Current Adaptive Optics Developments for Uplink Correction

Subjects: Telecommunications

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Conventionally used in astronomy, adaptive optics (AO) systems measure and correct for turbulence and, therefore, have the capability to mitigate the impact of the atmosphere on the ground-to-space communication links. Historically, there have been two main streams, respectively, advocating to use or not use adaptive optics on optical communications.

uplink adaptive optics pre-compensation ground-to-space optical communications

1. NICT Spatial Optical Communication Device

The Japanese National Institute of Information and Communications Technology (NICT) has recently developed a patent for an innovative compensation optical system capable of selecting the transmission path for the light wave Tx while considering the point-ahead angle [1]. The proposed system incorporates a reflective element in which a portion of the Rx signal is reflected outside the telescope by a deformable mirror (DM) and subsequently measured. As a result, the Rx signal encompasses both the downlink itself and a segment of the propagation path for the uplink. This system comprises two wavefront sensors (WFS) and two DMs. One WFS-DM pair is responsible for correcting the downlink, while the other WFS-DM pair pre-compensates the uplink and a section of the downlink.

2. ESA Optical Ground Station

The European Space Agency, through their program Scylight, has made significant investments in exploring atmospheric pre-compensation strategies for ground-to-space optical links. The ESA Optical Ground Station (OGS), situated at the Teide Observatory in Spain, is a 1-meter telescope that has been utilized for optical communication demonstrations since the early 2000s [2][3].

2.1. ALPHA-UP

ALPHA-UP, a prototype of adaptive optics designed for bidirectional communications, was deployed at the Coudé port of the ESA Optical Ground Station (OGS) [4]. Its primary objective is to enable bi-directional adaptive optics correction for the transmission of data between ALPHASAT and the OGS, both for downlink and uplink communications. To achieve this, it utilizes a shared 22 cm sub-aperture within the 1 m pupil, allowing the transmission and reception of laser beacons to and from ALPHASAT through the Coudé path of the OGS. To ensure an effective performance, ALPHA-UP is equipped with a 6 × 6 incoherent Shack–Hartmann wavefront sensor and incorporates spectral filtering, which helps prevent self-blinding resulting from the monostatic configuration.

ALPHA-UP represents a significant milestone as it is, to the best of the author’s knowledge, the first successful demonstration of pre-compensated feeder link correction. By pre-compensating 27 modes of atmospheric turbulence in the uplink communication with ALPHASAT, the ALPHA-UP system achieved an impressive 10 dB improvement in fading statistics compared to using only tip-tilt correction methods. ALPHA-UP is paving the way for uplink pre-compensation, demonstrating the advantages of adaptive optics in operational ground-to-space communications.

2.2. ALASCA: Advanced Laser Guide Star Adaptive Optics for Satellite Communication Assessment

The Advanced Laser guide star Adaptive optics for Satellite Communication Assessment (ALASCA) project aims to revolutionize ground-to-space laser communications by leveraging laser guide star adaptive optics (LGS-AO) technology to address the point-ahead problem [5]. It is set to transform the ESA OGS in Tenerife into an optical feeder link (OFL) test facility with a target technology readiness level (TRL) of 6 and plans for 24/7 operation. TRLs (based on the ISO 16290 standard) are used to assess the maturity level of a technology, ranging from 1 (basic principle) to 9 (deployed and proven to work in an operational environment). ALASCA aims to reach TRL 6, which represents a demonstrator model validating the critical functions of the technology in the relevant environment. Advancing to TRL 7 and beyond involves transitioning from a test bench demonstrator to a final functioning instrument that can be operated by the ground station personnel with basic knowledge of the system.

To achieve this, ALASCA builds upon the existing CaNaPy test bench, originally designed for night-time astronomical observations [6]. The CaNaPy system features a remarkable 70+ W 589 nm laser, currently unmatched in its capabilities. While most astronomical AO systems utilize a 20 W 589 nm laser, the higher power of the CaNaPy laser produces a brighter laser guide star to enhance the performance of the adaptive optics system during both day and night operations. ALASCA will expand the CaNaPy facility capability by upgrading both its hardware and software to specifically cater to the development of ground-satellite optical communication.

The daytime operation of a LGS-AO has been noted in the past as one impediment for LGS-AO being applicable to optical communications. Nonetheless, remarkable strides have been made in overcoming this limitation. The recent experiments have revealed that it is indeed possible to attain equivalent return flux even in daytime scenarios [7][8]. This notable achievement was made possible through the incorporation of ultra-narrow band magneto-optical filters (MOF) within the system configuration. The inclusion of this filter plays a crucial role in reducing the daytime bright background, with a 100,000:1 extinction ratio while maintaining an intrinsic throughput of 97% [8].

ALASCA marks a significant milestone as a pioneering system at TRL6, which leverages laser guide star adaptive optics as the optimal solution for uplink pre-compensation.

2.3. Coudé Laser Communications System

The Coudé Laser Communications System (CLCS) is part of the ESA OGS upgrades [9][10]. The CLCS is an adaptive optics system for bi-directional links incorporating atmospheric correction in both the downlink and uplink. In the receive direction of the optical system, the entire 1m aperture of the telescope is used to capture the incoming signal. In the transmit direction, the OGS telescope aperture is divided into quadrants, and a 20 cm beam is transmitted from each quadrant. The CLCS also incorporates various techniques to enhance the overall performance, including wavelength multiplexing, spatial diversity, and pre-compensation for each transmitted beam.

3. FEELINGS: FEEder LINks Optical Ground Station and VERTIGO Experiment

FEEder LINks optical Ground Station (FEELINGS) is ONERA's current development of a research optical ground station to explore and enhance technological advancements for both GEO feeder links and LEO links [11]. Notably, one of the key components integrated into FEELINGS is AO pre-compensation. The development of FEELINGS by ONERA is an extension of their previous endeavor, the FEEDELIO experiment. In this pursuit, they conducted the VERTIGO experiment in June and July 2022, serving as a pathfinder for the forthcoming development of FEELINGS.

During the VERTIGO experiment, ONERA successfully demonstrated optical transmission capability over a distance of 53 km while maintaining an elevation of 2 degrees. This remarkable achievement involved data transfer rates exceeding 1 Terabit per second (1 Tb/s) on a single channel [12]. To reach 1 Tbit/s, the link employed a dual polarized 84 GBd 64QAM signal, while the atmospheric turbulence was mitigated by adaptive optics. They showed that the received power distribution improved by 19.5 dB when tip-tilt correction was in place, while it increased by 28.1 dB when full AO was used instead. They also pointed out that in order to achieve a line rate of 1 Tb/s, a full wavefront correction was required in order for the forward error correction threshold of the received power to be above 35.53% on the 84 GBd 64QAM signal, with respect to 7.22% when only tip-tilt was corrected.

4. TOmCAT Optical Ground Terminal

The Terabit Optical Communication Adaptive Terminal (TOmCAT) is a current development of an optical ground terminal by TNO, specifically designed for terabit-per-second optical feeder links [13]. This project serves as a continuation of the earlier OFELIA experiment. In this phase of the project, the main objective is to showcase the effectiveness of AO pre-correction technology in a terabit optical ground station during daytime ground-to-ground link field tests. This experiment covered a distance of 10 km, with a significant height difference of 226 m between the terminals. To assess the point-ahead effect on the transmission, various point-angles were tested, ranging from 0 to 29 microradians. The outcomes of the experiments revealed a three-fold gain improvement in relative transmission path losses when pre-correcting 28 atmospheric modes. Furthermore, in conditions of strong turbulence, an average gain of 5 dB was observed compared to solely correcting the tip-tilt.

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