

Measuring the Index-of-Refractive Turbulence at High Altitudes through Optical Inter-Satellite Links

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this draft version of 20260810, full paper to be submitted by end of Sept. 2026

ABSTRACT:

Free-space Optical Communication offers a huge increase in data link bandwidth in future satellite communication scenarios, where one application is high-speed data repatriation of Earth observation data with relay-satellites. This concept is based on Optical Intersatellite Links (OISLs) for GEO-LEO relays systems, which can also simultaneously be employed for probing atmospheric parameters when the link's grazing height (GH) is lowered into Earth's atmosphere. Tomographic methods can then be applied to derive properties like attenuation by absorption and scattering, or the strength of the index-of-refraction and its turbulence (IRT) at specific geographic locations and altitudes. This concept is called **AMeLIT** (Atmospheric Measurements by Laser for deriving Intensity- and Turbulence-profiles).

We present analysis of AMeLIT-experiments between satellites in LEO (Sentinel) and GEO (TDP1/Alphasat) where the scintillation from atmospheric IRT at mesospheric and stratospheric altitudes was probed. Important first results of AMeLIT are hinting at stronger high-altitude IRT than predicted by classical models. Since such GEO-LEO links are limited to above specific geographic areas, we also propose a LEO-LEO OISL mission that allows similar measurements at global scale – **OpTAS** (Optical Tomography of the Atmosphere from Space).

Keywords: AMeLIT, EDRS, TDP1, OpTAS, index-of-refraction turbulence, optical turbulence of the atmosphere, optical inter-satellite link

INTRODUCTION:

Geostationary satellites (GEOs) operating on nearly circular equatorial orbits play a central role in modern communication, TV-broadcasting, and meteorological observation systems. These satellites orbit at an altitude of approximately 35786 km above the equator, with the same period as Earth's rotation. Thus, they remain fixed over a ground nadir point, stabilized further through regular station-keeping maneuvers. Consequently, from ground they are seen at a fixed position in the sky, independent from time of day or season.

Due to this prominent characteristic, hundreds of geostationary satellites are currently in operation. Furthermore, GEO-satellites can serve as relays for high speed data repatriation from aircraft or low-Earth-orbit (LEO) satellites. A particular implementation of an optical GEO-LEO relays is the European Data Relay System (EDRS) which consists of geostationary satellites (Alphasat-TDP-1, EDRS-A, and EDRS-C, launched in 2013, 2016, and 2019), receiving data via optical inter-satellite links (OISL) from Earth-observation satellites in LEO (Sentinel-1A and others) [Marynowski-TDP1-2022]. The EDRS operates optical links with coherent homodyne BPSK transmission at a signal wavelength of 1064nm, by employing the emission from amplified Nd-YAG lasers as carrier signals. With optical terminal apertures of 135 mm diameter, they allow a beam divergence of around 8.4μrad FWHM [Heine-Alpasat-2015]. After bridging the GEO-LEO distance, this small beam divergence enables a rather strong received power at the counter terminal of more than 100nW.

Besides the GEO-LEO relays scenario, OISLs are also employed in LEO mega-constellations to establish the communications network in space. Besides the 1064nm homodyne-coherent BPSK technology of EDRS, other laser wavelengths and modulation formats are applied in OISL scenarios (mostly 1550nm and 850nm) [Younus-2024].

It has been proposed to execute metrology tasks in parallel to operational OISL data comms, using the link hardware in a sensor-mode [Gig-COAT-2025]. Ample link margin would be available for such measurements, covering also the expected atmospheric attenuation.

With radio-frequency occultation (radio-occultation, RO), a similar technique is regularly applied for the characterization of planetary atmospheres (Earth and Mars), employing the microwave spectrum. With the matured technology of optical inter-satellite links for high-speed communication, today the probing of the atmosphere with a dedicated high-intensity optical ray becomes feasible, extending the principle of RO to optical carrier signals. Hence, with Laser-Occultation (**LO**) - higher precision measurements at improved spatial and spectral resolution can be realized, allowing regular three-dimensional characterization of an atmosphere's condition, for example the aerosol density and the distribution of trace-gasses such as carbon dioxide or methane [LasOcc-COAT].

Preceding grazing-experiments show a major impact of index-of-refraction turbulence (IRT) on the signal stability [Sterr-2016], and pure measurements of power-transmission are expected to show a significant response to the aerosol- and molecular absorption as well as to humidity and air density, due to the long horizontal path section during grazing.

In contrast to GEOs, low-Earth-orbit (LEO) satellites operate at altitudes typically ranging from approximately only 300 km to 2000 km which allows high-resolution observations of ground- or atmospheric features. They move rapidly relative to the Earth surface, typically completing one orbit within about 90 to 120 min.

Many Earth-observation missions employ near-polar or Sun-synchronous (SSO) LEO orbits in order to achieve near-global coverage through successive orbital passes. Representative examples include the polar MetOp satellite fleet, or ESA's several Sentinel missions.

In the context of the present study, we consider observations at a wavelength of 1064 nm, with received power levels as necessary for the OISL data communication link in EDRS. A major benefit of this wavelength is the lack of absorption lines from atmospheric molecules, which would otherwise falsify the grazing measurements of aerosol absorption [Gig-AttAbs-2022].

The GEO-LEO OISL geometry is specifically advantageous for atmospheric sounding applications as it features consecutive grazing measurements with lowering altitudes, over approximately a fixed geographic location (slight horizontal shifts apply) – thus quasi over a pillar.

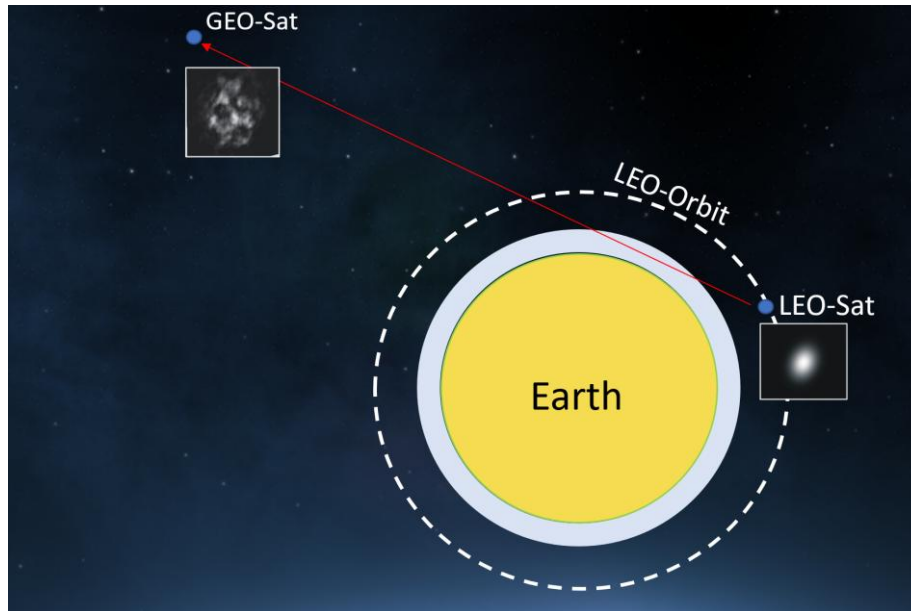


Fig 1: AMELIT-scenario between GEO and LEO

AMELIT ORBIT GEOMETRY

The Link between the GEO Alphasat/TDP1 and LEO Sentinel A-1 serves as testbed for the EDRS (European Data Relays System) where Earth-Observation Data is transmitted in a coherent optical link via a geostationary relay satellite. With the sun-synchronous LEO disappearing and reappearing every half orbit behind the Earth's poles, the optical signal traverses the atmosphere for several seconds, allowing measurements of attenuation and wavefront distortion down to ground level (Polar Grazing, PG). Due to the geometry of the grazing link above the Earth's sphere, the effects of the atmospheric layer in the link's vertex are most pronounced.

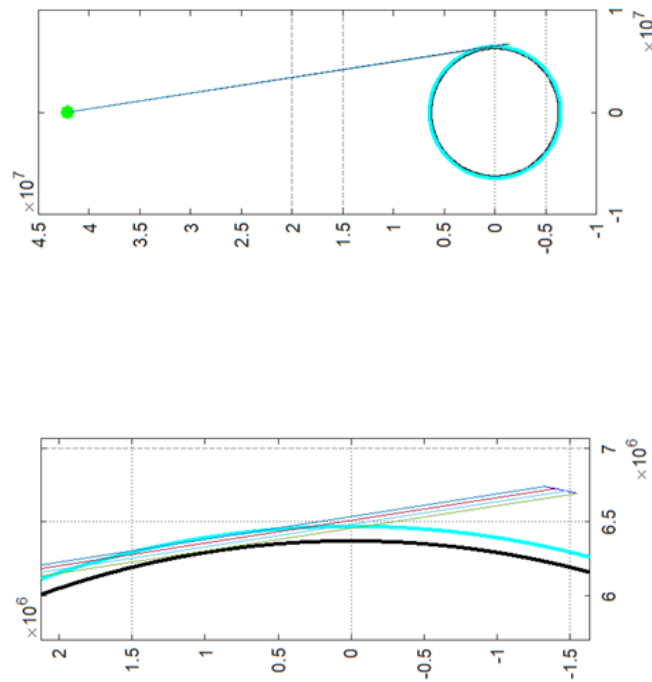


Fig 2: Orbit geometry during Grazing. The LEO is practically already behind the Earth when grazing happens {rework figure, add path of the GP-line}

A “polar” grazing events in this OISL scenario happens regularly nearly twice each orbit, when the LEO disappears (ingress) or reappears (egress) quickly behind the Earth’ poles.

When but the LEO’s orbital plane runs nearly perpendicular to the nadir direction of the GEO, the link will only intermittently graze into the atmosphere and reappear after a longer time. We call this “equatorial grazing” or “arctic grazing”, depending on where it is located geographically. Such grazing events allows measurements not only near the poles but also along the whole footprint circle (Fig. 3).

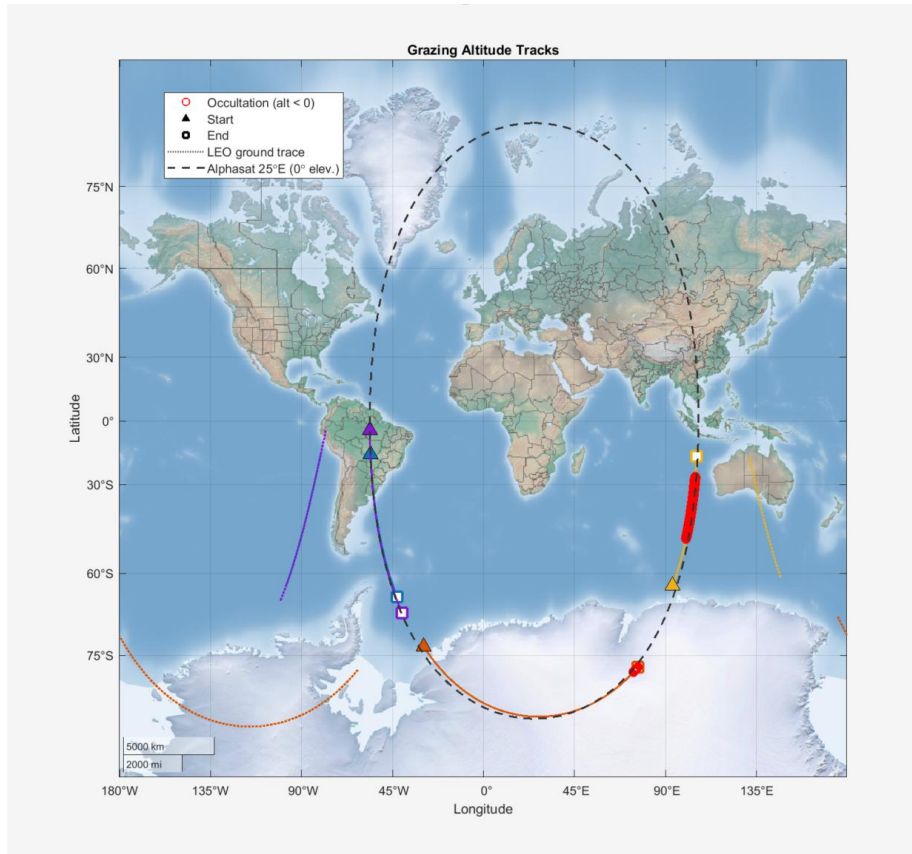


Fig. 3: Grazing paths of the AMELIT measurements with TDP1 and Sentinel-1A are all close to the 0° elevation circle.

GEOGRAPHICAL DISTRIBUTION OF AMELIT TELEMETRY:

From Fig. 3 we see potential AMELIT measurements over the Antarctic, Brazil, and the southern Atlantic and Indian Ocean. Fast landmasses of Asia, Greenland, and the Antarctic should also be assessed, however were not part of the current telemetry data.

Fig. 4 shows the height distribution of AMELIT data over geographic location.

Fig. 4: Summary of the available AMELIT data over geographic location.

Figure: Geometry of atmospheric IRT-impact along OISL

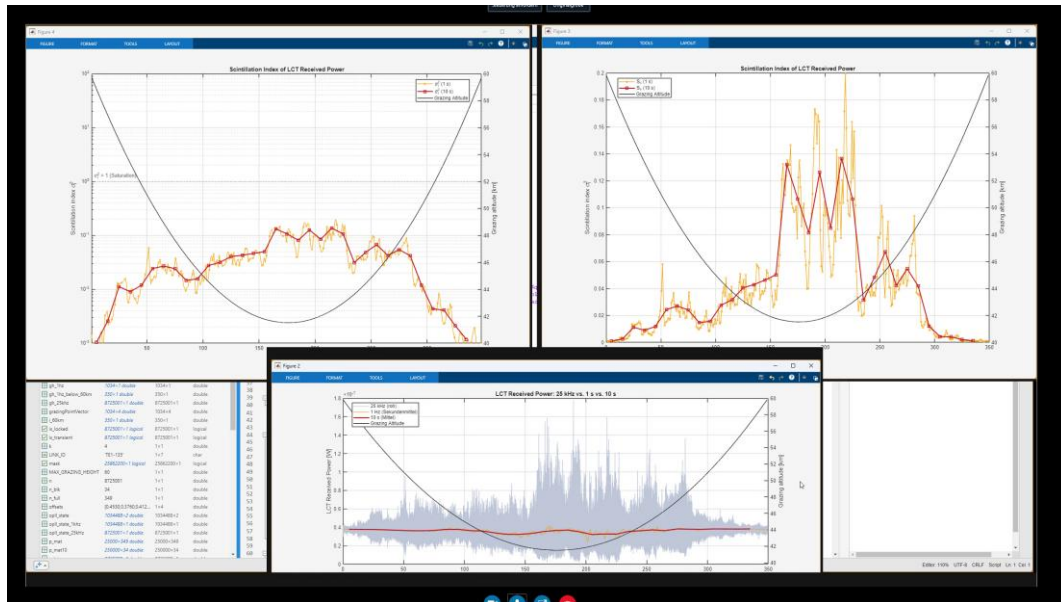


Figure: received power statistics over grazing point height

RESULTS OF AMELIT ON IRT ASSESSMENT:

- Signal-Scintillation in AMELIT from altitude and geographical location:
- Classical Hufnagl-Valley model of IRT over height, and relating scintillation to Cm2-model:

Figure: HV-Model compared to AMELIT

- Relating OISL signal-scintillations to IRT modelling:

Figure: High-altitude IRT / C_n^2 deduced from AMeLIT

Results to elaborate:

LinkBudgets of GEO-LEO EDRS from theory and optical power from tracking sensors

derive the results of “SI” over GH and geographic location: we should see Antarctic, Atlantic, IndianOcean, and Brazil (Northern hemisphere is missing)

connection between SI and the real turbulence strength (in form of C_n^2) - when Beam-Wander is NOT dominating, or when it is causing absolute link loss ...

provide plots and evaluation/parameters of fading behavior over different locations and GHs;
provide tables if Grazing-times for TDP1-Sentinel-1A ; summarize their orbital characteristics

EO-CONCEPT “OpTAS”: OPTICAL TOMOGRAPHY OF THE ATMOSPHERE FROM SPACE

A future space mission for atmospheric grazing measurements may consider circular LEO occultation geometries, in which two satellites with an OISL-connection fly in the same - near polar or sun-synchronous - orbital plane with a variable separation (of around 5000km depending on orbit-height). This allows atmospheric measurements at various

grazing-altitudes when the mission is operated over a longer time frame [11]. Similar concepts have been investigated in [12][13][14], where we concentrate on a twin-satellite follower orbit geometry.

In contrast to the AMELIT-concept between GEO and LEO where the grazing allows consecutive measurements of nearly-fixed geographic locations at decreasing grazing altitudes, in a LEO-LEO scenario the grazing would operate at a fixed height (when neglecting the non-spherical geoid-shape) and altitude-variation would be initiated by orbital distance maneuvers. The algorithms for extracting atmospheric parameters of the grazing location would have to be adopted accordingly, but with regarding the telemetry data (location, altitude of the links), similar evaluation can be deduced, while any location on Earth can be probed instead only the GEO-footprint area near the 0° link-elevation circle.

The retrieval algorithm would have to be adopted since grazing measurement time vectors would not run consecutively over the whole altitude range (as in the GEO-LEO scenario), but instead the measurements at different grazing heights would be separated by longer time intervals (i.e. several orbits), depending on the range separation operations.

Such configurations could thus provide substantially broader geographic coverage than GEO–LEO systems and may therefore be attractive for future global aerosol- and even molecular-sounding missions. The results of the present study suggest that the two geometries offer complementary capabilities: GEO–LEO OISLs provide favorable conditions for the testing of the measurement-principle and algorithms at fixed geographic areas, whereas a future LEO-LEO scenario can offer global coverage. Within the retrieval algorithm considered here, the GEO–LEO configuration yields the more accurate reconstructions and higher information content but at limited geographic coverage.

Further consideration shall be given to regarding the impact of water clouds as they become frequent below 15km altitude (depending on geographical latitude), since their attenuation might influence the metrology of aerosol content. Furthermore, the strong attenuation at lowest grazing altitudes might even influence the OISL communication system in a way that link stability is affected. Still, the beam distortions from atmospheric index-of refraction turbulence (IRT) can lead to strong signal scintillations leading to link abortion. Altogether, these circumstances indicate the necessity of a specified mission with optimized beam divergence, wavelength, robust beam tracking, and dedicated metrology sensors.

A potential mission for probing the whole planetary atmosphere called **OpTAS** (Optical Tomography of the complete Atmosphere from Space) is depicted below. It is based on an OISL between two LEOs in same average height, constantly traversing the atmosphere. The GH is varied when one of the satellites changes its position relative to the other. This allows the GH to vary between e.g. 100km and 10km. Together with a near-polar orbital plane and an oscillation of the LEOs' distance, the whole planetary atmosphere will be probed with different vertex points altitudes over several months or years, depending on geographic resolution and duration of mission.

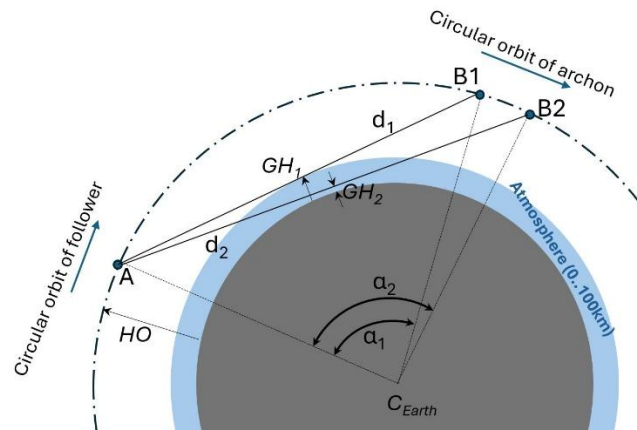


FIGURE: Follower-Orbit configuration with variable distance, for OptAS



Fig. The OptAS-scenario

SUMMARY AND OUTLOOK:

...This impacts the application of techniques like Adaptive-Optics-Predistortion for optical satellite-uplinks, or the operation of optical free-space communications with aerial vehicles at very low link elevation.

... Investigations of suitable wavelengths and tracking methodology is ongoing.

ACKNOWLEDGMENTS

The activities of the TDP1-programm are carried out on behalf of the Space Administration of the German Aerospace Center (DLR e.V.) with funds from the German Federal Ministry of Research, Technology and Space with the reference number 50YH2602.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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