ASTRO© CL: THE RADIATION HARD CONSTELLATION STAR TRACKER

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The ASTRO© CL is Jena-Optronik's compact star tracker, which is optimized for small satellites and constellations. The core driver of the ASTRO© CL design is bringing radiation robustness to compact constellation class star trackers. This goal is achieved by combining the system-on-chip FaintStar2 detector with specifically selected EEE-parts and radiation-hard optics as well as advanced image processing algorithms, which provide stable and robust performance up to end-of-life conditions. Hence, the ASTRO© CL star tracker is well suited for extended mission durations of more than 10 years in the challenging radiation-environments at H-LEO orbits between 1200 km to 1400 km and in MEO orbits of 8000 km.

The compact design of the ASTRO© CL star tracker allows its integration on small satellites. The footprint is 60 x 60 mm² with a height of less than 130 mm. It is equipped with a stray-light blocking baffle that reduces the sun exclusion angle to a 26° half cone angle. The overall weight is ~300 g, depending on the selected baffle configuration. The typical power consumption is 1 W.

The ASTRO© CL star trackers are delivered with the ASTROlib control software library, which is easily integrated into the onboard computer systems and already supports multiple architectures (e.g., LEON3/4, PowerPC and different ARM systems). Integrating the star tracker library directly into the onboard computer allows a more compact design of the star tracker. The included noise removal algorithms enable retention of the on-orbit performance for more than ten years even in the H-LEO and MEO orbits. The library also supports camera functionality of the ASTRO© CL.

With the ASTRO© CL being more compact than previous star tracker generations, also more compact optical ground support equipment has been developed. This includes the Optical Star Pattern Simulator (OSPS), which is equipped with an alignment mirror cube. The OSPS allows aligning the ASTRO© CL on small satellites with similar precision as for established "large" star trackers like the ASTRO© APS. In contrast to the large star trackers there is no need for a mirror cube directly attached to the ASTRO© CL. Hence, reducing the star tracker's mass and foot print.

The demand for high volume production in the constellation satellite market calls for efficient manufacturing, assembly, integration and test capabilities as well as processes. Jena-Optronik has established new production and test approaches that allow the completion of more than 12 units per week currently; aiming to reach a continuous output of 20 units per week within the coming year. This is enabled by the ASTRO© CL design with a reduced number of individual parts. The design features a single integrated central imaging and electronics board, which is assembled in highly automated processes. As a final manufacturing step, the new test approach allows to run streamlined acceptance tests for multiple units in parallel.

In this contribution, we present the ASTRO© CL design and performance with the ASTROlib. We summarize the design features that allow an optimal combination of compactness, performance and radiation hardness for satellite constellations. Moreover, we describe the high precision alignment concept of the OSPS ground support equipment, which replaces having a mirror cube on each single star tracker.

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INTRODUCTION

The ever-growing number of satellite constellations, in orbit and in preparation, calls for cost-efficient high-volume availability of satellite components – among them, star trackers as accurate sensors for the attitude and orbit control systems. At the same time, the constellations start to utilize higher LEO orbits between 1200 km and 1400 km as well as MEO orbits which enable efficient ground coverage and avoid congestion in the lower orbits. These higher orbits also have more stringent requirements with regard to radiation hardness, especially on long-term missions.

From the start, Jena-Optronik has designed its constellation class star tracker ASTRO© CL for cost effective production without making compromises concerning the radiation hardness. The ASTRO© CL combines the ESA qualified FaintStar2 system-on-chip detector[1] with specifically selected radiation hard EEE-parts (Latch-up free, TID ≥100 krad (Si) for all active parts) and radiation hard optics. The ASTROlib control software for the ASTRO© CL employs the fixed-pattern-noise (FPN) removal algorithms which are already well-proven in our ASTRO© APS star trackers[2]. These algorithms ensure effective noise removal coping with the total non-ionizing radiation dose (TNID) induced effects on the detector, like dark current non-uniformity (DCNU). Cost effective production is ensured via the simplified design in terms of the number of parts and the applicability of highly automated assembly processes. The core of the ASTRO© CL is a single integrated imaging and electronics board. The ASTRO© CL star tracker system comprises the optical head and the ASTROlib software library, which allows integration of the star tracker functionality directly into the on-board computing systems.

New ground-support-equipment was developed along with the ASTRO© CL to account for and support the more compact star tracker design. This includes the optical star pattern stimulator and alignment tool: the OSPS. The OSPS stimulates a static star pattern for the ASTRO© CL. It is equipped with an alignment mirror. This mirror on the OSPS replaces the need for having an alignment mirror on each single star tracker while allowing high accuracy alignment on spacecraft level. In addition, the individual star tracker alignment measurement for each unit may be skipped completely in favor and as precondition for a high MAIT production throughput.

ASTRO© CL DESIGN AND PRODCUTION PHILOSOPHY

The ASTRO© CL optical head consists of only four main modules: the integrated imaging and electronics board module, the lens, the housing and the stray light baffle (Figure 1). With regards to a streamlined production, the ASTRO© CL has been designed for automated assembly processes and consists of a low number of individual parts. The integrated imaging and electronics board is pre-assembled in fully automated processes and finally mounted into the board module frame. The board module provides adjustment capabilities to allow focal plane adjustment once the lens is installed. We have established a proprietary machine vision process that automatically evaluates the focal plane adjustment and supports the quick optimization of the adjustment for each assembly. Finally, the adjusted board module with the lens is installed in the housing and the stray light baffle with 26° (32° are available as well) half cone sun exclusion angle is attached. The acceptance testing process has been streamlined to test multiple units in parallel. Vibrational testing may be performed with up to 12 units in parallel and thermal cycling with up to 8 units (Figure 2). The whole process is easily scalable. Currently, an upgrade to reach a continuous output of 20 units per week is in implementation.

Figure 1: Exploded view of the ASTRO© CL showing the main modules (left), ASTRO© CLs lined up for final visual inspection (right).

The EEE-parts and the lens material of the ASTRO© CL have been selected giving special attention to radiation robustness. The integrated imaging and electronics board is the core of the system. It integrates the FaintStar2 detector along with the low drop out regulators for the power supply of the detector and the crystal oscillator which provides the system clocking. These EEE-parts are latch-up free (no events for LET up to 60 MeV/mg/cm²) and have total ionizing dose tolerances in excess of 100 krad (Si). The lens contains the same radiation hard glass types already used in our heritage star trackers like the ASTRO© APS. The effective transmission loss over the lifetime is <15% for the radiation critical low-Earth orbits between 1200 km and 1400 km.

Figure 2: Twelve ASTRO© CL on vibration test mount (left). Four ASTRO© CL in preparation for thermal testing (right).

The star tracker system is complemented by the ASTROlib control software library. The ASTROlib may be integrated directly with the onboard computing system or a separate processing unit. It supports multiple architectures and has already been deployed on LEON3, LEON4 and different ARM systems. Customers have already shown and confirmed the straightforward implementation of the application software library. Especially the TNID adversely affects the detector noise performance over on-orbit lifetime. As TNID increases the DCNU and number of white pixels on the detector increase as well. The ASTROlib includes our well-established algorithms for FPN removal[2]. These algorithms effectively counter the effects of the DCNU and white pixel degradation, retaining excellent attitude noise performance of the star tracker over the full 10-year lifetime in the high LEO orbits.

PERFORMANCE

The performance of the ASTRO© CL is determined based on a combination of laboratory experiments and analyses. The begin of life (BoL) attitude performance (without radiation loads) is obtained using a test bench with a high precision turntable and a collimating telescope stimulating a single star. These measurements yield data on the temporal noise (TN), the high spatial frequency error (HSFE) and the low spatial frequency error (LSFE). The TN covers noise contributors, which are spatially independent and uncorrelated within the time domain e.g., shot noise or dark current noise. The HSFE covers noise and systematic error contributions that are spatially correlated on scales of one pixel while being uncorrelated in the time domain. Lastly, the LSFE covers those contributions that are spatially correlated over scales covering the whole star tracker Field of View. Examples for HSFE are non-uniformities on pixel scales like DCNU. An example of LSFE are calibration residuals. The laboratory TN, HSFE, and LSFE data is used to calibrate our simulation test bench. The simulation test bench incorporates fully representative ASTROlib algorithms and star tracker control mechanisms to allow software in-the-loop testing using genuine detector images and generated star patterns. This way it provides the overall attitude accuracy of an ASTRO© CL star tracker with up to 16 tracked stars. Multiple engineering models of the ASTRO© CL were equipped with FaintStar2 detectors that have been exposed to TNID loads up to ~$2.3 \cdot 10^9$ MeV/g(Si) covering 15 years of GEO, as well as 1200 km and 1400 km LEO orbits with 10 years mission time. The laboratory data gained from these units has been used to teach our simulation models in order to gain reliable performance estimates throughout mission time and for various orbits. In our models, we assume that the radiative dosage increases linearly over lifetime. Both, TN and DC exhibit a linear increase with respect to TNID, while DCNU increases exponentially with an exponent smaller 1 with respect to TNID.

The resulting attitude accuracy for different orbit examples is listed in Table 1. It needs to be highlighted, that the BoL to EoL values are degrading only very slightly over the lifetime for all S/C rotation rates below 0.5°/s. This is due to the effective DCNU reduction by the FPN removal algorithms which are operable up to this angular rate. For comparison, a rotation rate of 0.8°/s is listed for BoL and EoL representing the performance without FPN removal algorithms.

Apart from attitude tracking, the BoL *acquisition* performance was measured in the laboratory using the in-house optical stimulator test bench (OSIL). The OSIL is able to stimulate star scenes covering the star tracker field of view anywhere on the celestial sphere. 10.000 randomly selected lines of sight (LoS) are displayed for the acquisition performance measurements at each tested rotational rate. Tests were performed at 30°C detector temperature. The BoL acquisition was ≥99.9% for rates up to 5°/s. The typical acquisition times are better than 2 s for rates up to 3°/s and better than 10 s for rates up to 5°/s*.

* Test results from optical stimulator test bench (OSIL), rate applied cross-boresight, mean acquisition time for 10,000 LoS with random distribution over the full celestial sphere

Table 1: Performance at detector temperature of 30°C

Orbit	Time on Orbit in Years	Rotational Rate** in °/s	Radiation	Attitude Accuracy (3σ) in arcsec	
				X, Y	Z
All	BoL	≤0.5	none	6	35
850 km, high inclination	10	≤0.5	moderate	7	46
GEO	15	≤0.5	moderate	7	46
1200 km, high inclination	10	≤0.5	high radiative dosage orbit	9	72
**Rate applied on cross-boresight axes; Significantly higher rotational rates are supported for acquisition and tracking in general; FPN filter threshold depends on ASTROlib update rate (e.g. 0.5°/s for 5 Hz)					

The EoL acquisition performance was established using the simulation test bench. The simulations yield an EOL acquisition coverage of ~99% over the full celestial sphere.

Beyond the star tracking functionality, the ASTROlib includes a photo functionality. Configurations of the ASTRO© CL optical head with lenses optimized for wide field of view imaging are available, as well.

ALIGNMENT CONCEPT

High precision star trackers like the ASTRO© APS are typically delivered with an alignment mirror cube to enable precise alignment measurements between the star tracker's boresight reference frame (BRF) and the spacecraft reference frame (SRF). This can also be used to gain precise alignment information between the star tracker and payload instruments that are equipped with alignment mirrors. For compact constellation class star trackers, such alignment mirror cubes would have significant impact on the star tracker volume and weight. Therefore, a different approach has been developed for ASTRO© CL.

Measurement and provision of alignment data of the BRF relative to the star tracker's mechanical reference frame are a possible work around to avoid the use of alignment mirror cubes. However, to attain similar precision this approach increases accuracy requirements on manufacturing tolerances of the spacecraft star tracker and payload interfaces (e.g., surface flatness, relative surface orientations) and assembly, driving the system cost.

With our OSPS[3] alignment tool we have developed an alignment approach that retains the high precision alignment capabilities of star trackers with mirror cubes without the need to permanently attach a mirror cube to the star tracker. The OSPS can be operated at standard atmospheric conditions and is shown in Figure 3.

Figure 3: OSPS - Alignment Tool (left), OSPS mounted on ASTRO© CL (right)

The OSPS is equipped with an alignment cube as an external angular referencing optical interface. The mirror cube has got highly flat surfaces on all outer planes which can easily be utilized, for example by a theodolite. A major advantage of the OSPS is its representation of a real star constellation. This real sky constellation enables to employ the ASTROlib flight software and to use its nominal attitude-tracking mode. By this mode a high measurement accuracy is present and measurement errors are minimized to ensure a high reliability of the measurement setup and therefore the resulting alignment of SRF to ASTRO© CL BRF. The functional principle of the alignment setup using the OSPS is illustrated in Figure 4.

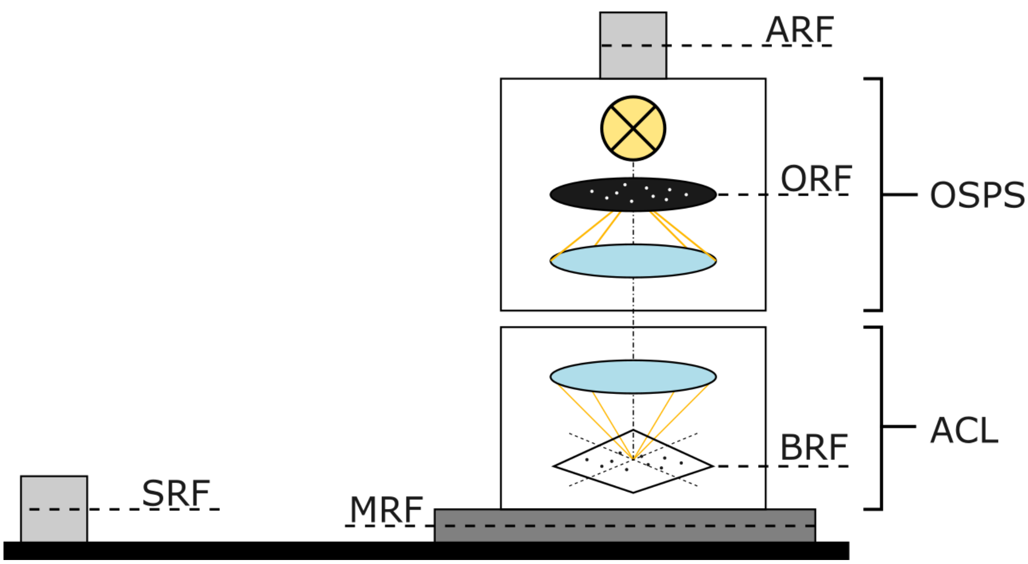

Figure 4: Functional principle of the OSPS measurement, also showing the OSPS Reference Frame (ORF) and Alignment Reference Frame (ARF)

Each OSPS comes with its individual calibration quaternion which is distributed with the calibration documentation of the OSPS. The calibration is described by the following rotation:

$$Q_{ARF} = Inv(Q_{STR} \times Q_{OSPS})$$

The attainable 3σ measurement uncertainty of the OSPS calibration quaternion is better than 25” around the cross-boresight axes x/y and better than 75” around the boresight axis z.

During spacecraft integration the OSPS is stimulating the ASTRO© CL star tracker resulting in an attitude quaternion output of the star tracker, together with the calibration quaternion of the OSPS it is possible to calculate the orientation between the star tracker boresight reference frame (BRF) and the Alignment cube reference frame (ARF). From this point, the alignment measurement process relative to the spacecraft reference frame is the same as for classical star trackers directly equipped with an alignment cube.

CONCLUSION

Jena-Optronik’s ASTRO© CL star tracker has been specifically designed to cater to the constellation market, featuring a compact footprint, allowing high volume production, while making no compromises with respect to radiation hardness.

The ASTRO© CL retains excellent performance throughout its on-orbit lifetime even in the high LEO orbits between 1200 km and 1400 km with their challenging high energetic particle environment. This is shown by our simulations, which are enhanced by laboratory data. The laboratory data includes measurements with fully integrated ASTRO© CL engineering models equipped with processing boards that have been irradiated to TNID levels representative of 15 years GEO/ 10 years within 1200 km and 1400 km LEO missions.

With the OSPS alignment tool, Jena-Optronik established a new approach that brings high precision alignment capabilities to constellation class star trackers without the need to increase tracker footprint, mass, or manufacturing tolerance requirements. This is realized by installing the alignment mirror cube on the OSPS instead of having it permanently installed on each star tracker.

ACKNOWLEDGEMENTS

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REFERENCES

[1] W. Ogiers, A. Gvozdenovic, K. Ruythooren, Z. Li, K. Van Wichelen, S. Kowaltschek, "Faint Star – An Intelligent Single- chip Sensor for Star Trackers", ESA GNC 2014, 9th International ESA Conference on Guidance, Navigation & Control Systems, Porto, Portugal, 2-6 June 2014

[2] U. Schmidt, "Intelligent error correction method applied on an active pixel sensor based star tracker", Proc. SPIE 5964, Detectors and Associated Signal Processing II, 59640J (14 October 2005); https://doi.org/10.1117/12.625107

[3] Jena-Optronik Patent "Constellation Simulator, System and Method for Calibrating a Star Sensor", Pub. No.: US 2024/0255325