An Envisioned Future for Space Optical Communications

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Abstract – Since the beginning of the Space Age, NASA has been a leader in developing space communications and navigation technologies—especially during the Apollo missions to the Moon and NASA's initial foray into deep space. To support future exploration and science needs, NASA is gradually introducing optical communications technologies to augment its radio frequency (RF) systems. Optical communications will enable new science and exploration missions by providing high data rates and better navigation over long distances. NASA has already flown several optical communications demonstrations, including the Lunar Laser Communications Demonstration (LLCD), the Laser Communications Relay Demonstration (LCRD), and the Terabyte Infrared Delivery (TBIRD) system. Historically, NASA has partnered with the Jet Propulsion Laboratory (JPL) and the Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL) to develop optical communications technology. In addition to pursuing optical communications, NASA's Space Communications and Navigation (SCaN) Program is undergoing a paradigm shift and moving away from government owned and operated networks to using commercial services whenever possible. In partnership with SCaN, NASA's Space Technology Mission Directorate (STMD) has identified key technologies that need to be developed to support future space communications and navigation, including enhanced RF, optical, and 3rd Generation Partnership (3GPP) cellular capabilities, as well as high-speed networking. This paper briefly describes some current and upcoming optical demonstrations and provides an overview of STMD's envisioned future for optical communications and navigation in the 2030+ timeframe.

I. Background

In the first couple of decades of NASA's existence, the Earth-based communications and navigation infrastructure to support human and robotic exploration was owned by NASA and operated either by NASA or its contractors. Eventually, NASA started to use commercial services to augment the government-owned infrastructure. Today, NASA is transitioning to a scenario where its missions use commercial services, wherever possible. For communications and navigation, this new paradigm means that NASA intends to mostly rely on commercial services for near Earth and most lunar missions; only some lunar missions requiring high-performance communications and deep space missions requiring very large apertures on Earth need to be supported by a NASA-owned network, such as the Deep Space Network.

II. Near Earth

There are two approaches for near-Earth space-to-ground communications: relay or direct-to-Earth . Communications via a relay satellite in geosynchronous orbit can provide continuous, near-real-time links since the relay satellite maintains a continuous link to the ground. Because links from a spacecraft to such a relay satellite involve long propagation distances, use of RF systems requires correspondingly large terminals and transmit powers. Using optical communications in a geosynchronous relay architecture can enable high data rates with smaller terminals due to the high beam directivity obtained with an optical carrier compared to an RF carrier. This optical relay capability has been demonstrated with systems like NASA's Laser Communications Relay Demonstration (LCRD) [1], which will soon demonstrate a link to the International Space Station in low Earth orbit [2]; the European Data Relay System [3]; and the Laser Utilizing Communication System (LUCAS) [4].

Alternatively, a relay satellite in a lower Earth orbit can be considered. While this approach may reduce the propagation distances between the spacecraft and the relay satellite, it will require a large constellation of both relay satellites and ground stations to provide continuous communications to ground. Several such systems are being developed commercially, such as SpaceX's Starlink [5] and Amazon's Project Kuiper [6], which indicates that private sector innovation in this area is accelerating quickly and dramatically. To help prepare for a future without the legacy NASA owned and operated Tracking and Data Relay Satellite (TDRS) System (which will be decommissioned in coming years), NASA is evaluating the feasibility of using only commercial services for future near-Earth missions. Via the NASA Communications Services Project (CSP), both SpaceX and Amazon will demonstrate relay optical communications for a NASA mission. Tapping commercial advances such as optical communications will ensure NASA missions have the reliable, secure, and continual space communications on which their long-term operations depend.

Space systems that do not require continuous or low-latency communications to ground may transmit their data directly to Earth. For this approach, the spacecraft must buffer data until a line-of-sight link to a ground station can be established. Such contacts may be infrequent (once per day or less), depending on the orbit of the spacecraft and the location and availability of the ground station. Moreover, these contacts may be of short durations—line-of-sight links from low Earth orbit to ground may only last for a few minutes. Using optical communications in such an architecture permits use of very small space and ground terminals and the ability to transmit data at very high data rates, enabling large volume transfers of data even with infrequent, short-duration links. NASA's Terabyte Infrared Delivery (TBIRD) program has demonstrated the capabilities of this approach, transmitting data from a small CubeSat in low Earth orbit to a ground station at data rates of up to 200 Gbps. TBIRD has recently demonstrated transmission of 4.8 TB of data in a single 5-minute pass over a ground station [7]. In the future, NASA would like industry to adopt this technology and operate commercial optical ground stations that provide services NASA missions could acquire.

III. Lunar

Human exploration and science activities at the Moon are expected to increase substantially in the coming decades. Efficiently supporting the communication and navigation needs of the numerous missions expected to be operating in lunar orbit, on the lunar surface, and in transit between Earth and the Moon will require shared communications and navigation infrastructure in the lunar vicinity and on Earth. Like space communications near Earth, communications architectures in the lunar vicinity will probably include both direct-to-Earth links and relay communications, depending on mission requirements. Optical communications will likely play a vital role in this future communications architecture, providing high-data-rate links to and from Earth and to and from lunar orbit with small terminals.

Optical communication from lunar orbit to Earth was first demonstrated more than 10 years ago by NASA's Lunar Laser Communications Demonstration (LLCD) program [8]. LLCD utilized a 10-cm optical aperture to establish duplex optical communication links between the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft in lunar orbit and three optical ground stations on Earth with 0.8 to 1-m apertures. LLCD demonstrated error-free downlink data rates of up to 622 Mbps using a 0.5-W optical C-band Pulse-Position Modulation (PPM) transmitter and high-sensitivity receivers utilizing superconducting nanowire detector arrays. Similar intensity-modulated formats were used for 20 Mbps uplink communications to an optically pre-amplified direct detection receiver aboard the LADEE spacecraft.

The recently published "National Cislunar Science and Technology Strategy" [9] identifies the NASA Artemis Program as providing the foundational elements for the future lunar communications architecture. While the uncrewed Artemis I mission, launched in November 2022, relied on S-band RF links to NASA's Deep Space Network, the Artemis II mission, the first to carry humans back to lunar vicinity since the Apollo missions, will also include an optical communications terminal, the Orion Artemis-II Optical Communications (O2O) Terminal [2]. While a ~6-Mbps S-band link will still be used for mission-critical data on the Artemis II mission, the optical downlink, which can operate at rates up to 250 Mbps, will enable downlinking of much larger volumes of mission data. The Artemis II optical downlink will allow the entire contents of the onboard storage to be downlinked during the mission, rather than having to wait for recovery of the flight recorders after the Orion crew module returns to Earth. The high-rate optical links will also enable real-time high-definition video interactions with the astronauts during the mission. The O2O space terminal is similar in size to the LLCD terminal, with a 10-cm optical aperture based on NASA's Modular Agile Scalar Optical Terminal (MAScOT) [10] design.

While the LADEE and Artemis-II missions both utilized direct-to-Earth optical communication links, future missions in lunar vicinity will likely benefit from a shared relay satellite in lunar orbit. Indeed, NASA is already making plans for radio-frequency relays in lunar orbit to support near-term Artemis communications needs [11]. Projections of future mission data requirements suggest that such a trunk link would likely need to operate at aggregate data rates of several Gbps to support exploration and science activities at the Moon. The LLCD and O2O link designs utilize intensity-modulated PPM with photon-counting detectors. Such approaches are well suited for power- and aperture-constrained links, as they enable excellent receiver power efficiencies of multiple bits per received photon. However, such links can be challenging to implement at data rates higher than ~1 Gbps. The use of PPM requires high-bandwidth modulation. For example, the 622-Mbps downlink demonstrated by LLCD with its half-rate forward error correction code required 5 GHz of modulation bandwidth. While the accessible unregulated C-band optical spectrum is much larger than 5GHz, modulation bandwidths of this magnitude can be difficult to achieve using space-grade transmitter electronics. Moreover, achieving photon-counting rates required to support receiver operation at Gbps-class data rates with low detector-blocking losses will require larger detector arrays than are presently available.

For these reasons, coherent modulation formats and receivers may be suitable for high-rate lunar trunk links and are being investigated for possible international standardization by the Consultative Committee for Space Data Systems (CCSDS). Employing phase-modulation formats, such as binary- and quadrature-phase-shift-keying (BPSK and QPSK), with coherent receivers can provide good power efficiency at extremely high data rates, as shown by the TBIRD demonstration. Coherent ground receivers that have been demonstrated to date (e.g., LCRD, TBIRD) require adaptive optics to enable efficient coupling to a single-spatial-mode coherent optical receiver. Such implementations are also expected to be applicable to high-rate trunk links from the Moon, which will have sufficient received power to estimate and correct the atmosphere-induced wavefront errors. As an example, a 10-cm MAScOT optical terminal with a 10-W transmitter in lunar orbit could support a 5-Gbps QPSK downlink to a 1-meter ground terminal with adaptive optics and a pre-amplified coherent receiver. This same terminal could support proximity links from lunar-orbiting and surface users at rates from a few Mbps to several Gbps, with much smaller apertures and transmit powers than would be required for direct-to-Earth links. Examples of such links are shown in Table 1.

Table 1. Example Lunar Relay Optical Links

Link	Transmitter	Receiver	Data Rate
Moon-Earth Trunk	10-cm, 10-W, QPSK	1-m, coherent	5 Gbps
Orion-to-Relay	10-cm, 1-W, PPM	10-cm, noncoherent	2 Gbps
Surface-to-Relay	5-cm, 1-W, PPM	10-cm, noncoherent	200 Mbps
CubeSat-to-Relay	2-cm, 1-W, PPM	10-cm, noncoherent	10 Mbps

NASA intends to work with industry to enable a robust lunar communications and navigation network to support missions in lunar orbit and on the lunar surface. For example, NASA has established the Lunar Communications Relay and Navigation Systems (LCRNS) project to design and procure from industry a sustainable, interoperable, long-term approach to lunar communications and navigation to support both human and robotic exploration. Use of international standards will enable a robust network consisting of multiple providers. While the near-term focus has been on RF communications, NASA hopes that operational optical communications services will be close behind.

IV. Deep Space

For deep space missions, however, NASA is not expecting commercial services suitable for such long distances to be available soon. Thus, NASA is planning to expand the capabilities of the Deep Space Network to eventually include optical communications. In 2017, JPL initiated the Deep Space Optical Communications (DSOC) Project [12] as a technology demonstration for deep space planetary distances. The Psyche mission selected by NASA's Science Mission Directorate agreed to host the DSOC Flight Laser Transceiver (FLT), with demonstration activities scheduled during the mission's early cruise to the asteroid Psyche-16.

The fully developed DSOC FLT is scheduled to launch onboard the Psyche spacecraft in October 2023. The FLT has been integrated with the spacecraft and is currently undergoing pre-launch testing. The Ground Laser Transmitter (GLT) [13], Ground Laser Receiver (GLR) [14], and a Mission Operations System (MOS) comprise the remaining DSOC system. Figure 1 shows an operational view of DSOC. Link initiation occurs when the GLT transmits the1064-nm laser beacon, using ephemerides provided by the Psyche Project. The GLT is located at the Optical Communication Telescope Laboratory (OCTL), near Wrightwood, CA. Assisted by spacecraft pointing, the FLT, equipped with actuators and sensors, will acquire and track the beacon. The 1550-nm downlink laser will then point ahead to illuminate the GLR. The GLR is located at the Palomar Observatory's Hale telescope, which is operated by Caltech Optical Observatories. The GLR instrumentation will enable downlink signal acquisition, detection, demodulation, and decoding of the serially concatenated pulse position modulated (SCPPM) signal, which conforms to the CCSDS High Photon Efficiency (HPE) standards [15], [16].

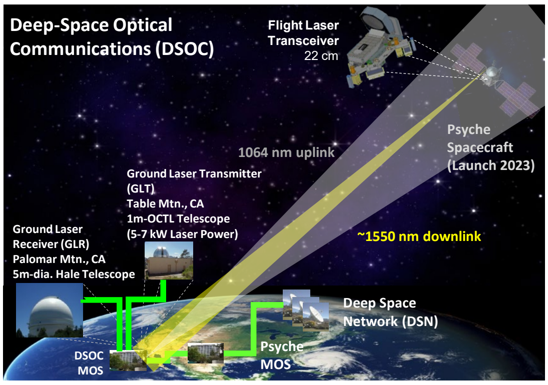

Figure 1. Operational view of the planned DSOC technology demonstration

The Psyche spacecraft will be 0.1 Astronomical Unit (AU) from Earth one month after launch, at which time DSOC technology demonstration (TD) operations will commence and occur weekly through June 2024, when the spacecraft reaches 2.5 AU. Starting in June 2024, nighttime line-of-sight opportunities will diminish, then disappear altogether, because the GLR can only operate between sunset and sunrise. Starting in January 2025, weekly TD operations will resume until September 2025. During this second phase, the Psyche spacecraft location will range from 1.5-2.5 AU from Earth. Over the full distance range of 0.1-2.5 AU, downlink data-rates from 1 Mb/s to 100 Mb/s are predicted.

DSOC Flight Subsystem — The FLT uses a 22-cm-diameter off-axis Optical Transceiver (OT) [17]. A 4-W-average-power Master Oscillator Power Amplifier (MOPA) Laser Transmitter Assembly (LTA) [18] is fiber coupled to the OT. The LTA supports 1, 32, 64, and 128-ary PPM modulation. A Geiger-mode avalanche-photodiode Photon Counting Camera (PCC) [19] detects the 1064-nm modulated uplink laser beacon signal. PCC signal processing provides centroid updates and demodulation and decoding of the 2-PPM modulated uplink for a fixed uplink data rate of 1.6 kb/s. The OT has active-passive isolation pointing assembly struts with limited steering, which can accommodate the full angular pointing uncertainty of the spacecraft. A point-ahead mirror integrated to the OT laser transmit-path implements the point-ahead of the downlink laser to GLR.

Figure 2 contains photos of the main DSOC components prior to integration with the Psyche spacecraft. The DSOC Accommodation Kit (DAK) serves as a thermal enclosure, so that the FLT can operate within allowable flight temperatures.

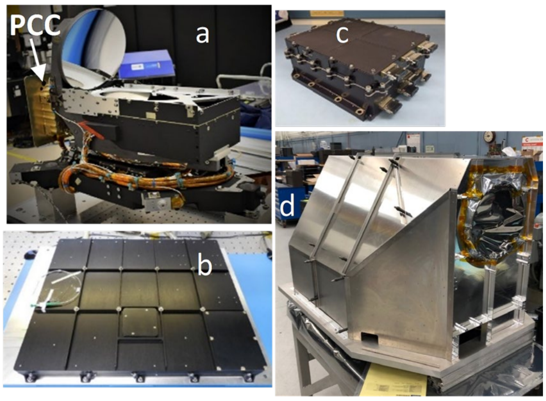

Figure 2. (a) OT with PCC mounted on struts, (b) MOPA LTA, (c) electronics module, (d) DAK enclosure.

Operations readiness tests coordinated by the DSOC MOS to validate the required telemetry flow across DSOC and Psyche mission elements are currently ongoing prior to launch.

Mars and Beyond — Successful execution of the DSOC TD will significantly mitigate the risk of implementing operational optical communications services for missions to Venus and Mars. NASA's roadmap to support human missions to Mars calls for a 100 Mb/s downlink from Mars when the planet is furthest from Earth (2.67 AU) along with optical ranging based navigational services. The system requirements to satisfy these objectives will be flowed down to future flight and ground sub-systems. Analysis calls for larger 40- to 50-cm-class flight apertures and 20- to 50-W-class 1550-nm flight laser transmitters. Correspondingly, effective collection diameters of at least 8 m are required on the ground.

Two-way ranging with the current HPE signaling scheme can support high-precision navigation. The

DSOC uplink laser pulse width, rise time, and jitter are inadequate to satisfy high-precision ranging requirements. In the future, lasers with the same average power will include improved pulse characteristics to overcome this limitation. Teams at MIT Lincoln Laboratory and JPL are currently working cooperatively to develop a proof-of-concept laser transmitter that will support ranging to Mars distances in the next 2-3 years.

Ground terminals with an 8-m or larger effective diameter will be required to operate at near-Sun pointing angles to avoid long outages. For example, the ability to communicate down to a 3° Sun-Earth-probe angle will limit the outage to 18 days for a Mars synodic cycle of approximately two Earth-years. Approaches to prevent insolation damage to the ground terminals and restrict excessive increase of additive background noise from sky radiance and stray light will need to be invented and implemented. To address both of these issues, aggressive spectral and spatial filtering techniques will be required to restrict noise adulteration of the optical communication signal. A technology development effort has been initiated at JPL to address the challenges near-Sun operations pose to ground terminals.

For the outer reaches of the solar system, Earth-transmitted beacon-assisted link acquisition and tracking pose increasing difficulty, especially through the atmosphere, without adaptive optics correction. Exploring use of Earth, the Moon, star fields, or even the Sun to point the spacecraft from such far distances appears necessary. Hybrid approaches that combine star trackers with the Earth, Moon, and/or Sun serving as celestial beacons are candidate approaches. Incorporating onboard inertial stabilization may also be a viable option. These approaches need to be explored to satisfy required laser beam pointing accuracy. Integrated system design, involving spacecraft attitude control and guidance and navigation control systems, also seem appropriate. Interfaces between onboard OTs and solid-state recorders or other storage media will also need to keep up with the enhanced data rates that optical communications can offer.

The need for beaconless operation does not mean optical navigational services cannot be implemented in the outer reaches of the solar system. Approaches such as transmitting lasers from favorable locations, including airborne or spaceborne assets, or utilizing adaptive optics uplink correction [20] need to be explored. Sensitive single photon-counting detectors on very distant spacecraft will likely be able to support two-way ranging, since detection of just a few photon arrivals will be adequate.

Future human exploration activities at Mars are anticipated to require return data rates >100 Mbps. For comparison, state-of-the-art RF communications systems in operation at Mars today deliver a few hundred kbps when Mars and Earth are maximally separated (~2.7AU). While existing space transmitter technologies could extend those rates to a few Mbps, physical spacecraft constraints limit feasible data return rates for RF systems. For example, a 100 Mbps RF return link from Mars at maximum range to an array of four 34-m receivers in NASA's Deep Space Network would require a 500-W Ka-band transmitter with a ~5.6-m transmit antenna. In addition, RF spectrum constraints would likely limit the ability of such a system to operate at higher data rates when, for example, the Mars-Earth distance is smaller. By contrast, an optical system designed to support such rates could be much smaller, both in space and on the ground. A 50-cm optical transmit aperture with a 50-W transmitter downlinking to an array of six 2.5-m receive telescopes could support rates >100 Mbps at the Mars maximum range. Moreover, the lack of spectrum constraints associated with optical transmission means that such a system could support rates of several Gbps when Mars is closer to Earth and much higher rates as technology for transmitter apertures and amplifiers evolve.

NASA's research and development efforts have heretofore focused on near-term Mars human exploration and science missions, with further development required to transition to operations. Attention to the regime beyond Mars will be forthcoming.

Conclusion

Optical communications is rapidly becoming a critical technology to enable space missions. Space agencies and commercial entities around the world are conducting optical communications demonstrations or even flying operational systems that provide mission-critical communications. NASA's plan is to use commercial communications services as much as possible in the near-Earth and lunar environments. For distances beyond the Moon, NASA believes it will have to use government owned and operated networks. However, significant research and development and investments still need to occur to enable optical communications technology to support the human exploration of Mars with data rates in excess of 100

Mbps at the maximum distance from Earth. Fortunately, the rapid maturing of this technology will enable new science and exploration missions throughout the solar system.

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