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Development of an Optical Communication Ground Network for Direct-to-Earth Data Repatriation Service

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Abstract

Today, satellite communication relies on well-established radio frequency technology. As data rate demands keep rising and spectrum congestion occurs due to the increase in number of missions, the incorporation of higher frequencies becomes inevitable. The Swedish Space Corporation has been researching the operational aspects of free-space optical communications and its impact on the ground segment for more than a decade, with particular emphasis on complementing the current space-to-ground data reception portfolio with the optical band as the market matures. This paper presents the initial efforts to design and develop an innovative optical ground network which will integrate geographically distributed optical ground stations as well as required network intelligence, to seamlessly provide a coherent service offering to its future users. The optical ground network is named NODES, for Network of Optical stations for Data transfer to Earth from Space and is partially funded by ESA's ScyLight programme. NODES will include the deployment of a network management centre for its ground segment operation and orchestration, as well as two optical ground stations to execute the free-space optical links with the counterpart laser communication terminals onboard the satellites. The paper presents the key product requirements, preliminary architecture, remote site selection supported through simulation, and the installation status of the first remote site of NODES, which will be in Australia.

Keywords: Communications Architectures and Networks, Ground Segment, Free-Space Optical Communication

Acronyms/Abbreviations

ConOps	Concept of Operations
DTE	Direct to Earth
EDRS	European Data Relay Service
ISL	Inter-satellite Link
JDRS	Japanese Data Relay System
LCRD	Laser Communications Relay Demonstration
LCT	Laser Communication Terminal
LEO	Low Earth Orbit
NMC	Network Management Center
NODES	Network of Optical stations for Data transfer to Earth from Space
O3K	Optical On-Off Keying
OCTL	Optical Communications Telescope Laboratory
OGN	Optical Ground Network
OGS	Optical Ground Station
RF	Radio Frequency
SDA	Space Development Agency
SLA	Service Level Agreement
SSC	Swedish Space Corporation
TT&C	Telemetry, Tracking and Command
WASC	Western Australia Space Centre

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1. Introduction

Free-space optical communications offer the opportunity of at least an order of magnitude higher data rates than current radio frequency (RF) technology. In addition, the narrow laser beam divergence capability reduces the risk of electromagnetic interference, jamming and eavesdropping, resulting in a more secure and resilient link without the RF bandwidth limitations. The optical technology also allows for a reduction in size, weight, and power on board the spacecraft, as well as smaller (optical) ground stations. On the other hand, technical challenges of free-space optical communications include degradation or disruption of the laser beam due to clouds, turbulence, and other weather impairments, as well as stringent pointing and tracking accuracy requirements.

Space agencies such as ESA, NASA and JAXA have researched optical space communications for over 40 years and demonstrated several scenarios including inter-satellite links (ISLs) [1, 2], lunar distance links [3], GEO-to-ground links [4-6], ISS-to-ground links [7, 8], and LEO-to-ground links [9, 10]. A particular case with a downlink of large data volumes to ground is typically referred as Direct-to-Earth (DTE). A recent LEO DTE payload by MIT's Lincoln Laboratory named TBIRD achieved a large step towards the realisation of very high throughput optical links from space-to-ground reporting data transmission of 200 Gbps from a CubeSat satellite (utilizing a modified COTS telecom transceiver to include adaptive repeat request) to the 1-m telescope OCTL in California (with adaptive optics and preamplification) [11, 12].

The European Data Relay Service (EDRS) servicing the Copernicus programme employs optical inter-satellite links as secondary payload and became the first operational space optical communication service in 2016 [13]. Other data relay endeavours with optical ISL capabilities have been announced by public (such as NASA's LCRD, SDA's Transport Layer and JAXA's JDRS) and private (e.g, Space-X Starlink) sectors. The interest on optical ISL for data relay infrastructure may not only be attributed to the technical benefits, but also to its strategic relevance.

For the space-to-ground scenario, the optical ground segment is also achieving higher technology readiness to allow a transition from demonstration to routine operations at a global scale, with several actors deploying new ground terminals around the globe [e.g., 10, 14] and ongoing efforts for optical ground network (OGN) [15, 16]. A simultaneous consolidation of both ground and space segments should thus allow to overcome the outspoken "chicken-and-egg" problem, where stakeholders hesitate to arrive too early to be serviced.

SSC (Swedish Space Corporation) is developing an optical ground network for a LEO-to-ground data service through NODES (Network of Optical stations for Data transfer to Earth from Space), which will span three and a half years and cover technical, standardization, regulatory, business and market aspects. As shown in Figure 1, the project spans 3½ years, starting from system requirements specification and subsystem development before system integration, service validation and finally service demonstration. The main components and stakeholders of NODES are shown in Figure 2. A network management centre (NMC) and two optical ground stations (OGSs) will be added to the network within the scope of the project. The first OGS will be commissioned at the SSC site in Western Australia at the end of 2023, and the second remote site is planned to be added to the network in 2024 (its location is still to be determined). The network will then be operationally demonstrated, and the project will close in 2025 when a viable starting point for a commercial service is expected to be reached.

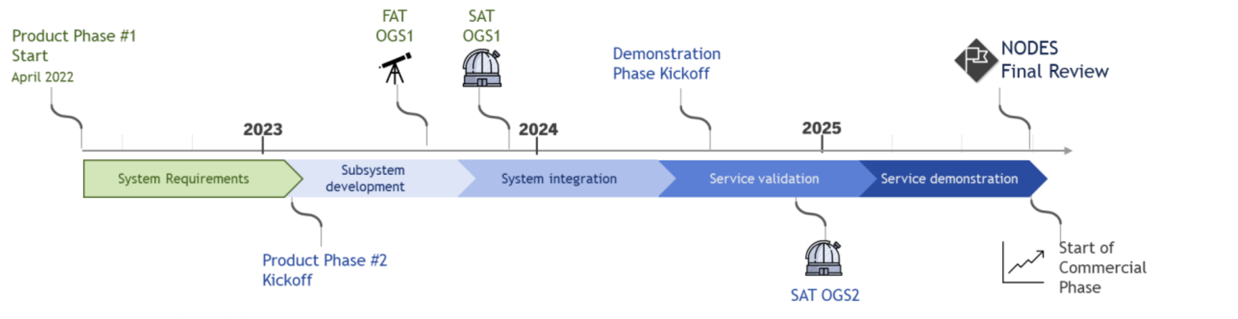

Fig. 1. NODES project timeline.

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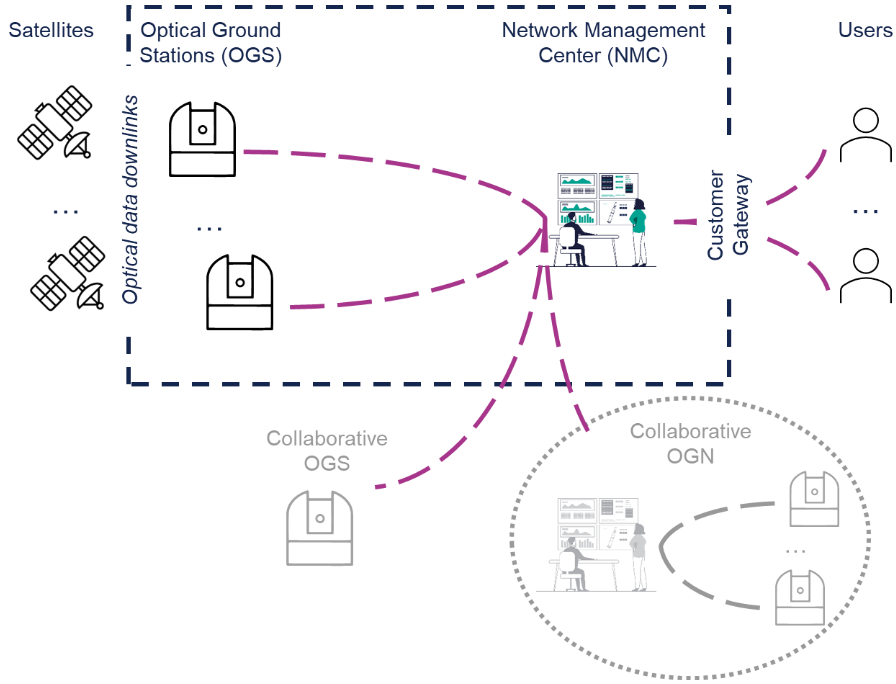

Fig. 2. NODES concept diagram with main stakeholders (optional stakeholders in grey).

The remaining of the paper is organized as follows: Section 2 provides an overview of the initial design of the OGN addressing its key product requirements, concept of operations (ConOps) and top-level architecture. In Section 3, supporting studies for remote site selection including a simulation framework are discussed. Finally, a status update on the preparatory work for commissioning of the first optical ground station in Western Australia is provided in Section 4.

2. Preliminary Design

This section describes technical aspects of the preliminary architecture of the NODES optical ground network. First, the main key product requirements of the service offering are identified. Next, several concept of operation possibilities are discussed. Finally, the architecture of the OGN and its main subsystems is provided.

2.1 Key Product Requirements

After an initial study, four top product requirements were identified for an OGN to fulfil operational service viability. Those key requirements are summarized below:

A. Process automation – the overall network should be highly automated and require minimal human intervention. This not only regards operation, calibration and maintenance of the optical ground stations, but also the core orchestration of the network including an agile and dynamic scheduling system where machine-to-machine interfaces are preferred.

B. Predictable availability – for the customer to receive a reliable service (a statistically predictable data delivery Service Level Agreement, SLA), the OGN should include several coordinated and geographically distributed OGSs which lessens the weather impact across the free-space optical links.

C. Turn-key user experience – the optical service should minimise customer's burden and ultimately provide and ease transition and/or compatibility with current radio frequency service offering.

D. Multi-mission capability – the service should support as many relevant users as possible. A disparity of laser communication terminal (LCT) models with different free-space optical interfaces exists nowadays, and standardization efforts have not been fully consolidated. Therefore, upgradability at OGS level is requested by design, which also allows for future technology advances.

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2.2 Concept of Operations

Traditional RF data reception services are based on pass booking across specific timeslots, and resources (e.g., antennas, basebands) were originally designed for manual exchanges. Although achieving a certain level of automation is possible and has been ongoing for years, backwards compatibility and a broad customer base with different needs may impose practical challenges.

As the optical service will be affected by a highly dynamic environment (mostly due to cloud impact), a transition to a concept of operations designed for automation and focused on total data delivery at network level (not per individual station) is deemed favourable [17, 18].

A ConOps candidate which aims to simplify the initial roll-out of the optical ground network where a gradual customer base is expected is the "opportunistic mode". This operational mode simplifies and minimizes the operator-customer burden as their respective counterpart terminals may attempt to establish a link once a possibility occurs based on ephemeris propagation and basic constraints (such as minimum pass time above certain elevation threshold). This apparent simplistic approach may incur lack of efficiency, however high data rates, simulation models including data delivery prediction and API (Application Programming Interface) upgrades for key-information exchange (e.g., weather forecasting, go/no go) may help overcome those inefficiencies.

In this scenario, the pointing, acquisition and tracking sequence shall be initiated, and a link establishment attempted every time the satellite passes within sight of a ground station. The customer is typically responsible for the orbital elements provision and commanding the spacecraft for data downlinking. The ground network provider then facilitates data reception and delivery through a terrestrial network to a pick-up point.

2.3 Architecture

The top-level architecture of the OGN to be developed within the NODES project is outlined in Fig. 3. The free-space optical communication interface is performed between the satellite and the optical ground stations (located at different remote sites in the network and geographically distributed). Each ground station is expected to receive O3K-modulated laser signals in the 1.5-µm band with varying data rates of up to 10 Gbps. The remote sites will be equipped with uplink beacons of several watts of optical power and a wide divergence angle, to help alleviate optical pointing demands. The payload data transmitted from the spacecraft to the ground will be redirected to a pick-up point for the user, which could be cloud-based. The NODES NMC performs monitor and control and orchestration. An interface between the NMC and the customer is also present, where the user provides updated orbital elements and pass configuration data (if any). The user is continuously informed about service fulfilment and data reception status (e.g., through a dashboard with key performance indicators).

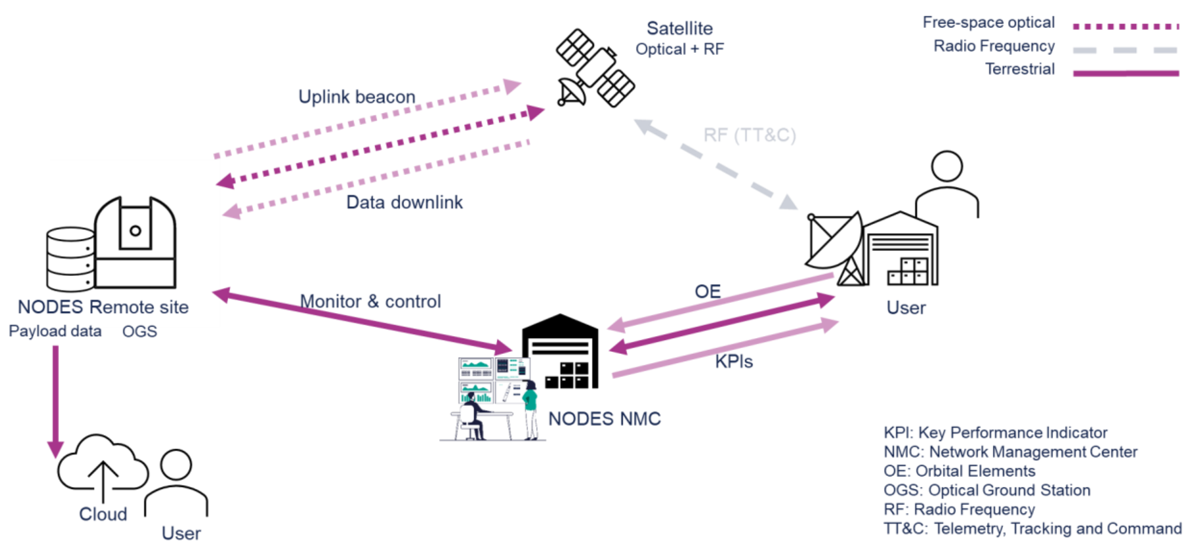

Fig. 3. NODES top-level architecture.

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The OGN has been segmented in the following modules, or subsystems:

- Service Monitor and Control
- Central Data Service and Network
- Service Management
- Remote Sites

The Service Monitor & Control will orchestrate the overall network and take care of the dynamic scheduling of the data transfer passes. Due to the unpredictable nature of clouds and atmospheric turbulence, the booking of the service will need to refrain from being pass-centric which is typically the case for an RF service, and instead a data-centric solution is envisioned. The scheduling system will need to be highly agile, as a scheduled pass might end up being only partly utilized or not utilized at all due to weather, in which case the next opportunity for data transfer must be found and prioritization over other contemporary passes of any mission by another customer must be determined. The focus therefore in the perspective of the customer must not be the individual passes, but the volume of data that shall be delivered within a predetermined amount of time.

The gathering and eventual merging of data will be supported by the Central Data Service and Network module, including the delivery of data to the end-user on the ground. The Service Management will be a platform where the user and network operator interface to agree on SLA and update about status and fulfilment. All these three modules are controlled from the NMC.

The fourth module, the Remote Sites, are the geographically distributed sites that include the OGSs, the interfaces for the OGN and any additional infrastructure to support the network, such as weather stations. The main building blocks of a conceptual remote site is shown in Fig. 4. The grey box constitutes the OGS with the front end consisting mainly of the telescope, mount and beacons, located under a slit dome. The back end of the OGS includes an OGS control unit, detectors, modem and data buffer, amplifiers, and beacon modulators, as well as weather monitoring and laser safety measures.

The main requirements of the remote sites include remote and autonomous operation, a secure interface with the NMC and a compatibility with different LCT providers, a requirement referred to as multi-mission capability. Modularity and upgradability are also beneficial to accommodate different technical and mission requirements as the market and standards mature. Compliance with at least the CCSDS O3K standard [20] is also a requirement.

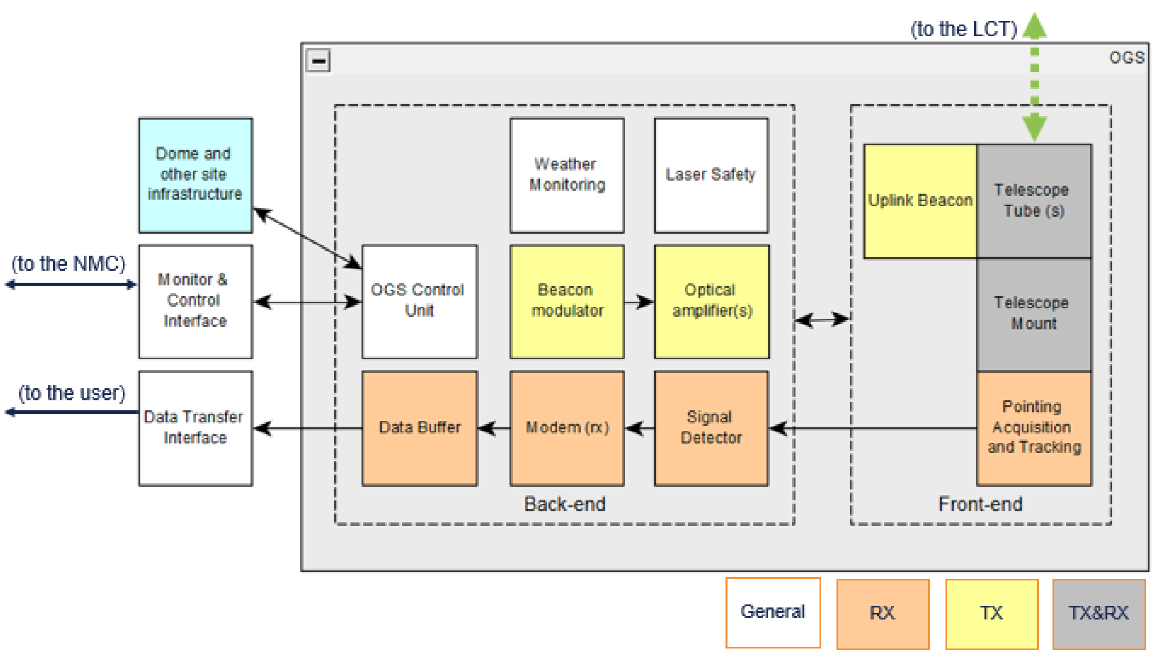

Fig. 4. Conceptual diagram of a remote site.

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3. Optimization of an Optical Ground Network

The geographical distribution of remote sites plays an important role in the performance of the network. Since the optical link is severely affected by the non-deterministic variable of weather in terms of cloud coverage and atmospheric turbulence, multiple sites are needed in the network that are separated sufficiently for the weather impact of the sites to be completely uncorrelated, to maximize the probability of successful data volume transfer per day. SSC operates a large number of remote sites around the world as a part of their TT&C and data reception service "SSC Connect" based on RF communication. To keep the installation and infrastructure costs to a minimum in the NODES project it is natural to firstly investigate the existing SSC sites as potential places for installation of OGSs for the new optical service. The sites are spread over five different continents (seven continents if also considering collaborative sites), and each site has a unique prerequisite and weather characteristics.

The cloud coverage of several potential remote sites has been modelled using the re-analysis meteorological model from Meteoblue. The model integrates open data measured at different locations into a data base and simulates weather parameters such as cloudiness, temperature and wind speed with an hourly resolution. Fig. 5 shows a comparison of modelled cirrus cloud thickness at the different sites of Santiago (Chile), Esrange outside Kiruna (Sweden), Tenerife (Spain), Inuvik (Canada) and Punta Arenas (Chile). From the histogram it can be deduced that the high latitude sites of Esrange and Inuvik have a much larger cloud coverage compared with the other sites. In each histogram, the corresponding modelled histogram of the SSC site WASC (Western Australia Space Centre) is shown in blue. WASC has been selected as the first remote site in the NODES network, as weather prerequisites are very good, it has good connectivity, and SSC is currently conducting other optical installations there, for SSA activities. It is therefore of current interest to find the optimal configuration of the network when a second remote site will be selected in the project.

The Meteoblue data has been used as input into simulations to evaluate the performance of an OGN. The simulation tool uses the space dynamic library Orekit in the estimates of for example satellite contact time, data volume transfer and latency of data retrieval of a specified ground station and satellite. The tool was developed by SSC and previous network performance analysis using this tool has been presented in [18]. Data transfer simulations are used in the NODES project to understand the typical performance of a network and will be crucial in designing a service level agreement that is based on a guaranteed data volume delivery over a specific time interval to a certain level of probability. The tool is also used as a guide in the selection of location of the second remote site in NODES, to optimize the network performance when only a small number of optical stations are incorporated. Table 1 gives an example of simulated contact minutes and average downloaded data volume based on a model space terminal, and number of passes per day, for the same sites as the cloud data presented in Fig. 5. These results were obtained with a simulated satellite in Sun-synchronous orbit at 700 km altitude. The data represent simulated averages over a period of 60 days and the total gives an indication of the network performance with one optical station at WASC and a second station at one of the other sites. The number of passes over the high-latitude stations (Esrange and Inuvik) are nearly twice as many as the passes over the lower-latitude stations, due to the high inclination that is typical of a LEO satellite in Sun-synchronous orbit. When taking cloud cover into account, the high-latitude stations, which from Fig. 5 showed much higher abundance of clouds, are still performing better in combination with WASC than the stations at lower latitudes. However, in terms of latency of data delivery (which is not shown here) the southern stations will outperform the high-latitude stations, as they are less likely to be blocked by clouds for longer periods of time. Other factors, such as terrestrial network connectivity, staffed sites and extreme weather and temperatures, are also considered in the selection of the second station in the NODES network.

Table 1. Example of simulation of performance of potential remote sites, as compared with the WASC site, based on a model space terminal and initial assumptions on OGS performances.

	WASC	Santiago	Total	WASC	Punta Arenas	Total	WASC	Esrange	Total	WASC	Inuvik	Total	WASC	Tenerife	Total
Contact minutes per day	2.6	2.6	5.2	2.6	3.6	6.2	2.5	6.6	9.1	2.7	6.8	9.5	2.8	4.4	7.2
Average GB per day	22.7	23.4	46.1	23.1	15.8	38.9	21	33.1	54.1	23.3	40.8	64.1	23.5	62.9	86.4
Number of passes per day	3.8	4	7.8	3.8	5.9	9.7	3.8	10.4	14.2	3.8	10.4	14.2	3.8	3.7	7.5

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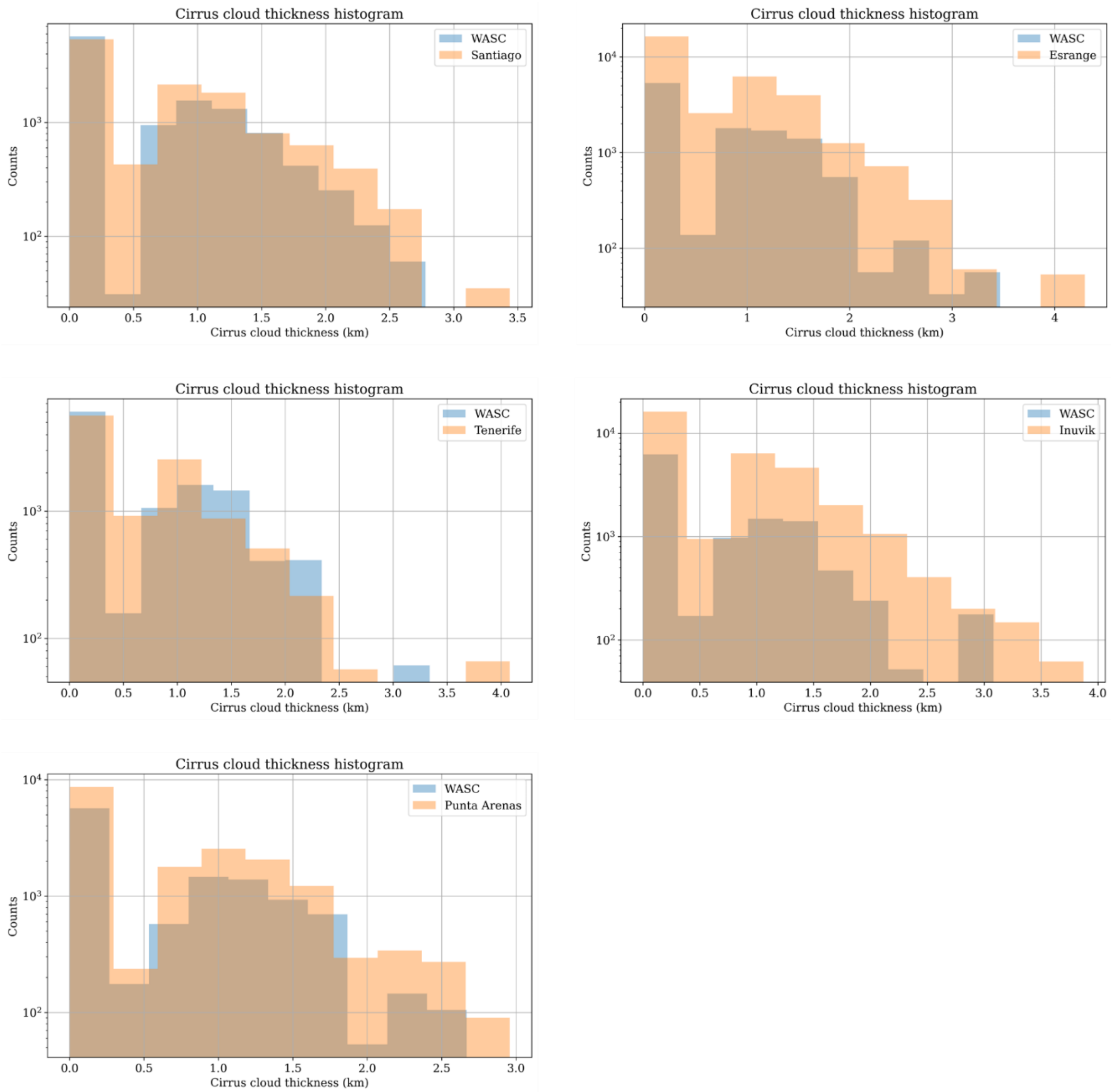

Fig. 5. Histograms showing the cirrus cloud thickness as modelled with Meteoblue, for sites in Santiago (Chile), Esrange (Sweden), Tenerife (Spain), Inuvik (Canada) and Punta Arenas (Chile). Each histogram shows the modelled result for the WASC site (Australia) in blue, as comparison.

4. Commissioning of the first NODES Station

The first OGS in the NODES network is a pilot station developed and manufactured by the French deep-tech photonics company Cailabs. At the core of the OGS is a 60-cm Cassegrain telescope to receive the downlink signal, on an automated alt-az mount. The free-space optical signal is routed through the receiving chain onto photodetectors, with data rate capability from 100 Mbps to 10 Gbps (current design of the pilot station, upgrades are possible). The OGS is currently under construction with factory acceptance test expected in the middle of 2023, after which it will be shipped, installed, and commissioned in Australia, at the WASC site.

WASC (shown in Fig. 6) is operated and maintained by SSC Space Australia Pty Ltd. The RF antennas at the site are remotely controlled from the SSC Network Management Centres in Kiruna (Sweden) and Horsham (USA). In 2022 the installation of another optical station, to be used for SSA (Space Situational Awareness) services, was conducted at the site. This station “AWARE” is remotely operated from SSC’s facilities in Stockholm, Sweden. The concrete building hosting the AWARE electronics at the WASC site can be seen in the left part of Fig. 6. The facility has since been completed with a dome for the telescopes and other additional infrastructure, and the station is operational. The NODES station for optical communication will be situated to the West of the AWARE station. The

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design of the supporting infrastructure in terms of dome and electronics shelter with local control room for maintenance is nearing completion after which installation will commence. The dome will be a 4.2 m diameter slit dome.

The OGS will further be equipped with a weather monitoring station, for meteorological characterization, with sensors for measurements of e.g., precipitation, wind speed, and atmospheric pressure as well as a white-light all-sky imager and a seeing monitor. The station is capable of measuring the strength of atmospheric turbulence through the C-DIMM (compact differential image motion monitor) [20], which will be mounted on a tracking mount especially developed for the Southern hemisphere, where a fixed star such as Polaris is not available. The weather station will be installed on-site before the OGS, already during spring 2023, to provide characteristics of the atmospheric conditions to inform the simulation work. Similarly, a second station will be installed at the SSC site in Santiago, to evaluate further the suitability of this site for the second OGS in NODES.

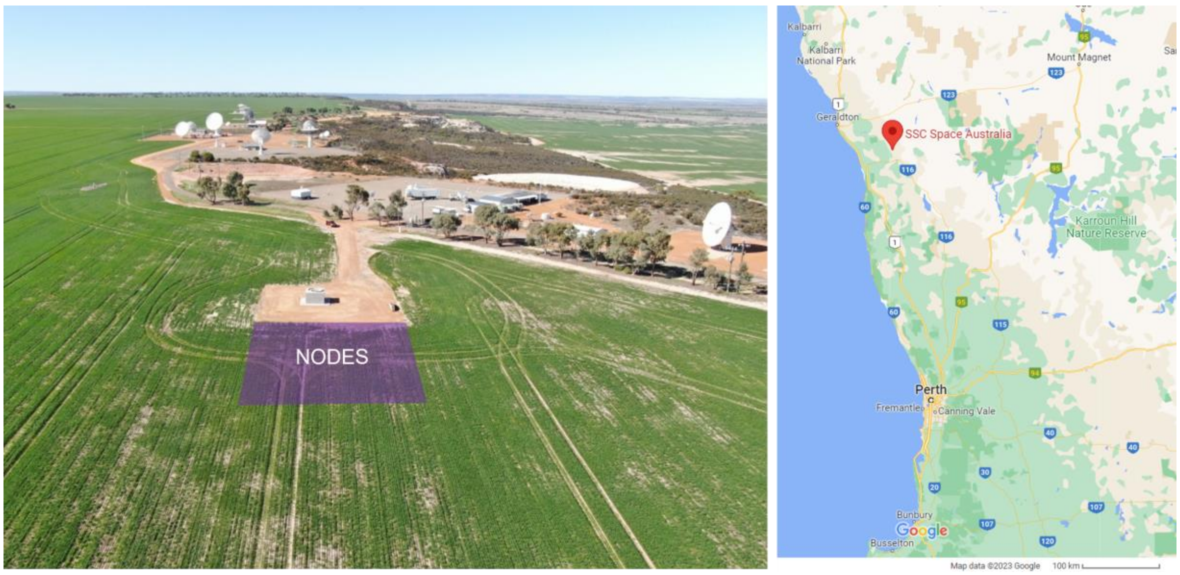

Fig. 6. Left: The WASC site, with the AWARE station in the image center. The site will be further extended to host the NODES station (purple overlap). Right: The location of WASC in Western Australia.

5. Results and Discussion

The NODES project focuses on the development of a satellite data repatriation service from space-to-ground using optical communication, initially targeting LEO Earth Observation customers. NODES started in April 2022 and the project work has up until this point been mainly focussed on requirement definition, system architecture, market prospection and analysis, risk management, and the procurement of the first OGS and two weather stations. Upon successful preliminary design review in 2023, the project will transition to development stage with critical design review planned in the autumn of 2023.

The first NODES optical ground station is a pilot station which will be installed in Australia in November 2023. The installation of a second station, which is targeted to be a commercial station that is fully automated and with a multi-mission capability, is expected to take place towards the end of 2024, at which time the project work will transition to operational demonstration.

The NODES project is advancing the readiness level of the ground segment towards enabling a future high-volume data delivery service directly from space-to-ground using optical communication. However, the development needs to be paralleled by an interest and investments in and standardization for the future capability from the space segment. The technical advancements of the space segment are catalysed by the development of intersatellite optical links, which have reached a mature technology level, where the deployment of optical terminals for space-to-ground communication is just starting to take off. To verify and test the NODES OGN in-orbit test partners with optical terminals are needed, with first opportunity to test already within the current year. Optical downlinks are a promising solution to the current data bottleneck experienced by satellite operators and will help Earth benefit from data gathered in space. It is also an auspicious means of communication for further distances such as lunar missions and beyond, and the fastest way to realisation is for the actors within both the space and ground segments to cooperate in advancing the technology.

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References

[1] T. Tolker-Nielsen, G. Oppenhauser, In-orbit test result of an operational optical inter satellite link between ARTEMIS and SPOT4, SILEX, Proc. SPIE, 2002, vol. 4635, pp.1–15.
[2] M. Motzigemba, H. Zech, P. Biller, Optical Inter Satellite Links for Broadband Networks, 2019 9th International Conference on Recent Advances in Space Technologies (RAST), Istanbul, Turkey, 2019, pp. 509-512.
[3] D. M. Boroson, B.S. Robinson, The Lunar Laser Communication Demonstration: NASA's First Step Toward Very High Data Rate Support of Science and Exploration Missions, Space Science Reviews 185, no. 1–4 (2014), 115–128.
[4] K. Araki et al., Performance evaluation of laser communication equipment onboard the ETS-VI satellite, Proc. SPIE Vol. 2699, Free-Space Laser Communication Technologies VIII, San Jose, United States, 1996, 27 January – 2 February.
[5] J. M. Perdigues, Z. Sodnik, H. Hauschildt, P. Sarasa, F. Porte-Proust, M. Wiegand, C. Rochow, D. Troendle, F. Heine, The ESA's optical ground station for the EDRS-A LCT in-orbit test campaign: upgrades and test results, Proc. SPIE 10562, International Conference on Space Optics — ICSO 2016, 105622V, September 2017.
[6] F. Heine, The European data relay system and Alphasat to T-AOGS space to ground links, status, and achievements in 2017, Free-Space Laser Communication and Atmospheric Propagation XXX, 2018, vol. 10524.
[7] A. Biswas, B. Oaida, K. S. Andrews, J. M. Kovalik, M. Abrahamson, M. W. Wright, Optical payload for lasercomm science (OPALS) link validation during operations from the ISS, Proc. SPIE 9354, Free-Space Laser Communication and Atmospheric Propagation XXVII, 93540F, March 2015.
[8] E. Samain *et al*., First free space optical communication in Europe between SOTA and MeO optical ground station, IEEE International Conference on Space Optical Systems and Applications (ICSOS), 2015, pp. 1-7.
[9] A. Carrasco-Casado, H. Takenaka, D. Kolev, Y. Munemasa, H. Kunimori, K. Suzuki, T. Fuse, T. Kubo-Oka, M. Akioka, Y. Koyama, M. Toyoshima, LEO-to-ground optical communications using SOTA (Small Optical TrAnsponder)–Payload verification results and experiments on space quantum communications, Acta Astronautica 139 (2017) 377-384.
[10] H. Yamazoe, H. Henniger, K. Iwamoto, The communication experiment result of Small Optical Link for ISS (SOLISS) to the first commercial optical ground station in Greece, IEEE International Conference on Space Optical Systems and Applications (ICSOS), Kyoto City, Japan, 2022, pp. 40-46.
[11] C. M. Schieler et al., On-orbit demonstration of 200-Gbps laser communication downlink from the TBIRD CubeSat, Proc. SPIE 12413, Free-Space Laser Communications XXXV 2023 – publication pending.
[12] C. M. Schieler, K. M. Riesing, A. J. Horvath, B. C. Bilyeu, J. S. Chang, A. S. Garg, J. P. Wang, B. S. Robinson, 200 Gbps TBIRD CubeSat downlink: pre-flight test results, Free-Space Laser Communications XXXIV, Vol. 11993 (2022), 200-206, SPIE.
[13] F. Heine, A. Sánchez-Tercero, P. Martin-Pimentel, N. Höpcke, D. Hasler, H. Zech, In orbit perfomance of tesat LCTs, Proc. SPIE 10910, Free-Space Laser Communications XXXI, March 2019.
[14] M. Birch, N. Martinez, F. Bennet, M. Copeland, D. Grosse, The Mount Stromlo Optical Communication Ground Station, IEEE International Conference on Space Optical Systems and Applications (ICSOS), 2022, 134-137.
[15] M. Krynitz, C. Heese, M. Knopp, K.-J. Schulz, H. Henniger, The European Optical Nucleus Network, 16th International Conference on Space Operations, 3–5 May 2021.
[16] F. Bennet, K. Ferguson, K. Grant, E. Kruzins, N. Rattenbury, S. Schediwy, An Australia/New Zealand optical communications ground station network for next generation satellite communications, Free-Space Laser Communications XXXII, 2020, Vol. 11272, p. 1127202, SPIE.
[17] P. Hyvönen, A. Vidmark, G. Baister, Operations of optical ground networks for small satellites, 4S Symposium 2016.
[18] P. Hyvönen, A. Vidmark, L. Francou, G. Baister, On-board Terminal Developments and Operations of Optical Ground Networks for Small Satellites, AIAA 2018-2477, SpaceOps Conference, 2018.
[19] CCSDS 141.0-B-1 – Recommended Standard + Pink Sheets for O3K – Optical Communications. Physical Layer, Feb 2020
[20] F. Jabet, 2021, C-DIMM: an autonomous, outdoor and fixed seeing monitor for astronomy, atmospheric studies and free space optical communications, Environmental Effects on Light Propagation and Adaptive Systems IV, 2021, Vol. 11860, pp. 6-10, SPIE.