A flexible low-cost optical communications ground terminal at NASA Goddard Space Flight Center

Conference Paper · March 2021

DOI: 10.1117/12.2582869

19 authors, including:

Robert Lafon
NASA

Patrick L. Thompson
NASA

Howard Garon
NASA

Daniel Albert Paulson
University of Maryland, College Park

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Robert E. Lafon[a], Armen Caroglanian[a], Haleh Safavi[a], Nikki Desch[a], Victoria C. Wu[a], Manuel Buenfil[a], Patrick Thompson[a], Scott Merritt[a] , Steve Hall[b], Howard Garon[c], Dan Paulson[c], John V. Speer[c], Mark Wilson[d], Ron Miller[e], Tom Haas[f], Bruce Trout[g], Richard Mason[g], Jerome Hengemihle[g]

[a]NASA-Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD, USA 20771
[b]Cimarron Software Services, Inc.,Peraton Inc.
[c]Science Systems and Applications, Inc.
[d]Stinger Ghaffarian Technologies Inc.
[e]Bay Engineering Innovations, Inc.
[f]Integrity Applications Inc.
[g]Microtel LLC

ABSTRACT

We present the status of ongoing work at NASA-Goddard Space Flight Center (GSFC) to build a low-cost flexible ground terminal for optical communication. Previous laser communication missions at NASA have been supported by one-of-a-kind ground terminals built specifically for each mission. If NASA is to build a global network of optical terminals to enable widespread use of optical communications, then a blueprint for an economical ground terminal able to support a variety of missions is needed. With this goal in mind, NASA is constructing a ground terminal in Greenbelt, Maryland to enable testing of new ground terminal technologies from industry to academia.
Keywords: laser communication, optical ground terminal, adaptive optics

1. INTRODUCTION

Optical communication offers a way for space missions to return collected data to Earth at high rates not possible with radio frequency communications. Additionally, the size, weight, and power requirements of an optical terminal needed for a given data rate are far less than that of an equivalent RF terminal. Given these advantages, it is expected that laser communications will be used on a growing number of spacecraft launched by NASA as well as other governmental organizations and industry.

To date a major impediment to widespread adoption of laser communication has been the lack of an existing ground network infrastructure. A mission that wishes to take advantage of laser communication not only needs to invest in an optical space terminal, but it must also finance the creation of ground terminals to receive the downlink signal. This adds significant additional cost. Missions that do decide to incur the cost of financing a network of ground terminals end up building highly specialized optical receivers that are operable as receivers for that specific mission only. Significant Non-Recurring Engineering (NRE) cost is invested to build highly specialized one-of-a-kind ground terminals that go into storage after that particular mission is over. This is not an economical approach and does nothing to grow the number of optical ground stations available to future missions. In essence, each mission that wants to take advantage of the benefits of laser communication has to start from scratch to provide a ground terminal network to support it. As long as this is the case, the cost for using laser communications will be too high for most missions to consider.

What is needed is a standard optical ground terminal design that is flexible enough to serve as a receiver for a wide range of future missions – a ground terminal that can be quickly reconfigured to receive downlinks at different wavelengths using different signal formats. By investing NRE once to develop such a flexible ground terminal and using it to create a minimal network of ground terminals, a path towards an organically growing network of ground terminals can be cleared. If the existing optical ground terminal network is not sufficient to meet the needs of a given mission, then that mission need only finance the procurement of additional copies of the flexible ground terminal. No additional engineering is required. When that mission has ended, it leaves behind a larger network that will now be available to support future missions. In this way the ground network can grow economically as the demand grows.

It is with this in mind that we are building a flexible Low Cost Optical Terminal (LCOT), which will be a prototype for NASA's future optical ground terminal network.

1.1 Background

Past NASA laser communication missions have made use of ground terminals that broadly fall into one of two categories: Compact, highly specialized ground terminals such as the Lunar Laser Communications Ground Terminal (LLGT) installed at the White Sands Complex (see fig 1 top), and highly flexible and reconfigurable large facility ground terminals such as JPL's Table Mountain Facility (see fig 1 bottom).

Figure 1. Top: Image of the LLGT at White Sands used to receive the 622Mbps downlink from the Lunar Laser Communication Demonstration (LLCD). Bottom: JPL's Table Mountain Facility used in many laser communication demonstrations such as LLCD and that will be used to receive the Laser Communication Relay Demonstration (LCRD) downlink.

The LLGT consisted of four 40cm diameter receive telescopes and four 15cm transmit telescopes custom built for the LLCD mission by MIT-Lincoln Labs. The LLGT was successful in receiving the downlink from the LLCD space terminal on board the LADEE spacecraft orbiting the moon. While it is planned to re-use much of the LLGT telescopes and optics (the Free-Space Optical System) for receiving the downlink from the Artemis manned mission to the moon in 2023 – the Optical to Orion (O2O) project – the entire optical system has to be disassembled and transported to an optical lab to modify it to be compatible with the different wavelengths used on O2O – a lengthy and costly process. This is not a design that would lend itself to being flexible and able to quickly transition from supporting one mission to another using different wavelengths. Additionally, the LLGT did not have Adaptive Optics (AO), making it impossible for it to support receiving a coherent communications format such as the Differential Phase Shift Keying (DPSK) format used by the Laser Communication Relay Demonstration (LCRD).

In contrast, JPL's Table Mountain Facility makes use of a 1-meter diameter telescope in a Coude configuration that directs the received light down to a laboratory located below the telescope where it can be sent to various different optical tables to support receiving of different communications formats. While this allows the TMF to have extreme flexibility it comes at the cost of a large infrastructure footprint and is not a model that lends itself to building many copies in many locations to support a growing number of laser communications missions.

2. THE LCOT FACILITY

2.1 The LCOT Site

In 2018 funds were allocated to build a dome and equipment shelter at the Goddard Geophysical and Astronomical Observatory (GGAO) to support work on laser communication to using an existing 25cm telescope to receive a downlink from LEO satellites. The dome was sized to support future use of a much larger telescope. The dome diameter is 16'. The equipment shelter is climate controlled and has interior dimensions of 10'x14'. The site has optical fiber connection to the GSFC main campus and ample electrical power available (see fig 2).

Figure 2. The location of the LCOT facility at the Goddard Geophysical and Astronomical Observatory (GGAO) approximately 2 miles northeast of the Goddard Space Flight Center main campus.

Shortly after construction was completed in 2019, direction was given to proceed with procuring a much larger 70cm aperture telescope to serve as a testbed optical ground terminal, with the goal of constructing a ground terminal that could be demonstrated as a receiver for the optical space terminal that will fly on the Artemis II manned mission to the moon in late 2023.

The equipment required to support optical communication with the Artemis mission would leave no space for operations in the equipment shelter, so additional office space was secured in a nearby building, with the possibility of eventually adding an additional shelter to house operations in the future (see fig 3).

Figure 3. Aerial view of the LCOT site.

The GGAO is already host to regular outdoor laser operations by the Satellite Laser Ranging station, so procedures for use of lasers on site are already well-established.

2.2 The LCOT Receive Telescope

When the project was funded to procure a large receive telescope to serve as the foundation of a flexible ground terminal, there were many considerations in deciding what would be most appropriate for use as a laser communication receiver. The goal was to construct a ground terminal capable of supporting missions from LEO to lunar distances. The telescope needed to have sufficient aperture to receive the weak signals from a space terminal at the moon, while also having the ability to precisely track a LEO traversing the sky at a large angular rate. The design of the telescope needed to lend itself to rapid reconfiguration of the optical systems that filter the received signal and couple it into the optical fibers that then carry the signal to the modem. The telescope also needed have a small infrastructure footprint.

As a basic framework, a large aperture telescope with a dual Nasmyth configuration offered the potential to provide maximum flexibility and ease of reconfiguration while requiring a small infrastructure footprint. A commercial 70cm telescope was found with this configuration: the Planewave CDK 700 (see fig 4).

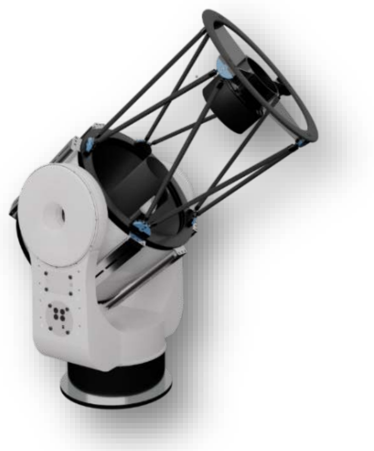

Figure 4. Model of the Planewave Instruments CDK700 telescope. Rotating tertiary mirror can direct the received light out along the elevation axis to the Nasmyth ports on either side of the telescope.

The CDK 700 optical design, however, was not optimal for our needs. The secondary obscuration of the CDK 700 was nearly 50% the diameter of the primary. This degree of obscuration not only reduces the amount of signal photons collected by the telescope, but also spoils the coupling efficiency of the signal into optical fiber due to diffraction effects. Additionally, the CDK700 was not designed to support the significant mass of the optical benches that would be mounted on the Nasmyth ports and the transmit telescope assembly that would need to be attached to the telescope body. Planewave Instruments did a significant redesign of the telescope to meet our requirements (see fig 5).

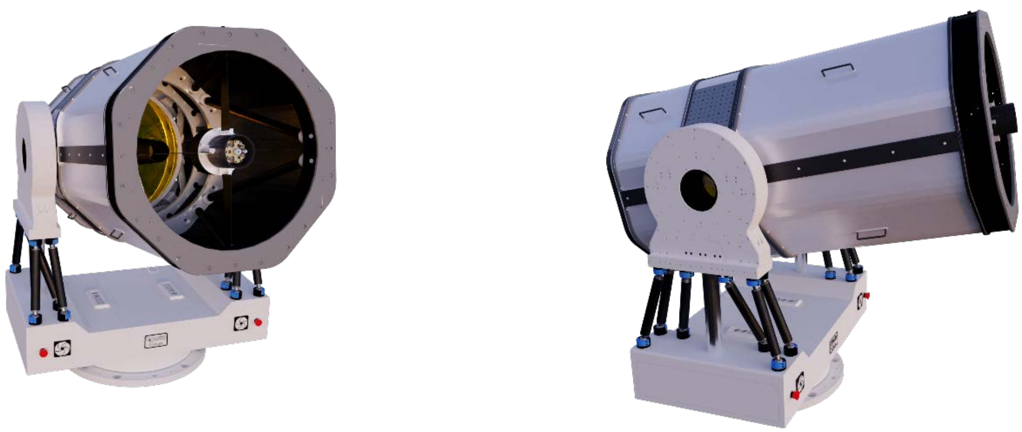

Figure 5. Render of redesigned Planewave Instruments 70cm diameter telescope.

The initial Corrected Dall-Kirkham optical design was changed to a Ritchey-Chretien dual Nasmyth design, reducing the secondary obscuration diameter to approximately 20% of the diameter of the primary. The mount was ruggedized to support the additional weight of the optical benches that would be attached to either side of the telescope. The telescope itself was strengthened to allow for the additional mass of a transmit telescope assembly and a solar window to attach to the telescope body. The structure is designed to support optical benches with a weight of up to 300 lbs. attached to either Nasmyth port. The telescope body is designed to support a transmit telescope assembly with a weight of up to 300lbs (see fig 6).

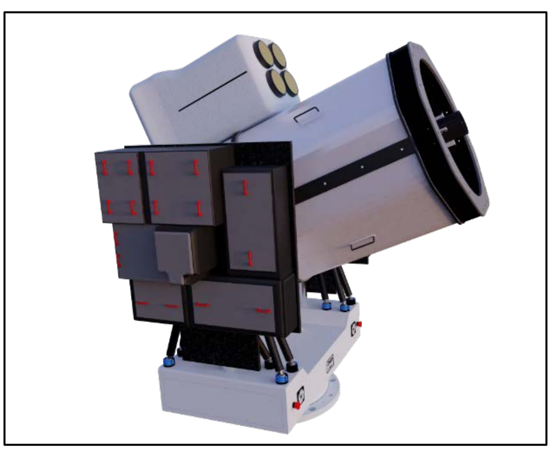

Figure 6. Conceptual rendering of the LCOT telescope with side-mounted optical benches and transmit optical telescope assembly attached.

The optical axis of the transmit telescope assembly will need to remain co-aligned with the optical axis of the 70cm receive telescope as the telescope moves in elevation. Given the mass of the transmit optical assembly, it is expected there will be some flexure between the transmit and receive optical axes as the telescope moves in elevation to track a target due to the changing gravity vector. In order to counteract this misalignment, the interface plate that mates the two optical assemblies together will have the ability to adjust the tilt of the transmit optical assembly in elevation in order to counteract any drift in co-alignment. This Robotic Piggy-back Mount (RPM) will adjust the tilt of the transmit optical assembly as the telescope changes elevation.

2.3 The LCOT optical benches

The LCOT telescope design includes a rotating tertiary mirror, allowing us to direct received light to one of two optical benches mounted on opposite sides of the telescope. This gives LCOT the ability to field two completely different sets of backend optics, potentially supporting reception of at least two different downlink formats. By designing the optical benches to be as wavelength-agnostic as possible, and ensuring that where wavelength-specific optics are used in the design they are field-changeable, each optical bench could support multiple downlink formats.

There are two broad categories of downlinked laser communication formats that LCOT will need to support: non-coherent formats such as the Pulse Position Modulation (PPM) format to be used on the ARTEMIS 2 mission to the moon, and coherent formats such as the DPSK format that will be used on the Laser Communication Relay Demonstration (LCRD) mission. Coherent communication signals must ultimately be coupled into single mode fiber – this requirement necessitates that LCOT have an AO system included on at least one of its optical benches (see fig 7).

LCOT is procuring an AO system from General Atomics Electromagnetic Systems Group (formerly Guidestar Optical Systems). The AO system will be installed on the port bench. GSFC is designing and will build the port bench optics that will collimate and filter the light and send it to the AO system and will include a wide field camera to assist in acquisition and tracking. The AO system will correct the wave front distortion caused by atmospheric turbulence and couple the signal into a single mode fiber. In situations where it is desired to use the port bench to receive non-coherent communications formats that do not require being coupled into a single mode fiber, the AO system can be reconfigured to correct for tip-tilt only, without attempting higher-order correction and couple the signal into a multimode fiber. The starboard optical bench will not have AO and will be used for non-coherent communication formats where the signal can be coupled into a larger multimode fiber. GSFC will design and build the starboard bench optical system.

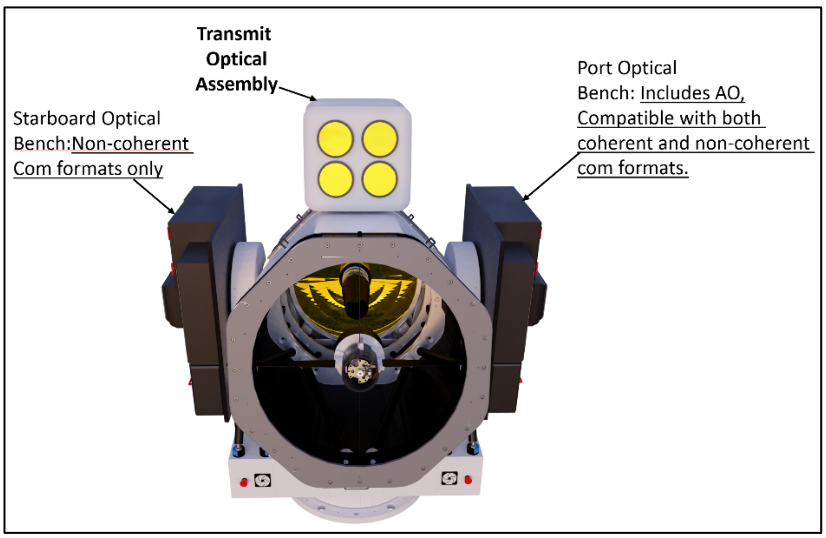

Figure 4. Illustration showing the Transmit Optical Assembly, and the port and starboard optical benches.

2.4 The Transmit Optical assembly

The transmit optical assembly will be mounted on top of the 70cm diameter receive telescope. The transmit optical assembly will consist of four ~15cm diameter transmit telescopes. Transmitting the uplink as four independent beams allows the uplink to make use of spatial and wavelength diversity to mitigate fading of the uplink signal at the space terminal. The entire transmit optical assembly will be mounted on the RPM that will allow compensation for any flexure in the alignment of the transmit and receive optical axes in elevation.

In order to keep the uplink design as wavelength-agnostic as possible, it will make use of reflective optics. The transmit telescopes use an off-axis parabola design so that there is no secondary obscuration that would spoil the transmitted beam quality. Each of the four transmit telescopes will have its own backend optics assembly that will include a tracking camera and fast steering mirror. The optical design will allow realignment in the field, allowing the transmit optical assembly to be quickly reconfigured to support different missions. The basic design of the transmit optical assembly is being done at GSFC but will be sent out to industry for the final build.

2.5 Adaptive Optics

In order to receive coherent optical communication formats such as the DPSK format used by LCRD [1], the signal collected by the receive telescope must ultimately be efficiently coupled into a single mode fiber. Uncorrected atmospheric turbulence prevents a large telescope from operating near its diffraction limit and the received signal would be imaged to a spot much larger than the 8μm single mode fiber diameter. This makes it impossible to couple more than a small fraction of the received light into a single mode fiber. In order to allow the telescope to perform near its diffraction limit, the wave-front distortion from turbulence must be removed, and this requires us to make use of sophisticated adaptive optics.

The LCOT project is procuring an AO system from General Atomics Electromagnetic Systems Group. The AO system will be mounted on the port side optics bench, and will provide the optics that collimate and filter the telescope output and send it to the AO system. In defining the specifications for the AO system a Fried parameter, r_o, of 2cm at 500nm wavelength and 45 degrees elevation angle was assumed. This assumption was based on observations at the LCOT site and translates to a r_o of approximately 7.8cm at the anticipated communication wavelengths, which are centered at 1550nm. This indicates that for our 70cm aperture a 10x10 sub-aperture deformable mirror would be minimally sufficient for correcting the expected level of turbulence. The AO system that has been procured, however, will utilize 16x16 sub-apertures and, with a change of relay lenses, could provide correction in the presence of even smaller r_o conditions given that the deformable mirror has 492 actuators.

One of the most stressing use cases of the AO system will be when tracking a LEO space terminal. The high slew rate of the telescope when tracking a LEO requires high update rates of corrections applied to the deformable mirror. It was specified that the AO will need to correct for a Greenwood frequency in excess of 150Hz based on analysis using the Hufnagel-Valley and Bufton models for C_n^2 and wind speed, respectively, as functions of elevation [2]. Given the specified Greenwood frequency is simply a requirement associated with a certain fiber coupling efficiency, the AO system is expected to have the ability to correct for Greenwood frequencies in excess of 150Hz.

Based on link analysis, the Artemis II lunar mission received flux will be too low to power the Shack-Hartmann wave-front sensor implemented in the AO system. However, the AO system is configurable to bypass the wave-front sensor and only provide tip-tilt correction to couple the received signal into a multimode fiber. This allows the AO system to be used for non-coherent communication formats as well as coherent. Since the Artemis downlink will use non-coherent PPM format [3], coupling the signal into a single mode fiber is not required.

2.6 Pointing and Tracking

While the Planewave Instruments' mount control software allows the telescope to track satellites when provided a pointing file, there will always exist imperfect knowledge of satellite position; this uncertainty can be substantial, which requires a pointing and tracking approach that can address slew rate and uncertainty without sacrificing required stability. To that end, auto-tracking capability is being developed by the GSFC software team, utilizing Planewave Instruments' mount control software interface to adjust mount tracking.

For the receive tracker, the fast steering mirrors will perform the fine tracking needed to keep the signal coupled into the optical fiber to the modem; for the uplink trackers, the fast steering mirrors will track the downlink and provide the offset required to compensate for range and time of flight (point ahead). Any gross errors will be offloaded to the mount for correction using the Planewave Instruments' mount control software interface, which allows users to send mount offset commands to adjust mount tracking.

After initial acquisition of the downlink, the control software that is being developed will monitor the position of the downlink in the receive telescope's port or starboard side wide field of view camera, depending on the side in use, calculate a mount adjustment using feedback from the receive wide field of camera and tracker fast steering mirrors as needed, then send corrections to the mount via the Planewave Instruments interface to adjust its tracking so that the downlink is kept near the center of the capture range of the uplink and downlink fast steering mirrors.

In this way, once the downlink has been observed in the wide field of view camera, the auto-tracking capability will keep the telescope tracking the downlink, even if initially given an imperfect ephemeris.

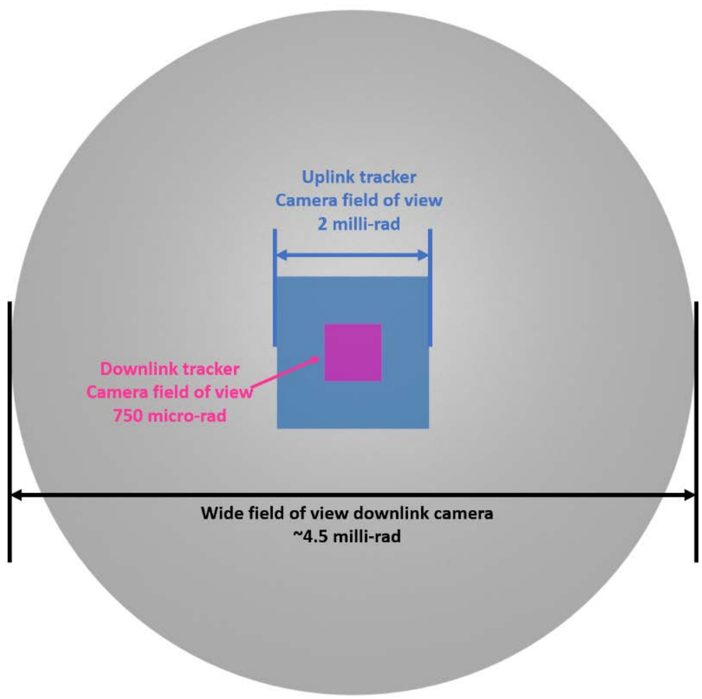

Figure 8. Illustration showing the relative fields of view for the downlink wide field of view camera, the uplink narrow field of view tracking cameras, and the downlink narrow field of view tracking camera.

3. LCOT GOALS

Currently the telescope and AO system are expected to arrive in April 2021. The AO system and other optics will be installed on the port optical bench and undergo extensive testing and characterization in the lab prior to installation on the telescope. The telescope will be installed in the dome upon arrival and will be used in control software development. The transmit optical assembly will be fabricated by industry with installation planned for the end of 2021. System integration and testing is planned to proceed throughout 2022 with a completion date of May 2023 in order to be ready for the demonstration with the Artemis II downlink from the moon in August2023.

It is envisioned that LCOT will become a valuable tool for developing a flexible multi-mission prototype ground terminal design. By having this facility located at GSFC it will be possible to quickly try out new technologies and techniques that could potentially reduce the costs and improve the performance of future ground terminals. With the ability to test against actual downlinks, LCOT will be able to measure the impact of atmospherics on optical communications links, which will inform site selection for future ground terminals. LCOT is attempting to use commercial technologies wherever possible, and where commercial solutions are not available, working to encourage their development. The goal is to invest in the engineering now so that future missions that want to make use of optical communication will have a single design available to them to purchase. A flexible design that can go on to be used for future missions with little or no rework will ensure that a global optical ground network can grow with demand as economically as possible.

LCOT will concentrate on the design of the optical subsystems needed to create a flexible ground terminal. Once working prototypes for the transmit and receive optical subsystems have been constructed, they will be tested against optical downlinks and evaluated for their performance in real-world conditions. By having a working optical ground terminal testbed at GSFC, new technologies can be evaluated quickly. Advanced detectors, optical filters, and other technologies can all be tried out on a ground terminal and evaluated quickly. LCOT will also serve as a field site where optical modems developed by industry or by other organizations can be tested against downlinks.

In the near-term LCOT is concentrating on demonstrating its capabilities by receiving the downlink from the ARTEMIS II mission to the moon, but we are taking great care to make sure that the design will be compatible with a wide range of potential missions ranging from LEO to lunar distances. In addition to ARTEMIS II and the Laser Communication Relay Demonstration, it is anticipated that there will be many potential LEO optical communications missions that LCOT may be tested against.

It is hoped that LCOT could be a facility that will foster partnerships with industry and other agencies to broadly advance the use of laser communications. It will also serve as a valuable tool for investigating emerging technologies such as quantum communications.

Finally, LCOT will give NASA scientists and engineers a facility where they can gain real-world experience with optical communications. It will give engineers a cost-effective way to try out new concepts and processes by providing the infrastructure for such testing. LCOT allows us to develop the prototype design for a flexible ground terminal that could serve as the backbone of NASA’s future global optical ground terminal network. In this way it is hoped LCOT will serve as a stimulus for innovation in optical communications and speed its widespread adoption by future missions.

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