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# ASTRO APS3 AND ASTRO CL - NEXT POWERFUL GENERATION OF COMPACT STAR TRACKERS

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Jena-Optronik's ASTRO© APS is the most successful single box autonomous star tracker with several hundred units under in-orbit operation and still on order. This star tracker product had its maiden flight in July 2013. Since then, ASTRO© APS operates flawlessly on AlphaSat providing 24/7 telemetry data under ESA contract over the past 8 years. We will give a brief update regarding the performance status at mid mission geo-lifetime for this on-market state-of-the-art star tracker product. Meanwhile, the development of the next generation of compact star trackers has been completed at Jena-Optronik. Based on the space qualified system-on-chip APS CMOS detector, FaintStar2, the ASTRO© series of Jena-Optronik star trackers has been modernized with the ASTRO© APS3 and the ASTRO© CL models. The latter one is specifically designed for the high volume constellation market. In the segment of the versatile high-rel autonomous star trackers, the ASTRO© APS3 will replace ASTRO© APS with an even wider range of functionality and performance using the outstanding electro-optical properties and functional capabilities of the FaintStar2 system-on-chip detector.

## INTRODUCTION

The design and development of autonomous single box star trackers has shown a continuous evolution over the last decades. Beginning with the integration of the first CCD based systems in the early 90-ties (e.g. ASTRO© 15); the star tracker designs became smaller, more lightweight, radiation robust, less power demanding but still more and more powerful in measurement accuracy and data throughput. This has been particularly pushed with the introduction of the CMOS APS detectors, driven by the ESA detector development road map, namely with the STAR1000 and the HAS2 devices. ASTRO© APS equipped with STAR1000 had its inaugural flight on AlphaSat in July 2013. Today we can look back to more than 8.5 years of flawless operation by applying a 24/7 data monitoring under ESA contract. The star tracker showed after 8.5 years geo-operation no indications of any degradation and faced several solar flare events during the operational time span so far.

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Following the detector road-map, ESA finished in 2020 with ams Sensors Belgium the qualification of the next generation CMOS APS detector, branded FaintStar2 (Ref. 2). This is the first space-qualified CMOS APS imager with data pre-processing and a Space-Wire interface on-chip. Therefore, FaintStar2 can be designated as a complete imager system-on-chip (SoC). Due to this quantum step in on-chip integration density of imager functionalities, the next generation of FaintStar2 based products can take full benefit in terms of compactness and performance.

Jena-Optronik baselined this new APS CMOS SoC detector in a building block strategy for several new AOCS sensor products. This paper focuses on the new star tracker products of the Jena-Optronik ASTRO© series with ASTRO© APS3 and ASTRO© CL.

The ASTRO© APS3 covers a wider motion-dynamic range than the predecessor product ASTRO© APS and is in addition solar-flare proof based on the powerful implemented onboard data processing. The paper will discuss the performance improvements achieved with the FaintStar2 based design approach and presents the most significant test results.

The ASTRO© CL compact optical head is counted among the < 300gram class star sensors and is also based on the FaintStar2 detector. With this combination, the ASTRO© CL is the most performant and robust constellation class star tracker in terms of measurement accuracy, angular rate tolerance and consequent radiation hardness. The ASTRO© CL has been designed for high-volume production serving the constellation market as very cost efficient star tracker optical head and/or as space camera for robotic and space situational awareness (SSA) applications. In this category of applications, the FaintStar system-on-chip experienced its first flight program in 2019 with MEV1 and MEV2 as the key opto-electronic element of the ASTRO©head navigation camera system. This system consist of six optical heads with different fields of view for long and close range stereoscopic imaging.

## ASTRO©APS Star Tracker Status on AlphaSat

The transition from CCD-based star trackers to the CMOS APS technology with respect to the in-orbit operations began for Jena-Optronik with the launch of ASTRO© APS on AlphaSat in July 2013. The unit serves here as technology demonstration payload in direct support to the laser communication terminal (Ref. 1). In a dedicated agreement between ESA and Inmarsat, Jena-Optronik has the opportunity to receive 3sec 24/7 star tracker telemetry data over the last 8.5 years. This provides an excellent database to study the long-term stability of a CMOS APS based star tracker under the specific geo-environment. The ASTRO© APS unit on AlphaSat is equipped with the STAR1000 detector. This CMOS APS detector is known to provide excellent radiation hardness. Therefore, for radiation critical missions the STAR1000 is still today the preferred choice. The HAS2 detector is in direct comparison to STAR1000 less radiation hard, but has the better electro-optical performance and is therefore used in ASTRO© APS for the programs requiring high motion dynamic.

Figure 1 shows the star tracker operational temperature history over the last 8.5years. As expected and well known, the operational temperature rises with lifetime. The obvious signature on the temperature plots in terms of drops are in accordance with the annual eclipse phases. Today the STAR1000 detector runs with a daily maximum temperature of +45°C. The attitude measurement performance is still as under BoL conditions thanks the implemented efficient background noise compensation algorithms (Ref. 3). Therefore, up to now ($T_{chip}$=+45°C daily) and after 8.5 years geo-operation, the thermo-electrical cooler does not need to be powered. The general functionality of the cooler and the other functional star tracker assets are tested at least once a year.

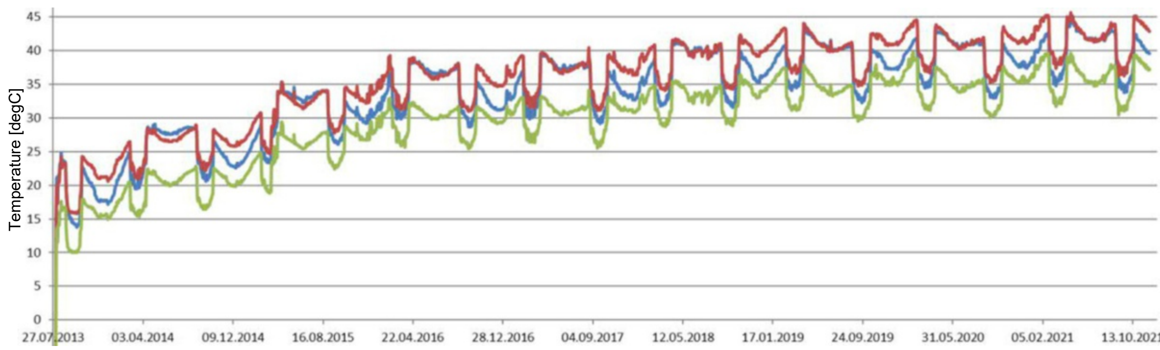


**Figure 1. Star tracker maximum daily operational temperature history over the last 8.5years (detector, optics, housing)**

Beside the continuous monitoring of the star tracker functional and performance figures, the health status of the STAR1000 CMOS APS detector is checked in detail once a year. For that purpose full image raw data sets are drawn by the photo mode and off-line evaluated regarding potential degradations in the pixel array blemish statistics. It is well known that especially the high-energy particle irradiation (proton, ions) can cause displacement damage in the regular silicon lattice of the detector substrate.

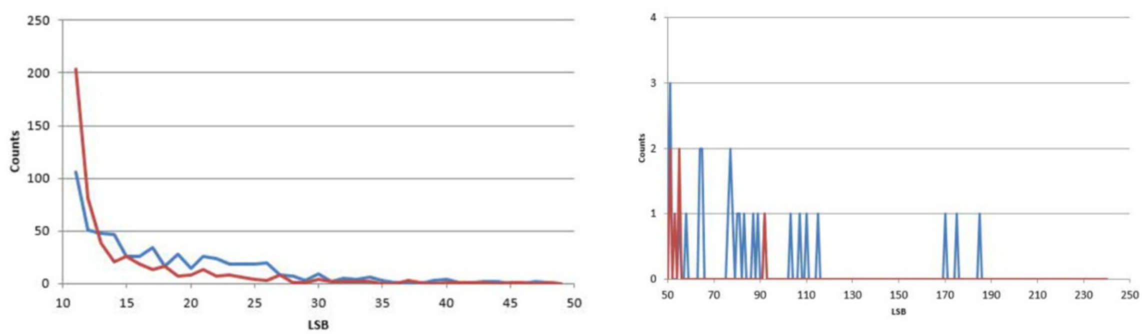


**Figure 2. STAR1000 histogram tail plots from a full 1k x 1k detector image at BoL ground test prior launch and after 8.5years geo-environment, Left: histogram tail from 10 … 50DN$_{10}$, Right: histogram tail from 50 … 250DN$_{10}$**

The figure above shows the magnified histogram tails from a full 1k x 1k raw image data histogram. The information of interest is in the tails, where a potential detector degradation could be seen. The red plot originates from a pre-launch ground measurement, representing the BoL detector status. The blue plot was drawn from the regular annual test in mid 2021, after approx. eight years geo-life time. The degradation seen is almost negligible and not performance relevant. Only a few (6) additional single white spots appear in between 100 … 200DN$_{10}$ (DN$_{10}$: digital number in the 10bit STAR1000 ADC dynamic domain). This confirms the extraordinary radiation hardness of the STAR1000 CMOS APS detector. Based on those results we can forecast another flawless star tracker operation for the second in-orbit life period. Over the last 8.5 years, some hundreds of ASTRO© APS (STAR1000, HAS2) star trackers have been ordered and launched into orbit. In this timeframe, we could collect valuable heritage information used for the development of the next generation ASTRO©-series star tracker units.

**FaintStar2 Based New AOCS Sensor and Camera Products**

With the next generation AOCS sensor and camera products, Jena-Optronik follows a building block strategy based on the FaintStar2 detector (Ref. 2). The high level of on-chip integration including image data pre-processing and Space-Wire interface implementation allows a further downsizing of the star tracker and camera units while improving the electro-optical performance.


**Figure 3. FaintStar2 based Jena-Optronik next generation AOCS sensor and camera products following the detector building block strategy.**

The ASTRO©head system to the left consist of 2x3 optical heads with different fields of view to support long- and short-range stereoscopic imaging for navigation and roboting. The camera system, based on the FaintStar technology, is flying on MEV-1 and MEV-2 missions launched in 2019 and 2020 (mission extension vehicle, Northrop Grumman SpaceLogistics).

The ASTRO© CL (ConsteLlation) represents in particular the unit downsizing capability enabled by the FaintStar2 system-on-chip detector. The design philosophy of ASTRO© CL emphasized to two topics; first to be simple in assembly and integration to support a high production throughput and seconds to make no compromises in robustness and radiation hardness by using consequently radiation hard EEE-parts and materials. ASTRO© CL can be supplied with constellation grade parts for cost efficiency but also with high-rel parts to reflect specific customer demands.

ASTRO© APS3 will replace in the near future the highly successful versatile star tracker ASTRO© APS, which is already in use at LEO, GEO, MEO, science and soon in a human space flight program. The main improvements compared to the ASTRO© APS are e.g. lower physical budgets, a the higher measurement performance, a high degree of modularity in design to respond on-time to customer configuration requests within a significantly reduced lead-time.

The high accuracy star tracker ASTRO© XP is also based on the FaintStar2 technology taking particulary benefit from the superior electro-optical performance of the detector with less than $0.7DN_{12rms}$ background noise at 62% peak quantum efficiency. ASTRO© XP is a 0.1arcsec class autonomous star sensor, targeted to the upcomming ESA science missions (Ref. 5).

The four products introduced here follow a building block stategy arround the FaintStar2 system-on-chip in the focal plane design and the software control and algorithmic support. This enables valuabe synergies in the engineering, assembly&integration procedures and the test environment like test equipment and test data evaluation.

**ASTRO©APS3 and ASTRO©CL Next Generation Star Trackers**

The table below shows the key performance parameters of the next generation versatile star tracker ASTRO© APS3 and the constellation star tracker ASTRO© CL. Both are using the FaintStar2 system-on-chip CMOS detector.

| **Parameter** | **ASTRO© APS3** | **ASTRO© CL** |
|---|---|---|
| Design APS3 & ACL:<br>• Rad-hard by parts level<br>• 1400km orbit ready<br>• solar flare proof<br>• latch-up free<br>• full Moon proof |  |  |
| Application: | Geo/Leo/Meo/Science/Human | Constellations/Small Sat/Geo |
| Limiting magnitude: | 7.0mi | 5.8mi |
| Attitude random error xy/z 3σ: | 2.4/12 arcsec at ≤ 0.1deg/sec | 6/30 arcsec at ≤ 0.1deg/sec |
| Tracking & Acquisition: | ≤ 6.0 deg/sec | ≤ 3.0 deg/sec |
| Update rate: | 8, 10, 16 Hz | 5, 10 Hz |
| Acquisition time: | real time "lost in space" solution | |
| TM/TC Interface: | SpW, MIL-1553, RS-422 | SpW |
| Operational temperature EoL: | -30 … +60°C | -30 … +45°C |
| Sun/Earth exclusion angle: | 26/22deg | 32/28deg … 26/22deg |
| Envelope: | 140 x 140 x 230 mm | 60 x 60 x 104 mm |
| Mass: | 1700g | 300g |
| Supply voltage: | 5/28/50/100$V_{DC}$ | 4.5 … 5.5$V_{DC}$ |
| Power Consumption: | < 5W | < 1W |
| EEE-parts: | high-rel | constellation grade … high-rel |

Both star tracker products follow the principles of a radiation-hard space borne design approach in terms of EEE-parts and materials selection, like the optics elements. By this reason, the small ASTRO© CL is also latch-up free and ready for the 1400km orbit constellations and small-sat applications in critical environments.

The ASTRO© APS3 incorporates the full data processing, a modular design with respect to the TM/TC interface options and the supply voltage in order respond to the specific customer needs. In addition to that, the manufacturing and test flow has been optimized by an assembly and integration friendly design as well as by automated test procedures as a spin-off from the ASTRO© CL high throughput production line.

The evolution of ASTRO© APS3 compared to ASTRO© APS can be identified in the high performance f#1.0 optics, the application of the FaintStar2 system-on-chip detector and a flexible versatile high throughput digital processing unit. The limiting star magnitude goes down to 7.0mi thanks to the high quantum efficiency of the detector and the very low background noise. The radiometric budget of the imaging system can be defined to 100.000e-/sec for a 5.0mi star. This allows robust star detection and centroiding at very small exposure times, enabling finally high angular rate capabilities. The ASTRO© APS3 star tracker can cope with up to 6deg/sec in initial attitude acquisition and attitude tracking around the cross boresight axes.

The FaintStar2 detector has been characterized in detail with respect to the radiation hardness in the ESA/ams Sensors qualification test program. The detector hardness to the total ionizing dosage was as good as expected and known from CMOS APS devices. The more challenging radiation environment is the displacement damage caused by the interaction with high-energy protons and ions (total non-ionizing dosage, TNID). For the error budgeting and end of life performance predictions, real test data was used in terms of post radiation raw dark field images taken at different chip temperatures. Figure 4 shows to the left the star image profile plot for a 5.0mi star at begin of life. In the middle plot the same star at end of life with an accumulated TNID dosage of 3.7E10p+/cm² 23.5MeV at +50°C chip temperature! By the application of the star tracker implemented data processing with the in-situ running DCNU and FPN compensation (Ref. 3) we get the robust star signal as seen to the right figure, again at +50°C chip temperature. That means, even under high accumulated TNID dosages, the star tracker shows at end of life still similar measurement performance compared to begin of life.

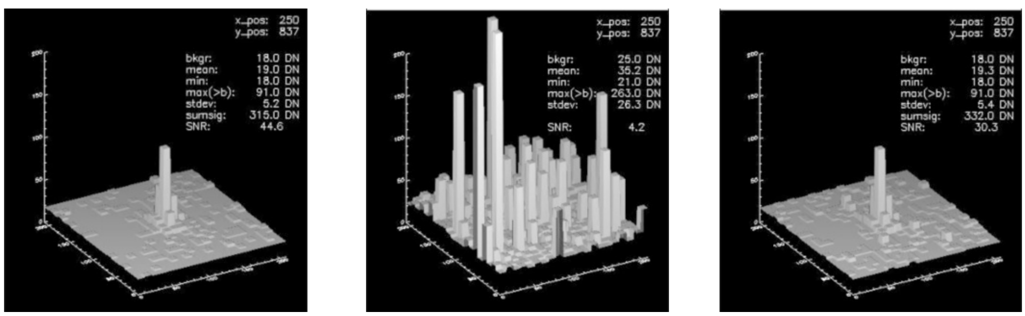


**Figure 4. Left: radiometric budget of a 5.0mi star at BoL +50°C, Mid: EoL at +50°C un-processed post-rad background, Right: EoL at +50°C with enabled background compensation.**

The ASTRO APS measurement performance at +45°C after 8.5 years in orbit operation on AlphaSat confirms impressively the efficiency of that background noise compensation technique. The implementation in ASTRO© APS3 has been furthermore improved using the in-orbit heritage accumulated so far and the increased data processing capability. With the new quality of data throughput, ASTRO© APS3 can handle peak solar flares in the lost-in-space acquisition condition and the attitude tracking. With those new features, the star tracker can be declared as solar flare proof and can be implemented in gyro-less AOCS architectures.

Figure 5 demonstrates a lost-in-space attitude acquisition, where the whole FoV needs to be processed for star objects and thousands of SEU patterns. The star tracker processing system discriminates in real time the SEU objects and performs with the nominated star objects an initial star pattern identification in real time, meaning within the same processing frame. This new capability allows an attitude re-acquisition under peak solar conditions, e.g. even after a regular blinding by the Sun or the Earth. This is a further step forward in making star trackers more and more robust and reliable under harsh in-orbit environments.

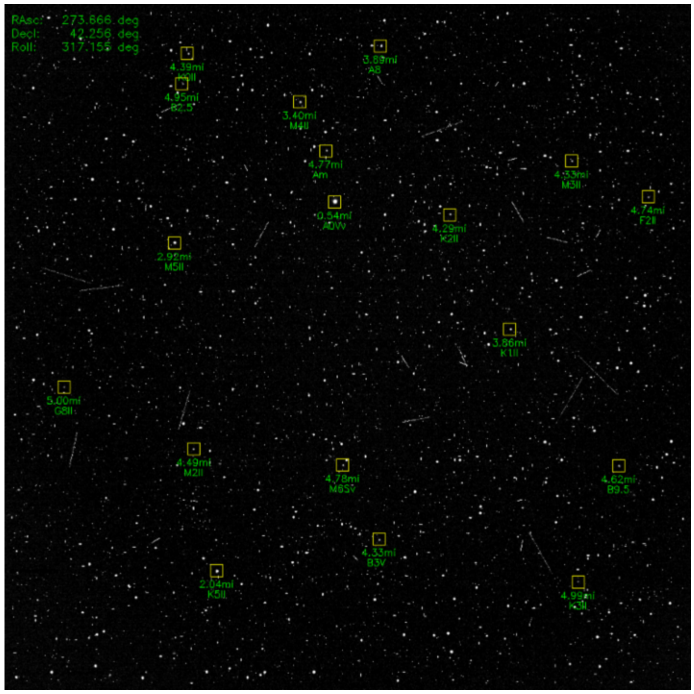


**Figure 5. Lost-in-Space acquisition and attitude tracking under peak solar flare environment.**

The implementation of the FainStar2 system-on-chip in the ASTRO© CL is the consequent move towards system miniaturization for the new-space- and constellation-marked while keeping the radiation hardness of a classical space-born design solution. Therefore, ASTRO© CL is latch-up free and able to serve for operations in the critical 1400km radiation environment. In the same manner as ASTRO© APS3, the CL takes benefit from the good radiometric budget by supporting angular rates in acquisition and tracking of 3deg/sec. These are new performance and robustness benchmarks for these class of constellation star trackers.

## CONCLUSION

Jena-Optronik developed the next generation of AOCS sensors and cameras in a building block strategy using the FaintStar system on chip technology with the FaintStar2 detector. The first in-orbit demonstration of FaintStar was launched in 2019 with the visual camera suite ASTRO©head on MEV1 and MEV2 (Northrop Grumman SpaceLogistics).

Based on this early FaintStar experience and the 8.5 years in-orbit heritage with CMOS APS star trackers under in-orbit operation, the next generation of autonomous star trackers was developed with the versatile tracker ASTRO© APS3 and the constellation star tracker head ASTRO© CL.

Both star trackers take benefit from the robust photonics budget due to the very low background noise of the detector and the fast optics design with an f#1.0 solution. ASTRO© APS3 will supersede the successful versatile tracker ASTRO© APS at the end of its product life. The physical budgets of ASTRO© APS3 have been reduced using the system-on-chip functionality while improving the measurement accuracy and data throughput. ASTRO© APS3 has a real powerful image processing capability, which enhances the range of potential applications beside the classical star tracking towards intelligent navigation tasks and the field of space situational awareness.

With the capability of solving the lost-in-space task under peak solar flare conditions, the ASTRO© APS3 tracker can be classified as solar flare proof, enabling the door for gyro-less AOCS sensor architectures, using star trackers only.

The ASTRO© CL takes full benefit in terms of miniaturization from the system-on-chip FaintStar2 design. ASTRO© CL is made for the constellation market and therefore designed to support very high production throughputs. With the application of FaintStar2 as fully space-qualified and radiation hard detector, constellation- and small satellite applications can be supplied first in time with a real robust space-born design. With this capability, the ASTRO© CL star tracker head is able to serve the radiation critical 1400km orbit.

## ACKNOWLEDGMENTS

Our special acknowledgement goes to the MEV1/MEV2 team of the former Orbital ATK prime, later Northrop Grumman SpaceLogistics, for their cooperation on the procurement activities of the Jena-Optronik ASTRO©head camera system for the MEV1 and MEV2 vehicles. This cooporation enabled Jena-Optronik to bring the FaintStar detector technology as the first AOCS sensor supplier into in-orbit operation. This experience and flight heritage could be beneficially used for the design and development of the FaintStar2 based next generation star trackers ASTRO© CL and ASTRO© APS3.

An outstanding key position in the external support to Jena-Optronik is assigned to Werner Ogiers, the father of the FaintStar2 in its senior CMOS APS imager design position at ams Sensors Belgium and today at Caeleste Belgium. Werner supported Jena-Optronik in all the engineering questions around the FaintStar technology with a very high level of responsiveness. Thanks Werners engagement we could bring the FaintStar technology with ASTRO©head in 2019 to the MEV1 and MEV2 launches with full mission success. The New York Times spectacular photo (27 Feb. 2020), showing the geo-spacecraft to be serviced with the Earth in back and taken by a FaintStar detector is still in all of our minds as a contemporary witness of a pioneering work.

The Jena-Optronik project team would also like to give special attention to ESA, in person of Steeve Kowaltschek for the advisory support in the pre-development Contract No. 4000131361/20/NL/AF. Steeve supervised in addition also the FaintStar ESA development program with ams Sensors Belgium as technical officer up to the successful qualification. With this activity, he became a pronounced FaintStar expert supporting the industry with its knowledge.

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