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Space Optical Instrument for GEO-Ground Laser Communications

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ABSTRACT

In the framework of the TELEO demonstration, a space optical instrument is being developed by a European consortium led by Airbus at Toulouse. This laser communications terminal will be placed on GEO orbit during the year 2023. Our flight laboratory will demonstrate new technologies (such as pointing mechanisms, optical amplifier, Infra-Red camera) and the associated concepts such as Pointing Acquisition and Tracking (PAT) strategy. The optical instrument is composed of a 26 cm telescope steered by a mechanism. The whole structure design ensures high performance of the optics thanks to a low distortion thermo-mechanical concept. A compact Focal Plane Assembly is accommodated under this telescope. It is used to manage with tremendously high rejection efficiency the high optical power Tx and the received beacon and Rx beams. Dedicated electronics also compose the terminal for highly stable thermal regulation, modes and PAT algorithms management, power distribution, mechanisms drivers, detector acquisition, laser sources and optical amplifiers. All the building blocks of the TELEO instrument are now being manufactured and their performances are being measured, before integration and final environment tests on the satellite.

Keywords: optical instrument, laser communications, feeder link, GEO satellite, in-orbit demonstration

1 INTRODUCTION AND CONTEXT

Airbus has been contracted with a telecom operator to fly a laser communications demonstrator called TELEO. After a development period of less than 30 months, this demonstrator is intended to be mounted on the BADR8 spacecraft to be launched in early 2023 and placed on a GEO orbit. TELEO on-board terminal (OBT) is expected to be operated during 2 years, starting from mid-2023, and its goal is to establish and maintain a bidirectional laser communication link with an optical ground station (OGS).

More specifically, the TELEO demonstration goals for the space segment are the followings:

- To demonstrate the performance of the following key technologies:
  - the telescope and pointing mechanisms, such as Coarse Pointing Mechanism (CPM) based on 3 dedicated linear actuators, Fine Pointing and Fiber Injection Mechanisms (FPM/FIM) based on MEMS technology and to validate the thermal regulation concept of an active terminal in GEO orbit,
  - the On-board Terminal pointing acquisition and tracking (PAT) performance under real conditions, such as µrad-Tx pointing accuracy with closed loop tracking, based on high performance PAT algorithms and accurate focal plane assembly co-alignment calibration method, the Fiber injection efficiency under real condition, and finally the acquisition duration,
  - the optical communication chain with Wavelength Division Multiplexing (WDM) and optical channel wavelength control through thermal regulation in relevant environment, the 10 Gbps differential phase shift keying (DPSK) modulation using Mach-Zehnder Modulator (MZM), optical analog demodulation, 10 Gbps on-off keying (OOK) demodulation and finally the Low Noise and High Power (up to several optical W) Optical Amplifiers (LNOA and HPOA) building blocks.
- To better know the behavior in space of the flown hardware, especially the Acquisition and Tracking sensor and the optical fibers under GEO conditions.

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On the overall system level, the objectives of TELEO demonstration are:

- To master link budget computation and forecasting by performing the accurate measurement of the received power (temporal atmospheric series) by mean of the Acquisition and Tracking Sensor and of the monitoring of injected power in the Rx Laser Communication Electronics (LCE).
- To push forward physical layer management for error free communication (joint optimization of power control, forward error code rate, interleaving duration) [1].
- To demonstrate analog optical uplink and digital optical feeder uplink and downlink under turbulences.

This paper describes the building blocks of the TELEO On-board Terminal (chapter 2). Its accommodation on the BADR8 spacecraft is then presented (chapter 3). Finally the main performances of the instrument are listed (chapter 4).

2 TELEO INSTRUMENT BUILDING BLOCKS

2.1 Overview of the instrument

The general architecture of the TELEO On-Board Terminal is illustrated in Figure 1. The transmitted (Tx) beam is colored in red, received (Rx) beam is colored in blue. The instrument (or aerial part) is on the left part of the figure, it includes the telescope hold by the Coarse Pointing Mechanism (CPM), the Focal Plane Assembly (FPA) and the Terminal Proximity Electronics (TPE). On the right of the figure, are three terminal electronics: the Laser Communication Electronics (LCE), the Laser Power Electronics (LPE, or booster) and at the bottom the Terminal Control Electronics (TCE).

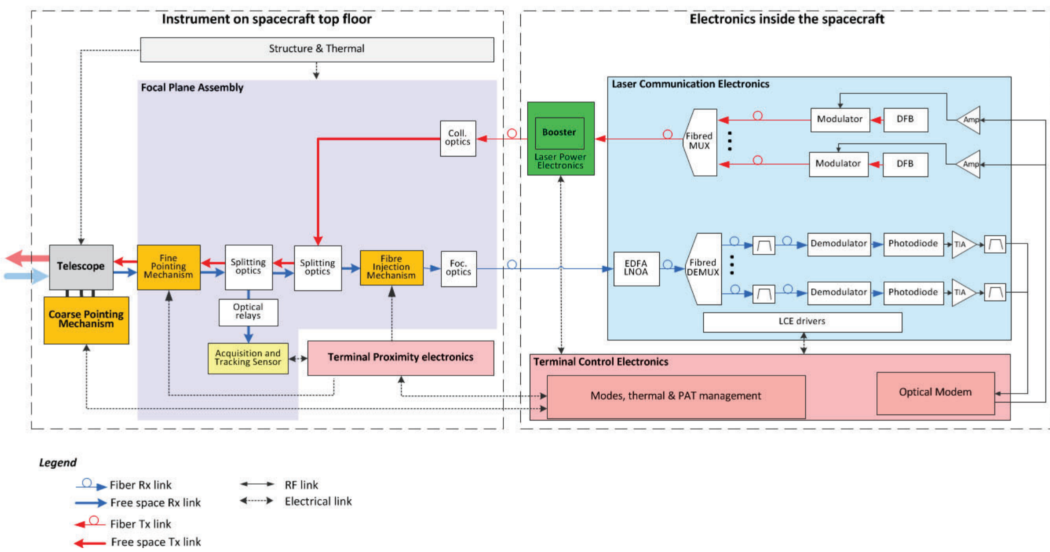

Figure 1. TELEO demonstrator on-board terminal functional architecture layout. Transmitted (Tx) beam is colored in red, received (Rx) beam is colored in blue. Left side of the figure presents the instrument (or aerial part). On the right side of the figure are three terminal electronics.

A layout of the TELEO instrument (or aerial part) is given in Figure 2. It is based on the TOP-M (Telecom Optical Payload, Medium size) provided by the COALA (Communication with Optical Aerial and Laser Assembly) Product Line of the Optics Instrumentation at Airbus, Toulouse. The instrument has two borders: the telescope primary mirror M1, leading to/coming from space (for Tx and Rx beams respectively) and the optical fibers (coming out of the booster in Tx part, and going to the LNOA-LCE in Rx part).

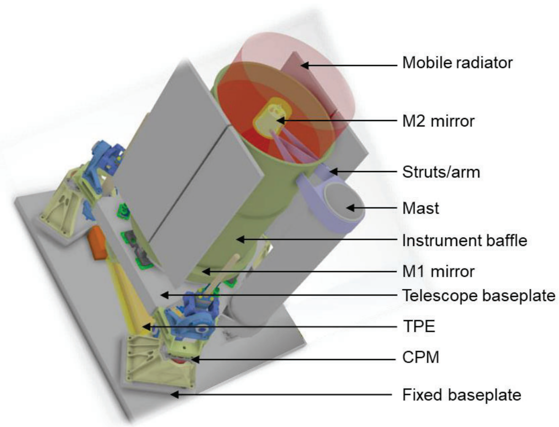

Figure 2. TELEO instrument layout. Terminal Proximity Electronics (TPE) is in yellow on the fixed part. Coarse Pointing Mechanism (CPM) is actuating the telescope (M1 & M2 mirrors) baseplate.

The building blocks of the TELEO On-Board Terminal are described in the following paragraphs (2.2 to 2.6).

2.2 Telescope

The TELEO telescope is a Cassegrain afocal telescope with a primary mirror of 260 mm diameter. It is also composed of a set of four lenses (collimator) to correct the optical aberrations in the field of the instrument and collimate the intermediate image. A sun filter is added to prevent the solar entries in the instrument. The overall optical design is optimized so as to reduce the straylight due to very high optical power of the Tx laser beam.

2.3 Coarse Pointing Mechanism

The Coarse Pointing Mechanism (CPM) is presented in the Figure 3. It is composed of 3 feet and holds the mobile assembly (at telescope baseplate interface). Each foot of the mechanism is composed of brushless motors actuating a dedicated screw to lift and orientate the mobile assembly. The goal of the CPM is to steer the whole mobile assembly on a ± 15° angular range to perform rallying, acquisition and part of the tracking of the terminal partner. Active and passive thermal control are implemented on critical areas to ensure full time operability. During launch the three feet are locked by a Hold Down and Release Mechanism (HDRM). The release of the CPM will occur after the spacecraft will be freed from the launcher, by releasing sequentially the 3 HDRM, designed to minimize shocks. The interfaces between the different components of its feet (foot pivots, gimbals) make the CPM isostatic after HDRM release.

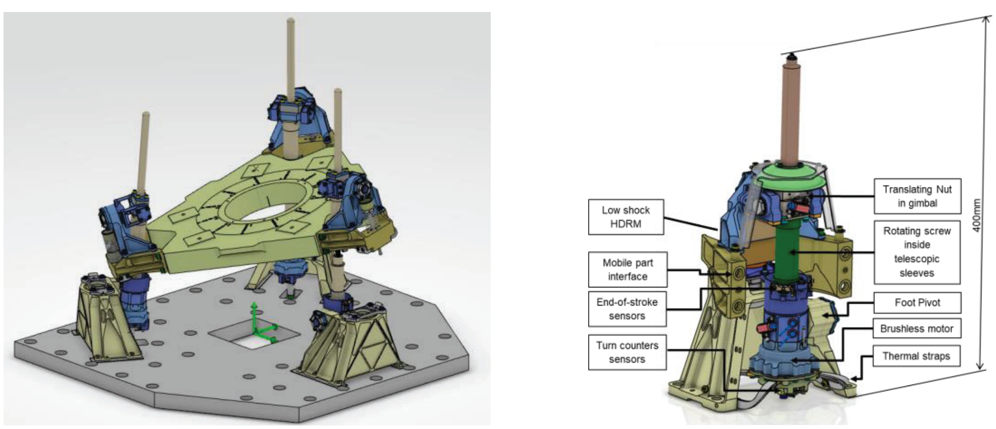

Figure 3. TELEO Coarse Pointing Mechanism principle of operation with three feet (left), single foot detailed layout (right).

2.4 Focal Plane Assembly

The Focal Plane Assembly (FPA) is a central equipment [2] for the TELEO On-Board Terminal. Its function is to manage several free-space laser beams: the communication Tx and Rx beams, calibration beams and beacon beam. The FPA is constituted of the following elements:

- On the baseplate are precisely aligned several optical elements such as focusing and collimating lenses (for Rx and Tx beams respectively), filtering and splitting optics (DBS; Dichroic Beam Splitter and PBS; Polarizing Beam Splitter). The Tx and Rx beams polarizations are orthogonal, they are linear in the FPA ("*p*" for Tx and "*s*" for Rx) between the fibers and the quarter wave plate (QWP), and circular (respectively right and left handed) between the QWP and the FPA output/input.
- The Acquisition and Tracking Sensor (ATS) is a fully qualified [3] Component Of The Shelf (COTS) matrix that detects the beam received from the partner terminal (beacon or part of the Rx com beam). This sensor is able to work in two distinct modes, the first is the full-frame mode, used during the acquisition phase at low bandwidth (typically up to several hundreds of Hz), and the second is the windowing mode, used during the tracking phase at higher bandwidth (typically few kHz). This device has the ability to have its integration time & window acquisition size automatically changed, it will also be used to perform the optical power metrology of the laser beam coming from the ground. Its sensitivity ranges from the pW level to the nW level (depending on integration times).
- The Fine Pointing Mechanism (FPM) allows fine and fast steering (up to the kHz level) of the Tx and Rx laser beams, and the Fiber Injection Mechanism (FIM) allows the proper injection of the free-space laser beam inside the Rx single-mode optical fiber. Those two identical devices are based on MEMS (Micro Electro Mechanical System) technology provided by SERCALO (see Figure 4). The mirror and the guiding system is directly made in a gold coated silicon wafer. Using moving coils with a fixed magnetic circuit (voice call principle), the reflective surface can be tilted of angles up to several degrees, with a good precision that goes down to the micro-radian. Those devices have been fully qualified (life tests in vacuum, mechanical tests, optical power handling tests) within the TELEO program.

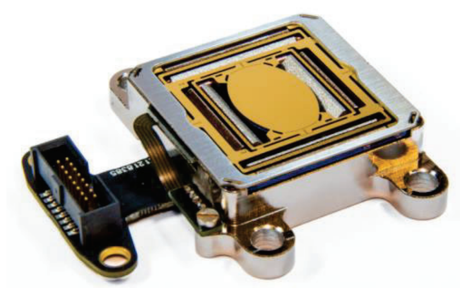

Figure 4. TELEO FPM and FIM devices

The key performances of the FPA are a good co-alignment of the Tx and Rx beams, a high transmission and good optical power balance of all the laser beams, a very high rejection & isolation between the received and transmitted beams and a low wave-front distortion (see chapter 4).

2.5 Terminal thermo-mechanical structure

The terminal thermo-mechanical architecture is described thereafter. M1 mirror is attached on the telescope baseplate with three bipods. The M2 mirror is hold by a single arm, fixed on the telescope mobile baseplate thanks to a single mast. The FPA is under the telescope baseplate. The FPM location coincides with the output pupil of the telescope. The CPM are sitting on the fixed baseplate. The Terminal Proximity Electronics is necessarily placed close to the FPA so as to reduce noise on signals going between the two equipment. A baffle is surrounding the telescope, and a cap is covering its mast. Radiators covered with Optical Solar Reflectors (OSR) provide with cold sinks to drain the thermal dissipation of the instrument, while Multi-Layer Insulators (MLI) ensure critical parts insulation. Several heating lines complete the thermal regulation making TELEO instrument thermally independent from the platform.

2.6 Terminal Electronics

There are four electronics in TELEO On-Board Terminal.

- The Terminal Control Electronics (TCE) is managing all the modes of the terminal software as well as PAT algorithms. It also ensures the power distribution of the other terminal electronics, the operational thermal regulation of the whole instrument, and the telecom data generation, emission and detection.
- The Terminal Proximity Electronics (TPE) is located close to the FPA on the fixed baseplate of the instrument. It ensures the power supply of the ATS detector, as well as of its TEC (thermo-electric cooler, ensuring the fine thermal regulation of the detector), and the current drive of the FPM and FIM at higher bandwidths for PAT control.
- The Laser Communication Electronics (LCE) [4] contains all the laser sources, modulators and InGaAs photodetectors necessary for telecommunication data generation and reception, and it also contains wavelength division multiplexers (WDM). The Rx part is connected to the FPA thanks to a single mode optical fiber that enters into the Low Noise Optical Amplifier (LNOA), used to amplify the telecom signal (see Figure 1 above) and also to monitor the injected power inside the Rx fiber. On the Tx part, the LCE is connected to the booster with a polarization maintaining single mode optical fiber.
- The Laser Power Electronics (LPE, or booster) [5] serves as high power optical amplifier. It is composed of two stages of amplifications based on EDFA and YDFA (Erbium and Ytterbium Doped Fiber Amplifiers). Stimulated emission is done by inversion of population in the Er and Yb electronic levels thanks to several pump diodes, which are combined to the fiber. From an input of few mW, the output power generated reaches several W, with a wall-plug-efficiency of close to 10%. The booster is connected to the FPA via a polarization maintaining single mode optical fiber.

3 TELEO INSTRUMENT ON-BOARD OF BADR8 SPACECRAFT

TELEO On-Board Terminal (OBT) will be accommodated on-board of BADR8 spacecraft, based on Airbus Eurostar NEO platform. The OBT will be split into two parts:

- The three electronics LCE, Booster/LPE and TCE are accommodated inside the spacecraft,
- The Instrument (or Aerial part) with the TPE is accommodated on the top floor of the spacecraft.

The two optical fibers going from booster to FPA (Tx) and from FPA to LCE (Rx) are routed on the spacecraft and protected. The electrical harness is routing between the TELEO equipment: the platform provides several 100 V power lines to the TCE that distributes to the other electronics. Dedicated CAN (Controller Area Network) bus for TeleMetries (TM) and Telecommands (TC) is also provided by the satellite so as to operate and check-on the terminal from the Mission Control Center in Toulouse. The TELEO terminal can be switched OFF at any time by the spacecraft, for instance upon a FDIR trigger (Fault Detection, Isolation and Recovery). The operation of TELEO is completely independent from the operation of the satellite. The thermal Non-Operational (NOP) regulation is ensured by the spacecraft itself to keep the TELEO equipment within their qualification temperature range, this NOP thermal regulation will especially be needed during orbit rising phase, and at the end of life of TELEO mission so as not to damage the spacecraft with broke-away debris.

It has been demonstrated that the On-Board Terminal causes no harm to the satellite, in terms of over-power consumption or dissipation, CAN bus overload, attitude disturbance when moving the CPM or shocks generated during their release, contamination, Electro-Magnetic Compatibility (EMC), payload antennas lobes free of obscuration, absence of optical glints impinging on attitude control instruments, and finally laser safety.

4 TELEO INSTRUMENT PERFORMANCE

4.1 Antenna gain parameters

To establish, maintain a laser link and transfer telecommunication data, the On-Board Terminal must have the highest possible optical antenna gain. The key parameters of this antenna gain and the associated terminal performances to be checked are summarized in the Table 1.

Table 1. Key parameters defining an optical antenna gain and associated terminal performances to be checked

Optical antenna gain key parameters	Related terminal performances to be checked
Transmission efficiency	Power transmission at low and high optical powers
	Obscuration, central and struts
	Fiber injection
	Power calibration
WFE performance	WFE at low and high optical powers
	Re-focusing capability
Pointing, acquisition and tracking performance	Beams emission and reception calibration
	PAT algorithms performances & calibrations
	Detection
	Noise and straylight
	Coarse and Fine Pointing
	Fiber injection
	Optical Line of Sight
	Near and far field irradiances
	Magnification

A discussion of the terminal performances is proposed thereafter. They are mainly measured by test either globally (*i.e.* at whole instrument level) or individually (and then recombined to get the overall performance), some are also simulated.

4.2 Optical transmission

The optical transmission of the FPA has been carefully led for all the optical paths in the specified wavelength ranges, both at low and high optical powers. The data collected by the telescope constructor (mirrors, collimator, and sun filter) are used to retrieve the overall optical transmission of the terminal.

The M2 mirror central and struts obscuration impacts are calculated following the step files of the telescope.

4.3 Wave-Front Error

The Wave-Front-Error (WFE) has been measured separately for the FPA and for the telescope. In the FPA, the measurement has been done both on Tx and Rx paths, allowing the pre-alignment of the collimators (compensation of vacuum effect taken into account). The telescope WFE measurement was regularly performed both along the line of sight and in the field of view and allowed to precisely align its optics and dimension the wedges for their mechanical mounts. The gravity effect on the WFE has been simulated and was cancelled in ±1g measurements configurations.

The optical power impact on the MEMS WFE (FPM) has also been measured in vacuum under several optical W.

4.4 Optical rejection and straylight

Due to very high dissymmetry between optical powers of the transmitted and received signals (100 dB for the Tx and Rx communication signals, 120 dB for the Tx and beacon signals), it is of outmost importance to carefully design and accommodate the optics of the instrument. Molecular and particular contaminations have an impact on beam scattering on the optics, generating straylight, the contamination must be controlled and monitored. A horizontal alignment of the telescope helped to reduce the dust deposition on the optics. The optics were tilted and wedged to also reduce the amount of ghosts in the FPA.

4.5 Line of sight calibration: Tx and Rx beams co-alignment

The patented principle of Tx and Rx beams co-alignment is presented in Figure 5. The direction of emission of the Tx beam is the reference for the terminal pointing. The output of the Tx fiber is imaged on the ATS via a biased corner cube that generates a set of six spots (in red). The barycenter of the hexagon is calculated (red cross) and serves as reference for the following calculations. The Rx fiber input is also imaged on the ATS thanks to LNOA Amplified Spontaneous Emission (ASE; set of six purple spots). The target location for the Rx spot is computed, based on the location of the Tx fibre, and the Point-Ahead Angle (PAA) required between Rx and Tx beams to account for light time-of-flight. The FIM is moved so as the barycenter of the six spots hexagon (purple cross) coincides to the Rx target (blue square). The incoming Rx beam (blue spot) will then be steered to the Rx target with the pointing mechanisms and will be injected in the Rx fiber. This calibration phase precedes any link establishment, described later.

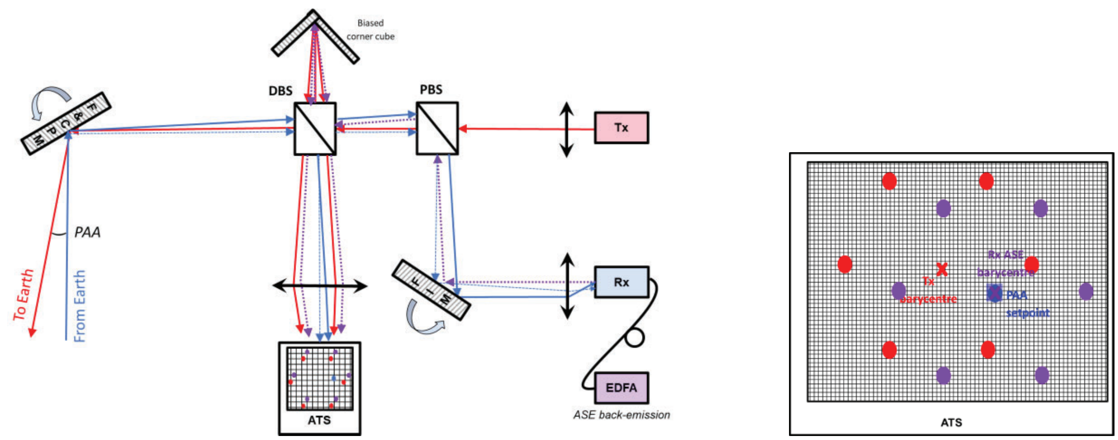

Figure 5. On the left side; focal plane line of sight calibration principle. Tx beam is colored in red, Rx ASE (Amplified Spontaneous Emission) is colored in purple, Rx beam is colored in blue. Inset on the right side; detailed layout of Acquisition and Tracking Sensor (ATS) matrix. The set of six spots for Tx calibration is colored in red, the set of six spots for Rx ASE calibration is colored in purple. Crosses are plotted the barycenters of those two sets. Point Ahead Angle is in light blue, Rx spot (blue dot) has to be brought on Rx target (same as PAA setpoint on the figure).

The abilities of the TELEO On-Board Terminal to quickly find its partner (acquisition phase), and to remain locked onto it (tracking phase) are key to the demonstration. These phases are briefly described in the Figure 6 below.

Due to external perturbations (thermo-elastics, launch micro-settings, alignment biases, satellite attitude control noise and bias), the intrinsic pointing direction of the terminal cannot be precisely known. The Uncertainty Cone (UC) is defined and calculated by combining all its error contributors, it is roughly two times larger than the terminal field of view (FoV). Thus, to establish the link, the OBT must scan its UC with its FoV. During this phase, the Optical Ground Station emits a divergent beacon beam that overlaps the uncertainty of position of the spacecraft. This beacon will be detected by the ATS during the UC scanning. Scanning will then stop and the beacon spot will be centered on the ATS at the Rx target location. The OBT will then emit Tx light to inform the OGS that it has been seen. The OGS will center itself with this downstream beam, and in return light-up its upstream beam. Both terminals will finally engage their respective high-performance tracking loops by commanding their fine and coarse pointing mechanisms. This overall hand-check is expected to last less than 1 minute.

During the tracking phase, the pointing performance is at its highest, both in terms of angular error (reduced to the µrad level) and bandwidth (up to several hundreds of Hz). The Rx communication spot is imaged on the ATS, its position calculated and compared to the calculated Rx target: an error signal is generated and processed by the PAT algorithms specifically developed, to send current commands to the FIM and FPM. The CPM is used to desaturate the FPM.

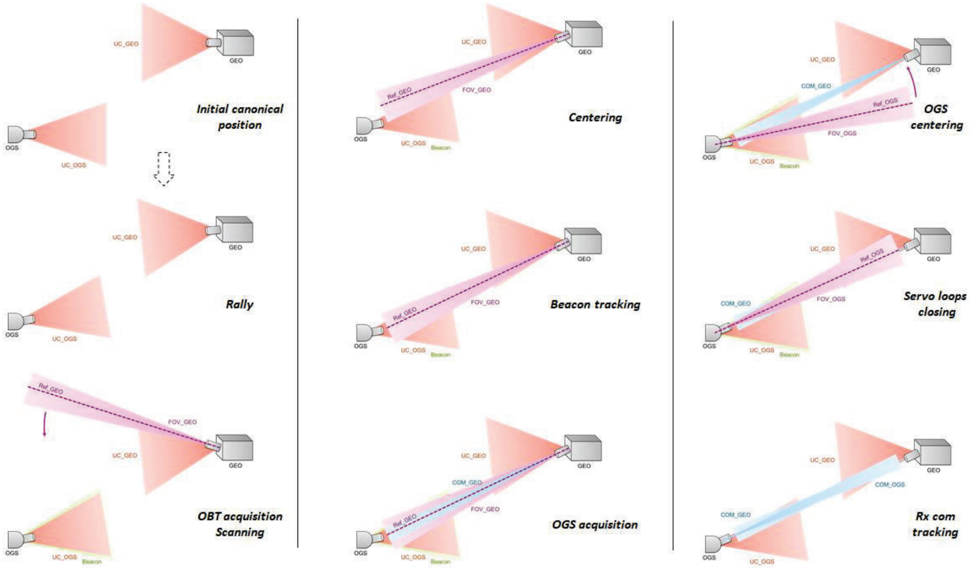

Figure 6. TELEO Pointing Acquisition and Tracking (PAT) sequence.

Dedicated tests were defined and are at this time currently implemented to check all those presented key performances of the On-Board Terminal. They will allow to calculate the optical antenna gain necessary to the laser communication link budget [1].

4.6 Instrument Size Weight and Power

TELEO on-board terminal has the following Size Weight and Power features:

- Its weight is 85 kg, split as follows: 30 kg on the mobile part, 30 kg on the fixed part of the instrument, 25 kg for the terminal electronics.
- The instrument footprint is roughly 700 mm × 600 mm, its height is roughly 750 mm when stacked during launch and roughly 850 mm when deployed.
- The power consumption ranges from 175 W in non-operational mode to less than 300 W in standard operational mode. Main contributor is thermal regulation, followed by the Terminal Control Electronics and then by the Laser Power Electronics (booster amplifier).

5 CONCLUSIONS AND PERSPECTIVES

The building blocks of the TELEO instrument are now being manufactured and their performances are being measured, before integration and final environment tests [3]. The integration on the satellite will then come by end of year 2022. Launch is expected to occur by first quarter of 2023 from Kennedy Space Center at Cape Canaveral (FA, USA). A few month-orbit rising phase will follow, and the first orbit tests will start by second half of 2023. TELEO On-Board Terminal will then be available for 2 years, to test modulation scenarios for telecommunication, light propagation through the atmosphere at 1550 nm, and to demonstrate several new technologies and associated concepts such as PAT performance.

Beyond the TELEO demonstration, the goal is to pave the way for future optical terminals to be used in other applications such as higher bit-rate GEO-feeder operational systems (VHTS), data transmission from GEO to ground (export market), data transmission from LEO to ground for Earth Observation missions [6],Quantum Key Distribution (QKD) or Deep-Space laser communications.

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