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Ground Segment Operations Concept for the Orion Artemis-2 Optical Communications System

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Abstract

The ACCESS Project (formerly Space Network) will implement an optical communications ground segment to support the Orion Artemis II Optical Communications (O2O) demonstration as part of the next manned human spaceflight mission to the moon, Artemis II. O2O implements laser communication (lasercomm) technology for operational use on the Orion series of spacecraft, as a development test objective (DTO), in order to demonstrate the feasibility and operational utility of lasercomm for human spaceflight missions.

O2O consists of three segments: Space Segment, Ground Segment, and Operations Segment. The Space Segment consists of the Space Terminal Element and the Orion spacecraft. The Space Terminal Element effort is managed by the GSFC Laser-Enhanced Mission Communications Navigation and Operational Services (LEMNOS) project in collaboration with MIT Lincoln Laboratory. The Ground Segment consists of an optical ground terminal (GT) at the White Sands Complex (WSC), which is being developed in collaboration with MIT Lincoln Laboratory, the Ground Segment Operations and Analysis (GSOA) element and Ground Data Element (GDE), and a second optical GT in the Optical Communications Telescope Laboratory (OCTL) at the JPL Table Mountain Facility. The Operations Segment consists of the Artemis II Mission Control Center (MCC), the Lasercomm Space Terminal Console (LSTC), and the Lasercomm Link Planning & Analysis Center (LPAC), all located at the Johnson Space Center (JSC).

O2O utilizes pulse-position modulation (PPM) direct-to-earth services resulting in an 80 Mbps downlink data rate from lunar orbit. The O2O concept of operations is to provide optical services for a minimum of 1 hour per day for each day of the Artemis II mission. O2O will utilize a 10-20 Mbps uplink data rate and 40-260 Mbps downlink data rate, depending on the Artemis II mission phase. The ACCESS project will also provide a centralized mission data interface for user data distribution and storage to the MCC and perform planning and scheduling of services in coordination with the Operations Segment for the O2O Ground Segment. The O2O Ground Segment will support the following O2O mission phases: Pre-Mission Planning; Daily Operations Planning; Event Execution; and Post-Pass Reporting. O2O will be used to exchange data files between Orion and the MCC and to distribute real-time video through the optical downlink service to the MCC; which would not be possible without the high-bandwidth link that O2O will provide to Orion.

In this paper, I will discuss the O2O Ground Segment development approach and how it will support these critical O2O functions: plan and schedule the contact; acquire and track the optical link; flow information bidirectionally; distribute information; and control and accommodate the system.

Keywords: optical communications; ground segment; operations; Artemis II

Acronyms/Abbreviations

DAR	Detailed Analysis Report
DTO	Development Test Objective
GDE	Ground Data Element
GSAP	Ground Segment Activity Plan
GSFC	Goddard Space Flight Center
GSOA	Ground Segment Operations and Analysis
GT	Ground Terminal
HDLC	High-level Data Link Control
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center

LEMNOS	Laser-Enhanced Mission Communications Navigation and Operational Services
LLGT	Lunar Laser Communication Ground Terminal
LPAC	Link Planning & Analysis Center
LSTC	Lasercomm Space Terminal Console
M&C	Monitor and Control
MAP	Mission Activity Plan
MCC	Mission Control Center
MIT/LL	Massachusetts Institute of Technology Lincoln Laboratory
NASA	National Aeronautics and Space Administration
O2O	Orion Artemis II Optical Communications
O2OGS	O2O Ground Segment
O2OGT	O2O Ground Terminal
OCTL	Optical Communications Telescope Laboratory
OUN	Orion Utility Network
PAT	Pointing, Acquisition, and Tracking
PPM	Pulse-Position Modulation
QLR	Quicklook Report
STE	Space Terminal Element
TMF	Table Mountain Facility
UDP	User Datagram Protocol
WSC	White Sands Complex

1. Introduction

The Orion Artemis II Optical Communications (O2O) effort is one of the Development Test Objectives (DTOs) for the Artemis II lunar mission. O2O is a National Aeronautics and Space Administration (NASA) Space Communications and Navigation initiative that demonstrates the operational capabilities of free space optical communications services for Human Spaceflight missions. Optical communications are a key part of the NASA Human Exploration and Operations Mission Directorate long-term approach for reducing latency while increasing capacity of the space communications infrastructure.

The Artemis II mission is the first crewed mission of the Orion spacecraft and is currently scheduled for launch in August 2023. It consists of the Orion spacecraft and the Space Launch System. The Artemis II mission is planned to take four astronauts on a 10-day trajectory around the Moon. This includes performing multiple trans-lunar injection burns. This DTO will be the first demonstration of free space optical communications with a crewed, lunar trajectory mission. The first O2O event will occur at the apogee of a highly elliptical orbit. Following that event, O2O is expected to operate for a minimum of one hour per day through one day prior to splashdown.

The focus of this paper is on the ground segment supporting the O2O DTO. The O2O Ground Segment (O2OGS) will provide direct-to-earth services to the O2O terminal throughout the duration of the mission. This paper provides a detailed description of the O2OGS architecture and the functions each element provides in support of the O2O DTO.

2. O2O DTO Overview

Figure 1 shows the top-level architecture of the system that implements O2O. The system is divided into the Space, Ground, and Operations Segments, each of which is comprised of several elements. The subject of this document is the Ground Segment. The color coding identifies the NASA organizations responsible for providing each element.

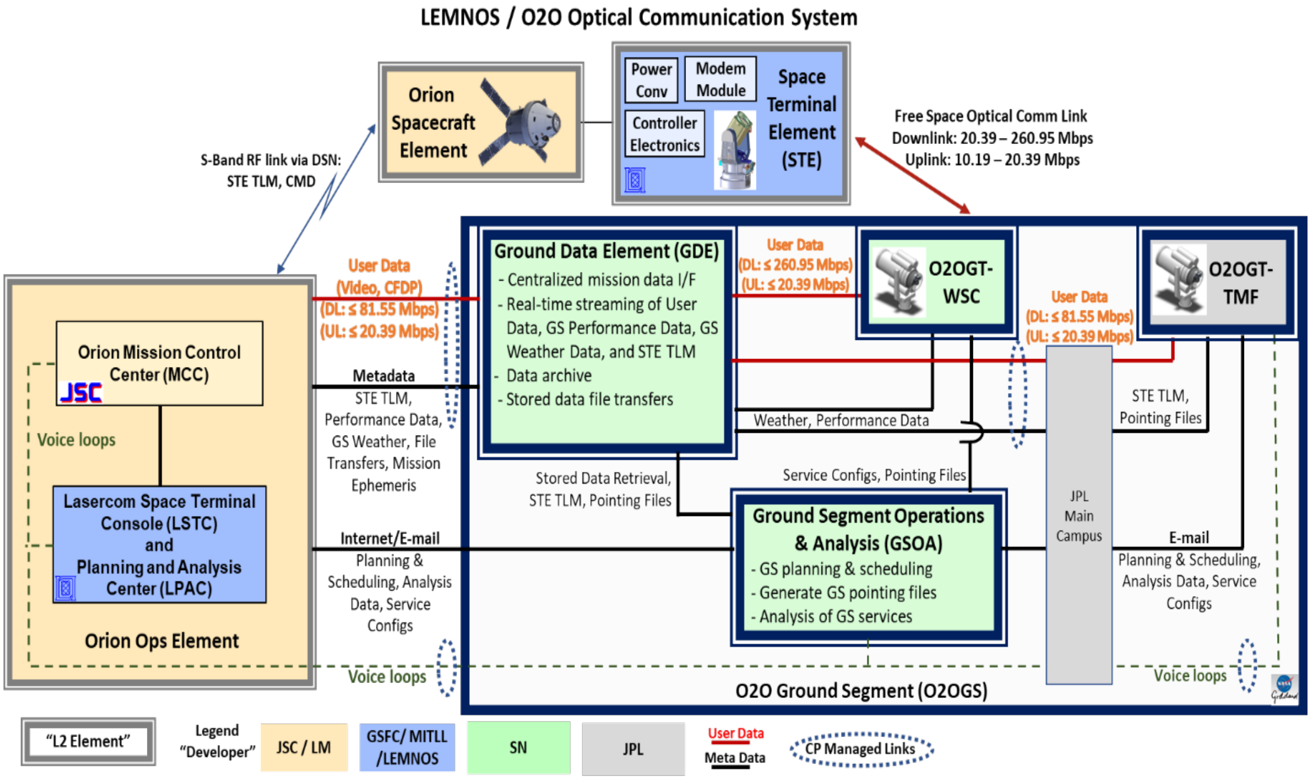

Figure 1. O2O Ground Segment Architecture

2.1 O2O Space Segment

The Space Segment includes the Orion vehicle, radio frequency phased array antennas, and the Space Terminal Element (STE). The STE, managed by the Goddard Space Flight Center (GSFC) Laser-Enhanced Mission Communications Navigation and Operational Services (LEMNOS) project and delivered by the Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL), will be mounted to the Orion spacecraft. The STE consists of an Optical Module, a Modem Module, a Controller Electronics module, and a Power Conversion Unit. The STE has an interface with the Orion vehicle electronics for O2O mission data and STE telemetry and command data [1].

2.2 O2O Operations Element

The Operations Element consists of the Orion Mission Control Center (MCC), the Lasercom Space Terminal Console (LSTC), and the Lasercom Link Planning & Analysis Center (LPAC). O2O operations are a highly cooperative effort among MCC, LSTC, LPAC, Ground Segment Operations and Analysis (GSOA) at the O2O Ground Terminal (O2OGT) – White Sands Complex (WSC) and O2OGT-Table Mountain Facility (TMF) operators and analysts. High-level functions of MCC, LSTC, and LPAC include generating the O2O Mission Activity Plan (MAP), operating STE, distributing mission ephemeris data, and analysing performance data.

2.3 O2O Ground Segment Elements

The O2OGS includes four elements: O2OGT- WSC, O2OGT- TMF, Ground Data Element (GDE), and GSOA element. At a high-level, the O2OGT-WSC and O2OGT-TMF support the free space optical communications requirements, the GDE supports the mission data storage and transport requirements, and the GSOA supports planning, scheduling, and analysis of ground segment assets and services.

2.3.1 *O2OGT-TMF*

The O2OGT-TMF includes the same functional components as the O2OGT-WSC. The O2OGT-TMF is designed, developed, operated and managed by the Jet Propulsion Laboratory (JPL) and is not discussed in detail in this paper.

2.3.2 O2OGT-WSC

The O2OGT-WSC includes the optics, electro-optics, and transceiver/modem equipment as well as various infrastructure components. The O2OGT-WSC also includes the centralized monitor & control subsystem that collects performance, health & status, and weather data from the WSC components, performs executive-level commanding of the WSC components, and manages the overall system state machine. The O2OGT-WSC supports the duplex free-space optical communications with the O2O STE. This includes support for the Consultative Committee for Space Data Systems High Photon Efficiency standard [4], which includes requirements for interleaving, coding, data encapsulation, etc. The infrastructure equipment includes the weather and atmospheric monitoring, environmental control, power, laser safety, and timing and frequency equipment.

2.3.2.1 O2OGT-WSC Development Approach

The O2OGT-WSC heavily leverages the system design, technology, and infrastructure implemented by the Lunar Laser Communication Ground Terminal (LLGT) located at WSC [5]. Table 1 describes the major system components and how the system design builds on the development accomplishments from other organizations in NASA to meet the O2O DTO requirements.

Table 1. O2OGT-WSC Subsystems and Assemblies

Subsystem/Assembly	Description
Optical Assembly	• 3 LLGT transmit telescopes reused with modifications; 1 telescope developed by MIT LL • 2 LLGT receive telescopes reused with modifications • Transmit & receive telescopes and back-end optics modified for the O2O wavelengths (modified by MIT/LL) • Mount, gimbal and dome refurbished, shown in Figure 1
Transceiver Assembly	• MIT/LL providing the transceiver assembly which included the transceiver and modem equipment • JPL supplying second copy of the TMF ground receiver to MIT/LL. MIT/LL will use the O2O transmitter electronics developed by Glenn Research Center • Procured superconducting nanowire single photon counting detectors.
Weather System	• Provide new Infrared Cloud Imager and other weather monitoring equipment;
Central Monitoring and Control Software	• Leveraging LLGT software to the maximum extent possible • New development to support enhanced monitoring and control functions, data distribution and analysis

Figure 2. O2OGT-WSC

2.3.3 GSOA

The GSOA is the prime interface for the ground segment operators. It consists of Monitor & Control (M&C) displays, analysis tools, voice loops, e-mail, and other analysis and coordination functions. This element provides the situational awareness data to system operators, allows the system analysts to troubleshoot anomalies and analyze system performance, and provides command and control capabilities for the O2OGS elements located at the WSC. The GSOA will also serve as the centralized location for ground segment planning and scheduling. However, the GSOA resides at the WSC and does not have remote command and control capabilities for the O2OGT-TMF. The

GSOA system provides the critical functions needed to collaborate with other operations entities residing at JSC and TMF to ensure the ground segment is prepared to support each O2O event.

2.3.4 GDE

The GDE is the data processing, network, and data storage infrastructure required to meet O2O mission data requirements. The GDE serves as the single mission data interface between the ground terminals and the Orion Operations Element as JSC. This approach simplifies the interface requirements and mission operations. The GDE is responsible for routing data, such as User Data, Performance Data, and STE Telemetry, between JSC, the GSOA, and both ground terminals. Additionally, the GDE is required to archive all User Data as well as data produced by the ground segment for troubleshooting and analysis purposes

3. Data Products

The data products supported by the four Ground Segment elements are shown in Figure 3. The data products are grouped into five categories: Mission Data, System Data, Planning, Optical Link Management, and External Coordination.

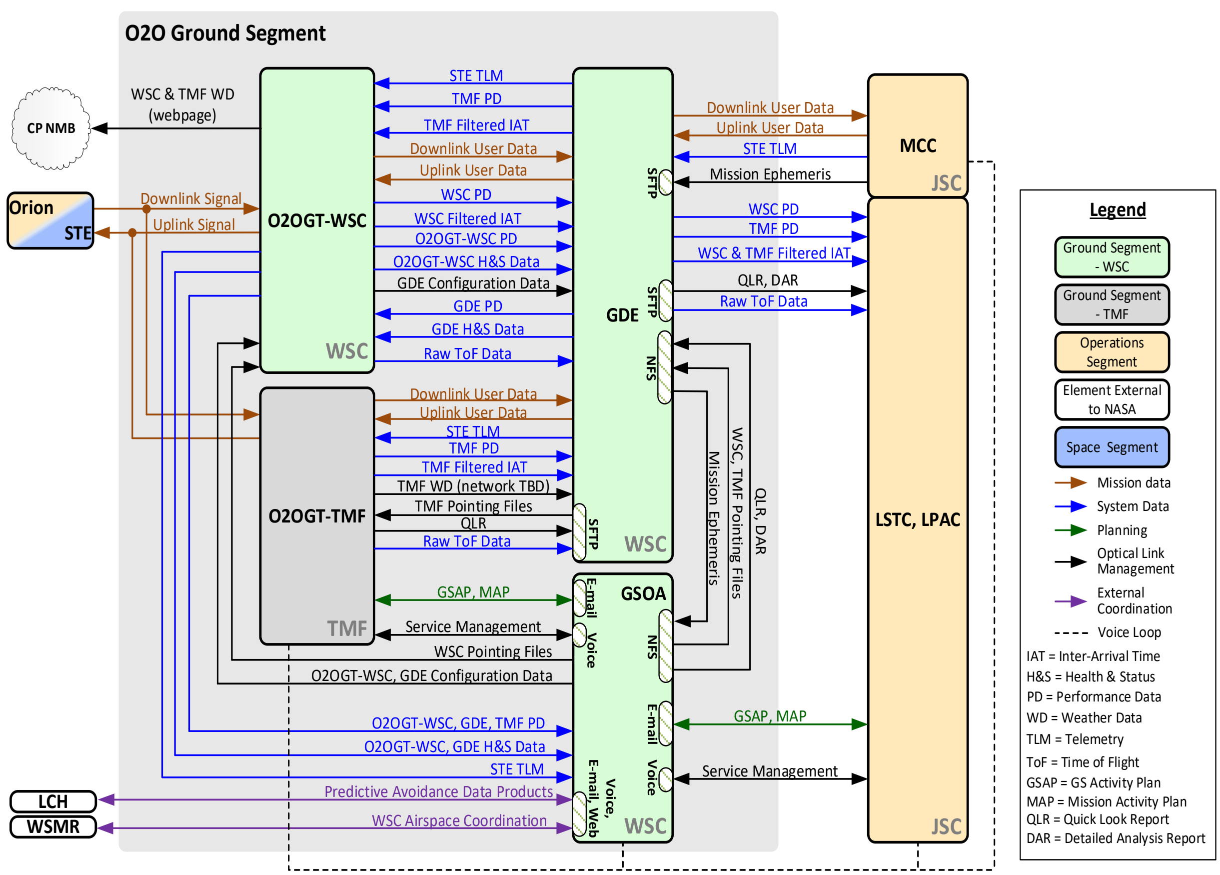

Figure 3. O2O Ground Segment Data Products

Table 2 lists the data products exchanged between the O2OGS elements as well as external entities.

Table 2. O2OGS Data Products

Product Category	Data Products
Mission Data	Downlink Signal Uplink Signal Downlink User Data Uplink User Data
System Data	GDE Performance Data O2OGT-WSC Performance Data

	WSC Performance Data TMF Performance Data GDE Health & Status Data O2OGT-WSC Health & Status Data STE Telemetry
Planning and Scheduling Data	Ground Segment Activity Plan (GSAP) • View Periods • Ground Terminal Availability • Weather Forecast • Additional Notes • Recommended Ground Terminal MAP
Optical Link Management Data	O2OGT-WSC/TMF Weather Data Mission Ephemeris WSC/TMF Pointing Files GDE & O2OGT-WSC Configuration Data Quick Look Report (QLR) Detailed Analysis Report (DAR) Service Management
External Coordination Data	White Sands Missile Range Airspace Coordination Predictive Avoidance

4. Critical Functions

During the mission phases, the Ground Segment supports the O2O DTO high-level critical mission functions.

4.1 Plan and Schedule Contact

Prior to the Commissioning Phase, the Ground and Operations Segments will plan the optical communication events that will take place during the Commissioning/Operations Phases. This planning considers Artemis II mission activities and the spacecraft ephemeris and includes preliminary ground terminal selection based on view periods. During the Commissioning and Operations Phases, the ground segment recommends a final ground terminal selection based on availability and weather. Event planning is supported by models implemented in the GSOA, as depicted in Figures 4 and 5. These include a Satellite Tool Kit (STK) model to generate pointing files and a MATLAB dynamic link analysis model. The GSOA operators used these tools to monitor the predictive and real-time atmospherics data and generate schedules files.

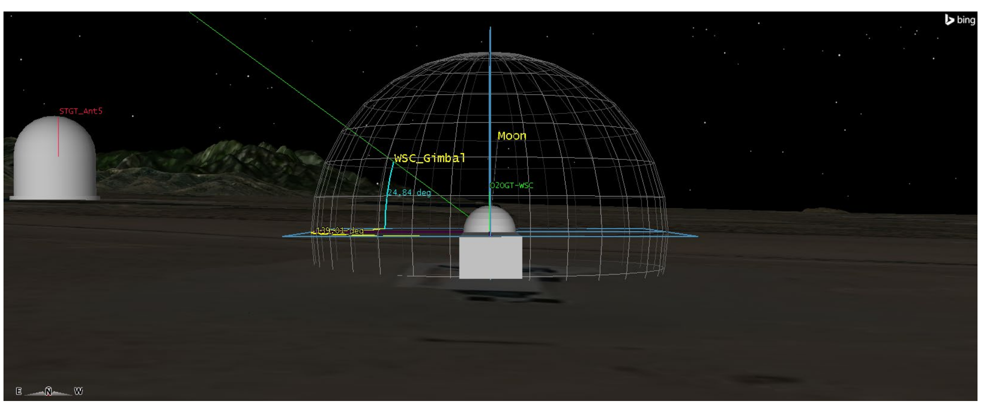

Figure 4. GSOA STK Event Planning Model for Generating Pointing Files

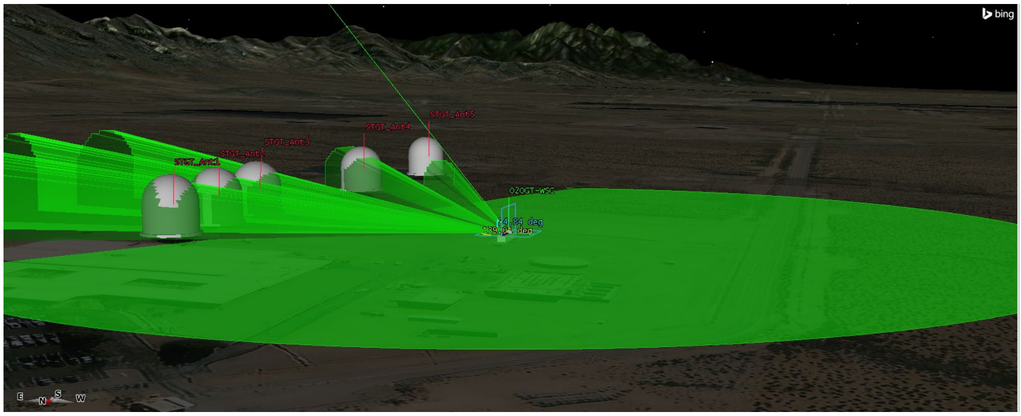

Figure 5. GSOA STK Event Planning

4.2 Acquire and Track the Optical Link

During the Commissioning and Operations Phases, the Operations Segment provides spacecraft ephemeris to the Ground Segment prior to each lasercomm event. These could be updates due to vehicle maneuvers or improved predictions from tracking services. The Ground Segment uses this information to point its telescope at the spacecraft and acquire the optical signal from the STE. After the acquisition is complete, it switches to a closed-loop tracking mode in preparation for transmitting and receiving user data.

The GSOA converts Artemis II ephemeris files to WSC and TMF ground terminal pointing files. The pointing files specify the azimuth and elevation angles in the local ground terminal reference frame. The ground terminals provide real-time support throughout the Pointing, Acquisition, and Tracking (PAT), including generating a beacon signal and performing a spatial acquisition scan as required.

4.3 Flow Information Bi-directionally

During the Commissioning and Operations Phases, the Ground Segment demodulates the downlink signal from STE and delivers it to the Operations Segment. It also receives user data from the Operations Segment and transmits it to the STE. Ground terminals support optical communications per the O2O Space-to-Ground interface specifications and the GDE provides a centralized interface between the operations element and both ground terminals for mission data

The O2O communication system functions as a transparent Ethernet bridge. Selected network traffic on the Orion Utility Network (OUN) is directed to the STE modem module, which encapsulates each Ethernet frame as a High-level Data Link Control (HDLC) frame payload after stripping extraneous fields such as padding. Each HDLC frame is then injected into a bit stream that is encoded, interleaved, and ultimately radiated by the STE as a free space optical signal. The ground terminal optical assembly receives and the ground terminal transceiver assembly processes that signal, generating a stream of Ethernet frames identical to the ones originally received by the STE modem module. The GDE Data Processor receives those Ethernet frames over a dedicated physical interface, records them, and sends each frame to the Orion MCC encapsulated in a User Datagram Protocol (UDP) packet.

Uplink User Data is essentially the reverse, with the Orion MCC sending a stream of UDP packets to the GDE Data Processor, each containing a single Ethernet frame. The GDE Data Processor de-encapsulates each frame, records it, and passes it on to the ground terminal transceiver assembly for processing and transmission.

The net effect of the communication path described above is that the Orion Utility Network and the Orion MCC's OUN-Ground network, the terrestrial analogue of the OUN, are in a single broadcast domain. From the OUN and OUN-Ground perspective Ethernet frames are transmitted, forwarded, and received as if the spacecraft and ground support systems are in the same room. The only observable difference is the latency due to the speed of optical signal propagation (up to 1.35 seconds when the Moon is at apoapsis). Various processing systems and terrestrial communication links may introduce small amounts of additional latency, but one-way light time dominates

4.4 Distribute Information

During the Commissioning and Operations Phases, the Ground Segment time-tags and stores all data. In cases where Downlink User Data is not delivered to the Operations Segment in real-time (e.g., due to terrestrial link bandwidth limitations), stored data is delivered to the Operations Segment after an event as a secure file transfer. Ground Segment performance, weather, health and status data is delivered to the Operations Segment in near real-time. Time of flight data is stored and delivered to the Operations segment at the conclusion of each day.

4.5 Control and Accommodate the System

During the Commissioning and Operations Phases, the Ground Segment calculates pointing angles from ephemeris data supplied by the Operations Segment. It also collaborates with the Operations Segment in decisions to change data rates or the active Ground Terminal, in response to changing optical link conditions. The GSOA operators are the primary point of contact for ground segment management, planning & scheduling, and operations activities. The GSOA operators monitor data from ground segment elements for situational awareness and provide the primary voice communication interface to operations element.

5 Operations Phases

The operation of the Ground Segment is organized around the spacecraft launch and subsequent optical communication events, during which data is transferred over the free space optical link. O2O events will occur for a minimum of one hour per day with the exceptions of the Artemis II launch/commissioning phase and the re-entry/splashdown period. STE Modem Module thermal constraints and Artemis II critical mission activities are the primary drivers which determine when O2O events can take place.

Prior to launch, the O2OGS is in the Pre-Mission Planning phase. Post-launch, the O2OGS cycles between the Planning, Daily Ops Planning, Event Execution, and Post-Event Reporting phases. These phases are shown in Figure 6. Regardless of the phase, all O2OGS equipment is maintained in a ready state and is adequately staffed when there is a line of sight to the spacecraft.

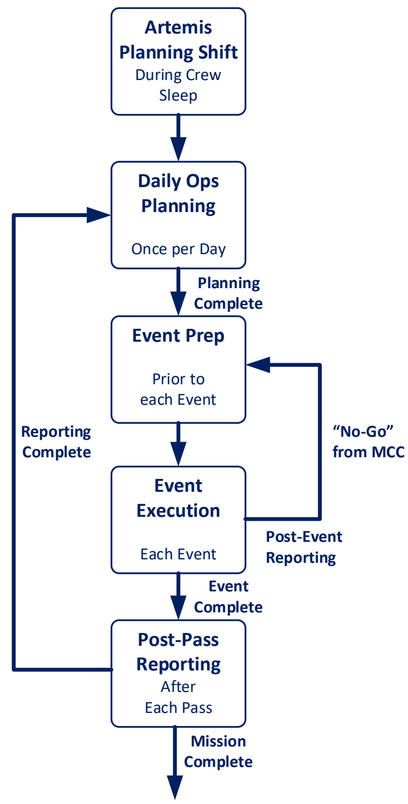

Figure 6. O2OGS Operations Phases

5.1 Planning Shift Phase

The Ground and Operations Segments work together to develop a preliminary MAP based on preliminary spacecraft activity schedules, predicted ephemeris, weather predictions, and DTO objectives for each event. The MAP includes ground station selection, times of operation and signal parameters. The O2OGS will then derive a GSAP from the MAP which contains additional information specific to the ground equipment, such as site-specific constraints (e.g., elevation constraints, Sun SEP constraints).

5.2 Daily Ops Planning Phase

The Ground and Operations Segments work together to finalize the plans for each day, including time(s) of operation, ground station selection, signal parameters, and DTO objectives for each event. This information is then rolled into updated versions of the MAP and GSAP. The Ground Segment calculates WSC and TMF Pointing Files using updated ephemeris data and aligns and calibrates the ground terminals through mount modeling, as necessary.

5.3 Event Execution Phase

The O2OGS prepares the ground station equipment at both ground terminals and the Operations Segment makes a final go/no-go decision on the event. If the decision is 'no-go,' the O2OGS transitions back to the Daily Ops Planning Phase. Otherwise, the selected ground terminal activates their uplink acquisition signal to allow the STE to point back to the selected GT, followed by the remainder of the PAT steps. Once the link is established, the O2OGS flows the Uplink and Downlink User Data. During an event, the O2OGS can respond to a request from the Operations Segment to switch ground terminals or change link signal parameters such as data rate. During each event, the O2OGS stores all mission data and data produced by the ground equipment.

5.4 Post Event Reporting Phase

After each event is complete, the O2OGS analyzes the stored data sets to identify any changes to ground terminal parameters that are needed for the next event. There are two reports produced during this phase: QLR and DAR.

Table 3 maps between the O2O DTO phases, critical functions and the O2OGS Operations phases.

Table 3. O2OGS Phases and the O2O DTO

O2OGS Phase	O2O DTO	
	Phases	Critical Functions
Planning Shift	Pre-Launch	Plan & Schedule Contact
Daily Ops Planning	Commissioning Operations	Plan & Schedule Contact Control & Accommodate the System
Event Execution	Commissioning Operations	Acquire & Track the Optical Link Flow Information Bidirectionally Distribute Information
Post Event Reporting	Commissioning Operations	Plan & Schedule Contact

6. Conclusions

O2O has implemented an Operations Concept that meets the needs of Artemis II mission, the O2O experiment, and the ground operations team that enables the flexibility required for an experiment and lays the groundwork for future Human Space Flight optical communications.

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