HIGH-ACCURACY STAR TRACKER ASTRO XP

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ABSTRACT

Jena-Optronik GmbH, located in Jena/Germany, has profound experience in designing and manufacturing star trackers since the early 80-ties. Today, the company has a worldwide leading position in supplying satellites and other spacecraft for telecom, earth observation, science and all kind of missions in various orbits with versatile and reliable star tracker systems. The future ESA science missions require high accuracy star trackers in the 0.1arcsec accuracy class to achieve the envisaged pointing budgets. Jena-Optronik received a pre-development contract (ESA Contract No. 4000112514/ 14/NL/BW) from the European Space Agency in order to demonstrate the feasibility of such a high accuracy star tracker within the challenging performance, mass and envelope requirements. The here identified key-enabling optics technology in terms of a compact 4-times folded fully reflective optical system opened the way forward to a second contract (ESA Contract No. 4000126831/19/NL/GLC/hh) to establish an engineering model optical head in form, fit and function, able to undergo pre-qualification tests.

The star tracker optics consists of a full catoptric design and is therefore free of any chromatic aberration. This is essential for a high accuracy star tracker, which uses guide stars from a wide range of different spectral classes. The only four optics main parts are made from fused silica. They build in the final assembly a self-sustaining optical system with a total lack of CTE mismatches. The high performance imaging system is completed with a FaintStar2 CMOS APS based focal plane. The FaintStar2 is the most advanced and space-qualified APS star tracker imager as a result of the ESA detector development roadmap. This detector comprises a complete system-on-chip including a space-wire interface.

The ASTRO XP EM optical head was integrated in Q4/2022. The paper presents insights in the optics- and focal plane technology as well as the design solution. First results from the engineering model test campaign will be published and discussed. The ASTRO XP optical head designed and manufactured is the most innovative star tracker ever designed at Jena-Optronik GmbH and beyond.

1 BACKGROUND INFORMATION AND INTRODUCTION

The objective of the high accuracy star tracker activity with ESA was to increase the star tracker attitude measurement accuracy by more than one order of magnitude down to < 0.1arcsec in the total error figure while keeping the design small and light weight. The future ESA science missions require a compact high accuracy star tracker able to be mounted on the payload bracket in order to fulfil the mission goals. In a first pre-development contract, ESA Contract Number 4000112514/14/NL/BW, a comprehensive design trade-off has been performed with the focus on the optics- and the focal plane design solution [1].
The desired sub-arc-second accuracy demanded a new thinking in optics design, structure raw material selection, algorithms and test approach. The optics trade-off between the field of view size in the range 2deg$_{\varnothing}$ … 8deg$_{\varnothing}$ and the 5-star minimum coverage deals with the system limiting magnitude (sensitivity) and the single star accuracy, both for a given CMOS APS detector.
The lower boundary of the analysed field of view range would require over 100,000 on-board guide stars to fulfil the 4π-coverage requirement. This was a significant drawback for the small field systems in the trade-off evaluation. At the other end of the investigated field of view range, at 8deg$_{\varnothing}$, the necessary pixel interpolation factor exceeded the feasible limitation for the given detector. Several optics design variants in the desired field of view range have been investigated and traded against feasibility and performance. The potential optical design solutions are dioptric, catadioptric or catoptric.
With the application of refractive elements only or in combination with reflective elements, a wide range of classical designs is possible. However, two major disadvantages have been identified. The refractive elements introduce chromatic aberrations in the optical systems. This affects significantly the stars centroiding performance for the spectral classes in between O, A …K and M. At seconds, the combination of the lens glass materials with the mechanical components cause thermo-mechanical CTE-stress in the optical system. The classical reflective systems have a total lack of chromatic aberration and can be well designed for a good thermo-mechanical stability. However, the achievable field size is rather low with < 2deg$_{\varnothing}$ and the envelope and mass is quite high.

Finally, the pre-development contract trade-off proposed a fully reflective compact four-mirror anastigmat (FMA). This kind of optics provides a very high degree of freedom in the parameter space, in particular when aspherical surface shapes are used. Figure 1 shows the design principle of reflective FMAs. To the left, a generic state of the art off-axis system is shown. However, such an arrangement was not down-selected for the high accuracy star tracker. The envelope and mass budgets exceeded the system design limits. The mid of Figure 1 shows an on-axis FMA with annular shaped mirror surfaces as the selected baseline solution.

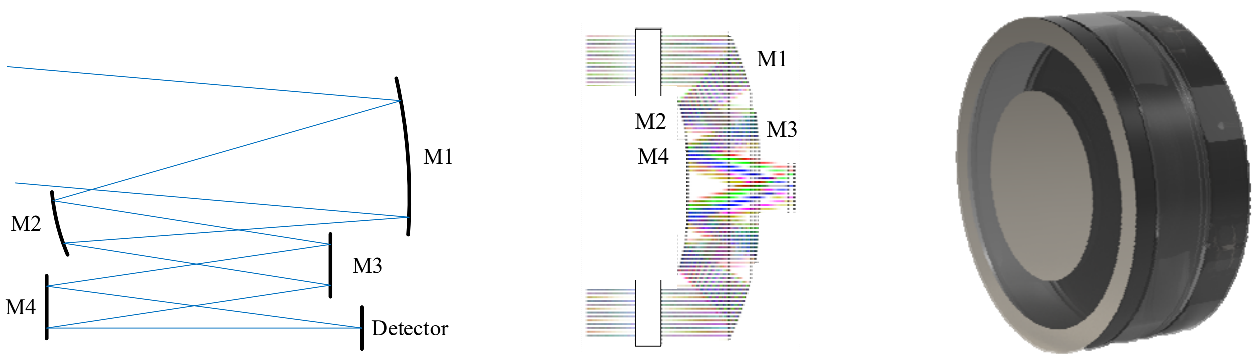

Figure 1. Reflective FMA designs: Left: state of the art off-axis solution; Mid: on-axis solution selected for the star tracker; Right: compact design realization

The mirror pairs M1/M3 and M2/M4 are precision machined on the same substrate. Therefore, the optics consists of only four structural parts: the two optics substrates, the parallel entrance window and the spacer ring.
The pre-development contract could demonstrate the feasibility of the optics and the focal plane [2]. With a focal length of 175mm at an effective aperture of $87mm_{\varnothing}$ the optics supports a circular field of view of < $4.5deg_{\varnothing max}$. The design goal with regard to a fully reflective medium field star tracker optics was fulfilled with that approach. An 8.2mi star shows a signal to noise ratio of 50. This is also in line with the 5-star coverage requirement to realize a cross boresight accuracy of 0.1arcsec. That promising trade-off and analysis results enabled a follow on contract (ESA Contract No. 4000126831/19/NL/GLC/hh). The main purpose of this activity was to establish an engineering model (EM) of the optical head in flight model-like form, fit and function. In addition, the EM shall be able to undergo pre-qualification test loads in the test campaign as a key requirement of the contract statement of work. This takes attention to the novelty of the optics design as well as the corresponding MAIT processes. In Q4/2022 the test readiness review was successfully performed with ESA.

2 ASTRO XP STAR SENSOR OPTICAL HEAD DESIGN

2.1 Overview

The ASTRO-XP optical head consists of the optical system as consequent catoptric design solution (reflective only), the focal plane with the CMOS APS detector FaintStar2 and the interface electronics. The electrical interface between the optical head and the electronic box supports redundant SpaceWire TM/TC lines, a synchronization signal and the power supply harness.
Figure 2 shows the evolution from the 3D-CAD model as a rendered picture, representing the status of the Detailed Design Review (DDR), to the real engineering model (EM) hardware. The successful manufacturing of the EM demonstrated the feasibility of the design approach as well as of the selected novel manufacturing processes.

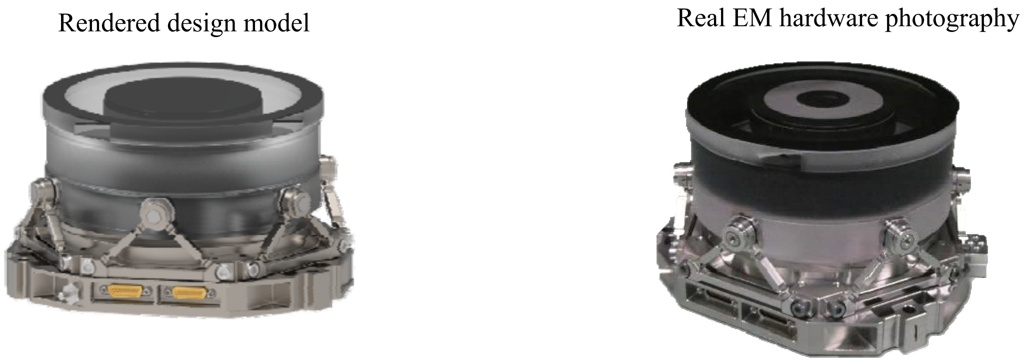

Figure 2. Evolution from 3D model (left) to engineering model hardware (right)

2.2 Optics

The optics trade-off in the pre-development phase proposed a catoptric on-axis FMA design solution. Only reflective elements are used for high quality star imaging with a total lack of any chromatic aberration effects. This has been identified as a mandatory optics design feature for a high accuracy star tracker in contrast to the classical refractive star tracker optics. All star spectral classes from blue (O-type) via Sun-like (G-type) to red (M-type) can be used for high performance star tracking with identical imaging quality over the field of view. As discussed in the introduction, the classical 2-mirror catoptric designs according to Schmitt-Cassegrain or Maksutov would need

refractive field correctors causing chromatic aberrations and were therefore no option. Each of the 4 mirror surfaces of the FMA design have an individual annular aspherical shape in order to realize the desired point spread function (PSF) over the field of view. On the left hand side of
Figure **3** the 3D-rendered optics parts are shown in an exploded view along the optical axis. The bulk material of these parts is fused silica (SiO_2). No other construction material is used. With that disruptive feature, the optics is self-sustaining and free of any thermo-mechanical CTE stress. The annular mirror pairs M1/M3 and M2/M4 are precision machined on the same circular SiO_2 substrate in just one manufacturing process. This manufacturing process causes therefore that M1 versus M3 and M2 versus M4 have neither tilt nor decenter uncertainties to each other. The FMA optics design with only four SiO_2 parts looks quite simple; however, the technology challenge is definitely addressed to the high precision aspherical surface polishing process. All aspherical surfaces fulfilled their specifications in the allowed peak-valley deviations as well as in the final surface roughness. The right figure below shows the already assembled M1/M3 substrate to the base plate via the flexible bi-pod elements. The interferometric acceptance test confirmed the aspherical surface shape within the specification limits.

Figure 3. Left: Rendered 3D-model of the FMA optics; Mid: cover plate with M2/M4 mirror group; Right: M1/M3 group with interferometric plot

The middle figure shows a photo of the aperture plate/M2M4-carrier subassembly. This subassembly will be set on top of the M1/M3 group (see right figure) in order to close the optics cavity in the final assembly step. The spacer is also precision machined to zero the residual tilt in between the mirror groups. Therefore, the only optics adjustment step is reduced to the lateral decenter in the xy-mechanical plane. The applied bonding technology (final fixation) for the optical parts remains in the pure SiO_2 system without any other foreign material that could cause thermo-mechanical stress.
Due to the 4-times folded optical path, the optics system with 175mm focal length is realized to utmost possible compactness level even in the z-dimension. The optics system is a fully self-sustaining design which does not require any supporting elements like tubes, rings, barrels, etc..

2.3 Focal Plane

The focal plane carries the CMOS APS detector in the image plane of the optics. Of course, it is self-explaining that the focal plane is also made from fused silica like all of the optics parts.
Figure 4 depicts the assembled focal plane part with its attitude to the optical head base plate. The unavoidable thermal mismatch in between the detector and the SiO2 focal plane structure material can be managed on the smallest area as possible and is seen as an optimum design solution.

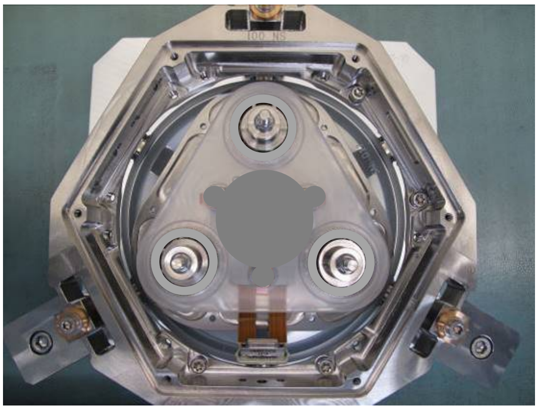

Figure 4. ASTRO XP SiO_2 focal plane

A small PCB holds the necessary detector proximity electronics, such like the clock oscillator and supply line buffering capacitors. The power consumption in the focal plane is kept to the absolute minimum to avoid unnecessary thermal stress.

2.4 Optical Head Interface Electronics

The interface PCB, mounted into the base plate bottom, holds the voltage regulators and the interface transceivers. Figure 5 shows the electrical block diagram of the optical head electronics. The CMOS APS detector is a system-on-chip requiring a minimum of proximity electronics.

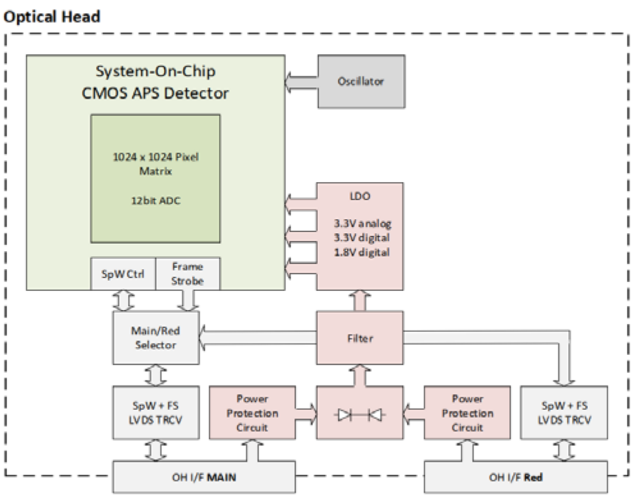

Figure 5. ASTRO XP optical head electrical block diagram

The FaintStar2 CMOS APS detector is controlled and read-out via an on-chip space-wire interface. In order to qualify the optical head to operate with redundant processing units, the space-wire TM/TC interface as well as the synchronization and supply lines need to be doubled to two connectors. This is a prerequisite to use the optical head in cross-strapped configurations.

3 ENGINEERING MODEL INTEGRATION

An engineering model of the ASTRO XP optical head was manufactured in 2022. It passed the test readiness review (TRR) for the pre-qualification campaign in Q4/2022. The successful assembly and integration of the ASTRO XP optical head demonstrated the feasibility of all the novel and challenging technologies, which involved:

- **Optics assembly:** An entire new process had to be developed for the tube-less glass-to-glass mounting of the optics. The fixation process involves the adjustment of the optical elements to each other in the order of a few micrometer.
- **Focal plane assembly:** The integration of the focal plane comprises the assembly of the image sensor and the small front-end electronics PCB to the SiO_2 glass substrate. This required the application of new processes and technologies.
- **Mounting of the optics to the baseplate mechanics:** This process is crucial for the optics-to-baseplate alignment. Hence, an approach had to be found to provide a stress-relived optics mounting while maintaining a maximum stability and symmetry.
- **Mounting of the focal plane to the optics:** Solutions had to be introduced here for the implementation of the focal plane adjustment in 5 degrees of freedom as well as for the final fixation after the adjustment.
- **Black coatings**: The inner cavity of the optics need to be black coated for efficient stray light suppression. This required the application of new technics by highly skilled workmanship in handling special designed jigs and tools. In Figure 9 some of the specialized handling and treatment procedures during the optics assembly and integration are shown.

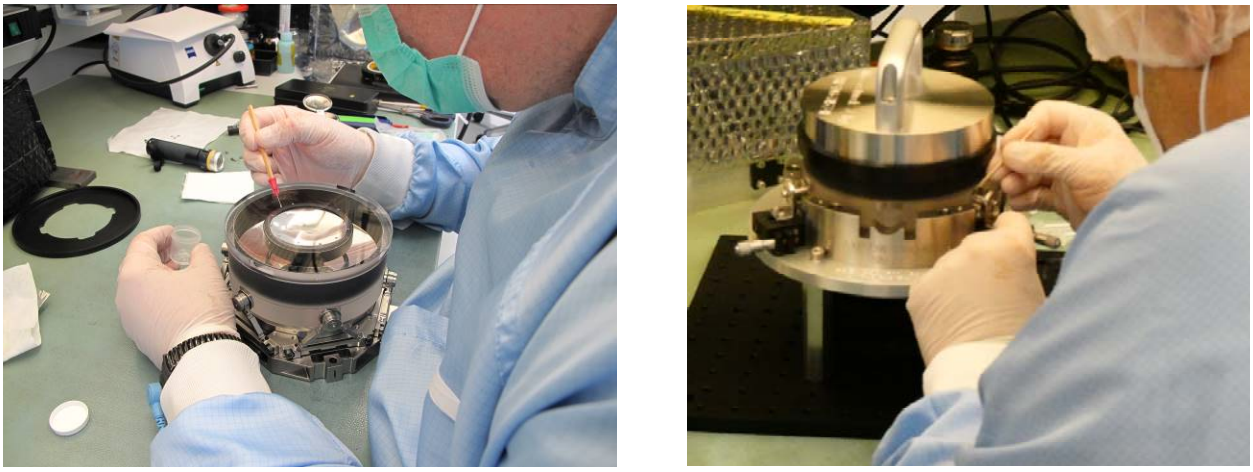

Figure 6. Left: Preparation for the black coating; Right: Mounting of the M1/M3 optics to the baseplate

4 ASTRO XP SYSTEM CONFIGURATIONS

The ASTRO XP high accuracy star tracker is a classical 2-box sensor system with a separated optical head and an electronics box. This was a mandatory approach in order to minimize the optical head power consumption. The optical head can be mounted close the sensitive payload benches on spacecraft level.
This star tracker architecture allows to define many different customer tailored configurations. Figure 7 presents the simplest configuration to the left as single string system. On right side, a redundant system configuration is shown. Not shown here, but also cross-coupled systems are feasible to realize.

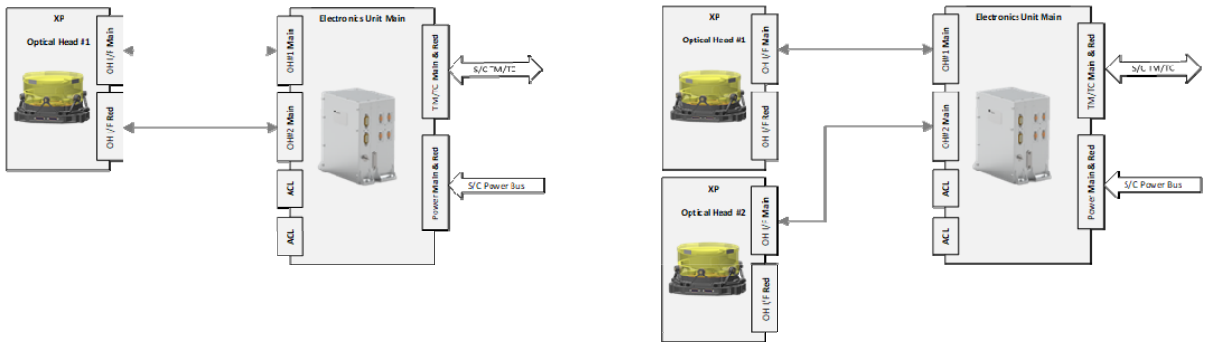

Figure 7. Left: Single string configuration; Right: Redundant optical head configuration

The ASTRO XP design is strongly driven towards the high measurement accuracy only. Consequently, the star tracker field of view is of medium size or rather small with only 3.3deg x 3.3deg. This limits the angular rate tracking performance significantly. In order to enhance the high accuracy star tracker angular rate performance to the state of the art level, Jena-Optronik proposes a hybrid system consisting of ASTRO XP optical heads and ASTRO CL or APS3 optical heads. Figure 8 demonstrates this idea with a hybrid system consisting of an ASTRO XP head, ensuring the high pointing performance, and two ASTRO CL optical heads to manage the higher angular rates. ASTRO CL optical heads can cover up to 3deg/sec and ASTRO APS3 optical heads can cover up to 6deg/sec. Any other combinations are also feasible, e.g. 2 XP heads etc..

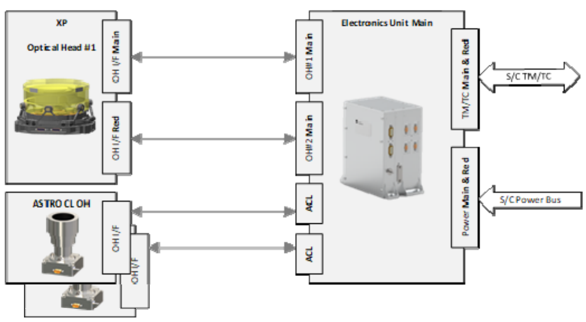

Figure 8. Example for an hybrid star tracker system covering very high pointing accuracy but also very high spacecraft dynamics

5 OPTICAL HEAD TEST PLAN

The successful test readiness review in Q4/2022 kicked-off the pre-qualification test campaign of the ASTRO XP optical head EM. The on-going campaign comprises the following test steps:

Functional and performance test: at the beginning and the end of the test sequence. Further functional and performance tests are performed between the mechanical- and environmental tests. This involves the characterization of the single star error budgets (temporal error (TE), high spatial frequency error (HSFE), low spatial frequency error (LSFE)), the BRF versus MRF alignment, the electro-optical performance as well as the functionality.

The measurement performance of the ASTRO XP high accuracy star tracker needs to be verified under laboratory environment based on single star measurements. Optical star pattern simulators for the stimulation of real multiple star scenarios are not available with an accuracy of better than 0.1arcsec. For that reason, a high accuracy 2-axes turn table is in addition equipped with a 3-beam two-axes laser interferometer. This allows reference star pointing with an accuracy better than 30mili-arcsec.

The single star performance is demonstrated by a so called “basic pointing test”, where a single star is pointed on several thousands of uniform distributed angular field positions. The angular reference from the laser interferometer is then compared the angular coordinate measurements of the star tracker optical head. In off-line post-processing the single star error budgets can be isolated in the temporal error, the HSFE and the LSFE, all together in the single star total random error. See the measurement results presented in the test section of this paper.

Mechanical environmental test: This test comprises at first the resonant search runs in all three axes in order to verify and to confirm the structural analysis. After that, the typical mission random- and sine-vibration loads are applied to the optical head. In a further test step, the load is increased to the agreed pre-qualification level with the agency. Finally, a shock test is applied to the EM optical head. All of these tests are enveloped by functional- and performance tests for characterization and trending analyses.

Thermal vacuum cycling: Under the thermal vacuum environment, the optical head will be characterized with respect to the alignment stability within the operational temperature range. This requires special designed test equipment in order to account the deviations in the sub-arc seconds range. The second focus in the thermal vacuum testing is directed to the limiting star signal-to-noise ratio towards the hot end of the operational temperature range. The optical head or in particular the focal plane is not equipped with a thermal electrical cooler. Such a device would introduce un-controllable thermal distortions in the focal plane.

Night-Sky testing: The night sky test shows in general the functionality of the overall star tracker processing chain up the attitude solution. However, a full scaled measurement performance verification is not possible due to the natural limitations given by the atmospheric extinction and more relevant by the “seeing” effect. The atmospheric extinction can be coped a bit by the selection of the test location, which should preferably a mountaintop (>3000m) in dry air environment. The seeing is a real limitation also for the large ground based professional telescopes. Scintillations in the close and far field of view air volumes lead to blurred and unstable single star measurements in the range of < 1.5arcsec (< 0.7arcsec excellent conditions). Therefore, the high accuracy star tracker cannot be verified down to the specified performance under night-sky environmental conditions. In the test results section of this paper the limiting seeing effect to the single star measurements is demonstrated. The pre-qualification tests including data evaluation will be finished within 2023. Figure 9 gives some impressions from the on-going test campaign.

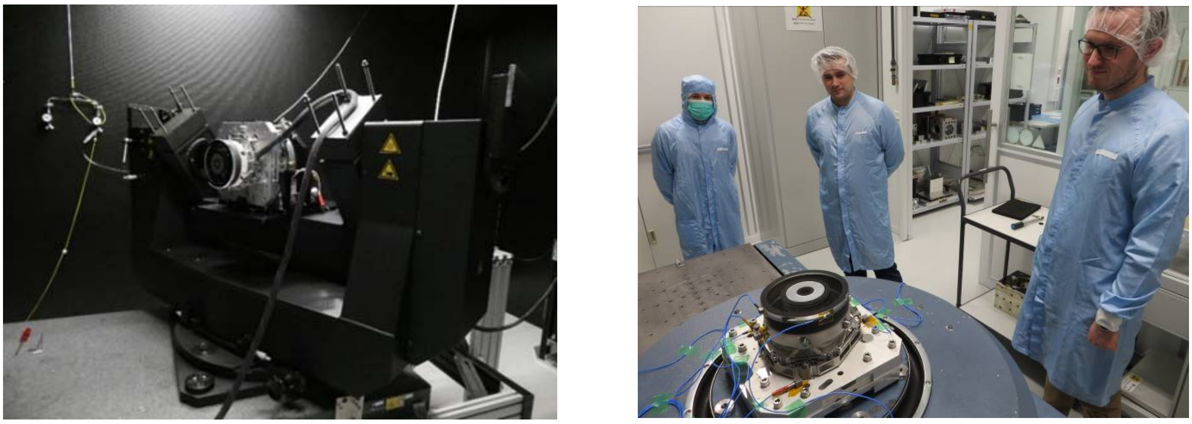

Figure 9. Left: ASTRO XP optical head EM mounted to a high-accuracy two-axis turntable with laser interferometer for single star performance measurements; Right: EM mounted to the shaker for resonant search and vibration load tests

6 EM TEST

6.1 Single Star Measurement Verification

For the ASTRO XP single star performance tests a dedicated optical bench in a separate dark room is reserved. The optical bench is isolated from the environmental vibrations and room temperature controlled to +20°C±0.5K. Figure 9 to the left shows the high precision two-axis turntable. Its accuracy alone is not sufficient to verify the star tracker single star accuracy below the requirement of 232mas. For this reason, the turntable is equipped with a 3-beam laser interferometer. The turntable is used for the star positioning in the field of view, whereby the interferometer is used to read out the star reference angles. For an exact zeroing adjustment of the boresight reference frame, the star tracker bracket can be fine-tuned in both cross boresight angles by piezo actuators.
A single star basic pointing test uses several thousand uniform distributed measurement points in the star tracker field of view. The angular references from the laser interferometer and star tracker measurements are stored. At each position at least 10 measurement are taken. With such a data set, the single star error budgets, such as temporal error HSFE and LSFE, can be derived. Figure 10 demonstrates the residual HSFE error for both axes over the square field of view after the separation of the LSFE and the temporal error.

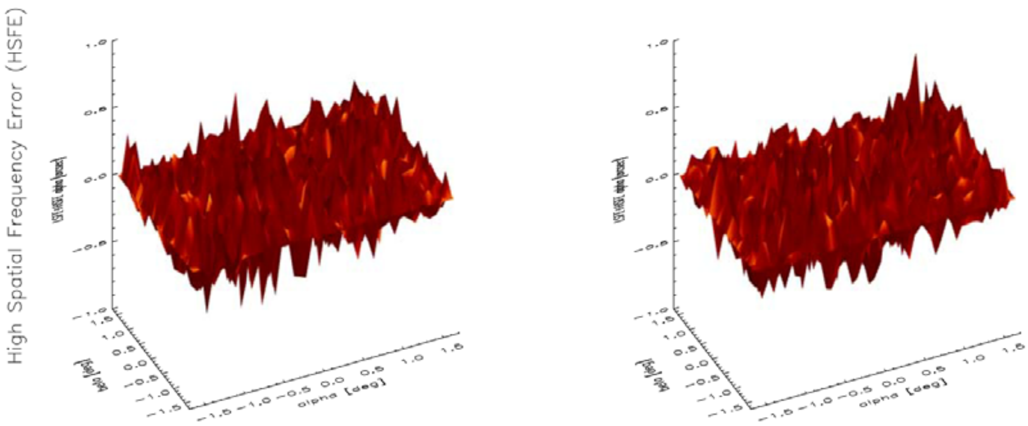

Figure 10. xy-axes HSFE error of 0.19arcsec 1σ for a 7.2 magnitude star

The optics field distortion is calibrated with a two-axis field polynomial. The remaining low frequency error over the field of view is counted into the LSFE budget. The individual field calibration coefficients are part of the optical head calibration data set.
A typical single star error contributor is the systematic pixel interpolation error as part of the pixel spatial error budget. The point spread function of the optics interacts with the pixel topology of the front illuminated CMOS APS detector. This results in the typical "S-curve" error over the pixel spatial domain. This "S-curve" characteristic varies in amplitude and phase over the detector field domain. In addition, the error signature can be cross-coupled between the detector axes. The implemented high processing capacity in the ASTRO XP electronics box allows a dedicated field dependent calibration and correction of the pixel interpolation error. Due to the fact, that the optics consists after its final integration only of a monolithic SiO_2 block, the imprinted pixel spatial error calibration remains valid in the typical star tracker operational environments.
Figure 11 demonstrates the performance of the pixel spatial error calibration over the whole detector field. Each star centroid of the basic pointing measurement is folded with its fractional part into a virtual pixel domain [-0.5, +0.5]. The red dots show the performance before the pixel spatial error calibration. The single star HSFE error could be improved from 0.29arcsec to 0.19 arcsec. This is treated as significant for the overall performance of the star tracker.

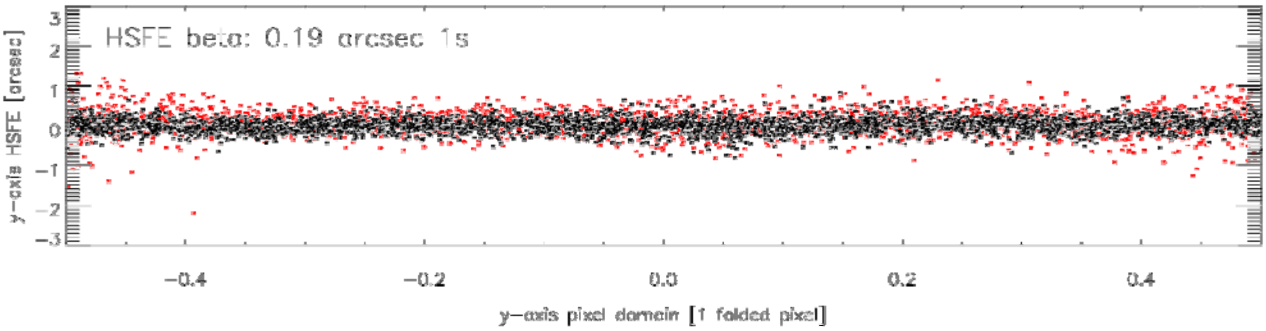

Figure 11. Single star HSFE error before (0.29 arcsec 1σ) and
after pixel spatial domain calibration (0.19 arcsec 1σ)

Figure 12 summarizes the measured single star error budget for a 7.2 instrumental magnitude [mi] star. This star brightness represents the mean magnitude of the on-board star catalogue.
The *temporal error* is much better than specified and predicted. That calls for the excellent low noise signature of the FaintStar2 detector and the efficient noise suppression in the real-time data processing.
The *HSFE single star budget* exceeds a bit the prediction but is still acceptable in the overall error budget to achieve the 0.1 arcsec 1σ in the attitude solution with multiple field of view stars (≥ 5).
In the *LSFE residuals* after the field calibration, we see only spatial frequencies of higher order than the field polynomial but with very low amplitudes.
In summary, the required single star total random error (LSFE/HSFE/TE) is as expected within the specification limits.

TE:	0.088 arcsec 1σ	0.090 arcsec 1σ
HSFE:	0.192 arcsec 1σ	0.192 arcsec 1σ
LSFE rms:	0.075 arcsec 1σ	0.089 arcsec 1σ
LSFE/HSFE:	0.206 arcsec 1σ	0.211 arcsec 1σ
LSFE/HSFE/TE:	0.224 arcsec 1σ	0.230 arcsec 1σ

Figure 12. Measured single star error budget for a 7.2mi star

A basic pointing test with several thousands of uniform distributed measurement runs up to 20hours. The measurement equippment needs to be stable during this time. The dark room is temperature controlled to +20°C±0.5K. The laser interferometer is also self controlled temperature stabilized during the measurement time.
Figure 13 reports in the top plot the single star noise during the 10 successive measurements per measurement field positon. This test comprissed 2800 field positions. Any outliers are analyzed and in case of temporal disturbances removed from the characterization data base.
The middle plot represents the laser interferometer noise over the 10 successive measurements and the whole basic pointing test session of 2800 points. The IFM noise amounts to < 11mas 1σ and is well below the test star noise. In the bottom plot, the IFM temperature during the 20hour measurement period is reported. The IFM runs stable within 0.1K arround the mean temperature.
This excellent stability of the measurement equippment is a significant prerequisite for the high accuracy star tracker qualification and acceptance tests.

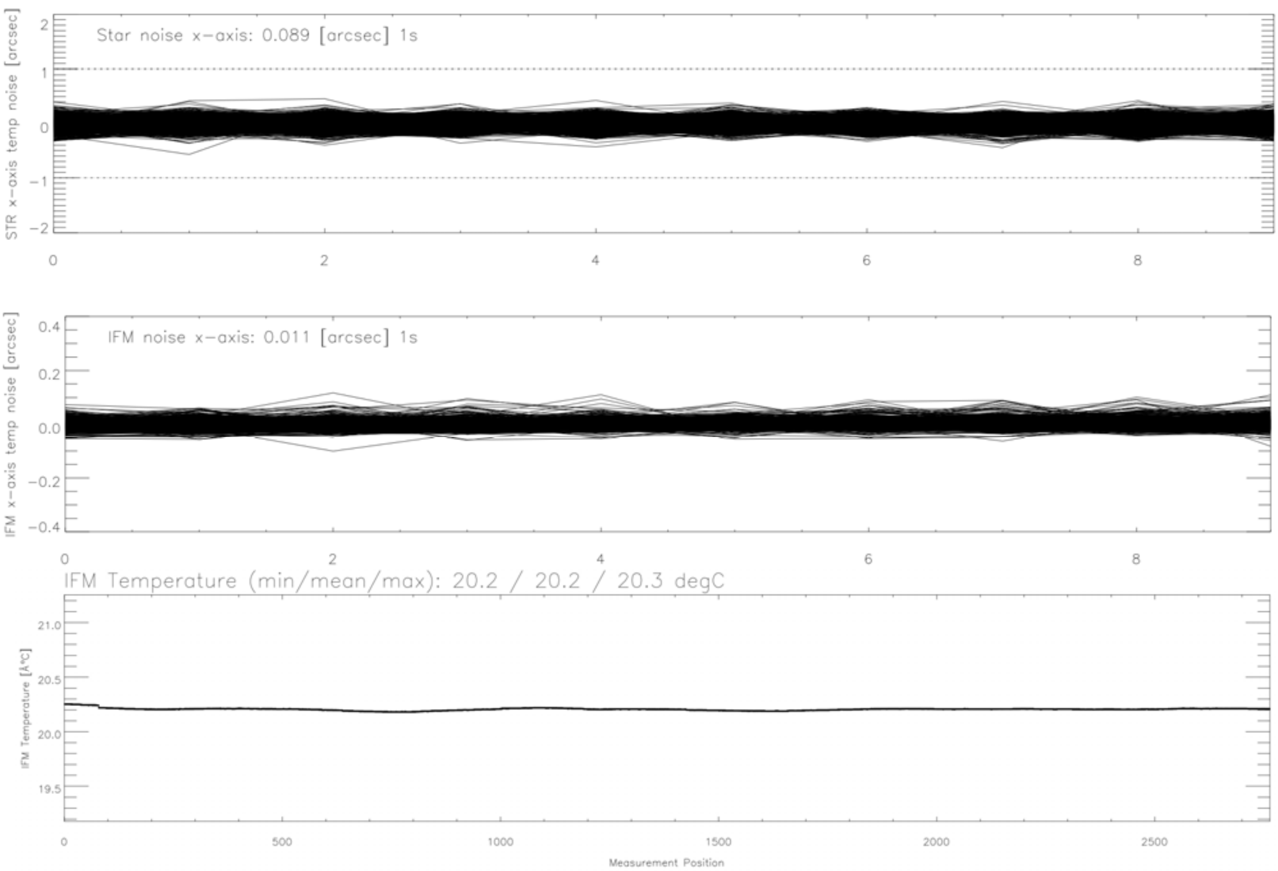

Figure 13. Stability of the optical bench during the 20hours basic pointing test; Top: single star noise over 10 successive measurements; Mid: Laser interferometer noise over 10 successive measurements; Bottom: Laser interferometer temperature over 20hours measurement time

The single star characterization tests under laboratory environment confirmed the predicted single star accuracy. Based on those results, the attitude solution can be provided with 0.1 arcsec 1σ in the total attitude random error budget for orbital angular rates of < 0.06deg/sec.
In order to cover higher angular rates, a hybrid system with ASTRO CL or APS3 optical heads is proposed, see Figure 8.

7 NIGHT-SKY TEST

The main purpose of night sky testing is to check the overall functionality of the high accuracy star tracker. The ultimate performance cannot be derived from ground based testing due the limitations given by the extinction and the seeing effect.

The extinction comprises the attenuation caused by the atmospheric conditions. In the best case the star can be detected on ground with 0.3…0.4magnitudes signal loss. This can be taken in mind when verifying the maximum possible limiting magnitude for star detection and tracking.

The more severe limitation for performance testing of the high accuracy star tracker is the seeing effect. Seeing describes the effect of star image blurring due to near field air turbulences or atmospheric air streams. The near field turbulences can cause air “schlieren” originated from heat spots from the unit itself or the immediate environment. This local turbulences let stars “move” in their local positon with < 1.5arcsec uncertainty. It can be seen that nearby stars show a strong correlation in their track over time. The atmospheric seeing causes all stars in the small field of view to show correlation. Therefore, 0.1arcsec 1σ performance of the star tracker cannot be shown on ground based test sessions.

Nevertheless, we checked the ASTRO XP EM on the night sky using the Jena-Optronik roof top test facility. The core element of that little observatory is a two axes high precision turntable (see Figure 14).

Figure 14. Jena-Optronik roof top test facility with a two-axis turntable

On May 26th 2023 we pointed the ASTRO XP optical head towards the Moon in order to check the imaging quality of bright resolved objects. The ASTRO XP optical head can be used as navigation camera as well as in combination with the high accuracy star tracker. The basline software will support both applications. At the focal length of 175mm, the Moon is imaged with a diameter of approx. 150 pixels. In order to resolve the surface structure, the exposure time needs to be shuttered down to 400µs. Figure 15 shows the Moon image in an ROI of 300 x 240 pixels within the star tracker field of view. The maximum pixel signal is exposed to 3340DN_{12} (12 bit digital numbers). The right hand side of Figure 15 presents the contrast edge profile of the Moon limb. There are only 2 pixels contrast slope over a 2500 DN_{12} counts edge. This confirms the excellent optics adjustment and final fixation. The engineering model test result confirm also the night sky test experience taken with the prototype unit in 2019.

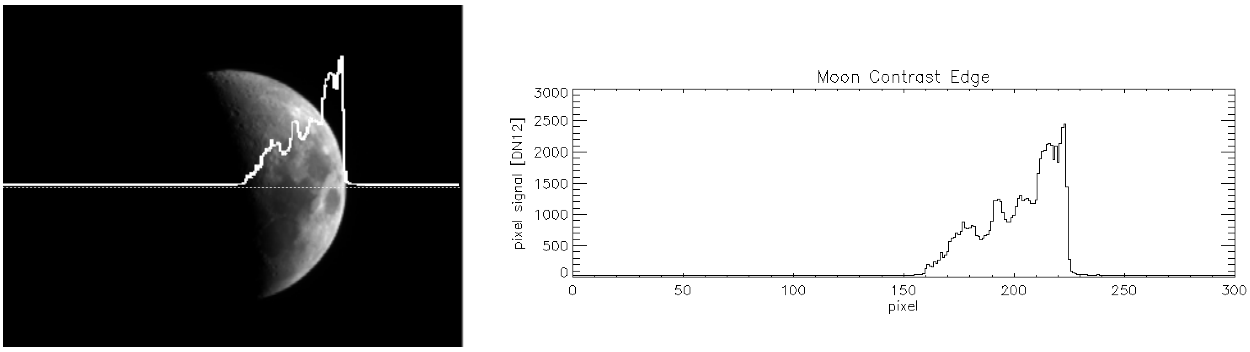

Figure 15. Resolved Moon imaging with 400µsec exposure time; Left: Moon in a 300 x 240 pixel ROI; Right: Moon contrast edge profile

Figure 16 shows a field of view tracking scenario during night sky testing at the Jena-Optronik roof top. The purpose of this test was in the first order the verification of the functionality of the engineering model optical head. As already explained we could not expect to see full performance due to the natural limitation by the extinction and the seeing effect. We could derive an extinction limited attitude temporal figure less than 0.12 arcsec 1σ in the xy-axes. The total attitude error (TE/HSFE/LSFE) suffers especially from the seeing limitation (typ. 0.8…1.5arcsec per star) and was measured with 0.26/0.24 arcsec 1σ in the xy-axes.

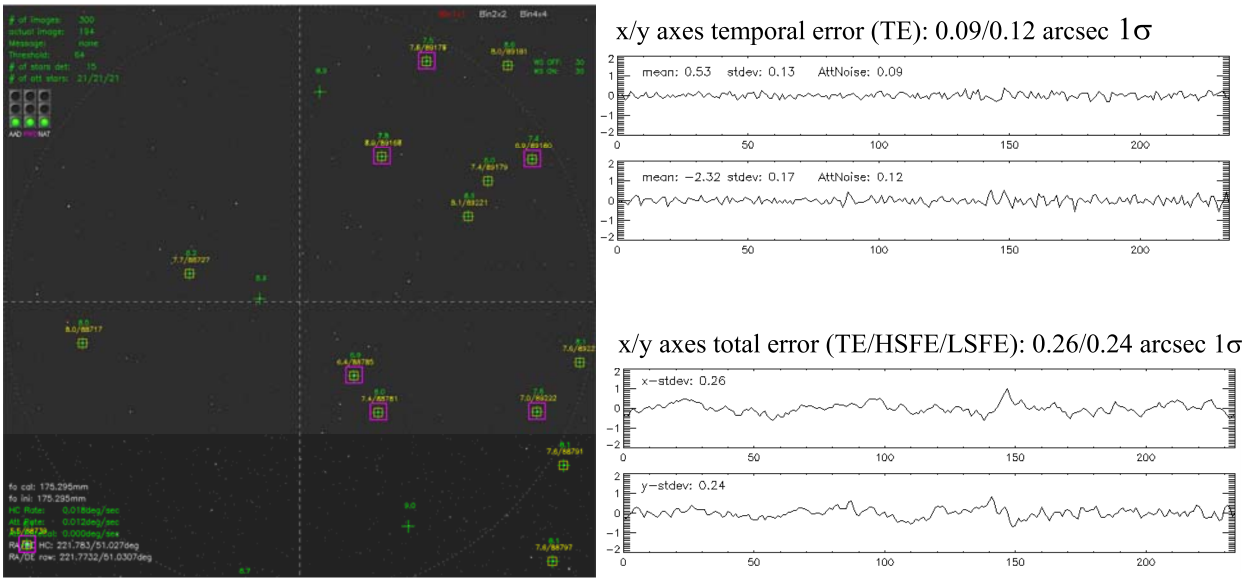

Figure 16. Left: field of view star scenario during night sky test; Right: xy-axes attitude noise performance (TE and TE/HSFE/LSFE) with the known extinction and seeing limitations

In Figure 17 on the next page, the present seeing effect during the night-sky experiment is high-lighted. The red plot shows the correlation coefficient in between all tracked stars at the same measurement time stamp. That coefficient shows the single star track dynamics, which is contained in all tracked stars. Stars with close angular distance to each other show strong correlation, which indicates near field air scintillation. The typical frequency of the observed seeing is in between 0.1…0.3Hz.

The night sky test will be repeated at an exclusive selected location, preferably on a mountaintop to reduce the extinction and properly the seeing under optimal conditions. However, it cannot be expected to see full performance under atmosphere. The identified solution is to verify the ultimate performance under ground test thermal-vacuum environment, which demands further investments in the test facilities.

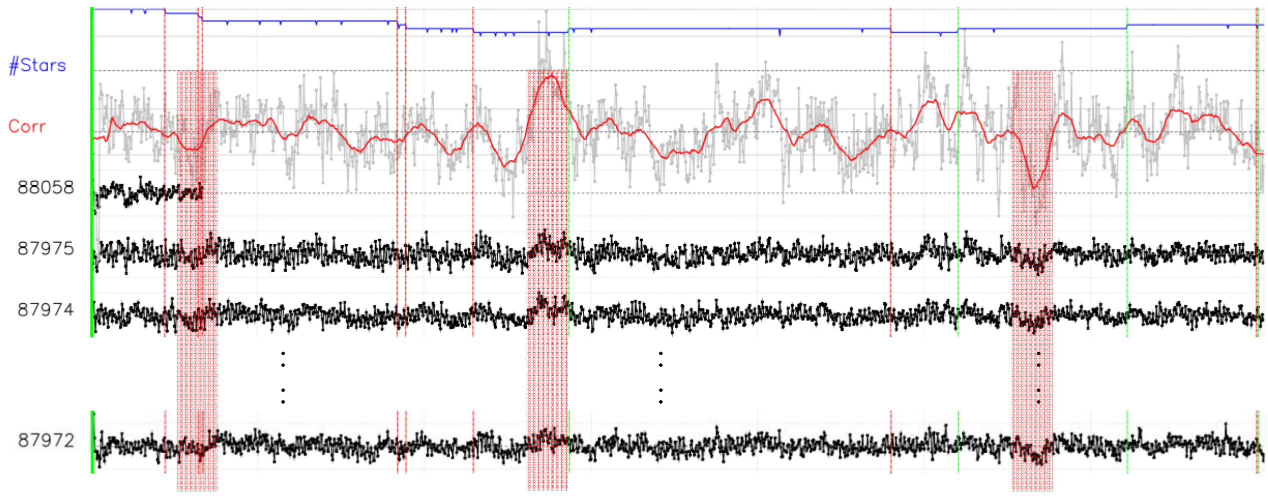

Figure 17. Track stars correlation analysis showing the "seeing" effect as limitation for performance verification under ground test atmospheric environment; Red solid line: Error introduced due to near- and far field seeing.

8 CONCLUSION

In 2014 Jena-Optronik received a development contract from ESA to study the design of a compact high accuracy star tracker. The optics trade-off proposed a novel on-axis reflective FMA design with a 4-times folded optical path. This compact design can be realised as self-sustained optical system with fused silica as the only bulk material.

Based on the very promising study results, ESA enabled a further contract to realize an engineering model in form, fit and function of a flight unit. Because of the new manufacturing, assembly and integration technologies, the engineering model shall be able to undergo pre-qualification test loads.

The test readiness review was held in Q4/2022. The test campaign is currently running with the functional and performance tests as well as the night sky tests. The EM characterization and data evaluation will be finished in 2023.

The single star based laboratory test results confirm the predicted error budget. The night sky test shows excellent imaging quality for stars but also for bright resolved objects like the Moon.

Jena-Optronik has demonstrated with the engineering model that a compact, low power and low mass high accuracy star tracker design is feasible. In preparation of a real science mission, Jena-Optronik is prepared to perform a comprehensive qualification test program with its experience and tailored test facilities.

9 ACKNOWLEDGEMENTS

The ASTRO XP project journey started in late 2014 with the predevelopment ESA contract No. 4000112514/ 14/NL/BW. The main emphasis was focused to figure out a design solution, which fulfils the tight requirements in terms of accuracy, mass and compactness. At this time there was no comparable system on marked which would fit into the required budgets. I appreciated the project work with ESA's technical officer, Mr. Phil Airey. We walked together along a lot of design tracks with trial and error, but moved slowly and continuously towards the right and brilliant solution. Thank you Phil for the respect, understanding and the great project experience.

Based on the promising predevelopment study results, the project was continued with the ESA contract No. 4000126831/19/NL/GLC/hh. The statement of work required to establish an EM of the optical head to be able to undergo pre-qualification loads. My special acknowledgements are addressed to Mr. Steeve Kowaltschek and his team. With the so far promising results of EM testing, we can look back to a successful project experience.

As explained in the paper, the ASTRO XP design incorporates new technologies in the manufacturing, assembly, integration and test procedures. Jena-Optronik thanks the local high-tech optics industry suppliers in the Jena valley for their extraordinary support. Without their worldwide unique expertise, the project would not have been successful.

On the same way, I would like to designate here our most skilled ASTRO XP workers in the integration department, namely Mr. Wolfgang Egerer and Mr. Uwe Werner. Wolfgang flattened the way with its professional experience to make the ASTRO XP optical head mountable. Uwe executed that complex mounting process with its excellent fine-motoric handling skills.

Mr. Jörg Reichardt joined the project from the very beginning as the lead engineer in the field of the opto-mechanics design. Many thanks to Jörg and its department for the numberless discussions and meetings finding the right way forward.

Mr. Daniel Adolf entered the project team as the leading test and verification engineer in the EM test phase. He participated actively with valuable contributions and its excellent comprehension.

At least I have to mention the project manager, Mr. Richard Würl. Project managers have to solve the schedule, cost, resources and progress equation every day, which is very hard sometimes. Thank you Richard for your endurance and your active engineering involvement.

10 REFERENCES

[1]. U. Schmidt, B. Pradarutti, ASTRO XP – High Accuracy Star Tracker, AAS 2018, Breckenridge, Proceedings

[2] U. Schmidt, J. Reichardt, P. Petruck, R. Würl, S. Fröhlich, I. Steinbach, ASTRO XP-First Test Results, AAS 2020, Breckenridge, Proceedings