

Latest news from FOGATA – Deployment of the fully automated DLR OGS in Almeria and first results with optical DTE communication

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Abstract

For many decades the RF spectrum remains highly prized, so much that various applications and systems have to share the same spectrum and regularly interfere with each other. With constant technical advances, higher frequency bands were regularly becoming attainable, thus relieving a bit the pressure on the RF spectrum usage. But each further step requires new equipment, and can only be solved for ground-based systems but not on-board. And it does not really solve one of the main drawbacks of RF based telecommunication which is that RF emissions are “visible” over larger areas. Therefore, the number of sources using the same spectrum within an area remains limited and this in turn restricts telecommunications.

Optical communications (OC) offer solutions to the problems encountered in RF which will improve sustainability of telecommunications in the future: particularly high directivity, optical spectrum mostly free. But it is highly sensitive to any disturbance in the line of sight. This explains why inter-satellite links are more and more prized and used, since conditions in space are favourable for OC.

Direct-To-Earth (DTE) OC remains particularly challenging with weather at the Earth’s surface. Here the classical RF approach with contacts between spacecrafts and ground stations almost 100% ensured does not apply anymore and requires completely new concepts for operations.

The DLR German Space Operations Center (GSOC) took up the challenge for a DTE OC testbed and deploys FOGATA (Free-Space Optical Ground Antenna TABernas) in Spain during the winter season 2024-2025. This station aims to achieve high-quality, high precision optical downlinks with a state-of-the-art telescopic system built with COTS equipment.

In this paper, after shortly introducing OC and its challenges, we detail the latest steps undertaken to install the DLR FOGATA in Spain. Our concepts for fully remote operations adapted to optical communication will be described. We will then present our first downlinks achieved with this telescope and assess the results. To conclude, we will demonstrate operations of FOGATA within a network of several OGS like the ESA European Optical Nucleus Network (EONN).

Keywords: DLR, GSOC, FOGATA, Optical Communications, Ground Station, EONN

Acronyms/Abbreviations

| | |
|--------|---|
| CCSDS | Consultative Committee for Space Data Systems |
| DLR | German Aerospace Agency |
| DTE | Direct-To-Earth |
| EONN | European Optical Nucleus Network |
| FOGATA | Free-Space Optical Ground Antenna Tabernas |
| GSOC | German Space Operations Center |
| GSSNG | Ground Station Scheduling Next Generation |
| LPD | Low-probability-of-detection |
| LPI | Low-probability-of-intercept |
| LEO | Low Earth Orbit |
| MOC | Mission Operations Center |
| NOC | Network Operations Center |
| O3K | Optical On-Off Keying |
| OC | Optical Communications |
| OGS | Optical Ground Station |
| QBUS | GSOC in-house messaging system |
| QORE | QBUS Core Framework |
| RF | Radio Frequency |
| SOFA | Small Optical Ground Stations Focal-Optics Assembly |

1 Introduction

1.1 Motivation for optical communication

The exponential growth of satellite launches and the constant increase of satellite data production for high-resolution Earth observation, scientific missions, deep space exploration, and satellite constellations have significantly raised the demand for a high-throughput Direct-To-Earth (DTE) communication. Common radio-frequency (RF) systems may be the most mature and reliable technologies but they are increasingly constrained by spectrum congestion, limited bandwidth, and new regulations. Optical communication (OC) offers a huge progress in data transmission capacity while almost removing any congestion problems. Its technology uses modulated laser beams in the near-infrared spectrum to support optical links with data rates of up to several tens or hundreds of Gbps under ideal conditions, far exceeding those of conventional RF systems. This makes possible near real-time transmission of large datasets, a critical need for upcoming satellite missions.

Furthermore, miniaturization of spacecrafts requires compact, low-power communication systems. Optical terminals offer high data rate per unit mass and power, making them ideal for modern space to ground communication.

If we continue the comparison with RF, in addition to low power consumption, compactness and high data rates, OC also has the following advantages:

- wider modulation bandwidths
- Higher spectral efficiency
- Simpler modulation (both SDA and O3K rely on On-Off-Keying)
- Low-probability-of-intercept (LPI)
- Low-probability-of-detection (LPD)
- No spectrum congestion

1.2 Key Challenges

Despite this long list of advantages, DTE OC faces unique challenges caused primarily by the properties of the Earth's atmosphere, the narrow beam widths of OC, and the strong dependence on weather conditions.

1.2.1 Atmospheric disturbances: weather conditions, turbulence, and scattering

One of the most critical limitations for DTE OC is sensitivity to atmospheric conditions. Weather conditions, particularly clouds, are an absolute blocker, rendering the link impossible during overcast conditions. Even thin clouds or high-altitude cirrus layers can scatter or attenuate the signals and degrade significantly the link, when not leading to a complete link loss. Other weather events like rain, fog, snow, haze and high humidity are all degrading or even blocking the optical path, as with clouds. Atmospheric turbulences, another limitation to DTE OC, affect the refractive index along the optical path. This results in beam scintillation, wander, and wavefront distortion. Any can degrade the

received signal quality and increase error rates unless compensated for. The third main problem is scattering and absorption of the laser beam, which are caused by aerosols, dust, and humidity, especially at lower elevation angles.

Overall impact from these disturbances is highly variable and requires the combination of real-time monitoring with weather forecasting to optimize link scheduling and operation. It is also possible to mitigate impact by deploying networks of ground stations in geographically diverse locations to ensure that at least one site has clear skies during a scheduled pass.

1.2.2 Pointing Accuracy and Tracking

Laser communication systems require extremely high pointing accuracy due to the narrow divergence of optical beams. Even minor misalignment can lead to complete loss of signal, unlike with RF systems. Tracking a LEO satellite, for example, requires the optical ground station (OGS) to follow very fast angular velocities with high precision. Additionally, the relative motion between the satellite and the ground creates Doppler shifts, fast-changing line-of-sight vectors, and the need for highly precise acquisition and tracking systems that can dynamically correct for deviations in real time. This obliges OGS to use high-resolution encoders, fast feedback loops, predictive orbital models, and in some cases, optical beacon acquisition systems to maintain a stable link. In fact, any latency in the control system can affect strongly the link performance.

1.3 Objectives

We will describe in this paper the plan of action to install FOGATA (Free-Space Optical Ground Antenna Tabernas), our OGS, in Spain. We will detail already executed tasks as well as mention which are still pending, since at the time of writing transport of FOGATA from Germany to Spain is still in preparation but not finalized. We will also describe our concepts for fully remote operations adapted to OC. We will then present our connectivity with the ESA European Optical Nucleus Network (EONN) to allow foreign scheduling of our OGS as part of a larger OGS network.

2 Deployment of FOGATA in Spain

2.1 Tabernas

As established previously, weather disturbances may block fully the DTE link on a regular basis. This might be prevented by using weather forecasting as well as real-time observations. If using forecasting, we can actually identify on a large time scale as well as on a large geographic scale where weather conditions are more favorable for an optical link from a satellite to the ground. The selected site in Spain, near the city of Tabernas in the region of Almeria, was carefully chosen after this in-depth analysis of critical environmental factors, aiming to optimize the availability and reliability of DTE OC.



Fig. 1 Map of Spain showing the location of FOGATA near Almeria (source: Google Maps)

One of the key considerations was in fact the frequency of clear skies. OC requires a direct line of sight with as little as possible atmospheric interference. Therefore, the site's high percentage of cloud-free nights throughout the year was a major advantage. This was established using the cloud fractional coverage measurements as depicted in Fig. 2). Additionally, the location is in an area with exceptionally low levels of light pollution. This reduces background noise in the optical spectrum and improves the signal-to-noise ratio for faint satellite signals, particularly during low-elevation passes.

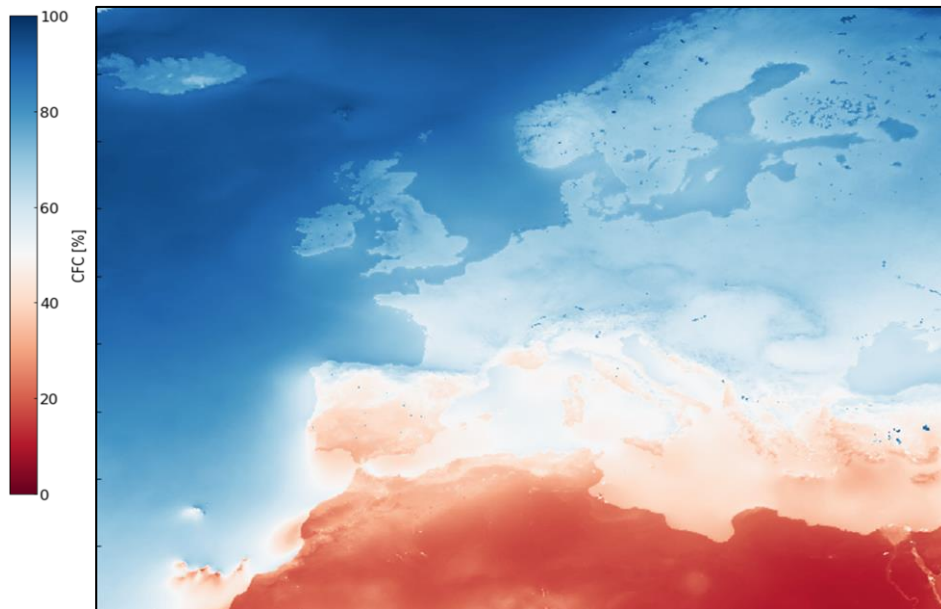


Fig. 2 Cloud Fractional Coverage in Europe (EUMETSAT, 2022)

Altitude also played a key role. The future location of FOGATA in Tabernas is relatively high, which minimizes atmospheric attenuation and turbulence by placing the optics above the denser and humid atmosphere, not to mention that orography is isolating the site (Sierra Alhamilla and Sierra de Filabres are surrounding), and the desert of Tabernas in general, from humid winds of the Mediterranean Sea. This results in improved link quality, greater stability, and reduced beam wander. Tabernas stable weather patterns, its low wind conditions and minimal temperature variation, further support reliable optical tracking and data acquisition from LEO satellites.

In summary, Tabernas offers the combination of meteorological, environmental, and atmospheric conditions which makes it ideally suited for our purpose of establishing DTE optical links.

2.2 Infrastructure on site

One of the main strategies behind FOGATA was to use mostly COTS components in order to lower costs and engineering while increasing the possibility to grow easily an OGS network. At the core of FOGATA is an optical telescope from Astelco, featuring a high-quality reflective design with an aperture of 60cm capable of collecting and focusing light from LEO satellites. The telescope is mounted on an alt/azimuth tracking system from Planewave that allows for precise positioning using high-resolution encoders and for real-time alignment required when tracking LEO satellites. The whole is covered by a dome to protect from the elements whenever the OGS is not tracking.



Fig. 3 FOGATA dome in Tabernas

To establish communication with the LEO spacecrafts, the telescope is mounted with SOFA (Small Optical Ground Stations Focal-Optics Assembly), an assembly developed by DLR IKN, the DLR institute for Communication and Navigation (IKN). SOFA's carefully chosen components secure the following functionalities:

- Reception of optical downlinks in near infra-red wavelengths
- Observation with daylight camera
- Transmission of beacon signal
- Measurement of optical signal power

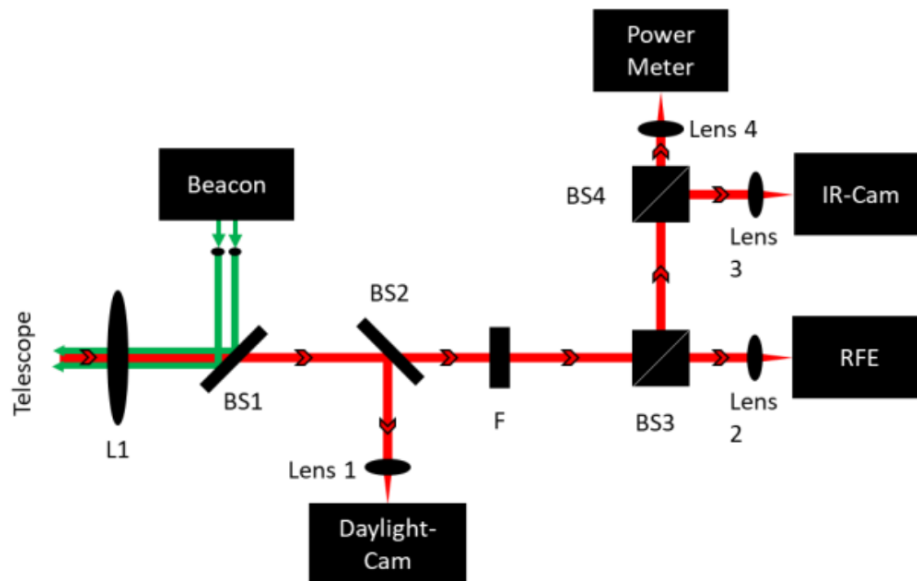


Fig. 4 Schematic beam path of the SOFA [1]

2.3 Monitoring and Control System

The Monitoring and Control (M&C) system, known as the QBUS core framework (QORE), was developed in-house and combines object-oriented programming principles with script-based workflows to enable automated operation of the OGS. Operating in a Linux environment, the system uses TCP/IP communication protocols for reliable data exchange. QORE integrates multiple components, including device drivers for the telescope subsystems, allowing

for continuous monitoring and control of each device. It features a web-based graphical user interface (GUI) that provides remote access for operational control and supervision. The system also incorporates alarm functionalities for fault detection and troubleshooting, as well as a local scheduler and sequencer that manage the automatic booking and execution of satellite passes. Additionally, a centralized database supports data management and logging. The system is capable of providing real-time tracking images, angular measurements and offsets, and power readings. Furthermore, when interfaced with a modem, it can also receive satellite payload data, enhancing its role in comprehensive optical ground station operations.

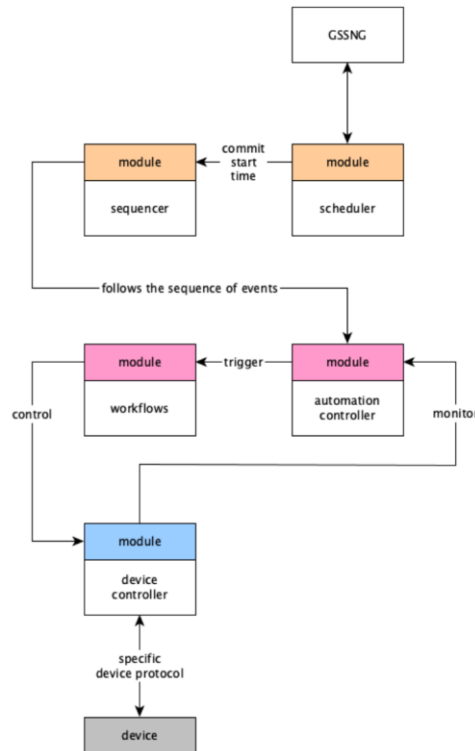


Fig. 5 Overview of QORE layers: schedulers => automation => device modules [2]

2.4 Scheduling system

FOGATA, more specifically QORE interfaces with GSOC scheduling tool GSSNG, which stands for Ground Station Scheduling Next Generation. GSSNG serves as the central coordination point between satellite missions and ground stations, in other words as operational hub where missions request contact windows and services from various ground stations to establish links with spacecrafts, while aiming at standardizing the scheduling process. GSSNG is the DLR central tool for all customers, whether DLR internal or external, to plan all telemetry, tracking & commanding (TT&C) activities and provides also planning for all other service categories within satellite communication (e.g. payload data reception, ranging, doppler). It differs from the legacy scheduler software which coordinated between missions and ground stations typically via email and was restricted to normal working hours. GSSNG replaces this outdated system, modernizing both the scheduling process and the coordination mechanisms between missions and ground stations. The key objective of GSSNG is to automate the scheduling workflow as much as possible, from distributing service package requests to resolving conflicts, ultimately enabling continuous 24/7 operations. Additionally, GSSNG establishes automated interfaces between itself and all supported missions, as well as between itself and the participating ground stations. To support this, a CCSDS (Consultative Committee for Space Data Systems) standard has been developed in collaboration with major international space agencies including ESA, NASA, JAXA, and others. This is the “chapter 902” of CCSDS which defines a standardized scheduling interface, ensuring that all ground stations worldwide can seamlessly interact with scheduling systems in a unified and interoperable way. [3] [4]

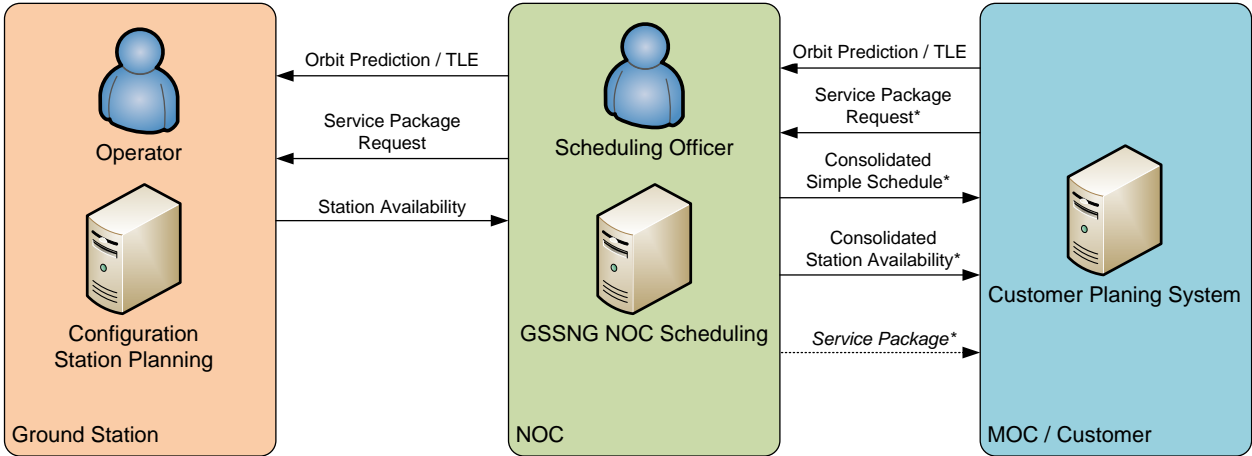


Fig. 6 GSSNG main scheduling interfaces

As a mission operator, your experience starts as a user/client connecting either via GUI or CCSDS interface to the system. You send service package requests, which GSSNG forwards to the requested ground stations. Then GSSNG collects confirmations and/or rejections from requested antennas and answers to you, the user/client.

The screenshot shows the GSSNG front end GUI with a table of confirmed service packages. The table has columns for various fields including ServicePackageID, RequestID, Comment, Spacecraft, Status, Project, Station, Antenna, BoA, EoT, and Es.

| Select | ServicePackageID | RequestID | Comment | Spacecraft | Status | Project | Station | Antenna | BoA | EoT | EoT | Es | Logs | |
|--------------------------|-----------------------------|--|-----------------------|------------|-----------|------------|---------|---------|-----|---------------------|---------------------|---------------------|---------------------|--------------|
| <input type="checkbox"/> | GSSNG-rrv-04p-1678366729332 | 0055ScheduleRequest_BOIS_CW18_20230401T084729-EE-1678366727076 | OFFLINE ONLY HR NR154 | BOIS | scheduled | BIROS_pjrq | WHM | | 569 | 2023-04-23 07:48:28 | 2023-04-23 08:06:29 | 2023-04-23 08:16:34 | 2023-04-23 08:21:04 | BIROS_NOMINA |
| <input type="checkbox"/> | GSSNG-rrv-04p-1678366729538 | 0055ScheduleRequest_BOIS_CW17_20230413T123217-EE-1678366727087 | HR NR154 | BOIS | scheduled | BIROS_pjrq | WHM | | 567 | 2023-04-24 07:20:38 | 2023-04-24 07:40:38 | 2023-04-24 07:50:28 | 2023-04-24 07:55:28 | BIROS_NOMINA |
| <input type="checkbox"/> | GSSNG-rrv-04p-1678366729531 | 0055ScheduleRequest_BOIS_CW17_20230413T123217-EE-1678366727087 | HR NR154 | BOIS | scheduled | BIROS_pjrq | WHM | | 569 | 2023-04-25 08:50:48 | 2023-04-25 08:22:46 | 2023-04-25 08:31:57 | 2023-04-25 08:36:57 | BIROS_NOMINA |
| <input type="checkbox"/> | GSSNG-rrv-04p-1678366729532 | 0055ScheduleRequest_BOIS_CW17_20230413T123217-EE-1678366727087 | HR NR154 T4 TO EUC | BOIS | scheduled | BIROS_pjrq | WHM | | 567 | 2023-04-28 08:45:17 | 2023-04-28 08:05:17 | 2023-04-28 09:12:25 | 2023-04-28 09:17:25 | BIROS_NOMINA |
| <input type="checkbox"/> | GSSNG-rrv-04p-1678366729533 | 0055ScheduleRequest_BOIS_CW17_20230413T123217-EE-1678366727087 | OFFLINE ONLY HR NR154 | BOIS | scheduled | BIROS_pjrq | WHM | | 569 | 2023-04-30 07:52:56 | 2023-04-30 08:12:56 | 2023-04-30 08:22:23 | 2023-04-30 08:27:23 | BIROS_NOMINA |
| <input type="checkbox"/> | GSSNG-rrv-04p-1678366729955 | 0055ScheduleRequest_BOIS_CW18_20230401T125642-EE-1678366727119 | HR | BOIS | scheduled | BIROS_pjrq | WHM | | 569 | 2023-05-01 07:27:13 | 2023-05-01 07:47:13 | 2023-05-01 07:57:03 | 2023-05-01 08:02:03 | BIROS_NOMINA |
| <input type="checkbox"/> | GSSNG-rrv-04p-1678366729956 | 0055ScheduleRequest_BOIS_CW18_20230401T125642-EE-1678366727119 | HR | BOIS | scheduled | BIROS_pjrq | WHM | | 567 | 2023-05-01 08:09:14 | 2023-05-01 08:29:14 | 2023-05-01 08:36:13 | 2023-05-01 08:43:13 | BIROS_NOMINA |
| <input type="checkbox"/> | GSSNG-rrv-04p-1678366729957 | 0055ScheduleRequest_BOIS_CW18_20230401T125642-EE-1678366727119 | HR | BOIS | scheduled | BIROS_pjrq | WHM | | 569 | 2023-05-05 07:17:18 | 2023-05-05 07:37:18 | 2023-05-05 07:47:19 | 2023-05-05 07:52:19 | BIROS_NOMINA |
| <input type="checkbox"/> | GSSNG-rrv-04p-1678366729958 | 0055ScheduleRequest_BOIS_CW18_20230401T125642-EE-1678366727119 | OFFLINE ONLY HR | BOIS | scheduled | BIROS_pjrq | WHM | | 569 | 2023-05-07 07:59:06 | 2023-05-07 08:19:06 | 2023-05-07 08:28:25 | 2023-05-07 08:33:25 | BIROS_NOMINA |

Fig. 7 GSSNG front end GUI with various confirmed service packages

3 Concept for remote operations

3.1 Requirements for FOGATA

In today's era of remote operations and low human interactions, it was obvious that DLR opts to operate FOGATA remotely and autonomously. Beside these two pillars for modern ground station operation, DLR required that FOGATA shall be integrated into the existing GSOC Network Operations Center (NOC) in the same way as any other DLR RF ground station would be, more precisely FOGATA is to appear to the customer like another antenna from our Weilheim ground station (WHM). These 3 points translated into the following requirements on our OGS:

- Autonomous operations
- Automated scheduling using same scheduling system as for WHM
- Remote monitoring and control capability
- Tools accessibility from WHM control center

3.2 *Selected solutions*

Autonomous operation is ensured by QORE, described in the previous chapter, which provides monitoring and control of the OGS without human in the loop. Of course, QORE is provided with a GUI remotely accessible, in case the WHM team needs to monitor and/or control the station manually.

Automated scheduling is secured through GSSNG, its interfacing module towards QORE and its counterpart in QORE. Based on the service package requests sent from GSSNG to QORE, FOGATA autonomously handles conflicts and accepts mission timelines and satellite ephemerides in formats such as CCSDS OEM [5] or TLE. It then automatically calculates acquisition windows, adjusts telescope pointing, and executes tracking sequences.

Remote monitoring and control are done through:

- Automated logging of monitoring parameters and task executions
- Remotely accessible GUIs with the help of specific network configuration.

3.3 *Adaptations specific to Optical Communication*

In the previous subchapters, we have addressed the requirements on FOGATA and the need to have this OGS as similar as possible to RF counterparts. OGS have also some specific requirements on top of the ones already discussed. Fine pointing is one of them and is typically solved with the mount using OEM as orbital elements for tracking instead of TLE which are less precise.

In addition to finer pointing requirement, OGS suffer from lower atmospheric conditions which may impair direct-to-earth (DTE) OC links [6]. When these links traverse the Earth atmosphere, signal transmission is affected by attenuation and scattering. Atmospheric attenuation, considering both molecular absorption and aerosol-related scattering and absorption, impact more or less severely wavelengths used for OC, along with link geometries. Many studies were realized to enable more reliable and efficient deployment of optical communication technology for space applications. To solve at least partially these issues, FOGATA focusses on improving responsive operations planning by allowing rapid changes in OGS schedule. For this, integrating weather prediction and local weather observation within the planning tool used by the mission operations center will be a key.

4 **Integration into ESA EONN Network**

The successful integration of our optical ground station into the ESA European Optical Nucleus Network (EONN) represents a significant milestone in the evolution of operational optical space-to-ground communication. EONN is ESA's framework for a collaborative, distributed network of optical ground stations designed to increase the availability, resilience, and capability of OC services for European and international missions.[7]

4.1 *Role and Benefits of Station Interoperability*

A key feature of EONN is the interoperability between participating stations, achieved through harmonized operational protocols, interface compatibility, and centralized coordination systems. This interoperability brings several important operational benefits:

- **Redundancy:**
In case of local weather issues, technical problems, or maintenance at a specific station, other network stations can take over scheduled service packages. This increases robustness and reliability of OC services.
- **Availability:**
OC is highly weather-dependent. By distributing ground stations across different geographical locations, EONN maximizes the chances of at least one station having proper atmospheric conditions at any given time. This leads to a significant improvement in operational availability compared to single-site solutions.
- **Global coverage:**
As the network expands, it will offer a coverage more and more important for OC, enabling additional opportunities with satellites. This is critical for LEO missions where contact times are limited.

4.2 *Network coordination and scheduling*

The initial Nucleus Network brings together OGS operated by ESA in Tenerife (Spain), TNO in The Hague (Netherlands), KSAT in Nemea (Greece) and DLR with our FOGATA in Almeria (Spain). These stations are all linked to the KSAT NOC in Tromsø, Norway, which also oversees KSAT's global network of 200 radio antennas across 22 locations. For users, this setup offers the convenience of a single operational interface, eliminating the complexity of coordinating with multiple ground stations and managing separate systems. Satellite contacts are booked via a KSAT central scheduling platform that accounts for satellite orbital parameters, weather forecasts, and operational availability across all participating stations. Conflicts are resolved automatically or via operator interaction, and contact times are dynamically adjusted based on real-time weather data. [8]

4.3 First Multi-Station Operations

Following integration and verification phases, FOGATA participated in its first attempt of coordinated multi-station operations. Tests involved several tracking and downlink campaigns of a spacecraft by the 4 initial EONN stations and it is important to mention that FOGATA took part from its preliminary location: on the roof of DLR GSOC in Oberpfaffenhofen. At the time of writing, FOGATA is waiting for the final checks before it will be sent to Spain. This should take place within the next months of 2025.

The campaign's primary objectives were to assess the network's ability to coordinate downlinks using a standardized interface and to establish OC links with a fast-moving LEO satellite. Our station successfully delivered both real-time tracking data and signal measurements.

Tests demonstrated the benefits of a network of OGS for OC, from higher data amounts gathered to higher flexibility and contact reliability. These initial results confirm the value of a distributed optical ground station network and validate the operational readiness of our station within EONN.

5 Conclusion

FOGATA development and commissioning mark a significant step forward in advancing operationalisation of DLR OC capabilities and in a broader way of German and European OC capabilities. Through this project, several key milestones have been achieved:

- Successfully system and subsystem verification and validation from the preliminary location in Oberpfaffenhofen
- Achievement of the major operational objective with fully (simulated) remote-controlled operations
- Successful tracking and evaluation of optical downlinks, also allowing measurements of OGS performances under various atmospheric and operational conditions.
- Integration of FOGATA into the ESA European Optical Nucleus Network (EONN) as a participant and enabler of multi-station coordinated operations with improved link availability, redundancy, and operational flexibility.

Looking ahead, the first main goal will be to install FOGATA at its main location near Tabernas, Spain, and to undergo on site acceptance tests. Several system upgrades and technology enhancements are also under consideration to further improve the station's performance and broaden its capabilities:

- High speed data handling: the OC will receive adequate high-rate data handling systems to receive, archive and deliver payload data to its customers.
- Establishment of FOGATA as a permanent and integral part of international optical communication networks. This includes further collaboration within ESA's EONN framework and readiness for future interoperability with other initiatives.

By continuously improving technical capabilities and operationalisation, we aim to contribute to the development of standardized, scalable, and secure optical communication infrastructures supporting both commercial and institutional missions. This vision places FOGATA not only as a national asset but also as a reliable actor ready to support emerging global markets with high-data-rate, low-latency direct-to-Earth optical communication links.

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