Space-to-Ground Optical Interface Verification for the Orion Artemis II Optical (O2O) Communications Demonstration

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Abstract[1]

The Orion Artemis II Optical Communications (O2O) system will demonstrate the operational utility of laser communications for the first crewed Artemis mission scheduled to launch next year. O2O will provide an optical link with data rates up to 260 Mbps return from the moon and up to 20 Mbps forward to the moon. The optical link employs a Serially Concatenated Pulse Position Modulation (SCPPM) communications signal, compliant with the Consultative Committee for Space Data Systems (CCSDS) standard, and a modulated uplink beacon for acquisition and collaborative tracking. O2O employs optical ground stations located at the White Sands Complex (WSC) and Table Mountain Facility (TMF) to support the Earth end of the link. We describe interface testing performed between the space and ground terminals to verify the physical layer communication and beacon signals.

1 INTRODUCTION

The Orion Artemis II Optical communications (O2O) Demonstration will demonstrate an operational optical downlink at up to 260 Mbps from the Orion spacecraft to an Earth ground station, as well as an up to 20 Mbps uplink from ground to the spacecraft [1]. The Artemis II mission launches the Orion spacecraft in 2024 taking four astronauts around the Moon [2]. O2O will provide a physical layer optical communications link for this mission, creating a transparent Ethernet bridge over which the vehicle can transmit and receive files, make real-time video calls, and stream real-time camera images and video.

The O2O demonstration brings together many different organizations within NASA, industry players, and MIT Lincoln Laboratory [3]. Figure 1 shows the overall architecture of the system. The different colors represent different organizations. NASA Johnson Space Center (JSC) owns the Artemis II mission and therefore the Orion space craft element (built by Lockheed Martin) and operations element. The ground segment is owned by NASA Goddard Space Flight Center (GSFC) ACCESS. The Space Craft Element (STE), or optical comm space payload, was built by MIT Lincoln Laboratory, in conjunction with NASA GSFC and industry.

This paper addresses the verification of the space to ground interface, shown in the purple box in Figure 1 and will focus on the methodology of space-to-ground interface testing required to verify the performance of the free space optical link. The interfacing elements will first be described, followed by the overall approach and available tools, and finally status for both space to ground verification.

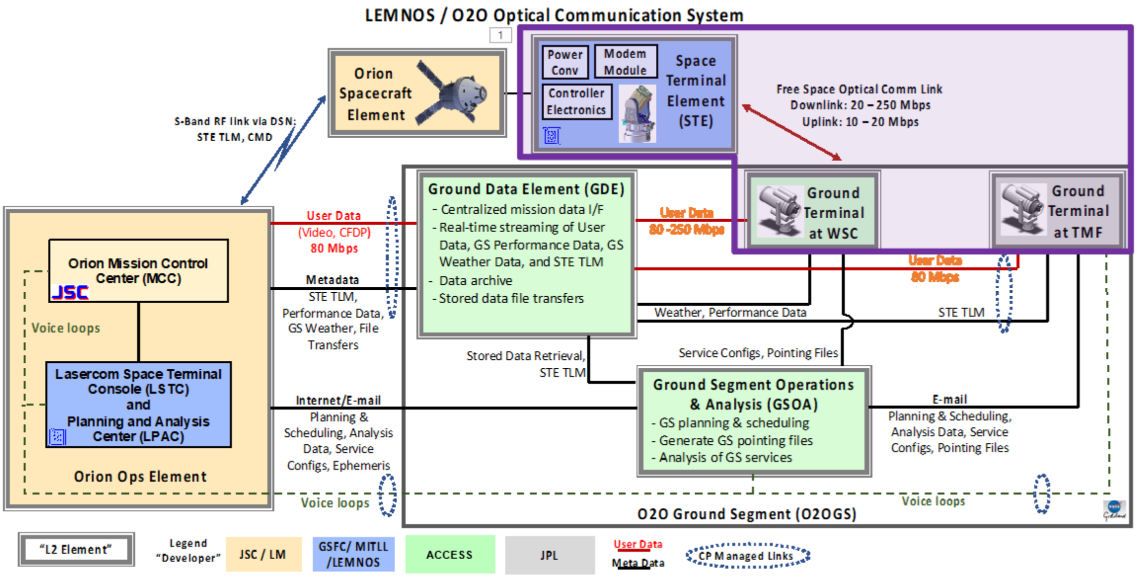

Figure 1: O2O mission level architecture diagram. WSC = White Sands Complex, TMF = Table Mountain Facility, TLM = Telemetry, JPL= Jet Propulsion Lab, L2 = "Level 2" architectural element, GS = ground station, LEMNOS = Laser Enhanced Mission Communication Navigation and Operational Services pipeline.

2 SPACE TERMINAL ELEMENT (STE)

The Space Terminal Element (STE), or space terminal payload, was developed by MIT Lincoln Laboratory and NASA GSFC in conjunction with industry. The STE consists of several modules: the Optical Module (OM), the Modem Module (MM), the Controller Electronics Module (CEM), and the Power Conversion Unit (PCU). In this paper, the focus is mainly on the OM and the MM. The OM consists of a gimballed telescope with a near-hemispherical field of regard along with additional backend optics. The OM receives a free space optical uplink (forward link), which consists of a 7 kHz modulated beacon beam used to acquire and collaboratively track the link, and an uplink communications beam on a separate wavelength. The OM transmits a free space optical downlink (return link) after applying the appropriate look-behind angles. The OM connects to the MM via transmit / receive single mode optical fibers.

The downlink / uplink communications optical beams are encoded / decoded by the Modem Module (MM). The MM was specified by MIT LL and built by CACI [4]; it adheres to the CCSDS High Photon Efficiency (HPE) standard specification and employs a Serially Concatenated Pulse Position Modulation (SCPPM) format, supporting 10 and 20 Mbps uplink data rates, and 20, 40, 81, 130, 195, and 260 Mbps downlink data rates [5]. The MM provides a 1-GbEthernet data interface to the spacecraft.

3 GROUND SEGMENT AND TERMINALS

The ground segment is owned by NASA GSFC ACCESS (formerly Space Network). Within the ground segment there are two optical ground terminals, Table Mountain Facility (TMF) [6] and White Sands Complex (WSC) [7], which can detect / transmit the free space optical communications signals, and produce a 1-GbEthernet data interface. Both ground stations have been used previously for the LLCD mission and provide diversity against cloud and weather outage during the short 9-day mission. TMF currently supports two ongoing lasercom missions: LCRD [7] and TBIRD [9]; it will soon support the DSOC/Psyche mission (launching in October 2023) [10].

Located in Wrightwood, CA, TMF is run by NASA's Jet Propulsion Laboratory (JPL). The TMF facility hosts the Optical Communications Telescope Laboratory (OCTL) and features a 1-m aperture (telescope). For the O2O mission, an array of 64 Superconducting Nanowire Single Photon Detectors (SNSPDs) will be used to detect the SCPPM signal from the space terminal and couple with free space optics, including baffling for background reduction. The uplink produced by TMF will employ four sub-apertures within the 1-m telescope. Each sub-aperture will use a 10 W High Power Optical Amplifier (HPOA) to amplify the uplink signal.

White Sands Complex (WSC), located in Las Cruces, NM, will employ separate uplink and downlink telescopes [10]. The uplink will transmit using four 15-cm telescopes, each amplified using 10 W HPOAs; the downlink will be received via two

40-cm telescopes each with an array of 16 SNSPDs and each coupled to a specialty multi-mode optical fiber. A fast-steering mirror with closed-loop tip-tilt tracking will be used to maintain high coupling efficiency without the need for adaptive optics.

4 INTERFACE VERIFICATION APPROACH

In order to test the space to ground link, it would be ideal if the STE / flight payload and ground terminals could be simultaneously available, with the STE located on a distant mountaintop in order to perform space to ground interface verification in a somewhat real-world free space scenario. Unfortunately, this type of test is generally difficult and very costly to perform. Furthermore, for this system, the flight payload delivery and spacecraft integration occurred in early summer 2023, and at that time the ground terminals were not completely assembled as they are not required until a few months before the mission begins (late 2024). Therefore, other methods to verify performance have been worked out using the available tools. These approaches, along with available tools, will be described here.

4.1 Tools

The following are tools available to perform interface verification:

1. **The MAScOT[2] Optical Test Set (MOTS).** MOTS is a free space optical testbed at MIT Lincoln Laboratory used for payload performance testing. MOTS relays free space optical signals from large beam space, to small beam space, and eventually to/from optical fibers. MOTS can deliver/receive a flat-top beam to/from the STE's OM. Fiber launchers transmit /receive the uplink/downlink signals. MOTS contains sensors and cameras to measure boresight, pointing performance, beam profile, and wavefront quality.
    a. **Spacecraft jitter emulator.** MOTS emulates spacecraft jitter using a fast-steering mirror driven by a given spacecraft jitter profile.
    b. **Point, Acquisition, and Track (PAT) camera.** The PAT camera is a wide Field of View (FOV) camera within MOTS used to asses boresight and pointing performance.
2. **Ground Modem and Atmosphere Emulator (GMAE).** The GMAE produces uplink (beacon, filler, and communications) signals and receives downlink signals (in fiber) when the actual ground terminal equipment is unavailable.
    a. **Photodiode detectors paired with bit-checkers**. The GMAE detects and verifies downlink communications waveforms using photodiode detectors and a bit-checker developed by NASA Glenn Research Center (GRC).
    b. **Fading emulator.** The GMAE emulates atmospheric links by driving Variable Optical Attenuators (VOAs) with computed time series emulating expected fading.
3. **Engineering Development Unit (EDU) modem.** The EDU modem, developed by CACI, is a functionally performing modem that is nearly identical to the flight modem in the STE / flight payload. The EDU does not use space qualified parts nor does it adhere to form factor or thermal properties required for the STE. The few performance differences between the EDU and flight modems have been characterized and noted.

4.2 Verification approaches

A number of approaches may be used to verify the end-to-end performance of the system:

A. **Flight payload / STE to Ground Modem**. The highest fidelity test which can be performed involves interfacing the free space beam produced by the STE with the fiber-coupled ground modem. MOTS provides this interface and allows us to perform all tests while the STE tracks through both space craft jitter and atmospheric fading. Since MOTS is not transportable any test using this approach has to be performed at MIT Lincoln Laboratory.

B. **Flight Modem only to Ground Modem**. It is possible to test a Ground Modem with just the Flight Modem, by accessing the MM transmit and receive fibers and bypassing the OM. This risk reduction testing is simpler than full up MOTS testing. Atmospheric effects can be added to this test via fade emulation. However, beacon tracking performance cannot be tested without the free space interface to the OM. The flight Modem has use constraints as it is integrated into the STE.

C. **EDU Modem only to Ground Modem**. The EDU modem can perform all the tests the flight modem can perform

[2] Modular, Scalable Optical Terminal.

(with a few performance differences noted). It is fully transportable and can be shipped to ground stations to support on-site testing. Once the flight payload / STE ships and is installed on the spacecraft, the EDU Modem becomes the stand-in for all testing.

In general, approach A was the preferred method to use for space to ground verification and was used whenever possible. However, going forward, Approaches A and B became unavailable as the STE was installed on the Orion spacecraft and not accessible for this type of interface testing. Approach B was a good risk reduction test method and it used to validate using Approach C, since Approach C will be used for all tests going forward (beyond Summer of 2023).

4.3 Beacon verification

The uplink beacon provides the initial signal to the STE, which acquires it on a wide FOV sensor and then subsequently tracks it to maintain the communications link. In order to verify the uplink beacon signal, the following tests must be performed:

B1. **Modulation frequency and pulse shape**. Verify beacon waveform compatibility with the STE acquisition and tracking sensor.

B2. **Wavelength(s) and filler rejection.** Verify beacon wavelength compatibility with the OM optical filter. Since multiple uplink lasers at slightly different wavelengths are employed by both of our ground terminals, all the laser wavelengths must be tested, ideally simultaneously. In addition, since the uplink beacon lasers are typically paired with filler lasers at a different wavelength, it is essential that the filler does not leak through the OM optical filter. It is also important to test with HPOAs which can degrade the signal by adding noise.

B3. **STE acquisition and tracking performance.** Characterize beacon acquisition by the STE and subsequent tracking performance of the STE.

4.4 Uplink comm verification

The uplink communications link must adhere to framing, coding, modulation, and interleaving based on CCSDS standard. The selected data rates are 10 and 20 Mbps for the uplink comm. Code Word Error Rate (CWER) performance requirements must be met while the system is tracking with space craft jitter, and while atmospheric fading is occurring.

Several tests were performed to validate compatibility and characterize performance of each ground terminal uplink transmitter subsystem:

U1. **Data flow.** Demonstrate end-to-end Ethernet data flow from the ground terminal transmitter to the MM to ensure compatibility at all steps in the framing, coding, modulation, and interleaving chain.

U2. **Uplink Performance with unamplified sub-system**. Characterize CWER performance of each independent *unamplified* uplink comm sub-system with the Flight and EDU modems. The MM reports the CWER and power measured with the modem’s internal optical power meter. The reported power can be compared with an externally calibrated optical power meter. These measurements can serve as the baseline performance measurement and provide the delta in performance between the Flight and EDU modems, which is useful going forward without the flight MM.

U3. **Uplink performance with amplified sub-system.** Characterize CWER performance of each independent *amplified* uplink comm channel. These measurements can quantify the potential degradation of the comm signals due to high power nonlinear effects such as self-phase modulation and four-wave mixing.

U4. **Uplink performance with multiple uplinks.** Characterize CWER performance of multiple combined amplified uplink comm channels with MOTS including tracking and fading. This is the most flight-like test that additionally measures the potential degradation of the aggregate comm signal from multiple channel interference effects.

U5. **Full performance measurement.** Characterize the communications link remains error-free while the tracking through atmospheric fading and with spacecraft jitter.

4.5 Downlink comm verification

The downlink communications link must also adhere to the CCSDS standard for data rates of 20, 40, 81, 130, 195, and 260 Mbps. CWER performance requirements must be met while the system is fine tracking despite space craft jitterand while atmospheric fading is occurring. The downlink ground detectors are arrays of SNSPDs which can be tested separately.

Several tests were performed to validate compatibility and characterize performance of each ground terminal uplink transmitter subsystem:

D1. **Bit check.** Demonstrate adherence to CCSDS modulation and coding using bit checker .

D2. **Data flow.** Demonstrate end-to-end Ethernet data flow from the STE to the ground terminal modem to ensure compatibility at all steps in the framing, coding, modulation, and interleaving chain.

D3. **Downlink detector performance**. Characterize CWER performance of each independent downlink SNSPD-based receiver sub-system with the Flight and EDU modems.

D4. **Full performance measurement.** Characterize the communications link remains error-free while the tracking through atmospheric fading and with spacecraft jitter.

5 STATUS

Verification of the STE to WSC ground terminal was mainly at MIT Lincoln Laboratory, where the ground terminal was developed. Selected uplink sub-assemblies from the TMF ground terminal were brought out to MITLL and underwent full-up testing with the EDU Modem, Flight Modem, and Flight Payload. The results are copious and are not shown here, but the completed (passing) tests (see Table 1, Table 2, and Table 3) and remaining work are tabulated below.

Table 1:Status of Ground Terminal Beacon Testing. See Section 5.2 for description of approaches. See Section 5.3 for description of beacon verification tests B1, B2, B3. Notes: WSC Uplink #5 is a backup sub-system for WSC.

	TMF – Beacon	WSC – Beacon
Approach A	B1, B2, B3 completed with U/L #3-4	B1, B2, B3 Completed with U/L #1-5
Approach B	n/a	n/a
Approach C	n/a	n/a

Table 2:Status of Ground Terminal Uplink Communications Testing. See Section 5.2 for description of approaches. See Section 5.4 for description of beacon verification tests U1, U2, U3, U4, U5. Notes: WSC Uplink #5 is a backup sub-system for WSC.

	TMF – Uplink Comm	WSC – Uplink Comm
Approach A	U1, U2, U3, U4, U5 completed for U/L #3-4	U1, U2, U3, U4 completed for U/L #1-5
Approach B	U1, U2, U3, U4, U5 completed for U/L #3-4	U1, U2, U3, U4 completed for U/L #1-5
Approach C	U1, U2, U3, U4, U5 completed for U/L #3-4 U1-U5 to be completed on U/L #1-2 prior to mission	U1, U2, U3, U4 completed for U/L #1-5 U5 to be completed on U/L #1-5 prior to mission

Table 3:Status of Ground Terminal Downlink Communications Testing. See Section 5.2 for description of approaches. See Section for description of beacon verification tests U1, U2, U3, U4, U5.

	TMF – Downlink Comm	WSC – Downlink Comm
Approach A	D1 completed	D1, D2, D3, D4 completed
Approach B	D1 completed	D1, D2, D3, D4 completed
Approach C	D1 completed D2-D4 to be completed prior to mission	D1, D2, D3, D4 completed D1-D4 to be repeated at WSC prior to mission

6 CONCLUSIONS

The O2O demonstration brings together many organizational players and contains a number of complex interfaces. Each of these interfaces requires verification (or validation) to ensure success. Verification of the space to ground optical interface and the tools and methodology used to approach this complex task have both been described. The verification process is ongoing, but sufficient testing has been performed with the flight payload that to warrant confidence in proceeding with ground terminal development using the EDU modem as a stand-in for the STE / flight payload.

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