

Orion Artemis II Optical Communications Architecture, Implementation and Test Systems

Peter Rossoni (Peter.Rossoni-1@nasa.gov)^a; Farzana Khatri (farzana@ll.mit.edu)^b; Bryan Robinson (brobinson@ll.mit.edu)^b; RJ McGraw (rmcgraw@mti-systems.com)^d; Chris Finegan (chris.finegan@nasa.gov)^f; Jonathon King (jonathon.b.king@nasa.gov)^c; Mike Bay (michael.bay@bayengineering.org)^e; Bob Schulein (bob.schulein@bayengineering.org)^e; Jeff Zinchuk (jeff.zinchuk@bayengineering.org)^e; Nikki Desch (Nikki.M.Desch@nasa.gov)^a

^a NASA Goddard Space Flight Center
8800 Greenbelt Rd
Greenbelt, MD 20771

^b MIT Lincoln Laboratory
244 Wood St
Lexington, MA 02420

^c NASA Johnson Space Center
2101 E. NASA Parkway
Houston, TX 77058

^d MTI Systems
5929 Talbot Rd
Lothian, MD 20711

^e Bay Engineering Innovations
3321 Pocahontas Dr, Edgewater,
Maryland, 21037

^f Peraton, Inc
1875 Explorer Street,
Reston, VA 20190

Abstract—The Orion-Artemis II Optical Communications (O2O) Payload provides data transfer (up to 260 Megabits per second downlink) for NASA's first crewed moonshot since the Apollo days. O2O's purpose and scope stress incorporating the operational utility of a high speed communication link with reduced Size, Weight and Power (SWaP). The promise of this technology is real time access to critical data, virtual presence and enhanced teamwork. This application of Optical Communications lays a foundation for the exploration ambitions of NASA, this nation and the world.

This paper describes O2O's operational architecture, based on the optical C-Band wavelength (1550 nm), its integration into NASA's Orion spacecraft and Mission Control Center (MCC) operations, and operational system certification. Of particular note are the intricacies of integrating designs with different performance goals. The architecture, integration method, certification and operations are key to what will be an essential component of future space missions, both robotic and astronautic.

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1. INTRODUCTION

Free-Space Optical Communications (FSOC) or Optical

Comm, has been around for decades. From initial space-to-air and -ground experiments to massive constellations of inter-satellite links, the technology provides data rates exceeding 100 Gigabits per second (Gbps) at ranges up to 5000 km [1]; 600 Mbps at lunar distances [2], and 1 Mbps at half a billion km [3]. The highest rate, shortest range solution uses coherent modulation, which is available commercially. The longer range applications use a special scheme in which power efficiency is the dominant consideration in link design. To date, these communications systems have functioned as fairly standalone (or proprietary) systems wherein the provider and user are well-coordinated or adhere to internal or otherwise established communications standards.

What happens when such a high performance link is integrated to an existing architecture and the goals are to improve data transfer rates by a factor of 100? This paper describes one process. The O2O initiative accomplished that in the Artemis II mission-critical environment. While the optical and Radio Frequency (RF) free-space links are parallel between space and ground, both need integration to a network on either end. This ambitious goal means that top-level and strategic systems engineering needs to be applied to the end-to-end system, and the operations team needs to run both links simultaneously. Future concerns include developing networks sufficient to handle 2-10 Gbps multiple-wavelength optical from lunar in work by NASA, and similar networks compatible with the data rates to support humans on Mars.

The O2O effort began in 2016, around the time of Orion's Critical Design Review (CDR). At this relatively late stage, impacts to the host had to be minimized, impacting cohesive and optimal system integration. As a result the system weighed more, used more power, and operated at lower rates than an organically designed system would have. A consistent, top-level systems perspective is key to successful future lunar and deep space presence, where high-performance, dependable infrastructure such as a robust

communications system will be essential. Future deep space systems could support Gbps level rates.

This paper is organized as follows. After an overview of the end-to-end Optical Comm system in Section 2, which encompasses the flight Orion spacecraft to the Mission Control Center (MCC) at NASA Johnson Space Center (JSC) Houston, Section 3 of this paper describes each constituent element. Section 4 delves into accommodations -by discipline- that had to be made to incorporate O2O. Section 5 describes the certification testing approach and Section 6 discusses interim results. Section 7 provides a summary of improvements likely to make integration smoother in the future.

2. SYSTEM OVERVIEW

This section describes the architecture, interface control and certification -or verification- status.

The O2O end-to-end functional system consists of five serially connected elements between the flight spacecraft and the ground user at MCC, shown in Figure 1:

- Orion Spacecraft Element (OSE) and Orion Utility Network (OUN)
- Space Terminal Element (STE), which forms one end of the optical link

- Ground Terminal Element (GTE) receivers and transmitters, the other optical link terminal
- Ground Data Element (GDE), for user data and telemetry archive and relay
- Orion Operations Element at MCC Houston

Except for the S-Band link between MCC and Orion, the four interfaces in each link between the five elements must be tailored to O2O's high data rates and governed by Interface Control Documents (ICDs).

Utilizing this architecture to its full capability requires comparable performance from all high rate data links. The paths shown in Figure 1 are serial, so each is essential to system function. Multiple ground terminals provide selective redundancy against weather-related outages, which are a greater concern for optical systems.

The O2O Level 1 requirement is to downlink data from the OSE to the MCC at selectable rates of between 20 and 260 Mbps, with a minimum of 60 Mbps for 1 hour per mission day. Table 1 lists the links, which are governed by applicable ICDs.

Even in this relatively modest-performing application, the factor limiting data rates is the network on either end, not the optical link. Matching performance between systems is always a key challenge for integrating new elements.

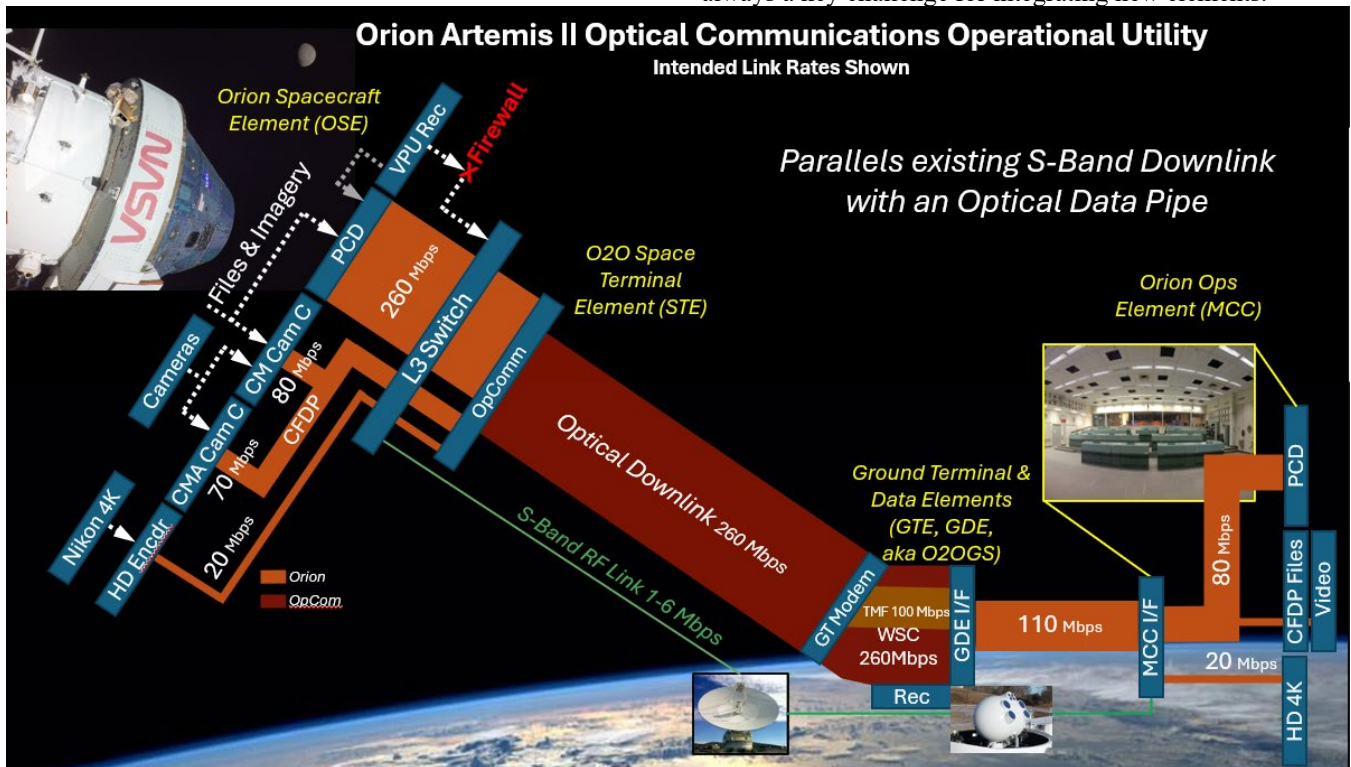


Figure 1 O2O Data Paths

Table 1 Element Links and ICD Data Rate

Link	Data Rate (Mbps)
Orion Spacecraft Element (OSE)-STE via OUN	80
STE-Ground Terminal Element (GTE) via FSOC	260
GTE-GDE – White Sands	250
GTE-GDE – TMF	110
GDE-MCC firewall via terrestrial commercial provider	110
MCC internal via OUN-Ground	60

3. COMMUNICATIONS ELEMENT DESCRIPTIONS

Figure 2 is the block diagram version of Figure 1, highlighting the element forward and return data sources and their respective paths.

Orion Spacecraft Element—The OSE is the Orion flight spacecraft, containing data systems, sensors, cameras and computers used by the crew aboard, as well as all the mission critical and support equipment. It also maintains a Gb Ethernet Onboard Utility Network (OUN) with several data collection components, including Camera Controller and Level 3 Utility Network switch to connect most Orion components. Imagery, data generation and Demonstration Flight Instrumentation (DFI) devices and systems onboard can leverage the Optical Comm pathway. Connection to the STE is via an ethernet bridge and L2 VLAN. Many of the file transfers handled by O2O use the Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol (CFDP). The OUN is the mission-critical network on the vehicle. There is a separate network, the Orion Data Network (ODN) which employs a time-triggered, safety-critical Ethernet protocol used by the flight computers.

Space Terminal Element—The STE onboard Orion is composed of flight optical modem, optical module, controller electronics and power conversion unit, each with unique interfaces to the Orion Spacecraft. Optical Communication with the GTE conforms to the CCSDS High Photon Efficiency (CCSDS-HPE) standard.

Ground Terminal Element—The GTE is the optical receiver for the STE downlinked data, and also provides an uplink to the STE for file uploads and CCSDS transfer protocols. This encompasses two optical ground stations. NASA/GSFC supplied one at the White Sands Complex (WSC), New Mexico, and NASA/JPL supplied the other at its Table Mountain Facility (TMF) in California. Their communications protocols conform to CCSDS-HPE and are each equipped with telescopes, electro-optics, transceiver/modem, pointing, acquisition and tracking systems and Monitor and Control (M&C) systems.

An experimental third ground station at Canberra, proposed by the Australian National University (ANU), will attempt to

establish contact with the STE on Orion. While not part of the baseline mission, this could serve as an important demonstration of the ability to expand optical networks in general, enhancing the utility of this potent resource.

The GTE includes a command and control Ground Segment Operations and Analysis (GSOA) function at WSC, which performs scheduling, GTE analysis, generates GTE pointing files and compiles performance, health & status, and weather data. These data are combined into pre-pass activity plans and post-pass reports in both Quick-Look and Detailed Analysis formats.

Ground Data Element—The GDE located at WSC is the single mission data interface between the GTEs and the Orion Operations Element at JSC (“Orion Ops”). It routes and stores user data, performance data, and STE status and health to the Lasercom Space Terminal Console (LSTC) in the JSC MCC for monitoring, analysis and troubleshooting.

The GTE, GSOA and GDE constitute the O2O Ground Segment (O2OGS). The O2OGS and STE share heritage in the 2013 highly successful Lunar Laser Communications Demonstration (LLCD) mission. Interfaces have been well-established, and the links demonstrated full function, both in laboratory and field tests, as well as in orbit [2, 3].

Orion Operations Element—“Orion Ops” is located at JSC’s MCC (see Figure 3). It is divided into the Mission Critical Environment (MCE) and Mission Support Environment (MSE), each with dedicated LANs. The MCE has specialized servers and processors and firewalls to the outside OSE and GDE. The Mission Support Environment (MSE) houses the LSTC and the Laser Link Planning and Analysis Center (LPAC). The LSTC and LPAC connect to the GDE only through the intervening MCE network. The networks use Ethernet frame-in-UDP-packet for a simple, robust connection, but less efficient dataflow. Good coordination with the GSOA in the O2OGS enables ephemeris, performance data, and daily activity plan distribution for each daily contact and subsequent reports.

A key challenge for the OSE and MCC is to certify their networks to the performance levels (data flow protocols and rates) commensurate with the level of operational utility that O2O seeks to provide to Artemis II.

4. ACCOMMODATIONS

This section highlights some of the interfaces and customizations needed to accommodate the O2O and Orion systems, both on the flight and ground (MCC) sides. Significant time and effort went into developing the relevant ICDs, in the expectation of realizing the O2O system benefits. Nonetheless, some compromises were involved in the late-stage optical link addition. The architecture guiding these accommodations was developed prior to the O2O Preliminary and Critical Design Reviews (PDR and CDR).

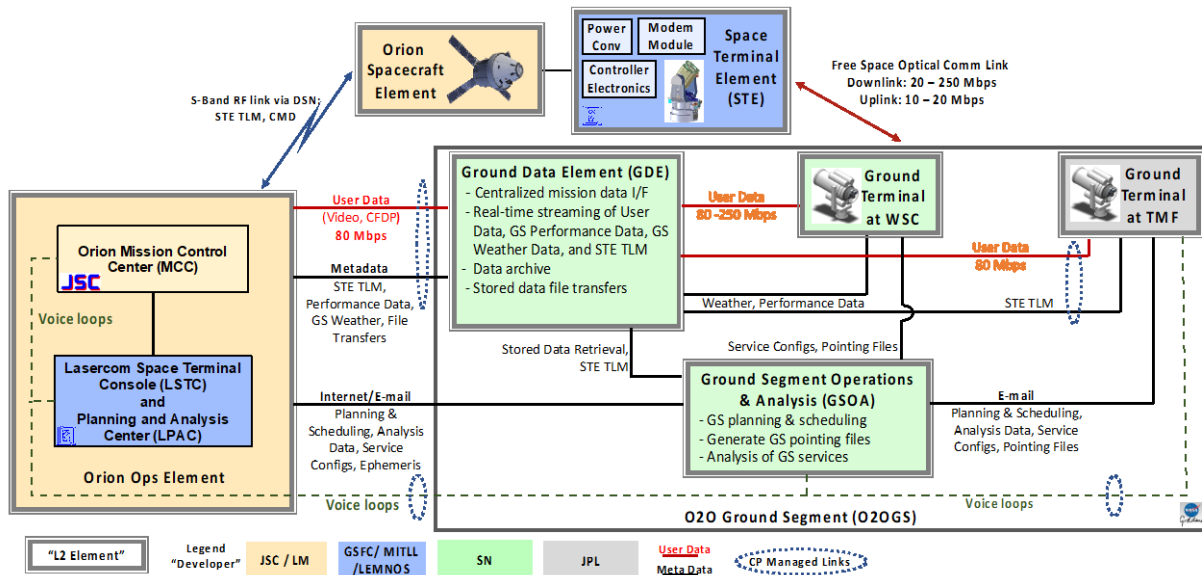


Figure 2 O2O Mission-Level Communication Architecture

Mechanical

All flight STE components were mounted on unique brackets with vibration isolators, as were many of the existing Orion components, such as the Power Distribution Units. The mounts had to make use of existing hardpoints on the Crew Module Adapter structure; typically O2O could not rely on dedicated mechanical mounting features.

This resulted in a 10-25% mass penalty, depending on the unit.

Thermal

Similarly, the STE does not use Orion cooling loops, leading to a “cold biased” thermal design, in which self-heating and electric heaters compensate for heat loss through the structure or radiation. A late review of Orion thermal test data briefly indicated that modem temperatures at the enclosed inner wall would exceed modem limits, cutting down the operational time, or even preventing power-on and operations during certain sun-biased attitudes. A subsequent correction of the thermal model resulted in positive margins, even for operation through the entire 8-10 hour view period.

This could have ended very differently, with limited opportunity for O2O to operate and provide the useful operational benefits of high rate data links. The mass of the extra heaters, blankets and radiators was less than Orion-supplied cooling loop hardware, thus saving mass for the mission as a whole

Power

O2O was designed for the typical 28-volt robotic mission power system, requiring a power conversion unit weighing almost 5 kg to step down the Orion 120-volt system.

Guidance, Navigation and Control

The OSE sends detailed Orion quaternion and state vectors for operational navigation, or “OpNav,” information to the STE over the onboard ODN. Combined with alignment measurements between the STE and OSE master reference, this enables the STE Pointing, Acquisition and Tracking (PAT) system to accurately point at the ground station within worst-case predicted pointing errors. Additionally, the STE has its own star tracker, which can leverage OSE timing information to locate its target GTEs on the ground.

Optical Ground Segment (GTE, GSOA and GDE)

The ground stations use existing optical facilities, therefore needed no physical accommodations from the Artemis program.

The MCC and GDE developed an ICD specifying maximum and recommended data rates, user data encapsulation, data exchange methods, such as email, voice loop or Secure File Transfer Protocol (SFTP). Within the O2OGS, the GSOA, GTE and GDE were developed in close coordination, resulting in well-established interfaces, resulting in smooth operations. The GTE-to-STE optical interface is governed by a Space-to-Ground ICD, developed separately from Orion.

Operations

Protocols for human spaceflight demand that only specially trained Integrated Communications Officers (INCOs) at the MCC generate, check and issue commands to the space vehicle. Thus all commands from the O2O LSTC are pre-developed, stored in the MCC and called up by the INCOs when ready for use. Command fine-tuning is accomplished with parameters (e.g. optical acquisition settings). Commands may be grouped into blocks for more

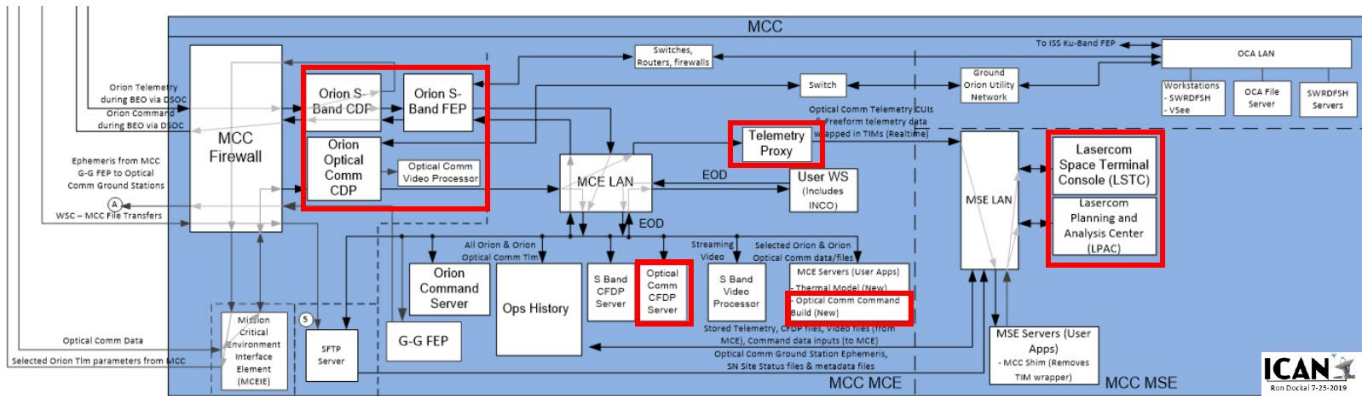


Figure 3 O2O Accommodations in the MCC (highlighted in red)

efficient use of operator and INCO time. Macro scripts were developed and implemented to speed telemetry value verification.

MCC Network

Incorporating O2O into the Orion operations at the MCC included critical additions both hardware and software as shown in Figure 3:

- Separate, dedicated Communication and Video Data Processors (CDPs and VPUs) in parallel with the existing S-Band units, with associated software modifications
- CFDP Server for Optical Comm
- Mission System Environment Consoles for the LSTC and the LPAC
- Software to allow block command and data exchanges

The INCO team at the MCC sends O2O-specific commands and receives telemetry to operate the STE Controller Electronics via an RS-422 path to OSE over the S-Band link. These use the detailed block commands with specialized parameters for various operational scenarios were generated for additional flexibility as real time mission needs dictate.

Additional features at the MCC support the higher data throughput from O2O. On the left in Figure 3, large user data files come into the MCC through the firewall to the CDP and VPU before forwarding to the Optical Comm CFDP server for immediate use or storage. STE telemetry passes through the MCE Interface Element (MCEIE) before entering the MCC firewall, and forwarding by the MCE LAN to the MSE LAN for use by the LSTC and LPAC. Also shown is the Optical Comm command build repository, where pre-defined LSTC commands are ready for INCO usage during ops.

The next section describes certification of the O2O system to the Artemis architecture.

5. REQUIREMENTS AND CERTIFICATION

The STE flight components undergo environmental qualification per their respective ICDs. The fully integrated STE undergoes Comprehensive Performance Test (CPT) to verify all high-level requirements are satisfied. The CPT includes tests such as power-up, optical receive and transmit power, Pointing, Acquisition and Tracking tests, etc. Likewise, the O2OGS at the ground terminals are certified through ground readiness tests (GRTs) driven by governing ICDs. The OSE and MCC element certifications use established practices under the auspices of JSC Mission Control and the Artemis program tailored for the O2O Development Test Objective. Finally, a series of Mission Readiness Tests (MRTs) assure all components, elements and links function together properly as if in flight. This is known as Test Like You Fly (TLYF)

Certification testing (or verification) of the communication dataflow occurs first at the element level using actual or flight-like interfaces and test hardware prior to delivery, and then in multiple, overlapping segments leading to end-to-end system certification. As with most free space communication systems, a piece-wise approach is needed due to the respective elements' disparate physical locations. The OSE and STE are already integrated at KSC, optical ground terminals are at WSC and TMF, and Orion Ops is located in Houston. True end-to-end testing is not feasible prior to launch, since there is no flight-like pathway bridging STE and GTE. The team therefore follows the overlapping strategy outlined in Figure 4, where the solid lines represent the flight data flow, and the test flow follows the dashed lines.

For the STE-to-GTE link, a Ground Modem and Atmospheric Emulator (GMAE) and its counterpart, the Space Modem and Atmospheric Emulator (SMAE) verify and compare against operational optical downlink and uplink waveform performance parameters. These include amplitude, pulse width, extinction ratio, jitter/phase error, SNR, etc. Waveform trending ensures flight, engineering unit or lab-based optical waveforms are effectively identical. These overlapping link verifications assure the integrity of the end-to-end path. Similarly, multiple GDE emulators, known as "Baby GDEs," after checkout per the ICD, may be

located at the different element facilities, providing a mission-like network interface.

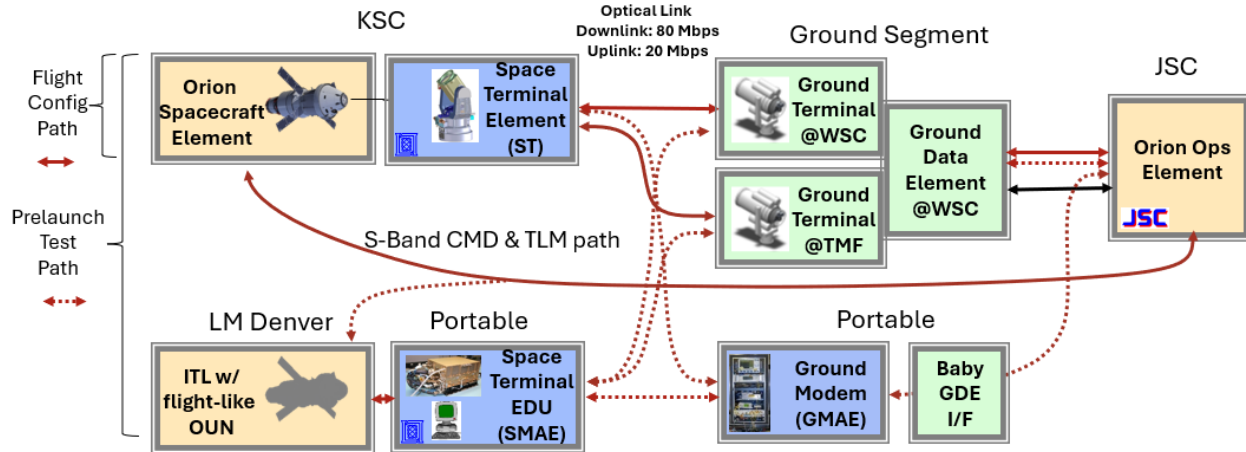


Figure 4. MRT Schematic, Featuring Portable Emulators, showing Mission Data Paths by Solid Lines, and Test Paths by Dashed Lines

The certification approach allows for GMAE and SMAE insertion onsite at either ground terminal (WSC or TMF), or the Integrated Test Lab (ITL) in Denver, where Lockheed has set up an OSE ground “twin.” This could either simulate the terrestrial link with its own constraints or bypass the slower terrestrial links and any non-mission-like interfaces that could impede high rate testing. Collocating at ITL also allows for more efficient troubleshooting. Depending on test type or scenario, the actual ground terminals are introduced for greater realism and proficiency exercises. Orion also maintains separate Virtual Test Beds (VTBs) for expanded test opportunities.

A significant challenge is managing the differences between laboratory settings and operational mission environments assuring that each is suitably functional and flight-like, with interfaces that match the operational scenario to be tested. For example, an element or segment in an isolated lab environment may not accurately represent the actual timing and interleaving of high rate data transfer in the presence of other network traffic while in operations.

Element Certification and Beyond

The STE flight elements are fully certified for delivery once they pass their Pre-Ship Review, in which all governing documents, requirements and tests are satisfied. Likewise, the O2OGS, containing operational elements, must pass a milestone called the Ground Operational Readiness Review (G-ORR). Between G-ORR and launch, the ground stations conduct Proficiency exercises and training to build robustness into their operations.

Simulations, in which INCOs and the O2O team practice real time commanding and telemetry monitoring and analysis, serve to train the teams for flight operations and ready them for off-nominal scenarios. When Orion conducts real-time mission simulations, the Optical Comm ground elements, GTE and GDE (along with LSTC, GSOA and LPAC) may participate, to provide the highest level of thoroughness. These exercises are geared to build operator proficiency with the many system elements, and habituate them to the procedures, facilities and work environment they are likely to encounter during mission operations.

Finally an end-to-end (as much as feasible) test is performed in a manner that closely mimics the flight mission configuration and operation. The goal is to truly test-like-you-fly (TLYF), with mission INCOs and representatives from the various data users (such as the Imagery team and Command and Data Handling operators) and O2O flight STE and ground segment operators. TLYF brings together all the mission personnel with actual mission hardware and software in final, flight configuration so as to replicate the actual flight conditions. This assures an accurate assessment of overall system performance in as realistic fashion as possible.

6. RESULTS

The MRTs were designed to prove out TLYF end-to-end certification. Emulators transferred mission commands, telemetry or data in order to close the loop and validate mission pathways shown in Figure 4. Table 2 summarizes the MRT campaign strategy.

Table 2 MRT Summary

MRT#	Mission Functions	Pathways Tested
1A	Flight Command and telemetry – uplink	MCC/OSE/STE
1B	Ground Command and telemetry – downlink	GTE/GDE/MCC
2A	Flight Command and data path – fwd-return loop	MCC/OSE/STE/GMAE/MCC
2B	Ground Command and data path – return downlink	SMAE/GTE/GDE/MCC
3	Flight Day 1 simulation over MRT 2A path – fwd-return loop	MCC/OSE/STE/GMAE/MCC
4	Nominal ops over MRT 2A path – vary data sources and quality	MCC/OSE/STE/GMAE/MCC
5	Nominal ops over MRT 2A path – vary ground stations and transmission parameters	SMAE/GTE/GDE/MCC

MRTs 1A and 1B verify that all command and telemetry pathways are intact and functional. MRTs 2A and 2B introduce high rate user data to test the links’ performance. MRT 2A uses the ground modem emulator, verifying the STE transmission, while 2B uses the Space Modem emulator, and verifies the GTE ground terminal receipt of signal. MRTs 3 and 4 focus on the entire loop from MCC, through the spacecraft and back to MCC, with only the GMAE standing in for the O2OGS. MRT 5 uses the SMAE to focus on the ground segment, varying ground station selection and transmission parameters such as search pattern for initial acquisition and data rate.

MRT and Integration Progress

At the Lockheed Martin Integrated Test Lab (ITL) from 2020 to 2022, the power, OpNav and Telemetry and Control interfaces were validated (MRT 1). The ITL supported real-time monitoring and commanding from MCC in Houston during tests of the Orion communication system [4]. During this time, the team started to encounter data rate limitations in both the Orion onboard flight and MCC ground networks. Symptoms included packet arrival out of order, gaps in the data flow, and Non-Acknowledges (“NAKs”) in the network stream.

Other support functions also needed ringing out, with MRT dry-runs and updated database and console display content in early 2023.

In mid-2023, the STE flight hardware was mechanically and electrically integrated to the Orion spacecraft. Safe-to-mate procedures verified each wire connection, uncovering only one hardware discrepancy in the Space Wire connector, which was corrected on the OSE side of the interface. Safe-to-mate was followed by a final CPT on the STE. The STE optical link was verified via a Fiber Test Port into the telescope optics, which linked the STE to the GMAE. Diagnostics indicated the STE was fully functional.

Later that year, the team attempted to run MRT functional tests 1, 2, 3 and 4, incorporating the STE into operations. This proved out the OSE-to-STE interfaces successfully, but the end-to-end dataflow still fell short of rates needed for O2O certification. Thus the MRTs were partially complete, leaving the needed fixes to be validated through regression testing at a later date.

2024 and 2025 were dedicated to dry runs and regression testing to construct and verify a suitable testing system to mimic the flight configuration and address dataflow and hardware configuration issues. All up MRTs were again hampered by data flow issues in the OUN and MCC.

Troubleshooting in this latest phase was helped significantly by a “patch cord” or “wired” connection approach, wherein the free-space optical link was replaced by patch cord. This greatly enhanced flexibility in setting up and conducting troubleshooting tests. Thus the ITL, VTB labs with SMAE (simulating flight network elements) and Baby GDE and GMAE emulators (which mimicked the ground segment) could be leveraged as needed when the flight or ground mission elements were unavailable. The emulators allowed tests to focus in on problem areas.

Additional test equipment helped to identify dataflow problems and ascertain their characteristics. Judiciously placed “packet sniffers” pinpointed specific links subject to data loss. A network emulator helped the lab-based test beds more realistically simulate the actual mission implementation and behavior of data in transit. Key features included inserting the 1-second time-of-flight latency due to lunar distances; simulating the level of data “burstiness” during dataflow; and monitoring packet arrival order.

Troubleshooting steps assured correct configurations, including verifying flight-like hardware (or understanding components’ provenance) in the test labs, or older software versions caused by configuration control processes forcing implementation delays for reviews and approvals. Correcting the test lab configurations eventually allowed testing to proceed.

MRT Status

Ultimately, the network sleuthing effort identified two key data flow pinch points: one onboard Orion, and one in the MCC.

The prime imagery management unit onboard Orion is the Camera Controller (CC), which sends packets over the OUN flight network at an adjustable cadence. The CC drivers were not synching properly with the Layer 3 switch, causing gaps and NAKs. Fine-tuning this cadence enabled the systems engineers to optimize the interface with the Layer 3 switch,

enabling dataflow at rates commensurate with the O2O requirements.

One factor in this mismatch was buffer size on the OUN Layer 3 switch. Ultimately, the with adjusted cadence handles O2O rates as long as all network users share the high rate paths. This requires the coordination through the Orion flight activities team. The cadence interval change was approved by the Orion software control board and implemented in the flight software.

On the ground, the MCC CFDP software engine was found to be issuing user interface messages at an excessive rate, impeding user data flow. A CFDP driver update reducing the message rate solved this issue. The update was incorporated in the ground software controlling the CFDP, and testing demonstrated error-free data flow at the required rates.

Maximizing the Link

Finally, it remained to exercise the O2O data flow at its maximum rate of 260 Mbps. Due to bandwidth limits on the terrestrial commercial fiber link between the GDE and MCC, O2O will store its highest rate real time data on the GDE at WSC. Testing for this scenario occurs during MRT 5. For flight, a dedicated slot in the mission timeline is set aside for this saturation of the optical link, due to the unique commanding required.

Testing in a flight-like manner remains a key objective. Progress towards this goal continues as O2O participates in Mission simulations, Orion matures the test beds and more flight-like procedures and configurations become available. With the identified fixes and end-to-end TLYF tests completed in late 2025, the O2O certification is complete and ready for launch in 2026.

7. SUMMARY

O2O is high data rate, end-to-end communication system linking Artemis astronauts with the mission control center in Houston. The operational benefits include improved monitoring and control of the Orion spacecraft; improved anomaly response; better access to critical data; and enhanced virtual presence between space and ground users and participants.

The key challenges discussed here included

- maintaining configuration control between flight and test hardware and software
- staying abreast of developments on each side of an interface especially during the long development cycle
- fine-tuning existing networks to perform at rates higher than originally planned

This paper has detailed the O2O data flow design and certification process, including some of the challenges associated with integrating elements of disparate design heritage. The lessons to be taken from this experience

include:

- design for key requirements early on;
- minimize compartmentalization and
- take a systems-level approach to end-to-end design.

O2O has broken ground not only in the implementation of laser comm in an operationally useful way; the project and dedicated team members across multiple organizations have overcome numerous practical challenges in the network implementation for space communications.

O2O is the first step on a path toward high-speed optical communications for lunar exploration and beyond, with benefits to the Artemis program and its international partners.

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BIOGRAPHY



***Peter Rossoni** received a B.S. in Mechanical Engineering from the University of Massachusetts in 1987, and a Professional Masters in Controls Engineering from the University of Maryland, College Park in 2017. His career started in the Structural Dynamics Branch, followed by work in spacecraft development with the Small Explorers program (SMEX). Peter went on to lead Mechanical Systems on the ST-5 series of satellites. Peter has supported the systems and project management teams on the ICESat-2 ATLAS instrument, LCRD and LEMNOS/O2O laser communications projects. He has been with NASA's Goddard Space Flight Center since 1985.*