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Update on the German and Australasian Optical Ground Station Networks

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ABSTRACT

Networks of ground stations designed to transmit and receive at visible and infra-red wavelengths through the atmosphere offer an opportunity to provide on-demand, high-bandwidth, secure communications with spacecraft in Earth orbit and beyond. This work describes the operation and activities of current free space optical communications (FSOC) ground stations in Germany and Australasia. In Germany, FSOC facilities are located at the Oberpfaffenhofen campus of the German Aerospace Center (DLR), the Laser-Bodenstation in Trauen (Responsive Space Cluster Competence Center, DLR), and the Research Center Space of the University of the Bundeswehr Munich in Neubiberg. The DLR also operates a ground station in Almería, Spain, as part of the European Optical Nucleus Network (EONN). The Australasian Optical Ground Station Network (AOGSN) is a proposed network of 0.5–0.7 m class optical telescopes located across Australia and New Zealand. The development and progress for each node of the AOGSN is reported, along with optimization of future site locations based on cloud cover analysis.

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1 | Introduction

Free space optical communications (FSOC) uses lasers to communicate information. These lasers are typically in the infrared band and communication protocols can be modulated on properties such as laser amplitude or phase. Laser light offers substantial advantages for inter-satellite and Earth-satellite communications over conventional radio frequencies [1, 2]. Channel bandwidths that use FSOC are higher than those that use radio frequencies [3]. Additionally, the FSOC transmitter and receiver hardware is smaller, lighter, and more efficient [4, 5].

These features are attractive for the designers of spacecraft, where the size, mass, and power budgets are highly constrained. Demand for higher quantities of data from space is increasing for conventional activities such as Earth observation and global telecommunications [6]. Ever higher rates of data will be required as crewed space missions start to take place in cislunar space, on the lunar surface and further afield at Mars [7, 8]. FSOC operations encounter lighter spectrum licensing requirements and also offer communication channels that can be made robust against eavesdropping using quantum processes [9–12]. This is a feature available with FSOC that is of particular interest to sectors where security is paramount, including government, defense, and global banking.

The majority of existing FSOC links have predominantly been inter-satellite links, facilitating data relay and satellite networks [13, 14]. However, the challenges posed by transmitting optical communication signals through the atmosphere require further experimentation and technological advancements. These developments are crucial to enable widespread FSOC adoption to meet the demands of the international satellite communication market. This is particularly important for high-performance systems requiring advanced techniques such as coherent communications, high-speed applications, and scenarios intolerant to loss. Coherent and high-speed applications require excellent phase and amplitude control which necessitates adaptive optics to correct for atmospheric turbulence. Loss intolerant systems such as deep-space or some quantum communication systems require developments in specialized detector technology, communication protocols, and error correction. Establishing research-grade optical ground station terminals will accelerate the development of these technologies to enable future growth of the FSOC market.

An FSOC ground station requires a cloud-free line of sight between it and a client space asset to establish a communications channel. Even in sites with the highest fractions of cloud-free skies, there will be periods that a site will be obscured by cloud, or unavailable for operations for reasons such as maintenance. A network of FSOC ground stations provides a mitigation against these situations encountered by a single FSOC ground station. Such a network would comprise a number of FSOC ground station nodes, where each node is sufficiently distant from the others so that the weather conditions at that node are as uncorrelated as possible with those experienced at the others [15–17].

Cloud coverage is the principal constraint on the performance of an optical ground station network (OGSN), and predicting network performance has been the subject of a significant quantity of literature. The German Aerospace Center (DLR) has developed a model for network performance estimation with pre-selected sites around Europe and a means of diversity estimation using spatial correlations of cloud cover [16]. Assuming site independence or empirical outage measurements, large European networks are proposed with a predicted reliability of 98% to 99%. The ONUBLA+ software has been proposed as a means to collect and analyze cloud fraction data for any proposed OGSN. It then uses these data to predict and characterize the performance of that network in the form of reliability values [15, 18, 19] (see also Section 2.3). These reliability values are also dependent on the particular mission being served, the quantity of stations, and the location of each station. To achieve high levels of reliability using stations around the Mediterranean, sometimes, three stations are sufficient. More generally, and to obtain availability above 99%, five or more stations are usually required.

The diversity and reliability of an Australasian Optical Ground Station Network (AOGSN) was explored in a recent publication [20], which also proposed a complete analytical solution to network diversity for uncorrelated optical ground stations (OGSs), which was not analyzed in previous works. A base AOGSN with three nodes was found to have a 6.4% outage probability and a larger AOGSN with eight nodes had a 0.02% outage probability. A spatially resolved means of network optimization, that is, without pre-selecting locations, was also shown. Australia and New Zealand were generally shown to be excellent locations for an OGS network due to the low cloud fraction and large geographic area, which offers minimal site-to-site correlation and broad coverage [20].

In this work, an overview of the establishment of optical ground stations in Europe and Australasia is presented, as well as a report on the optimization of node placement to most efficiently expand on existing infrastructure with site optimization in New Zealand.

2 | German FSOC Ground Stations and Network

Several research institutes in Germany have established or are establishing FSOC ground stations and programs of FSOC research. The DLR is leading research on the definition of FSOC standards such as Consultative Committee for Space Data Systems (CCSDS) and has already proposed global FSOC-enabled communication solutions [21]. A significant step towards global connectivity has been the establishment of the European Optical Nucleus Network (EONN) initiative [17]. Space Agencies and industry have allied to create this multi-site, multi-mission OGS network, which will support common optical space communications standards. Participating parties contribute operation time on self-funded optical ground stations to an integrated network that is made available to the space community as a service. The DLR, as one of the founding members, contributes its OGS in Almería, Spain, to the EONN. The DLR has also developed extensive expertise on optical ground stations over the years, and it is continuously extending its own optical antenna park.

2.1 | Technological Precursor Site: DLR Oberpfaffenhofen

The DLR Institute of Communications and Navigation (IKN) has been developing optical ground stations since 2004. Initial experiments were made using a 0.4-m telescope and the first coherent satellite laser communications terminal (LCT) onboard the TerraSAR-X Satellite, with interlink campaigns conducted at Oberpfaffenhofen and Calar Alto. This initial ground station was later permanently installed on the rooftop of IKN for experiments with the Japanese OICETS/Kirari satellite with its LUCE-Terminal, performing the first low Earth orbit (LEO) satellite data downlinks in Europe [22]. Additional experiments were performed, such as aeronautical Quantum Key Distribution (QKD) [23] and laser links with Jet Propulsion Laboratory (JPL)'s OPALS terminal on the International Space Station (ISS) and Japan's National Institute of Information and Communications Technology (NICT) SOKRATES [24] mission. Following those experiments the facility was upgraded and is now equipped with a larger 0.8-m telescope and a Coudé beam path to a laboratory, as shown in Figure 1.

The Optical Ground Station Oberpfaffenhofen – Next Generation (OGSOP-NG) was commissioned in 2021 and is currently employed in establishing bidirectional links using AO AND AO-predistortion for geostationary satellites. It is also used for the checkout of LEO satellites carrying Optical Space InfraRed link System (OSIRIS) terminals [25], including the Flying Laptop [26], BIROS [27], and PIXL [28]. Future utilization will include tests with the upcoming OSIRISv3 satellite terminal capable of

data downlinks in excess of 10Gbit s⁻¹, commissioning of inter-satellite link terminals (CubeISL), and experimentation with QKD satellite terminals (QUBE) [29].

The Transportable Optical Ground Station (TOGS) was built in 2011 by DLR IKN to enable temporary OGS operations at remote locations. It consists of a 0.6-m aluminum telescope in an airfreight-sized box that also holds the operations computer and any receiver and transmitter equipment for data transmission, as well as mechanics to extend the telescope and mount from its container, see Figure 2. This assembly can be stored and transported by a custom-built vehicle that also holds an operations room. TOGS was operated on the Island of La Palma for demonstrating the optical remote control of robotic operations from space [30] and performed FSOC links to a supersonic jet fighter in flight [31]. It is now regularly used for OSIRIS checkout operations and for joint observations of LEO laser downlinks in conjunction with other OGSs from DLR [32].

Based on the developments for the IKN-OGSs, development of the operational ground station in Almería (Free Space Optical Ground Antenna Tabernas [FOGATA]) and at the DLR-site Trauen (Laser Ground Station Trauen [LaBoT]) are in progress, making use of the Small OGS Focal Assembly (SOFA) unit as communications equipment. In preparing these sites, the German Space Operations Center (GSOC) has realized a separate test facility at its premises in Oberpfaffenhofen, 350m from OGSOP-NG. Residing on the rooftop of the DLR building, this new facility serves to host the initial engineering models of the station equipment to be used at future remote OGS sites. Instruments are integrated in the operational



FIGURE 1 | The OGSOP-NG 80-cm Ritchey-Chrétien Telescope and adjacent functional Diagram of OGSOP-NG with Coudé-Room underneath hosting various experiments for AO and QKD. Image: DLR.



FIGURE 2 | TOGS with its transport van that also contains the operations room. Image: DLR.

network and control environment at DLR for verification and validation campaigns at system and sub-system level. Protected by a roll-off cabin, a diverse range of telescopes and mounts have been installed. The latest setup consists of a mid-range commercial-off-the-shelf (COTS) telescope (TS 0.3 m-f/8-Ritchey-Chrétien-Astrograph, TS-Optics, Munich, Germany) on a precision mount (L-350, PlaneWave Instruments, Inc). Depending on the particular instrument attached to the telescope, the measurements include (1) pointing and tracking accuracy with a camera-based setup [32], (2) optical signal strength with an InGaAs-PIN-based photoreceiver (OE-200-S, FEMTO, Berlin, Germany), and (3) bit-error-rates utilizing optimized detector heads (APDRFE-100M and APDRFE-1G, joint development of DLR and LiPaCom, Puerger, Germany). The setup can be equipped with the DLR SOFA to create a complete OGS including various transmission sources. All components are remotely controlled using an in-house developed monitoring and control (M&C) system [33].

2.2 | Small Optical Ground Stations Focal Assembly: SOFA

The SOFA [34], shown in Figure 3, is a small, fully integrated, low-cost instrument that is intended to be mounted on new COTS or existing astronomical telescopes, thereby enabling optical communications. This allows for the cost-effective and easy deployment of a fully functional optical ground station. The SOFA unit comprises two low-resolution cameras. An infrared light camera provides fine-tracking information and a visible light camera is used to create a pointing model. The SOFA unit is thereby able to provide all the required information to the telescope mount to achieve highly accurate open-loop pointing as well as closed-loop tracking of satellites. The optical signal is detected with two single pixel detectors: a calibrated indium gallium arsenide (InGaAs) PIN photo-receiver for an assessment of the optical signal quality and a fast avalanche photo-diode (APD) for data reception. The SOFA unit is equipped with two spatially diverse uplink channels to provide a static or modulated beacon to the satellite and for uplink communications.



FIGURE 3 | The Small Optical Ground Station Focal Assembly (SOFA) as mounted on DLR's FOGATA telescope.

The SOFA unit is currently deployed on the OGS FOGATA in Almería, Spain, as well as on the OGS LaBoT in Trauen, Germany. Further deployments are planned to the OGS of the University of Auckland, New Zealand, to the OGS of the University of the Bundeswehr Munich, Neubiberg, Germany, and to the OGSOP-NG in Oberpfaffenhofen, Germany.

2.3 | German Optical Ground Station Network

The DLR manages the integration of several optical ground stations into a German Optical Ground Station Network (GOGSN) (cf. Figure 4), consisting of five stations: (1) OGSOP-NG, (2) FOGATA, (3) LaBoT, (4) Optical Ground Station–Neubiberg (OGS-NBB), (5) Optical Ground Station–Neustrelitz (OGS-NSG). The GSOC of the DLR is building the FOGATA [36] at the Plataforma Solar de Almería, a solar research site of the Spanish Centre for Energy, Environmental and Technological Research (CIEMAT). DLR/RSC³ (Responsive Space Cluster Competence Center) together with their prime contractor DiGOS Potsdam are implementing the Laser-Bodenstation (*engl: Laser Groundstation*) Trauen (LaBoT) [37, 38], the SPACE Research Center of the University of the Bundeswehr Munich is currently setting up the affiliated OGS at their Neubiberg (NBB) campus [39], and the Technical University of Berlin is going to realize a combined FSOC and Satellite Laser Ranging (SLR) station at the DLR site Neustrelitz (NSG). The OGSOP-NG in Oberpfaffenhofen of DLR IKN is already operational and is used for various FSOC experiments [40].

Table 1 gives an overview of the specifications for these ground stations. Network load is handled via a reactive planning process, taking into account spacecraft visibilities and terminal constraints, as well as actual weather conditions at the OGS locations [41]. Station telemetry is shared utilizing the CCSDS standard for Service Management [42] allowing for automated scheduling. In addition, the European Optical Nucleus Network can be accessed via the respective application programming interface (API). All OGS follow the design of a robotic observatory consisting of an Ritchey-Chrétien (RC) telescope on a precision mount within a dome and with a (containerized) control section hosting the electronic system. They will be featured with a common instrument (SOFA) to harmonize their air-to-ground interface gearing them towards compatibility with the upcoming CCSDS standard Optical On/Off Keying (O3K) [43].

Cloud coverage at the GOGSN and EONN locations was analyzed using the ONUBLA+ software. This software uses a database of cloud coverage measurements generated by weather satellites to determine the cloud-free availability of a selected location. Multiple locations can also be selected simultaneously, simulating a network, to determine cloud-free availability on a network-wide level. This availability metric is defined as the percentage of time when at least one location has cloud-free visibility. Using this method, the GOGSN and EONN were simulated in ONUBLA+ to determine their cloud-free availability using data generated by the MeteoSat Second Generation satellite from 2009 to 2017. In the cases where the exact location of each OGS was not present in the weather database, the closest location available was selected. Specifically, for the GOGSN, only Oberpfaffenhofen and Neustrelitz locations were available. The other locations were substituted by Munich instead

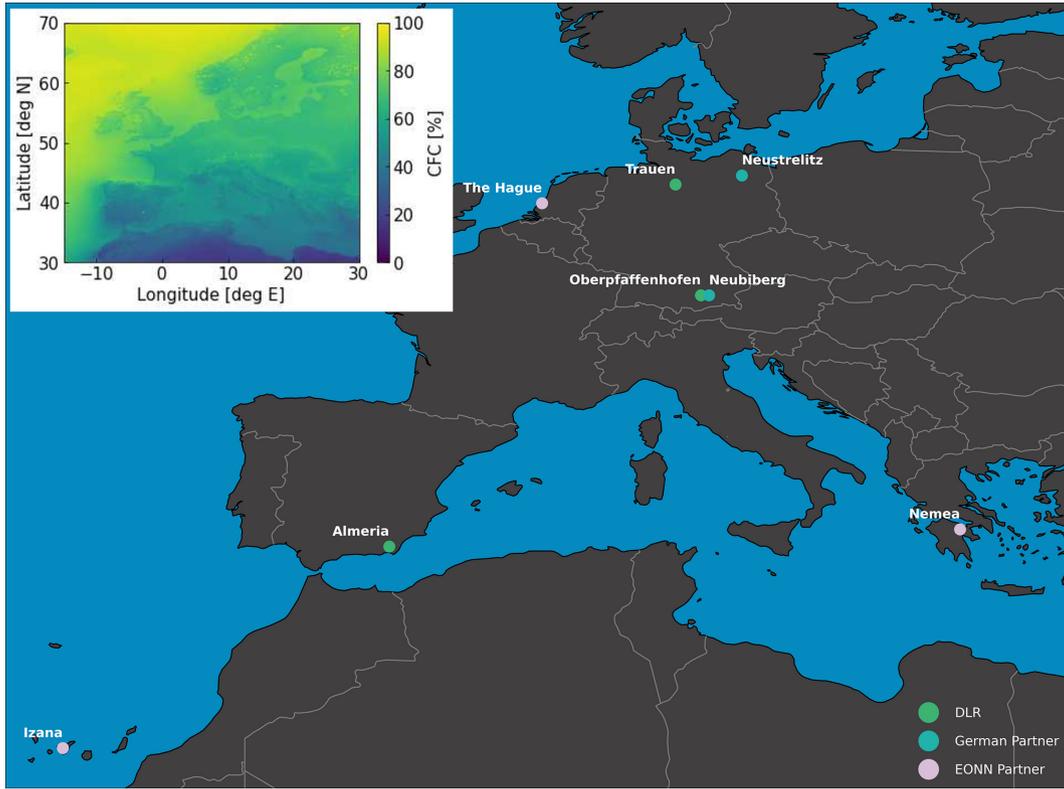


FIGURE 4 | German Optical Ground Station Network with access to the European Optical Nucleus Network. *Inset:* Average Cloud Fraction Coverage (CFC) in Europe [35]. Cloud Fraction Coverage refers to the proportion of the sky that is covered by clouds at a given time and location. It is typically expressed as a percentage (0% meaning a completely clear sky and 100% meaning total cloud coverage). FSOC sites at more southern European latitudes experience lower cloud coverage on average.

TABLE 1 | Features of the German Optical Ground Station Network nodes.

	FOGATA	LaBoT	OGS-NBB	OGS-NSG (prelim.)	OGSOP-NG
Location	Almería, Spain	Trauen, Germany	Neubiberg, Germany	Neustrelitz, Germany	Oberpfaffenhofen, Germany
Min. satellite elevation [deg]	10	20	5	5	5
Height a.s.l. [m]	489	72	549	66	615
Primary aperture [mm]	600	700	700	700	800
Wavelengths (Rx) [nm]	1064, 1550	1064, 1550	1064, 1550	1064, 1550	589, 850, 1064, 1550
Wavelengths (Tx) [nm]	1530, 1590	1590	1590	1590	1064, 1590
<i>Standard compatibility</i>	CCSDS O3K, SDA	CCSDS O3 K	CCSDS O3 K	CCSDS O3 K	CCSDS O3K
Mean availability	65%	25%	34%	32%	34%

of Neubiberg, Munster instead of Trauen, Granada, instead of Almería. The cloud-free availability values will be compared to real-world experience using terminals aboard the upcoming missions SeRANIS [44] and CubeISL.

locations, besides Almería, show a higher correlation between each other than to the EONN sites. Correlations among locations belonging to different networks show the lowest correlation values.

Figure 5 presents the cloud fraction correlation values for every GOGSN and EONN location combination. The GOGSN

In Figure 6, the network-wide outage probabilities are shown for single and combined networks; outage probability is only

dependent on cloud blockage events. Hence, the GOGSN shows only a 84% cloud-free availability, while EONN shows a higher 95% availability. Despite having more OGS sites, the GOGSN has a higher correlation among locations, and German locations do not have the most favorable weather. The EONN has more locations in Mediterranean areas and a wide-spread distribution.

3 | Australasian Optical Ground Station Network: AOGSN

The AOGSN is a partnership between the Australian National University, the University of Western Australia, the Commonwealth of Australia represented by the Defence Science

and Technology Group of the Department of Defence, and the University of Auckland, New Zealand. The AOGSN is made up of existing and proposed research infrastructure including optical ground stations and advanced instrumentation technology to demonstrate networking capability across Australia and New Zealand [9]. This section describes the current node capabilities in Australia and site optimization for node establishment in New Zealand and then presents an analysis of the combined network.

3.1 | The Australian National University

The Australian National University (ANU) Quantum Optical Ground Station (QOGS) is a 0.7-m telescope designed for high-performance optical communication. With a small (<25 %) central obscuration and no corrector optics, the telescope is optimized for high-throughput transmission of visible and infrared optical signals. The QOGS is situated at the Mount Stromlo Observatory in Canberra, Australia, in a purpose-built facility. Instruments are hosted on either Nasmyth foci or on optical benches fed via Coudé beam path. The Coudé room can contain four large optical benches each addressable by optics individually, providing a stable and consistent environment to host both experimental optical instruments and established infrastructure. Multiple locations for optical benches enable equipment from partners, collaborators, and experimental infrastructure under development to access the telescope in an optimum fashion, with only a steering mirror needed to switch between instruments. The first optical communication downlink campaign started in April 2024 with first laser light received on 04/04/2024. The telescope is a high-performance PlaneWave Instruments Inc. RC700 [45] capable of tracking satellites in LEO with a minimum keyhole, even when fully loaded with additional payloads [46]. ANU has demonstrated adaptive optics enhanced quantum communication over a horizontal free-space link and developed adaptive optics for FSOC including satellite-to-ground links [47].

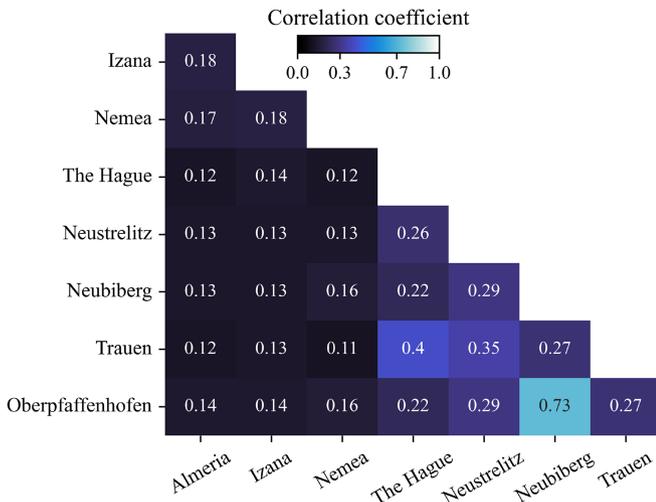


FIGURE 5 | Cloud fraction correlation matrix for the GOGSN and EONN locations, based on the ONUBLA+ software tool using a weather database generated from Meteosat Second Generation satellite measurements from 2009 to 2017.

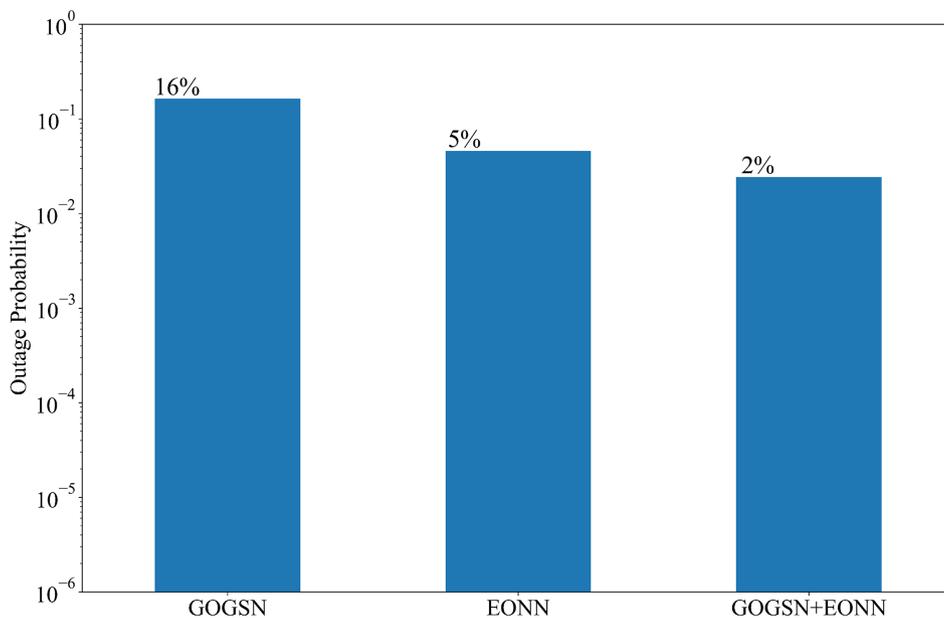


FIGURE 6 | Outage probabilities for different network configurations in Europe. The complement of this value quantifies the proportion of time during which at least one OGS has clear-sky visibility.

The ANU QOGS is currently being upgraded to include support for continent-scale optical communication networking with academic and industry partners. This includes support for both CCSDS and Space Development Agency (SDA) optical communication standards. The pulse-position modulation format in the CCSDS high photon efficiency standard will be supported from near-Earth orbits up to Lunar distances, with an advanced program of work supported by Australian Space Agency's Moon-to-Mars Demonstrator Mission program [48]. This capability will be unique in the Southern Hemisphere and enable future near-Earth missions to achieve high data-rates over optical communication links. On-off keying communication protocols will be supported with a commercial detector and modem solution to enable high-speed data rates to satellites in low Earth orbit. This solution will be further enhanced as ANU deploys cutting-edge adaptive optics to enable extremely high data rates and more advanced communication protocols including coherent and quantum communication.

3.2 | University of Western Australia

The University of Western Australia (UWA) is constructing TeraNet, a three-node optical ground station network within the AOGSN. Centered in Western Australia and funded by the Australian Space Agency's Moon-to-Mars Demonstrator Mission program [48, 49], the aims of the TeraNet project are to deploy the technologies needed to realize the potential of optical communications between ground and space and to develop a transportable ground station.

TeraNet builds on the success of UWA's demonstrations of free-space optical links for metrology and communications [50–54]. Demonstration highlights include (i) a SmartSat CRC funded project achieving robust single-mode fiber coupling between a deployable optical terminal on the ground and airborne

retroreflectors, (ii) a 100 Gbit s⁻¹ dual-polarization quadrature phase shift keying (DP-QPSK) link established across 700 m (1.4 km folded length) to a drone mimicking a LEO satellite pass [55], and (iii) links to both a fixed wing aircraft and a helicopter at 5 km line-of-sight distance (10 km folded [56]). Through the Australian Space Agency's Moon-to-Mars Feasibility Mission [57], a precursor to the current Moon-to-Mars Demonstrator Mission, a NASA-O2O compatible high photon efficiency link to a drone was demonstrated [58].

TeraNet-1, previously dubbed the Western Australian Optical Ground Station [59], is a 0.7-m PlaneWave Instruments Inc. CDK700 installed on the roof of the physics building at the UWA campus in Perth. It serves as the main research platform where the existing infrastructure and convenient location allow for rapid testing and innovation. The first downlink campaign using the DLR's Flying Laptop is ongoing with first light received on 20/05/2024. TeraNet-2 will be the centerpiece of TeraNet; it will be based on a PlaneWave Instruments Inc. RC700 and located at the Mingenew Space Precinct approximately 340 km north of Perth. This site experiences one of the lowest fractions of cloud cover in the world [20] and is home to NASA's MOBLAS-5 Laser Ranging Station, the most productive station in the International Laser Ranging Service network.

TeraNet-3 is a deployable ground station consisting of a PlaneWave Instruments Inc. CDK17 (0.4 m aperture) mounted on the back of a dual-cab utility vehicle (Figure 7). It is being designed for rapid deployment to demonstrate the benefits optical communications can bring to remote/transient situations such as mine sites, disaster zones, or forward defense deployments. First downlink commissioning is planned for 2024 and will be conducted at ESA's New Norcia Station using DLR's PIXL-1 spacecraft. In addition to serving as a demonstrator for a rapidly deployable ground station, TeraNet-3 will also serve as a vehicle for outreach activities, both figuratively and literally.



FIGURE 7 | The TeraNet-3 mobile optical ground station.

All three TeraNet nodes will be equipped for direct detection optical communications to and from LEO, with DLR providing access to its OSIRIS payloads for commissioning. Thales will also provide access to its Optel- μ terminals, subject to availability. TeraNet-1 will also incorporate superconducting nanowire single-photon detectors, making it suitable for high-photon efficiency lunar communications in the future. TeraNet-2 will additionally be equipped with higher order adaptive optics for advanced capabilities, including coherent communications and optical timing and positioning. By the end of the Moon-to-Mars Demonstrator Mission, TeraNet will transition to commercial operations.

3.3 | Defence Science and Technology Group

The Defence Science and Technology Group (DSTG) optical ground station, currently under development, is located in Adelaide, South Australia. A major focus of activities is the assessment and investigation of mitigation strategies for the detrimental effects of the Earth's atmosphere on optical satellite communications. The research emphasis is on sites at low altitudes, which may be desirable locations from an operational perspective but where the effects of atmospheric turbulence are more significant.

The optical telescope is a 0.5-m diameter Dall-Kirkham telescope with gold coated mirrors and an L-600 tracking mount manufactured by PlaneWave Instruments Inc. Single mode fiber collimators, to be used for the uplink transmitters, are currently under development and will be mounted on the sides of the main telescope. For initial laser downlink demonstrations, an optical communications payload assembly (Figure 8) has been constructed, comprising a beam-splitter, an InGaAs camera, and an avalanche photodetector based communications receiver. The camera, interfaced to the beam-splitter transmit port, is used for alignment and link acquisition and tracking. The communications' receiver is interfaced to the beam-splitter reflected port. The assembly is mounted at the telescope's focus using a lens relay in each arm, with focal lengths selected to adjust the respective FOVs for the acquisition camera and the photodetector. In future, the telescope will be augmented with an adaptive optics payload developed in collaboration with ANU.

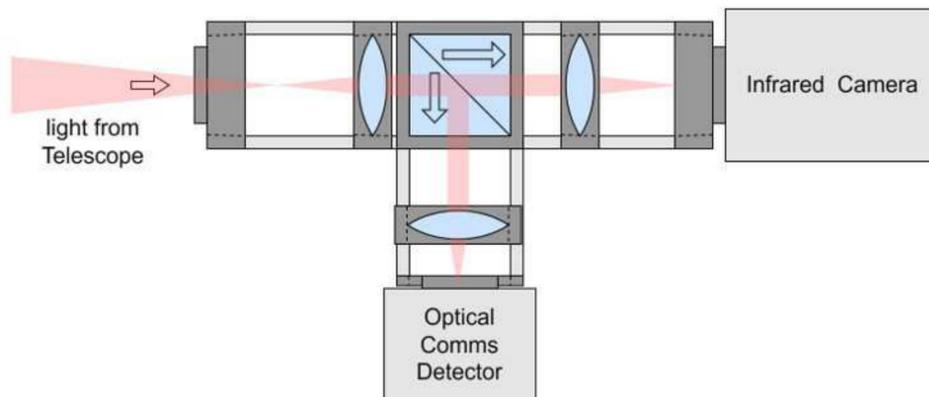


FIGURE 8 | Diagram of the DSTG telescope optical communications payload.

3.4 | New Zealand Optical Ground Station Sites

A feasibility study for establishing an FSOC ground terminal in New Zealand as part of an international network was conducted in 2021 [60]. A brief summary follows for each of the possible sites that were assessed based on access requirements and existing facilities. The results of the assessment are then combined with CFC statistics from ANU.

The most northerly site initially considered was the University of Auckland field station at **Ardmore**, in the North Island. The site is flat and at low altitude with power, communications, utility services, and a basic mechanical workshop facility. The other North Island site is **Urenui**, which is a settlement on the west coast, 300 km south of Auckland. It lies in a region of lower than average cloud fraction coverage.

Near the northeastern tip of the South Island, the **Black Birch** Observatory site was the center of operations for an earlier site testing program for an astronomical observatory [61], but no facilities remain. **Birdlings Flat** is an area 40 km south of Christchurch that is the site of the Tāwhaki National Aerospace Centre. Further south, the University of Canterbury operates the **Mount John Observatory** in Otago, which is the home of four professional telescopes. Road access is excellent, mechanical and electrical engineering facilities are available onsite, and there is accommodation for extended stays by observers and staff.

Approximately 180 km southwest of Mt. John, there is an Atmospheric Research Station (ARS) at **Lauder** in Central Otago. The ARS has an extensive array of existing atmospheric sensing equipment, including spectrometers, radiometers, all-sky cameras, and clear-sky detectors. **Kopuwai/Obelisk** is a mountain peak 60 km southwest of Lauder. The peak is accessed by an unsealed road which is one of the highest in the country. Finally, at the southern tip of the South Island, the **Awarua** satellite ground station (SGS) is located approximately 10 km from Invercargill, New Zealand's southernmost and most westerly city.

Figure 9 shows a plot of cloud fraction coverage for New Zealand. It is observed that the lowest values occur in the mountainous regions in the South Island of the country.

An outcome of the initial feasibility study was that two additional sites were considered. These were **Waiheke Island**, 50 km east of Auckland, and the satellite communication station near **Warkworth**, 60 km north of Auckland.

A site diversity analysis for the potential OGS sites was then performed, and the results are shown in Figure 10. The spatial correlation analysis used data obtained during 2015–2022 using the Advanced Himawari Imager (AHI) on Himawari-8 [20]. Two

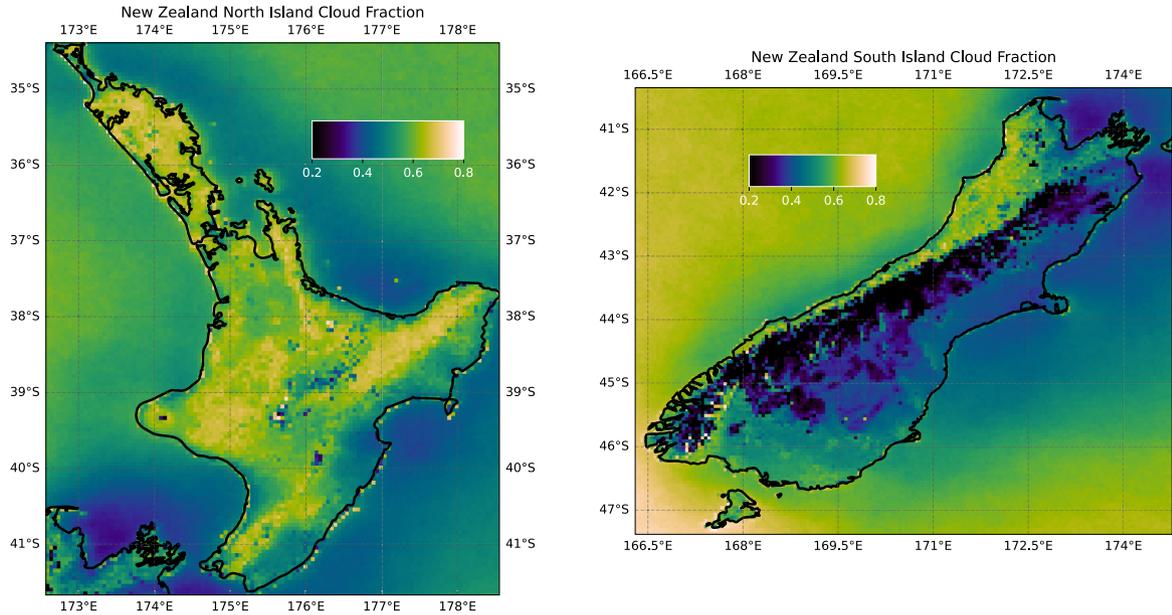


FIGURE 9 | Cloud fraction coverage for New Zealand, showing the North Island (left) and South Island (right). A CFC value of 1.0 in this plot corresponds to 100% cloud coverage.

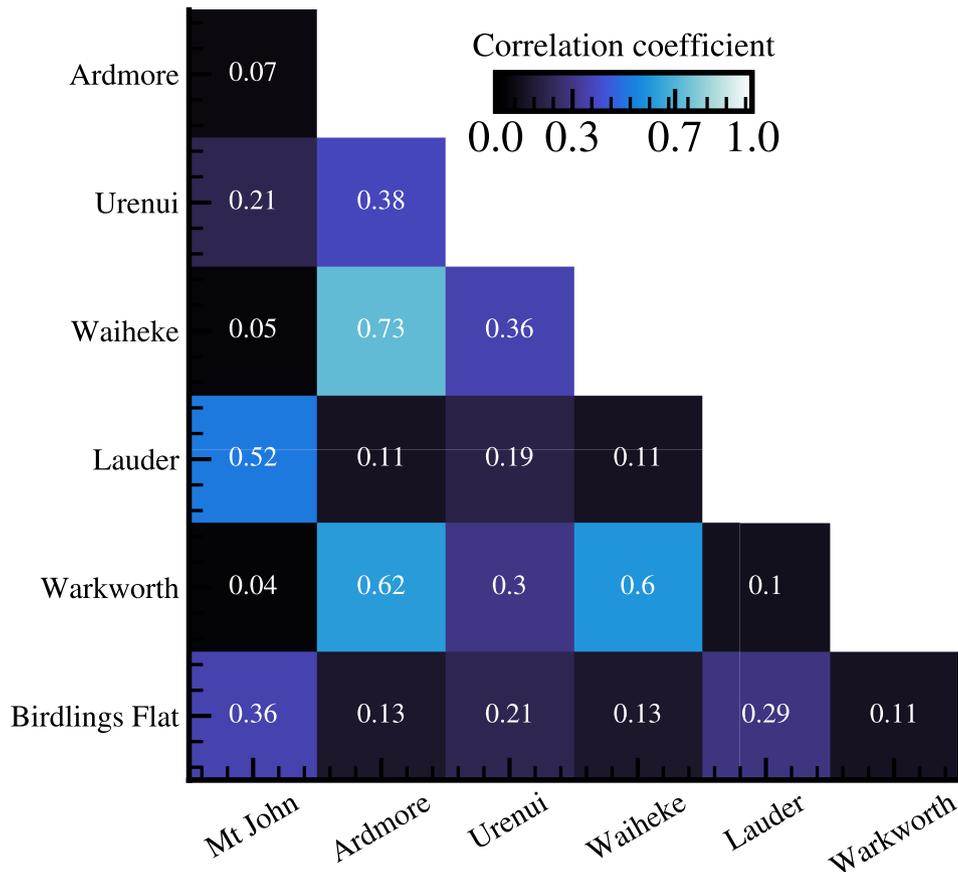


FIGURE 10 | Cloud fraction correlation matrix for prospective New Zealand OGS locations. Measurements with AHI/Himawari-8 from 2015 to 2022.

sites, **Black Birch** and **Kopuwai**, are shown in Figure 11 but excluded from further analysis. The **Awarua** site was also considered in the feasibility study but was similarly excluded from the site selection.

Sites that are geographically close, such as the Auckland regional sites of Ardmore and Waiheke, show relatively high correlation values, as would be expected from sharing similar weather patterns. These data are useful when considering where a second ground station node could be built in New Zealand, based on the location of a first ground station. Additional ground station nodes would improve the reliability of the NZ contribution to the Australasian network. A complete three-site diversity correlation analysis of NZ nodes remains for future work.

In order to accelerate activity and capability in FSOC operations, New Zealand researchers have developed a prototype FSOC ground station at the Ardmore site, named the Taiaho Observatory [62]. A 3-m observatory dome (PD10, Technical Innovations) has been installed and houses an L-350 mount from PlaneWave Instruments Inc. The intended payload comprises a DLR SOFA unit [34] and an RC telescope with a 0.25-m primary. Installation of the OTA and SOFA unit is planned for Q4 2024. For calibration and early testing purposes, a secondary telescope (0.3-m LX200GPS, Meade Instruments) has been mounted on the L-350. A set of three all-sky cameras, developed by National Institute of Water and Atmospheric Research Ltd (NIWA), have been deployed at various sites, including one at Ardmore. These cameras generate cloud image data, which is being used in current research into short-term (i.e., on the time-scale of a typical LEO satellite pass) cloud coverage forecasting. Finally, in order to progressively characterize the Ardmore site as an OGS, an integrated seeing monitor (Miratlas S.A.S) was installed, which comprises a turbulence monitor and weather station. A paper is in preparation where the cloud coverage statistics for New Zealand will be compared with estimates derived from all-sky camera data.

3.5 | Combined Australian–New Zealand FSOC Network Performance

An outage probability analysis has been performed to optimize the AOGSN configurations and highlight the improvements gained from adding New Zealand OGS nodes to extend existing Australian OGS sites. The analysis considers a network-wide outage as the situation when all sites are simultaneously blocked by cloud. Networks in Australia and New Zealand have been assumed as base or full variants, with the set of sites corresponding to these configurations in the title of Figure 12. Outage probability estimates are made using the spatially correlated neuron spike model and with cloud fraction data from the Visible Infrared Imaging Radiometer Suite aboard the Suomi National Polar-orbiting Partnership satellite and cloud fraction covariances from the Advanced Himawari Imager aboard *Himawari-8* [20]. The nodes used in Figure 12 can be identified in Figure 11.

A particularly important result in Figure 12 is the 3% outage probability of the existing 3 OGS nodes in Australia being reduced to 0.57% with the addition of two OGS in New Zealand, that is, Ardmore and Mt John. Note that this analysis only considers minimization of outage probability and not relative improvements to total throughput or coverage area. New Zealand provides benefits to longitudinal coverage, which are not expressed by Figure 12.

It is noted that the outage probability analysis presented for the GOGSN, EONN, and their combination (Figure 6) is only dependent on cloud blockage events. The same is true for the analysis for the various embodiments of the AOGSN (Figure 12). The sources of cloud coverage data differ only to the extent that different geostationary Earth orbit (GEO) weather satellites were used. The methods for outage probability differ in that ONUBLA+ either uses the empirical outage estimate over the measurement period or assumes independence, while the Australasian outage probabilities were computed using the semi-analytical Monte Carlo solution of Birch et al. [20]. Direct comparisons between

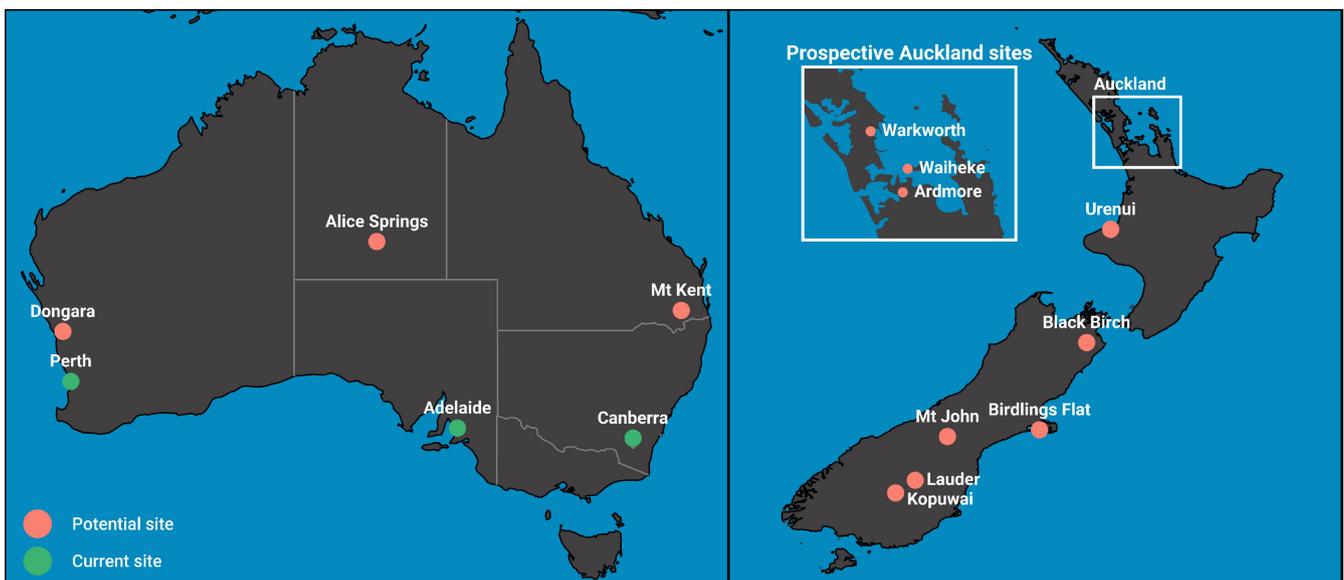


FIGURE 11 | The proposed Australasian Optical Ground Station Network [6, 20], with nodes across Australia and New Zealand. Green dots indicate current OGS while red dots indicate potential sites.

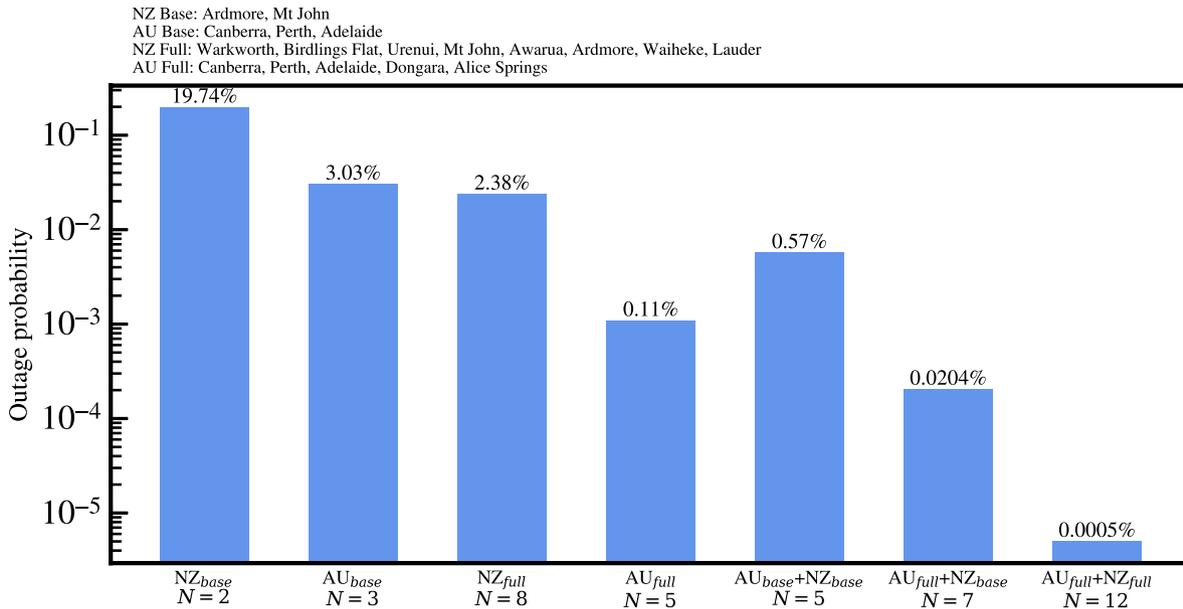


FIGURE 12 | Outage probability for numerous AOGSN configurations. This is defined as the probability that all nodes in a network simultaneously suffer an outage due to cloud fraction and is computed using the spatially orrelated Bernoulli model [20]. Cloud fraction data are from the *Himawari-8* geostationary weather satellite.

outage probabilities computed from each methodology are not available. However, a valid quantitative comparison of varying network performance within each set of results is possible.

4 | Network Status and Future Development

A summary of the major scientific results achieved so far by the OGSN referenced in this work or status is presented in Table 2. Future research work includes improving the throughput of the optical channel for FSOC, securing it using quantum technologies, and maximizing the resilience of FSOC ground segment networks. This section summarizes some of the work underway in Germany and Australasia towards these goals.

4.1 | German FSOC Research

Current research areas associated with the FSOC ground stations network in Germany include measurements of the optical channel to analyze and forecast the availability of optical links in dependence on the geographical location. The results will facilitate updates on existing, or the definition of new, site diversity and channel models. Basic research on the optical channel is the foundation for further developments of FSOC systems. For example, a precise characterization of the optical channel facilitates the development of new transmission techniques such as multiple-input multiple-output (MIMO) for free space optical (FSO) systems [64]. A related field of research is the development of new forward error correction codes to counter atmospheric disturbances.

4.2 | Adaptive Optics

FSOC systems use adaptive optics to improve performance [47, 65]. The Mount John Observatory (MJO) is one of the

leading candidates for an OGS in New Zealand, and as there are existing installed telescopes, work has commenced on developing AO capability at this facility. A low-order (tilt) closed-loop adaptive optics system has been installed on the Boller & Chivens telescope at MJO [66]. System design parameters were sourced from earlier work developing a turbulence site profile [67]. This system was originally developed to partially correct for the adverse effects of imaging space debris through the Earth's turbulent atmosphere [68]. Target objects included large, defunct satellites, in both LEO and GEO. More recently, the tilt AO corrector was used to improve the stability of fringe patterns generated by a modified Michelson interferometer used to measure spatial coherence of satellites for space domain awareness. The tip-tilt adaptive optics system was used to stabilize interferometric images of possible point-source objects, such as the Capstone capsule, within a field-of-view that was based on estimated positions of the capsule. The basic principle behind the approach was to measure spatial coherence of essentially point source objects using the interferometer to provide positional data. However, the 0.6-m telescope used for this research was too small to capture and resolve interferometric data. However, the resolution was sufficient to be able to verify positions within the FoV of lower magnitude (brighter) point source objects.

4.3 | Quantum Secured Communications

QKD is a method in which communicating parties generate and share a secret key where the presence of an eavesdropper can be inferred by fundamental quantum mechanics [69] and requires FSOC to enable quantum security on a global scale using satellites. QKD via free-space links between Earth and space has been demonstrated [70] in which the Micius satellite distributed secret keys between two optical ground stations in Xinglong, China, and Graz, Vienna.

TABLE 2 | Significant results and/or planned advances from the partner institutes.

Partner	Achievement	Completion or reference(s)
DLR	AO-predistortion to geostationary satellites and OSIRIS terminal communications to LEO	[25–28]
	Deployment of SOFA units to FOGATA, LaBoT, and (planned) OGS-NBB, UoA, and OGSOP-NG	In progress
	OSIRISv3-Terminal (Ov3) developed Demonstration of 10 Gbit s ⁻¹ LEO downlink	Demonstrated in lab at 10 Gbit s ⁻¹ Pending mission availability
ANU	ANU QOGS completed	December 2023 [63]
	First downlink with qogs from FlyingLaptop	April 4, 2024
	QOGS upgraded with complete lunar communications system	(Planned) 2025
	QOGS upgraded with full adaptive optics for high-speed data downlinks	(Planned) 2026
UWA	First downlink with TeraNet-1 from FlyingLaptop	May 20, 2024
	100 Gbit s ⁻¹ DP-QPSK 1.4 km link at LEO angular tracking rates	[55]
	TeraNet-3 (deployable ground station) first downlink	(Planned) 2024
DSTG	OGS comprising 0.5 m primary	In progress
NZ FSOC	Taiaho Observatory established, University of Auckland	[62]
	First FSOC downlink from DLR OSIRIS terminal	(Planned) Q4 2024

Quantum link-based FSOC systems typically support three channels that propagate signals through the atmosphere, that is, an optical link at 1550 nm, a beacon, also at 1550 nm, and a quantum channel at 850 nm. Experimentation into a fifth-order dual-mirror (woofer-tweeter) AO system is underway at the Department of Electrical & Computer Engineering at the University of Canterbury to provide enhanced performance at these wavelengths.

Each optical ground station discussed in this work will in principle be compatible with QKD though any particular ground station's suitability to perform QKD using a particular space mission would need to be assessed based on the compatibility of transmit and receive apertures. For example, a 0.3m transmission aperture on a LEO satellite would require a *meq* 1 m receive aperture to achieve a positive secret key rate using continuous variable (CV) QKD [71, 72]. Further network simulation of this type will be necessary to refine the technical specifications of a QKD-capable network.

4.4 | Network Funding and Governance

A Memorandum of Understanding (MoU) was signed in October 2022 between the Australian National University, the University of Western Australia, the Defence Science and Technology Group of the Department of Defence, and the University of Auckland. The MoU recorded the intention of the parties to establish the organizational structure, governance mechanisms, and operational model for the AOGSN, subsequently to be formalized in a Consortium Agreement. The Consortium Agreement is currently under development.

The DLR has been an advisor to the parties of the AOGSN since its inception. New Zealand FSOC research activities have been

supported by New Zealand's Ministry of Business, Innovation and Employment (MBIE) via a series of grants under MBIE's Catalyst Fund [73]. This funding became available following the signing by MBIE and DLR of a Letter of Intent (LoI) at the International Astronautical Congress in Bremen in 2018 to enable joint research collaboration.

The Australian SmartSat Cooperative Research Centre (SmartSat CRC) is “a consortium of universities and other research organizations, partnered with industry that has been funded by the Australian Government” [74]. Most recently, the New Zealand Space Agency (NZSA) and SmartSat CRC signed a MoU to collaborate on joint research and development projects. Under that MoU, funding will be made available to joint New Zealand and Australian projects to “explore how to coordinate a network of Australasian optical ground stations that can actively support space exploration” [75].

The Australian Space Agency has supported the development of the AOGSN with several funding awards across Australia including in 2023 awarding funding to ANU and UWA individually for optical communication networking programs.

4.5 | Network Management

Once operational, a network such as the proposed AOGSN has an estimated data bandwidth capacity in the tens of terabits per day [20]. Such a network will require significant data storage and processing management, with the additional complication of being highly distributed by design. This spatial distribution will mean that each node will require significant local data storage rather than relying on centralized or cloud-based storage.

They will also not be able to rely heavily on centralized control systems. These requirements are the same as those necessary for the implementation of Delay Tolerant Networking (DTN) protocols, a set of standards to embed information into datastream headers that make transmission through different network nodes possible despite disconnections and delays. Nodes that do have reliable terrestrial networking will be able to take advantage of the ability to stream data to centralized storage and processing facilities. The network architecture will also be designed to be compatible with relevant CCSDS AND SDA standards.

Network testing and evaluation will be a multi-stage process, beginning with general network simulations using software such as NS-3 or OPNET [76]. The next steps will include DTN-specific and OGSN-specific simulations to validate the network capabilities, utilizing more specialized simulations such as ONE [77]. This will include OGS hardware simulation/integration (e.g. expected delays from target selection to link initiation due to tracking time), unexpected link disruption, simulated link handover between nodes, short- and long-term weather forecasting to enable link planning, and data management (including delivery, validation, and deletion). The penultimate testing will encompass the complete OGSN hardware and software stack but using simulated satellite passes to feed data into the network, before finally testing with on-orbit assets such as those mentioned in Section 2.1.

Software and hardware resilience to long-term, automated operation will also be important factors to assess, particularly for more remote nodes. Mitigation of these challenges will include enabling nodes to operate semi-independently, providing sufficient computational resources to allow tracking and up/down-link operations, the implementation of software fail-safes, as well as providing redundant/backup hardware on site to minimize downtime caused by component failure.

Similar to commercial data centers, OGSN will likely be affected by factors such as network congestion or resource contention. The limitation of each node to track a single target will necessitate a system of prioritization for temporally-close satellite overpasses, possibly requiring the use of less-optimal nodes to attempt links with lower priority targets. The scheduled nature of satellite passes should eliminate unexpected network loads, simplifying network resource management.

4.6 | Network Expansion

The utility of each ground station could be extended by connecting to wider ground based fiber networks to link a satellite with multiple ground locations near each optical ground station. Moreover, the distributed network of OGSs constitutes an excellent test-bed to showcase new application scenarios and demonstrate new hardware and software developments.

A natural expansion of the proposed network would be to include the Antarctic continent in order to provide the continent with a high-bandwidth solution that it currently lacks. Australia and New-Zealand are active in research in Antarctica, occupying coastal locations including Casey, Mawson Davis, and Scott bases. These provide possible locations to start expanding the

network to the Antarctic region thanks to the existing logistics and relative ease of access. The geographic location of the continent is advantageous to this technology [6] as polar-crossing orbits are favored by many satellite operators, and therefore there could be many overhead passes of a polar station per day. The interior of the continent, where internet access is the most challenging, has ideal weather conditions for such technology. The skies are among the clearest in the world, with 20% cloud cover [78]. There is also ample evidence that seeing conditions are excellent which attracts astronomers to the continent [79–81]. Even during the daytime, which can last for months, there are periods where the seeing drops to less than 1 λ due to the thermal balance between the atmosphere and the highly radiating ice.

To establish a truly global optical communication ground station network, the German and Australasian networks could be combined. The success of such an endeavor will require the continued exchange of best practices and knowledge, and progressively increasing coordination between each network.

5 | Discussion and Limitations

This work focuses on aspects of ground station networking that are somewhat unique to FSOC ground station networks. While heavy cloud cover and other atmospheric effects can impact some radio-frequency bands, their effect is more drastic on FSOC links. As such the study is limited to the operational and technological considerations of how and where FSOC ground stations should be deployed to enable networking in the context of providing site diversity. This is only part of the picture and the authors acknowledge that there are several other aspects of networking ground stations that must be included to develop a complete picture of FSOC ground station placement. Some of these aspects are controllable: for example, the placement of fiber-optic cable and other required infrastructure to enable these ground stations. Network topology and fundamental architecture need to be included but will depend on many factors that are individual to existing satellite communication businesses and governments and are hence excluded from consideration in this study.

The networks described in this review are still under development and without equivalence in scale. The work described provides an overview of developments to enable a global scale OGSN through research partnerships to demonstrate the increased capacity promised by OGSNs. Funding for such research and development has been prioritized in Australia and New Zealand, indicative of a regional recognition of the potential of global FSOC. Challenges remain, however, and not merely in the technological space of instrument design and establishing individual OGS installations. Substantial work remains in the administrative space for developing operational collaborations within and across national borders. This work would consider to what extent the characteristics of existing global research networks, comprising shared infrastructure and research outputs [82–84], can be adapted for a global FSOC network. To start to tackle these challenges, a research project led by the University of Auckland and the University of South Australia has been funded to research the potential modes of operation and governance of an Australasian network of OGS nodes [85].

Each separate FSOC research initiative reported draws financial support from a range of sources, such as national or state government, university, or commercial interests. Access to experimental data generated by these research activities can be restricted by the funder or funders. The extent to which access is made available to data or other research outputs from a network comprising research institutions is a matter of current discussion. Readers interested in collaborative FSOC research using the resources of one or more of the host institutions, including data downlinks, are encouraged to contact the relevant author(s) for more information.

6 | Conclusions

Spacing ground stations in longitude across the globe provides favorable network access to satellites for typical orbit choices for a telecommunications satellite cluster. Australia and continental Europe are two large land masses extended longitudinally and are developing technologies and operational facilities suitable for inclusion in an optical communications ground station network. The research and commercial opportunities in FSOC have resulted in increased funding for this area in Australia and New Zealand as Germany continues to build upon its history of research leadership in FSOC.

Site testing is a key ingredient in establishing where optical ground stations might be most favorably placed in an FSOC network. This work presented the two-site correlation values for several locations in New Zealand, derived from an analysis of satellite cloud coverage data. The analysis also included measures of outage probability of a network comprising various combinations of FSOC terminals wholly within each of Australia and New Zealand, and across both nations. The addition of two New Zealand nodes in an Australian network decreased the outage probability of the combined network from $m3\%$ to $m0.6\%$. Owing to New Zealand's geographical north-south orientation, additional FSOC terminals would generally only add to the resilience of the network against local weather patterns and would not add more coverage as would come from extending the network further in longitude.

Author Contributions

N.J.R. contributed to Sections 1, 3.4, 4.5, and 6. J.A. contributed to Section 3.4. T.T. contributed to Section 4.6. M.B. contributed to Sections 1 and 3. J.E.C. contributed to Sections 1, 3.4, and 4.6. S. Weddell contributed to Section 4.2. M.T.S. and O.T. contributed to Section 4.3. R.T.S. and A.K. contributed to Sections 2.3 and 4.1, K.M. contributed to Section 3.3. D.G., J.R., and M.T.K. contributed to Sections 2 and 4.1. S.R. contributed to Section 2.3. F.B., K.F., K.G., E.K., A.L., C.Q., S.S., M.S., K.W., and S. Walsh are senior group leaders and/or have responsibilities for research groups.

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Conflicts of Interest

The authors declare no conflicts of interest.

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