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

A report for esa

CASE STUDY: Silicon Pore Optics

know.space

June 2022

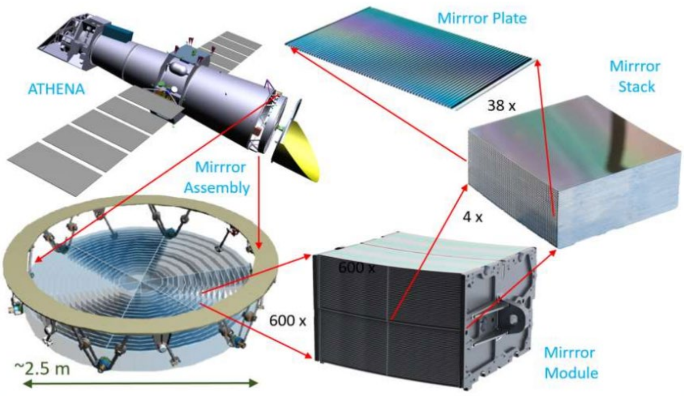
Meeting the challenge of the largest X-ray optics ever built, with high resolving power, low mass and large effective area …

Talks to develop the next generation of European space observatory started in 1999, around the launch of XMM Newton, and highlighted from the very beginning that **existing optics technology would not be suitable to build telescopes of the scale envisioned**. Indeed, technologies such as polished glass, nickel electroforming and foil optics, would lead to optics that are too heavy, expensive and/or are not able to produce the required large area or resolution. The concept of **Silicon Pore Optics (SPO) was thus invented and developed in the following two decades to respond to this gap**.

SPO has now become the mission-enabling technology for ATHENA, the second large class mission in the ESA Science Programme. The mission requires the largest X-ray optics ever built. Overall, ATHENA's mirror is composed of:

- 600 mirror modules
- ~100,000 mirror plates
- ~300 m^2 of polished and coated area

ATHENA's huge size will thus require modularisation, industrial production and new and innovative facilities for assembly and verification. Cost and schedule compliance is also critical to ensure the mission launches in 2035.



ESA

… by delivering SPO, revolutionary new X-ray optics for ATHENA …

cosine

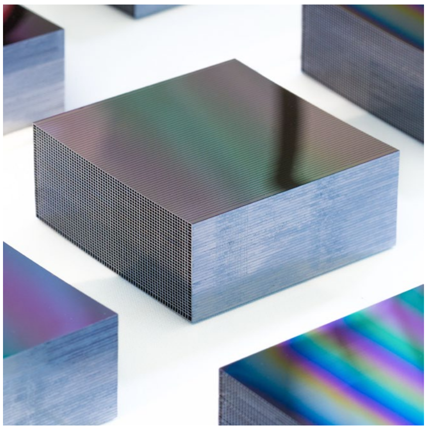
cosine has participated in various ESA-funded studies to explore SPO, and was **subsequently selected to lead a large European consortium** composed of many industry and academic stakeholders to develop SPO for ATHENA.

cosine

The company was chosen due to its heritage in X-ray optics and applied physics, which equipped it with skills, capabilities and experience that could be leveraged. cosine is based in the Netherlands, a country which historically participated in a lot of ESA activities in optics.

Over the past 2 decades, and with involvement from cosine and its partners, ESA has driven the development of SPO, originally under the Technology Research Programme (TRP), and later under the Science Core Technology Programme (CTP). cosine works in collaboration with its consortium partners, building on their expertise and adapting equipment and technologies, refining the SPO for ATHENA in a cost-effective way. Overall, activities are progressing on all fronts, which includes:

- Industrial mirror plate production at Micronit and Teledyne e2v
- Automated mounting of mirror plates at cosine
- Assembly of mirror modules at PTB/Bessy-II (and later at ALBA)
- Mirror assembly demonstrators at ADS and TAS
- Mirror modules AIT into the optical bench at Medialario
- Hexapod support and aligning system at Sener
- AIT and X-ray test facilities


ESA

The consortium's SPO technology offers high performance for missions using X-ray optics, providing good resolution and reliability while providing a large effective area and ensuring low mass. For ATHENA specifically, cosine demonstrated that SPO meets the mission area density requirements, and that it can offer a resolving power ~11 times better than established technologies for the same area and mass. Furthermore, the use of SPO in ATHENA is compatible with programmatic constraints around the budget and schedule.

… with potential for significant socio-economic benefits

While the SPO technology is currently shifting from development to manufacturing stage, some initial socio-economic benefits have begun to emerge, with the promise of many larger, benefits to come through its successful qualification and commercialisation – for the company, their customers and partners, and for the broader European industrial landscape.

Developing an innovative process for mass-producing high performance mirror modules for future high energy astrophysics missions

Increase in Technology Readiness Level (TRL)

As stated, ESA has been providing leadership and support for the development of SPO technology since the beginning, which has been essential for the continued success in evolving the technological readiness of the material.

CTP has provided the essential funding to carry SPO through the so-called innovation 'valley of death', which refers to the gap between more academic research/proof of concept (TRL 1-4) and industrial commercialisation, where many new technologies do not reach the necessary maturity and hence fail. Thanks to ESA's CTP support, the work undertaken by the consortium led by cosine has currently progressed SPO technology to a TRL of between 5 and 6.

Job creation

cosine anticipates to have increased the number of employees working on SPO nearly threefold between 2015 and 2030.

Within the company, cosine had around 10 full time employees (FTEs) working directly on SPO during 2014/15, which has risen up to 25 FTEs as of 2022, adding new jobs that doubled the amount of people working on this project. As they shift from the development phase to the manufacturing phase, they aim rise up to at least 30 FTEs for SPO MM production. These jobs were created at cosine, with even more created and/or supported by sub-contractors during flight model (FM) production.

This highlights how cosine's work on SPO has directly contributed to job creation and highly-skilled employment within the Dutch economy.

New processes

In order to produce SPO, cosine and its partners had to create an innovative process that did not exist before.

This includes the concept of **mass production**, which was not previously utilised within the company, as well as introducing techniques for coating processes. Much of the machinery required for SPO was spun-in from the semi-conductor industry (among others), where cosine then adapted the process in order to fit their needs. For example, a machine normally used for diamond cutting is now being used for silicon cutting.

Increased potential revenues

For large space missions where the key factor is the big x-ray telescope itself, the optical components play a core role, and hence sit at around ~10% of the overall budget. Therefore, the budget may reach around €120-130m for the mounted mirror modules, meaning approximately €15m flowing into industry across Europe per annum.

cosine itself has an annual turnover of around €10m per year, for which their optics business unit makes up around €6m of that annual revenue. ESA CTP is therefore a large first customer of their SPO technology. This revenue will only increase as SPO shifts into the flight stage.

The high-energy optics section of the business for cosine sits at around 50% of their turnover. This is expected to stay the same in terms of revenue percentage only because as the SPO optics begin to grow, so too should other aspects of their business, including potential terrestrial applications of SPO technology.

New collaborative ecosystem

Since developing the optics for ATHENA is such a long-term, complex process to reach the technological requirements of the mission, cosine has led a large consortium in order to deliver the SPO solution.

Partnerships and networks have been formed through SPO so that the company can purchase existing technology, tuning it for their specifications for ATHENA, as well as learning new processes, creating a broad ecosystem of companies for cosine to work with.

Through its SPO work, cosine has built more than 30 new partnerships with industry and academia in and beyond the space sector.

New terrestrial applications

cosine is utilising its CTP-funded activities to inform the development of Laue lenses, which could potentially improve radiotherapy treatment accuracy and recovery outcomes for cancer patients.

Currently, it is challenging to reflect hard X-rays and gamma rays with a mirror, since they can pass through most materials. One of the ways to diffract them is by using crystal planes, as in the case of a 'Laue lens'. However, the challenges with this solution include the fact that its production is difficult, and if regular crystals with flat crystal planes are used, the focal spot of the lens will never be smaller than the dimensions of the crystals themselves.

Compared to currently used radiotherapy equipment, which uses gamma-ray sources operating at MeV energy, the Laue lens solution is important because it can not only focus rays, but also act as a filter. It can select a narrow band pass of wavelength, which is the key for replacing dangerous and decaying gamma-ray sources with safer X-ray tubes.

cosine is aiming to develop Laue lenses that enable sub-MeV radiotherapy, providing a potential solution for targeting resilient tumours and also sparing the patient's skin thanks to a highly-focused beam. Since the radiation dose would be delivered in a small, well-defined volume, it would cause less damage to surrounding tissue whilst avoiding the production of radioactive waste. The company aims for this to be a complementary, effective tool for radiation therapy, and it is currently under development at TRL 3.[1] Wider benefits if this is brought to market could include better recovery outcomes, thanks to the increased treatment accuracy, benefitting both the health of society, as well as providing cost savings for governments and individuals. This could have considerable positive financial implications, when taking into consideration the cost of cancer has been estimated to sit at around €199 billion for Europe (in 2018)[2].

Additional terrestrial applications include offerings to the semi-conductor industry, although these are currently under NDAs. The semiconductor market is fast-growing (CAGR of 10.4% between 2016 and 2021), and was valued at around €550 billion in 2022[3], highlighting **opportunities for cosine to expand revenues**.

Creating an ecosystem of cross-sector partnerships and technology usage

Spin-in and spin-out technological opportunities

A pan-European ecosystem of SMEs has been created through SPO development, which has created spin-in and spin-out technological opportunities as well as cross-sector partnerships

SPO utilises technologies and processes spun-in from various sectors. This spin-in was critical to enable the development of this ground-breaking new X-ray optics technology. Benefiting from the vast existing investments in the semiconductor and automotive industry, the SPO technology was able to be developed and demonstrated efficiently and cost effectively, using non-space tools, materials, products and processes.

The starting material for the SPO production are the highly-evolved latest generation silicon wafers, which offer optimal figure and surface finish and are currently manufactured in large quantities to produce the chips in computers and telephones, meeting the requirements for ATHENA's X-ray optics. These wafers are produced using standard semiconductor equipment and processes, ensuring low cost and high quality and reliability. Other examples for spin-in elements are:

- The mandrels, which are polished from silicon using established optical manufacturing
- The plate manufacturing, which uses fully automated equipment and standard processes from the semiconductor industry
- The coating, which uses solar panel and display industry technology and equipment
- The stacking, which uses semiconductor cleaning and robotics processes and tools
- The metrology, which is based on automotive and display industry measurement systems

[1] cosine, 2022. *Laue lens for radiotherapy*. Available at: https://www.cosine.nl/cases/laue-lens-for-medical-applications/
[2] European Journal of Cancer, 2020. *The cost of cancer in Europe 2018*. Available from: https://www.ejcancer.com/article/S0959-8049(20)30026-5/fulltext
[3] Alsop, T. 2022. *Semiconductor industry sales worldwide 1987-2022*. Available from: https://www.statista.com/statistics/266973/global-semiconductor-sales-since-1988/

Because much of the machinery and processes have been used before in other industries, cosine was able to be more efficient in purchasing the required equipment and adapting the techniques from the original industry to their own requirements.

However, **there is also a spin-out aspect to this work**, since some approaches needed were not an exact match. For example the semiconductor industry is more used to working with very "round" shapes, whilst SPO required square shapes with sharp edges. Therefore, the semiconductor actors had to grow their own capabilities, evolving a new, unique technology based on previous approaches.

cosine also worked with universities that had expertise in their chosen sub-domains through its consortium, taking something that is more conceptual into practical application.

Overall, **almost every country in Europe has had some involvement with the development of SPO, creating a Pan-European ecosystem of SMEs that are building new cross-sector partnerships and collaborations**.

Job creation in wider supply chain

The silicon pore optics technology has a large consortium of actors involved in its development, and while cosine is playing a central role for the development of the mirror modules, this feeds into the larger optics elements being produced by other actors.

There is a wide array of suppliers receiving money from CTP, including funds that go into equipment, sub-suppliers and academia. The two plate supplier companies, for example, have around 15 people per company being supported financially for the SPO development.

Overall, **the work done on developing the optics for ATHENA will support more than 100 jobs through to flight phase for these suppliers, integrators and other actors**.

Mass production process

While there has been discussions for many years about the need to shift towards a mass production approach within the space sector, this has predominantly centred around the concept of mega constellations and the need to produce many smallsats of the same size and payload requirement.

Even then, the reality of mass production for a satellite is not large-scale; for example, OneWeb Satellites can produce two satellites per day[4]. Furthermore, there are challenges in mass production in space manufacturing, since there is often a lack of standardisation and the need for different designs and specifications. These challenges can also be seen in the mass production of other innovative technologies surrounding space activities.

cosine's approach to SPO however has introduced mass-production on a large scale, being able to produce many mirrors. Since they require an order of mirrors in the hundreds of thousands for the ATHENA mission, it introduced an element of mass production that is not common for ESA missions or space in general, where there is a need for using a vast amount of the same component. The company's activities under CTP have led to the development of fully automated stacking robots that can elastically deform and directly bond tens of patterned silicon wafers on top of each other, with micro-meter and arc-second accuracy. There could be potential additional usages of techniques such as this; the ability to mass-produce these mirrors has set cosine up to be able to address terrestrial markets as well, broadening the scope of impact.

[4] Harebottle, A., 2021. *Satellite manufacturing in the Era of Mass Production*. Available from: http://interactive.satellitetoday.com/satellite-manufacturing-in-the-era-of-mass-production/

Providing the key solution for enabling future x-ray space missions

Enabler of future space missions

The development of SPO enables future space science missions such as ATHENA, providing the technical means to launch a telescope offering a 2-order magnitude improvement in space x-ray optics performance over existing missions

Not only has the consortium led by cosine been selected as part of the upcoming ATHENA (Advanced Telescope for High-ENergy Astrophysics) mission, but **it is developing a key component without which the mission could not succeed**.

ATHENA is the L-class mission designed to address the Cosmic Vision science theme 'The Hot and Energetic Universe', seeking to map hot gas structures and determine their physical properties, as well as search for supermassive black holes. With its state-of-the-art scientific instruments, it will provide an important contribution to the questions of how ordinary matter assembles into the large-scale structure of the universe, and how black holes grow and shape the universe. It is due to be launched in 2035.

As mentioned, the complexity of ATHENA is based on the need to balance area density and resolving power, with no solution available when the mission was first conceived. It will be the **largest X-ray optics ever launched**, requiring an unprecedented surface area with 300m^2 of mirrors, and will match the performance of other Great Observatories like ALMA and JWST. Therefore, the work cosine, its partners, and ESA have done in developing the SPO technology will provide a solution to this challenge, enabling the mission with its innovative approach.

Furthermore, silicon pore optics could be used in future optical-focused missions, since it is providing a high-quality, mass-produced technology. One of these examples is ARCUS, a proposed X-ray space observatory by NASA, which is currently in Phase A of development, and which would utilise SPO technology if the mission is greenlit (decision in the summer of 2022). NASA's selection of SPO as a phase A contender for ARCUS highlights that the technology is at the forefront of the industry and is seen as one that can meet stringent mission requirements.

Increased European competitiveness on the export market

SPO technology also provides an avenue for increased competitiveness of the European landscape, with the most advanced form of this technology on the market.

An American solution is also under development, however, they originally attempted to produce something similar but with glass as the material instead. Since that approach was not successful, they have shifted to a silicon approach also. Nevertheless, the European consortium is leading on this technology and are at a higher technology level.

Furthermore, other countries have indicated an interest in utilising silicon pore optics, such as India and China. These countries also fly high resolution X-ray telescopes, and while they may be smaller missions or not be currently as advanced as those in the US or Europe, it is not expected to be long before they will also be developing new missions that could necessitate SPO as a solution.

Supports European non-dependence

As mentioned, the SPO approach supported by ESA CTP with cosine and the consortium is currently the most advanced form of this solution that will be available.

This is providing a European-developed product, formed from a pan-European network, that is not subject to outside restrictions and enables ESA to have access to high-quality optic solutions that are not dependent on other countries. This is an important aspect to consider, since SPO forms such an integral part of ESA's ATHENA mission.

Would these benefits have been realised without ESA?

cosine and its partners would not have developed the SPO technology without ESA support, going back to 2005. Indeed, cosine highlighted that its development activities are traditionally bound to its ability to secure end-customers.

ESA

ESA offered steady support throughout the development of SPO in 'valley of death' TRLs, despite obstacles in the development of the XEUS space observatory project (which was SPO's initial main intended application). **ESA's willingness to take technology development risks was critical**, as private organisations tend to be risk averse, especially considering the fact that there was relatively little recurrence in the space sector in the past decades.

Additionally, cosine's established skills, capabilities and experience in X-ray optics and applied physics, some of which were acquired through previous ESA projects, were emphasised as key enablers to the activities and benefits outlined in the previous sections.

> *"You need an ESA-type of stamina to develop this technology, because of the long-term development requirements. ESA took up much of the development risk, and helped create a network of companies for cosine".*
>
> *Max Collon, cosine BV*

... plus further development and benefits to come

cosine plans to remain involved in designing elements for space missions. Indeed, in addition to its work on ATHENA, the company is involved in the phase A preparation of a US-led mission (ARCUS), which highlights the attractiveness of the SPO technology. The requirements for ARCUS are lower than for ATHENA, but the missions remain similar. With a potential launch in 2028, the US mission would thus constitute a helpful pre cursor to the ESA mission (launched in 2035) and support job and revenue growth for cosine should the company's technology be selected for implementation. Similarly, the Dutch company highlighted that it received interest for its participation in smaller missions led by rising spacefaring nations (e.g. China and India). While still in the preliminary phases, **the company expects demand for its products and services from these stakeholders in the coming years**.

cosine also indicated that it invests in adapting and maturing its SPO technology for terrestrial applications. This could then be spined-out into various sectors, like material science, semiconductor, security and scanning equipment, and medical diagnostics, resulting in benefits across the board. **cosine's new mass production capabilities, which is a new infrastructure for the Netherlands**, will also enhance the company's offering, strengthening its market position. Overall, these spin-outs in terrestrial applications are anticipated to lead to further growth for the company and the Dutch economy.

CTP funding is thus expected to enable cosine and its partners in various countries to secure recurring business for space and non-space customers.