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Double Axicons to maximize Optical Feeder Links transmission on conventional telescopes

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ABSTRACT

In this paper we speak about the double-axicon unit built for the CaNaPy instrument, the LGS-AO backbone of the ESA ALASCA TRL6 facility, to demonstrate Optical Feeder Links for Satellite Communications in 2023 using Laser Guide Star Adaptive Optics technologies.

The ALASCA system will co-propagate a guidestar laser ($\lambda = 589$ nm) and an infrared laser ($\lambda = 1075$ nm), using the monostatic approach through the entire 1-m Optical Ground Station (OGS) at Teide Observatory, Canary Islands (Spain). Provisions have been made to use either the full aperture or a section of the OGS primary mirror.

The OGS telescope secondary mirror would introduce 30% central vignetting losses on the uplink laser beams. In order to minimise the losses, a double-axicon module shapes the gaussian beam as an annulus, thus optimises the laser profile to match the telescope pupil and nulls the losses, achieving the most efficient coupling to the OGS telescope.

We present the CaNaPy axicon module design and analysis for the 589-nm laser as well as the ALASCA axicon module design for the OFL; we describe the tests done and the gain achieved in power transmission when shaping the laser compared to propagating a conventional Gaussian beam through a telescope with a non-negligible central obstruction.

Keywords: Axicon, Monostatic Propagation, Adaptive Optics, Optical Feeder Link, Laser Guide Star

1. INTRODUCTION

CaNaPy is a night-time demonstrator for Laser Guide Star Adaptive Optics technologies at visible wavelengths with direct application to satellite optical communications. The project, in collaborative agreement between the European Southern Observatory (ESO) and the European Space Agency (ESA), provides a testbed for validating a variety of significant innovations: a 60+ W CW 589nm laser, the uplink laser beam pre-compensation on sodium Laser Guide Stars (LGS) in pulsed laser operation, and the pyramid wavefront sensor applied to LGS. CaNaPy consists of an adaptive optics bench to be installed at the Optical Ground Station (OGS) owned by ESA at Teide Observatory in 2023.

CaNaPy is the backbone of ALASCA, the Advanced Laser guide star Adaptive optics for Satellite Communication Assessments, led by Microgate with participants from Microgate, A.D.S. International, LumiSpace, Durham University, TOPTICA Projects, and Istituto Nazionale di Astrofisica (INAF). ALASCA aims to become a 24/7 operational facility equipped LGS-AO technology for atmospheric pre-compensated Optical Feeder Links.

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1.1 ALASCA

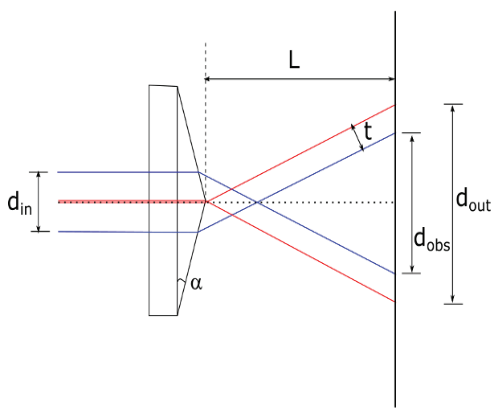
The ALASCA (Advanced Laser guide star Adaptive optics for Satellite Communication Assessments) project aims to develop a reliable optical communication uplink from an optical ground station (OGS) to communication satellites. The ALASCA main objective is the demonstration of a fully fledged, TRL6 operational facility that will enhance the performance of Optical Feeder Links (OFL) at the ESA Optical Ground Station in Tenerife, Spain based on Laser Guide Star Adaptive Optics technology. The project is based on the development of an upgrade of the hardware and software of the CaNaPy test facility jointly developed by INAF, Durham University and ESO.

The ALASCA laser propagation system (for both guidestar laser and infrared laser) will be designed following a versatile approach. A reconfigurable launch system will allow monostatic propagation through the entire 1-m aperture, and side launch using a smaller area of the OGS primary mirror.

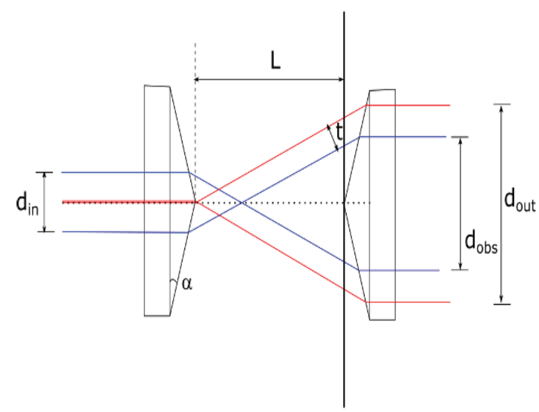
The monostatic propagation of any laser through a telescope with a considerably large secondary mirror imposes an additional challenge for the system; the OGS secondary mirror would introduce significant central vignetting losses on the laser beams. Fortunately, an axicon-based laser shaping system can optimise the laser profile and convert the usual Gaussian into an annulus for efficient coupling to the OGS telescope.

1.2 The Axicon

Axicons are refractive optical elements with a flat front surface and a conical rear surface. The rays near the edge of the beam entering the axicon get located at the inside edge of the annular beam when exiting. Likewise, the rays at the centre of the incident beam get located around the edge of the annular beam when exiting.
The axicon was first introduced by John H. McLeod, 1954[1] as an optical element to generate zero-order Bessel beams, a beam comprised of rings equal in power to one another. The single axicon is illustrated in Figure 1(a). The output Bessel beam is defined by the outer diameter (Eq. 1) and the annulus thickness (Eq. 2), as a function of the axicon cone angle (α), the input diameter (d_{in}) and the distance to the image or to a second optical element (L) (Figure 1(b)).



(a)



(b)

Figure 1. Schematic of the single axicon (a) and the axicon pair (b)

$$d_{out} = 2Ltan((n-1)\alpha), \tag{1}$$

where L is the spacing between the two optical elements, n is the refractive index of the material, and α is the cone angle.

$$t = \frac{1}{2}d_{in}, \tag{2}$$

where d_{in} is the diameter of the input beam.

When the beam exits the first axicon and illuminates the second axicon (in opposite direction with respect to the first one), the rays become parallel and a collimated annular beam is generated as the output of the axicon pair. The annulus width remains constant within the propagation distance and it is just related to the diameter of the input beam, the axicon cone angle, and the spacing between the two elements.
Single axicons have been previously used in various applications like imaging with extended depth of field,[2] laser glass cutting,[3] or fluorescence microscopy,[4] among others. When combined with a second axicon element, double axicons can also be found in corneal surgery procedures[5] and optical trapping systems.[6]

The CaNaPy system already integrates the axicon pair as a laser shaping system for the guidestar laser and the communications laser. The CaNaPy axicon subsystem receives the free-space propagated laser and produces a collimated annulus whose obscuration ratio is equivalent to the OGS obscuration ratio (35%). The annulus is relayed by the upstream optical elements until the telescope output.

2. OPTICAL DESIGN OF THE DOUBLE AXICON

Independent axicon pairs are envisaged for the two lasers in CaNaPy and ALASCA (LGS and IR). The only differences between the two are the glass coating and the spacing between the optical elements to ensure the OGS obscuration ratio is achieved on the laser beam.

The axicon pair consists of two axicon elements symmetrically arranged along the propagation axis. There are two possible configurations: tips facing each other and flat surfaces facing each other. The latter has been chosen for the axicon pair design.

The vendor Asphericon has been selected as the provider of the optical elements based on the quality of their off-the-shelf axicons. The 20-degree axicon has been chosen among the available options. The selected angle reduces the spacing between the two elements in the axicon pair configuration and simultaneously produces an output annulus with the OGS obscuration ratio. The optical layout is shown in Figure **??**

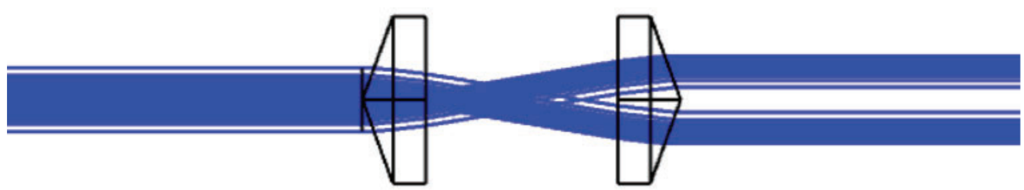


Figure 2. Axicon pair optical layout

2.1 Light Distribution Analysis

The axicon pair delivers a collimated zero-order Bessel beam defined by an output diameter of 13.5 mm and an obstruction ratio of 0.35 (between the diameters of obscured and illuminated areas). The obstruction ratio matches the OGS ratio between primary and secondary mirrors. Figure 3 shows the light distribution created by the axicon pair with an input gaussian beam of diameter 8.77 mm at the 2% intensity level.

2.2 Wavefront Analysis

Zemax OpticStudio uses ray tracing to simulate the light propagation through the optical system. The wavefront calculation is based on a collection of rays travelling through the optical element to the image plane sampling

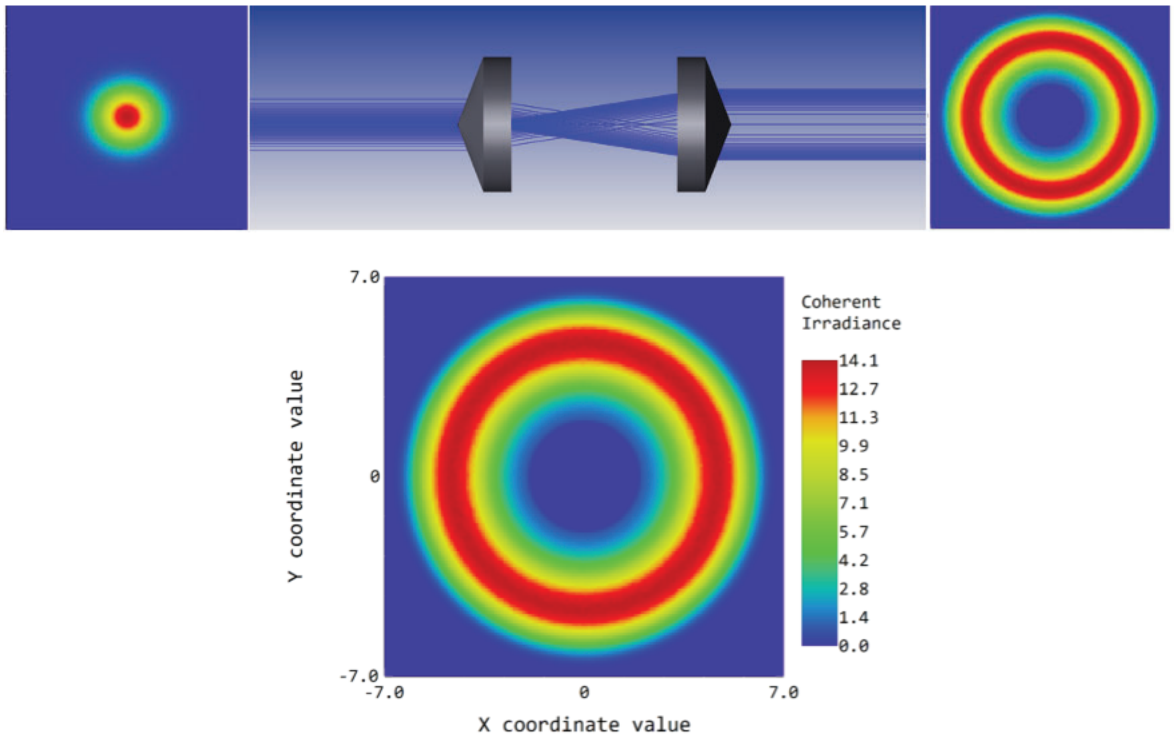


Figure 3. Light distribution of the annulus generated by the axicon pair from a collimated gaussian beam.

the entire pupil. The axicon central area (also known as dead zone*) generates a discontinuity in the ray tracing and thus, in the wavefront computation. In order to perform the wavefront error analysis, a negligible decentre of 0.1μm needed to be introduced to avoid the chief ray encountering this zone.

The wavefront error of an ideally aligned axicon (besides the trivial decentre) is shown in Figure 4 for the 1075-nm wavelength. No effects on the wavefront are visible at the output of the axicon pair.

2.3 Thermal Behaviour

A thermal analysis has been performed over the operating range of -15^{o}C to 20^{o}C as per the expected operating temperature range. An aluminium housing has been considered the worst-case scenario (CTE = 23.5 x $10^{-6}/^o$C) to perform the thermal study.

Results are shown in Figure 5. The maximum detected change as a result of the temperature variation in the axicon spacing is 24 microns which would only change the obscuration ratio by 4 x 10^{-4}. Therefore, no athermalization of the final system is required.

3. AXICON LASER SHAPING FOR THROUGHPUT OPTIMISATION

Physical optics propagation has been used to compare the Point Spread Function of the system at 38000 km. A Zernike focus element has been placed at the output of the optical assembly to focus the beam at a distance of 38000 km (Figure 6). The axicon pair performance has been compared to a gaussian beam launched through the entire OGS primary mirror and obstructed by the telescope secondary mirror (Figure 7).

The Point Spread Functions at 38000 km for both cases (axicon and obstructed gaussian) have been computed using the physical optics propagation modules of two independent numerical simulation tools (PASSATA[7] and

*The *optical dead zone* of an axicon refers to the area around the apex of the axicon where the optical properties are not defined as a result of the manufacturing process.

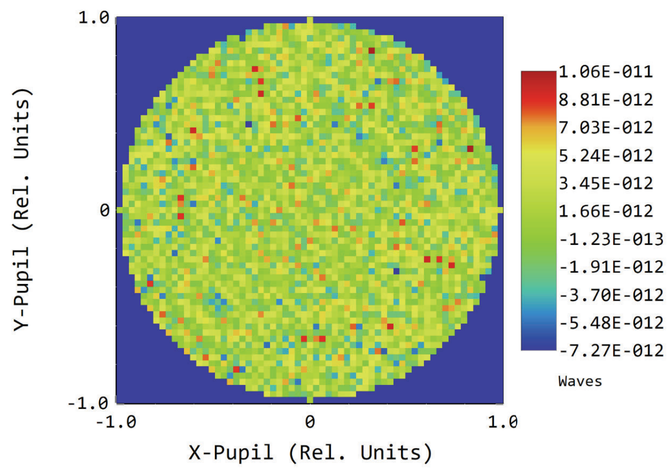


Figure 4. Wavefront map at the output of the axicon pair (wavelength = 1075 nm)

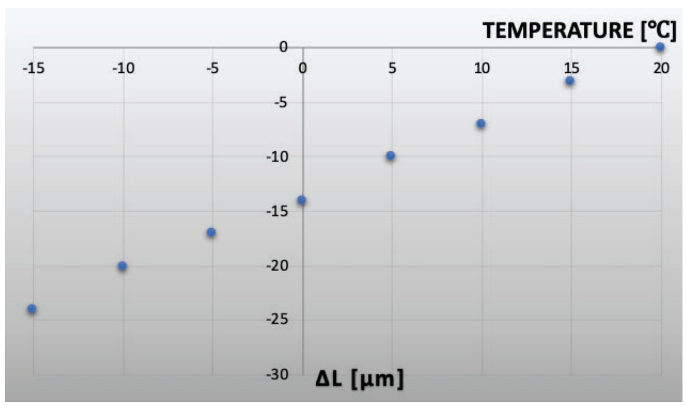


Figure 5. Thermal effects on the spacing between axicons (L) with Aluminium 6061 housing (CTE = 23.5 x $10^{-6}/^{o}$C).

AOTools[8]). We observe that the two PSFs match perfectly. For reference only one of the PSF computations is shown in Figure 8.

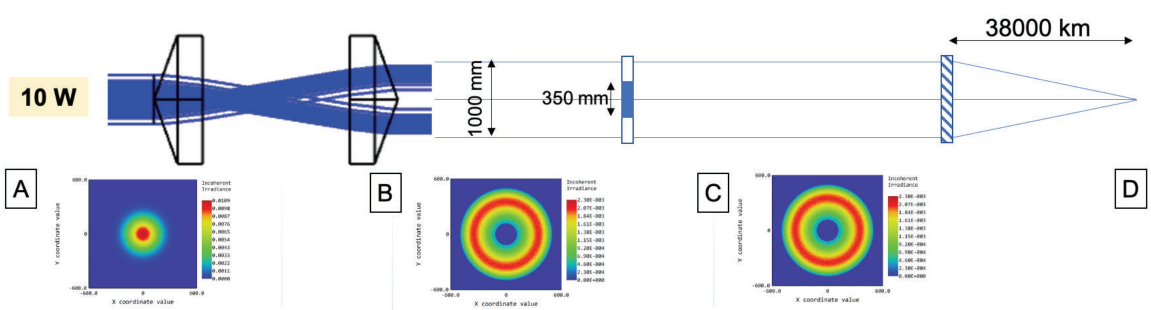


Figure 6. Physical optics propagation of the annulus exiting the axicon pair to a distance of 38000 km.

Physical optics propagation using the optical design software Zemax OpticStudio reveals that with an input power of 10 W, the axicon pair introduces minimum losses (9.803 W), whereas in the case of the obstructed gaussian the output power is reduced to 7.581 W at 38000 km. By shaping the beam using an axicon pair, there

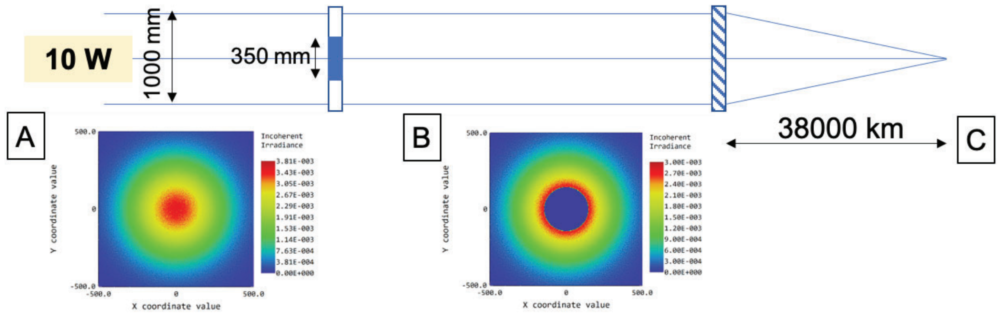


Figure 7. Physical optics propagation of an obstructed gaussian beam to a distance of 38000 km.

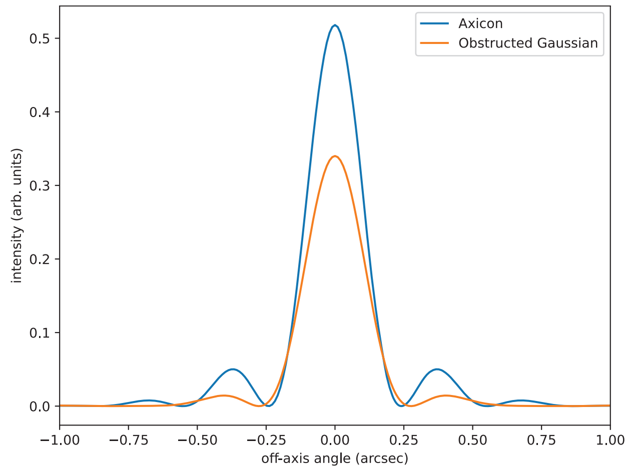


Figure 8. Comparison of the Point Spread Functions (corresponding to location D in Figure 6 and location C in Figure 7) of a beam after being shaped by an axicon pair and a gaussian beam obstructed by the secondary mirror. PSFs computed using AOTools.[8]

is no noticeable effect on the shape of the Point Spread Function in the far field (38000 km).

4. CONCLUSIONS

The CaNaPy axicon pair and future ALASCA laser shaping module has been extensively analysed and tested in the laboratory. The alignment strategy has been clearly defined based on the most sensitive adjustments that will have larger effects on the wavefront error; high precision mechanisms will be used to adjust the position and angle of each axicon with respect to each other, and of the assembly with respect to the propagation axis.

Numerical thermal analysis of the CaNaPy axicon subsystem has also been performed showing negligible variation in the output obscuration ratio, indicating that no athermalization of the final system is required.

The axicon pair subsystem will allow ALASCA to propagate the guidestar and the infrared laser through the entire OGS 1-m aperture, and considerably reduce the coupling losses that otherwise would limit the output power and overall system performance.

The axicon laser shaping system would reduce power losses and improve the overall performance of any system relying on this type of laser launching approach.

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