Dual Use Star Tracker and Space Domain Awareness Sensor In-Space Test

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ABSTRACT

Star tracker has been a popular attitude sensor for spacecraft. Its full-frame video-output may be utilized for Space Domain Awareness (SDA). A newly developed dual-use sensor of combined star tracker and SDA functionalities has advantage of size, weight, power, and cost (SWaP-C). The planned in-space test will verify performance and functional requirements for both star tracker and SDA sensors. Full-frame data will be stored and downlinked to the ground for SDA post-processing and demonstration. The outcome will accelerate the Technical Readiness Level (TRL) of this innovative sensor from TRL-5 to TRL-7 via test and demonstration in a relevant space environment.

1. INTRODUCTION

Star observation based attitude determination systems have gained in popularity for modern spacecraft in the last two decades. Numerous research has been devoted to the star tracker hardware development [1-10] as well as the use of star trackers [11-16]. In the past decade, Space Domain Awareness (SDA) has become an increasingly important capability due to the concerns of safely operating satellites in proliferated Low Earth Orbit (LEO) and Geosynchronous Earth Orbit (GEO) congested environments as well as potential adversary events to the satellites [17-19]. Similar to star tracker functionality, SDA also utilizes optical sensors to detect and track objects in space against a predetermined catalog [20-21]. Therefore, a star tracker is well suited for SDA functionality [22] and as such a dual-use star tracker was funded by United States Government for development.

The purpose of in-space testing of this star tracker is to verify performance and functional requirements of both star tracker and SDA sensor functionalities in a relevant space environment in order to accelerate the Technical Readiness Level (TRL). In particular, a successful SDA product requires rigorous sensitivity modeling [23] and mission specific design [24]. In this paper, the development and requirements of this dual-use star tracker, its proposed test plan and scenarios, along with the resulting technology maturity and enabling future capabilities will be discussed.

2. BALL MAST CT-2020

Ball Aerospace (Ball) developed a new star tracker (the CT-2020) that was designed to optimize performance as well as size, weight, power, and cost (SWaP-C) by utilizing weighting functions [25]. The CT-2020 is designed to remain operational for 18 years while expose to the GEO environment or 7 years in LEO environment. This moderate accuracy star tracker (MAST) provides attitude accuracy of 1.5 arc-sec (1σ) at end of life (EOL) conditions for both LEO and GEO environments. When used in a typical spacecraft arrangement of two star trackers mounted perpendicular to each other, the system provides 1 arc-sec (1σ) 3-axis knowledge to the host spacecraft. The CT-2020 also functions with degraded performance on highly agile spacecraft with body rates up to 8 deg/sec.

The CT-2020 star tracker consists of five primary components as shown in Fig. 1: a unitary lens and lens housing structure, focal plane assembly (FPA), electronic circuit cards, a radiation shield, and a light shade. The core of CT-2020 is a compact mechanical design that places electronics around a cylindrical housing. The cylindrical housing also holds the lens assembly. The electrical assembly arrangement yields a balanced thermal environment to minimize thermally induced boresight shifts. The detector placement behind the lens dissipates heat and provides a stable mount. The detector package is hermetic and includes an integrated thermoelectric cooler (TEC) for precise temperature control. The features of the major CT-2020 components are summarized in Table 1.

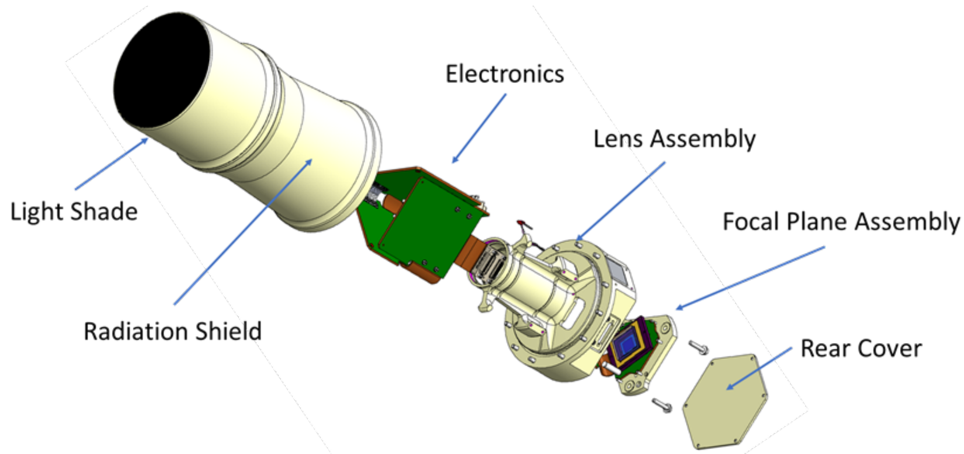

Fig. 1. CT-2020 Star Tracker

Table 1. Major Components of the Ball CT-2020 Star Tracker

Component	Description
Focal Plane Assembly	A domestically produced Staring Technology for Enhanced Linear Line-of-sight Angular Recognition (STELLAR) image sensor [26] as shown in Fig. 2: • Back-side-illuminated (~90% quantum efficiency (QE) at 600nm), high efficiency monolithic Complementary Metal–Oxide–Semiconductor (CMOS) • Resolution 1024x1024 pixels • 10 frames per second at full resolution • Full system-on-a-chip with integrated digital architecture capable of command and control that generates all internal timing for exposure control • Radiation-hardened design robust to radiation levels > 50 krad (Si) and immune to single event latch-ups (SEL) and multi-frame single event upsets (SEU)
Lens Assembly	• 10 deg field of view (FOV) • Exceptional boresight stability robust to thermal and mechanical environment • Optimum placement of the aperture stop allowing for volumetrically small and high performing Sun shade design
Electronics	All-digital custom-made application-specific integrated circuit (ASIC) processor: • Significantly reducing the part count compared to traditional field-programmable gate array (FPGA) processor • Simultaneous output of full frame image and centroid/attitude data enabling SDA capability • Efficient low voltage power supply (LVPS) board distributing the necessary power, while providing electromagnetic interference (EMI)/electromagnetic compatibility (EMC) robustness • Latest radiation hard and flight proven electronics architecture
Interface Ports	• Standard command and telemetry data via either a MIL-STD-1553 or RS-422 interface • Full frame video data from the FPA to the host platform via a separate Channel-Link interface • Simultaneous access to imagery data without compromising star tracker operation • Allowing the star tracker to be used as an alternative sensor for SDA or as a local camera for inspection or rendezvous and proximity operations (RPO)
Flight Software Design	Decades of Ball heritage in star tracker software (CT-602/CT-633 MAST and HAST-402 high accuracy star tracker (HAST) [3]) • Heritage HAST image processing algorithm • General architecture from a flight proven design suitable for the most critical missions • On-board star catalog derived from Department of Defense (DoD) Standard GNC Celestial Catalog (DS-GCC) and in compliance with DoD Instruction 4650.06 on Positioning, Navigation and Timing Management.

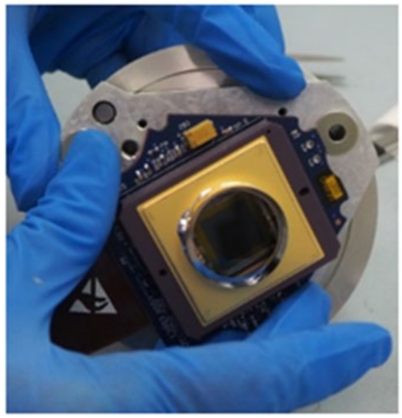

Fig. 2. Fully Packaged STELLAR

3. USSF DEVELOPMENT TEST AND EVALUATION PROCESS

The planned in-space test on this dual-use CT-2020 star tracker is to collect operational performance data to verify the functional requirements in order to accelerate its maturity from TRL-5 to TRL-7 by testing and demonstration in a relevant space environment. In addition, testing the CT-2020 in space affords an opportunity to exercises tactics, techniques, and procedures in the operational environment. It can also be utilized as a training platform for space operators.

The potential platform to accommodate this star tracker for in-space test needs to satisfy the requirements listed in Table 2. CT-2020 may fly on the International Space Station (ISS) but LEO is not the preferred orbit. Rather, it is preferable for the CT-2020 to fly at GEO in order to exercise the specific SDA functionality designed for US Space Force (USSF). A near-term flight opportunity for the CT-2020 was identified to be a hosted payload on Tetra-3 satellite, which is managed and operated by Department of Defense (DoD) Space Test Program (STP) [27]. Tetra-3 will be launched on an Evolved Expendable Launch Vehicle (EELV) while mounted on an EELV Secondary Payload Adapter (ESPA) ring for a rideshare into GEO orbit in 2023. The ESPA is outfitted as a free-flying Long Duration Propulsive ESPA (LDPE) spacecraft.

Table 2. CT-2020 Accommodation Requirements

Requirement	Description
Mass	3.4 kg
Volume	5.7” diameter, 11.75” height
Power	8W max.
Input Voltage	28V unregulated
Data Interfaces	MIL-STD-1553/RS-422: control and telemetry Channel Link: full frame data
Data Rate	2MB/frame, 10Hz frame rate

York Space Systems is currently building the Tetra-3 spacecraft as shown in Fig. 3 based on their heritage S-Class platform. This platform is specifically designed as a testbed to test and demonstrate prototype hardware in a relevant space environment. The CT-2020 will be mounted on the midst of the allowable experimental payload volume shaded in green. The platform is designed to adapt to the CT-2020 mechanical, thermal, and electrical interface definition as listed in Table 2. Fig. 4 depicts the Tetra-3 spacecraft envelope on the LDPE to give the reader a sense of its size, and dimensions with respect to the LDPE’s outer ring ESPA structure [28].

Tetra-3 has two likely payloads in the current configuration including CT-2020. Its key accommodation capability includes 10W continuous power supply or 100W at 10% duty cycle to test payload, payload mass up to 25 kg, and dimension up to 15”x15”x15” which is the green volume shown in Fig. 3. The platform features a GPS receiver, 3 reaction wheels, and its own set of two star trackers for three-axis stabilization with 0.005 deg pointing knowledge and 0.01 deg pointing accuracy. Note that CT-2020 is not planned for use in Tetra-3's attitude determination system. It also equips with a laser rangefinder and an infrared (IR) cameras used for RPO. Additional data interface provision is provided to accommodate the channel link data interface required by the CT-2020. The S-Band telemetry and commanding data link with the Air Force Satellite Control Network (AFSCN) augmented by the Commercial Augmentation Services (CAS) and civil networks will be ground networked to the Research, Development, Test and Evaluation (RDT&E) Support Complex (RSC) located at Kirtland Air Force Base in Albuquerque, New Mexico. The X-Band downlinked star tracker and SDA mission data will likewise go to the RSC for post-processing.

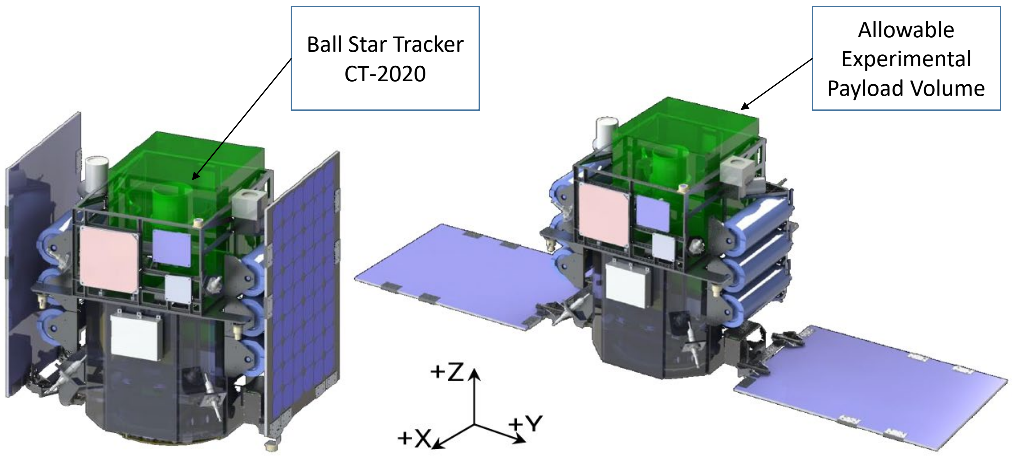

Fig. 3. Tetra-3 Satellite Rendering; (Left) Solar Arrays Stowed; (Right) Solar Arrays Deployed[1]

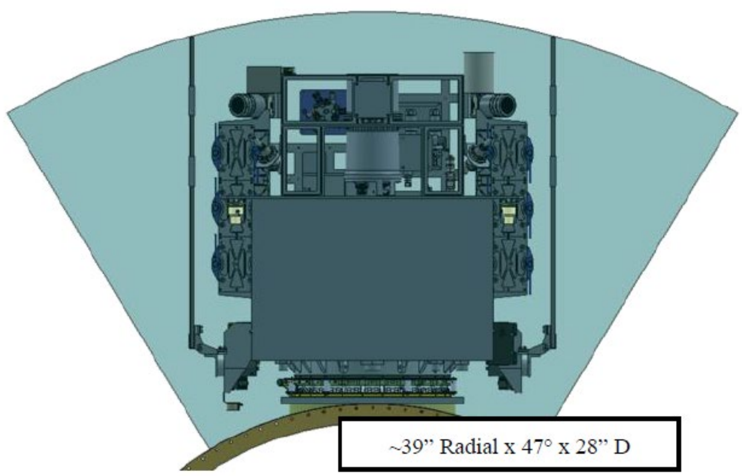

Fig. 4. Tetra-3 Envelope on the Long Duration Propulsive ESPA (LDPE)[2]

To support SDA in real-time, the full-frame 10 Hz data rate at 2MB/frame would require approximately 21MBps mission data-downlink capability. Due to the constraints of Tetra-3 platform on the memory size, downlink data rate, and real-time computing capability needed to perform lossless data compression or other on-board processing to alleviate downlink data limitations, selective sets of 10 Hz full frame data will instead be stored and downloaded to the ground during the test for subsequent post-processing afterwards.

[1] Graphics used with permission of York Space Systems
[2] Graphics used with permission of York Space Systems

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4. STAR TRACKER FUNCTIONALITY IN-SPACE TEST PLAN

The star tracker test objectives are categorized into multiple events by functionalities, including Power ON and Initialization, On-Orbit Calibration, Nominal Attitude Tracking, Maneuver Attitude Tracking, Sun Exclusion Angle Verification, Earth Blinding, Moon Blinding, Lost Track Recovery, and Star Tracker Test Data Analyses. Fig. 5 shows the operational States and Modes in CT-2020, which will be used in the in-space test planning.

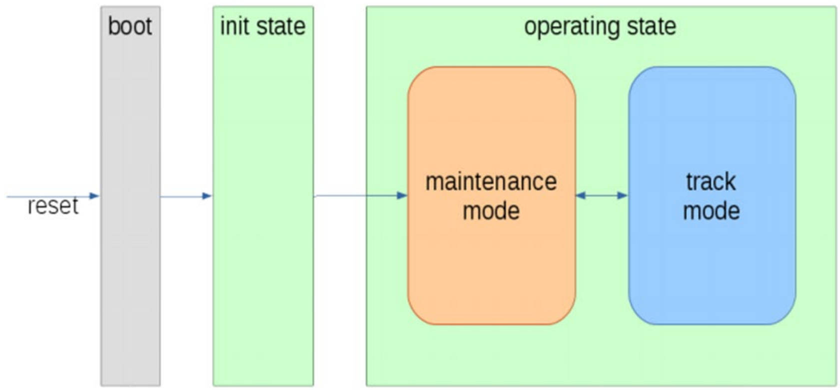

Fig. 5. Operational State and Mode Diagram

Upon power-on, the CT-2020 enters a Boot State, during which regular telemetry is not produced. The flight software (FSW) determines which boot image to load by a host platform provided word in the non-volatile memory. Then the FSW transitions to the Init State. While in this state, the host spacecraft cannot command the star tracker and the star tracker only produces status telemetry as it completes various startup-related tasks.

Once the system is initialized, the FSW further transitions to the Operating State and enters Maintenance Mode. In Maintenance Mode, the CT-2020 may be commanded to perform various memory-related tasks, including uploads, downloads, and cyclic redundancy checks (CRC) on specified regions of memory. The tracker also starts producing a synchronization pulse while in the Maintenance Mode, and pixel data are available via the Channel-Link interface.

The host spacecraft must send a command to initiate the change from Maintenance Mode to Track Mode. The tracker enters this mode in the Lost-in-Space condition without a priori knowledge, which requires either host platform provides attitude or at least four stars are identified then tracked by a pattern recognition technique [29] in order to exit this condition. The minimum four tracked stars can be achieved by either autonomous full-field search or a direct search command from the host platform. Once in Track Mode, all telemetered values are updated at the output frequency of 10 Hz. The CT-2020 stays in Track Mode until a reset occurs, or until commanded to Maintenance Mode by the host platform. Note that the nominal tracking in Track Mode relies on four or more stars in the field of view (FOV) being tracked for an attitude solution. When less than four stars are tracked, the attitude solution output would be temporarily suspended until total four starts identified and tracked again. The lost track recovery within the Track Mode is either autonomous or commandable via the host platform.

4.1 Power ON and Initialization

The first in-space test event demonstrates the star tracker can be powered on, execute commands, generate and deliver telemetry to the ground station. By design, CT-2020 is expected to initiate autonomously and stay in the Maintenance Mode after the unit is powered on. Once the host platform commands the star tracker to transition to the Track Mode, a full performance attitude solution will be achieved within 10 second and the corresponding data products delivered via downlink telemetry to the ground station for data analysis.

Note that CT-2020 does not have a switch on/off command function. The ground operation crew will send a command to the host platform to provide electricity to CT-2020. This power-on action will trigger the star tracker's initialization sequence. Once the star tracker is successfully initiated and autonomously transitioned to the

Maintenance Mode, the next objective is to demonstrate the star tracker accepts and executes all the commands issued from the ground via host platform. For example, the direct search command instructs the star tracker to autonomously search, acquire and track up to eight stars in regions of the tracker FOV with intensities above the pre-set threshold, and provide a 10 Hz full frame video output. This test event also demonstrates the star tracker will respond to other commands, such as stop tracking any individual star while maintaining track on the other stars.

The maintenance functionality is also demonstrated in this event. By design, a command from the host platform is required to transition from Maintenance Mode to Track Mode. Once in Track Mode, the ground commands the star tracker via host platform to stop all the normal operation and switch into the Maintenance Mode. The ground crew will then perform memory upload/download, star catalog updates, FSW upgrade, algorithms and spatial calibration on-orbit, and general on-orbit maintenance activities. While in Maintenance Mode, the star tracker is not actively tracking stars, but instead performs memory uploads, downloads, maintenance, etc.

In addition, the test event also demonstrates mode selection during trouble shooting. This functionality will be performed by the normal boot sequence as well as by manual selection to any mode desired.

Lastly, this event demonstrates the data handling and downlink telemetry. The purpose is to collect multiple frames of data, store in the memory provided by the host platform. This test depends on the amount of data storage provided by the host platform. For example, Tetra-3 built by York has a maximum 144 GB memory allocated for all the payloads; if memory is needed for only the CT-2020, then the York platform can store up to 114 minute segments at 21 MBps. After a segment is successfully transmitted to the ground, the data stored in the spacecraft memory will be cleared and set ready for the upcoming recording. This sequence will be repeated as necessary until all desired segments are recorded and transmitted to the ground. This sequencing will be planned after the operational profile is identified, as described above, and will take into account availability of AFSCN daily scheduling.

This test event will validate the power-on and commanding functionality of the star tracker using telemetry data against the expected values collected from the ground tests. Similarly, this test event will validate other functions such as anomaly troubleshooting, software, algorithms, and spatial calibration updates.

4.2 On-Orbit Calibration

The second event will demonstrate CT-2020 can be calibrated in preparation for nominal operations by removing a majority of the bias. This calibration event in Track Mode must be repeated prior to each subsequent functional and performance test event in this test plan. The calibration ensures consistent measurements, in particular the stability of CT-2020's Boresight Reference Frame (BRF) with respect to its Mechanical Reference Frame (MRF) at the mounting interface to the host platform that may be shifted due to launch and thermal variations. The calibration is achieved by comparing measured stars on FPA against the known star positions stored in the on-board star catalog to update the star tracker parameters.

This test event also verifies the following alignment requirements:

- The shift in the BRF with respect to the TMF is less than 10 arc-sec, peak-to-peak, per coordinate due to launch environments;
- The shift in the BRF with respect to the TMF is less than 2 arc-sec per axis over a ten-minute period given a baseplate change within 5 °C at the mounting interface;
- The shift in the BRF with respect to the TMF is less than 10 arc-sec per axis over the baseplate temperature range of -25 to +45 °C;
- CT-2020 demonstrates the capability of executing a periodic on-orbit calibration to recover performance pending on the spacecraft structural stability as a function of thermal deformation, and the nature of the operational orbit; and
- CT-2020 produces an output of time stamp for star-direction and attitude telemetry and allows the host spacecraft to synchronize the time stamp on a 10-Hz-frame boundary. This stamp indicates the time of validity.

Note that the host spacecraft is expected to provide best effort on temperature control in the -25 to +45 °C range at the baseplate using temperature sensors and/or heaters during the testing.

4.3 Nominal Attitude Tracking

This test event demonstrates the nominal attitude determination and tracking functionality when the satellite is in a stationary orbit and not performing any maneuver or slew to change the satellite orientation as well as the star tracker FOV. The tracked star-position unit-vectors and an attitude solution in terms of quaternion at a 10 Hz output rate with less than 300 milliseconds latency will be demonstrated by this event. The synchronization of the CT-2020's internal clock to the host platform's clock will also be demonstrated. The key telemetry to watch include: a) X and Y angular position of the tracked stars in MRF, b) Attitude solution in terms of quaternion that relates the MRF to a celestial coordinate frame, c) brightness and an identification number for each star being tracked, d) lens temperature(s), e) detector temperature(s), f) a measure of the focal plane background signal, and g) general health and Fault, Detection, Isolation, and Recovery (FDIR) status. In order to correlate the in-space measurements with ground testing, and the digital twin models, it is necessary for the host platform to either outfit the baseplate with thermistors and heaters, or at least measure the temperature at the baseplate. The platform temperature telemetry should be monitored as well. This event consists of multiple test cases at various baseplate temperatures to verify the star tracker's requirements as below.

The full performance attitude accuracy across a boresight of less than 1.5 arc-sec (1σ) per axis, and a roll attitude accuracy about boresight of less than 15 arc-sec (1σ) until EOL will be verified. The primary contributor to EOL degradation in star tracker performance is due to radiation degradation on the image sensor. Ball has completed extensive radiation testing on the image sensor and developed a high fidelity models to simulate the degradation. Therefore, Ball will take Beginning of Life (BOL) data on-orbit, compare with model, and project performance at EOL. Note that the lost track scenarios of less than four tracked stars in the FOV and their recoveries will be fully exercised in a later event.

Similarly, the test will demonstrate that the 1) random measurement error (RME) will not exceed 3.0 arc-sec (1σ) per star for each axis, 2) low spatial frequency error (LSFE) will not exceed 1.0 arc-sec (1σ) per star, per axis, at the median star magnitude, and 3) the intensity of a tracked star with a 1-sigma error will be less than 0.25 Instrument Magnitude (MI) until EOL of the CT-2020. As for reference, RME is the combination of noise equivalent angle (NEA) temporal error and high spatial frequency error (HSFE). The median star magnitude in the on-board star catalog is approximately 5.5 MI.

The timing knowledge accuracy of the measurement of the star position unit vectors and attitude solution is less than 20 microseconds. The CT-2020's internal clock will stamp the star measurements to the host spacecraft at a time referenced to that clock. With the synchronization signal from the host platform, CT-2020 can report the star measurements referenced to the host spacecraft's clock instead. The host platform can then compare the time receiving output from the star tracker against the time stamp in the measurement to find out the latency.

To prove that the CT-2020 meets all the requirements when held to a baseplate temperature range between -25 and +45 °C, the host platform needs to provide best effort on temperature control during this testing. For each star-tracker performance-measurement, it is necessary to obtain the spacecraft attitude solution simultaneously with the star tracker performance measurement, and associated baseplate temperature measurement.

4.4 Maneuver Attitude Tracking

This event demonstrates the nominal attitude determination and tracking functionality while the host platform is slewing that change the star tracker FOV or performing delta-V maneuver. This test focuses on proving the star tracker's capability of maintaining track on celestial coordinate frame when the host spacecraft is slewing with various speeds up to 8 deg/sec. The CT-2020 will also demonstrate the functionality of generating full performance for star crossing rates less than 0.5 deg/sec. Finally, the reduced RME performance at EOL as listed in Table 3 for star crossing rates up to 8 deg/sec will be verified.

Table 3. Star Angular Rate (deg/sec, per axis) Predicted EOL RME Performance

Star Instrument Magnitude	Star Angular Rate (deg/sec, per axis), EOL RME Performance in plain text (seconds of arc, 1-sigma)						
Mi	0.0-0.1	0.1-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-3.0	3.0-8.0
2	0.72	0.86	0.92	1.01	1.11	1.24	1.77
3	0.76	0.92	1.03	1.14	1.31	1.64	2.89
4	0.87	1.10	1.33	1.59	1.90	2.67	5.92
5	1.12	1.58	2.14	2.71	3.24	5.03	16.38
5.32	1.29	1.85	2.52	3.32	4.11	6.47	
5.9	1.69	2.60	3.86	5.87	8.74	13.70	
6.5	2.31	3.95	Not Applicable				
Integration Time (s)	0.098000	0.049000	0.029000	0.023000	0.020000	0.016000	0.008000
Internal Rate [hz]	10	19.6	32.3	40	45.5	55.6	100

Additionally, this test event is designed to explore the attitude and star measurement performance over 80% of the 4π steradian sky coverage with a 95% goal, which is dictated by the orbit of the host satellite and orientation of the star tracker on the host spacecraft.

Again, this test event is conducted in a temperature setting relative to the space environment to prove that the CT-2020 meets all the requirements when held to a baseplate temperature range between -25 and +45 °C. The host spacecraft must provide best effort on temperature control during this testing.

4.5 Sun Exclusion Angle Verification

In this event, the CT-2020 will slew toward to the Sun for a certain period-of-time then slew away to determine the level of performance degradation while the Sun is inside the exclusion angle. This event will also point the star tracker toward the Sun to measure thermal response. The telemetry to watch includes attitude, individual star measurement, timestamp, quality of 10 Hz video output, housekeeping data, and fault monitors. Those telemetry data are used to compare against the expected values to validate performance and verify bright object in particular. Multiple test cases will be designed to verify the following requirements:

- Full performance with the Sun at an angle ≥ 15 or ≥ 25 degrees (depending on the light shade option) as measured from the boresight of the tracker to the edge of the solar disk.
- A Bright Object Indicator in the CT-2020 will be turned on when the Sun is present within the Sun exclusion angle.
- Degraded performance in less than 2 minutes after solar exposure has transitioned ≥ 20 degrees from the tracker boresight;
- Full performance in less than 30 minutes after solar exposure has transitioned ≥ 20 degrees from the tracker boresight;
- The star tracker does not sustain any permanent damages after the boresight is exposed under the Sun for one hour while the CT-2020 is power OFF.

4.6 Earth Blinding

In this event, the CT-2020 slews toward the Earth for a certain period-of-time until it either completely loses the functionality or suffers an undetermined performance reduction depending on the orbital altitude. Then the CT-2020 will slew away once these conditions occur. This allow the CT-2020 to recover normal performance while Earth is still inside the exclusion angle or when Earth is out of the exclusion angle. The star tracker should regain full performance star-position unit-vectors or an attitude solution with a fully illuminated Earth whose limb is ≥ 12.5 or ≥ 25 degrees (depending on the light shade option) from boresight. The Bright Object Indicator in the CT-2020 is expected to flip on when Earth is in the FOV of the tracker. The key telemetry to watch includes attitude data, individual star measurement, time stamp, quality of 10 Hz video output, housekeeping data, and fault monitors.

4.7 Moon Blinding

This test event is similar to the previous test event on Earth Blinding. It demonstrates the performance reduction with Moon in the tracker FOV. The CT-2020 slews toward to the Moon for a period-of-time and then slews away. The telemetry data, such as attitude, individual star measurement, time stamp, quality of 10 Hz video output, housekeeping data, and fault monitors, will be collected and analyzed to characterize the CT-2020's performance with the moon in the FOV. The Bright Object Indicator is expected to be ON, when Moon is in the FOV of CT-2020.

4.8 Lost Track Recovery

When the CT-2020 is commanded to enter Track Mode, it is automatically in the Lost-in-Space condition until four stars are identified and tracked (acquired autonomously by full-field search or by host spacecraft's direct search command), at which time it starts providing both star vector measurements and attitude telemetry. The CT-2020 stops the attitude solution output either when, 1) the number of tracked-stars is less than four, or 2) there is no star tracked at all (a Lost-in-Space condition). This test event will verify the CT-2020 can recover from such scenarios to providing full attitude performance data.

In the scenario of less than four tracked stars, the CT-2020 is expected to autonomously perform a full-field search or direct search for host platform commanded star(s) until it reacquires enough stars to provide a full attitude solution. Since the remaining tracked stars maintain partial attitude information during the process, the newly found star(s) are compared to the on-board star catalog at their corresponding celestial locations so that the recovery is expected to be fast whenever enough stars available in FOV.

In the scenario of complete loss of all tracked stars resulting in a Lost-in-Space condition, a full-field search or direct search for specific stars commanded by the host spacecraft along with the time-consuming star-pattern match-algorithm [27] is executed. The recovery is expected to be completed within 10 sec whenever four valid stars are available in the FOV.

There is a variety of conditions when less than four stars may be tracked by slewing CT-2020's FOV to various spots in the sky, e.g., a solar impingement, earth limb impingement, etc. Testing will occur at various slew rates to determine time required to obtain track on stars, perform the Lost-in-Space algorithm, and begin producing an attitude solution.

4.9 Test Data Analysis

This event is to analyze the telemetry data downloaded to the ground. The analyzed data will be used to verify the star tracker performance against the requirement, and used to validate the digital twin model and simulation fidelity. For example, the time required to achieve Lost-in-Space solution with 99.5% probability or higher after initial power on is analyzed under a set of conditions. These conditions include high/low body rate conditions with different views of the celestial sphere, high/low body rate conditions with the Moon in the FOV, and high/low body rate conditions as a function of solar exclusion angle.

5. SPACE DOMAN AWARENESS IN-SPACE TEST PLAN

The second part of this planned in-space test is to verify requirements for the CT-2020 SDA functionality.

5.1 Features of Space Doman Awareness Using CT-2020

The CT-2020 carries additional capability to output 10 Hz full-frame image while conducting its regular star tracking activities. This means that, along with the frame-data, it continuously provides attitude tracking quaternion data that effectively and accurately registers up to eight stars in the output frame. Since star registration is often one of the first steps associated with SDA mission data post-processing, the CT-2020 reduces the ground or on-board algorithmic complexity by performing this function internally.

The full frame data rate at 10 Hz is around 21 MB/sec. Even though Ball does manufacture real-time image processing hardware that reduces the raw images for on-board SDA observations, for this upcoming in-space demonstration, full-frame data will be stored on-board and downloaded to the ground for image processing to convert and reduce the raw data for observations. On-board lossless compression, if applied, can reduce this data rate by a factor of two or three.

An advantage of simultaneous star tracking is that the frame integration time between 10 and 98 msec is controlled internally by the CT-2020. This time range is generally shorter than what would be preferred for tracking SDA objects at GEO. Fig. 6 shows the expected visual magnitude sensitivity as a function of frame integration time, as evaluated by Ball's high-fidelity Visible Sensor Model, which shows a limiting magnitude of about 8.3 with the CT-2020s maximum integration time of 98 msec. Fig. 7 converts the limiting magnitude to a target size at range calculation, where a 20% diffuse (Lambertian) target with a 1 m^2 projected area is visible at 2,000 km range.

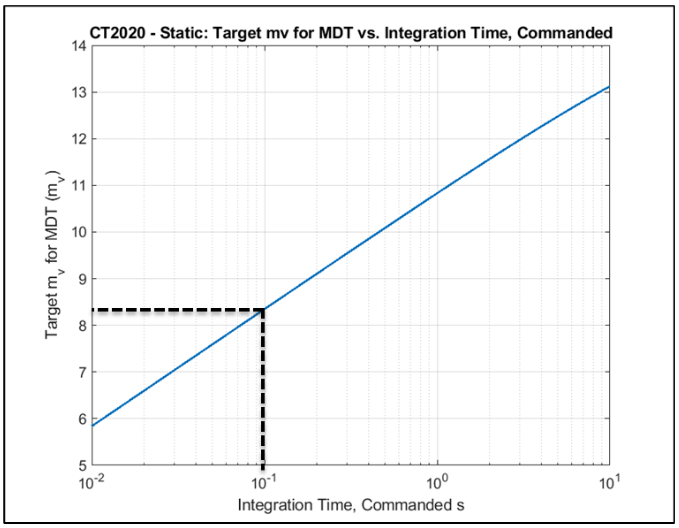

Fig. 6. CT-2020 Maximum Detectable Target (SNR=6) Visual Magnitude vs. Frame Integration Time

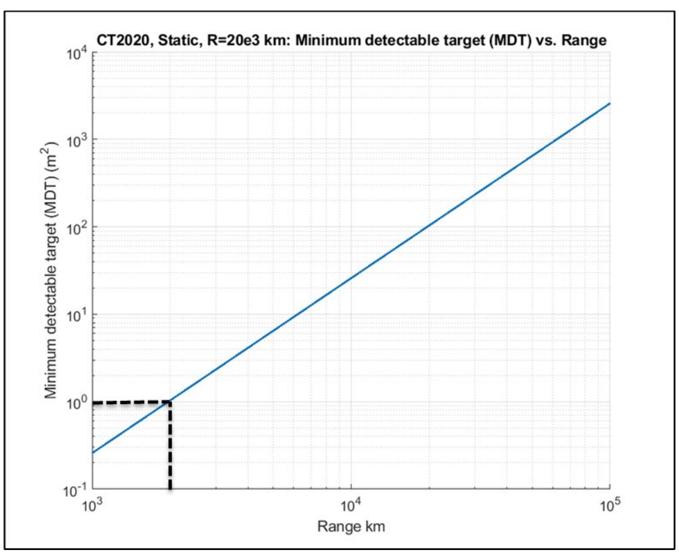

Fig. 7. CT-2020 Minimum Detectable Target Size (SNR=6) with 98 msec Frame Integration Time

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For the above performance modeling, both jitter and target smear effects have been removed from the analysis. Due to the CT-2020's relatively large instantaneous FOV, nominal host jitter effects have negligible impact by design. Furthermore, if velocity matched filtering (VMF) is used within the applied mission data processing to integrate target motion both within frames and over co-added frames, then the effect of target smear on signal-to-noise-ratio (SNR) is minimized and can be deemed negligible for the purposes of these predictions.

To achieve greater sensitivity, frames can be noncoherently co-added to generally provide a root-N SNR performance improvement as the number of co-added frames are increased. Here, combining 10 seconds worth of 98ms frames results in co-adding 100 frames. As shown in Fig. 8, this boosts the limiting visual magnitude to almost 11, which when evaluated using Fig. 9, increases the maximum detectable range for a 1 m^2 target to about 7,300 km. Co-adding 1000 frames over 100 seconds results in maximum ranges ~12,000 km.

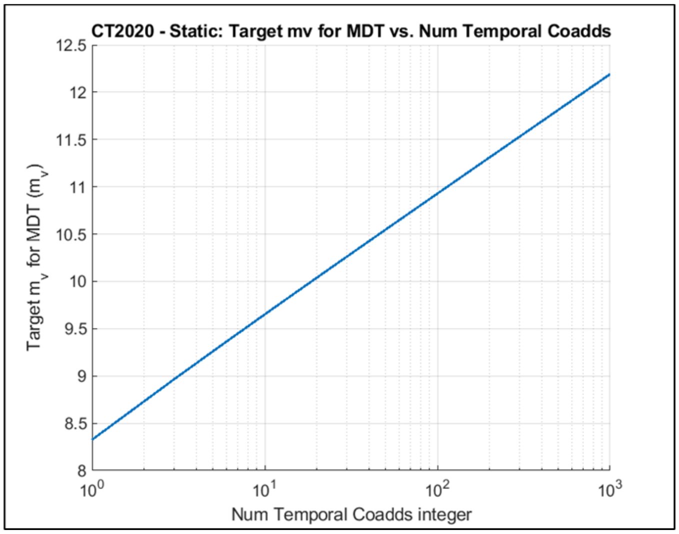

Fig. 8. CT-2020 Maximum Detectable Target (SNR=6) Visual Magnitude vs. 98 msec Frame Co-Adds

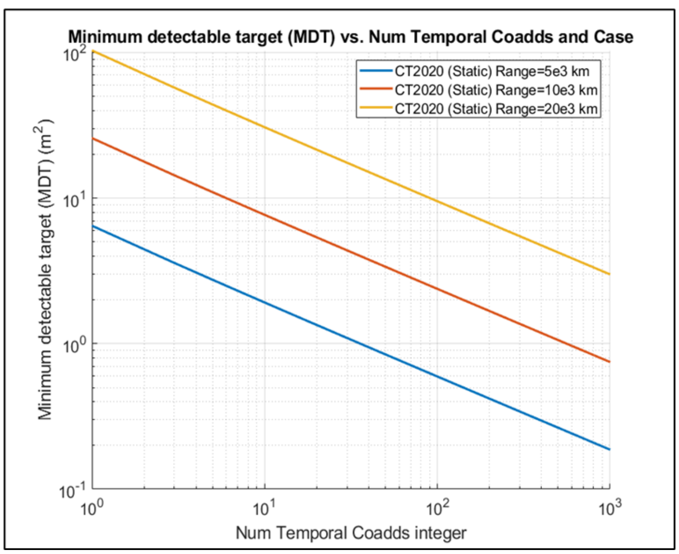

Fig. 9. CT-2020 Minimum Detectable Object Size (SNR=6) vs. 98 msec Frame Co-Adds

The CT-2020 is inherently a small SDA sensor, so one must reasonably expect proportional performance when compared to larger-class sensors. However, by co-adding frames, local awareness can be achieved to maximum

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distances of >10 Mm, which is sufficient to monitor a local portion of the GEO belt or to assert general local space awareness.

5.2 Ground Segment to Support Space Doman Awareness Test

SDA data that is collected on-board will be transmitted to the ground for subsequent mission data post-processing. On-board, full-frame data is collected and stored. After transfer to the ground, the data is analyzed for SDA content. Fig. 10 illustrates the processing steps that are applied to the data for each received frame. The resultant output are the locations, in terms of right ascension and declination, of all of the detected space objects (non-stars) in each frame. These observations are then made available for subsequent orbit determination processing to convert and fuse observation series (over many frames) into full 6 degree-of-freedom state vectors. The observations may also be shared via the DoD's Unified Data Library (UDL) for the benefit of other end-users.

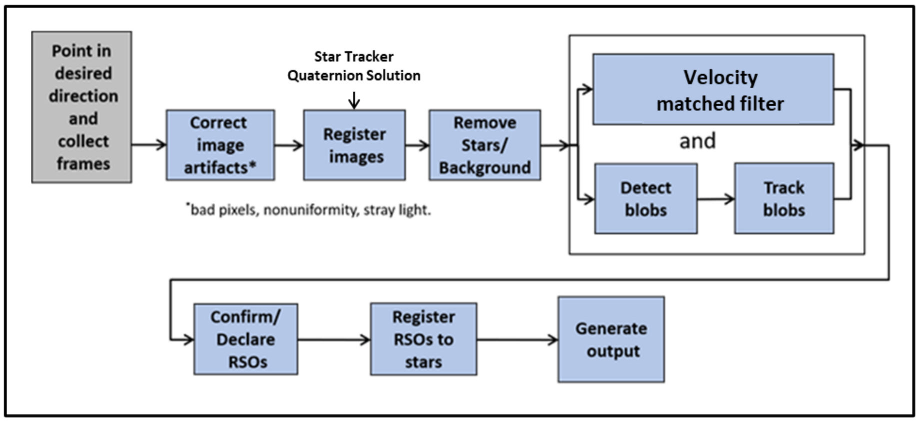

Fig. 10. Image Processing Steps for SDA Mission Data Post-Processing

In Fig. 10, mission data processing starts with non-uniform background correction and the suppression of image artifacts, such as bad pixels. Next, the star-tracker quaternion-solution is used to map each pixel of the raw data image to the inertial (celestial) reference frame. The following step identifies and discriminates stars from other space objects and subtracts the star signatures (streaks) from the image leaving only space objects. After this, two separate techniques are used in parallel to detect and characterize space-object signal-energy. The first technique, VMF, is used to identify low SNR space objects, where multiple target motion hypotheses are considered to non-coherently stack frames and integrate smeared target energy within each frame. The results of VMF are combined with a second technique, "blob" detection, which is a single-frame detection technique for bright target space objects. After detection, the outputs from the two techniques are merged to avoid duplication between the two approaches. Finally, the detections are converted from pixel-space to inertial-space using the quaternion-derived pixel map generated previously. Once complete, all the metadata (timestamp, location, SNR, brightness, etc.) associated with each detection is combined into a common message structure standard appropriate for orbit determination and data sharing.

5.3 In-Space Test Events to Demonstrate Space Doman Awareness

Below are two planned events for demonstrating SDA functionality in the upcoming in-space test. It should be noted that SDA events might be conducted in any order or cadence, with the only inherent condition that the on-board SDA data buffer not overflow its maximum storage capacity.

The first test event is to collect SDA data in the Easterly[3] direction along the GEO belt. The host platform will orient CT-2020 in azimuth to point Easterly with a small elevation (e.g. 7 degree) towards the Earth to capture GEO Resident Space Object (RSO) targets. 10 Hz frame data will be captured and stored for at least 30 seconds with a goal of 300 seconds.

[3] Easterly direction is the direction of flight and is commonly called the Ram direction

The second test event is to collect SDA data in the Westerly[4] direction along the GEO belt. Similarly to the Easterly Data Collection event, data will be collected when the CT-2020 is oriented in a Westerly direction. 10 Hz frame data will be captured and stored for at least 30 seconds with a goal of 300 seconds.

After each event, test data will then be transferred from on-board storage to the ground for subsequent SDA mission data post-processing and analysis. On-board SDA processing is not planned for the upcoming in-space test-flight but will follow in a future flight.

6. CONCLUSION

A new Ball MAST CT-2020 was funded by the Government for development to meet the Defense Industry Base (DIB) need and compete in the global market. This dual use star tracker features additional functionality as a SDA sensor. To mature this star tracker from TRL5 to TRL7, USSF is planning to conduct an in-space test on this star tracker to characterize the performance and verify requirements in a relevant space environment in terms of both star tracker and SDA functionalities. The main features of this MAST, planned in-space tests, and planned flight on DoD STP Program's Tetra-3 spacecraft were discussed in detail. The challenges of this upcoming in-space test include the temperature control at the CT-2020 baseplate for tracker performance verification and correlation as well as video downlink bandwidth for the SDA demonstration. Since SDA is a new feature beyond CT-2020's heritage at Ball, it will be fully exercised on the ground in this upcoming flight as a learning step. Once the conceptual operation is proven, the on-board SDA processing test with processor enhancement will be conducted in the follow-on flight, which will also serve as a technical demonstration for in-space computing. The candidate follow-on flight includes a newly initiated in-space developmental test (iSDT) persistent platform, which is being worked by the authors [30].

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