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PERFORMANCE TESTING THE ADVANCED CT-2020 DOMESTIC STAR TRACKER

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At Ball Aerospace, we have developed the advanced CT-2020 star tracker featuring a new state of the art CMOS detector with exceptional radiation tolerance and performance suitable for spacecraft in any orbital regime. Performance testing has verified the CT-2020 can achieve single head accuracies of better than 1.5 arc-second autonomous attitude output (total error), while also allowing for customer driven “directed search” mode for even higher accuracy performance. A qualification unit was tested to and met the qualification requirements of the Space and Missile Systems Center Standard SMC-S-016. Thermo-mechanical stability testing verified that the innovative lens design and detector package mount is stable over launch and on-orbit environments. Stray light performance verified the CT-2020 lightshade, which is coated with Surrey NanoSystems’s Vantablack, provides a Sun exclusion angle of less than 33 degrees while minimizing the star tracker’s size and weight. Software testing verified the user can export full frame data from the image sensor while simultaneously tracking stars at full accuracy. Low angular rate bright star testing correlated very well with high fidelity models and the design unit showed exceptional calibration performance in Ball’s state of the art flight proven test systems. Details of the qualification unit test results will be discussed in the paper.

INTRODUCTION

Ball Aerospace designed the CT-2020 with the goal to enhance existing domestic, economically viable and merchant supplier production capabilities to produce Star Trackers using advanced Complementary Metal Oxide Semiconductors to achieve flexible performance.

The effort allowed Ball to design a star tracker with a focus on competitive cost and technical performance. The CT-2020 uses the STELLAR CMOS device to help in achieving these goals while also adhering to comprehensive Ball Aerospace parts quality and traceability standards.[1, 2] With the exception of the Sun shade coating, all CT2020 components are domestically procured from trusted sources.

The STELLAR is a new system-on-a-chip detector featuring a low noise, radiation hard, backside illuminated pixel design with true correlated double sampling architecture. The detector array allows for global (snapshot) mode which does not require geometry corrections needed when using CMOS detectors with rolling shutter readouts. The high quantum efficiency of the detector allows for sufficient signal generation while using smaller volume, as well as more cost effective

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and better performing optics.[1] The STELLAR chip provides high speed full frame data which allows for processing of the entire scene.

This paper discusses performance testing used to qualify the engineering unit design on the commercial medium accuracy version of the CT-2020 with total attitude cross axes output uncertainty in the 1 arc-second range. The 1 arc-second output uncertainty is a total attitude error containing both high and low frequency error components. Also included are test results after exposure to the environments outlined by the Space and Missile Systems Center Standard SMC-S-016. Results from the qualification testing verify the design choices in conjunction with extensive lessons learned and heritage from prior star trackers built by Ball, results in a compact, high performing flexible star tracker at a competitive price point.

THE CT-2020

The CT2020 star tracker is a fully integrated design (Figure 1). The implementation avoids a separate electronics box or extra cabling and allows for a compact package that combines the detector, electronics, radiation and Sun shield in a single assembly that is easy to test in its final flight configuration. The implementation also incorporates a Ball patented detector mounting technique that yields exceptional thermal and mechanical stability over anticipated operational environments. The following sub-sections of this document highlight features and sub-systems of interest.

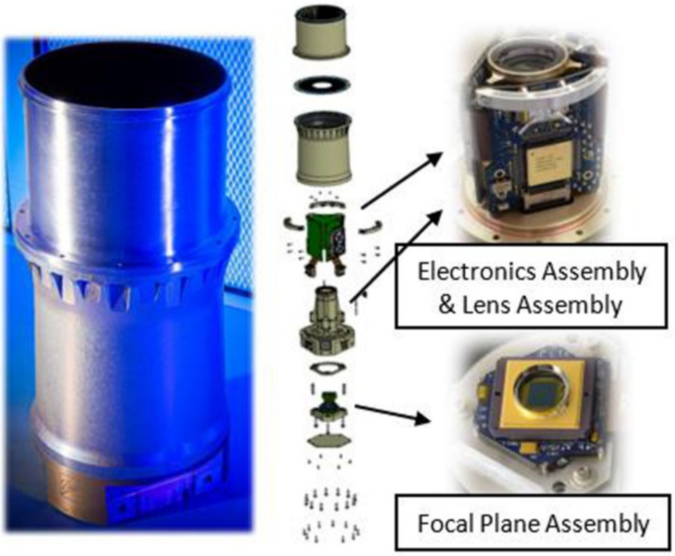


Figure 1. The Ball CT-2020.

Lens Design

The CT2020 lens was designed for a ~10 deg field of view (FOV). The lens design incorporates lessons learned from the Ball High Accuracy Star Tracker (HAST) and yields performance close to the HAST optical implementation at a fraction of the cost. The lens shows stable point spread function behavior and boresight stability across mechanical and thermal environments. The CT2020 lens minimizes lateral color effects on star centroid error. Additionally, the lens design incorporates an optimum placement of the aperture stop that allows for a volumetrically small and high performing Sun shade design. The lens design is optimized such that an appropriate point spread function can be achieved over the FOV without costly focusing techniques. The integrated electronics design that surrounds the optical train allows for a thermally balanced implementation that yields sub-arcsecond boresight stability over a wide operational temperature range.

Mechanical Design

The mechanical structure design is optimized for cost effective manufacturing and assembly. At the core of the CT2020 is a compact, elegant mechanical design that incorporates symmetric placement of electronics around a mechanical housing that accommodates the lens and CMOS detector (Figure 1). The carefully designed symmetric electrical assembly arrangement yields a favorable thermal environment that minimizes thermally induced boresight shifts. The detector placement behind the lens is efficient in dissipating heat as well as providing a stable mount for the rest of the structure. An innovative mounting technique of the detector package allows for excellent thermal conductivity and thermo-mechanical stability over launch and on-orbit environments.

The standard offering of the CT2020 includes a ~33 degree light shade which minimizes stray light reflected onto the lens assembly using a coating of Surrey NanoSystems's Vantablack.

Detector

The STELLAR detector (Staring Technology for Enhanced Linear Line-of-sight Angular Recognition) represents the latest technology in active pixel sensors.[1, 2] The STELLAR device is a back-side-illuminated (~90% QE at 600nm), high efficiency monolithic CMOS with a resolution of 1024x1024 pixels. The detector runs at 10 frames per second at full resolution (1024x1024) and can achieve higher frame rates in sub-sampled region of interest mode. The implementation is a full system on a chip with integrated digital architecture and command and control that generates all internal timing for exposure control while supporting global shutter readout and integrated analog to digital converter. The integrated design substantially reduces part count and support electronics complexity.

The STELLAR pixel design allows for true low noise correlated double sampling (CDS) implementation. The low noise, high efficiency detector enables the compact and high performing architecture of the CT2020. The detector package also features a high efficiency TEC to maintain stable mechanical and electro-optical performance. In addition to a dynamically autonomously-updated pixel non-uniformity correction, the TEC set point is on-orbit adjustable to maintain performance as the device ages.

STELLAR is developed and produced on-shore utilizing an on-shore foundry.

Electronics

The CT2020 takes advantage of the latest radiation hard and flight proven electronics architecture (simplified electronics architecture for the CT2020 is shown in Figure 3). The electronics implementation is also optimized for cost and performance by means of reducing part count and matching required performance to parts pedigree.

The efficient low voltage power supply board distributes necessary power while providing EMI/EMC robustness. At the heart of the processing electronics is an all-digital on-shore custom made ASIC that significantly reduces the part count compared to traditional FPGA + processor applications. The ASIC is a radiation hard, high performing and cost effective solution in providing the necessary capabilities required by the CT2020. The ASIC also handles the simultaneous output of full frame image data and centroid/attitude output data. This is a feature that enables significant space situational awareness capability (details are beyond the scope of this paper). Full frame video data is output via high speed channel-link interface while standard command and telemetry are handled via either a 1553 and/or RS-422 interface (space wire option is also available but currently not supported). A sample of the full frame video output was collected while imaging Orion's Belt (Figure 2). During full frame video testing stars with apparent magnitudes as dim as 8.0 where visible. The user can also access non-full frame video data (pixel regions of interest for each tracked star) via the standard telemetry interfaces (Figure 3).

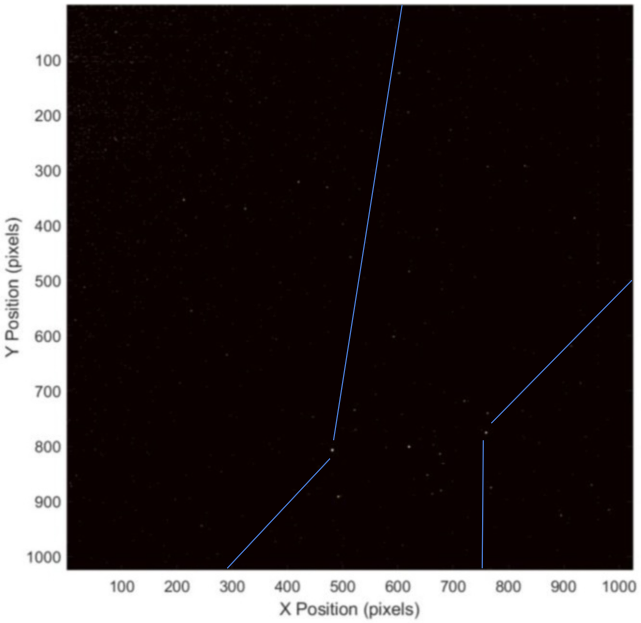


Figure 2. Full frame image showing a section of the Orion Constellation during night testing. The three brightest stars form Orion's Belt (apparent magnitudes of 1.7, 2.0 and 2.2).

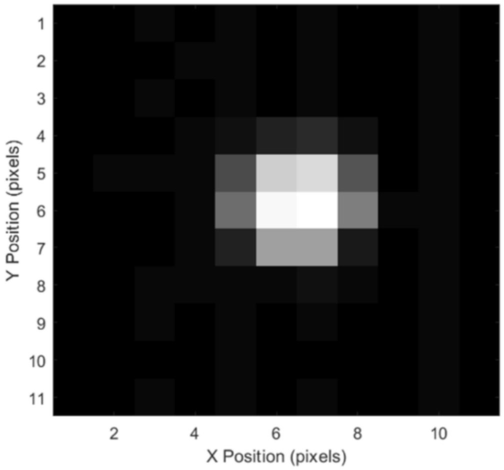


Figure 3. RS422 telemetry image showing the Alnitak triple star system (one of the three stars in Orion's Belt.

The electronics architecture also supports a fully integrated test interface (further discussed in the software section of the document) that can emulate on-orbit operations with the CT2020 hardware in the loop (“environment simulator”). The interface allows for simulated images and commands that bypass the detector be injected and processed by the CT2020 hardware. HAST like capability also allows for optional spacecraft provided accurate angular rate input which further improves accuracies and track capability at high rates. Optional spacecraft provided host pulse can also increase the accuracy of time relevance of telemetry knowledge. In the presence of a host provided sync pulse the CT2020 will synchronize to it. The CT2020 will also output its own sync pulse in case the user desires to synchronize to the CT2020.

All the electronics components used in the CT2020 are domestically sourced from trusted suppliers. The ASIC development and procurement utilizes on-shore foundry and a trusted supplier. The ASIC contains multiple cores including a processing core specifically developed for the CT2020. The electronics components are suitable for the most radiation adverse environments with all components being rated to at least 100kRad with most components being radiation hard to 300kRad.

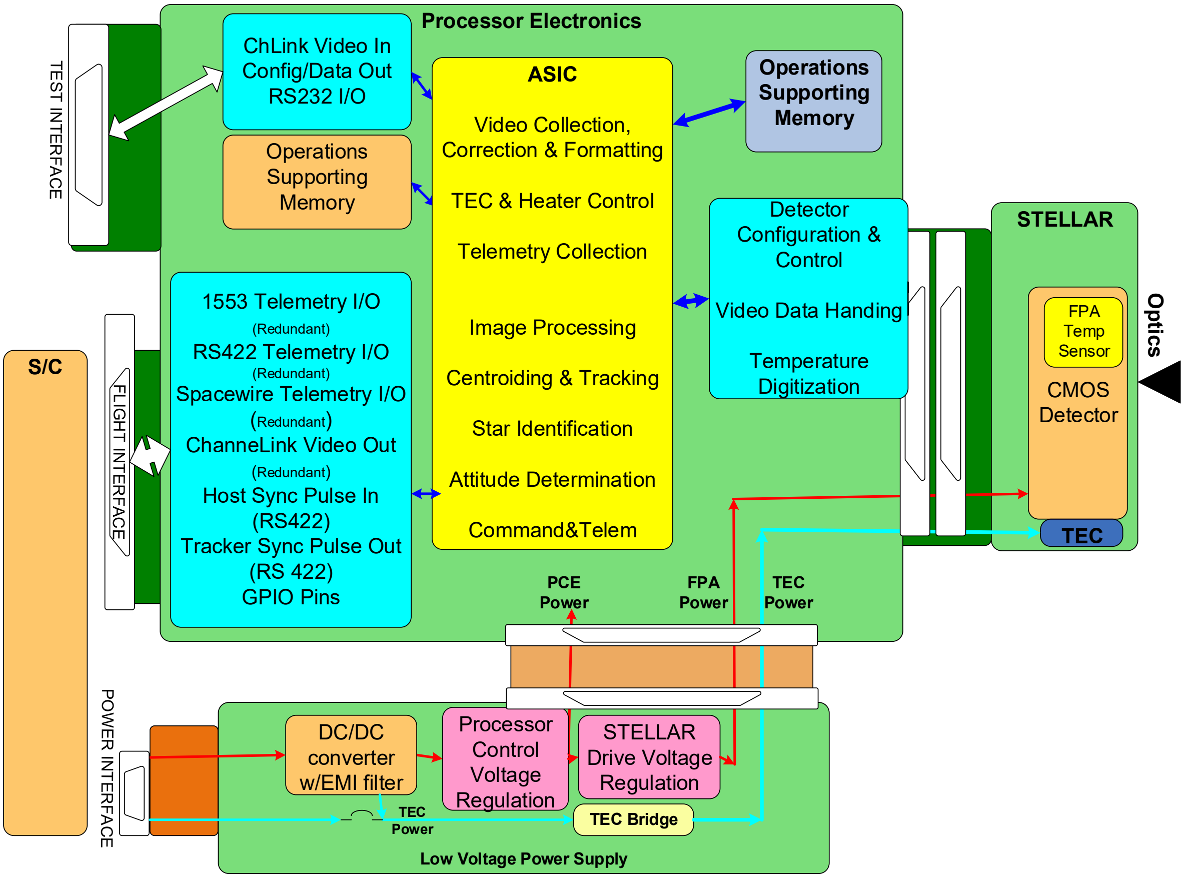


Figure 4. Simplified electronics architecture.

Software

The software implementation leverages decades of Ball heritage in providing star tracker sensors (CT602, CT633 & HAST). The software integrates the HAST image processing and general architecture therefore taking advantage of a flight proven design that is suitable for the most critical missions. The software architecture allows for cost effective, flexible and modular development. Notably, multiple on-orbit upgradable modules are used to recover star tracker performance as the unit ages in its operational environment. Dark image data is saved during operation and can be used to correct for dark current non-uniformity changes by command. Self-calibration capability allows for spatially induced field effects (plate scale) to be corrected on orbit via command. Similarly, the star catalog can be updated on orbit to minimize stellar proper motion impact on performance as well as instrument magnitude shifts due to radiation aging effects. The software also implements logic that allows for operation in high radiation environment while minimizing impact to performance. High angular rate operation without notable degradation in performance is achieved with internal, HAST like, real time optimization of image smear via autonomous dynamic integration time adjustment. Even higher performance can be achieved with optional spacecraft provided angular rate input. The software also implements an “environment simulator” interface that is internal to the CT2020. The implementation seamlessly bypasses the detector and injects simulated pixel video downstream, exercising the hardware and flight software. The simulated images are fed in via the test interface connector of the CT2020 and can be provided by Ball furnished mobile test station or generated by the user. The capability allows for ground testing of hardware in the loop while the tracker is installed on the spacecraft. Simulation of spacecraft specific CONOPS enables risk reduction for mission specific maneuvers, dynamics and orientations. The software development process of the CT2020 adheres to HAST like requirements on trusted code generation and operational verification. The entirety of the CT2020 flight software and operating system is developed by Ball Aerospace without usage of any third party packages.

CT-2020 QUALIFICATION TEST RESULTS

The presented design of the CT2020 was optimized for efficiencies in manufacturing and test. The electronics layout as well as the opto-mechanical design allow for cost savings and automation improvements in manufacture, assembly and test. Use of Ball’s state of the art flight proven test systems achieves exceptional calibration performance over the anticipated operational environment.

An engineering qualification unit was tested to the qualification requirements from the Space and Missile Systems Center Standard SMC-S-016. The unit was also tested to verify performance and matched the designed expectation. The unit was built and tested in Q3 of 2020 and completed in Q1 of 2021. The CT2020 Qualification test plan is shown in Figure 5.

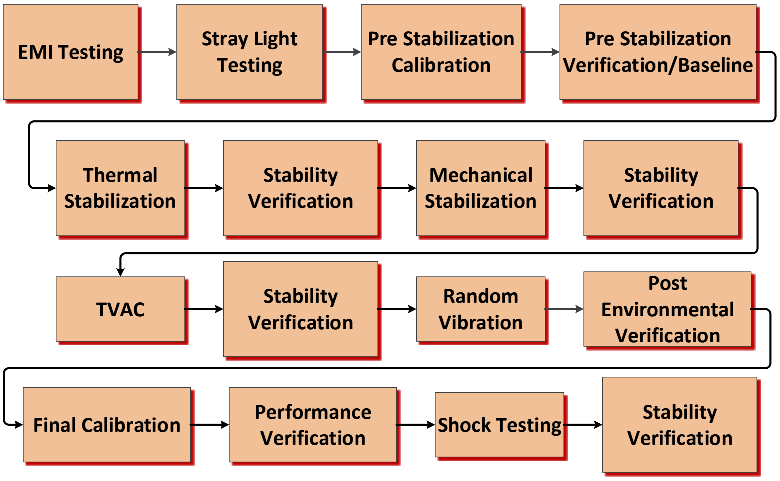


Figure 5. CT-2020 qualification test flow.

The qualification testing includes electromagnetic interference (EMI) testing at levels as defined by MIL-STD-461G, random vibration at levels as defined by GSFC-STD-7000A, and thermal vacuum testing at levels as defined by the SMC-S-016. Shock testing was also performed based on Ball heritage spacecraft requirements. The entirety of the qualification testing revealed CT2020 meeting all expectations and requirements including pre and post qualification performance testing.

Spatial calibration and performance characterization testing was conducted in Ball's HALOS facility (angular knowledge of less than 0.5 arc-seconds, chamber shown in Figure 6).

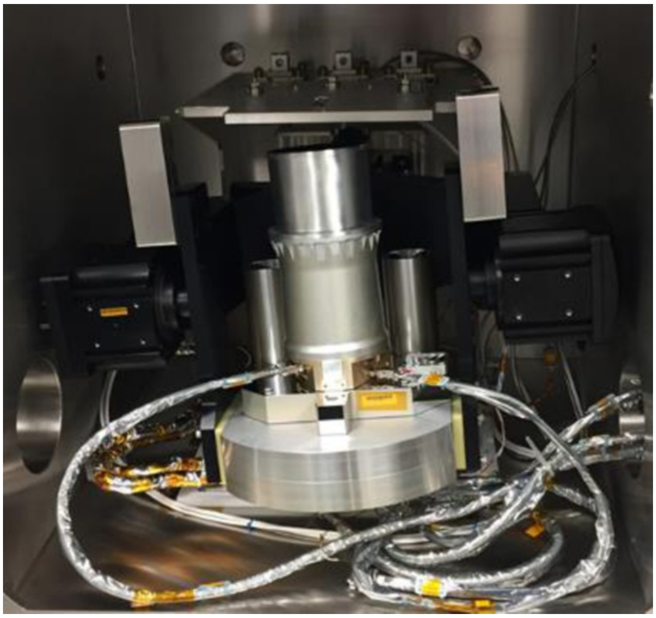


Figure 6. HALOS performance and calibration.

Attitude Error Results

The CT2020 provides customers with both full autonomous attitude output as well as the capability of “directed search” mode of operation where the user can command specific regions of interest for the CT2020 to process, implementation which is tailored for customers seeking the highest possible performance. A HAST like approach is employed which includes a comprehensive error tree that includes noise sources from both temporal and spatial effects.

The primary error contributors to the CT-2020 are per star per axis low spatial frequency error (LSFE) and random measurement error (RME) that are further combined to produce total attitude error. LSFE are errors with long spatial correlation length such as optical aberration and are minimized during ground spatial calibration. RME captures errors with short correlation length and temporal errors such as detector noise and smear induced effects at higher angular rates. A portion of the LSFE was measured during the qualification units spatial calibration. The primary portion of the RME was also measured in a separate performance test.

A simplified CT-2020 error tree is shown Figure 7 and details the measured test results in green. The error tree provides both per star per axis contributors and how they are combined to produce total attitude error. The performance testing verified the CT-2020 is capable of approximately 1 arc-sec attitude performance at angular rates of 0.5 degrees/sec. RME was also tested at rates up to 1.5 degrees/sec and showed performance gracefully degrades at the maximum rate while still maintaining track of stars at up to 8 deg/sec. Note that the software allows for 8 stars to be tracked at all rates and detector exposure times.

The quoted performance includes all spatial and temporal error components as well as worst case velocity aberration effects, star catalog errors and worst-case Sun angle.

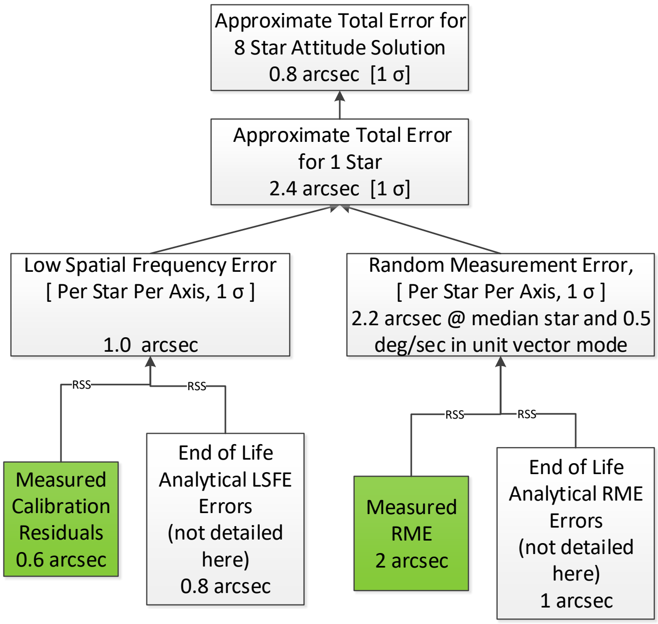


Figure 7. CT-2020 attitude error tree.

Boresight Temperature Stability

Lessons learned from the High Accuracy Star Tracker were incorporated into the CT2020 design, yielding stable boresight as a function of baseplate temperature. The boresight temperature correction (calibration fit) of the CT2020 closely follows the HAST precedent and the calibration utilizes our state of the art ground test systems. The calibration fit is flexible and can accommodate various temperature set points depending on application for a mission tailored boresight residual behavior. The CT2020 was tested over a wide range of temperature in terms of boresight stability (~ -12C to ~ +35C). The post calibration boresight residual gradient (in arcsec/degC) is shown in Figure 8. Boresight residual gradients of less than 0.05 arcsec/degC are readily achievable around the base plate temperature calibration points.

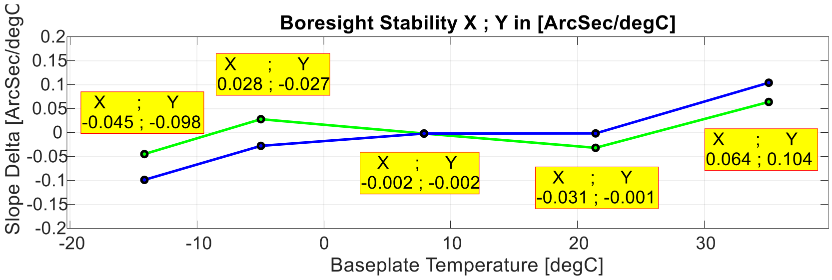


Figure 8. Measured CT-2020 boresight stability in units of arcsec/degC.

Mechanical Stability Results

The engineering unit was exposed to two rounds of thermal vacuum testing, two rounds of random vibration testing and a shock test. The setup for the first random vibration test is shown in Figure 9. The thermal vacuum cycles were performed per the SMC-S-016 profile and summarized in Table 1.

Table 1. TVAC Test Profiles.

Test	Thermal Cycles	Temperature Range (degC)
TVAC Settling	8	-25 to 45
TVAC Qualification	40	-25 to 45

The random vibration tests were performed per the GEVS profile and summarized in Table 2. The shock test is summarized in Table 3.

Table 2. Random Vibration Test Profiles.

Test	Overall Level (G_{RMS})	Duration (sec/axis)
Random Vibe Settling	6.8	30
Random Vibe Qualification	14.1	90

Table 3. Shock Test Profile.

Frequency (Hz)	Acceleration (g's)
100	57
1500	1556
10000	1556

Figure 9. Photograph of mechanical stability testing.

After each of the five environmental tests, the engineering unit was moved to the HALOS facility to check for optomechanical shifts. In the HALOS facility a light source is imaged by the star tracker in an array of locations about the field of view. The star tracker reported light positions are compared to the true locations measured by the facility to determine angular performance across the field of view. Changes to the angular performance from a baseline HALOS measurement were used to quantify the optomechanical shifts due to the environmental tests.

Figure 9 shows the boresight and platescale optomechanical shifts due to each environment. In the HALOS facility, boresight is the angle parallel to the collimated light source. Platescale shift is the movement between the detector and lens assembly.

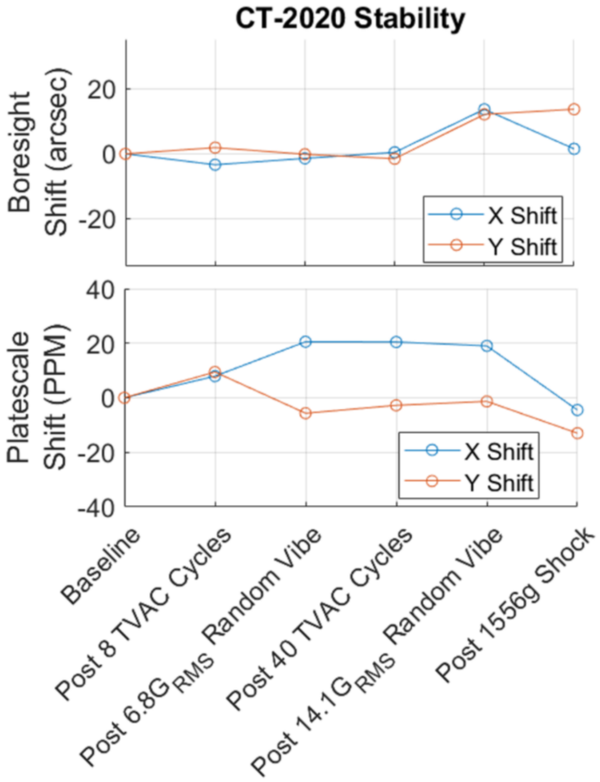


Figure 10. Mechanical stability results along X/Y-axis.

The CT-2020 boresight shifted less than 20 arcseconds across all environments. The repeatability of the HALOS facility with respect to platescale is 20 parts per million, therefore no discernable platescale shift could be found due to exposure to the environments. Both the boresight shift and plate scale shift due to launch environments were well within expectation.

In summary the CT-2020's robust opto-mechanical design allow for excellent optomechanical stability over launch and on-orbit environment.

Stray Light Results

Stray light data was collected as a function of angle from boresight. During stray light testing, the CT-2020 was mounted on a rotary stage in our Stray Light Facility. The front aperture of the tracker is placed at the center of rotation and illuminated fully with a solar simulator source consisting of a Xenon arc lamp, collimating off-axis parabola, and fold mirror. Figure 11 shows the CT-2020 during stray light testing. The solar simulator source beam approximates the angular divergence of the Sun (~0.5°), and a calibrated photodiode is used to measure the irradiance of the source relative to the Sun before scaling the measured results to full Sun.

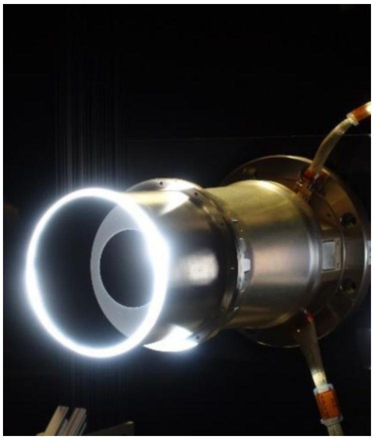


Figure 11. Photograph of the CT-2020 stray light testing.

Image data was then collected with the tracker positioned at discrete boresight angles. The CT-2020 is then pulled back from the light beam so that pixel data can be collected quantifying Rayleigh scatter of the air in the test chamber. This data allows direct characterization of the Sun Exclusion Angle.

The attitude performance error tree (Figure 7) includes a maximum allowed stray light signal (in the end of life analytical RME box) of approximately 4000 DN/sec. Therefore any stray light signal less than 4000 DN/sec will give the tracker full attitude performance.

The final processed results are provided in Figure 12. The test shows that the CT-2020 is capable of a full performance attitude solution when the Sun angle is greater than or equal to ~31 degrees from Boresight. For conservatism, the advertised Solar Exclusion angle for full performance is set at 33 deg.

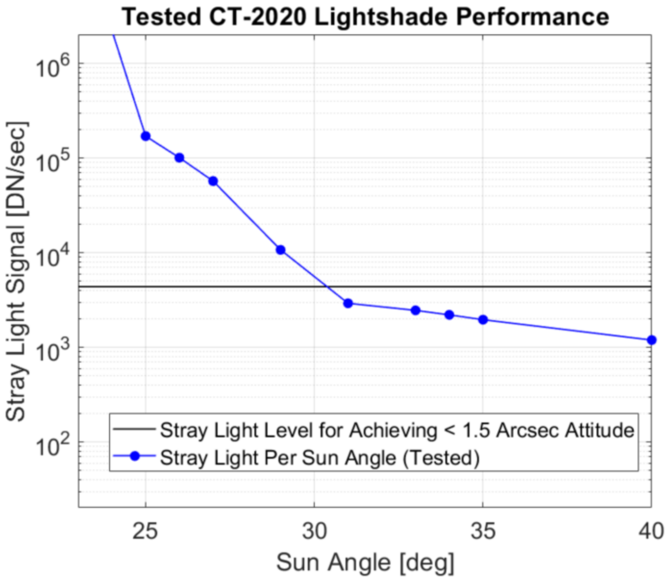


Figure 12. CT-2020 stray light performance results.

EMI/EMC Results

The CT-2020 was tested per the MIL-STD-461G electromagnetic interference specifications in the Ball Aerospace XL EMI test cell. Eleven EMI/EMC tests were performed as summarized in Table 4.

Table 4. EMI/EMC Test List.

Test	Description
CE101	Conducted Emissions, Current Probe Method
CE102	Conducted Emissions, LISN Method
RE101	Radiated Emissions, Magnetic Fields
RE102	Radiated Emissions, Electric Fields
CS101	Conducted Susceptibility, Power Lines
CS106	Conducted Susceptibility, Power Lines, Transients
CS114	Conducted Susceptibility, Bulk Cable Injection
RS101	Radiated Susceptibility, Magnetic Fields
RS103	Radiated Susceptibility, Electric Fields

The CT-2020 was configured as shown in Figure 13. The unit showed excellent compliance to the MIL-STD-461G testing. Negligible outages against MIL-STD-461G were observed during RE102 and RS103.

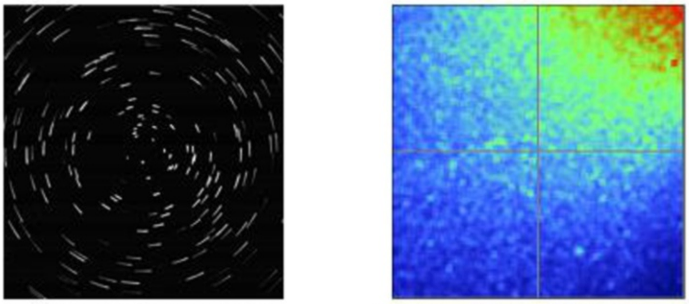
Figure 13. Photograph of the EMI test setup of the CT-2020.

CONCLUSIONS

Ball Aerospace has recently designed and tested a star tracker with a focus on competitive cost and technical performance. The result is a compact, high performing and operationally flexible star tracker at a cost competitive price point. Qualification testing of the engineering unit shows the CT-2020 is available to provide less than 1.5 arcsec accuracy performance after exposure to environments mandated by SMC-S-016 and as described in this paper. The CT2020 provides the community with a domestic source for star trackers that utilizes on-shore trusted suppliers, secure systems and secure flight software. The CT2020 is expected to be available in Q1 of 2022.

APPENDIX: CT-2020 CORE CAPABILITIES (PER FOV)

- Fully integrated architecture, no external electronics unit necessary
- Capability of fully autonomous or “directed search” operation
- In addition to standard attitude telemetry output, three axis angular rate output also provided
- On-orbit upgradable software, star catalog, algorithms and re-calibration
- Single FOV full attitude uncertainty 1 arc-second, one sigma at 10Hz. Accuracies < 1 arc-second available for tailored missions
- Fast lost in space solution time with use of hash table based algorithms
- Space situational awareness capable providing simultaneous full frame video output correlated with standard attitude telemetry output
- Radiation hard by design CMOS detector and radiation hard by design ASIC
- Suitable for LEO/GEO (up to 18 years GEO)
- Low volume, low power (<12W) low mass (<3.75kg including light shade)
- RS422, MIL-STD 1553, for standard telemetry; Channel link for high speed full frame video
- Optional host sync pulse interface input for high precision time sync
- Optional host provided angular velocity vector for high accuracy high rate operation
- High angular rate operation (up to 8 deg/sec)
- Integrated alignment features without the need for an externally mounted alignment cube
- Integrated LED for polarity testing and functional testing
- Comprehensive environment simulator for hardware in the loop testing
- Meets attitude sensor relevant SMC requirements
- All US trusted suppliers, secure systems and secure flight software



Built in Environmental Simulation Exaggerated for illustration purpose (80 deg/sec angular rate with 600 deg/sec/sec acceleration)

Built in LED for Functional and Polarity Testing LED is software command able and provides ability to verify polarity of tracker once mounted on the spacecraft

Figure 14. Sample of the built in features of the CT-2020.

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