Socio-economic benefits from ESA's Science Core Technology Programme

A report for esa

CASE STUDY: High Accuracy Star Tracker

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The need for a more accurate, smaller, and lighter star tracker …

High accuracy star trackers are **essential sensors** that determine the attitude of spacecraft. They do so by scanning the celestial sphere (capturing images) to identify known stars and constellations contained in their catalogue, using their onboard processing system. They then analyse the placement of surrounding stars relative to the payload to determine the satellite's attitude in order to enable star tracker navigation. This is a key technology that enables Science and EO missions, in GEO and deep space.

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Existing technologies are not suitable for the ambitious next generation of ESA missions: European solutions cannot currently provide the levels of accuracy required, and the only other high accuracy star tracker on the market is too heavy and export-controlled.

Therefore, ESA has funded technology development projects first through the General Support Technology Programme (GSTP) and now the **Science Core Technology Programme** (CTP) for a high accuracy star tracker that could meet the demanding requirements of upcoming missions, most notably ATHENA. The objective is to have a fully qualified, flight-ready solution in the next few years.

… to enable ESA's next generation of ambitious and demanding missions …

This ambitious technology development project has been conducted by Jena-Optronik, a German subsidiary of Airbus Defence and Space.

Jena-Optronik

The company builds off a rich heritage, having worked on star trackers for more than 45 years and being located in a regional specialised modal optics cluster. Jena-Optronik products have been trusted and equipped on critical missions by key aerospace companies and space agencies globally.

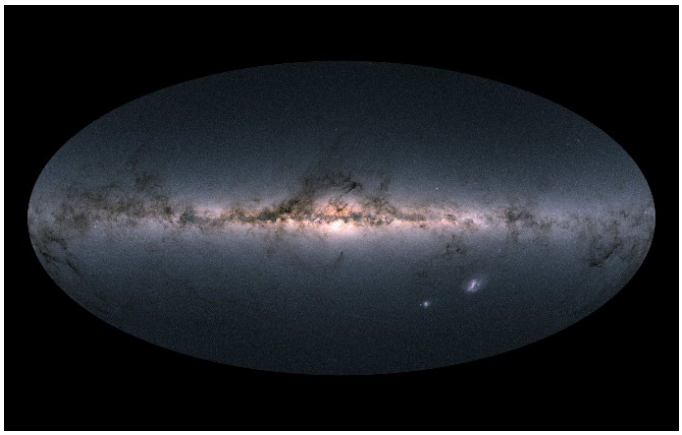
Jena-Optronik

Jena-Optronik has developed the ASTRO XP, an autonomous high accuracy star tracker of the 0.1 arcsec class. The company used a unique low expansion material, which provides an extremely high level of **stability** within the space environment.

This new product is also highly resilient to radiation, and is **compact**, **lightweight** (≤2.6kg for optical head only), and **low-powered** (<1W for the optical head). It is 100% reflective and leads to no chromatic aberration.

Jena-Optronik's ASTRO XP offers a combination of pointing accuracy, spacecraft resource consumption and mass that is unmatched on the market for a 0.1 arcsec class star sensor, both in Europe and the US.

These are crucial features that ensure that the product provides as little interference with the satellite's payload instruments as possible and meets the demanding requirements of ESA's next generation of missions, such as ATHENA. Overall, ASTRO XP is a **critical technology** that helps maximise the return of valuable scientific and EO data. Jena-Optronik won the Thüringen Innovation Award for this novel disruptive optics technology in 2020.



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… with potential for significant socio-economic benefits

Whilst the ASTRO XP star tracker for the ATHENA mission is still undergoing developments, some initial socio-economic benefits have begun to emerge, with the potential of many larger impacts to come through its successful use for space science missions and for other fields of application – both for the company and for the broader European industrial landscape.

Introducing a competitive, high-accuracy European star tracker to the global market

New knowledge and expertise

New **knowledge**, **expertise** and **processes** developed within the ASTRO XP project can have wider-reaching impacts through integration into Jena-Optronik's approach to their products.

The main challenge for Jena-Optronik in developing the ASTRO XP for ESA was in seeking to increase the star tracker attitude measurement accuracy whilst keeping a compact design. This required new thinking in optics design, structure raw material selection, algorithms and test approach – particularly regarding the High Spatial Frequency Error and Noise Equivalent Angle.[1]

This new thinking for design in comparison to standard state-of-the-art solutions included improvements in the technological fields of **optics**, **materials** and **precision machining**, with an update in the onboard star catalogue (compiling data from ESA's GAIA mission) for the angular reference. Even the verification and test strategy regarding the test equipment and environment needed a new approach, since the turn tables used to-date as angular references had limitations for accuracies <0.3arcsec, and the temperature stability and mechanical vibrations within the test environment needed to avoid creating limiting effects for the performance measurements.[2]

This new knowledge and expertise for the company can translate into their approaches for their star tracker product range going forward, both in terms of the technological approach and processes, as well as their ability to provide such high accuracy quality solutions for the market. The electronics and algorithms utilised have synergies across their product range and design roadmap.

[1] Schmidt, U., and Pradarutti, B., 2018. *ASTRO-XP High Accuracy Star Tracker.* Astronautical Sciences AAS/AIAA Guidance, Navigation and Control 2018, volume 164.
[2] Schmidt, U., et al. 2020. *ASTRO XP – First Test Results. Astronautical Sciences AAS/AIAA Guidance, Navigation and Control 2020*, volume 172.

Increased competitive advantage

Through its participation in the ESA CTP, Jena-Optronik has developed a new product that it is now planning to bring to market as a high accuracy offering, which from an overall technical perspective is not available from any other competitor.

As a company, Jena-Optronik has positioned itself as a leading global competitor in the field of Attitude and Orbit Control Systems (AOCS) for satellites, and has provided a range of star tracker products for many years. However, by developing such a **high-accuracy solution**, it has been able to bring a **disruptive technology to market** that allows the company to distinguish itself from its global competitors.

A decade ago, more than 75% of the global star tracker market was commanded by three European companies[3], and the landscape within Europe has not changed much in the interim, with Jena-Optronik placed as one of three major European sources for high-end star trackers. Due to its **key position** and niche nature of the high-accuracy end of the star tracker market, it is important that Jena-Optronik can differentiate its offered solutions, and this can be achieved through developing a product that reaches a level of accuracy that is not available elsewhere in Europe, as well as applying its newly-acquired knowledge and expertise from its development to its wider range of products, as outlined above.

New market opportunities

The Astro XP star tracker has potential fields of application in Earth Observation missions in GEO and LEO orbits as well as further space science missions, opening **new market opportunities** for Jena-Optronik.

These new market segments include providing **fine pointing for laser communications,** especially for inter-satellite communication. Since the beginning of space exploration, most missions have used radio frequency communications to send data to and from spacecraft. However, as new missions become more complex and generate more data, there is a rising need for enhanced communications capabilities. One way to address this is with optical communications, which could provide significant benefits for missions such as bandwidth increases of 10 to 100 times more than radio frequency systems, as well as a decrease in communications payload size, weight and power requirements, leading to more room on board for science instruments and less drain on the spacecraft's power supply.[4] Therefore, ASTRO XP has the potential to be a key component for the fine pointing in laser communication systems in the future.

Another field of application is with **precise ground mapping** from Geo-Stationary Orbit (GEO) for metrology, which is the science of measurement, including all theoretical and practical aspects of measurement and seeking accuracy, reliability and repeatability. ASTRO XP can support 17m ground resolution from 36,000 km in orbit. It can also support high resolution imaging with onboard geo-data determination, with the ability to support 0.4 m ground resolution from 800km in orbit (Low-Earth Orbit).[5]

Finally, there are wider applications for a high-accuracy star tracker than just the ATHENA mission (ASTRO XP's initial intended application). For example, it can provide **stellar pointing** in the L1 Lagrangian Point, which is a key position for observing the larger universe by a multitude of science missions, and is applicable for AOCS use in deep space missions. Therefore, ASTRO XP could be used or adapted for integration on other space science missions.

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[3] The European Space Agency, 2012. *Europe dominating satellite star tracker market.* Available at: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Europe_dominating_satellite_startracker_market
[4] National Aeronautics and Space Administration, 2022. *Laser Communications Relay Demonstration.* Available at: https://www.nasa.gov/mission_pages/tdm/lcrd/index.html
5 Jena-Optronik, ASTRO XP Fields of Application

Developing advanced technological solutions in order to achieve high accuracy, compactness and stability

Advanced technological improvement

Jena-Optronik has improved state-of-the-art start tracker technology representing the 1 arcsec class by one order of magnitude in **accuracy to 0.1 arcsec**.

In order to achieve the high-accuracy requirement of this ESA CTP project, Jena-Optronik had to increase to approximately a **factor 10 on performance improvements**, seeking to advance almost all contributing technological domains, including optical systems, digital imaging, processing algorithms, astrophysics, material selection and verification and test approaches. One of the challenges was **improving the design to 0.1arcsec**, whilst still maintaining the unit to be cost **competitive** and **moderate in mass**.

The optical measurement system, or the "optical head" has been designed as a separate unit from the remaining electronics (the "electronics unit") so that there is a minimum amount of mass, envelope and power consumption of the hardware close to the spacecraft's primary instruments and hence **removes risk of interference/disruption**. Jena-Optronik has also included a FaintStar image sensor that was developed under contract with ESA, and which provides high radiometric performance and low power consumption.[6]

Conventional solutions for star trackers, where each lens is housed in an optics build, have limited thermal abilities for optics, since each component is made of a different material, with different thermal expansion coefficients. Conversely, the ASTRO XP is made fully of fused silica material, maintaining a low thermal expansion coefficient and avoiding mechanical stress, hence allowing the technology to operate in a **wide range of temperatures** without thermal-induced misalignment. This means that the solution is **highly stable**.

This star tracker also has a full catoptric design, which means that the imagine formation process only uses light reflecting mirrors (as opposed to systems which use both mirrors and lenses). Indeed, ASTRO XP maintains an optical path with four reflections using the primary mirror two times, and this 'folded' optical path allows it to have a **compact design**.

Finally, the onboard star catalogue for the angular reference utilised the GAIA Data Release 2 (DR2) package, which provides the most accurate astrometric data set used for this type of technology. Its catalogue of approximately 45k stars, as a combination of acquisition stars and fine attitude tracking guide stars, can be used to achieve **100% coverage over the celestial sphere**.[7]

All of these capabilities combined have resulted in a solution that is high in accuracy, extremely compact, and stable within the space environment.

Potential cost-effective alternative solution

Star trackers are the most accurate instrument within an Attitude and Orbit Control System (AOCS), and are at the centre of three-axis attitude determination for the spacecraft. However, to some extent a spacecraft must be stabilized before the star tracker can begin to determine the attitude, and so typically, a gyroscope therefore complements the star tracker for the initial stabilisation of the spacecraft. Furthermore, whilst a star tracker is highly accurate, it historically has presented a slow update rate, requiring additional sensor and sensor fusion algorithms to provide faster output; gyroscopes are hence also used for high-frequency attitude updates.

[6] Jena-Optronik, 2022. *ASTRO XP.* Available at: https://www.jena-optronik.de/products/star-sensors/astro-xp.html
[7] Ibid

The disadvantage of having a gyroscope within the AOCS is that they can often be costly or heavy.[8] Therefore, an alternative solution of developing a star tracker or 'stellar gyroscope' that can operate at high update rates and eliminate the need for traditional gyroscopes onboard a spacecraft are being investigated. A complex spacecraft mission operating without a gyroscope would benefit from significantly lower power consumption, mass and complexity in comparison to a spacecraft with a conventional attitude determination system.[9] A high accuracy star tracker such as Jena-Optronik's ASTRO XP could hence be a **potential alternative cost-effective solution**.

A unique European solution that acts as a key enabler for future space science missions

Increased European competitiveness

Europe has positioned itself at the **forefront of star tracker technological development** with the development of the ASTRO XP solution.

This does of course come with the recognition that continued innovation is essential in maintaining its leadership when countries such as the US and China are pushing for their own star tracker developments.

As mentioned, the development of the ASTRO XP has positioned Jena-Optronik as a leader within the European landscape, offering a solution at a standard of accuracy that is not available elsewhere in Europe. Additionally, the only competitive product on the market to achieve the high-accuracy of 0.1arcsec comes from an American competitor. However, this product has a higher mass compared to the <7 kg solution overall of ASTRO XP (or ≤2.6 kg for optical head only), as well as a greater power demand as opposed to the <1W low-powered solution (for the optical head) from Jena-Optronik. This is due to the fact that the competitor product uses refractive optic technologies rather than the mirror technology developed by Jena-Optronik, which has allowed their solution to be highly compact, small and lightweight.

Overall, this means that this project is supporting the European development of a solution that is highly competitive on the global market, especially considering its low-powered, low-mass impacts will support the ability of a spacecraft to have **more capacity for its complex scientific instruments**, as well as retaining a **longer-lifespan** or battery life due to less power demand. Furthermore, it has also brought new capabilities and knowledge to the European landscape.

Enabler of future missions

The ASTRO XP star tracker is being developed with the aim to help enable the upcoming L-class ATHENA – Advanced Telescope for High-Energy Astrophysics – space science mission.

ATHENA will be an X-ray telescope that is being developed under ESA's Cosmic Vision science theme of 'The Hot and Energetic Universe'. Due to launch in 2035, ATHENA seeks to map and study large-scale gas structures and determine their physical properties, survey supermassive black holes, and explore high-energy astrophysical events such as supernova explosions and energetic stellar flares.[10]

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[8] Marin, M., and Bang, H., 2020. *Design and Simulation of a High-Speed Star Tracker for Direct Optical Feedback Control in ADCS.* Sensors (Basel). 2020 Apr; 20(8): 2388.
[9] Liebe, C., Gromov, K., and Meller, D. *Toward a Stellar Gyroscope for Spacecraft Attitude Determination.* Journal of Guidance, Control, and Dynamics Vol. 27, No. 1, January–February 2004
[10] European Space Agency, 2022. *ATHENA: Mission Summary.* Available at: https://sci.esa.int/web/athena/-/59896-mission-summary

A star tracker with such high accuracy is required for this mission since ATHENA must point its main instrument with precision towards the star fields, and operate in inertial pointing; to arrive at such a stationary position for **high quality scientific observations**, it is therefore necessary to have an extremely high accuracy star tracker. The mission would potentially utilise the ASTRO XP as a payload application for the metrology system for the main telescope, monitoring its stability, and then two other ASTRO XP for star tracking and payload monitoring.

Another future mission where the ASTRO XP could be a key enabling technology includes the Laser Interferometer Space Antenna (LISA) mission. Due to launch in 2037, LISA is an L-class ESA mission designed under the Cosmic Vision Theme of 'The Gravitational Universe', seeking to observe the growth and merger history of massive black holes, understand the dynamics and characteristics of unexplored regions surrounding black holes, precisely measure tens of thousands of binary star systems, and probe the 'dark' and early universe through the detection of primordial gravitational waves.[11]

Beyond deep space science missions, ASTRO XP also has applications closer to Earth, with the potential to enhance the performance and stability of upcoming **Earth Observation Sentinel missions**.

Expanding European non-dependence

Star tracker solutions are a key enabling technology for space science missions and deep space exploration, as well as potential inter-satellite communication systems for EO satellites. That, combined with the fact that Europe has already established itself as a leader within this market, highlights the importance of **retaining non-dependence** of the technology in future developments. This is especially the case for a star tracker that can achieve 0.1 arcsec, since the only other solution on the market at such accuracy falls under export restriction regulation which puts in place more barriers for its use within European missions, as well as highlighting a gap in European capabilities which the ASTRO XP aims to address. This means that ESA has access to high-accuracy star tracker solutions that are **not dependent on other countries**.

It is important to note that due to the unit parameters, ASTRO XP sits in an accuracy class that is on the export control list, so requires a license if exported to certain countries. However, this does not restrict its use within Europe, nor does it remove the possibility of export as long as the license is granted.

Would these benefits have been realised without ESA?

ESA

ESA was the catalyst and enabler for the development of this industry-leading high accuracy star tracker. Jena-Optronik emphasised that GSTP and CTP investments were critical, as the company would not have funded these early R&D activities on its own due to the considerable NRE (non-recurring engineering) costs and risks.

Overall, ESA was key in equipping Europe with an unrivalled star tracker, enabling the next generation of ambitious Science and EO missions, and providing Jena-Optronik with a new product that it would not have developed otherwise.

> *"The initiating events were ESA's funding and its technology development programme."*
> - *Uwe Schmidt, Richard Würl (Jena-Optronik)*

[11] European Space Agency, 2022. *LISA: Science Objectives.* Available at: https://sci.esa.int/web/lisa/-/61366-science-objectives

… plus further development and benefits to come

Jena-Optronik is expected to continue the development of the ASTRO XP, reaching full flight qualification long before the launch of the ATHENA mission in 2035. Once qualified, it aims to be used in other science missions, potentially ones such as LISA, as outlined in previous sections. The company could also pursue opportunities to include its high accuracy star tracker on missions in GEO orbits, as it would notably be useful for fine pointing for laser communication, precise ground mapping for metrology, and high-resolution imaging with onboard geo-data determination. Overall, contract awards for these missions are anticipated to support employment, strengthen skills and capabilities and enhance the visibility of Jena-Optronik.