DEEP SPACE OPTICAL COMMUNICATIONS (DSOC)

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ABSTRACT

NASA's future deep space science and exploration missions will require enhanced communications and navigation services. Laser communications offers expanded bandwidth and the potential for satisfying this need, with comparable mass and power as state of the art telecommunication systems. Consequently, NASA is planning a Deep Space Optical Communications (DSOC) technology demonstration, to retire the risk for future enhanced optical communication services. NASA's upcoming Psyche Mission scheduled to launch in August of 2022 plans to host a DSOC flight laser transceiver (FLT) for demonstrating optical links from deep-space to earth. Existing ground assets retrofitted with laser transmitters and photon-counting receivers will be used for the technology demonstration. Advancing optical technology from near-Earth ranges to deep space (> 0.01 astronomical units or AU) involves orders of magnitude increased link difficulty (defined as data-rate × squared distance). The plan to bridge the difficulty gap implements new technologies developed over the past two decades. These technologies emphasize high photon efficiency (HPE) with the use of high-peak-to-average power laser transmitters in space, and single photon-counting sensitivity detectors, that together support signaling schemes for achieving approximately 2-3 information bits per detected photon. Implementing HPE schemes relies on accurate and stable pointing of narrow laser beams from space platforms using active control. Key developments needed for future technology infusion, following a successful DSOC technology demonstration, include, cost-effective ground infrastructure, long term reliability of space lasers and detection systems, and solutions for high precision laser ranging. The current status of the DSOC Project and plans for future development will be discussed in this paper.

1 INTRODUCTION

NASA's future missions will require returning larger data volumes, faster, from deep space missions. Both higher resolution science instruments and human exploration will be enabled by this capability. Optical communications offers these capabilities for approximately similar mass and power burden used by state of art telecommunications systems. With this in mind JPL has been pursuing a technology demonstration of deep space optical communications. Following nearly four years of technology development and maturation under the NASA's Space Technology Mission Directorate (STMD) Game Changing Development Program (GCDP) and the Human Exploration and Operations Mission Directorate (HEOMD) Space Communication and Navigation (SCaN) Program, the JPL DSOC Project [1] is planning a technology demonstration (TD). The TD is funded jointly by the STMD/Technology Demonstration Missions (TDM) Program and HEOMD/SCaN Program. Figure 1 illustrates the TD system architecture. The Psyche Mission [2] spacecraft, scheduled to launch in August 2022,

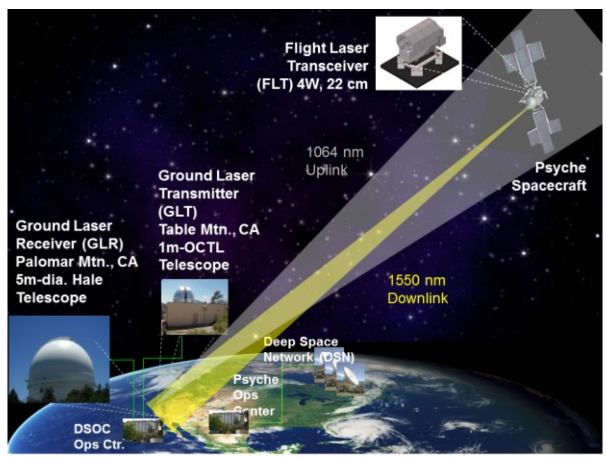

Figure 1 DSOC Operational Architecture

is planning to accommodate the Flight Laser Transceiver (FLT) being developed by the DSOC Project,. The DSOC TD opportunity was incentivized by the NASA Discovery Program announcement of opportunity through which Psyche was selected. The DSOC TD will transmit laser beacon transmitted from the ground to the

FLT on-board the Psyche spacecraft. The FLT will acquire and track the beacon assisted by the Psyche spacecraft coarse pointing and on-board attitude knowledge. The acquired beacon will serve as a pointing reference for returning the downlink laser to earth. The DSOC Ground Laser Transmitter (GLT) will use the Optical Communication Telescope Laboratory (OCTL), 1 m diameter telescope, located at Table Mountain, CA. OCTL will be retrofitted with a high power (5 kW average) laser transmitter. The Ground Laser Receiver (GLR) requiring a large aperture will use the 5m diameter Hale telescope at Palomar Mountain, CA. The angular separation between the GLT and GLR is less than the downlink laser beam width (8-μrad) from a distance of ~ 0.2 AU. Data-rates ranging from 0.2 Mb/s to > 200 Mb/s well be demonstrated over the 0.2-2.7 AU link range. A photon-counting optical receiver integrated to the Hale telescope will perform optoelectronic conversion and subsequent signal processing for extracting the information.

The uplink (beacon) and downlink laser wavelengths are 1064 nm and 1550 nm. The choice of wavelengths is driven largely by fiber laser and amplifier technology and the communications requirements. Deep space optical communications involves a huge increase in distance, relative to near earth applications. Defining link difficulty as data-rate × squared distance indicates a 60 dB increase in difficulty for returning the same data-rate from Mars versus the Moon. Merely scaling of power and aperture does not provide a viable solution.

DSOC has developed technologies to overcome the difficulty gap. High photon-efficiency communications, requiring high peak to average power laser transmitters and single photon sensitive detectors, will allow demonstrating communications with 2-3 information bits per detected photon. The faint downlink signal will be transmitted using spatially narrow beam-width lasers, thereby introducing a pointing challenge. Given typical spacecraft platform stability, active control will be required to achieve accurate pointing. Ground laser beacon acquisition by the FLT uses a 256 μrad field-of-view detector and a +/- 4 mrad field of regard realized using active struts for stabilizing the line-of-sight in the presence of spacecraft platform disturbance and attitude. Downlink pointing to the ground receiver, with appropriate point-ahead angle, will use the beacon as a pointing reference. The beacon signal delivered to the FLT is dim, requiring a photon counting camera (PCC) for sensing. The dim beacon will support low bandwidth pointing control and low rate (1.6 kb/s) uplink data-rates at a distance ofg 1 AU.

DSOC technologies include a 1550 nm, 4 W average power flight laser with a peak-to-average ratio of 160, and a variable repetition frequencies of 100's of MHz. The laser operates with sub-nanosecond pulse-widths with < 0.1 nm spectral linewidths. The 22 cm diameter off-axis flight transceiver receives the 1064 nm beacon laser signal using the PCC. The flight transceiver includes active isolation pointing assembly struts (IPA-S) for vibration isolation and low bandwidth closed loop control.

On the ground tungsten silicide (WSi) superconducting nanowire single photon detector (SNSPD) array forms the front end of the photon counting receiver to be integrated to the Hale telescope.

The DSOC Project is integrating and implementing the technologies so that the flight transceiver can be hosted by the Psyche spacecraft in time for launch in August 2022.

2 METHODOLOGY

Deep space communications has and will continue to be mission enabling. Historically the frequency and performance have been increasing [3].

2.1 State of the Art

Today deep space communication and navigation typically carries a high gain X-band or Ka-band system. These systems provide excellent mission support for returning science and telemetry. Projecting into the future scaling to higher power transmitters and larger antennae to satisfy future demand translates into increased mass and power. RF systems are also constrained by bandwidth regulations

2.2 New Approach

Optical services, if they could be implemented, would result in a significant augmentation of the current radio frequency capability. For near-earth missions optical has matured beyond technology demonstrations and transitioning into operational status.

An order of magnitude improved downlink deep space data-rate performance with comparable mass and power as state-of-art telecommunication systems is the goal to pursue.

To accomplish this goal driving requirements are, firstly, a technology demonstration from deep space, secondly, an earth receiving infrastructure for operational use, and finally improved reliability and scaling for operationally robust and redundant systems.

The DSOC Project TD will address the first of by validating: (i) acquisition, tracking and pointing of narrow lasers to and from deep space; and (ii) signaling performance that supports deep-space links.

2.3 Future DSOC Use Cases

An orbiting telecommunication infrastructure around Mars that includes optical services [4] is an achievable by the end of the next decade. For human landing and operations safety, the required high resolution mapping and high rate communication can be significantly augmented with optical communications. Streaming multiple channels of high definition imagery supporting human exploration will be enabled. Higher uplink data-rates will also be supported within the constraints of atmospheric turbulence induced earth to deep space laser propagation effects.

2.4 Challenges and Rewards

Key challenges in this development approach are (i) timely deployment of ground infrastructure to support flight operations (ii) validating the long term operational reliability, primarily of flight lasers and detectors and (iii) scaling flight transceiver performance to satisfy the future performance demands.

A key operational challenge is optical link availability. Atmospheric disturbances and signal blockage by clouds will reduce the optical link single path availability. Active mirror optics to mitigate atmospheric distortion and an increase in the number of geographically dispersed ground stations provides multiple paths for the optical signal to raise the link availability.

Models addressing the effects of thermal cycles, radiation induced damage and darkening of detectors, optics and fibers need validation.

Scaling of flight transceivers to larger diameter and higher power lasers will be introduce additional pointing difficulty and engineering of laser components to withstand higher peak power.

Overcoming these challenges will provide NASA with robust, reliable, lower size weight and power communication systems that can augment performance significantly.

3 PROGRAMMATICS

The first step, a technology demonstration of deep space optical communications is currently funded and in Phase B progressing toward preliminary design review in 2018.

Studies for the development of cost-effective large ground apertures that can support daytime operations are also currently funded by HEOMD/SCaN..

Through HEOMD/ScaN Planning, Programming, Budgeting and Execution (PPBE) process future studies for the next generation DSOC have been proposed with a planned start dates of FY 2020. The proposed studies include developing and implementing ground detectors and receivers for larger aperture collectors. Studies for atmospheric mitigation, especially for reducing the penalty for daytime performance are included. For flight systems the development of higher emitted isotropic radiated power (EIRP) flight transceivers is planned.

3.1 Development Plans

Studies for realizing cost-effective larger operational ground apertures to support deep-space optical communications with possible development of a pathfinder capability [1, 5] in the middle of the next decade are underway. The use of existing RF antennae to provide mirrored surfaces without significantly impacting RF performance is being studied. This approach would result in 8-11 m class optical apertures that operate to within < 10° of the sun with 30-40% efficiency. Successfully implementing such a capability at a single site, such as Goldstone, CA, by the end of the next decade would support operational demonstrations advancing both space and ground systems, while augmenting existing deep space communications services. Success with this approach will result in additional ground assets for implementing site diversity.

The costs for both developing the next generation DSOC that includes, ground receivers for larger aperture collectors along with atmospheric mitigation and scaled up flight transceivers are in planning and review

3.2 Development Milestones and Dates

The key development milestones for deep space optical communications are:

1. Perform a successful TD in the 2022-2024 time frame
2. Develop a single ground based large aperture collector equipped with photon counting receivers for daytime link operations in the 2025-2030 time frame
3. Advance reliable higher EIRP optical transceivers. This will require lightweight large (50 cm class) transceivers and higher average power (20 W class) laser transmitters. Deploy a Mars orbiting optical transceiver in the 2028 time frame returning at least 75 Mb/s from Mars farthest range. Target a 75 kg mass and < 250 W power.

3.3 Partnering

Partnering with other NASA centers FFRDC's such as MIT-Lincoln Laboratory is underway. Industry is also involved in providing advanced lasers, actuators and detectors.

Partnering with international space agencies for site diversity of ground sites will also prove cost effective. Involving astronomy, solar astronomy and Cerenkov radiation community on implementing large apertures will be instructive.

4 WIDER VISION

Laser ranging measurements over the laser link in support of navigation is an expected extension of the technology. A number of light science applications akin to radio science performed by telecommunications systems today but with higher resolution and at optical frequencies will follow.

5 CONCLUSIONS

Deep space optical communications is on the verge of an important TD milestone that will qualify flight hardware, demonstrate key flight and ground technologies and link processes setting optical communication for prime flight support uses.. Having a successful TD will result in a demand for operational ground infrastructure, longer time reliability of flight lasers, sensors and actuators. Some work toward these goals is underway but unless a commitment is made an opportunity will be lost. Once the capability is infused further enhancements such as high precision ranging and light science will follow.

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