The EXoplanet Climate Infrared TElescope (EXCITE): Gondola Pointing & Stabilization Qualification

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ABSTRACT

High precision sub-arcsecond pointing stability has become a capability widely utilized in the balloon-borne community, in particular for high resolution optical systems. However, many of these applications are also pushing the state-of-the-art with regards to detector technology, many forms of which require some level of cryogenic cooling and active dissipative cooling systems to achieve target performance specifications. Built on the success of the Super-pressure Balloon-borne Imaging Telescope (SuperBIT) experiment, we present the results of improved technologies and design methodologies applied to the EXoplanet Infrared TElescope (EXCITE), which uses active cryogenic systems to achieve detector performance while requiring pointing stability at the 100 milliarcsecond level. Results from EXCITE's recent balloon-borne campaign are presented within the context of Super-pressure Balloon (SPB) and Long Duration Balloon (LDB) applications.

Keywords: balloon-borne, sub-orbital, sub-arcsecond, stabilization, qualification, cryocooler, active fluid loop

1. INTRODUCTION

The EXoplanet Infrared TElescope (EXCITE) is a balloon-borne instrument designed to demonstrate highly precise infrared (> 850 nm) spectrographic measurements of exoplanets.[1–3] Directly leveraging the success of the Super-pressure Balloon-borne Imaging Telescope (SuperBIT),[4] the EXCITE Gondola is designed to provide the required stability with explicit mitigation of vibrations from on-board cryocoolers as well as disturbances self-induced from active fluid cooling loops required to provide heat dissipation for those subsystems (Figure 1).

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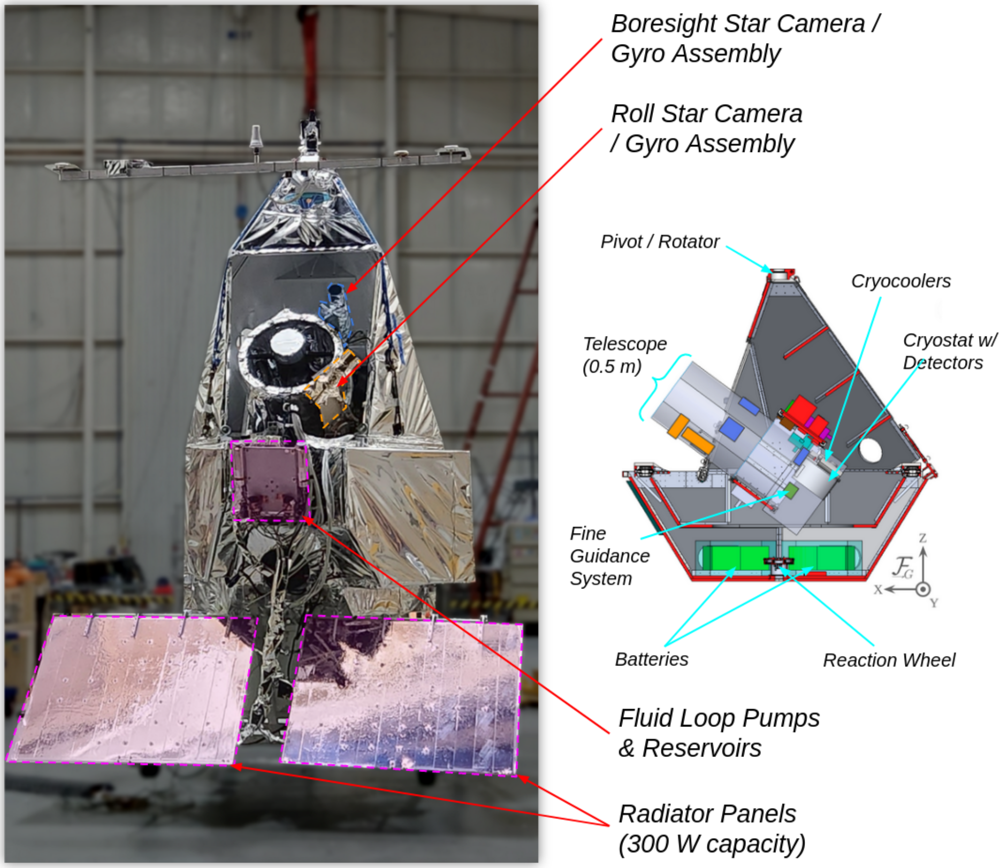

Figure 1. (Left) As-integrated EXCITE Gondola with radiator panels and fluid cooling loop for cryocoolers during preflight highbay testing; (Right) Gondola cross-section schematic identifying primary components within the three-axes gimbal-stabilized system as well as back-end optics and the cryogenic receiver.

In preparation for its first engineering flight, EXCITE has undergone extensive ground-based testing to demonstrate and calibrate pointing performance under flight-like disturbance conditions. Unlike previous missions such as SuperBIT, EXCITE employs actively damped dual cryocoolers to cool science detectors to 50 K as well as a sophisticated 300 W active cooling loop to dissipate excess power to the sky (a separate submission discusses the design and performance of these systems).[5] Amid these larger scale and higher frequency disturbances, sub-arcsecond stabilization must be achieved through a) judicious passive dampening of potential structural resonances, and b) active compensation from the pointing stabilization system, both of which are presented here. In particular, modifications to the three-axes gimballed pointing and stabilization system as well as to the tip-tilt back-end focal plane stabilization are discussed herein.

To summarize, the EXCITE Gondola, as the primary vehicle for science instrumentation, is constrained by these high-level engineering requirements:

- **Better than 0.1 arcsec (RMS) optical stability:** to allow for host star targets to remain on the EXCITE spectrograph instrument to within tolerance demanded by science measurements;[1]
- **Stabilized observation times on order 30–90 minutes:** to provide continuous, uninterrupted observation on EXCITE targeted host stars to within the limitations of the balloon-borne trajectory;[1]
- **Continuous target observation over 1–3 days:** to allow for continuous re-acquisition of any given EXCITE targeted host star to meet science-driven specifications for total observation time;

- **Cryocooled receiver with 300 W power dissipation:** to mitigate power requirements of the EXCITE cryocoolers that provide 50 K cooling power for the EXCITE receiver;[5] and
- **Robust operation in the balloon-borne environment:** to provide the above requirements in the unique thermal, pressure, radiation, and uncontrolled trajectory aspects of stratospheric flight.

Altogether, EXCITE sets a new precedent for high performance, sub-arcsecond stabilized balloon-borne instrumentation with cryogenic cooling capabilities.[1,4] This work presents the pre-flight Gondola pointing qualification results from the EXCITE 2023 campaign in preparation for the upcoming August 2024 test flight with the Columbia Scientific Balloon Facility (CSBF-NASA) in Ft. Sumner, New Mexico. Altogether, this serves as commissioning for the upcoming EXCITE Science Flight from Antarctica in 2026.

2. METHODS

Building on the SuperBIT approach,[4] EXCITE employs both mechanical- and controls-based modifications to improve upon robustness of the Gondola and Fine Guidance System (FGS) against self-induced vibrations from on-board active cooling devices.

To improve on the mechanical rigidity of the SuperBIT-style honeycomb structure that comprises the EXCITE Gondola, dampening materials are implemented in the mounting of the fluid cooling loop pumps and reservoirs, which are the primary source of on-board vibrations. This serves to decouple vibrations from the pumps from three-axes stabilization and FGS control loops. Furthermore, fluid loops crossing through the three-axes gimbal frames are secured with cable guides that aid in decoupling any fluid disturbances from the gimbal structure. Further information on fluid cooling loop design and implementation is available in literature.[5]

The EXCITE cryocoolers employ active dampening of vibrations by phase-matching the dual motor system in a way that cancels out the majority of exported disturbances.[5] For the remaining disturbances, the EXCITE Gondola employs higher-order filtering to reject any potential leakage in cryocooler active dampening, which can be configured during pointing tuning in-lab and in-flight. Calibration and gain parameters are incorporated into the FGS controller to improve configurability for in-flight tuning based on pre-flight measurements made of residual cryocooler vibrations in-lab. Further information on cryocooler design and implementation is available in literature.[5]

In pre-flight qualification, on-sky testing of the EXCITE Gondola and FGS with these mechanical- and controls-based configurations is limited on the ground by "seeing" at 1–2 arcseconds. Thus, qualification consists of two stages: in-lab telescope alignment and on-sky pointing & stabilization validation, with final verification in near-space conditions to be confirmed at float altitude during the August 2024 test flight.

2.1 In-lab Telescope Alignment

The EXCITE instrument utilizes a high-performance, diffraction-limited commercial-of-the-shelf (COTS) 0.5 meter telescope to image stellar targets as part of EXCITE's exoplanet science goals.[1] On the back end, the EXCITE FGS servos a high-bandwidth (closed-loop 50 Hz), high precision piezoelectric tip-tilt actuator and fold mirror that stabilizes the telescope focal plane at 0.1 arcseconds or better to within a +/- 2 arcsecond total actuator throw on the sky. From this, a dichroic beamsplitter splits the incoming beam between the EXCITE receiver and the FGS camera used as primary feedback for the FGS control of the tip-tilt actuator. While EXCITE receiver instrumentation does not dictate stringent requirements with respect to telescope performance,[1] the control effectiveness of the FGS is directly affected by telescope throughput, optical quality, and point-spread-function (PSF). For throughput, Figure 2 shows the effects of science-band-defining constraints that limit spectrum access of the FGS camera at higher wavelengths. For optical quality and PSF, static components can be mitigated FGS control software; however, dynamic changes can obfuscate true focal plane motion and thus impose erroneous feedback for the FGS.

Since atmospheric effects at ground level induce dynamic changes at the 1–2 arcsecond level, independent optical and opto-mechanical testing of the EXCITE telescope, back-end optics, and FGS must be performed in a laboratory environment with well calibrated sources in order to determine and mitigate the intrinsic telescope dynamic effects that would be observed in flight. The telescope and back-end optical system are aligned on an

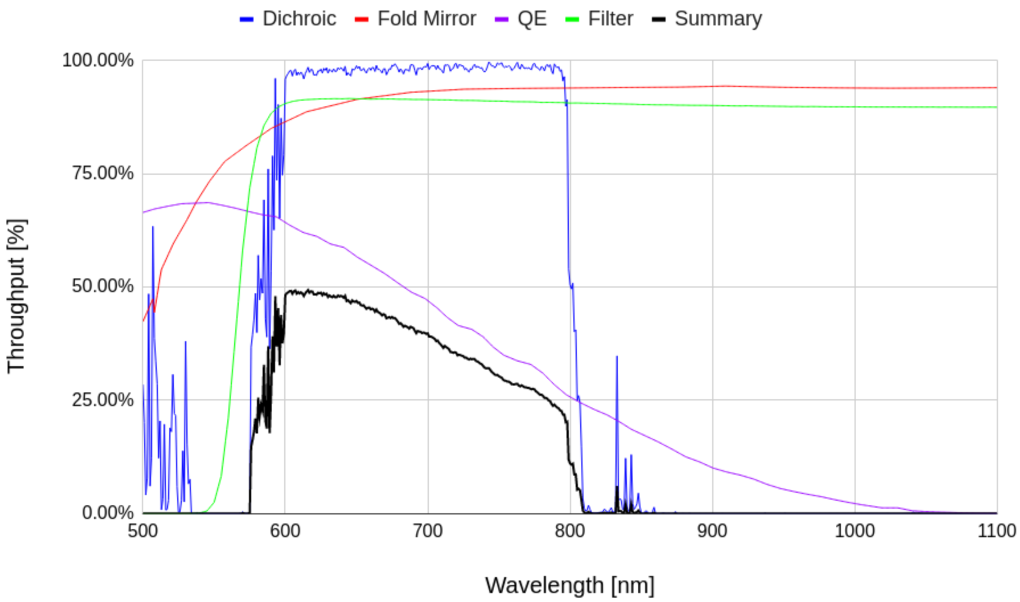

Figure 2. Throughput of the EXCITE telescope and back-end optical system as seen by the FGS; contributions from the FGS fold mirror (red), dichroic beam-splitter (blue), a band-defining FGS filter (green), and FGS camera quantum efficiency (purple) are shown along with the net throughput (black).

optical table with an artificial collimated source, which is then used to validate closed-loop FGS performance in a flight-like manner. This closed-loop FGS validation is performed with inertial sensors (e.g. rate gyroscopes) integrated in the control loop, as would be the case in flight, to correct for FGS camera latencies and to provide higher bandwidth feedback ($>$ 50 Hz). Using calibrated vibration sources, the attenuation performance and overall 0.1 arcsecond stabilization specification of the FGS can be validated within the EXCITE flight system, but independently from the three-axes gimbal pointing stabilization and on-sky effects from the ground. Further, controller bandwidth, exposure time, disturbance amplitude, etc. operating limits for the FGS can be probed extensively prior to flight installation within the EXCITE Gondola.

From this, FGS performance can be independently verified at the 0.1 arcsecond level (or better) in a modular way that separates out any effects from ground-based testing of three-axes Gondola pointing stabilization while exercising the tuning and parameter space of the FGS, the results of which inform in-flight operations.

2.2 On-Sky Pointing & Stabilization Validation

The EXCITE instrument and all the constituent components of science instrumentation are assembled, integrated, and tested in highbay environment in a way that allows for flight-like suspension and complete operational verification of all subsystems pre-flight. In addition to verifying Gondola performance open-loop (i.e. dead-reckoning with inertial sensors only), the EXCITE instrument can be extensively tested on the sky up to the seeing limit from the ground, which is typically 1–2 arcseconds. Although flight performance is expected to be significantly improved, as observed with SuperBIT, verification at the seeing limit on the ground is sufficient to show that three-axes Gondola stabilization is capable of control to within the +/- 2 arcsecond on-sky throw of the FGS.

EXCITE Gondola three-axes stabilization implements the flight-verified SuperBIT architecture[4] that is comprised a series of staged and stabilized gimbals. First, the Outer Frame controls azimuth or yaw of the balloon-borne payload via a large reaction wheel and precisely actuated pivot (aka. rotator) that connects the Gondola to the balloon and provides a means by which excess angular momentum may be dumped. This architecture also exploits pendulation-coupling gyroscopic effects that have been shown to dampen Outer Frame pendulations that may be induced in-flight.[6] Second, the Middle Frame is actuated about the Outer Frame in the roll direction in

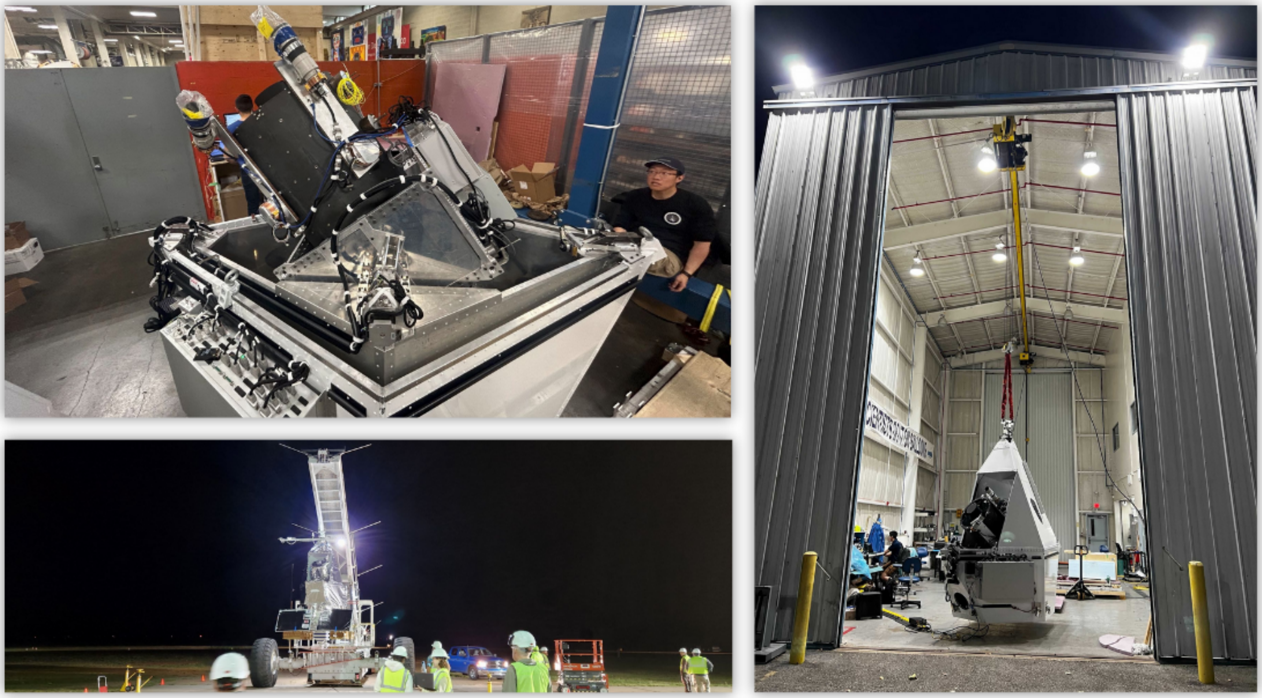

Figure 3. Ground-based in-lab and on-sky testing of EXCITE pointing and stabilization systems at the Brown (top-left), Palestine, TX (right), and Ft. Sumner, NM (bottom-left), in increasing degree of flight-readiness up to end of campaign in October 2023.

order to provide more directly coupled control with the pendulation modes of the balloon-borne payload. Last, the Inner Frame, which contains the telescope and all EXCITE science instrumentation, is actuated about the Middle Frame in the pitch direction with a dual-servo system that provides coarse control to a target elevation within a 20–60 degree range as well as fine stabilized control within +/- 6 degrees of a given target elevation.

In addition to high fidelity rate gyroscope inertial feedback mounted directly to the EXCITE telescope, highly precise sub-arcsecond capable star cameras are used both for direct attitude determination (aka. lost-in-space) as well as for high control bandwidth differential feedback for sub-arcsecond stabilization and gyroscope bias compensation. In order to provide high sensitivity in all three axes in a way that is co-located with the telescope focal plane, two star cameras are mounted directly to the EXCITE telescope: a Boresight Star Camera (BSC) that is co-pointed with telescope and provided pitch and cross-pitch information, and a Roll Star Camera (RSC) that points off axis to provide telescope roll information. During highbay testing, the performance of these star cameras not only provides the direct on-sky verification of three-axes stabilization, but allows for calibration of these star cameras both on a per-device level as well as in the relative offset tuning between the star cameras, the telescope, and the FGS.

Altogether, on-sky pointing and stabilization verification provides pre-flight verification of the overall performance of the system while allowing for operational exercising of tuning and calibration procedures that would be performed in-flight.

3. RESULTS & DISCUSSION

In preparation for flight, EXCITE underwent several mock campaigns and simulated flight operations from January 2023 to October 2023 (Figure 3). This included initial independent Gondola on-sky performance verification at StarSpec Technologies; as-delivered telescope alignment verification and the first complete telescope / Gondola assembly at Brown University; telescope alignment and on-sky pointing verification as-integrated at the

Columbia Scientific Balloon Facility (CSBF-NASA) in Palestine, Texas; and extensive science instrumentation integration and testing in-lab and on-sky of the now flight-ready EXCITE instrument at the test flight launch facility in Ft. Sumner, New Mexico.

The results provided here show the final flight-ready verification of the EXCITE Gondola and FGS as demonstrated in September 2023, which altogether qualifies the EXCITE instrument for flight. All testing during the Ft. Sumner campaign, as reported here, include full operation of all flight systems, including active self-induced vibrations from the cryocoolers as well as on-board disturbances from active fluid cooling loops that traverse the Inner, Middle, and Outer frames of the Gondola, the mitigation strategies for which are described in the previous section.

3.1 Three-axis On-Sky Pointing Stabilization

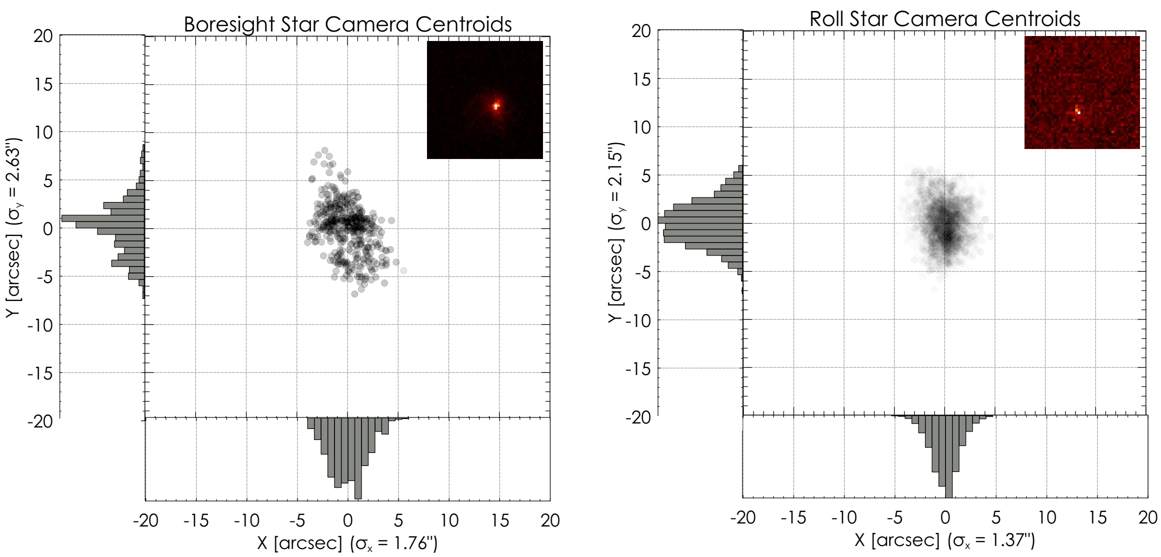

Figure 4. On-sky pointing performance of the Gondola three-axes gimbal stabilization system, demonstrated at the ground-based seeing limit from the CSBF-NASA Ft. Sumner test flight facility in September 2023; BSC (left) and RSC (right) centroid distributions over 5 minutes of observation are shown (black) with 2D distributions per axis (gray); sample thumbnail images of the target star per camera are shown in the top-right corners for each camera.

Full three-axes pointing was directly validated at the seeing limit (1–2 arcseconds) over multiple ground-based "simulated flights", which served the dual purpose of exercising system performance while training flight operators in in-flight tuning and calibration operations. Example results from one of these simulated flights is shown in Figure 4.

At a high level, both star cameras show three-axes Gondola stabilization consistent with the 1–2 arcseconds seeing limit. The BSC shows that Y (cross-pitch) stability is notably worse than in X (pitch) with a potentially bimodal distribution. Although non-isotropic seeing could be a cause, as perhaps suggested by the shape of the BSC PSF, other factors include non-linear static friction of cable harnessing making contact with the highbay floor whilst suspended, wind effects through the highbay door from the outside, and non-linear non-flight-like suspension from the highbay crane. Contributions from some or all of these factors are likely since these had been shown in-lab to be disturbances that act preferentially in azimuth, which is consistent with the cross-pitch direction. Similarly, the RSC shows stability in X (roughly telescope roll) consistent with seeing while stability in Y (roughly telescope cross-pitch) has a slightly wider distribution. This can be attributed to the same effects as suggested for the BSC, but to a lesser extent given that the RSC mounting angle couples cross-pitch motion to the Y distribution less directly than for BSC, which is directly co-pointed with the telescope.

In this way, EXCITE Gondola performance is demonstrated directly at the seeing limit despite self-induced vibrations from cryocoolers and fluid cooling systems as well as amid degree-scale disturbances and Outer Frame motion within the ground-based highbay environment. Since a seeing-limited result is attained at this level, flight conditions, which do not suffer effects from ground-based highbay testing and have a theoretical 0.01 arcsecond seeing limit from the stratosphere, are expected to allow for three-axes stabilization at well below the sub-arcsecond level. Based on the in-flight performance of SuperBIT, the in-flight three-axis stabilization performance can be expected at the 0.2–0.3 arcsecond level (RMS), limited only by the pixel scale and noise characteristics of feedback sensors. This is a likely case for EXCITE given that in-lab testing open-loop (i.e. dead-reckoning without star camera sources) repeatedly demonstrated three-axes pointing stability at the 0.2–0.3 arcsecond level with cryocooler and fluid loop components active. In any case, both the in-lab and on-sky performance show that the EXCITE Gondola is fully qualified to provide a level of pointing stability sufficient for further focal plane stabilization from the FGS.

3.2 Fine Guidance System (FGS)

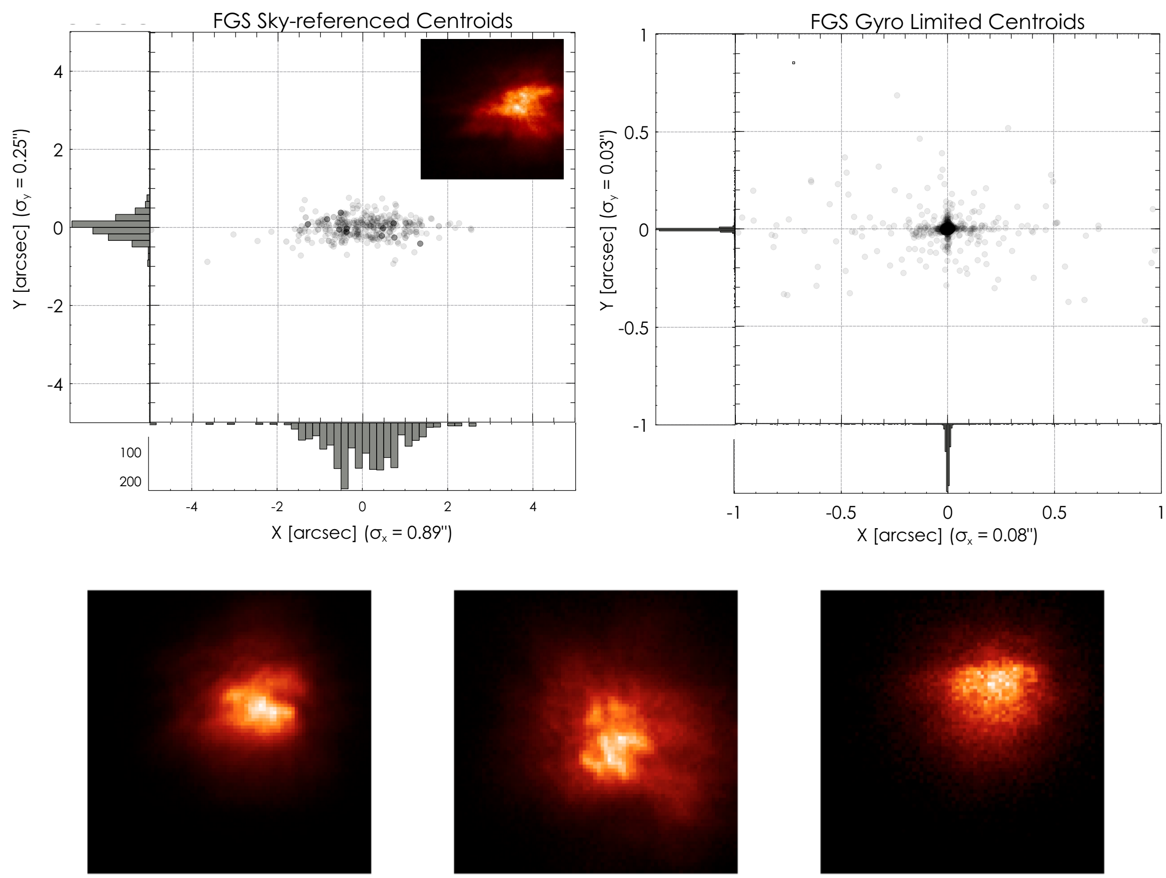

Figure 5. Pointing performance of the FGS following full independent alignment and calibration of telescope optics on the bench at the CSBF-NASA Ft. Sumner facility from August to October 2023; on-sky (top-left) and gyro-only (top-right) FGS centroid distributions over 5 minutes of observation are shown (black) with 2D distributions per axis (gray); sample thumbnail images of the target star during this demonstration run are shown (bottom row) to emphasize the effects of ground-based seeing in obfuscating pointing feedback.

Throughout multiple campaigns, FGS performance was directly demonstrated at the sub-arcsecond level and inferred at below 0.1 arcsecond from optics alignment and gyro-limited results while pointing on the sky in a highbay environment. Example results from multiple simulated flights are shown in Figure 5.

From these results, it is clear that on-sky verification of FGS performance at the 0.1 arcsecond level is not possible due to effects of seeing, where the thumbnail images in Figure 5 show the extent to which the FGS-observed PSF fluctuates dynamically on a frame-by-frame basis. Despite this limitation, the FGS still able to attenuate residual inertial disturbances from the three-axes stabilization stage at a level that is consistent with sub-arcsecond performance. A broader, multi-modal distribution in the X direction (telescope cross pitch) suggests either non-isotropic seeing effects as strongly implied by the asymmetry of the FGS PSF shown in Figure 5 and / or cross-pitch leakage from the three-axes stabilization stage. Overall, the on-sky FGS results from the ground should be considered a first-order verification of FGS functionality in that an effective attenuation is achieved outside of the in-lab benchtop testing of the telescope and back-end optics performed earlier in the year.

Benchtop testing of FGS systems through the telescope and back-end optics independent of the three-axes stabilization stage had previously shown beam stabilization at well below the 0.1 arcsecond requirement. To infer the level of performance that could be achieved with the FGS in the fully integrated system, FGS gain parameters were tuned in a non-flight configuration to preferentially weight inertial measurements (i.e. rate gyroscopes) over FGS camera feedback. In this way, a gyro-limited performance specification is obtained while the full EXCITE system is pointing and stabilizing on-sky, as shown in Figure 5. These results show that the gyro-limit performance of the FGS is at the 0.02–0.08 arcsecond level (RMS), meeting the 0.1 arcsecond specification, with asymmetry between X (cross pitch) and Y (pitch) likely due to leakage from the three-axes stage.

Note that this is an inertial result that does not reflect on-sky centroid distribution, which is limited by ground-based seeing, and as such, should be taken as a pre-flight qualification of the FGS pending final test flight verification in the balloon-borne environment. That said, similar pre-flight results obtained by SuperBIT had been shown to be sufficient in-flight over nearly 500 hours of successful observation time during SuperBIT's 2023 science flight, which repeatedly demonstrated a 0.04 arcsecond (RMS) focal plane stability over 30 minute timescales. It is expected that similar results will be verified by EXCITE during the upcoming test flight from Ft. Sumner in August 2024.

4. CONCLUSIONS

The EXCITE system had been successfully assembled, integrated, and tested over multiple campaigns in 2023 leading up to flight-readiness at the launch facility in Ft. Sumner, New Mexico. Final pre-flight qualification through ground-based testing showed seeing limited performance of the three-axes Gondola system with the cryocoolers and fluid cooling loops active as would be the case during flight (notably traversing the gimbal frames in a way that induces further disturbances). Benchtop testing of the FGS independent from Gondola three-axes stabilization showed the capability of the FGS in providing focal plane stabilization at well below the 0.1 arcsecond requirement, and the first-order attenuation performance of the FGS within the fully-integrated system was verified on-sky at the sub-arcsecond level. Gyro-limited FGS performance was inferred through pointing stabilization on-sky with preferential (non-flight) weighting on inertial measurements over FGS camera feedback, which indicates that the FGS would likely meet the 0.1 arcsecond requirement during flight. All results of three-axes Gondola and FGS performances are strongly supported by the success of the SuperBIT system that the EXCITE instrument directly leverages.

Altogether, the pre-flight system qualification of the EXCITE system sets a new precedent for highly stabilized and highly precise pointing specifications for cryogenically-cooled balloon-borne instrumentation. At broader scope, EXCITE stands as a technological marker for advances in satellite-based instrumentation, demonstrating that state-of-the-art cryocooled devices can be effectively stabilized for high precision applications even in a more dynamically volatile balloon-borne environment. In-flight verification during EXCITE's upcoming test flight in August 2024 as well as the prospective EXCITE science flight from Antarctica in 2026 will continue to establish the viability of this approach to scientific ballooning instrumentation. This approach to high performance balloon-borne instrumentation is currently being further developed and employed at StarSpec Technologies for both long duration balloon (LDB) applications, such as EXCITE, as well as super-pressure balloon (SPB) applications similar to SuperBIT over a broad range of scientific and commercial implementations.

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