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Optical Communications Systems for NASA's Human Space Flight Missions

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ABSTRACT

The Laser-Enhanced Mission Communications Navigation and Operational Services (LEMNOS) office at Goddard Space Flight Center (GSFC) manages two NASA optical communication related projects, the Orion EM-2 Optical Communications Terminal (O2O) and the Integrated Laser Communications Relay Demonstration (LCRD) Low-Earth Orbit (LEO) User Modem and Amplifier Terminal (ILLUMA-T) projects. The main goal of LEMNOS is the advancement and implementation of optical communications systems and technologies for NASA missions. The O2O mission is sponsored by NASA's Human Exploration and Operations (HEO) Mission Directorate. The O2O project will provide optical communications capability to the Orion series of spacecraft, starting with the demonstration of operational utility on EM-2. It will be the first time a human exploration mission will rely on optical communications for its high-bandwidth link. ILLUMA-T is sponsored by the Space Communications and Navigation (SCaN) Program Office. It is destined for the International Space Station (ISS) as an external payload attached to the Japanese Experiment Module - Exposed Facility (JEM-EF). The ILLUMA-T project is developing an optical communications user terminal to demonstrate high bandwidth data transfer between LEO and the ground through the geosynchronous LCRD relay. ILLUMA-T will be the first demonstration of a LEO user of the LCRD system, pointing and tracking from a moving spacecraft at LEO to GEO satellite and vice versa, end-to-end operational utility of optical communications, and 51 Mbps forward link to ISS from ground. Both projects are collaborations between GSFC, Massachusetts Institute of Technology – Lincoln Laboratory (MIT-LL), and a number of contractors.

Keyword list: Optical Communications, Laser Communications, Lasercom, LEMNOS, O2O, ILLUMA-T, Space Communications

I. INTRODUCTION

Traditionally NASA has relied on radio-frequency (RF) signals for the majority of its communications needs. Even though RF links have shown to be reliable they are significantly less capable in moving large amounts of data as compared to optical links. Other issues include large antenna footprint, weight, power consumption per transmitted bit, and spectrum limitations which are progressively getting worst as commercial cellular companies continuously demand more spectrum for commercial utilization.

The data and communications needs of crewed space missions have been steadily increasing, driving the need for higher-capacity links. As NASA prepares for the next major step in human space exploration, it is ready to explore the applicability and advantages of optical communications for future manned missions. The desire is to update the Apollo-era RF communications systems to a more modern, internet like, high-bandwidth system. Such a system will

significantly enhance astronaut capabilities to perform their activities and for ground operators to communicate and remotely control spacecraft functions.

The use of optical communication for space systems has been under development since the early 1970s. These efforts were aided by the massive investment during the early 2000s in the terrestrial optical fiber communications industry that helped develop the technologies and components used in optical communications. Compared to radio-frequency technology, optical communications promise significantly higher data rates (as much as a hundred times more) in smaller size, weight, and power (SWaP) packages.

II. PAST AND CURRENT OPTICAL COMMUNICATIONS ACTIVITIES AT NASA

The discovery of lasers in the early 1960 initiated the efforts for the development of optical communication systems for space applications.¹ It wasn't until 1995 for the first successful demonstration of optical communications from space.² Development of communication systems accelerated in the 2000s with a number of successful demonstration. These efforts were aided by the huge investment in the terrestrial optical fiber communications industry that helped develop the technologies and components used in optical communications. Components such as semiconductor lasers, electro optic modulators, and high-power erbium-doped fiber amplifiers (EDFAs) became readily available. Furthermore as the cost of such fiber components dropped their reliability increased significantly aided by the rigorous environmental and reliability requirements of the Telcordia certifications.

2.1 Lunar Laser Communications Demonstration (LLCD)

NASA's first demonstration of optical communication came in 2013, with the Lunar Laser Communications Demonstration (LLCD) mission, aboard the Lunar Atmosphere Dust and Environment Explorer (LADEE)³. LLCD was a collaborative effort between NASA Goddard Space Flight Center (GSFC), NASA Jet Propulsion Laboratory (JPL), and Massachusetts Institute of Technology-Lincoln Laboratories (MIT-LL). LLCD demonstrated several key attributes of optical communication systems such as error-free data downlink rates of up to 622 Mb/s from the moon (400,000 km). The closest performance by an RF Ka-band radio system was achieved by the system onboard the Lunar Reconnaissance Orbiter (2009) that used a 0.75 meter antenna to deliver data at 100 Mb/s. Even though the space-based laser terminal provided significantly better performance as compared to the RF system it required only half the mass (30.7 kg as compared to 61 kg) and 25 percent less power (90 W as compared to 120 W).⁴ Another important capability demonstrated by LLCD was a 20-Mb/s uplink, which can be crucial for human space exploration systems since it can be used for real time high-definition video conferencing with astronauts from the moon. Finally the LLCD mission demonstrated precision ranging to the spacecraft, achieving centimeter level range resolution.

2.2 Laser Communications Relay Demonstration (LCRD)

Currently NASA is developing the Laser Communications Relay Demonstration (LCRD) mission. LCRD will be a long term demonstration of a relay based optical communications system. It is designed to demonstrate high-bandwidth, bidirectional optical communications relay services between geosynchronous orbit (GEO) and Earth or LEO users. The mission objectives are:

- Demonstrate bi-directional optical communications between Geosynchronous Earth orbit (GEO) and Earth
- Measure and characterize the system performance over a variety of conditions
- Develop operational procedures and assess applicability for future missions
- Provide an on-orbit capability for test and demonstration of standards for Direct-To-Earth (DTE) and relay optical communications.

The project is a collaborative effort between NASA GSFC, NASA JPL, and MIT-LL, and will fly on an Orbital ATK (OATK) satellite.

The LCRD payload consists of two independent laser communication terminals, which are connected via a new electronic switch to provide high-speed frame switching and routing between the two optical space terminals (OSTs) while also serving as the interface to the host spacecraft. With two optical space terminals, LCRD can relay information between two ground stations or an orbiting spacecraft at LEO and a ground station. LCRD has an additional High Bandwidth bi-directional communications path via the Host Radio Frequency (RF) link for added flexibility and enabling demonstrations of diverse optical communications architectures and scenarios.

III. LASER-ENHANCED MISSION COMMUNICATIONS NAVIGATION AND OPERATIONAL SERVICES (LEMNOS)

The Laser-Enhanced Mission Communications Navigation and Operational Services (LEMNOS) office at GSFC was established to manage the development of optical communication space terminals. Currently the LEMNOS office manages two projects, the Orion EM-2 Optical Communications System (O2O) and the Integrated Laser Communications Relay Demonstration (LCRD) Low-Earth Orbit (LEO) User Modem and Amplifier Terminal (ILLUMA-T) projects. LEMNOS is part of the Exploration and Space Communications (ESC) Projects Division at NASA's GSFC which is responsible for a significant part of NASA's communications.

3.1 Integrated Laser Communications Relay Demonstration (LCRD) Low-Earth Orbit (LEO) User Modem and Amplifier Terminal (ILLUMA-T)

ILLUMA-T is a NASA mission sponsored by the Space Communications and Navigation (SCaN) Program Office. It is destined for the International Space Station (ISS) as an external payload attached to the Japanese Experiment Module - Exposed Facility (JEM-EF). ILLUMA-T's overarching objective is to demonstrate an optical communications user terminal capable of high bandwidth data transfer between Low Earth Orbit (LEO) and a ground station via a geosynchronous (GEO) relay satellite. The ILLUMA-T payload will communicate primarily with the LCRD (Laser Communication Relay Demonstration) payload (which will be located at GEO). The LCRD payload will then relay the information to one of two dedicated ground stations on the surface of the Earth. The ILLUMA-T payload will also be capable of pointing to a ground station; however, this a contingency mode for use if LCRD is unavailable. ILLUMA-T will be the first demonstration of a LEO user of the LCRD system. It will demonstrate pointing and tracking from a moving spacecraft at LEO to the GEO relay satellite, and vice versa, and end-to-end operational utility of optical communications with return link rates from ISS to ground of up to 1.244 Gbps and forward link rates from ground to ISS of up to 51 Mbps.

The potential operational optical links of the ILLUMA-T payload are illustrated in figure 1. The primary link, shown as a solid arrows, connect the ISS to the LCRD payload at GEO. The contingency link, shown as dashed arrows connect ILLUMA-T payload to ground stations.

The ILLUMA-T payload will be installed on the Japanese Experiment Module-Exposed Facility (JEM-EF). Figure 2 shows a schematic of the ISS and the location where ILLUMA-T payload will be installed. The ILLUMA-T will be facing forward as the ISS orbits the earth.

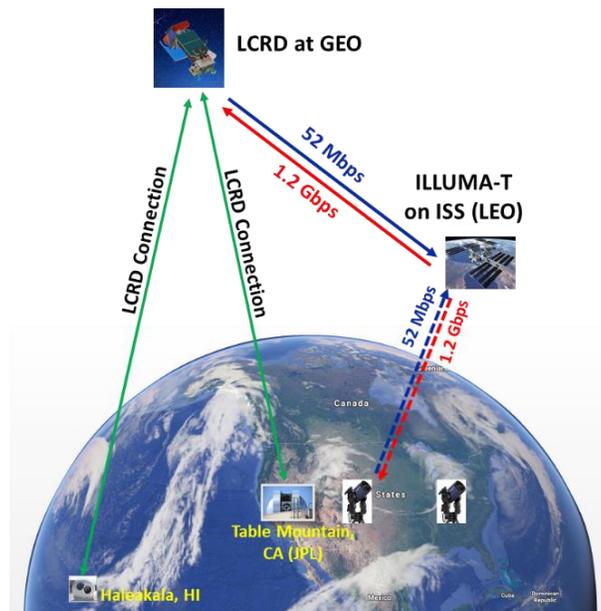


Figure 1: ILLUMA-T operational characteristics. Primary mission requirement is to communicate through LCRD

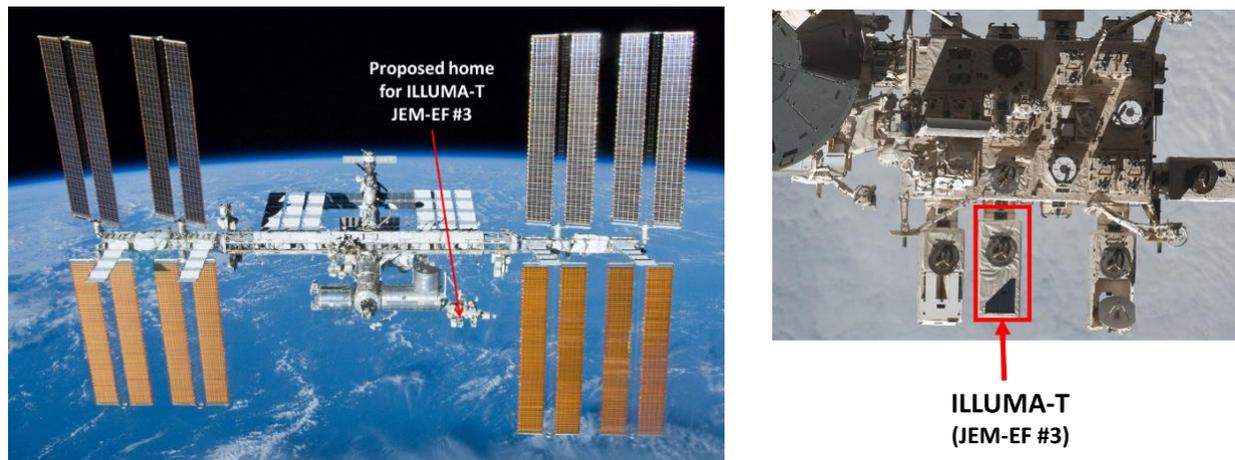


Figure 2: Schematic of the ISS and location where ILLUMA-T payload

The details of the ILLUMA-T payload are shown in Figure 3. On display in figure 3(a) is the ILLUMA-T enclosure. It shows the relative positioning of the optical module with respect to the Payload Interface Unit (PIU) which is the interface between the payload and the JEM-EF/ISS, and the H-fixture and grapple fixture which are used for robotic transfer of the payload. Figure 3(b) displays the various parts and subsystems of the ILLUMA-T payload and their relative positioning. There are four key subsystem in ILLUMA-T:

- a. **Optical Module Subsystem:** The center piece of the communications payload located on the inclined platform at the front of the payload. It is responsible for both transmitting and receiving the laser signals carrying the information. On the transmitting side it receives the amplified optical signal from the modem and directs towards earth, while on the receiving side it collects the light signal, couples it to a fiber that will take it to the modem.
- b. **Modem Subsystem:** The subsystem where information received from the ISS network in the form of electrical signals, is formatted and modulated on laser signals, amplified and then directed through fiber to the optical module. On the other direction it receives the signal from the optical module, converts it to electrical signal and sends it to the ISS
- c. **Controller Electronics Subsystem:** It is responsible for controlling the optical terminal, accepts commands, gather operational parameters and provide information to operators
- d. **Power Converter Unit (PCU):** A unique ISS and Orion subsystem responsible for converting the available 120V to 28V, mostly common on unmanned spacecraft platforms

3.2 Orion EM-2 Optical Communications Terminal (O2O)

O2O is a NASA project sponsored by NASA's Human Exploration and Operations (HEO) Mission Directorate. O2O's main objective is to provide bi-directional optical communications capability to the Orion Multi-Purpose Crew Vehicle (MPCV) series of spacecraft, starting with the demonstration of operational utility on Exploration Mission-2 (EM-2). It will be the first time a human exploration mission will rely on optical communications for its high-bandwidth link. The O2O project is a collaborative effort between GSFC, MIT-LL, JPL, and NASA's Johnson Space Center/Lockheed Martin.

EM2 is a ~7-14 day mission that will transport humans to lunar vicinity for the first time since the Apollo missions. The primary communications link for the Orion vehicle is an S-band RF link that operates at rates of up to a few Mbps. The optical communications capability being developed for EM-2 will demonstrate direct-to-Earth return rates of up to 80-250 Mbps and forward rates up to 20 Mbps. The link architecture is very similar to the LLCDC design.

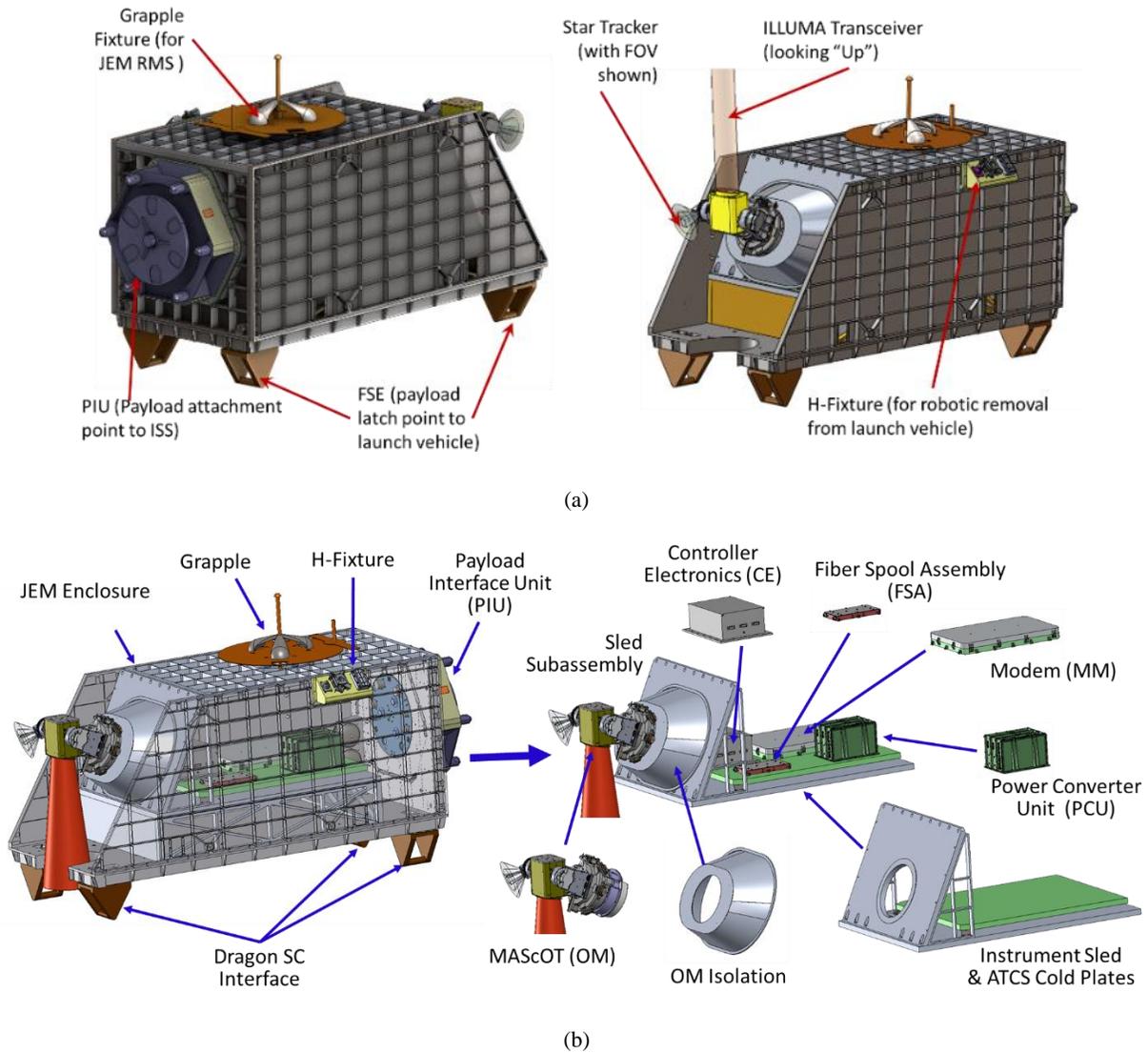


Figure 3: (a) ILLUMA-T enclosure (b) Details of ILLUMA-T Payload

The graphic in Figure 4 depicts the O2O project high level architecture. Bidirectional communication will be established between the Orion spacecraft at the moon and the Orion operations center at Johnson Space Center through the O2O terminal located in the Crew Module Adapter, an optical ground terminal, and the SN ground network.

The key subsystem of O2O is the optical module which is responsible for accurately pointing the laser light towards earth and the optical ground station. This optical module will be coupled to a 1-W 1550-nm pulse-position modulation (PPM) modem to provide the downlink to Earth. A small ground terminal coupled to photon-counting detectors will be sufficient to receive the downlink signal at the planned data rates. The O2O project is classified as a Development Test Objective (DTO) project the optical link will not be used all the time, rather it will be primarily used for high-rate file transfers to and from the Orion vehicle, video streaming and other applications over the course of the EM-2 mission.

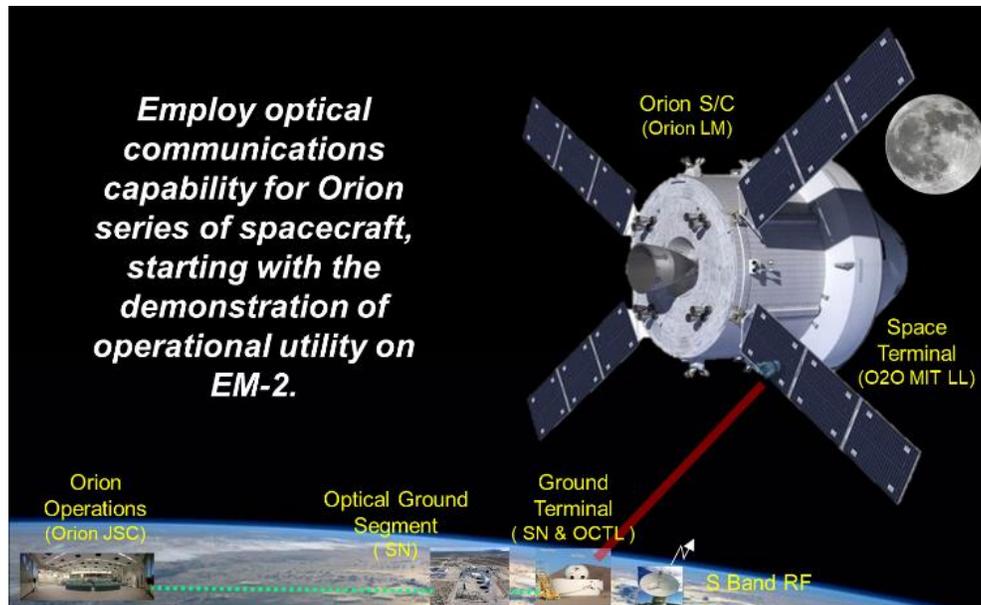


Figure 4: O2O high level system architecture

The O2O hardware is mounted onto the Orion spacecraft in three distinct zones. The Optical Module and the Controller Electronics Module are mounted on the exterior of the spacecraft on the Crew Module Adapter (CMA) via its own vibration isolation system to isolate against the Orion launch loads. For better thermal coupling and dissipation, the Modem Module and the Power Converter unit are co-located on a vibration-isolated pallet mounted to the interior of the CMA. The arrangement of the three modules with respect to the CMA is illustrated in Figure 5.

3.3 Modular, Agile, Scalable Optical Terminal (MAScOT)

In an effort to support the varying needs of future missions, NASA together with MIT-LL have evolved the optical terminal technology that was developed for previous missions, like LLCD and LCRD. Recent development efforts have focused on evolving optical module design to make it more capable and reduce recurring costs associated with meeting various mission requirements. Both O2O and ILLUMA-T are using a common optical terminal based on a new design developed at MIT-LL for use in a wide variety of laser link scenarios, the Modular, Agile, Scalable Optical Terminal (MAScOT), see the schematics in figure 6.⁵ MAScOT was first developed to provide a terminal for spacecraft in LEO where wide field of regard and fast slew rates are required. Key features of the MAScOT architecture is its modularity and scalability. The ILLUMA-T and O2O programs will demonstrate the viability of the MAScOT design for space missions, maturing it for operational use on future space missions. While current efforts are developing ~10-cm user terminals, larger apertures based on the same terminal design are also envisioned for future applications.

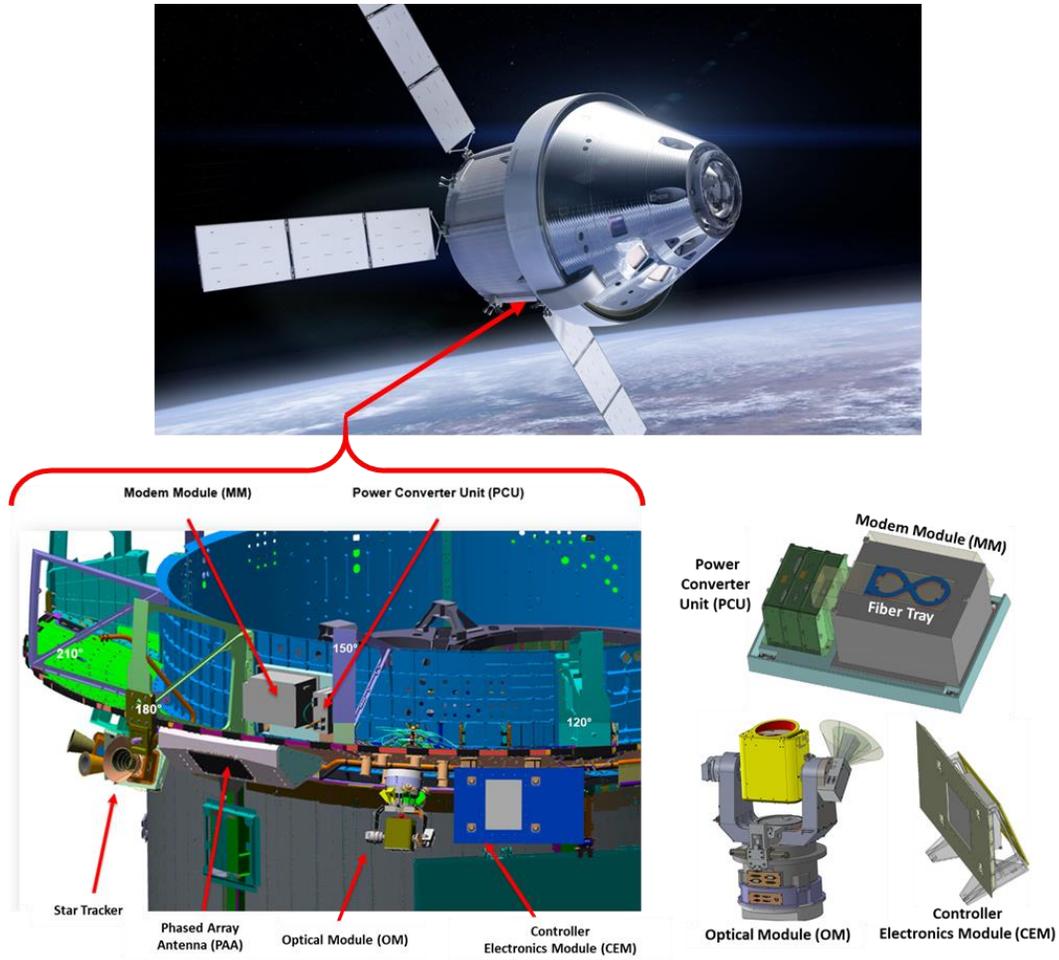


Figure 5. Depiction of where O2O optical communications modules on the Orion Spacecraft, and each of the three Modules: 1 – Optical Module, 2 – Controller Electronics Module, and 3 – Modem Module and Power Converter Unit.

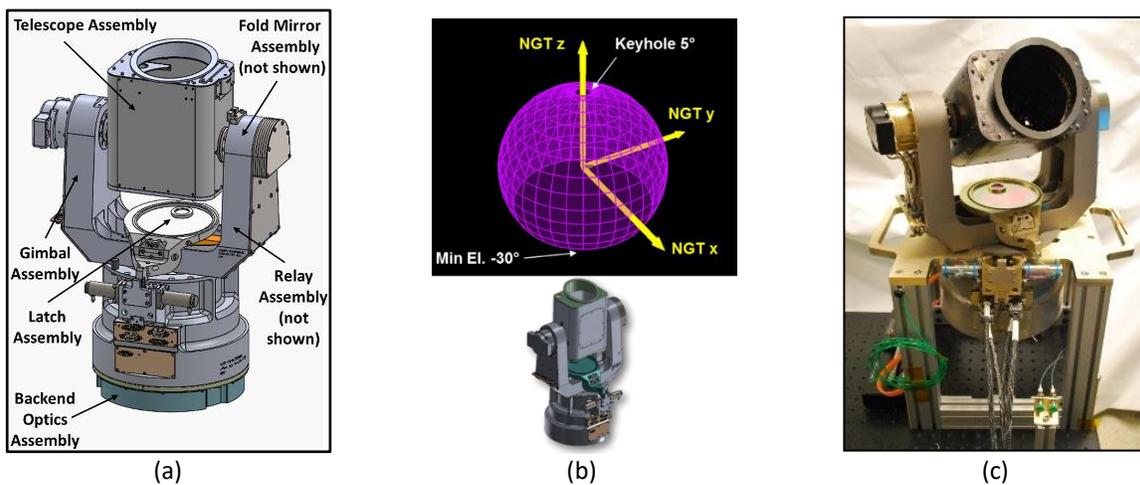


Figure 6: MAScOT Optical Terminal (a) as-built CAD, (b) Gimbal Field Of Regard (FOR), 90° to -30° by 360°, and (c) Photograph of engineering unit, 10-cm MAScOT developed for use on Orion and the ISS

MAScOT has greater than hemispherical field-of-regard with pointing and tracking capabilities that can support fast-moving platforms in low-Earth orbit as is the case of the ISS. The 10-cm aperture is coupled to the back-end optics assembly via a Coudé path. The MAScOT terminal is coupled to a modem via optical fibers which connect to the back-end optics assembly. The MAScOT architecture is modular in that its subassemblies (the telescope, latch and gimbal, and back-end optics) may be developed independently by different groups so long as they adhere to specifications at the subassembly interfaces. The architecture is scalable in that various sizes of telescope may be accommodated without significant changes to the other subassemblies. For these reasons, it is believed that this terminal design will find many applications in cis-Lunar space and beyond.

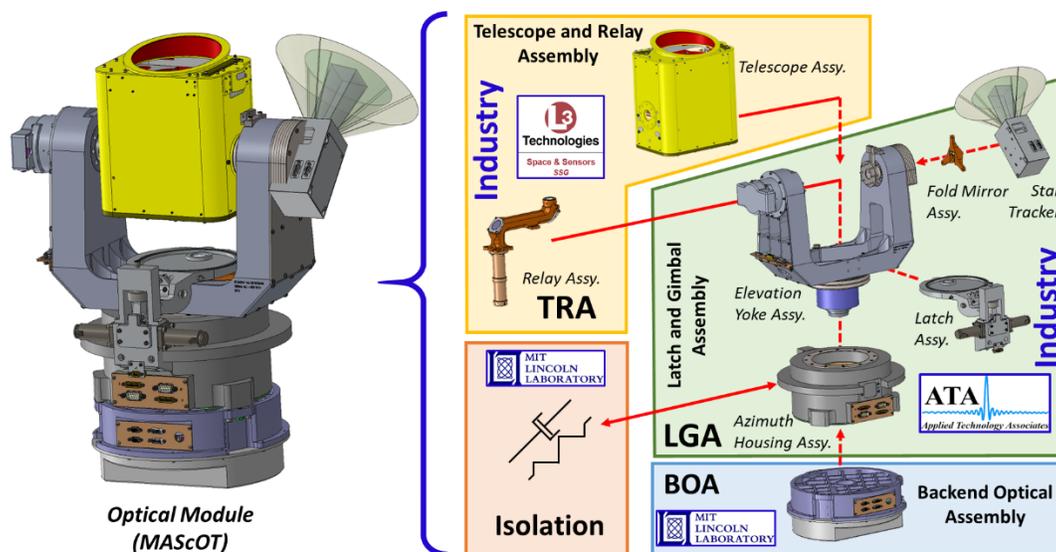


Figure 7: Optical module subassembly breakdown and industry partnerships

An important aspect of the O2O and ILLUMA-T optical terminals development is industry participation. A significant part of the optical module subassemblies will be provided by industry as a result of competitive proposal processes. The schematic in figure 7 shows the various optical module subassemblies and the various companies responsible for putting it together. This was done for several reasons including taking advantage of industrial knowhow and expertise in optical communication, and to make sure that industry will be able to satisfy the needs of future missions. It is also expected that adaptation of industrial processes will reduce the cost of optical communication equipment and making them more affordable.

IV. SUMMARY

The use of optical communications systems can enhance space missions by providing high-data-rate space-to-ground links at ranges from low-Earth orbit to lunar orbit and beyond. The upcoming ILLUMA-T and O2O demonstrations will advance the applicability of optical communications for space missions by demonstrating operational utility of optical communications and make a strong case for their future use in human exploration missions as well as scientific missions. They represent important opportunities to demonstrate key characteristics of optical communications based systems and are natural precursors to planned deployment of the next generation communications relay system (Optical TDRS) and deep space optical communications. Both projects employ a common modular optical terminal architecture that can be scaled to different sizes for use in a variety of missions. Finally the LEMNOS project is following a seeded industry partnerships approach to develop the needed subassemblies in an effort to take advantage of industrial knowhow, cost control, and to make sure that that future missions can rely on industry for their optical communications hardware needs.

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