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Optical Communications Feasibility Study for Science Mission Located at Sun-Earth Lagrange Point L2

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Abstract

NASA's Exploration and Space Communications projects division recently completed an investigative study, researching the feasibility of integrating optical communications capabilities onto a science-based mission orbiting at Lagrange Point 2 (L2). Optical communications has been demonstrated and integrated into many low-Earth-orbiting missions, however, using the technology as far as L2 needed to be thoroughly researched and proven similarly as efficient as the mission's planned radio frequency (RF) system, but preferably more efficient that the equivalent RF systems. The investigation team was charged with assessing the feasibility of including optical communications on the mission without interfering with its primary science objectives. This came to be known as the "Do No Harm" approach to accommodation. As science and detection technologies become more advanced, data rates and communications requirements continue to evolve. Missions with complex science instruments have a need for more optimized communications capabilities. Optical communications technologies provide NASA and industry missions with increased data rates and quicker response times, allowing scientists to access more data than ever before. Missions utilizing optical communications will have a lighter and more efficient method of transmitting data to users on Earth. The team investigating this opportunity discovered that including an optical communications payload on board the mission to provide a bi-directional link between the spacecraft and Earth-based ground stations is feasible and reaches data rates that are comparable to, and even exceed, the mission's RF system. In the course of their investigation, the team also discovered significant navigation and ranging benefits provided by the optical communications payload (OCP).

Keywords: optical communications, space communications, Lagrange points, optical modules

Acronyms/Abbreviations

Goddard Space Flight Center	GSFC
High Power Optical Amplifier	HPOA
Lagrange Point 1/2	L1/L2
Lunar Atmosphere and Dust Environment Explorer	LADEE
Lunar Laser Communications Demonstration	LLCD
Laser Communications Relay Demonstration	LCRD
Massachusetts Institute of Technology's Lincoln Laboratory	MIT LL
Networks Integration Management Office	NIMO
Optical Communications Payload	OCP
Optical Module	OM
Orion Artemis-2 Optical Communications System	O2O
Pulse Position Modulation	PPM
Radio Frequency	RF
Technology Enterprise and Mission Pathfinder Office	TEMPO

1. Introduction

As science and detection instruments become more advanced, NASA missions continue to evolve in their data requirements and communications needs. As a response to this rapidly evolving need, optical communications capabilities are being targeted for future missions to meet their data rate and communications efficiency requirements. Optical communications technology has been demonstrated on multiple missions and has exhibited readiness for inclusion on NASA's future flagship missions and observatories.

NASA's Technology Enterprise and Mission Pathfinder Office (TEMPO) located at Goddard Space Flight Center (GSFC) completed a study to assess the feasibility of including an optical communications system on a NASA science mission stationed at Lagrange Point 2 (L2), which will heretofore be denoted as "the mission."

Prior to this study, the mission baselined the use of S-band and Ka-band radio frequency (RF) communications systems to meet its communications requirements. In order to comply with the non-interference requirement of the feasibility study, no changes were made to the baseline RF system. However, if feasible from a technical and programmatic standpoint, including an optical communications payload on the mission would provide clear benefits to the mission and to this optical communications mission of opportunity.

The study has determined that a bi-directional optical communications link between an Earth-based ground station and the L2 orbit is feasible, reaching data rates comparable to the mission's RF system. Additionally, the study has discovered significant navigation and ranging benefits and capabilities using the optical link to the mission, capable of ~3 cm precision ranging.

After analyzing the study results, it was concluded that the inclusion of an optical communications system, Optical Communications Payload (OCP), could benefit the mission, and provide additional capabilities in the areas of science data delivery and optimetric ranging for orbital determination purposes.

1.1 Benefits

There are significant benefits for missions utilizing optical communications systems. In addition to requiring less size, weight and power on board the spacecraft, the data capabilities when using optical communications are drastically increased. The mission at L2 is an observatory and will have multiple high-definition instruments capturing images and data; having an OCP on board would significantly benefit the mission's ability to capture and send high-resolution images back to Earth for analysis. Furthermore, by adding an OCP to the spacecraft, the mission not only becomes an advocate for optical communications in deep space but also becomes a pathfinder for future missions with similar use-cases and data volume needs. Additionally, the mission can benefit from optimetric ranging capabilities of the OCP, providing ~3 cm ranging accuracy between Earth and L2.

2. The Study

This study was the result of contributions from a small, yet highly experienced team with wide-ranging areas of expertise. The various disciplines of subject matter expertise were required in order to ensure the accommodation and capabilities of the OCP on the mission was well understood and sufficiently evaluated for feasibility.

2.1 Technology Questions and Objectives:

To facilitate the study, these initial questions were posed to guide the investigation:

- Can we close the link to L2 with pulse position modulation (PPM) technologies at hundreds of megabits per second?
- How do we interface with the mission's main data system?
- What are the pointing, jitter and vibration environments and requirements for an optical terminal on the mission?
- What is the use case and operations concept?
- Will future terminal designs that provide the basis for the OCP be capable of supporting optical communications from Earth to L2 by the time of the mission's need date?

2.2 Technology Traceability

Another primary step was determining what existing technologies could be used to base the mission's OCP off of. Much of the technology being targeted for use on the mission's OCP is traceable to the Orion Artemis-2 Optical Communications System (O2O). O2O will leverage optical communications technology for use on the Orion Multi-Purpose Crew Vehicle. The terminal will enable live, 4K ultra-high-definition video from the Moon. The type of optical communications terminal being used by O2O is being developed by the Massachusetts Institute of Technology's Lincoln Laboratory (MIT LL) and industry partners. The progression of the technology leading up to the terminal design is shown below:

Fig. 1. Optical Communications Technology Progression

These O2O-based terminal components include the following items, with technology traceability notes following each item. Many of the technologies are similar to those included on the Lunar Laser Communications Demonstration (LLCD) and the Laser Communications Relay Demonstration (LCRD).

Optical Module (OM)

- MIT LL design, in collaboration with industry
- Incorporates lessons learned from previous OM design generations (LLCD and LCRD)
- Interfaces to modem module via fiber connection
- Scalable design, allowing larger aperture sizes if required

Controller Electronics

- Provided by industry based on legacy designs
- Similar designs have been used on LLCD and LCRD
- Hosts processor that runs the pointing, acquisition and tracking flight software
- Controls and manages the gimbal pointing of the OM as well as acquisition states

Modem Module

- In development by an industry vendor based on MIT LL requirements and guidance
- Interfaces to OM via fiber connection
- Contains the optical detector and transmitter
- Processes PPM and applies encoding schemes

Fig. 2. NASA's Lunar Laser Communications Demonstration (LLCD)

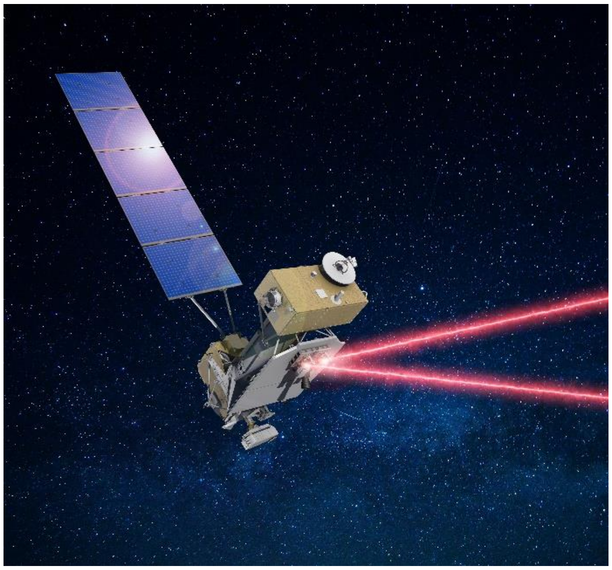

Fig. 3. NASA's Laser Communications Relay Demonstration (LCRD)

3.0 Mission Concept

3.1 Overview

The mission concept is similar to that of the 2013 Lunar Laser Communications Demonstration (LLCD), which proved optical communications capabilities in the lunar region up to 622 Mbps. LLCD was a non-interference, OCP hosted on the Lunar Atmosphere and Dust Environment Explorer (LADEE). Following that model, the OCP on board the study's mission would be operated in a non-interference approach during periods of operation that do not impede upon the mission's primary objectives. Additionally, the mechanical, electrical and data accommodations between the OCP and the mission would not interfere with the primary spacecraft systems or instrument performance.

The optical communications approach for the mission that was studied included:

- A single, bi-directional optical communications link between Earth and the mission spacecraft at the L2 location.
- A single optical ground terminal located at one of NASA's existing communications ground station locations
- A single payload operations center located at GSFC, which would control and monitor all OCP experiments and operations.

3.2

In general, the optical communications technology being proposed for use on the mission's OCP has been developed, matured and refined over the course of several optical communications demonstrations, and performed by different nations and organizations around the world beginning more than two decades ago.

Each demonstration matured the optical communications technology or concepts in some way, generating lessons learned and progressing the technology. As discussed in the "Technology Traceability" section, three related NASA optical communications missions have had a direct role in maturing the specific implementations and designs of the primary components in the proposed OCP for the mission.

Including:

- 2009-2014: NASA Lunar Laser Communications Demonstration (LLCD)
- 2011-Present: NASA Laser Communications Relay Demonstration (LCRD)

- 2013-Present: NASA/MIT LL Terminal Development Orion Artemis-2 Optical Communications (O2O)

As each of these missions complete their objectives, the specific technologies, designs and demonstrations of concepts are matured to a greater level. Additionally, advancements are occurring in components, parts, materials and subsystem designs in the commercial industry, enabling each generation of designs and optical terminal components to take advantage of the evolved and enhanced technologies.

3.3 Key Trades

Early in the study effort, the team explored and identified several areas and considerations that would be considered a trade study or a constraint to the trade space. In general terms, the primary trade categories explored are as follows:

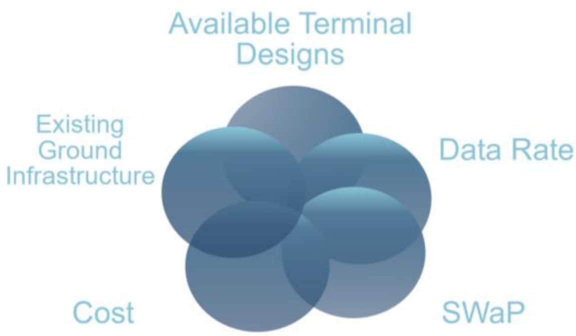

Fig. 4. Key Trade Considerations

However, due to the OCP's delivery timeframe to the proposed mission, a key consideration for the OCP study was the re-use of existing optical and ground terminal designs rather than a design-from-scratch or redesign effort. Therefore, the traditional grass-roots, trade-space and figures-of-merit trade study process would have been limited in value due to the restricted number of variables and implementation options available. Instead, a set of constraints and a small number of discrete trade options were defined and explored while staying within the bounds of the technology that is understood to be available and obtainable by the time it is needed for the mission's OCP delivery date.

The key trades and constraints were defined as follows:

3.3.1 Flight Terminal Trades:

Existing Terminal Designs (Trade)

This trade evaluated two primary optical terminal designs, which both provide readily available components without significant technology development investments. Both optical terminal designs that were assessed were very similar in design, but had some differences in capabilities and requirements.

Considerations:

The primary considerations utilized during this trade were the following:

- Direct to Earth link capability
- Modulation type that is best suited for long-distance links (L2 to Earth)
- Environmental considerations such as mechanical, thermal and radiation

Optical Module Size (Trade)

This trade evaluated two primary options related to the actual size / collection area of the optical telescope itself. This is an important factor that directly ties into link budget calculations, link performance and relates to other parameters like volume, power and mass of the OCP.

Considerations:

- Sufficient aperture size to facilitate adequate link margin considering desired downlink data rate and link distance between L2 and Earth
- Limiting volume, power and mass allocations to minimize OCP accommodation requirements
- Design maturity of different aperture sizes varies depending on aperture design

Power Level (Constraint)

This trade evaluated multiple transmit power levels for the OCP to utilize for the downlink direction. The power level selection needed to be of sufficient power to close the link with adequate link margin. Therefore, the link budget calculations were a critical input to this trade.

Considerations:

- Sufficient transmit power to close the link from L2 to Earth, assuming desired downlink data rates
- Limiting volume, power and mass allocations for required High Power Optical Amplifier (HPOA) to accomplish desired power level
- Design maturity of different HPOA designs depending on desired power level. As power increases, design maturity typically decreases

3.3.2 Optical Link Trades:

Link Budget (Constraint)

The OCP link budget was essentially used as a unifying factor, or cross-tie, between multiple other trades during the study. The link budget sources information for some trades, but depends upon information from other trades. Therefore, the link budget itself is not a trade, but a collection of setting "knobs" that can be turned to adjust various performance parameters, essentially allowing for the optimization of the other technical trades.

Encoding (Constraint)

Various encoding schemes can be considered for optical communications links, depending on the needs of that particular link. In this particular case, in order to maintain compatibility with existing O2O-based designs and assets, the team remained consistent with the CCSDS optical communications standard encoding schemes.

Modulation (Constraint)

Various modulation schemes can be considered for optical communications links. As stated above in the Encoding section, a conscious decision was made to remain consistent with the CCSDS High Photon Efficiency (HPE) optical communications standard, in order to maintain compatibility with existing assets and designs.

Data Rates (Trade)

Two different data rates were investigated using the link budget tools and inputs from the other trades and constraints. The first data rate was a comparable data rate to the existing RF systems being utilized for the mission. The second data rate was selected to exceed the mission's existing RF system capabilities. These two data rates gave the team a "minimum threshold" rate and an "ultimate goal" rate. Both rates were assessed using detailed link budget calculations, and both closed the optical communications link with adequate margin. The main differences between the two rate capabilities factored into volume, power and mass accommodation requirements, as well as ground terminal receiver configurations. Both rates are viable, but final decisions about data rate will depend on the trade factors and constraints mentioned above.

3.3.3 Ground Terminal Trades:

Ground Terminal Design (Constraint)

Multiple ground terminal designs can be considered for optical communications applications. Given the tight time constraints for the mission being evaluated, the ground terminal design assumption was constrained to only utilize the O2O ground terminal design for the minimum threshold capability. The ultimate goal rate scenario would require modifications and upgrades to the existing terminal designs.

Power Level (Constraint)

The transmit power from the ground terminal perspective would be dictated by the link budget, but allocated using a standard network service request through the Networks Integration Management Office (NIMO) at NASA's GSFC.

Number of Terminals (Constraint)

There are significant benefits to having multiple optical ground terminals available, including weather mitigation, redundancy and geographic dispersion. However, for purposes of this study, it was constrained to a single ground terminal due to the do no harm, non-critical approach to the mission of opportunity.

Ground Station Locations (Trade)

Multiple candidate ground station locations were reviewed and considered. Given the timeframe and compatibility considerations stated earlier, a single ground terminal located at an existing NASA ground terminal location was selected, building upon infrastructure being installed for the O2O mission. Future missions of opportunities may be able to make use of additional NASA sites, as well as commercial leased service locations.

Elevation Limit for Ground Terminal (Trade)

Two different elevation angle limits for the optical ground terminal were assessed. In order to stay within the realm of predictable link performance through atmospherics, the ground terminal operations will be constrained to only operate at an elevation angle of 20 degrees or higher. Under 20 degrees of elevation may be possible, but could result in more unpredictable communications link results.

Network/Terminal Usage (Constraint)

As mentioned above, the allocation of services using the optical ground terminal at the NASA site will use a standard network service request through GSFC's NIMO.

3.3.4 Terrestrial Connectivity

Payload Operations Center/End-Point Locations (Constraint)

For assumption and feasibility purposes, we assumed use of existing terrestrial circuits between GSFC and NASA ground terminal location. The payload operations center that will run the OCP communications link and assess / monitor performance was assumed to be located at NASA's GSFC.

By considering a combination of constraints and discrete trades, the team was able to recommend designs and solutions quickly while remaining within the bounds of terminals and designs that can be obtained, integrated, tested and delivered before the mission's need date.

4.0 Payload Accommodations

Based on the completed trades mentioned above, the study team was able to define an envelope of OCP payload accommodation assumptions. This facilitated in the assessment of potential accommodation locations on the mission spacecraft.

The following were key factors in considering payload accommodation requirements with the mission spacecraft:

- Volume envelope / keep out dimensions
- Mass allocation
- Power allocation (supplied from spacecraft bus)
- Mechanical disturbances (to and from spacecraft)
- Thermal management and control / dissipation
- Data interfaces to mission systems
- Pointing constraints / allowances

These areas of accommodation needed to be coordinated closely with the mission's systems engineering group, as they depend upon interfaces with the spacecraft itself. Given the "do no harm" nature of the OCP for the mission, these accommodation requirements were not allowed to drive changes or modifications on the spacecraft.

5.0 Conclusion

After completion of the study, it was determined that optical communications between a ground terminal on Earth and the NASA science mission stationed at L2 is technically feasible using the design solutions recommended in this paper. A 90-day study evaluating the feasibility of applying optical communications to the mission was successfully completed and recommendations were made to the mission management. An OCP can be constructed and delivered to the mission prior to the start of mission's payload integration by using existing O2O-based optical terminal technology. If the mission decides to incorporate optical communications, the optical link with the mission's OCP would be capable of data rates up to 97 percent of the mission's RF system rates using the "minimum threshold" data rate option, but exceeding the mission's RF system rates using the "ultimate goal" configuration. Additionally, it was determined that performing optimetric ranging measurements in the ~3 cm range is possible using the selected OCP configuration. The mission can become a platform of opportunity for deep space optical communications, further enhancing NASA's space communications capabilities.

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