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The European Optical Nucleus Network

Martin Krynitz[a]*, Clemens Heese[b], Marcus Knopp[c], Klaus-Jürgen Schulz[b], Hennes Henniger[a]

[a] *Kongsberg Satellite Services, Prestvannveien 38, N-9291 Tromsø, Norway*
[b] *ESA / ESOC - European Space Agency, Robert-Bosch-Straße 5, D-64293 Darmstadt, Germany*
[c] *DLR / GSOC – German Space Operations Center, Münchener Str. 20, 82234 Wessling, Germany*
* Corresponding Author

Abstract

As terrestrial data transmission capacity has been growing quickly, spacecraft to Earth data-rates also need to increase to enable new applications. While K-band (26 GHz) payload data links become a commodity offering multiple Gbps data rates for future Earth Observation missions from Low Earth Orbit, e.g. for the Copernicus program, increasingly stakeholders are looking into optical solutions for spacecraft to ground data links with the expectation of 10 Gbps and multiples thereof. However, the development of optical communications from space to ground has been slow due to the lack of an operational and reliable ground segment that can receive data at multiple locations, mitigating the link blockage by clouds, integrate it in the cloud and make it available to the end user in near real-time. All this within a competitive cost level compared to traditional radio frequency (RF) services. The European Optical Nucleus Network is an initiative between Space Agencies and industry to over-come the lack of availability of an optical ground station network. This is achieved by creating a multi-site, multi-mission network which supports common CCSDS standards and space-terminal implementations available to spacecraft operators with optical communication systems onboard. The idea is that participating parties contribute operations time on self-funded optical ground stations to an integrated ground station network that is made available to the space community as a service. The initial European Optical Nucleus Network consists of optical ground stations from ESA-OPS on Tenerife (Canary Islands), DLR-GSOC in Almeria (Spain) and KSAT in Nemea (Greece). These will be connected to the KSAT network operations center (NOC) in Tromsø that also controls KSAT's 200 RF-antennas on 22 sites around the globe. From a user perspective this allows a single point of contact and frees the user from managing multiple sites and integrating these through different interfaces. The European Optical Nucleus Network will be the first operational ground station service of its kind made available to the market. Challenges in establishing these initial stations have been multiple. A lack of standards has meant that technologies like multi-mission modems, beacon lasers and optical detectors have not been available off-the-shelf and proprietary solutions become cost drivers. The ground station design, while different for each Nucleus station, focuses on using commercial-off-the-shelf components, where available, to build stations that are cost compatible to radio frequency solutions, e.g. by using low cost but observatory-grade telescopes. Also, robotization of operations is essential. During 2021 the first three Nucleus stations will be installed and connected to the Tromsø NOC. Focus will be on gathering operational experience to guarantee a stable service that can compete with traditional RF operations. The DLR/Tesat PIXL-1 mission will be used for testing the network using first operational concepts, and the first customer will be the TOSIRIS 10 Gbps laser-terminal onboard the Bartolomeo platform on the International Space Station in 2022. Once the market develops the network can quickly be expanded globally based on the experience gathered from earlier stages. Besides for LEO missions, the Nucleus network is also planned to be tested for Lunar missions, as optical technology enables data communication that is more cost efficient than traditional RF solutions. This is since optical solutions allow a significant reduction of the necessary transmit and receive aperture diameter for the same or even higher data-rates as the laser signal has a more focused footprint.

Keywords: (Optical Communications, Lunar Communications, Ground Station Network)

1. Introduction

The increasing amount of data generated by low Earth orbit (LEO) spacecraft and the lack of available spectrum in the traditional downlink bands, especially X-band, requires new high-rate communication technologies. To this end, free-space optical (FSO) communications has the potential to outperform radio frequency (RF) systems. The advantages of optics are that download speeds can be in the tens or even hundreds of Gbps and frequency licensing as well as signal interference are less of an issue than for RF. [3,4]. Besides that, communication terminals in space and on ground are much smaller, more lightweight and consume less power than RF terminals. Also, at long communication distances the smaller beam spread offered by optical frequencies becomes an advantage [1].

Disadvantages of FSO are the lack of standardization and lack of cost-effective turn-key ground station equipment as well as the sensitivity of the optical equipment to environmental influences like dust and humidity. Additionally, FSO links strongly suffer from atmospheric effects on the beam propagation through the Earth atmosphere [5,6,8]. Links can not only be temporary blocked by clouds but also under clear-sky conditions they suffer from strong signal fading due to atmospheric turbulence. Therefore, the Concept of Operations (CONOPS) of a mission is mainly affected, since the non-deterministic downlinks demand a higher flexibility from mission planning and satellite control.

Nevertheless, we see a global interest in using optical space links. While intersatellite links will be their most natural application, they are also useful from satellite to the ground (S2G). Driver of this trend are new space companies that are bothered about their future data volumes being handled by RF-only solutions. Hence, several CubeSat builders are integrating optical downlink capabilities into their platforms on the backdrop of the advantages that optical technologies offer onboard of the satellite (smaller, lighter, cheaper). If FSO S2G communications stand the test with these risk-taking players, it will most probably become accepted in the traditional Agency driven arena. For instance, the Copernicus Program is studying optical links for future generations and is using the European Data Relay Satellite (EDRS) system for optical inter-satellite-links already.

Still, over the past decade the community has been confronted with a chicken and egg problem: due to the lack of a ground segment, the FSO space segment does not develop at the desired pace and due to the low number of satellites flying, an FSO ground segment investment cannot be motivated. Further, due to the experimental nature of the first flying optical payloads the operational budget is missing to pay the first optical ground stations for their services. Nevertheless, optical downlinks have the potential to become an essential part of data downlinks especially in the new-space domain.

This paper discusses first the challenges on the way of setting up an optical ground station network followed by presenting key parameters of the European Nucleus network optical ground stations currently being established as the first of their kind. In Chapter 4 an outlook of the long and near-term future development of the European Optical Nucleus Network is presented.

2. The European Optical Nucleus Network

The above-mentioned chicken and egg problem has been identified by both Space Agencies and industry and led to the establishment of the European Optical Nucleus Network. This is an informal collaboration where different organisations have agreed to self-fund optical ground stations and to connect them into one network. All partners have been aligning each other in terms of technical parameters and services to offer to make available a consolidated ground station capacity. The network is made available to those interested in operating FSO S2G links and omit the need to procure a dedicated ground segment for a single mission. The European Optical Nucleus Network gives access to multiple optical ground stations through a single interface and makes RF resources available if required. The founders of the network are ESA ESOC, DLR GSOC and KSAT. The entire network will be available by beginning of 2022. All parties agree to have an interoperable multi-mission approach based on CCSDS (The Consultative Committee for Space Data Systems) standards.

3. Challenges

Prior to this European Optical Nucleus Network initiative optical ground stations were only experimental and scientific. In this chapter we discuss the challenges in establishing an operational optical ground station network mature enough to fulfil operational needs.

3.1. Licensing

Even if it is communicated that optical communication is license free this is not fully true. While no license is needed for receiving optical signals from space, the ground beacons that are normally required to better align the space and ground terminals to each other [2], make the optical ground stations (OGS) to become active systems radiating laser beams. Radiation of high power laser signals (typically several Watts in the optical L-band) triggers laser safety regulations (i.e. aviation safety, work safety, etc. to minimize the risk of laser accidents, especially those involving eye injuries) that must be fulfilled and usually also requires approval by the authorities.

While getting RF licenses is an internationally well-established process, approval to use laser ground beacons is not well defined and, therefore, potentially more complex and time consuming than RF licensing. For example, if active monitoring of the sky for flight traffic should be required, this can add substantial operations cost.

3.2. Cost Miss-Match

While RF ground stations for a few hundred thousand Euros can provide downlink rates of up to 3.5 Gbps in Ka-band (2.8m reflector-antenna), optical systems today often do not provide significantly more downlink rate (e.g. the maximum rate according to the upcoming CCSDS O3K standard is 10 Gbps per wavelength-channel) but come with the drawback of frequent link outages caused by cloud blockage and strong signal variability by fading [8]. To be competitive with RF it is important to find ways to keep the CAPEX for an OGS in the same range or lower than for a RF ground station.

Presently, the only way to reach the cost target is making use of MOTS (modified commercial of the shelf products). While observatory telescopes and telescope gimbals are normally optimized for observation or imaging, the goal of the OGS is to build a stable photon bucket focusing the light from the space terminal onto an optical detector. That means the gimbal must operate at angular speeds necessary for tracking LEO satellites. The telescope and the optical alignment need to be stable over a wide range of temperatures and sun illumination conditions. This requires modifications to the available commercial of the shelf (COTS) optical systems.

3.3. Multi-Mission Approach

Each RF ground station operator knows the importance of having multi-mission ground stations to minimize mission specific equipment. In the RF domain this is relatively simple as downlink schemes are fully standardized and software solutions (e.g. software defined radios) take over more and more and replace dedicated, expensive hardware solutions.

A full standardization through all layers of communication (Physical Layer, Coding & Synchronization, Data Link Protocol) is still missing for FSO space communications but is on its way through CCSDS (CCSDS 141/142). The current lack of standards makes it complicated to build a multi-mission OGS serving all space terminals. The only thing which is agreed and widely accepted to be non-proprietary is collecting the light coming from the satellite with telescopes of 40 cm to 80 cm clear aperture, with the laser in the optical C-band (vacuum wavelength ranging from 1530.33 nm to 1567.13 nm). This frequency has the advantage of being the same as used in terrestrial optical communications, where a range of low-cost COTS components exist.

For the wide-angle acquisition beacon wavelength, the CCSDS O3K standardization as well its partial implementations (e.g. OSIRS by TESAT/DLR, SOLISS by Sony or Optel-μ by Thales) use different wavelengths and strategies [9,10,11].

In summary, the only common feature the present OGS can provide is collecting the light which is in the optical C-band coming from the space terminal and providing that light signal to the mission specific proprietary equipment. This still differs in data rates (e.g. current space terminal implementations support 100 Mbps to 10 Gbps), modulation schemes (OOK, PPM), synchronization and coding etc.

3.4. Lack of Operational Experience

While some reference optical ground station solutions are currently in "operation", these are built for the purpose of single mission support and scientific evolution of the downlink as well as for measuring channel behaviour. These ground stations rely on human-operator based operations and are not connected to a multi-mission Network Operations Centre. They do not operate autonomously and through remote operations. Therefore, no operational knowledge for regular, automated routine support is available.

The European Optical Nucleus Network addresses this and brings together the operational knowledge of agency and industry partners to exchange their experience and to build upon their knowhow in the decades-long support of fully automated RF passes.

3.5. Optical Modems

The availability of multi-mission modems is a key step in the shift from scientific evaluation of optical links focusing on the proof of concept towards an operational service making satellite payload data available to the customer on ground on a regular basis.

While in the RF domain coding and synchronisation standards are agreed and various COTS modem implementations are available on the market, in the optical domain the standardization is still ongoing and optical space terminals of different suppliers use partly proprietary formats. This requires that the optical modem of a multi-mission ground station needs to include different modes. WORK Microwave took the challenge and developed a flexible MOTS optical modem (AR-80-OPT) which is currently used in the Optical Nucleus Network. This modem is based on a RF high availability technology and can support the currently flying OSIRIS space terminal family. Further, it can be re-programmed to support the upcoming CCSDS standard and other space terminals.

3.6. Optical Receiver

One could expect that optical on-off-keying detectors and receives for data-rates up to 10 Gbps are available for a low cost and with high maturity. However, todays terrestrial fibre communication works with much higher data-rates and industry does not provide many components for these relatively low data-rates. Unlike the terrestrial fibre-channel the FSO-channel is a fading-channel and the variation of the received power and the frequent interruption of the signal requires special implementations in the optical receiver. Additionally, compared to terrestrial fiber communication relatively large detectors are needed to ensure a good coupling efficiency from the telescope to the detector. This is because the atmosphere is distorting the optical signal when going through the atmosphere resulting in larger focal spots. The nucleus partners are currently testing different optical receiver solutions and sharing the results.

4. The Optical Nucleus Network Ground Stations

The Optical Nucleus Network shares optical ground station resources to make capacity available to multiple missions. This results in reduced cost compared to a mission dedicated network and reduces financial risk and investments necessary for the ground segment.

One advantage when combining optical ground stations is that site-diversity for cloud-blockage mitigation is achieved. As the Optical Nucleus Network is connected to the KSAT network operations centre in Tromsø (TNOC) for the mission-user only a single point of contact exists which handles the booking and scheduling of the optical ground segment. From a user perspective this frees the user from managing multiple sites and integrating these through different interfaces and communication lines. Further, RF antennas can be booked which will be required by most missions.

4.1. Technical Data Sheet

Specifications are summarized in Table 1 and a more detailed description is provided in the following sub-chapters.

Table 1: OGS Key Parameters

	Nemea	**Almeria**	**Tenerife**
Downlink wavelength support range	*1529-1569nm*	*1529-1569nm*	*1529.5-1568 nm*
Telescope main aperture diameter	*50 cm*	*60 cm*	*80 cm*
Elevation angle support range	*20° to 90°*	*10° to 85°*	*10° to 87° (LEO)* *10° to 89° (GEO)*
Max. operation wind speed	*15 m/s* *(18 m/s gust)*	*15 m/s* *(18 m/s gust)*	*14m/s*
Operational min. sun-distance	*20°*	*20°*	*TBC*
Tracking modes	*Program-track* *Auto-track*	*Program-track* *Auto-track*	*Program-track* *Auto-track*
Temperature operational range	*-15°C to 40°C*	*-5°C to 35°C*	*TBC*
Acquisition Beacon Source	*1589.3nm, 5W (peak)*	*1589 – 1591nm, 5W (peak) TBC*	*1591.26 nm, 5 W* *1590.4 nm, 8 W*
Acquisition beacon divergence angle *(1/e² full-angle)*	*632 μrad*	*1000 μrad* *TBC*	*500 μrad*
FoV of auto-track system	*8.5x6.8 arcmin*	*15x12 arcmin* *TBC*	*8.6 arcmin (diameter)*
Absolute pointing error*	*< 5 arcsec*	*< 10 arcsec*	*< +- 103 arcsec (99% confidence)*
Auto-track accuracy	*1 arcsec RMS* *max. error 3 arcsec*	*1 arcsec RMS*	*0.41 arcsec RMS*
Site (mean) clear-sky probability	*Summer: 80-95%* *Winter <60%*	*Summer: >75%* *Winter: >55%*	*81%*
Site long term average seeing	*Day: 2.7 arcsec* *Night: 3.6 arcsec*	*TBD*	*Day: 2.2 arcsec* *Night: 1.8 arcsec*
Site WAN connectivity	*10 Gbps*	*10 Gbps*	*10 Gbps*
Location coordinates	*Lat. 37°50'42.5"N* *Long. 22°37'24.0"E* *278.7 m above sea level*	*Lat. 37°5'36.3''N* *Long. 2°21'31,1''W* *498 m above sea level*	*Lat. 28°17'58.7"N* *Long 16°30'38.5"W* *2382 m above sea level*
Start of operations	*May 2021*	*Q2 / 2022*	*Q4 / 2021*

* pointing error is driven by orbit file (e.g. CPF or OEM) accuracy

4.2. ESA-ELRS: IZN-1

ESA ESOC initiated the development of a 2nd generation robotic optical ground station in 2017 for laser ranging (LRS) of satellites and space debris. This station consists of an 80 cm class astronomical Ritchey-Chretien telescope on a direct drive alt-azimuth mount, that is fast enough to reliably track LEO satellites and objects with arcsec precision.

The telescope supports four instruments to be mounted on Nasmyth foci. Switching between instruments is performed via a computer actuated mirror with highly repeatable angular positioning accuracy. One Nasmyth port is occupied for laser ranging and another one is used for optical communication.

In 2019, ESA decided to upgrade the laser ranging station (ELRS) with an optical communication instrument, complying to the CCSDS 141b1 standard on physical layer optical communication. The station in is called IZN-1 in optical communication mode, following ESA's naming convention of ESTRACK RF stations: Izaña is the mountain ridge on which the installation hosting Teide Observatory is located. The station specification is detailed in table 1.

The telescope is located in a dome that allows to open only a small moving slit centred around the telescope aperture, to avoid thermal distortion of the installation and degraded 'dome seeing' during daylight operation.

In optical communication mode, the station is designed to be laser-eye-safe. It will also be equipped with an optical aircraft detection system and related sensors to allow robotic and safe Class-4 laser operation.

This optical ground stations serves as a European reference implementation for a fully robotic, operational optical ground station with three fields of applications: satellite laser ranging, optical communication, and space debris observation.

The primary objective is to demonstrate that 1st generation optical ground stations can advance from astronomical observatories into fully integrated remote-controlled machines. It serves as a platform for ESA's industrial partners, to pioneer and test new concepts for 2nd generation optical ground stations, relying purely on machine-to-machine interfaces and is open for further activity proposals for automation and novel concepts. One of the first use-cases is the Optical Nucleus Network, integrating the station into the KSAT network operation centre (TNOC), enabling optical data return requiring only human intervention to scheduling link on the network.

4.3. Almeria Free-space Optical Ground Antenna Tabernas

DLR GSOC has been operating remote robotic telescope stations for a couple of years. Those stations are designed for the observation of objects in the geostationary regime contributing to the global optical sensor network SMARTnet™ [7]. They served as a blueprint for the OGS design.

First steps in the field of free-space optical space-to-ground communications have been taken with the implementation of a channel measurement system. It is based on a commercial off-the-shelve (COTS) astronomic telescope and a custom-designed optical bench carrying a couple of sensors to characterize laser links. Both, the SMARTnet™ sensors and the channel measurement system are remotely controlled by custom monitoring and control (M&C) software suites developed in-house or together with partner entities.

With the OGS Almeria, named Free-space Optical Ground Antenna Tabernas (FOGATA) after its location in the Andalusian semi-desert, DLR GSOC aims at the expansion of its antenna park. Currently, DLR operates several RF antenna stations in the L, S, X, Ku and Ka frequency bands at the ground site in Weilheim for 24 hours a day, seven days a week by rotating shift work. Several missions can be supported simultaneously (multi-mission operations). Moreover, the Earth receiving stations of EDRS System in Harwell and Redu are remotely controlled from Weilheim.

Based on a long-standing cooperation between Germany and Spain, the OGS is located at a test site of the Spanish Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT): the Plataforma Solar de Almeria (PSA) is a solar technology research and development center about an hour 's drive south west of the famous Calar-Alto-Observatory. There, 230 VAC and 400 VAC power grids secured by uninterrupted power supplies (UPS), diverse facilities like workshops, office space and sanitation, as well as high-speed access to the national research and education network of Spain (RedIRIS) are provided.

The FOGATA design is based on an astronomical Ritchey-Chrétien reflecting telescope (600mm aperture, F/6.7) on a high-precision mount in altitude-azimuth or azimuth-elevation configuration, respectively. It is equipped with a closed-loop tracking system allowing for precise tracing of LEO satellites by reference signaling in the NIR spectrum. The telescope is protected by a fast-rotating slit-type astrodome (4.2m diameter) resting three meters above the ground. By that, the machinery is not only weatherized but also effectively shielded against sunlight during daytime operations. Control equipment is accommodated in a temperature-controlled container next to the dome.

At its back-focus the telescope is furnished with an optical transceiver, which provides separate optical receive and transmit paths. A digital processing unit connecting to an opto-electric converter at one of the sensor ports in the receive path embodies the classical signal modem.

Fig. 1. SMART-01: Robotic telescope station of DLR GSOC at the Sutherland Observatory in South Africa, which serves as a blueprint for the FOGATA. Credit: H. Fiedler (2017).

4.4. KSAT Low Complexity OGS Nemea

KSAT is one of the first movers in optical LEO-to-Ground optical communication and has installed its first small aperture, low complexity OGS in Greece. The OGS is hosted by OTE S.A. at the Nemea ground station site, where OTE provides all the infrastructure necessary for operating high availably ground stations including 1st level on-site support.

In order to make use of available infrastructure (high-speed terrestrial network, site infrastructure, RF-backup, …) and to be able to support optical space terminals in an ISS (International Space Station) orbit while not facing the harsh environment of high-latitude sites KSAT decided to co-locate its first OGS with KSAT RF antennas in the mid-latitudes at Nemea.

The OGS is compliant to the Optical On-Off Keying (CCSDS 141b1) draft standard and is designed to become cost competitive to the KSAT^{Lite} service which KSAT is currently offering in the RF domain.

The challenge has been to bring all building blocks (telescope, gimbal, weatherization/dome, remote-control system, acquisition beacon, receiver back-end interface, etc.) together into a design which is not on a bread-board level but results in an automated, cost-efficient, operational, multi-mission optical ground station service.

To reduce non-recurring engineering costs a design based on modified commercial of the shelf components (MOTS) has been selected. Available subsystems from the field of professional observatory technology (e.g. remote and robotic telescope stations), satellite communications prototype ground station, etc. have been selected.

Figure 2 shows a photo of the Nemea OGS. The telescope is mounted more than three meters above the ground to avoid ground layer turbulence which is reduced by up to half by elevating it by two meters.

Its mount has an altitude-altitude configuration proposed by Mayall and Vasilevskis (1960) for optimum satellite tracking performance and avoidance of an "antenna" keyhole (no blind spot near the zenith, and for objects near the celestial equator).

The dome is a one-part completely retractable structure with the UV resistant plastic fabric. It is not connected to the telescope foundation to avoid coupling of vibrations caused by wind to the telescope system. The dome allows automatic positioning of the telescope before satellite tracking to reduce the time when the optics are exposed to the environmental conditions and to increase laser safety by shielding the beacon. The remotely controlled dome fully folds away before tracking to avoid any air bubbles with different temperatures surrounding the telescope and causing additional optical turbulence (also called dome seeing).

Fig. 2. KSAT's optical ground station in Nemea after installation in January 2021

4.5. Location Selection for Optical Ground Stations

Optical ground station networks are ideally located in climate zones, with little cloud coverage and predictable weather as well as favourable atmospheric seeing. This is one reason for the placement of the Optical Nucleus Stations in the South of Europe. Further, a high-altitude location reduces the impact of the atmosphere which is the case for Tenerife. It is expected that the Nucleus network will be augmented with more locations that fulfil the requirements preferred for FSO.

5. Future Development of the Optical Nucleus Network

The next step is to validate the operational readiness of the Optical Nucleus Network by testing against the PIXL-1 CubeSat in-orbit demonstration mission. The availability of a satellite in orbit to test against is of great importance for ground station calibration and site acceptance testing. Thanks to the support of the Institute of Space Systems / University of Stuttgart preliminary testing has already been performed with Flying Laptop. It is the first satellite of the Small Satellites Program at the university and carries an optical terminal built by DLR. TESAT launched PIXL-1 in February 2021 with its first NewSpace CubeLCT terminal onboard into orbit in partnership with DLR. PIXL-1 will be used for testing of the full ground station network. This is in preparation for supporting the TOSIRIS terminal which will be installed on the Bartolomeo platform on ISS in 2022. TOSIRIS supports downlink speeds of up to 10 Gbps and will be the first fully commercial mission using optical data communication.

Beside validating the operational readiness, the extension of the network is being investigated. In general, the Nucleus network is open for anyone willing to connect his own optical ground station to the network, if the basic CCSDS protocol rules are implemented. Once the market develops the network can quickly be expanded globally based on the experience gathered from earlier stages.

Another point that must be addressed in future optical ground networks is an overall system optimization considering not only the downlink but also the entire signal processing chain which must be flexible enough to handle the variations of the FSO channel. This requires flexible near-real-time scheduling of all elements in the signal chain to adapt to the current atmospheric conditions at the different OGS locations. This flexibility should make dynamic re-scheduling of downlinks and adapting the data-rate during the satellite pass possible. Optical communication with the spacecraft has an impact on satellite control, mission planning and scheduling of the ground station network. It is a key interest of ESOC and GSOC to advance the optical CONOPS.

In a medium-term perspective the use of the Optical Nucleus Network for Moon-to-Earth communication is promising. There is an increasing interest in Lunar missions and high rate Moon-to-Earth communication will become an important service required. This is not solved through RF networks today. In the Moon to Earth link scenario optical communication clearly outperforms RF. While RF ground station antennas need to be larger than approximately 13 meters to achieve high rates, optical ground stations can manage this with telescopes in the 1 to 1.5-meter class. For example, the NASA LLCD project proved already in 2013 that with a 1-meter OGS, downlink rates of 40-622 Mbps are possible for Lunar distances. As the receive system aperture diameter is a main cost driver, the investment in an optical ground station network for Lunar support is significantly lower than for big RF ground station antennas. Therefore, FSO should be able to decrease service cost for high rate lunar data backhaul. Especially as telescopes up to 1.5 meter are observatory grade telescopes which are cost efficient. Considering the advantages of FSO for lunar-distance links the OGSs of the Optical Nucleus Network are planned to be equipped with hardware (e.g. detectors and modems) supporting the HPE (High Photon Efficiency) communication scheme which is already fully standardised by CCSDS. The currently available telescope apertures of the Nucleus stations are a good start for Lunar communications but not able to reach highest rates. The current approach focuses on validating the optical ground network concepts, but the network can then easily be extended with larger apertures for higher rates if required.

6. Summary

While the atmosphere poses a challenge, FSO is promising for the next generation of data downlinks supporting higher speeds and longer distances. The cooperation within the European Optical Nucleus Network has shown to be a good way to prepare for the future and in particular lunar communications look promising. It is also an example of Industry and Agencies cooperating without financial gain but a common interest to enable future technologies.

7. References

[1]: H. Hemmati, Deep Space Optical Communications, Jet Propulsion Laboratory, California Institute of Technology, (2005).

[2]: H. Hemmati: Near-Earth Laser Communications (Optical Science and Engineering, Band 143), ISBN-13: 978-0824753818, (2008).

[3]: H. Henniger, et. al.: Analysis and Comparison of new Downlink Technologies for Earth Observation Satellites. Radioengineering, 25 (1), Seiten 1-11. Czech Technical University. DOI: 10.13164/re.2016.0001 ISSN 1210-2512(2016).

[4] B. Epple, H. Henniger: Discussion on Design Aspects for Free-Space Optical Communication Terminals. IEEE Communications Magazine, 45, ISSN 0163-6804(2007).

[5] H. Henniger, W.Otakar: An Introduction to Free-space Optical Communications. Radioengineering, 19 (2), Seiten 203-212. ISSN 1210-2512(2010).

[6] H. Henniger: Transmission Performance Analysis of Free-Space Optical Communications using Gilbert-Erasure Channel, in IEEE Transactions on Communications, vol. 60, no. 1, pp. 55-61: 10.1109/TCOMM.2011.100511.090237 (2012).

[7] H. Fiedler, J. Herzog, M. Ploner, M. Prohaska, T. Schildknecht, M. Weigel and M. Klabl: SMARTnet(TM) – First Results of the Telescope Network, European Conference on Space Debris, Darmstadt, Germany, (2017).

[8] D. Giggenbach, H. Henniger: Fading-loss assessment in atmospheric free-space optical communication links with on-off-keying, Optical Engineering, vol. 47, (2008).

[9] C. Schmidt, C. Fuchs: The OSIRIS program- First results and Outlook, IEEE International Conference on Space Optical Systems and Applications , (2017).

[10] Iwamoto, Kyohei et. al.: Experimental results on in-orbit technology demonstration of SOLISS, Proc. SPIE 11678, Free-Space Laser Communications XXXIII, 116780D (2021).

[11] T. Thieme, Thomas et. al.: OPTEL-μ: A Compact System for Optical Downlinks from LEO Satellites, SpaceOps2012.