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FEELINGS : the Onera's optical ground station for Geo Feeder links demonstration

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Abstract— ONERA is currently developing an experimental Optical Ground Station (OGS), FEELINGS, dedicated firstly to GEO-feeder links to investigate GEO-feeder link optimization and related scientific and experimental issues, and to pave the way of future OGS, with high capacity and operability. Extension to LEO links is already included. We present the FEELINGS OGS design and current status. We discuss how critical scientific issues related to GEO-feeder links will be addressed through it.

Keywords—*adaptive optics, GEO feeder links, optical ground station*

I. INTRODUCTION

The future of ground-space communications will rely on high capacity optical links between the ground and GEO satellites, the so-called GEO-feeder links [1]. Still, it implies, among others, development of performant, cost effective and highly operational optical ground stations (OGS).

On the downlink several demonstrations including long-term exploitation [2] have demonstrated that a commercial exploitation is already possible. For the uplink, point ahead angle (PAA) anisoplanatism compromises the link performance [3][4]. Feeder-link ground station projects are now under development with tradeoffs to be made on baseline architectures and key performance drivers [5-7].

In that respect, some critical scientific and technological issues need to be addressed, such as fine calibration and optimization of the PAA, mitigation of turbulence effects,

both downlink and uplink. Adaptive Optics (AO) may represent a game changer, in particular for uplinks through precompensation, ensuring additional link margin and increased operability. These entail however handling of anisoplanatism.

Development and design of OGS also means a precise understanding and estimation of link budget on sky down to detection, including atmospheric transmission, actual pointing errors, turbulence conditions and AO performance. All these elements shall be evaluated and compared to models to refine systems design.

It also means developing high power sources compatible with wavelength division multiplexing, but also integrating them within the OGS, ensuring shape of the beam, isolation of up and downlinks, diffusion on optics.

Finally, operability of such OGS will closely depend on instrument stability, and if needed control and identification of instrument evolution, robustness to turbulence and weather conditions.

To address these challenging issues, ONERA is currently developing an experimental optical ground station, FEELINGS (FEEder LINKs optical Ground Station). This OGS aims at tackling the scientific and technological risks related to GEO-feeder links, propose and validate concepts, components or algorithms to pave the way of future operational OGS, with high capacity and operability. FEELINGS also aims at addressing LEO links. We present the

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FEELINGS OGS design and current status. We discuss how critical scientific issues related to GEO-feeder links will be addressed through it.

II. FEELINGS TOP LEVEL SPECIFICATIONS

A. Scientific goals

The FEELINGS ground station has been designed as a pathfinder for fully automated AO based GEO feeder link ground stations.

In this aim, the key scientific objectives are:

- To demonstrate the feasibility of :
 - emitting a pre-compensated high power high stability optically modulated signal for uplink (baseline)
 - receiving on the downlink a high data rate modulated signal (goal).
- To demonstrate the understanding of the obtained performance from built-in models and environmental conditions.
- To provide a testbed to investigate AO control laws more adapted to PAA limitations.
- To demonstrate robustness to variable turbulence conditions paving the way to fully automated AO system,
- To investigate the possibility to anticipate the availability of an optical link,
- To demonstrate the understanding and provide an experimental proof of the limiting phenomenon for each critical sub-system: AO (anisoplanatism, robustness to non-stationary conditions), optical architecture (including telescope), booster amplifier, point ahead angle mirror.

B. Main requirements

Based on these scientific goals, top level requirements can be identified:

- The FEELINGS station is a demonstrator for bidirectional GEO feeder links. It shall allow investigating the various concepts and technologies for future operational stations dedicated to bidirectional high-throughput optical telecommunication links with GEO satellites.
- As the baseline for the FEELINGS will be located station will be to be stationed in a given place in France, in a given place. As a goal, the FEELINGS station shall be transportable, allowing experiments around the world, in limited cost and time delays.
- FEELINGS shall be designed for various GEO targets.
- As a goal, FEELINGS shall be designed to work on LEO or MEO high data rate optical communications, but for the downlink only. The In-Orbit Demonstrator by Airbus and ISS Bartolomeo payload shall be considered as top priority LEO/MEO targets.
- The wavelengths of the uplink and downlink shall be compatible with the developments in optical satcoms of

French companies (OGS and payloads). Priority is given to 1550 nm telecommunication.

- FEELINGS shall address the case of a purely monostatic configuration, where the uplink and downlink share the exact same pupil.
- FEELINGS shall address the case where the uplink shares only a portion of the downlink pupil. The change from previous configuration may not be automatized but shall then require minimal manual intervention.
- FEELINGS shall have an uplink beacon, co-aligned with the downlink telecom signal, in a manner that is stable over time, i.e. the misalignment must stay within a small fraction of the beacon divergence.
- Non coherent communication links are considered as a baseline, but the system shall allow as far as possible extension to coherent links.
- FEELINGS shall provide its own high power high stability optically modulated source for basic uplink, but shall be able to host external systems and interface with client communication system (reception-emission).
- FEELINGS should be operated many hours in a row, by day and night.

III. OGS MAIN FEATURES

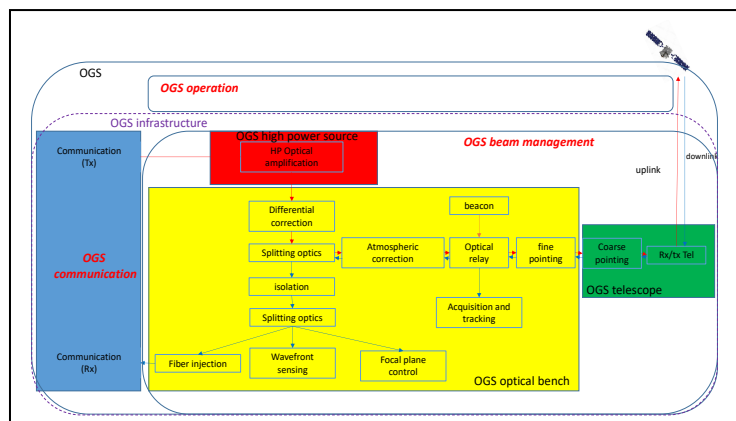


Fig. 1. Functional description of the OGS. Main functions are in red. Colored boxes indicate the main sub-systems.

A. System functional analysis and description

The main functions of OGS are (see Fig. 1 and 2):

- **OGS Operation:** it ensures the correct operation of the OGS. It includes typically link programming, local conditions monitoring, anomaly management and overall OGS management;
- **OGS beam management:** these functions relate to the communication beam shaping and transfer from / to the satellite. These also concern opto-mechanics control and opto-electronics parameters adjustments;
- **OGS communication:** these functions ensure proper conversion of signal to be emitted or received, including mux/demux and amplification of signals;
- **OGS protection:** these functions are related to the protection of the OGS and its personal, either on site or during transportation if any.

As the OGS may accept a client communication signal, the OGS communication functions may be provided by a host system. The interfaces are then to be finely defined with the client system, but shall be basically:

- for feeder link: the collimated uplink source at the entrance of the uplink path;
- for GEO downlink: the downlink single mode fiber output.

balanced by additional anisoplanatism. Mispointing error has then an increased impact, leading to higher specification on PAA calibration (0.2 μ rad accuracy). This leads to high constraints on PAA control, performed in open-loop, and calibration. [8] also showed that the relative gain brought by a 60 cm aperture with respect to the 20 cm case depends on the interleavers.

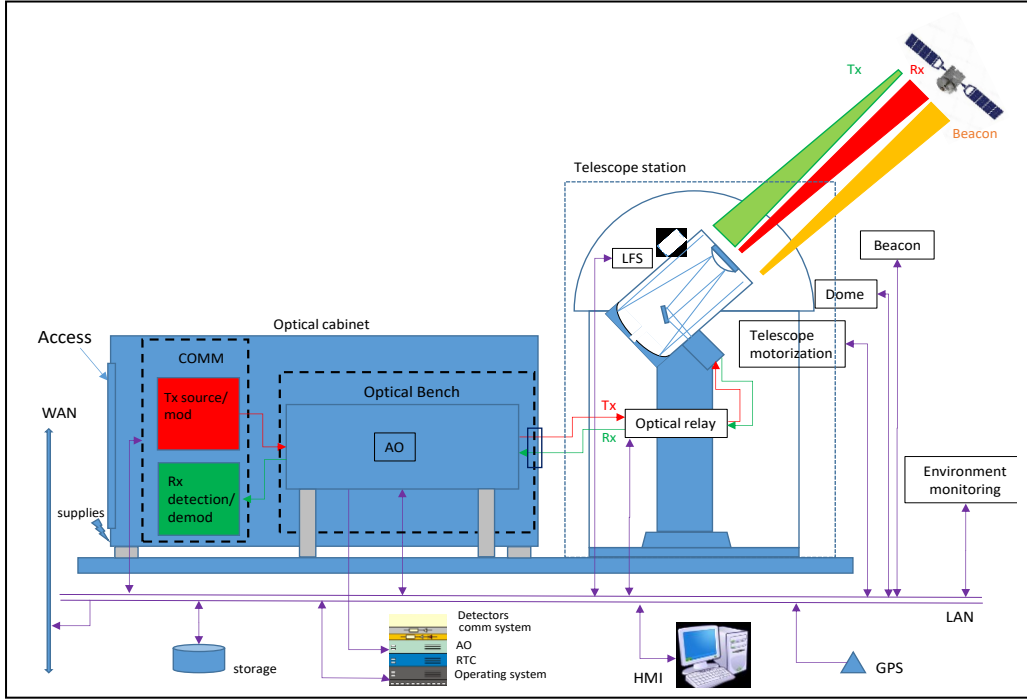


Fig. 2. Functional description of the OGS. Main functions are in red. Colored boxes indicates the main sub-systems. LFS: Large Field Seeker.

B. System design main assumptions and drivers

Most of the assumptions for the system analysis have been introduced in [8]. Hybrid turbulence profiles have been proposed, and the worst conditions (corresponding to propagation conditions encountered more than 90% of the time) considered for system design. It leads to typical values at 1.55 μ m of 4 cm Fried parameter (r_0), 6.8 μ rad anisoplanatic angle (θ_0) and a log-amplitude variance (σ_χ^2) of 0.079 (30° line of sight). The distance to satellite is 38609 km and the elevation is supposed to be close to 30°. The payload power is assumed to be 3 W (HICALI like) [9]. Then a 60 cm downlink aperture (30% central obscuration) has been considered to ensure proper downlink margins. Now considering uplink, the on-board receptor is assumed to be 25 cm diameter. The uplink considered is 25 Gbps DPSK, with a 50 W source. Based on these hypothesis as well as atmospheric transmission assumptions, a 1.7 dB and 1.6 dB additional link margins were exhibited in addition to the 3 dB standard link margin respectively for 20 cm or 60 cm emitting aperture. This analysis, in terms of performance and link budget assessment, has been recently comforted by our field experiment, the FEEELIO project [10]. More recent details are available in [11], this conference.

This analysis also showed that PAA and related static mispointing, coupled to aperture diameter, is a key driver in the final performance and link margin. A larger emitting aperture (60 cm) improves geometrical gain but can be counter

A specific design has thus been considered for PAA control, as well as the ability to switch manually from the 60 cm to 20 cm aperture uplink so as to validate this analysis.

Another key driver in the optical system design is the isolation of the various optical paths. In an AO compensated GEO feeder links, uplink and downlink paths must have a part in common (the one where the turbulence correction is applied through deformable and tip-tilt mirrors), thus need an efficient beamsplitting method. The uplink power can be up to 100 W, while on the downlink the wavefront sensor needs about 1 nW to work properly. There's therefore a 110 dB difference in flux between the uplink and the downlink, and thus a very demanding need for optical isolation of the downlink (at least 120 dB/130 dB or the wavefront measurement will be perturbed). Beamsplitting may be all the more difficult as uplink and downlink wavelengths are usually very close together leading to small bandgap (5 to 10 nm). This leads to highly efficient beamsplitting in combination with beam shaping and backscattering reduction strategies.

System design shall account for polarization management and allow proper separation of the polarized beams, without significant impact (polarization insensitive optics).

In addition, our system design shall comply both with the GEO feeder case and also with the LEO downlink experiments. As such, the AO system design has been adapted to meet both requirements, though it leads to a somehow over-specified system for the pure GEO feeder link case.

Finally, our system aims at evaluating and tackling these scientific and technological risks related to GEO-feeder links.

As such it tries to implement the necessary functions and algorithms to evaluate turbulence conditions and performance but also to optimize the AO performance on both links.

IV. FEELINGS DESIGN

Design of the optical system, and in the first place of the AO system, is thus a compromise between high performance and robustness in the one hand, versatility and ability to address GEO feeder links and LEO downlinks in the other hand.

Detailed description of the system analysis and design is not addressed here and will be the object of a dedicated article. Design solution clearly benefitted from our previous experience within the FEELIO project [10, 12]. We provide the main features of the resulting system.

A. OGS overview

The FEELINGS OGS (see Fig. 3) is based on a 60 cm telescope, able to withstand up to 100W uplink at least. To allow addressing GEO feeder links as well as LEO downlinks a coudé focus has been selected. The telescope provides tracking ability for LEO satellites.

While downlink is always ensured by the full aperture, two concurrent configurations are considered for GEO feeder links: a 60 cm full aperture, or a 20 cm decentred aperture, each configuration providing potential advantages that will be investigated [8].

The OGS is equipped with a Miratlas Integrated Sky Monitor to provide detailed weather and turbulence conditions monitoring.

The optical and communication systems are installed into a refurbished 20 feet container. The overall installation can be operated from a close-by control room.

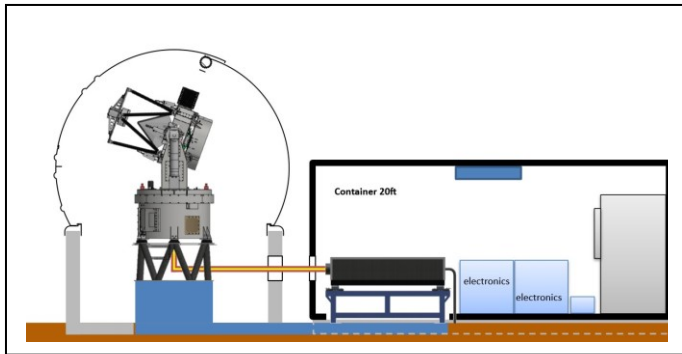


Fig. 3. Sketch of the overall FEELINGS station including telescope, shelter and optical system.

B. Optical system design

The AO system is based on a 17x17 sub-aperture Shack-Hartmann wavefront sensor, including a FLI CMOS C-Red2 detector, and a 292 actuator ALPAO deformable mirror coupled to a fast Tip-Tilt mirror. The overall AO loop is controlled at a 4.7 kHz, this value being mostly driven by the LEO case.

The AO system provides turbulence mitigation for the downlink signal and precompensation of the uplink beam, either on the 60 cm full aperture or the 20 cm reduced aperture. The Real-Time-Controller (RTC), provided by

Shakti, shall allow investigation of various algorithms for both wavefront sensing and control.

The optical system provides single mode fiber injection of the downlink signal that can host any client detection system. In addition, various diagnosis tools are included to finely evaluate the real-time performance and the characteristics of the channel. Polarization is controlled all along the path to ensure proper management and injection of polarized signals.

Considering the uplink beam, the system embeds in baseline a 30 W (goal 50 W) laser source, based on an optical fiber amplifier (BOOFEE) developed at Onera. Optical modulation of the uplink signal is performed, DPSK modulation is considered. However, the optical bench can also interface with host sources. Telecommunication system can also be interfaced with BOOFEE to propose a fully operational telecommunication system.

As mentioned previously, PAA is a key driver in the final uplink performance. A typical 18.5 μ rad PAA is introduced on the uplink laser. While a 1 μ rad rms accuracy on PAA is provisioned as a baseline, a 0.2 μ rad rms accuracy is considered as a goal [8], leading to a dedicated design and calibration strategy.

Uplink and downlinks are typically considered respectively in the [1540, 1550] nm and [1560, 1570] nm bands, with a 5 nm bandgap (though 10 nm would be less demanding). However, the current design allows flexibility and these ranges can be modified in some extent.

Particular attention has been paid to the optical isolation of the various optical path due to the significant discrepancy between uplink and downlink optical powers. While our OGS is not dedicated to the 1 kW range uplinks, our goal is to demonstrate the ability to manage such discrepancies and implement dedicated beam shaping and isolation solutions that could be extended to higher power designs.

The OGS provides a 10 W beacon, with adjustable divergence and wavelength, in the [1570, 1605] nm band, to ensure proper Pointing Acquisition and Tracking (PAT) protocol. While the telescope ensures coarse pointing, and the AO system the ultimate fine pointing, an intermediate stage allows medium pointing accuracy and stabilization in particular during the PAT protocol, in the optical relay between telescope and AO system.

Finally, the operating system is a home-made software, derived from previous experiments [10].

C. Project current status

The FEELINGS OGS has now passed its final design review.

Long lead items procurement has been triggered in early 2021, so that telescope procurement is on-going. An Astelco 600 mm telescope, with a coudé path has been selected, ensuring both GEO and LEO high precision tracking. It is equipped with a motorized slit dome. Shelter procurement is currently being contracted.

Key AO components such as main sensors (cameras, wavefront sensor) and actuators (deformable mirror, beam-steering actuators) are received and under testing.

The remaining optical, mechanical and electrical components are currently under procurement.

Assembly, Integration and Testing (AIT) shall be pursued till beginning of 2023, so that the overall system be ready for installation and commissioning mid-2023.

We consider both in lab and on sky testing. The laboratory tests shall rely on our turbulence simulator, PICOLO [12], that allows to reproduce low elevation LEO turbulence cases (see Fig. 4), but can be compatible with the GEO case, or used for pure functional validations.

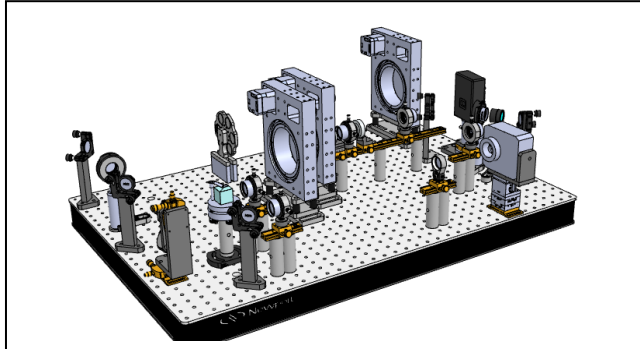


Fig. 4. 3D Opto-mechanical design of the PICOLO turbulence simulator. It integrates 3 turbulent layers in rotation and can reproduce low elevation LEO configuration, including phase and scintillation effects.

Site installation is of course a key issue. Various options located in the south of France are currently under consideration, and shall represent the baseline implementation of the OGS, though ability to displace the overall OGS shall remain possible, even if the final concept is not as an easily transportable OGS as in [13] for instance.

D. OGS exploitation

Considering that the FEELINGS station will be available mid 2023, our goal is to propose the OGS for either GEO or LEO links demonstrations. First systems to be on sky and accessible would be respectively BADR8 and LASIN. But the FEELINGS OGS could address other payloads with small adjustments, and participate to various campaigns, to assess:

- Mitigation solutions to address the key challenges of GEO feeder links: PAA and anisoplanatism handling, optical isolation, high power optical sources and modulation etc.
- Mitigation solutions or new concepts for LEO downlink optimization: low elevation links, adaptive AO solutions etc.
- Development and testing of concepts for automated AO based OGS
- Characterisation and modelling of the optical link, participation to turbulence profile databases
- Assess multi-point architecture and hand-over strategies [14].

V. CONCLUSION

Onera is currently developing and integrating the FEELINGS OGS for feeder link communication. We have proposed a short description of the system scientific goals and the main requirements, its design. The system should be on sky mid-2023. The FEELINGS OGS shall address both GEO feeder links and LEO downlinks. Its main goal is to address the main scientific and technological challenges of these two applications to pave the way for future operational systems.

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