Modem Module Development for NASA's Orion Spacecraft: Achieving FSO Communications Over Lunar Distances

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Abstract: NASA's Orion spacecraft will employ free-space optical communications over 400,000-km from the lunar vicinity to Earth, using an 80-Mb/s downlink and a 20-Mb/s uplink. This paper discusses an overview of the link and optical modem. © 2020 The Author(s)
OCIS codes: 060.2605 (Free-space optical communication), 010.1300 (Atmospheric propagation).

1. Introduction

As part of the Artemis missions, NASA plans to use the Orion capsule with the space launch system (SLS) rocket to take astronauts into orbit around the moon in 2022 [1, 2]. NASA will employ a free-space optical (FSO) communications link between the Orion spacecraft at cis-lunar distances (i.e., 40,000 to 400,000 km) and ground stations on Earth (Fig. 1(a)) called the **O**rion Artemis-**2 O**ptical Communications (O2O) mission. The primary goals of O2O are to provide real-time streaming HD and/or 4K video streams, as well as support large data buffer downloads during the mission. A successful O2O demonstration will provide important risk reduction for the benefit of future missions, such the next Artemis mission targeting 'boots on the Moon' in 2024. As shown in Fig. 1(b), the space terminal under development consists of four unique modules: 1) the optical module (OM) that includes a telescope, small bench optics, and pointing hardware, 2) the modem module (MM) that converts the spacecraft Ethernet to an optical waveform and vice versa, 3) the controller electronics (CE) that handles commands and telemetry to and from the spacecraft, OM, and MM, and 4) the power convertor unit (PCU) that provides 28-V power to the MM and CE, which then provides power to the OM. Fig. 1(c) shows the 'black box' modem module with its various interfaces to other modules and the spacecraft.

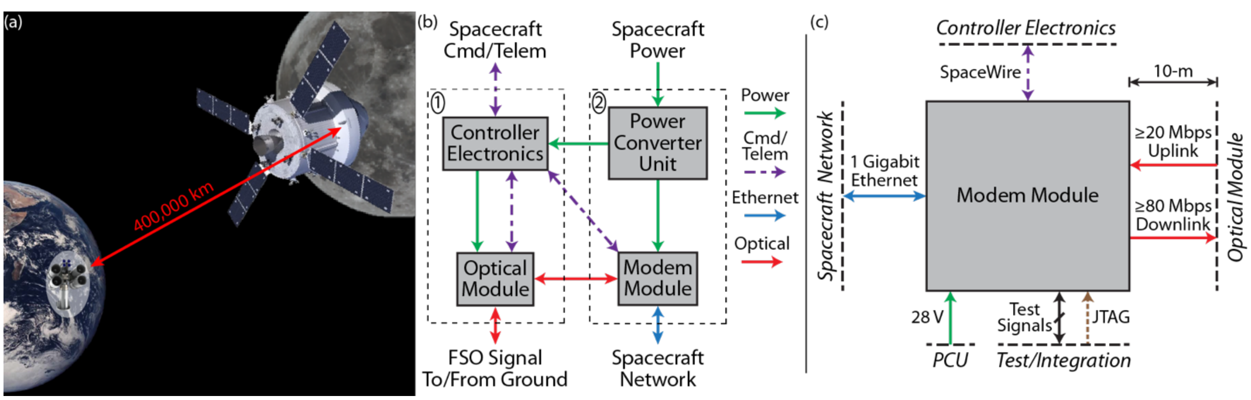

Fig. 1: (a) Moon-to-Earth FSO link overview, (b) space terminal overview showing modules and interfaces. ① and ② denote modules on the outside and inside of the spacecraft, respectively. (c) Modem module interface overview. PCU: power convertor unit.

2. Link Design

Establishing an efficient free-space optical link over a distance of 400,000 km requires careful link design to ensure a sufficient number of photons per bit arrive at the receiver for the link to close. Furthermore, the telescope gimbal has to sufficiently isolate the telescope from spacecraft vibrations and other motions to enable accurate pointing of a transmit signal to a ground terminal on Earth.

1.1. Data Flow Overview

The intent of the O2O mission is to exchange data between the Orion spacecraft and the ground. Fig. 2 depicts the data flow that is accomplished by using the optical link to make a connection between the Ethernet network on the Orion spacecraft and the Ethernet network on the ground. Effectively, the O2O space and ground terminals serve as a "pseudo Ethernet wire." By design, the O2O space and ground terminals are transparent to layer 2 (i.e., do not have MAC addresses). All Ethernet packets sent to either the O2O space or ground terminals are transmitted through the FSO link.

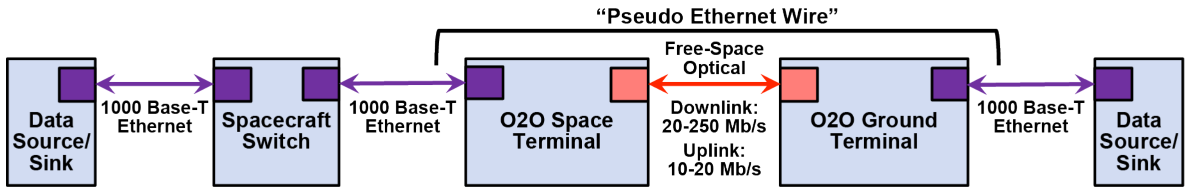

Fig. 2: Data flow between the Orion spacecraft and the ground

1.2. Communication Modes

The O2O demonstration intends to use the optical link over distances from 40,000 to 400,000 km, which requires data rate scaling in order to support communications over such a wide dynamic range of distance. Table 1 shows the downlink and uplink communications modes, which include nominal rates of 80 Mb/s for the downlink and 20 Mb/s for the uplink, and fallback modes at lower data rates. The downlink also includes higher rate modes that can be used when the spacecraft is closer to Earth. The common data rate of 20 Mb/s between the downlink and uplink enables loopback testing. All communications modes use pulse position modulation (PPM) with strong forward error correction (FEC). Support for different data rates is accomplished by varying either clock rate, PPM order, or FEC code rate. The O2O waveform, including FEC and interleaving, is based on the CCSDS high photon efficiency (HPE) standard that uses serial concatenated PPM (SCPPM) [3, 4].

Table 1: Communications modes

Mode	*Clock Rate (GHz)*	*PPM Order*	*Code Rate*	*Effective User Rate (Mbps)*
Downlink 1	0.50	32	1/3	20
Downlink 2	1.00	32	1/3	40
Downlink 3	2.00	32	1/3	80‡
Downlink 4	2.00	16	1/3	130
Downlink 5	2.00	16	1/2	195
Downlink 6	2.00	16	2/3	260
Uplink 1	0.25	32	1/3	10
Uplink 2	0.50	32	1/3	20‡

‡Nominal rates at lunar distance

1.3. Link Budget

Table 2: Notional link budget

Downlink 3 Link Budget

Space Terminal	Tx Power	0.0	dBW
	Losses & Imp Penalty	-7.0	dB
	Aperture Gain	106.1	dB
Free Space	Space Loss	-310.2	dB
	Atmospheric Atten.	-1.0	dB
Ground Terminal	Aperture Gain	118.2	dB
	Losses & Imp Penalty	-14.0	dB
	Power into Rx	81.0	dB ph/s
Coding Theory	Theoretical ph/bit	-2.1	dB ph/bit
	Theoretical Rx Power	76.9	dB ph/s
	Margin	4.1	dB

Uplink 2 Link Budget

Ground Terminal	Tx Power	+10.0	dBW
	Losses & Imp Penalty	-12.0	dB
	Aperture Gain	109.7	dB
	Array Gain	6.0	dB
Free Space	Space Loss	-310.2	dB
	Atmospheric Atten.	-1.0	dB
Space Terminal	Aperture Gain	106.2	dB
	Losses & Imp Penalty	-14.0	dB
	Power into Rx	83.5	dB ph/s
Coding Theory	Theoretical ph/bit	6.3	dB ph/bit
	Theoretical Rx Power	79.3	dB ph/s
	Margin	4.2	dB

Table 2 shows notional downlink and uplink link budgets for the nominal rates at lunar distance. For the O2O mission, a single space telescope aperture will support both uplink and downlink communications in the 1550-nm telecom band. The downlink utilizes a 1-W optical amplifier, and the space terminal is estimated to have 7 dB of implementation penalty due to telescope losses and pointing, acquisition, and tracking (PAT) losses. The diffraction-limited aperture gains for the space (10-cm) and ground (40-cm) terminals, and the free-space propagation loss over 400,000 km, are calculated values [5]. The ground terminal consists of a single receive telescope that couples light to single photon detectors (SPDs) [6]. The ground terminal implementation penalty of 14 dB consists of telescope losses, tracking losses, fiber mode mismatch, imperfect transmitted signal extinction and polarization extinction ratios, polarization dependent losses, and SPD blocking probability. This will lead to a net power detected by the SPDs of approximately 81 dB photons/s (ph/s). The theoretical number of photons/bit required for the 80 Mb/s signal is -2.1 dB ph/bit after accounting for PPM order, FEC code rate, atmospheric fading, and SPD detection efficiency [7]. The result is a required power of 76.9 dB ph/s, which provides 4.1 dB of link margin.

The uplink consists of a 4×15-cm telescope array that each transmit at 10 W, and have transmitted signals separated in frequency by 1.6 GHz to facilitate rf filtering of the beat tones in the receiver. For the uplink, the transmit implementation penalty arises from telescope losses, PAT losses, loss due to allocating some transmit power to the beacon, and imperfect Strehl ratio loss. The space terminal is estimated to have 14 dB of implementation penalty from telescope, PAT losses, and optical receiver implementation, yielding 83.5 dB ph/s at the receiver. The required power at the space terminal for 20 Mb/s is 6.3 ph/bit, which accounts for PPM order, FEC code rate, atmospheric fading, and pre-amplified photodetection. The corresponding received power is 79.3 dB ph/s that leaves 4.2 dB of link margin.

3. Modem Module Overview

Currently, the O2O MM is being designed and built by an industry partner. The O2O MM is being designed to operate in a cis-lunar orbit for up to 1 month. Longer duration missions will be possible with appropriate part substitutions and/or additional radiation protection. Many of the specifications for the O2O MM are inspired by the modem module in the Lunar Lasercom Demonstration (LLCD) that successfully demonstrated a 622-Mb/s downlink and 20-Mb/s uplink from the NASA LADEE satellite in lunar orbit to Earth [6]. In particular, the MM is specified to have a mass less than 11 kg, a maximum power consumption less than 62 W, and a volume less than 1,161 in^3. The MM electronics will consist of mostly EEE level 3 (or better) parts that meet minimum radiation requirements. Other parts, such as the electro-optics that do not have space grade versions, will go through additional testing and risk evaluation. The MM will undergo various environmental tests: vacuum bake out, shake, shock, thermal vacuum, and EMI/EMC.

The MM transmitter is specified to produce a 1-W optical output with a polarization extinction ratio >14 dB, and an optical signal-to-noise ratio greater than 30 dB. The MM transmitter also needs to produce a waveform with an extinction ratio greater than 25 dB to produce high-fidelity low-duty-cycle PPM waveforms. The MM receiver clock recovery will need to operate successfully on a signal with Doppler and atmospheric turbulence. Any residual beat tones between the four uplink lasers will also need to be appropriately filtered.

The O2O modem module will support time of flight (ToF) measurements between a ground terminal and the space terminal in order to provide cm-class ranging of the Orion spacecraft. ToF measurements involve phase locking and frame locking the downlink signal to the uplink signal, which is tied to an atomic reference. In this way, there is a fixed time offset between the uplink and downlink signals that allows determining the overall round trip time of a signal from a ground terminal to the space terminal and back again. Initially, ToF will only be supported when the uplink is in mode 1 or 2, and the downlink is in mode 1, 2, or 3 due to the exact integer relationship in the number of frames and bits per second between these modes. Processing of the ToF data from the recorded frame departure and arrive time stamps will yield extremely accurate timing information, thus enabling cm-class ranging of the spacecraft.

4. Summary

A successful O2O mission demonstrating high-speed data transfer and real-time streaming HD and/or 4K video from lunar orbit to the Earth will provide a path towards more widespread use of FSO communications on spacecraft, for future Artemis missions and beyond. Additionally, the FSO communications signal can be used for ToF to provide cm-class ranging capabilities.

5. References

[1] "*NASA Moon and Mars*" (2019). Accessed on: Sep. 9, 2019, [Online]. Available: https://www.nasa.gov/moontomars/.
[2] B. S. Robinson, T. Shih, F. I. Khatri, D. M. Boroson, J. W. Burnside, O. Guldner, S. Constantine, J. Torres, T. M. Yarnall, C. E. DeVoe, W. Hubbard, D. J. Geisler, M. L. Stevens, O. V. Mikulina, N. W. Spellmeyer, J. P. Wang, R. Butler, M. Hogan, T. King, and A. Seas, "Laser communication for human space exploration in cislunar space: ILLUMA-T and O2O," in *Proc. SPIE 10524, Free-Space Laser Communications XXX, 105240S*, (2018).
[3] "Optical Communications Physical Layer," in *CCSDS 141.0-B-1,* (The Consultative Commitee for Space Data Systems (CCSDS), 2019).
[4] "Optical Communications Coding and Synchronization," in *CCSDS 142.0-B-1,* (The Consultative Commitee for Space Data Systems (CCSDS), 2019).
[5] H. Hemmati, *Near-Earth Laser Communications* (CRC Press, 2009).
[6] D. M. Boroson, B. S. Robinson, D. V. Murphy, D. A. Burianek, F. Khatri, J. M. Kovalik, Z. Sodnik, and D. M. Cornwell, "Overview and results of the lunar laser communications demonstration," in *Proc. SPIE 8971, Free-Space Laser Communication and Atmospheric Propagation XXVI, 89710S*, (2014).
[7] D. M. Boroson, *Optical Communications: A compendium of Signal Formats, Receiver Architectures, Analysis Mathematics, and Performance Comparisons*, DTIC, ESC-TR-2005-060 (MIT Lincoln Laboratory, 2005).

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