat lift requirements within a range of expected flight temperatures. Simulations to assess the impact of exported vibrations from the cryocoolers show that they should have negligible effect on the pointing stability of the instrument.

The heat dissipation system for the cryocoolers uses gravity-assisted copper-methanol thermosyphons attached to heat sinks at the evaporator ends and aluminum radiator panels at the condenser ends. Critically, this system has no moving parts. EXCITE must dissipate to space 300 W of heat generated at the cryocooler compressors and necks. Skin temperatures of the cryocoolers during flight are expected to be lower than the preliminary results from thermal modeling due to updated heat sink designs. A prototype thermosyphon was fabricated and showed that thermal gradients between evaporator and condenser are about 5 °C for both the maximum and minimum elevation angles that the EXCITE instrument can observe.

The EXCITE cryogenic system significantly reduces complexity compared to a liquid system, while also reducing the mass and footprint of the receiver. This helps to minimize the differences between SuperBIT and EXCITE, assuring EXCITE will achieve SuperBIT's flight-demonstrated pointing stability. Being one of the first balloon-borne experiments to use compact pulse-tube cryocoolers, EXCITE has the potential to be a replicable balloon platform to perform benchmark science while advancing the development of infrared space instrumentation.

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