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# AA-STR MKII: DEVELOPING A NEXT GENERATION AUTONOMOUS STAR SENSOR

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Leonardo has the capability to provide Star Sensors for a wide variety of mission requirements and applications, ranging from high accuracy pointing of scientific instruments and platforms, to medium field of view sensors with autonomous attitude determination capability for Earth Observation and Telecommunication (TLC) programs. Leonardo's High Resolution Star Trackers have been used in all the ESA telescopes (ISO, SAX, SOHO) since 1995. Medium FOV Star Trackers have been used in many scientific missions (ROSETTA, MARS EXPRESS, MRO, NEW HORIZONS, JWST, BEPICOLOMBO, HAYABUSA-2, DART, SPP) and standard GEO TLC platform (AlphaSat and SpaceBus 4000 platform). By leveraging on the increased computational and data storage capabilities available today on the market, Leonardo is replacing its APS autonomous Star Tracker (AA-STR) with a next generation star sensor combining the advantages of reduced size, mass and power consumption, with agility and suitability for high performance and severe radiation environment missions for GEO TLC, Commercial and for applications such as Earth Observation, Science and Deep Space.

The key development concepts aimed to exploiting the computational capability by implementing algorithms to improve robustness and to expand Star Tracker operability in severe space environments.

The present paper presents the solutions adopted in the AA-STR MKII design, to minimize the Star Tracker's size, mass and to reduce costs and lead time by minimizing the number of parts and simplifying assembly and testing procedures.

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## INTRODUCTION

The development of the AA-STR MKII star tracker leveraged on Leonardo's vast know-how and experience in the development and production of CCD (A-STR) and APS based (AA-STR) star trackers.

The development of Leonardo's first APS based autonomous Star Tracker (AA-STR) dates to 15 years ago. An evolution of the AA-STR, the SpaceStar Multi-Head Star tracker consists of up-to three Optical Heads (each one containing a baffle, optical system, focal plane and proximity electronics) and a SW hosted and running in the Spacecraft Computer.

While AA-STR is a plug and play Star Tracker that provides as output attitude quaternion, SpaceStar instead provides pixel partially preprocessed and attitude determination algorithm implanted in SW running on S/C System. M. Morresi et al.

Thanks to its simplified processing electronics, SpaceStar product is still on the market.

The AA-STR implemented electrical components that are becoming obsolete. In addition, AA-STR performance, functionalities and robustness, which were satisfactory at time of development, today may be improved considering the extended computational capabilities and greater data storage that are today available.

The AA-STR MKII, developed under ESA General Support Technology Programme (GSTP) and internally cofounded by Leonardo, intends to solve the AA-STR obsolescence, improve functionalities and performance (mass, envelop, power consumption) and simplify assembly and test procedures.

The AA-STR MKII development is based on a mix of innovation and a direct flight proven re-use. Major innovations have been introduced in the electronic design that features state of the art electrical component and in optics where an aspherical lens has been introduced. Focal Plane, materials and processes are inherited from the former flown AA-STR and SpaceStar designs.

The design criteria of AA-STR MKII will allow for a smooth replacement of the former AA-STR, providing at same time improvement of functionalities and performance.

## AA-STR MKII SENSOR OVERVIEW

The new AA-STR development (AA-STR MKII) design takes strong heritage from the former flown Star Trackers (CCD and APS based) developed by Leonardo[1,2].

AA-STR MKII is an autonomous star tracker (medium FOV) constituted by a unique and compact assembly that includes the following modules:

- An electro-optical module, including the optical system, that images a zone of the sky on the APS detector;
- The electronics to control the APS detector, to process the pixel data and execute the Flight SW for attitude acquisition / tracking and data /command:
- The power supply conditioning for interfacing the Primary Power bus;
- Baffle providing appropriated protection against light from Sun, Earth or other bright objects outside the FOV or reflected by the S/C itself;
- A main structure that supports the above listed modules.

A photo of the AA-STR MKII is reported in Figure 1.

The key characteristics of the AA-STR MKII compared to the former AA-STR are reported in Table 1.

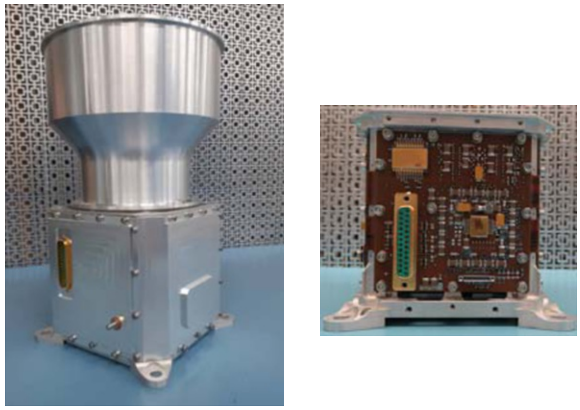

**Figure 1. AA-STR MKII overview (left) and main structure details (right)**

The main housing consists of a main structure in Aluminium alloy realised by machining. It supports the baffle and the electro-optical module (Optical System plus Focal Plane) and provides fixation to the electronics boards. The mechanical layout was engineered to optimize mass and envelope with respect the former AA-STR design and to allow customers to benefit from improved performance in terms of structural stability (first resonance frequency at 700Hz), and resistance to vibration environment (24 grms).

The Electro-optical module is a mix of innovation and flight-proven re-use. The Focal Plane Assembly is based on the previous heritage (A-STR, AA-STR and SpaceStar), which is considered the best solution in terms of performance and flight heritage (TRL-9). The focal plane is based on APS detector[3] and its operating temperature is controlled by a Termo-Electric cooler. The introduction of new processing algorithm allows to work at high APS operative temperature, to reduce power consumption and to maintain full attitude accuracy performance when APS spatial and temporal noises increase at End Of Life.

The major innovation is introduced in the optics design. One aspherical lens has been introduced, reducing the number of overall lenses in order to gain a decrease of mass and envelope. When compared to the former design, the AA-STR MKII optical barrel is 26 mm shorter than optical barrel AA-STR (Figure 2)

**Figure 2. AA-STR MKII Optical Barrel (on the left) vs AA-STR Optical Barrel (on the right)**

**Table 1. A AA-STR MKII features vs AA-STR features**

| | | AA-STR MKII | AA-STR |
|---|---|---|---|
| Mechanical Architecture | Mass (Kg) | 2.3 | 2.6 |
| | Envelope (mm) | 136 x 136 x 247 | 156 x 164 x 283 |
| | Random Vibration (grms) | 24 | 20 |
| | Shock (g) | 2000 | 2000 |
| Interfaces | Bus Voltage (V) | [20÷52V] (100V opt) | [24÷52V] (100V (opt) |
| | Data I/F | 1553 ; RS422 (opt) ; SpW (opt) | 1553 ; RS442 (opt) |
| | Frequency (Hz) | 10 , 8 (opt) | 10 ; 8 (opt) |
| Performance | Power consumption (W) | ≤5 ; ≤8 (@ 60°C) | ≤5.5 ≤12 (@ 60°C) |
| | Sun Exclusion Angle (deg) | 25 | 26 |
| | Earth exclusion Angle | 25 | 25 |
| | Moon | Robust in FOV | Robust in FOV |
| | Acquisition robustness (°/s) | Up to 2.5 | Up to 1 |
| | Tracking robustness (°/s) | Up to 3 | Up to 2 |
| | Boresight stability (arcsec/s) | ≤ 0.1 | ≤ 0.15 |
| | Bias (arcesc) | 10 | 12 |
| | FOV Error XY/Z (arcesc) | 1.5 / 4.5 | 2 / 5 |
| | Random Error (arcesc) | 4.3 / 35.4 | 7 / 60 |
| Environment | Operating temperature (°C) | [-30 ÷ 60] | [-30 ÷ 60] |
| | Survival temperature (°C) | [-40 ÷ 70] | [-35 ÷ 65] |
| | Life time in GEO (years) | 18 | 18 |

**Digital electronics**

The digital electronics (Figure 3) is based on a Microcontroller CPU for Aerospace Applications. The System on Chip (SoC) implements the Processing Unit, volatile RAM, SpaceWire I/F, Mil Std 1553 I/F and PWM controller. Internal features have been implemented in the electronic design allowing for a reduction of electronics components with consequent cost and PCB size benefits.

An external Magnetic RAM (organized in independent banks) is used to store Application SW, Nominal and Redundant Boot SW. An external Static RAM is added to achieve further margin on memory budget. The current data I/F is a MIL-1553 I/F but design can be tailored to work with RS422 or SpaceWire I/F.

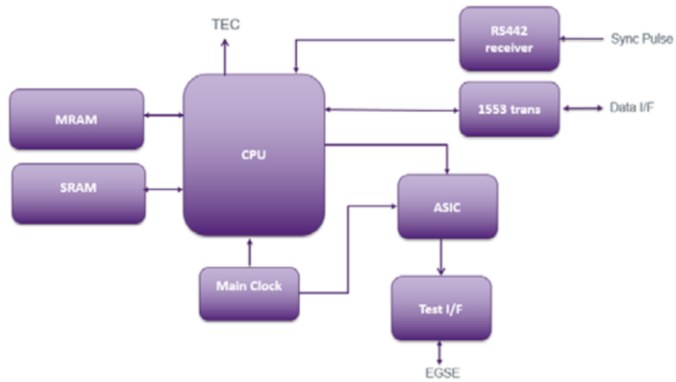


**Figure 3. Digital Electronics block scheme**

An ASIC, under development, is implemented to interface the APS detector and to perform pixel pre-processing. The ASIC logic is ported from the previous FPGA design used by the flight proven SpaceStar Star Tracker. The ASIC has been introduced to reduce both power consumption and overall cost of electrical parts.

The CPU processing capability offers a good ratio between CPU processing load and overall power consumption, while the large processing capability (~ 8 times when compared to the former AA-STR design) allows an extended processing load, allowing for more complex algorithms to be introduced to extend Attitude Acquisition and Attitude Tracking while requiring reduced cooling effort of APS.

**Overview of functionalities**

The AA-STR MKII operative modes (Figure 4) are:

- Stand-BY (SBM) mode for full TM/TC functionality after power-on or reset.
- Autonomous Attitude Acquisition Mode (AAM) to acquire attitude from Lost in Space.
- Autonomous Tracking Mode (ATM) to update autonomously and continuously the attitude and angular rate.
- Commanded Tracking Mode (CTM) to be used for on-ground calibration and for star position measurement accuracy evaluation
- Camera Mode (FOTO) to acquire image. Raw pixels can be downloaded over 128x128 pixel window or a full frame in a compressed format can be acquired.
- Maintenance (SWM) mode for SW patching (upload/download) and parameters modifications.

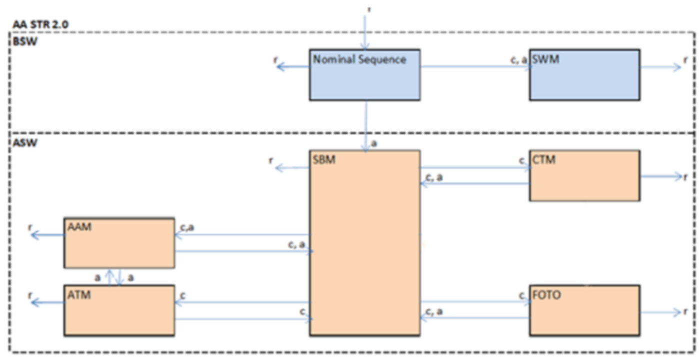


**Figure 4. Operative Modes**

The new design allows to operate Attitude Acquisition at angular speeds up to 2.5 deg/s and Attitude Tracking at rates up to 3 deg/s with high APS temperature. The high APS operative temperature allows a reduction of power consumption, keeping full attitude accuracy performance when APS spatial and temporal noises increase at End Of Life.

In AAM mode, raw pixels belonging to the large acquired image are partially processed by ASIC to shorten as much as possible the processing time and the duration of the operative cycle.

In ATM, a strong flexibility on pixel pre-processing has been introduced with a dual mode of operations according to dynamic conditions:

- Dedicated “flat field compensation” algorithm has been implemented for star position measurement accuracy improvement at low angular rates;
- Dedicated pixel processing based on a criterion of star signal distribution has been implemented to improve detection capability at high angular rates.

Self-calibration algorithms (focal length and optical distortion)[4] have been designed in order to allow improvement of accuracy requiring simplified ground test set up reducing cost of facilities.

**Self calibration algorithm (In-Flight Autonomous Calibration)**

Spatial FOV accuracy is largely dominated by optical distortion and focal length calibration knowledge.

As a standard procedure, star trackers are subjected to optical on-ground calibration. Relevant parameters are stored then in the flight SW. This methodology has clearly some limitations:

- Calibration accuracy depends on the accuracy of the adopted set up. High accuracy can be achieved only when expensive set up are used;
- In-flight accuracy depends on the stability of the optical system and of the focal plane against the thermal and mechanical environment occurring at launch and in flight.

To solve these limitations, in-flight calibration is used. In the frame of the AA-STR MKII development, taking advantage of the increased computational capability of the CPU, two new algorithms have been implemented:

- 2D focal length calibration (vertical and horizontal)[5];
- Fully autonomous calibration algorithm (distortion self-calibration).

The first type of algorithm uses the distortion parameters as computed on ground and refines horizontal and vertical focal length separately.

A sensor that was subjected to on ground calibration has (typically) a FOV error of 4 arcsec. 2D focal length in flight calibration allows to achieve the same levels of accuracy with sensors that weren't subjected to any on ground calibration. When 2D focal length calibration is instead applied to a sensor that was calibrated on ground, a FOV error as low as 0.8 arcsec can be achieved.

Figure 5 reports the focal lengths estimation on X and Y axes when an error of 0.1mm is added on both focal lengths. As it can be noticed, the correct focal lengths are recovered after few tracking cycles.

The fully autonomous calibration algorithm is always applied to an uncalibrated sensor. In this case, the residual FOV error can be reduced to approximately to 1 arcsec.

Thus, in summary if we start from an uncalibrated unit the fully autonomous calibration leads to better performance. If we start from a calibrated unit, 2d focal length refinement algorithm provides best performance.

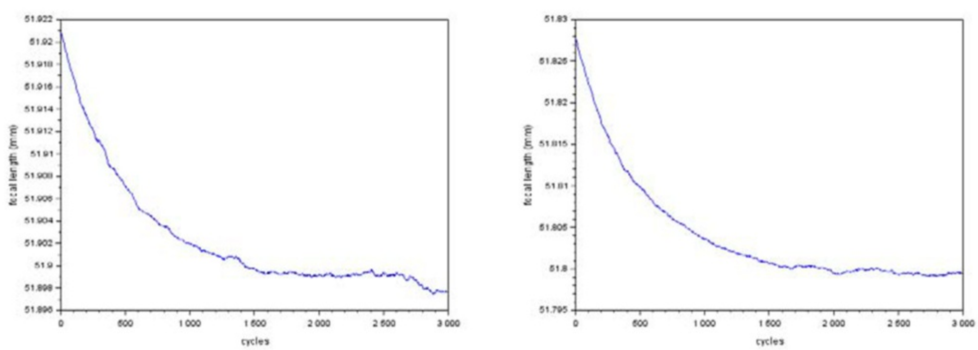


**Figure 5. 2D Focal length estimations**

**SW development philosophy**

The software is implemented with automatic code generation by using Model Driven Architecture (Matlab/Simulink®) that it is introduced for the first time in Attitude Sensors programs at Leonardo.

The Model Driven approach guarantees the representativeness of mathematical model used to predict performance versus in flight software, and a time reduction from the System modelling to SW implementation (by using the automatic code generation) making also simpler future SW re-use and modification.

Differently from the traditional paradigm, in the model driven approach the focus of the development is on Model generation as the Flight code is then generated automatically from the Simulink® Model (Figure 6). This innovative method unequivocally aligns the mathematical model to the Flight SW, assuring the predicted in-flight performance are obtained with the algorithm as implemented in the real Star Tracker HW.

The Model Driven development workflow is based on:

- The Model In the Loop (MIL): verification of the model requirements;

- The Processor in the Loop (PIL): adherence to the generated code with the model;
- Hardware in the Loop (HIL): check of the correct behavior of the SW on a target representative of the final HW like the Engineering Model.

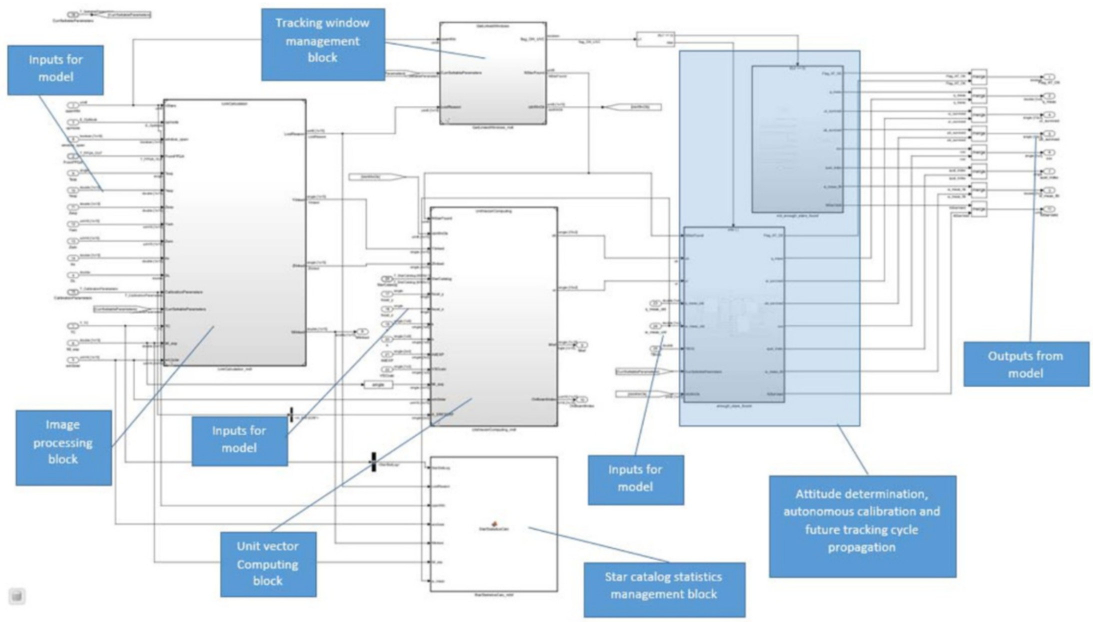


**Figure 6. AA-STR MKII Attitude Tracking Mode Simulink® Model**

## AA-STR MKII DEVELOPMEN ROADMAP AND TEST RESULTS

The AA-STR MKII design has been validated by a combination of analysis and test. One Optical Head Bread Board (OH B/B) fully representative of the flight optics design (lens radiation hardened, optical barrel and retaining rings in titanium), and one Digital Electronic Bread Board (ELE B/B) reproducing Electronic design but with commercial components have been manufactured and tested in order to validate PDR design at subsystem level.

Following the validation on B/B models, one Engineering Model (EM), representative in form fit and function of AA-STR MKII FM has been manufactured and is currently under testing.

### OH B/Bs test results

OH B/B was tested performing interferometric measurements on the stand-alone Optical Module employing an interferometer at wavelength 633 nm (Figure 7). The measured coma and astigmatism was in line with the specification.

Following interferometer test, the Optical Module was integrated on an existing Focal Plane Assembly for Star spot quality check (Figure 8). Single Star accuracy measurement were performed using the Leonardo test set-up that is usually used for the Flight Model test campaign (Figure 7). FOV error and High Frequency Spatial error were characterized for different star magnitudes (Mi 3.2, 4.5, 5) and spectral classes (8000K, 6700K, 2500K).

Results were in line with expectations:

- Star spot, Focal length and optical distortion law are within P/F criteria
- Residual errors at single star level (FOV and Random error):

   - 3.6 arcsec (H) / 2.4 arcsec (V)
   - 10.7 arcsec (H) / 10.5 arcesc (V)

- Focal length does not significantly change w.r.t Star Class so that a fine focal length tuning vs star class is not needed in On Board Star Catalogue, any focal length error will be recovered in flight by the autonomous calibration during nominal Attitude Tracking.

The measured magnitude is stable over the sampled FOV grid as shown in Figure 9.

**Figure 7. OH BB Interferometer test (left); OH BB mounted on performance test bench (right)**

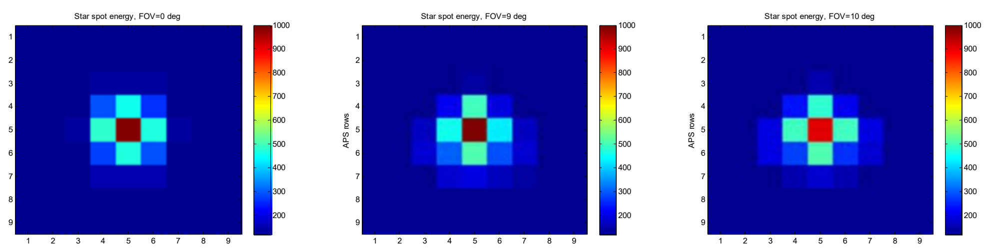


**Figure 8. Star spot energy at FOV=0° (left); FOV= 9° (middle), FOV=10 (right)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 3.26 | 3.23 | 3.25 | | | |
| | 3.25 | 3.23 | 3.21 | 3.21 | 3.21 | 3.23 | 3.21 | |
| | 3.27 | 3.21 | 3.21 | 3.18 | 3.20 | 3.22 | 3.26 | |
| 3.28 | 3.21 | 3.15 | 3.16 | 3.22 | 3.22 | 3.27 | 3.22 | 3.28 |
| 3.27 | 3.31 | 3.16 | 3.31 | 3.19 | 3.16 | 3.26 | 3.21 | 3.35 |
| 3.29 | 3.33 | 3.19 | 3.20 | 3.23 | 3.20 | 3.26 | 3.25 | 3.31 |
| | 3.30 | 3.29 | 3.27 | 3.25 | 3.29 | 3.27 | 3.32 | |
| | 3.34 | 3.36 | 3.35 | 3.33 | 3.32 | 3.36 | 3.34 | |
| | | | 3.40 | 3.41 | 3.38 | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 3.26 | 3.25 | 3.27 | | | |
| | 3.26 | 3.25 | 3.25 | 3.23 | 3.22 | 3.24 | 3.25 | |
| | 3.27 | 3.25 | 3.22 | 3.17 | 3.27 | 3.21 | 3.28 | |
| 3.28 | 3.27 | 3.22 | 3.20 | 3.21 | 3.18 | 3.20 | 3.26 | 3.29 |
| 3.29 | 3.28 | 3.25 | 3.21 | 3.20 | 3.20 | 3.22 | 3.25 | 3.27 |
| 3.32 | 3.28 | 3.28 | 3.22 | 3.28 | 3.19 | 3.24 | 3.30 | 3.29 |
| | 3.29 | 3.28 | 3.25 | 3.23 | 3.26 | 3.29 | 3.32 | |
| | 3.31 | 3.31 | 3.33 | 3.31 | 3.33 | 3.35 | 3.33 | |
| | | | 3.40 | 3.35 | 3.37 | | | |

**Figure 9. Average magnitude measurements over sampled FOV**

**Electronic B/Bs test results**

An Electronic B/B has been used to perform test at PCB level (power consumption, memory and CPU timing), and HW-SW I/F check. All tests were successfully completed.

Thanks to the full FM representatively, the Boot SW and Application SW have been loaded on the MRAM and the Flight SW runs on real target. ELE B/B was introduced in the functional test set-up, so that SW timing budget was performed and Telemetry was acquired when a synthetic sky image was simulated by Electrical Stimuli Generator (ESG) and injected via test I/F on to ELE B/B (Figure 10).

The measured processing time of the Attitude Tracking Mode with autonomous calibration running, showed a margin higher than 50% with respected the allocated time (100ms). Therefore, it has been demonstrated that the processing capability is well sized to support the Application SW designed with automatic code generation.

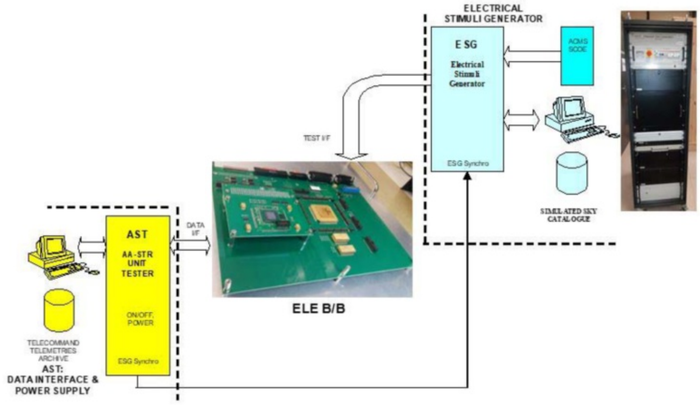


**Figure 10. Electronic B/B in functional test set-up**

**EM test results**

The test campaign on the Engineering Model started in Q4 2021. The EM test plan consists in a replica of qualification test plan but excludes environmental test. Functional and performance test, mass verification, Electrical Test, Straylight test, Night Sky test, Resonance frequency characterization will be executed on EM.

At time being mass verification, electrical and performance tests have been completed, confirming the features as presented in Table 1.

Performance test (Figure 11. EM mounted on performance test bench) was executed, providing the following residual errors after calibration (Star Mi 3.0, 2700K)

- FOV error: 3.7 arcesc (H axis); 2.6 arcesc (V axis)
- Random error: 6.8 arcesc (H axis); 6.1 arcesc (V axis)

The Random error performance are better than performance achieved on BB. As expected, the new pre-processing algorithm (flat field estimator) improves the random error, indeed pixels was processed with the old method in BB.

The Intra-pixel error over the sampled FOV is provided in Figure 12.

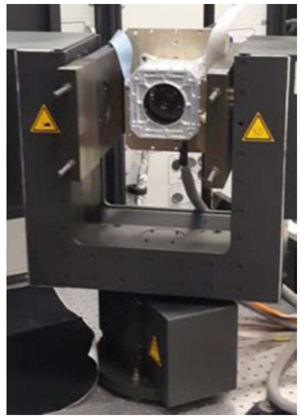

**Figure 11. EM mounted on performance test bench**

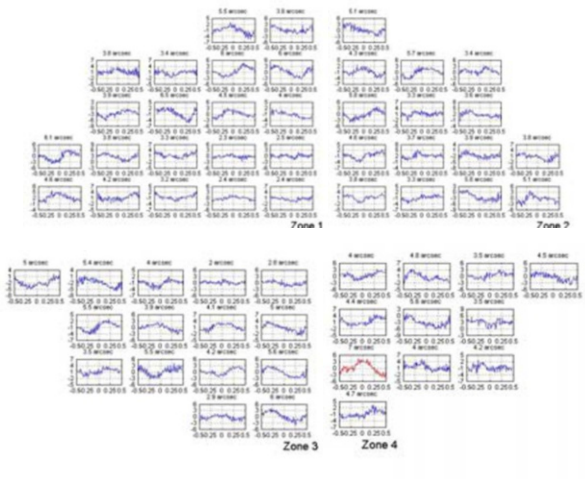


**Figure 12. intra-pixel error distribution vs FOV**

## CONCLUSION

After the A-STR, AA-STR series for which about 150 units have been produced, and SpaceStar product series for which more than 300 units have been produced (still under production), the next generation Leonardo autonomous star tracker (AA-STR MKII) is going to be available.

The AA-STR MKII has been designed with the aim of solving the obsolescence present in the previous AA-STR and represents its natural evolution, allowing it to be easily introduced in S/Cs where AA-STR was used.

Its design represents a mix of heritage and innovation: Focal Plane Assembly is directly inherited from the previous flight proven SpaceStar, Materials and processes also claims flight heritage, attitude acquisition and tracking algorithms have been directly inherited from previous designs.

Taking advantage of the increased computational and data storage capabilities, the new processing algorithm allows maintaining full accuracy even when working at high APS operative temperature, reducing power consumption.

Flown attitude determination and tracking algorithms were modified to improve attitude acquisition & tracking robustness in high dynamic condition.

A dual mode of Autonomous in-flight calibration (focal length and optical distortion) have been introduced. These kinds of autonomous calibrations will facilitate the on ground activities. In fact, full performance are achieved after in-flight calibration refinement starting from a reduced initial accuracy achievable with a simplified on ground calibration.

The software, implemented with automatic code generation by using Model Driven Architecture (Matlab/Simulink®), guarantees the representativeness of mathematical model used to predict performance versus in flight software, reducing the time from the System modelling to SW implementation making also simpler future SW reuse and modification.

The major innovation, the introduction of the aspherical lens in the AA-STR MKII optical design, allowed minimization of optics size with consequent reduction of overall mass and star tracker envelope, keeping the good performance of the AA-STR.

At this time, AA-STR MKII design has been successfully validated through Optics and Electronic B/Bs. The Engineering model, FM representative in form fit and function, is confirming B/B results and it is completing test campaign. Full qualification will be achieved on EQM currently under manufacturing by end ’22.

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## REFERENCES

[1] M. Alvarado, S. Massier, E. Brouillard and R. Bettarini, "AlphaSat, the First In-Orbit Experience of the New European Large Platform AlphaBus.” GNC 2014, 9th International ESA conference on Guidance, Navigation & Control Systems

[2] R. Bettarini, F. Boldrini, D. Procopio and D. Temperanza, “The APS based Star Tracker after one year of In-Flight.” AAS 11-085, American Astronautical Society 2011.

[3] R. Bettarini, F. Boldrini, D. Procopio, S. D’Halewyn and D. Temperanza, “On-Ground and In-Flight Qualification of the AlphaBus Platform APS based Star Tracker.” AAS 10-046, Ameri-can Astronautical Society 2010.

[4] Puneet Singla, D. Todd Griffith, J.L. Crassidis and J.L. Junkins, “Attitude Determination and Autonomous On-Orbit Calibration of Star Tracker For GIFTS Mission.” AAS/AIAA Space Flight Mechanics Meeting, January 2002

[5] Micha Schmidt, Dave Salt, “Herschel Pointing Accuracy Improvement, SpaceOps 2012 (The 12th International Conference on Space Operations).