Deep Space Communication with the ANU Optical Communications Ground Station

Michael Copeland[a], Francis Bennet[a], Marcus Birch[a], Kate Ferguson[b], Doris Grosse[a], Elisa Jager[a], Noelia Martinez Rey[a], and Tony Travouillon[a]

[a]Advanced Instrumentation Technology Centre, Research School of Astronomy and Astrophysics, Australian National University, Canberra, Australia
[b]ANU Institute for Space, Australian National University, Canberra, Australia

ABSTRACT

The Australian Nation University (ANU) Quantum Optical Ground Station (QOGS) has been constructed in Canberra, Australia. Instrumentation is under development to enable lunar communications with QOGS. A receiver system and beacon transmitter will be installed on the telescope that is compatible with the Optical to Orion (O2O) terminal that will be onboard the Artemis II mission. Communication with spacecraft beyond the Moon is also possible by moving the receiver hardware to a larger telescope. The ANU operates Siding Spring Observatory where a 3.9 m or 2.3 m telescope could be used for deep space communications.

Keywords: Free space optical commuinication, ground station, instrumentation, lunar communication

1. INTRODUCTION

Free space laser communication offers several advantages over traditional radio frequency (RF) technologies for deep space communication. Higher data rates over longer distances are possible with the space terminals requiring lower size, weight and power (SWaP). The significantly smaller wavelengths of an optical signal means that the beam divergence is much smaller than RF communications, meaning less power is required to transmit over a long distance.

While there are advantages of free space optical communications over RF, there are some limitations that must be considered. Adverse weather such as cloud, rain or strong turbulence can limit the availability of a ground station site for links. Outages due to poor weather can be minimised by diversity in the ground station network to ensure there is always an available site for a link.[1] The small divergence of the optical signal also means the terminals require very precise pointing to maintain a link.

Over long link distances, such as to the Moon and beyond, an efficient modulation scheme is needed to make use of the photon starved signal. Pulse Position Modulation (PPM) is one such scheme used in the Consultative Committee for Space Data Systems (CCSDS) high photon efficiency (HPE) standard. In PPM the information is encoded by the temporal location of a single pulse within a slot.[2,3]

2. ANU QUANTUM OPTICAL GROUND STATION

The Quantum Optical Ground Station (QOGS) was completed and formally opened in December 2023. QOGS is located at Mt Stromlo Observatory in Canberra, Australia. The QOGS telescope is a 70 cm Planewave Instruments RC700 Ritchey-Chrétien design which is installed in a 6.5 m dome. Figure 1 shows a cutaway view of the building and dome interior. The facility features two levels with an optical lab on the bottom level and the telescope is mounted on a pier extending from a optical lab to the upper level. In the future a coudé path will be built to direct the light collected by the telescope to the optical lab. The are four ports in the pier for the beam to exit to allow multiple instruments to be set up in the lab and selected by a rotating mirror to a given port.[4,5] The completed facility is shown in figure 2 along with the RC700 telescope installed in the dome.

Send correspondence to Michael Copeland
E-mail: michael.copeland@anu.edu.au

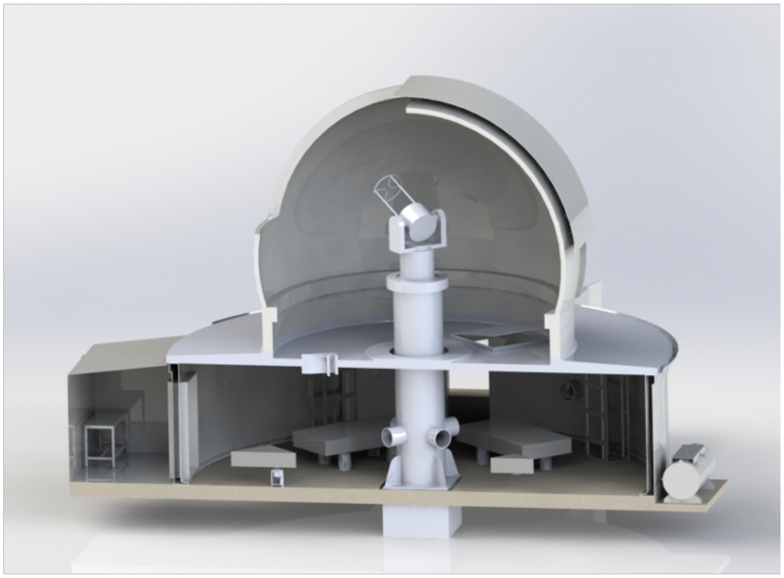

Figure 1. Cross sectional view of QOGS facility with the telescope and dome on the top level and optical lab below.

The initial instrumentation will be installed directly onto the RC700 which has two Nasmyth ports and mounting points for piggyback instruments. The RC700 was developed with input to improve utility for laser communications applications. The mount has been strengthened to hold additional weight of 135 kg on each Nasmyth port and 135 kg on the top and bottom mounting surfaces on the OTA. There is also a relatively small central obscuration and no corrector optics, enabling higher throughput through the telescope which is important for photon starved links. The same RC700 telescope is in use at the Low Cost Optical terminal (LCOT) at Goddard Space flight Center.[6]

3. LUNAR COMMUNICATIONS WITH QOGS

The lunar communication instrumentation under development for QOGS is to be compatible with the Optical to Orion (O2O) terminal on the Orion spacecraft for the Artemis II mission.[7] The geographical location of QOGS in Canberra, Australia gives expanded coverage with the existing ground stations in North America to allow fo

Figure 2. Left: Outside view of the completed QOGS facility. Right: The RC700 telescope installed on the pier inside the dome.

more link opportunities. An additional ground station site also provides redundancy if there are link outages due to poor weather.

The primary objective for the lunar communications instrumentation on QOGS is to provide downlink support for lunar missions. This will reduce risk to the project to ensure the system can be operational to support lunar missions. Development of the transmitter will still be ongoing so the capability for bi-directional communications can be added in the future. For a receiver system, the ground station still requires the ability to transmit a beacon to establish a link with the spacecraft. Therefore the optical assembly for the transmitter will still be built so the beacon can be produced. Figure 3 shows a render of the receiver and beacon transmitter assemblies installed on the RC700.

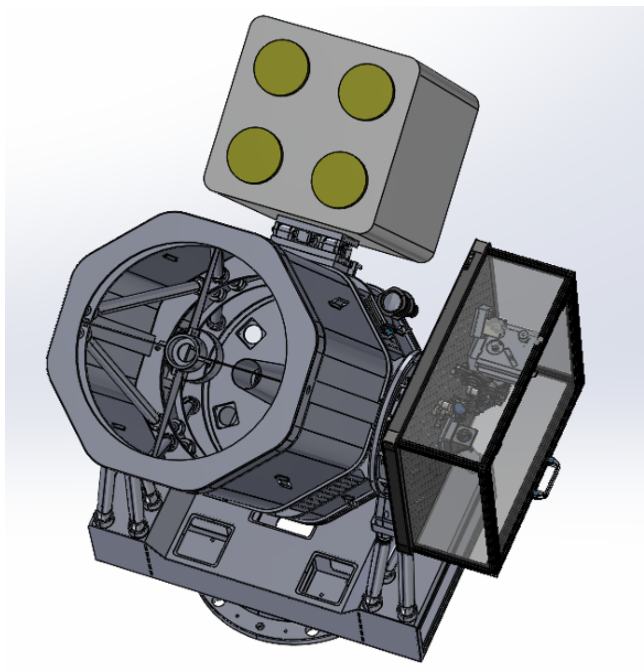

Figure 3. Render of RC700 telescope with receiver instrument installed on the Nasmyth port and beacon transmitter installed as a piggyback.

3.1 Receiver Design

The receiver system will be installed on one of the Nasmyth ports of the RC700. The layout of the receiver is shown in figure 4. The system design is relatively simple and is comprised on mostly off the shelf parts.

The light collected by the telescope is directed to the Nasmyth port and a fold mirror folds the beam onto the plane of the breadboard. At the Nasmyth focus of the telescope is a iris which can be used to reduce off axis light entering the receiver to reduce background noise. After the focus is a second fold mirror an a lens to collimate the beam. The collimated beam is then reflected off a fast steering mirror (FSM) which is located in the pupil plane of the telescope. The FSM is used to provide fine steering to maximise coupling of the signal to a fibre for detection in the receiver system.

After the FSM the beam passes through two motorised filter wheels which can be used to select different optical filters. The addition of the filter wheels allow for flexibility in the receive optical assembly for different spacecraft. Filters for different downlink wavelengths can be selected and neutral density filter can also be added if required when conducting links with low Earth orbit (LEO) satellites where the photon flux is high.

A beamsplitter after the filter wheel is used to reflect 98% of the signal to a fibre coupler for detection. The remaining 2% is transmitted through the beamsplitter and onto a camera which is used to drive the FSM in a closed loop.

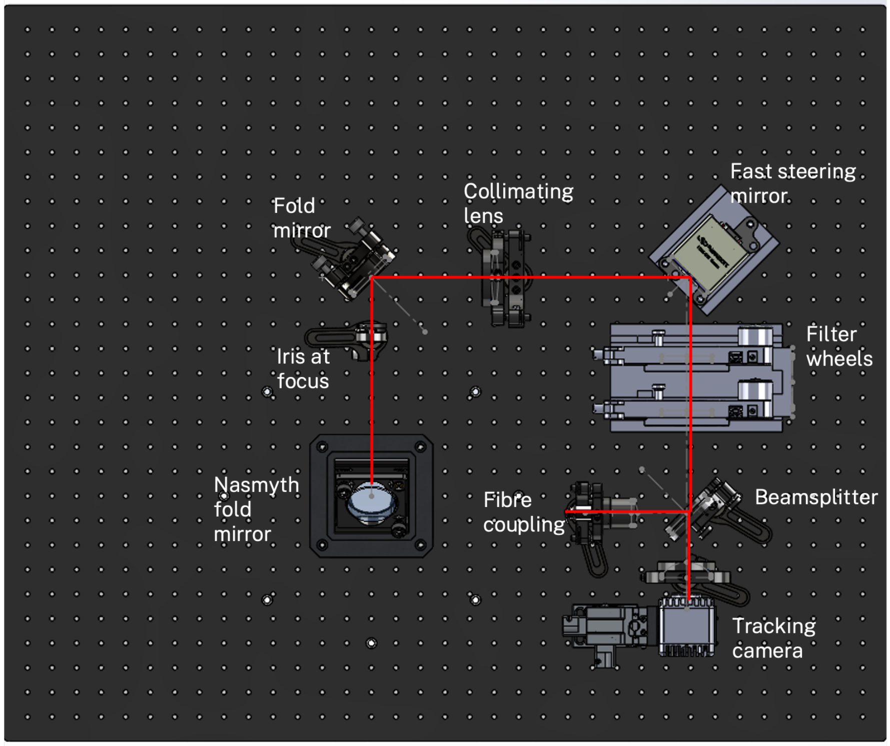

Figure 4. Layout of the Receive Optical Assembly used to couple light collected by the telescope into a few mode fibre.

The fibre will be a few mode fibre (FMF) with a graded index core of around 20–30 μm diameter. The FMF will be routed through the telescope pier to the optical lab below containing the superconducting nanowire single photon detector (SNSPD). The FMF is selected to match the fibre within the SNSPD system as much as possible to minimise coupling losses. The SNSPD we have chosen for the receiver is a 16×1 array with a total detection area of 16×16 μm in size.

The PPM signal detected by the SNSPD will be demodulated with an FPGA receiver. An FPGA card combines the 16 output channels from the SNSPD and performs timing recovery, codeword alignment, and deinterleaving. A second card is used to decode the combined signal.[8]

3.2 Receiver Testbed

To test the functionality of the system and verify its performance, a testbed will be setup to create a PPM signal and emulate fading expected in the free space channel. Figure 5 shows a block diagram of the receiver test bed.

The PPM signal is generated on an FPGA board and is encoded to a laser with an electro-optic modulator. Some of the modulated signal is sampled to monitor the signal that is generated. The modulated signal is passed through an optical amplifier and though a channel emulator. The channel emulator features a variable attenuator to simulate the losses expected over the link to the moon and a second modulator which is used to simulate fading due to the effects of atmospheric turbulence. The signal is detected by the SNSPD array and the signal decoded in the FPGA receiver.

3.3 Beacon Design

The beacon system will be dedicated optical system which is mounted as a piggyback on the RC700. The optical assembly for the beacon will be designed so it can be used for a full transmitter in the future. The optical assembly will feature four identical and individually operated channels which are separated to minimise the effects of scintillation due to atmospheric turbulence and reduce the chances of fades occurring at the spacecraft.[9] Each channel will transmit a beacon signal and filler at up to 10 W of optical power. The beacon is modulated with

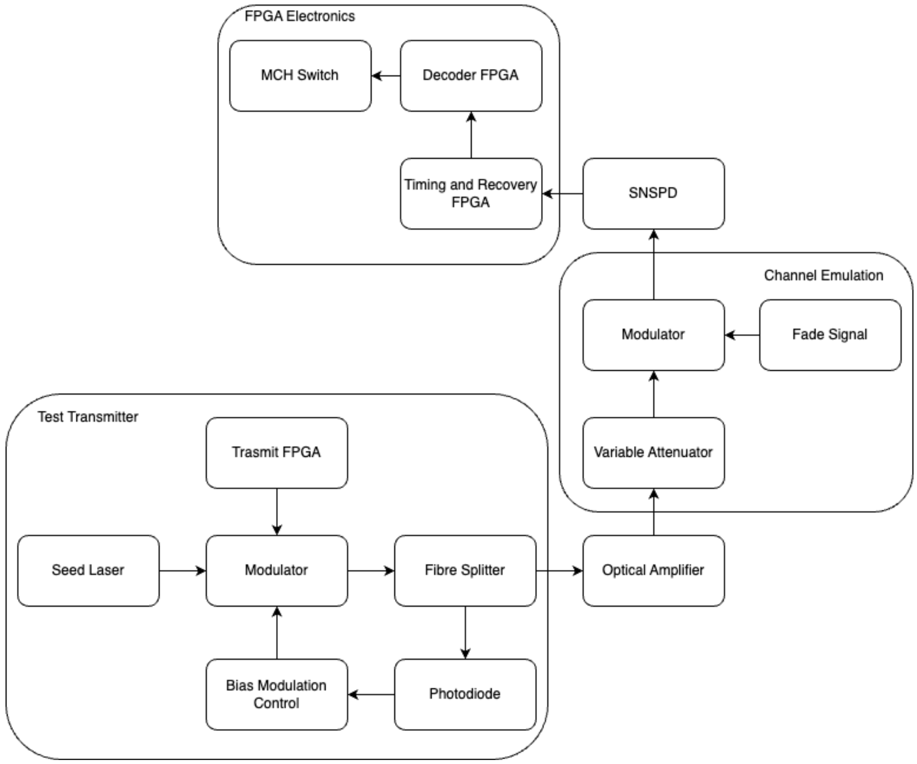

Figure 5. Block diagram of testbed to generate PPM signal in the lab and decode with the SNSPD and receiver FPGA electronics.

a 7 kHz square wave are requires an out of phase filler to be added before amplification so the amplifier will see a constant power. A block diagram of each channel in the beacon transmitter is shown in figure 6.

The optical design of the beacon system is shown in figure 7. The amplified beacon light is coupled into free space from a fibre and collimated. The collimated beam is transmitted through a dichroic beamsplitter and is

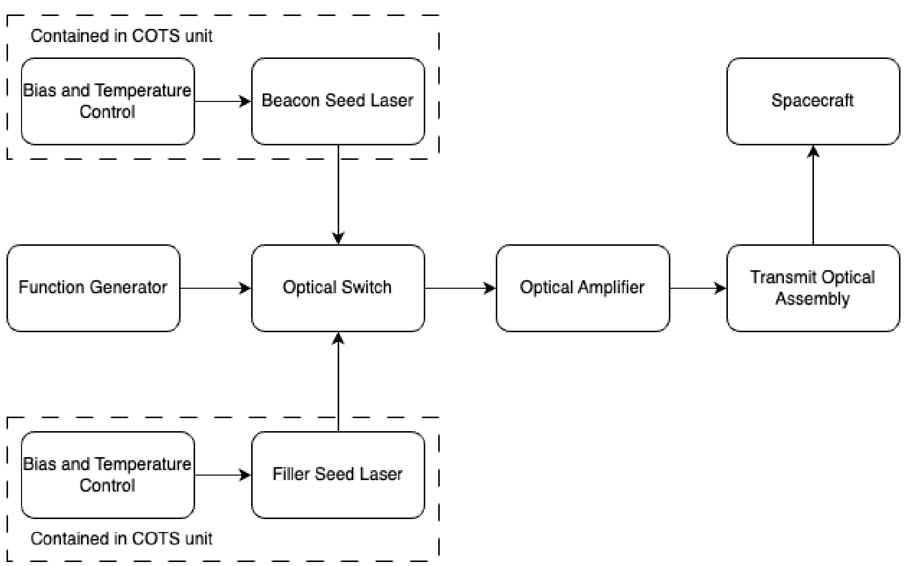

Figure 6. Block diagram of beacon transmitter architecture.

reflected off a FSM. The FSM is used to maintain pointing to the spacecraft and apply any corrections due to the point ahead angle. The beam is passed through a refractive telescope to expand to around 12 cm where it will propagate to the spacecraft. To control divergence of the uplink beam the negative lens position is controlled so the divergence angle can be increased to around 100 μrad during the acquisition phase.

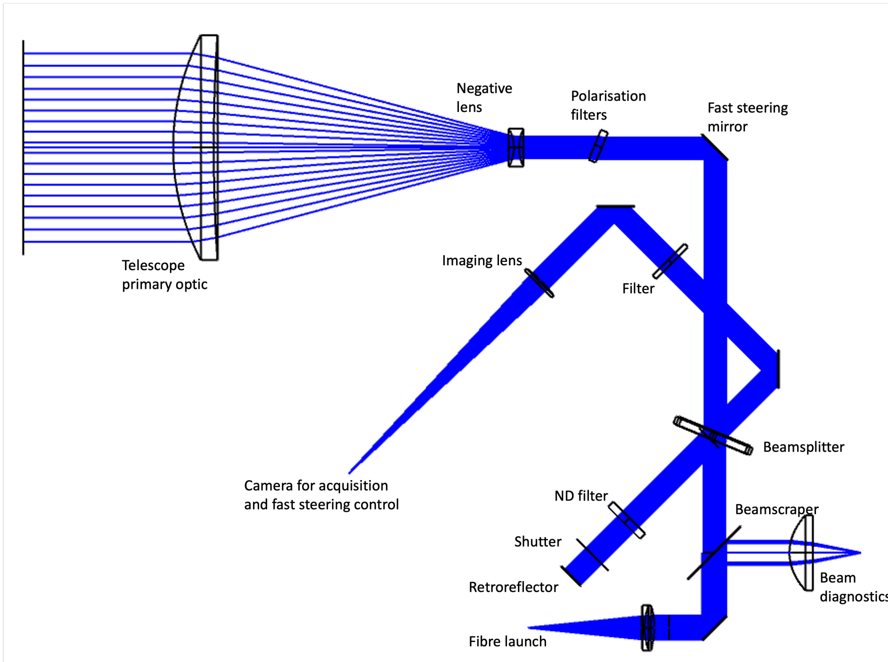

Figure 7. Optical layout of a single channel in the transmit optical assembly.

The downlink signal from the spacecraft is also collected by the beacon transmitter to assist with acquisition and maintain closed loop control of the FSM. The downlink beam is resized by the telescope and reflects off the FSM. The beam will reflect off the dichroic beamsplitter and is imaged onto a camera which is used to drive the FSM control loop.

During alignment of the optical system a small fraction of the uplink signal will be reflected off the beamsplitter and can be used to co-align the uplink and downlink beams. During normal operation a shutter is in place to act as a beam dump. When aligning the system, the shutter will be open to allow the beam to reflect off a retroreflector so the uplink beam can enter the tracking camera path. If each channel is pointed at a star then the uplink beam can be overlapped with the star image to achieve co-alignment.

4. COMMUNICATION BEYOND THE MOON

To communicate with spacecraft which are beyond the Moon a larger telescope is required to collect the faint signal. The ANU operates Siding Spring Observatory (SSO) outside of Coonabarabran, NSW. SSO operates many telescopes including the 3.9 m Anglo-Australian Telescope (AAT), and a 2.3 m telescope. Instruments can be installed on the AAT at Cassegrain focus or potentially at the end of the coudé path, and the 2.3 m telescope has an available Nasmyth port.

The receiver SNSPD and electronics from the QOGS receiver can be moved to either telescope at SSO to enable deep space communications. As the SNSPD is fed by a few mode fibre the system can be installed on any telescope and the receiver optical system designed to maximise coupling into the fibre. A similar concept to the QOGS receiver system will be followed with the optics modified to suit the AAT or 2.3 m telescope.

5. CONCLUSION

The ANU Quantum Optical Ground Station construction has been completed and development is underway to equip QOGS with instrumentation for lunar communications. The receiver will be installed on the Nasmyth port of the telescope and will be used to couple the collected light to a few mode fibre and feed the signal to an SNSPD array. Once the communications signal is detected by the SNSPD it will be demodulated with an FPGA based modem. To act as a receiving station the facility will also require a beacon transmitter for spacecraft acquisition and pointing. The beacon system will transmit four spatially separated beams at slightly detuned wavelengths. The transmit optical assembly will be designed for communications capability so the system can be upgraded to do bi-directional communications if needed. Deep space communication is also possible by moving the receiver detector and electronics to a 3.9 m or 2.3 m telescope at Siding Spring Observatory.

REFERENCES

[1] Birch, M., Beattie, J. R., Bennet, F., Rattenbury, N., Copeland, M., Travouillon, T., Ferguson, K., Cater, J., and Sayat, M., "Availability, outage, and capacity of spatially correlated, Australasian free-space optical networks," *Journal of Optical Communications and Networking* **15**, 415 (jul 2023).

[2] CCSDS 142.0-B-1, "Optical Communications Coding and Synchronisaton. Blue Book," (2019).

[3] CCSDS 141.0-B-1, "Optical Communications Physical Layer Communications. Blue Book," (2019).

[4] Bennet, F. H., Ferguson, K., Grant, K., Kruzins, E., Rattenbury, N., and Schediwy, S., "An Australia/New Zealand optical communications ground station network for next generation satellite communications," in [*Free-Space Laser Communications XXXII*], Hemmati, H. and Boroson, D. M., eds., **1127202**, 1, SPIE (mar 2020).

[5] Birch, M., Martinez, N., Bennet, F., Copeland, M., and Grosse, D., "The Mount Stromlo Optical Communication Ground Station," *2022 IEEE International Conference on Space Optical Systems and Applications, ICSOS 2022* , 134–137 (2022).

[6] Lafon, R. E., Bai, Y., Caroglanian, A., Dailey, J. M., Desch, N., Garon, H., Hall, S., Miller, R., Paulson, D. A., Safavi, H., Sekulic, P., Speer, J. V., Thompson, P., and Wu, V., "NASA's Low-Cost Optical Terminal (LCOT) at Goddard Space Flight Center," in [*Free-Space Laser Communications XXXV*], Hemmati, H. and Robinson, B. S., eds., 32, SPIE (mar 2023).

[7] Copeland, M., Bennet, F., Birch, M., Ferguson, K., Grosse, D., Martinez Rey, N., and Travouillon, T., "A transmitter and receiver for lunar communications on the ANU Optical Ground Station," in [*Free-Space Laser Communications XXXV*], Hemmati, H. and Robinson, B. S., eds., 29, SPIE (mar 2023).

[8] Downey, J. N., Tedder, S. A., Vyhnalek, B. E., Lantz, N. C., Marsden, M. A., Simon, W. P., Bizon, T. P., and Zeleznikar, D. J., "A real-time optical ground receiver for photon starved environments," in [*Free-Space Laser Communications XXXV*], Hemmati, H. and Robinson, B. S., eds., 26, SPIE (mar 2023).

[9] Kim, I. I., Hakakha, H., Adhikari, P., Korevaar, E. J., and Majumdar, A. K., "Scintillation reduction using multiple transmitters," in [*Free-Space Laser Communication Technologies IX*], Mecherle, G. S., ed., **2990**, 102–113 (apr 1997).

[10] Sayat, M., Birch, M., Thearle, O., Copeland, M., Jager, E., Bennet, F., Lam, P. K., Rattenbury, N., and Cater, J., "Experimental effects of turbulence on coherent states in a free-space channel using adaptive optics for continuous variable quantum key distribution," in [*Quantum Computing, Communication, and Simulation IV*], Hemmer, P. R. and Migdall, A. L., eds., **12911**, 14, SPIE (mar 2024).