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Focal Plane Assembly demonstrator for two-way laser communication link

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ABSTRACT

Bertin Technologies delivered to its partner Airbus Defense and Space the focal plane assembly (FPA) of the TELEO payload on-board the BADR-8 geostationary satellite for ArabSat, one of the world’s top satellite operators. TELEO is a new-generation of optical communications technology in space. This payload demonstrator (DM) will enable very high capacity analogue optical feeder link communication.

This FPA is intended to be mounted on a telecommunications satellite scheduled for launch in early 2023 and it should have a minimum lifetime of 2 years on a GEO (Geostationnary Orbit) spacecraft, in addition to a several month-orbit rising.

Its objective is to establish and maintain a two-way laser communication link with an optical ground station (OGS), for a full-scale proof of concept.

This paper will present an overview of the mission, the equipment and its challenges. A focus will be made on part of the alignment process and qualification performed to validate the DM design.

Keywords: Focal Plane Assembly, optical communication, satellite, instrumentation, flight system

1. INTRODUCTION

1.1 TELEO mission

Optical space telecoms have been around for several decades. In the 1990s, the first inter-satellite links were developed. These solutions are now mature and many low earth orbit (LEO) satellites have adopted them.

More recently, the need for speed and openness of communication channels is pushing towards the use of optical solutions between satellites and the ground. The technology is growing rapidly and it is very likely that optical link solutions will be available on most satellites in the future, both in low earth orbit and in geostationary orbit (GEO). Beyond the positioning aspects, the use of optical links in GEO orbit remains a challenge. The distance of 36,000km adds a factor of 10 to the current mature solutions.

Since 2018, Bertin Technologies has been contributing to the upstream development of solutions for future inter-satellite and satellite-to-earth optical communication programs in collaboration with ADS (Airbus Defense & Space) which develops the other main sub-assemblies of the optical communication instrument[1].This program is supported by CNES and ESA. After several years of stagnation, satellite optical communication technologies are expected to become widely used due to the expected saturation of current terrestrial communication networks. This saturation is the result of the exponential growth of the exchanged data. The terrestrial optical technologies, which have made it possible to remedy this situation "on the ground" (increase in data rates through the use of optical fiber), will be extended to the satellite level, in free space propagation.

In 2020, Bertin Technologies delivered a first breadboard of the focal plane assembly to Airbus Defense and Space to validate most of the concept and to comprehend the alignment method. Following the delivery of this breadboard and within the framework of the TELEO project, Airbus Defense and Space then asked Bertin Technologies to develop and integrate a flight demonstrator of this FPA. Delivered to the BADR-8 prime contractor a couple of months ago, the FPA demonstrator has been developed by Bertin Technologies in one year and is currently being integrated on the satellite.

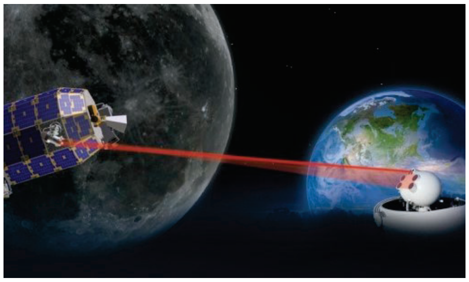

Figure 1. Artist view of optical telecommunication satellite-to-earth

1.2 Focal Plane Assembly overview

In the framework of the TELEO project, BERTIN has manufactured a focal plane assembly (FPA) to be used for the laser communications instrument of the TELEO demonstrator, precursor for future feeder laser links applications.
The FPA demonstrator model (DM) has an optical, mechanical and thermal design largely derived from a breadboard (BB) already developed in the FOLC2 (Feeder Optical Link Communication Chain) project.

The focal plane allows to establish a bidirectional link (management of laser beams) between the satellite and the ground station. The transmission and reception channels are embedded, split in polarization, separated in wavelength and in space and aligned across the focal plan.
The beam from the light signal emitted by the satellite is collimated and sent to a ground receiving station. The return beam from the ground station is received and focused in a fiber, before being sent to the satellite' signal processing stages.

In more detail, the function of the focal plane assembly is to route in free space the laser beam issued from booster amplifier of the terminal (transmission part) to the telescope assembly (via a Fine Pointing Mechanism) and the laser beam collected by the telescope assembly to the reception channel (reception part) of the terminal (via a Fiber Injection Mechanism) and to the acquisition and tracking sensor. The pointing acquisition and tracking system (PAT) is an innovation proposed by ADS and integrated in the focal plane. It is part of the ADS intellectual property.
The wavelengths are in the C-band (1530 / 1565 nm).
The booster output optical power baseline is several Watts and the focal plane has been designed and manufactured according to this baseline.

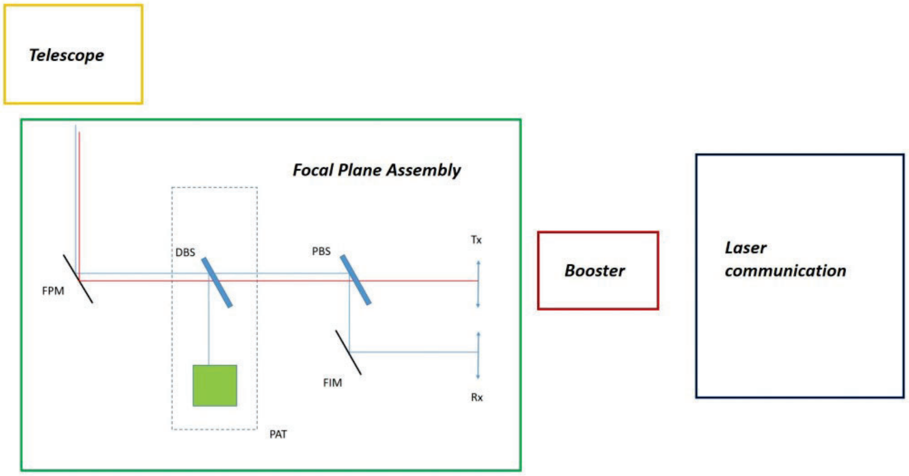

Figure 2. Focal plane assembly overview

1.3 Focal Plane Assembly challenges and solutions

Beyond the usual reliability constraints of onboard space applications dedicated equipment, the objectives as compactness (looking for solution of mass lightening), long-term perspective of lowering costs (preparation of further serial phase) had to be met while guaranteeing the FPA performances:

- Functionalities achievement of spatial multiplexing / demultiplexing space: the proximity between a high power transmission channel and a reception channel that must detect low power signals implies optical isolation difficulties.
- Ground and flight calibration based on spectral filtering: the thermomechanical stability and the high rejection rate (from transmission to reception) needs are very high.

The technological challenges of a focal plane for optical telecom are numerous such as fiber collimators or thermomechanical stability of optical structures. Specific points have been studied for the FPA development. The objective is to be able to combine the transmission and reception functions of an on-board optical link within a limited volume and mass. The critical parameters are:

- Transmission of the emission signal from the laser fiber to the output telescope with good optical quality
- Transmission of the reception signal from the telescope to the processing fiber
- Minimum coupling between the emission signal and the reception fiber
- Thermal dissipation management due to high power transmission
- Opto-mechanical stability of the assembly under space environment constrains

In order to address these various challenges, design solutions were carried out to ensure first sufficient isolation of the receiving fiber from the transmitted light. Beyond spectral filtering, integrated in the reception fiber and in order to limit the straylight, the optical study was strongly pushed and each component was specified with wedges in order to have the reflections out of the reception fiber. Simulations of the optical diffusion were carried out by taking into account the various phenomena imagined (surface roughness, impurities and dust, defects in the volume of materials). Very specific optical treatments (dense coating) have been developed (filter function for beamsplitter, AR coating) demanding high substrate surface quality.

An important optimization concerned the design of the collimator in particular for the emission one. As the optical power level became higher and higher (several Watts), the materials and the assembly process had to be finely customized to manage the high power dissipation and not degrade the properties. Focus has been put on fiber output where the light density is strong. Simulations and tests have been necessary to define the assembly and bonding process.

The opto-mechanical stability of the structure has been studied using finite element models of the assembly.
Thermal and mechanical analysis have been performed to check the consistency of the design with the specified environment (thermal vacuum environment and mechanical environment as quasi static loads, vibrations loads and shocks). The whole structure fits in a volume of less than 10 liters for a mass of around 2kgs.
Materials choice (Invar, Kovar, Aluminium) and specific features as flexure blades have helped to design interface points by taking into account the thermal gradients on the FPA interface plate, the stiffness and the resistance to mechanical environment (in order to push the first eigen mode beyond 150Hz).

An important part of the design concerns the PAT (Pointing Acquisition and Tracking) system. This assembly must take part of the energy of the various beams in order to send it to a sensor able to determine the angular deviations and thus, to control the correction mirrors to ensure the link. The balancing in intensity on the sensor of the various signals required a meticulous spectral management of the various optical components used. Indeed, the difference in power between the transmission signal and the reception signal is close to 10 orders of magnitude. In order to see both signals at the same time, specific optical treatments have been used.

The thermomechanical stability is necessary to maintain the alignments and calibrations performed on the ground after launch, in the usual space environment for a LEO or GEO application, and taking into account the alignment strategy using the active components (detector and mirrors) The stabilities sought are on the scale of the dimensions of the single mode optical fibers used for these applications (diameter of about 10 µm): stabilities better than a few tens of µm and hundreds of µrad are sought.

2. ALIGNEMENT PROCESS AND PERFORMANCES

In the scope of assembly and alignment of the focal plane, means and methods have been specifically developed.
Design optimizations have been implemented to make easier the alignment process. Additional adjustment points were introduced at the folding and beam pointing control mirrors level. These were necessary to correct the alignment errors between the beams and the mechanical structure. Alignment principle of the fibered collimators was modified to allow a better sensitivity during adjustment stages.
During the year 2021, focus has been put on two benches in particular. These are alignment benches for pointing and centering the transmit and receive beams in the exit pupil of the focal plane. Both of them required R&D efforts in order to make them operational for the breadboard manufacturing but also for a mass production, already anticipated.

2.1 Angular alignment

The objective of the first bench is to perform the angular alignment of the transmission and reception laser beams with each other and with the mechanical reference (baseplate). For this, the focal plane itself has been used as a component to adjust but also as a means of measurement. This allows us to guarantee an alignment with uncertainty levels below 1mrad.
The development of the procedure required many trials until the best option was found. The simplified sequence is as follows:

- The entire focal plane is placed on a flat reference mirror. Thus, the surface of the mirror becomes representative of the mechanical reference.
- The transmission beam is then switched on and its return, after reflection on the reference mirror, is observed on the internal camera of the system. This metric is used to make a first adjustment.

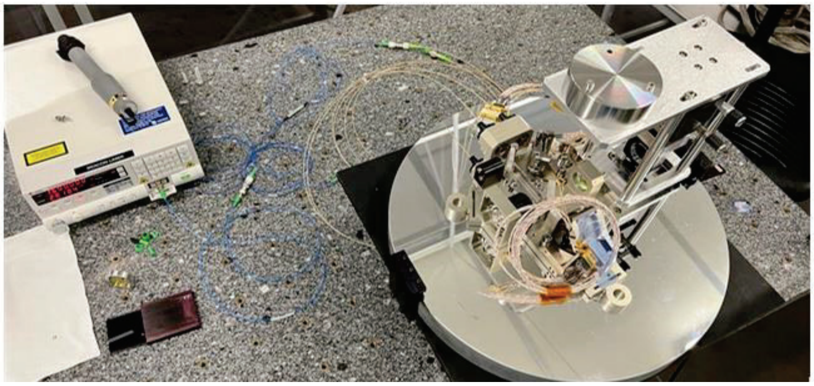

Figure 3. Assembly allowing the alignment of the three parameters transmission, reception and mechanical reference

- A tooling corner cube is then inserted at the focal plane output. The transmission (emission) beam, still on, is now reflected by the cube and can be tracked on the camera. A defocusing allows to center the cube on the beam.

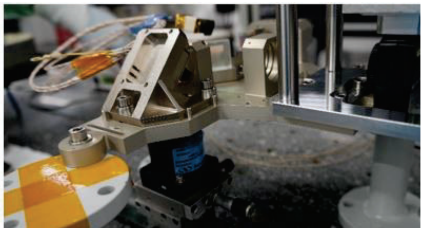

Figure 4. Configuration with the corner cube

- After readjusting the focus, we observe the difference between the beam position on the internal camera with the one obtained with the mirror return. These two positions should, if the adjustment is correct, be confused. This metric is used to finalize the adjustment of the emission on the mechanical reference.

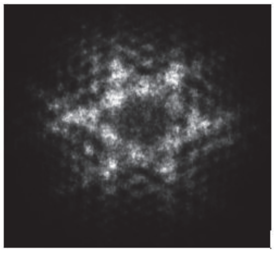

Figure 5. Setting of the corner cube balance

- Finally, the reception channel is illuminated by the fiber. The position of the return on the camera after reflection the reference mirror is then noted.
- This last metric allows us to complete the adjustment in order to have the transmission, reception and mechanical reference together.

Once the alignment of transmission beam has been done with regards to the mechanical reference interface plane, reception Rx is aligned onto transmission Tx by placing wedged shims under and flat shims on the sides of mirror.
The co-alignment of the two beam (0.63mrad) is within specification (<1mrad). However, the alignment of the beams with regards to the interface plane does not match the requirement of 1mrad. This results in an offset of the beam with regards to the mechanical reference that will need to be compensated towards the telescope.
Alignment capacity with this method can be better the specifications (depending the set of shims resolution). But the objective here is to obtain a sufficient alignment which allows to be centered on the active mirrors and to keep travel margins for a fine adjustment in flight.

2.2 Beam centering

Once the beams are pointing in the same direction, the objective of the second bench is to ensure that the transmission and reception beams are aligned in position too.
In a similar way to the previous method, the objective here is to align the transmission and reception beams with the pupil output (we are interested now in the position in XY and not the pointing angle around X and Y). For this, the pupil output of the focal plane is imaged.

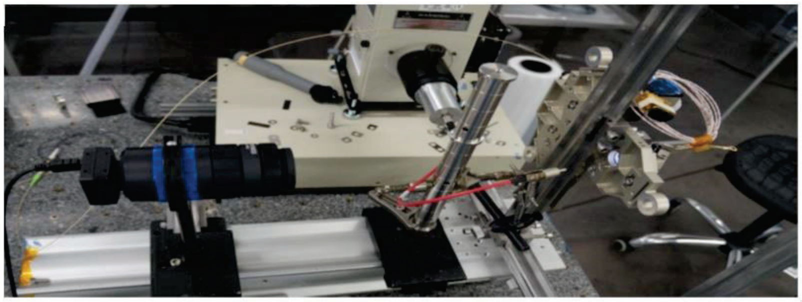

Figure 6. Mounting for beam centering adjustment

Pictures hereunder show an example of the image obtained. The left image shows the pupil without any beam. The right image shows the same pupil with the presence of the emission beam. The settings ensure that the beam remains centered on the pupil.

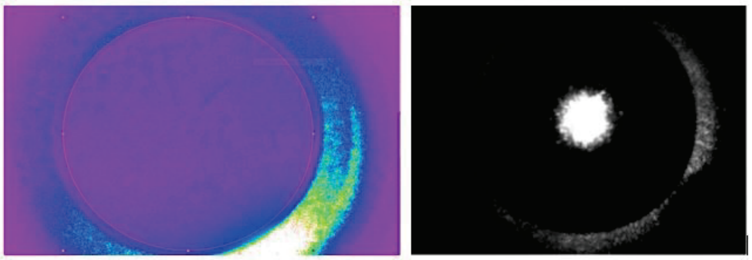

Figure 7. Example of the emission channel setting on the pupil output

The requirement for centering of the beams is met: 32µm is obtained for Tx with regards to the mechanical reference and 23µm for Rx beam with regards to Tx beam position (for <100µm specified).

3. QUALIFICATIONS AND RESULTS

In order to validate the design of the components allowing to manufacture the focal plane, tests and/or qualification have been identified for the following items:

- High power collimators and management of the thermal dissipation at the end of the transmission fiber due to Fresnel reflections at the interface.

The design of the collimator interface has been optimized since the breadboard to take into account the thermal dissipation issue. A gluing interface has been envisaged. Nodal simulations have been performed to assess the glue type, the needed surface of gluing, the material of the fiber connector, the thermal expansion coefficient difference).

Mock-up of the collimator has been done to test the interface and check the thermal dissipation efficiency on transmission with input power of several Watts.

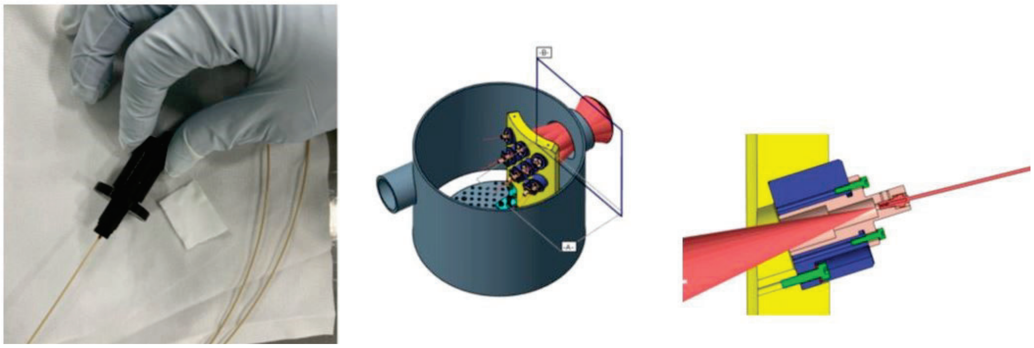

Figure 8. High power collimator integration and high power transmission measurement tests under vacuum

- Radiation resistance of the absorbing glass constituting the optical density

Optical densities made of KG3, a material manufactured by SCHOTT and absorbing in the SWIR band, are new components integrated in the optical path of the DM. It was necessary to carry out a qualification (radiation tests) of this material for space applications to assess a solution depending on results (optical density to be used without or with shielding, necessity to develop another solution of reflective optical plate...).

The linear absorption value is measured by the same bench before and after exposure to radiation (Fig 9.a).

It can be noted that the radiation causes a darkening of the material in the visible (Fig 9.b).

This evolution suggests the phenomenon of aging of optical densities. Indeed, an optical density by absorbance has a natural tendency to darken with time.

The evolution of the linear coefficient has been checked in the band of interest, around 1550nm. Unlike the visible, the material tends to become clearer as the radiation dose increases. The phenomenon does not seem linear with the thickness ((Fig 9.c). However, compared to the linear absorption of the material (-3.5mm-1), we are talking about a few percent change in the worst case. It was therefore decided to accept this evolution as negligible in view of the values obtained.

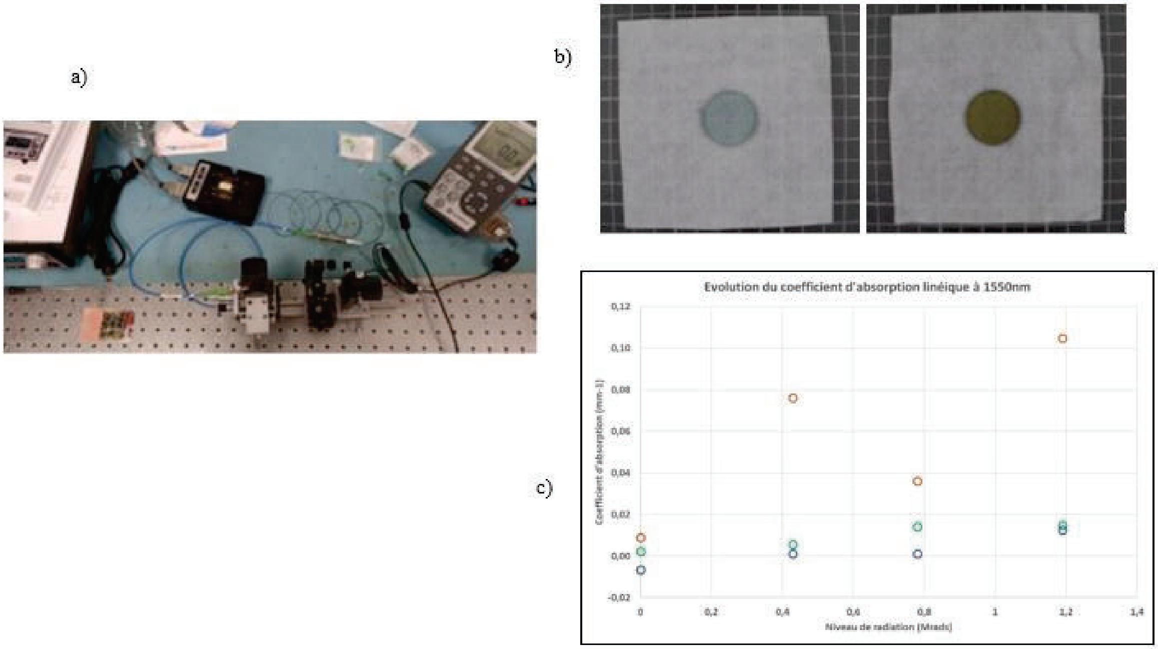

Figure 9. a) Absorption measurement bench b)Worst case – 2mm density – before and after radiation c) Evolution of the linear absorption coefficient of KG3 as a function of the radiation level for different thicknesses

- Specific optical coating (polarization separation filtering; dichroic separation filtering; differential spectral filtering; anti-reflection treatments).

The qualification, performed by CILAS, has been carried out by subjecting samples to environmental tests (damp heat, thermal vacuum cycling, radiation, cleaning / solvents compatibility) and by verifying the stability of the performances (visual inspections and spectral measurements; adhesion test of the treatment) at the end of the environmental tests.

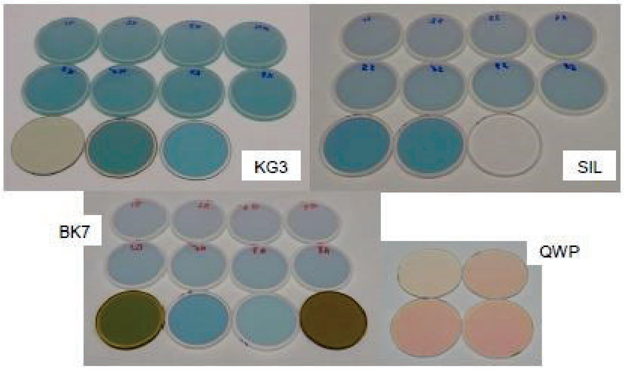

Figure 10. Samples inspection after environmental tests – Credit: CILAS

- Gluing process / qualification of glass-metal bonding

Assembly of the gluing samples has been qualified to assess the mechanical strength of the glue join depending on the glued materials: SiO2 / Invar and Zr02 / Alumina mount

The qualification has been carried out by subjecting samples to environmental tests (damp heat, thermal vacuum cycling) following by mechanical tests on glue joint (tensile and shear stress).

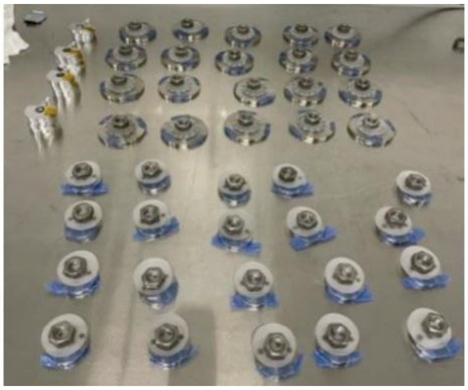

Figure 11. Gluing samples preparation

- Design and manufacturing of a structural and thermal model of the focal plane assembly

This model is representative of the flight model in terms of mechanical interfaces, mass and center of gravity localization with regards to mechanical referential frame. The aim of the structure model is to recall the finite element model, to determine the amplification factor and to verify the acceleration level at critical component location (fibered collimators, optical components, mirrors and detector).

4. CONCLUSION

Elementary mock-ups as well as a complete breadboard have been realized between 2019 and 2020. In 2021, in the frame of TELEO project, a flight demonstrator has been assembled, aligned, tested and delivered in 2022 to ADS for a launch in 2023. Specific tooling and alignment processes have also been developed and consolidated in order to anticipate serial production.

The focal plane developed for the TELEO mission in the framework of FOLC and FOLC2 implies only one transmission and reception channel. Beyond this first technological building block, Bertin Technologies has been solicited within the framework of a larger consortium for the expansion of the functions towards the free space multiplexing of a large number of laser beams, each carrying a specific communication channel. One objective of this new program is to design and prototype an upgraded version able to manage power of several tens of Watts. This initiative, named COOP (COmmunication OPtique), is supervised by CNES. This is a first recognition of the work done so far.

ACKNOLEDGMENT

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[1] Berceau, P., “Space Optical Instrument for GEO - Ground Laser Communications,” ICSO, (2022).