Status of NASA’s Deep Space Optical Communications Technology Demonstration


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DSOC Motivation

- State of the art RF communications continues to provide robust service
  - Expect performance to eventually level out due to bandwidth constraints**


- Overarching NASA Technology goal is
  “… seek increased data-rates (10 to 100 times) without increasing mission burden in mass, volume, power and/or spectrum.”

- Optical Communication sub-goal
  “… provide higher data rate links for near-Earth and enable more efficient photon-starved links for deep space

Ongoing development with NASA support

Deep-Space Optical Communications (DSOC)

Operational architecture for technology demonstration
- Flight terminal hosted by Psyche spacecraft
- Existing ground assets
  - Retrofit
    - Laser transmitter
    - Photon-counting receiver

Ground Laser Transmitter (GLT)
Table Mtn., CA
1m-Optical Communications Telescope Laboratory (OCTL)
(5 kW)

Ground Laser Receiver (GLR)
Palomar Mtn., CA
5m-dia. Hale Telescope

Deep Space Network (DSN)

Flight Laser Transceiver (FLT)
4W, 22 cm dia.

Psyche Mission Ops Center

1064 nm Beacon & Uplink
Max rate 1.6 kb/s

1550 nm Downlink
Max rate 267 Mb/s

Psyche Spacecraft
Tech. Demo Objectives & Approach

- **Validate deep space optical communications**
  - Link acquisition re-acquisition at both ends of link
  - Tracking of beacon and beacon assisted point-ahead angle implementation’
  - Flight ground signaling compatibility in presence of Doppler and Doppler rates
  - Bi-directional data transfer (unsymmetrical)
  - Performance under diverse link and atmospheric conditions

- **Deep space optical communications involves increased link difficulty**
  - Mbps × AU² targeted by DSOC ranges from 5 -18 compared to
  - 30 dB increase in link difficulty compared to lunar distance
  - Use high photon-efficiency (HPE) emerging CCSDS Optical standard signaling
    - Physical layer
    - Coding and synchronization layer
  - Utilize new technologies for photon-counting and low bandwidth pointing control assisted by spacecraft coarse body pointing
DSOC Tech. Demo Constraints

- NASA/JPL has been pursuing the development of deep space optical communication for decades

- Based on readiness through years of incremental technology development NASA has arranged to accommodate a DSOC tech demo hosted by the planned Psyche Mission
  - Selected by Discovery Program to explore the asteroid Psyche-16
  - Primary science objective is to determine whether Psyche-16 is a core or if it is unmelted material
  - Psyche scheduled for launch in summer of 2022 with a 21-day launch window
    - Schedule constraint

- DSOC tech. demo constrained by:
  - Scheduling around Psyche mission activities and ground assets (Palomar)
  - Cloud free line of site at Palomar and OCTL simultaneously
    - Studies indicate an average of about 50% joint availability with seasonal variations
  - Limitations of Palomar telescope to operate in the daytime
  - Psyche trajectory

Artists rendition of Psyche-16
Link Conditions

- Psyche trajectory for observer at Palomar:
  - Range
  - Air-mass
  - Sun angles

- “Night” operations for nearly 250 days after launch

- “Day” operations restricted to 25° SEP (TBC)

- Possible to meet Level 1 requirements within year from launch
  - Likely requires two contacts per month
  - Frequency of contacts needs further analysis

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Link Conditions (cont.)

- Doppler shift/rates within optical filter widths and receiver synchronization algorithms
  - Downlink uses narrower filter and would be set based on predicts
  - Uplink filter would accommodate Doppler shifts

- Point ahead angles for downlink exceed FLT camera FOV
  - Factored into design
  - Plan to use calibrated strain gauge sensors on point-ahead mirror when PA angle exceeds FOV
DSOC Concept of Operations

- DSOC tech demo operations concept is under formulation
  - Assumptions
    - Transmit ground laser beacon using predicts while Psyche powers FLT and coarse points to Earth
    - DSOC performs step-stare to search for beacon in s/c pointing uncertainty space
    - FLT stabilizes line-of-sight to Earth with beacon assisted closed-loop control
    - Points downlink to Earth while Ground Receive is pointing to Psyche using predicts
    - Receive and store downlink
  - Telemetry gathered and stored at FLT for post pass transmission to ground
  - Limited “real time” telemetry during pass
**DSOC Predicted Downlink Performance**

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**Summary of initial downlink analysis**

- Assumes 4 W average laser power @ 1550 nm transmitted through 22 cm aperture transceiver
- Received by 5 m diameter ground aperture and detected using photon-counting detector assembly
- Pulse position modulation (M-ary PPM) orders with M=16, 32, 64, 128 with discrete slot-widths of [0.5, 1, 2, 4, 8] ns
- Discrete code rates of 0.33, 0.5 and 0.6667
- Inter-symbol guard times (ISGT) used to assist temporal synchronization
- Results show represent fits to data obtained after initial analysis
- Atmospheric model derived transmission, sky radiance and “seeing” *(models have been authenticated with site statistics gathered at Table Mtn., CA and Goldstone, CA)*

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![Graph showing DSOC Predicted Downlink Performance](image)
DSOC Predicted Uplink Performance

- **Uplink delivers mean irradiance at FLT aperture for acquisition/tracking**
  - 4.5 pW/m² irradiance needed for acq./track
  - Modulated beacon allows background subtraction
  - Low-rate (max 1.6 kb/s) uplink data

- **Retrofit multi-beam laser beacon @ 10645 nm to OCTL telescope**
  - Baselining 10 × 500 W total of 5 kW average power
  - Beacon average power supports
    - Uplink data to 1 AU
    - Acq./trk reference to at least 2.6 AU
FLIGHT LASER TRANSCEIVER DEVELOPMENT
The Flight Laser Transceiver (FLT) makes up the flight subsystem:

- Silicon carbide (SiC) Optical Telescope Assembly (OTA) receives beacon and transmits downlink.
- Photon Counting Camera (PCC) detects “dim” 1064 nm laser beacon transmitted from Earth.
- Isolation Pointing Assembly (IPA) “floats” OTA to stabilize and steer OTA line-of-sight.
- Laser Transmitter Assembly (LTA) delivers high peak power pulse train modulated by downlink data.
- Electronics – firmware/software platforms, power and clock distribution for “floating” and stationary parts, power and data interface to spacecraft.
Prototype FLT Assemblies

Power Supply Unit
216 × 209 × 81 mm

PCB Board

Sensor Package

PCC Camera

Laser Transmitter Assembly (LTA) (Fibertek): Laser Optical Module (LOM) and Laser Electrical Module (LEM)

LOM
LEM

Optical Transceiver Assembly

IPA Assembly with “dummy” load
laboratory characterization

Spring and Music Wire Suspension

Disturbance Emulator

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Nov. 14, IEEE International Conference on Space Optical Systems and Applications  Pre-Decisional Information -- For Planning and Discussion Purposes Only
Flight Photon Counting Camera
Signal Detection

- Pixel modified square-law statistics are used to distinguish modulated signal from background
- Statistic from maximum pixel is compared to threshold to detect signal
- For Mars far-range case, statistic integration time of 20 - 40 msec is sufficient to achieve $10^{-6}$ probability of missed detection
- In practice, platform stability will limit integration time
• Uplink UC centroid changes as Earth flux increases, MSQ centroid does not
• MSQ centroid jitter increases with increasing Earth flux
  – At <1.5e5 Earth counts/sec/pixel, per axis jitter < 1 μrad
• Earth-beacon centroid difference ~ 1 pixel in X, ~0.75 pixel in Y (8 μrad, 6 μrad)
• Earth flux per pixel for Mars 2.7 AU ~1.6e5 counts/sec/pixel (assuming 1 nm filter, 3 dB optical losses, 40% DE, irradiance of 0.0087 W/m²/sr/μm)
• Measured values track simulation results using Gaussian blocking model
• Downlink jitter < 0.16 μrad per axis
• Additional results with better calibrated measurements expected in next few months
LTA Performance Results

- LTA prototype built and tested in preparation for flight
  - Demonstrated performance and select environmental requirements met
  - Maintaining high temporal ER critical over all PPM orders and pulse formats

Pulse format
- PPM 16-128, 25% Guard time, 0.5 – 8 ns with min/max test pattern, ~4W
DSOC FLT Development Status

• **Verified**
  – Laser performance and TVAC, vibe, radiation testing and analysis
  – Photon-counting camera performance in laboratory
    – Centroid estimation algorithms with background subtraction in presence of Earth radiance noise
    – Uplink data demodulation
  – Isolation pointing strut performance in laboratory with gravity off-load
  – Optical Transceiver Assembly performance with aluminum assembly; also verified SiC mirror separately
  – End-to-end downlink testing at a few operating points (ongoing activity)

• **Completed System Requirements/Mission Definition review on Nov. 1-2, 2017**

• **Work to go**
  – Assemble functional prototype Flight Laser Transceiver (FLT) in laboratory testbed
    – Test acquisition, tracking and pointing using gravity off-load and ground support equipment
      – Perform end-to-end information testing prior to PDR
  – Complete preliminary design and build of FLT assemblies
  – Procure and develop EMs and Flight hardware for the FLT
  – Develop ICD with Psyche Mission and understand accommodation
    – Initiated
  – Integrate and test FLT (performance and environmental)
  – Verify flight – ground signaling compatibility with flight hardware

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GROUND DEVELOPMENT
DSOC Ground Subsystem

- **DSOC technology demonstration would utilize**
  - Ground Laser Transmitter at OCTL telescope near Wrightwood, CA
    - Retrofit high power (5 kW) laser transmitter
  - Ground Laser Receiver at Hale telescope at Palomar Mountain, CA
    - Retrofit photon-counting detector and signal processing electronics
  - Mission ops center for coordinating ops (not shown)

- **Ground Laser Transmitter (GLT)**
  - 1070 nm Ground Lasers

- **Ground Laser Receiver (GLR)**
  - Photon-counting ground detectors
  - 50% Eff. WSi nanowire arrays

- **Optical Communication Telescope Laboratory (OCTL)**
  - 1m aperture
  - Az/El Drive

- **Hale Telescope**
  - 5 m aperture
  - Palomar Observatory
  - RA/DEC Drive
DSOC Ground Development Status

- Initiated discussions with Caltech Optical Observatories (COO) for the use of Hale telescope at Palomar Mountain
  - Trade location of DSOC detector at Coudé versus Cassegrain focus
  - Analyze and test impact of telescope use in the daytime (insolation and thermal effects causing “seeing” for nighttime observers)
  - COO staff would support this work after August 2017

- Uplink laser selection for retrofitting to OCTL telescope for ground transmitter
  - Plan to modulate pumps on high power optical amplifier to achieve 500 W average power 2 kW peak power lasers
  - Packaging of lasers for DSOC is work to go
DSOC Ground Detector Development

- Detector fabrication and characterization is ongoing
  - Fabricated 64-wire tungsten silicide (WSi) superconducting nanowire single photon (SNSPD) detector array
  - Verified characteristics of 320 μm diameter detector (optical micrograph and packaged SNSPD shown below)
  - Detector has been characterized and shown to meet all required specifications
  - Preparing to support end-to-end link tests in laboratory
    - Includes interface to backend signal processing electronics
  - Detector signal conditioned at 40K stage
  - Routed out of cryostat to 64-channel comparator
  - Initiating end-to-end information testing
DSOC Ground Development Status

### Signal processing functions
- Synchronize received data to DSOC symbol frames
  - Compensate clock phase and frequency dynamics
  - Strip off inter-symbol guard time slots
- Estimate signal and background parameters and form log-likelihood ratios
  - Estimate codeword frame boundaries
  - Remove frame alignment sequences
  - De-interleave sub-channel symbols
  - Decode data and return information bits
- Functions are in various stages of verification through simulation
  - High fidelity simulations (results shown)
  - Verified few operating points in laboratory
  - Rigorous calibration and repeatability pending

[Diagram of Ground Receiver Signal Processing Functional Architecture]

#### Nighttime cruise (265 Mbps)
- **Ideal channel**
- **DSOC receiver**
- **Capacity threshold**
- **Expected downlink power**

#### Mars far range (230 Kbps)
- **Ideal channel**
- **DSOC receiver**
- **Capacity threshold**
- **Expected downlink power**
Summary

• Preparing for NASA’s first technology demonstration of optical communications from deep space
  – Pre-cursor to enabling human exploration and enhancing high-resolution science
  – Developing Flight and Ground system to support demonstration

• DSOC Project privileged to be hosted by Psyche
  – Provides excellent operational opportunities that are needed for learning how to provide future optical services for NASA missions

• Understand and managing risks involved with DSOC technology demonstration

• Team is excited with this great opportunity
BACKUP
• Notional encounter with 16 Psyche