Optical Ground Station for Free-Space Optical Communication Research and Experimentation

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***Abstract*—Free-space optical (FSO) communication based on laser technology is a promising opportunity for the next-generation ultra-high data rate links from satellites to ground and vice-versa. To investigate and demonstrate the feasibility of space-to-ground laser links, we conduct a small satellite mission at the Research Center Space of the University of the Bundeswehr Munich (UniBw M). Core of this mission is the satellite ATHENE-1 in a non-geostationary orbit (NGSO). Among other payloads, this satellite is equipped with an optical laser terminal for high-speed data up- and downlinks. The ground segment will comprise an optical ground station (OGS) at the campus of the UniBw M in Neubiberg, Germany. In this paper, we provide an overview of the planned FSO communications experiments and, in particular, introduce and describe the setup of the OGS. The OGS is currently under construction, full operational capability is planned to be end of 2023.**

***Index Terms*—laser communication, optical ground station, free-space optical communication, small satellite mission**

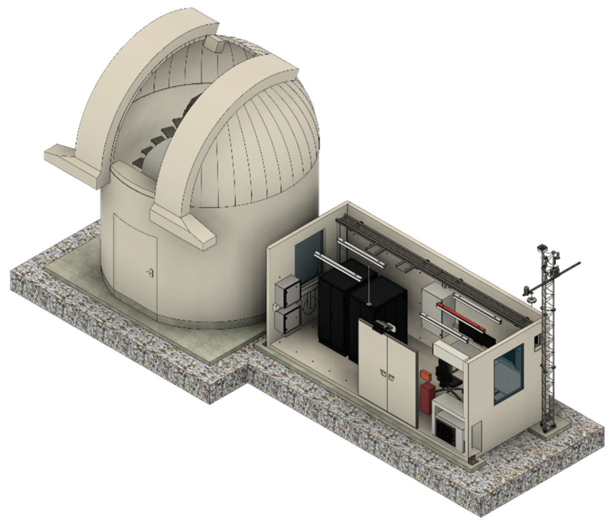

Fig. 1. Graphical illustration of the optical ground station in Neubiberg.

I. Introduction

Thanks to the recent advances in laser communication and the maturity of this technology, free-space optical (FSO) links are currently discussed as a complement to classical radio frequency (RF) communication links between spacecraft and ground-based terminals. As an example, optical gateways for feeder links to satellites in the geostationary (see [1], [2], [3]) or non-geostationary orbit (NGSO) (e.g. [4]) are proposed to address the huge data rate demands in modern satellite networks. In addition to the much larger bandwidth and thus higher data rates, laser communication has some advantages over classical RF links. FSO laser links offer a greatly reduced susceptibility to interference. Due to the much smaller beams, laser FSO communication links inherently provide security on the physical layer against eavesdroppers and jamming resistance against adversaries.

To investigate and demonstrate the feasibility of new technologies in space and on ground, we conduct the satellite mission Seamless Radio Access Network for Internet of Space (SeRANIS) at the Research Center Space of the University of the Bundeswehr Munich (UniBw M). In addition to our own research, SeRANIS will establish an open research environment for the community to support space-related investigations as well as over-the-air (OTA) test and demonstration activities. Core of this mission is the satellite ATHENE-1 in a NGSO. Having a mass of about 200 kg, ATHENE-1 will support more than 15 various payload and platform experiments from different disciplines [5]. The payload of ATHENE-1 will include a laser communication terminal (LCT) for high-speed data up- and downlinks [6]. This LCT will be equipped with a dedicated coarse pointing assembly to be independent of the spacecraft's attitude and shall demonstrate the feasibility of optical space-to-ground links for routine operations. The ground segment of SeRANIS consequently comprises an optical ground station (OGS) that will be established at the campus of the UniBw M in Neubiberg, Germany (see Fig. 1).

Apart from high-speed data up- and downlinks to and from ATHENE-1, a second goal of the OGS is to investigate the optical channel. The atmospheric channel using FSO laser communication has not been fully investigated yet. Available performance characteristics of FSO laser communication under real conditions are still sparse, but are necessary in order to form the foundation for theoretical models (e.g. in [7]) on the transmission channel for this innovative technology. The OGS will serve as a ground-based laboratory to conduct measurement campaigns in order to characterize the physical effect of the atmosphere on laser communication between the space-to-ground and ground-to-space paths. The main technical parameters of the OGS and a related link budget estimation

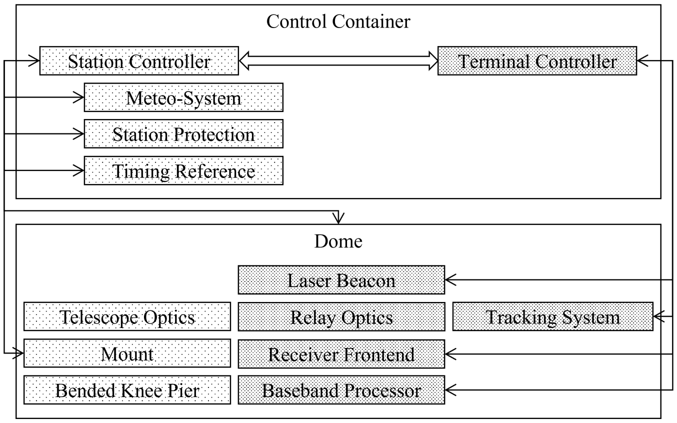

Fig. 2. Functional block diagram of the OGS with its main building blocks.

to NGSO and geostationary satellites are provided in Section II and III, respectively. Before we conclude in Section V, we summarize local weather conditions in Section IV.

II. The Optical Ground Station in Neubiberg

The OGS in Neubiberg will be delivered by the system integrator DiGOS GmbH, Germany. It is identical in design and technical features to the Laser Bodenstation Trauen (LaBoT) from the German Aerospace Center in Trauen, Germany [8], and comprises the telescope including the optical tube assembly, the terminal assembly, and the control container. A diagram of the main functional building blocks is given in Fig. 2. The telescope and terminal assembly are protected by a dome having a diameter of $4.6\,\mathrm{m}$ and a height of almost $6\,\mathrm{m}$, sufficiently large for a comfortable working environment (see again Fig. 1). The visual axis of the telescope is at $3.85\,\mathrm{m}$ for a free $360°$-view and to mitigate ground-turbulence.

The Ritchey-Chrétien telescope is based on a Nasmyth design [9] and has an aperture of $70\,\mathrm{cm}$. The mirrors are coated with a protected aluminum surface that provides a high efficiency in the visible and in the near-infrared wavelength range from $1000\,\mathrm{nm}$ to $1700\,\mathrm{nm}$. Three exit pupils support various optical instruments, such as a beacon laser, an optical camera, or a modem together with an optical receiver front-end. The laser beam can remotely be switched between the three foci using a motorized mirror.

The rotation speed of the dome achieves $10\,°/\mathrm{s}$, which is sufficiently high for all kinds of low earth orbit (LEO) missions. The control software achieves an open-loop tracking accuracy of $10''$ together with the directly driven mount based on two-line elements or consolidated prediction format. Closed-loop tracking is realized by a fine-tracking system as part of the terminal assembly to improve the tracking accuracy to below $3''$. Manual pointing using azimuth and elevation or ascension and declination coordinates in steps of $1''$ is also possible.

The control container provides a working area for monitoring and control purposes. The hard- and software of the OGS features multiple support functions, such as an Aircraft Detection Unit with Automatic Dependent Surveillance - Broadcast (ADS-B), a Laser Safety Unit with a laser interlock controller, and a Station Protection Unit using a wind and rain detector to survive certain weather conditions. In case an alarm is detected the dome shutter is automatically closed in less than $20\,\mathrm{s}$.

The communication links from and to the LCT onboard ATHENE-1 will be based on the Consultative Committee for Space Data Systems (CCSDS) standard optical on-off keying (O3K). Our goal is to achieve data rates of up to $1\,\mathrm{Tb/s}$ in the downlink (DL) and $100\,\mathrm{Mb/s}$ in the uplink (UL), respectively. Apart from high-data rate up- and downlinks, the OGS will additionally be utilized to conduct channel measurements and to investigate atmospheric conditions for various elevations. Future enhancements and modifications of the OGS shall support also coherent modulation schemes with wavelengths of $1064\,\mathrm{nm}$ as well as experiments for space-based quantum key distribution (QKD).

TABLE I
UL and DL link budget example between OGS and ATHENE-1 and between OGS and the GEO satellite Alphasat

Parameter	**ATHENE-1**		**Alphasat**	
	UL	**DL**	**UL**	**DL**
wavelength / nm	1590	1550	1064	
mean source power / dBm	36	30	37	33.4
Tx internal loss / dB	3	1	3	1
Tx aperture / m	0.075	0.02	0.075	0.124
Tx antenna gain / dB	105.5	94.3	109	113.4
pointing loss / dB	0	3	0	3
link distance / km	891		38 315	
free space loss / dB	256.9	257.1	293.1	
elevation angle / °	35		33.3	
atmospheric losses / dB	1		1.5	
Rx aperture / m	0.02	0.41	0.124	0.41
Rx antenna gain / dB	91.9	118.4	111.3	121.7
optical loss Rx / dB	2	4	2	4
power on detector / dBm	−29.5	−23.5	−42.4	−34.2

III. Link Budget Analysis

TABLE I provides a rough link budget estimation for LEO and GEO scenarios to assess the received power values achievable with our OGS following the simplified methodology treated in [10]. For the LEO case we choose the $1550\,\mathrm{nm}$ LCT aboard ATHENE-1 as the counter terminal, which will be equipped with a $2\,\mathrm{cm}$ transmitter (Tx)-/receiver (Rx)-aperture and be signalling at $1\,\mathrm{W}$ of optical power. ATHENE-1 will be placed into a $550\,\mathrm{km}$ altitude sun-synchronous orbit; here, we exemplarily provide the assessment for a satellite elevation of $35°$. As an example for a potential geostationary earth orbit (GEO) remote station, we choose the $1064\,\mathrm{nm}$ LCT aboard Alphasat providing a $12.4\,\mathrm{cm}$ aperture and $2.2\,\mathrm{W}$ of optical transmit power.

Ignorant of the exact values, internal losses have been presumed for both space terminals. Moreover, pointing losses are based on experience. Also, we do only consider atmospheric attenuation according to [10] and neglect short-term unit mean power variations from index-of-refraction turbulence (IRT). For uplinks we consider the pointing accuracy sufficient to disregard mechanical jitter, and we ignore boresight errors.

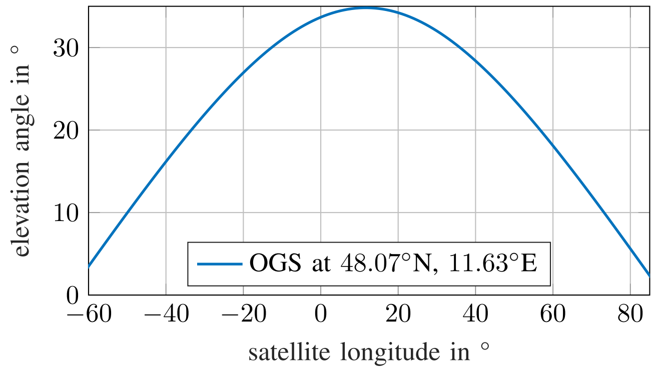

Fig. 3. Visibility and elevation angle of GEO satellites from the location of the OGS in Neubiberg, Germany, considering local surrounding conditions.

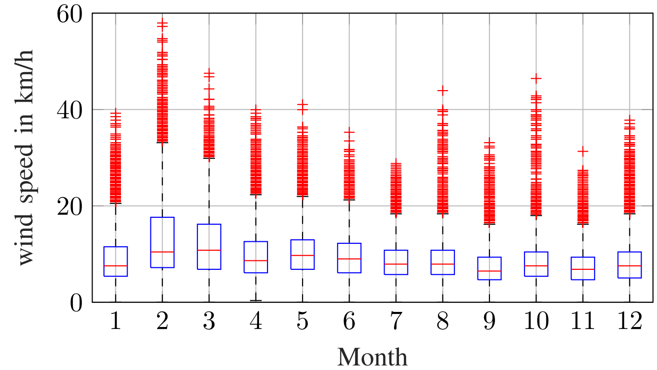

Fig. 4. Box plot of monthly wind speed in Munich (two-year average between 2020 and 2021).

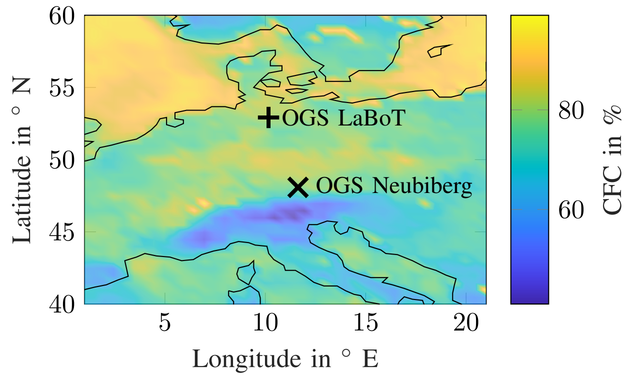

Fig. 5. One-year average CFC over Central Europe [13].

For the downlinks we have taken into account the obscuration of the optics when calculating the Rx antenna gain. The optical losses at the OGS have been verified experimentally. Considering state-of-the-art data receivers based on avalanche photodetectors [11] the received power on detector values allow for enough margin to achieve $1\,\mathrm{Gb/s}$ transmissions from and $100\,\mathrm{Mb/s}$ transmissions towards LEO (ATHENE-1 down-/uplink). In the GEO scenario signal strength is significantly reduced; however, the GEO LCTs usually implement coherent modulation schemes providing additional gain.

IV. Availability and Visibility Analysis

A central feature of FSO communication is its reliance on a free line-of-sight (LOS) between the terminals, which is easily impeded by environmental barriers. Local surrounding conditions at the location of our OGS in Neubiberg, Germany, are advantageous so that elevation angles down to $5°$ are possible in all directions without any blockage. Fig. 3 shows the visible geostationary arc from our OGS. This allows the connectivity to GEO satellites on orbits between $80°$ E and $60°$ W. With $140°$ in total, a huge part of the geostationary arc lies in the filed of view leading to a high flexibility in the choice and the number of GEO satellites that can be covered. To give an example, the LCT on Alphasat (see [12]) at $25°$ E is seen at an elevation angle of $33.3°$.

Local wind conditions are summarized in a box plot in Fig. 4. The plot contains data points from two years of measurement. Each data point constitutes a 10-minutes average. The median of the monthly wind speeds do not exceed $10\,\mathrm{km/h}$. The threshold for the station protection system to enter a save mode of operation where the dome automatically closes is at $40\,\mathrm{km/h}$. With only a few extreme outliers, mainly in winter and some in autumn, the OGS can be safely operated almost over the entire year.

Assuming LOS between the terminal and the satellite without any ground-based obstacles, cloud covering access to the ground station is then the major restraint. In addition, atmospheric attenuation and IRT impair the optical carrier inducing vibrant signal fading. To assess the expected availability of the optical link in Neubiberg, Germany, the average local weather conditions are briefly discussed in the following.

Fig. 5 shows the average CFC in 2016 over Central Europe. The map has been generated using satellite weather data from EUMETSAT [13]. The map shows that, on an average basis, a CFC between $60\,\%$ and $80\,\%$ must be expected, basically independent of the location in Central Europe. However, areas in high altitudes like the Alps experience generally less cloud coverage than areas in lower altitudes.

Fig. 6 shows the monthly CFC for the location of our OGS in Neubiberg, Germany. The data show a median value from $60\,\%$ to $80\,\%$, with the lowest values within the summer months and the highest values in winter season. In comparison to RF based transmissions, FSO communication is, therefore, usually considered unreliable, which currently prevents the admission of optical LEO or GEO space-to-ground links, in particular in the scope of military applications. Nevertheless, the need for higher bandwidths has led to the development of various strategies to reduce the disadvantages associated with free-space optics, like the utilization of forward error correction (FEC) and signal interleaving to correct for atmospheric disturbances. Mitigation of availability constraints due to cloud coverage could be realized by a network of OGSs at meteorologically convenient locations. The establishment

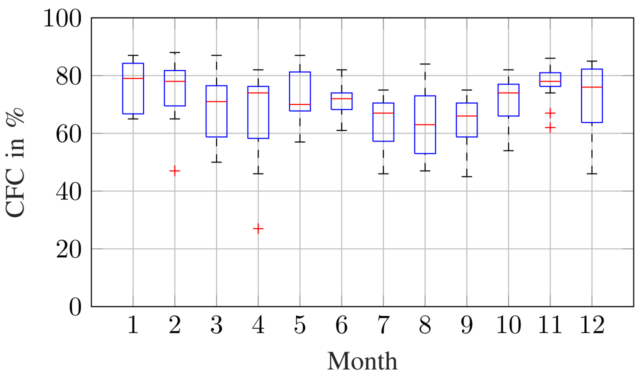

Fig. 6. Box plot of monthly CFC between 2004 and 2017 at Munich.

of robust, remotely monitored and controlled OGSs is a prerequisite to implement such a site diversity scheme. With the LaBoT from the German Aerospace Center in Trauen, Germany, which is approximately 650 km far off Neubiberg, a second OGS already exists (see again Fig. 5). Another example is the OGS in Almería, Spain, [14]. The station in Almería is already part of the European Optical Nucleus Network, an initiative between Space Agencies and industry to realize a network of geographically distributed OGSs [15]. With such a network of OGSs one can gain the necessary operational experience and allow appropriate site diversity measurements. Optical link outage analysis as shown in [16] or [7] can be validated by measurements, and novel site diversity schemes can be developed and tested.

V. Conclusion

We have presented the technical details and current status of the optical ground station (OGS) in Neubiberg, Germany, that will be implemented in the frame of the satellite mission Seamless Radio Access Network for Internet of Space (SeRANIS). Full operational capability (FOC) of this OGS is planned in the fourth quarter of 2023. Together with the laser communication terminal (LCT) onboard the satellite ATHENE-1, the main purpose of this OGS is to establish a high-speed data up- and downlink, and to realize a free-space optical (FSO) communication testbed supporting end-to-end over-the-air (OTA) experiments. Further research topics include optical channel measurements, and the planned enhancements of the station will allow communication based on coherent modulation schemes as well as space-based quantum key distribution (QKD) experiments. As one part of multiple laboratories in the frame of SeRANIS, this OGS provides an excellent research facility that is open for the space community to support OTA test and demonstration activities of new equipment or conducting of experiments.

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