Status of NASA's Deep Space Optical Communication Technology Demonstration

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Abstract— **With NASA funding, the Deep Space Optical Communication (DSOC) Project at JPL is planning a system level technology demonstration of optical communications from deep space. A 22 cm diameter flight laser transceiver (FLT) is being developed for space flight. The FLT will be designed to transmit an average laser power of 4W at 1550 nm and receive a weak 1064 nm laser signal (> 100 femtowatts). Use of the Hale telescope at Palomar Mountain, CA, retrofitted with a photon-counting receiver to detect the downlink from space, is planned. The Optical Communication Telescope Laboratory (OCTL) at Table Mountain, CA will transmit a 1064 nm laser beacon to serve as a pointing reference for the FLT and support low-rate uplink data-rates. The DSOC FLT is part of the baseline payload for the Psyche mission spacecraft recently selected for flight by NASA, providing link demonstration opportunities during the mission cruise phase. Link demonstration opportunities at distances of approximately 0.1 to 2 astronomical units (AU) are expected. The DSOC system is being designed to support downlink data-rates of 0.2 to > 200 Mb/s and uplink data rates of approximately 1.6 kb/s. A status update of DSOC Project activities on flight and ground development will be summarized in this paper.**

Keywords—optical communication, deep space, photon counting,

I. INTRODUCTION

Increased instantaneous data-rates and data volumes are needed by future NASA deep-space missions for supporting higher resolution science and human exploration. Education and public outreach through use of streaming high definition imagery is an additional benefit from increased telecommunications capacity. NASA's overarching communications goal [1] is "…increased data rates (e.g. 10 to 100 times) without increasing the mission burden in mass, volume, power and/or spectrum…" Optical communications systems offer the potential for lower mass, volume and power while operating in an uncongested spectral region, relative to the tried and proven radio frequency systems. Therefore, developing and operating optical systems can provide significant augmentation to NASA's telecommunications toolbox. The planned technology demonstration is intended to prove the operability and reliability of optical links from deep space. This paper provides an update on progress toward implementing what could be one of the first technology demonstrations of deep space optical communications.

Over the past two decades NASA has funded optical link demonstration programs [2] that resulted in the recent highly successful Lunar Laser Communication Demonstration (LLCD) [3] in 2013. In parallel, technology development for advancing the readiness of a deep space optical system, emphasizing Mars-Earth distances has been pursued. A host platform for the technology demonstration was sought through the NASA Discovery Program 2014 announcement of opportunity solicitation. In early 2017, NASA selected the Psyche mission for exploring the asteroid 16 Psyche, which would host an optical transceiver for the sought after technology demonstration. The Psyche Mission, scheduled to launch in the summer of 2022, plans to accommodate a deep space flight laser transceiver (FLT) developed by the Deep Space Optical Communications (DSOC) Project at JPL. The DSOC Project also plans to develop a ground sub-system to demonstrate optical links from ranges covering approximately 0.1 – 2 AU, during the first year of the Psyche Mission cruise phase. Extended operations beyond the first year are not ruled out.

The remainder of this paper presents a status update of NASA's deep space optical communication technology demonstration. Section II provides an overview of the DSOC Project goals and objectives. Section III provides a brief description of the Psyche Mission spacecraft trajectory and nominal concept of operations for the technology demonstration. Sections IV and V describe the FLT and Ground sub-system. Section VI summarizes planned DSOC performance and Section VII presents brief concluding remarks.

II. OVERVIEW OF DSOC

The DSOC Project at JPL is advancing the conceptual design of the previously reported Deep-Space Optical Terminals (DOT) [4] beacon based system architecture. The primary target is Mars with scalability to farther ranges. The DSOC architecture is represented in Figure 1.

The FLT is part of the baseline payload for the Psyche Mission spacecraft. The FLT would transmit downlink at approximately 1550 nm and receive uplink at approximately 1064 nm. A transceiver aperture diameter of 22 cm transmitting 4W of average downlink power is planned.

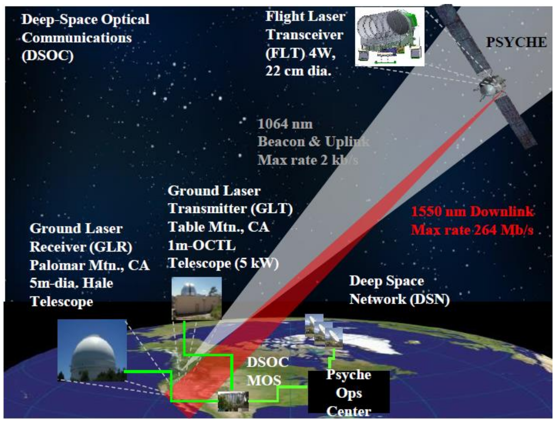


Figure 1 DSOC beacon-based architecture

The FLT would receive approximately 100-femtowatts (fw) of uplink transmitted from the ground sub-system.

The DSOC Project ground sub-system will utilize separate, existing, assets retrofitted with a high power laser transmitter and a photon-counting receiver. In order to satisfy the uplink power at the FLT, over the 0.1 – 2 AU range, 200-5000 W laser power will be transmitted. The expected 1550 nm downlink irradiance varying between 100's of pw/m^2 to 10's of fW/m^2 will require large ground collection area (at least 4 m diameter) for demonstrating high data rates. Satisfying these requirements simultaneously with a single optical asset will present formidable implementation challenges, particularly for the needed optical isolation of > 150-dB. Therefore, separate assets are planned for the DSOC technology demonstration. The NASA/JPL Optical Communication Laboratory (OCTL) 1m diameter telescope will be retrofitted with a high power laser beacon assembly for the Ground Laser Transmitter (GLT). The 5m aperture diameter Hale telescope at Palomar Mountain, operated by the California Institute of Technology Optical Observatories (COO), will serve as the Ground Laser Receiver (GLR). An advanced photon counting receiver being developed at JPL will be retrofitted to the Hale telescope. Figure 1 also shows the DSOC Project mission operations system (MOS), the Psyche Operations Center and the Deep Space Network (DSN) that will be needed to coordinate and support the DSOC technology demonstration.

The DSOC ground sub-system will serve as a cost effective means of supporting the planned technology demonstration. One of the disadvantages of non-collocated ground assets will be a reduction in the joint probability of cloud-free line of sight for both Palomar Mountain and Table Mountain, compared to what could be achieved at either of the sites. Future operational optical ground subsystems will trade achieving extremely aggressive optical isolation with a single large aperture, versus collocating separate transmitting and receiving assets to improve link availability related to cloud-free line of sight

The DSOC Project technology demonstration will address two key challenges. Firstly, beacon assisted link acquisition and tracking with subsequent downlink pointing, factoring in the point-ahead angles 10's of downlink beam-widths. Secondly, transmitting and receiving high-rate optical downlink.

The acquisition tracking and pointing (ATP) functions will involve implementing line-of-sight control coordinated with the spacecraft coarse pointing assistance. The high-rate downlink relies on implementing high photon efficiency (HPE) signaling based on pulse-position modulation (PPM) with photon-counting. The emerging Consultative Committee for Space Data Systems (CCSDS) optical standards have adopted the HPE signaling scheme that will be implemented by the DSOC Project.

In addition to the two main challenges, low rate uplink (1.6 kb/s) will be demonstrated with day and nighttime link operations under diverse link and atmospheric conditions. Daytime operations will be constrained by the use of existing ground assets and their capabilities, since no modifications of the existing assets are planned.

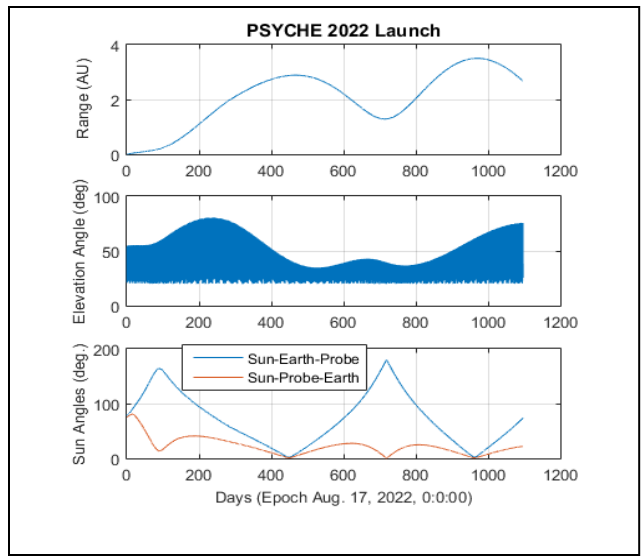


Figure 2 Psyche spacecraft trajectory

III. PSYCHE MISSION

Agreed upon mechanical, thermal, electrical and data interfaces are planned between the FLT and the Psyche Mission spacecraft. As mentioned, the spacecraft would assist link acquisition by coarse pointing and providing attitude and position updates. Documenting these interface agreements are ongoing. Likewise, interface agreements between respective operations centers to coordinate ground operations are also planned.

The Psyche spacecraft plans to launch in the July-August of 2022. Figure 2 shows the time dependent variation of distance, elevation angle and sun angles for an observer at Palomar Mountain CA, for a notional launch date of August 17, 2022. The sun angles indicate that link opportunities from approximately 1 month after launch to approximately 200 days would occur at nighttime for the GLR. On the other hand the FLT would encounter relatively small sun-probe-earth (SPE) angles. Beyond 200 days from launch the link opportunities transition to daytime with decreasing sun-earth-probe (SEP) angles. A constraint on the technology demonstration would be to establish a daytime cutoff angle below which the Hale telescope cannot be used. This angle will be established by forbidding any direct sun illumination of the telescope primary mirror, as well as, thermal management of heating of the telescope dome interior and structure due to insolation.

The rapid rate at which the spacecraft recedes from Earth results in a range of 2.5 AU approximately one year after launch. Depending on the frequency of contacts the DSOC Project is able to negotiate with the Psyche Mission and the COO optical link, demonstrations from representative Mars ranges could be covered in about 1 year.

Doppler frequency shifts as high as 10's of GHz and point ahead angles of more than 40 downlink beam half-widths will be factored into the DSOC spectral filtering, timing synchronization and pointing design.

IV. DSOC FLT DESCRIPTION

Key technologies planned for the DSOC FLT are the laser transmitter assembly (LTA) [5], the photon counting camera (PCC) [6] and the isolation and pointing assembly (IPA).

These technologies are integrated to optics and electronics in order to achieve all the required technology demonstration functions. The optical transceiver assembly or OTA has an actuated mirror in the transmit path for implementing point-ahead angles. Additionally, a tiny fraction of the outgoing laser light is redirected on to the PCC so that transmitted spot position relative to the received beacon can be measured.

All the elements of the FLT have been prototyped and functionally tested at the unit level. Integration of the elements to test the flight sub-system is ongoing.

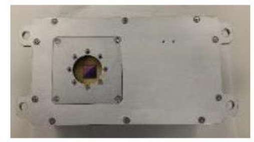
Figure 3 shows photographs of the prototyped elements, with the exception of the electronics. These assemblies will be flight qualified for the FLT.

The OTA shown is manufactured from Aluminum with the same optical design [7] planned for the FLT. For the FLT further light-weighting of the OTA is being explored. The LTA is shown with a separate optical module (LOM) and electrical module (LEM) whereas for flight these modules will be integrated into a single package. The IPA is comprised of four struts shown in a test setup. The struts have actuators and sensors that stabilize the line-of-sight. Additionally the struts have the ability to point over a limited field of regard so that spacecraft body pointing assisted acquisition, tracking and pointing can be implemented. In Figure 3 the IPA is shown in the laboratory testbed configuration where a gravity off-load is required.

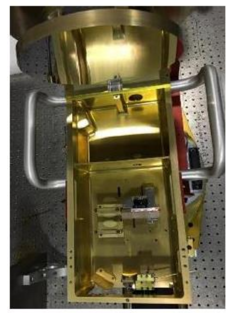
V. DSOC GROUND SUBSYSTEM

The ground sub-system is comprised of separate transmitter and receiver stations with a mission operations center for coordinating activities between the GLT and GLR and with the Psyche Mission.

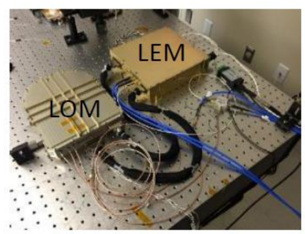
For the GLT, high power beacon lasers will be integrated to the OCTL telescope. In order to avoid unacceptable scintillation induced fades of a single laser propagating through the turbulent atmosphere, multiple-beams will be implemented so that incoherent averaging in the far-field will mitigate fades. Using multiple beams has additional advantages of using lower



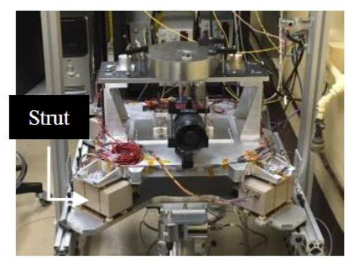
Photon-Counting Camera (PCC)



Optical Transceiver Assembly (OTA)



Laser Transmitter Assembly (LTA)



Isolation Pointing Assembly (IPA)
in test configuration

Figure 3 Prototypes of key elements of the FLT

power individual lasers with redundancy. The multi-beam beacon at OCTL will be a scaled-up version (in power and number of beams) of the beacon assembly developed to support the Lunar laser Communications Demonstration [8]. Laser safety measures for the higher transmitted power is planned.

The GLR will use the JPL developed tungsten silicide (WSi) superconducting nanowire single photon detector (SNSPD) array [9]. These detectors operate at approximately 1K. For use with a large aperture telescope a 64-wire array with approximately 300 micrometer diameter and free-space coupling is planned. A 64-channel read-out integrated circuit is being tested for feeding a signal processing [10] assembly that will extract code-words by performing temporal synchronization, demodulation, decoding and de-interleaving of the downlink signal.

Figure 4 is a photograph of the detector development testbed at JPL. The cryostat houses the packaged SNSPD array shown as an inset in Figure 4. Free-space coupling optics shown are used to couple light into the detector through a window in the cryostat. The 64 channel readout to the signal processing rack is also shown. Signal light from the DSOC LTA driven by representative FLT electronics can be coupled to the detector, for compatibility and performance testing.

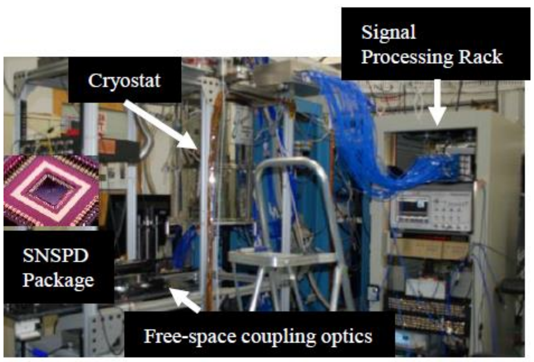


Figure 4 SNSPD detector test setup with signal processing backend

VI. DSOC PERFORMANCE

Figure 5 shows a graphical summary of estimated link performance with favorable, nominal and adverse allocations for system and atmospheric parameters.

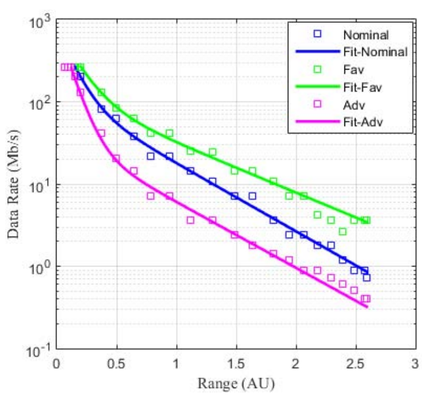


Figure 5 DSOC downlink link performance estimated bounds

The nominal and favorable estimates shown in Figure 5 carry at least 3-dB margin while the adverse estimates carry at least 2-dB.

Uplink performance has a threshold for supporting acquisition and tracking that is estimated at approximately 100 fW of power incident on PCC. At the incident power levels uplink data-rates of 1.6 kb/s are satisfied with at least 3 dB link margin at 1 AU ranges.

VII. CONCLUSIONS

A cost-effective technology demonstration architecture using existing (non-collocated) ground assets retrofitted with transmitters and receivers and a FLT deployed on the Psyche Mission spacecraft was described. A successful technology demonstration would validate beacon-based optical links and serve as a critical stepping stone toward future operational optical flight transceivers. The FLT design will be scalable to larger aperture diameters and transmitted downlink laser power in order to satisfy more aggressive data return volumes from Mars ranges or extend link capability to farther ranges. The technology demonstration would also validate the photon-counting receiver and high power laser transmitter for future operational optical communication systems. A critical pending development will be dedicated ground assets with adequate aperture diameter for receiving deep-space signals; 8-12 m diameter ground collectors are targeted and will be the subject of future reports. With growth of the receiving aperture diameter, scaling of the photon-counting detector diameters will be pursued. The DSOC technology demonstration offers unique opportunities and challenges in both implementing optical technologies and flight system engineering.

The DSOC Project is currently preparing for a Systems Requirement and Mission Definition Review. The Preliminary Design Review is planned in the latter half of 2018. Active testbeds integrating prototype hardware is currently ongoing for verifying acquisition tracking and pointing and end-to-end information transfer.

ACKNOWLEDGMENT

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