Deep Space Optical Communications

National Aeronautics and Space Administration

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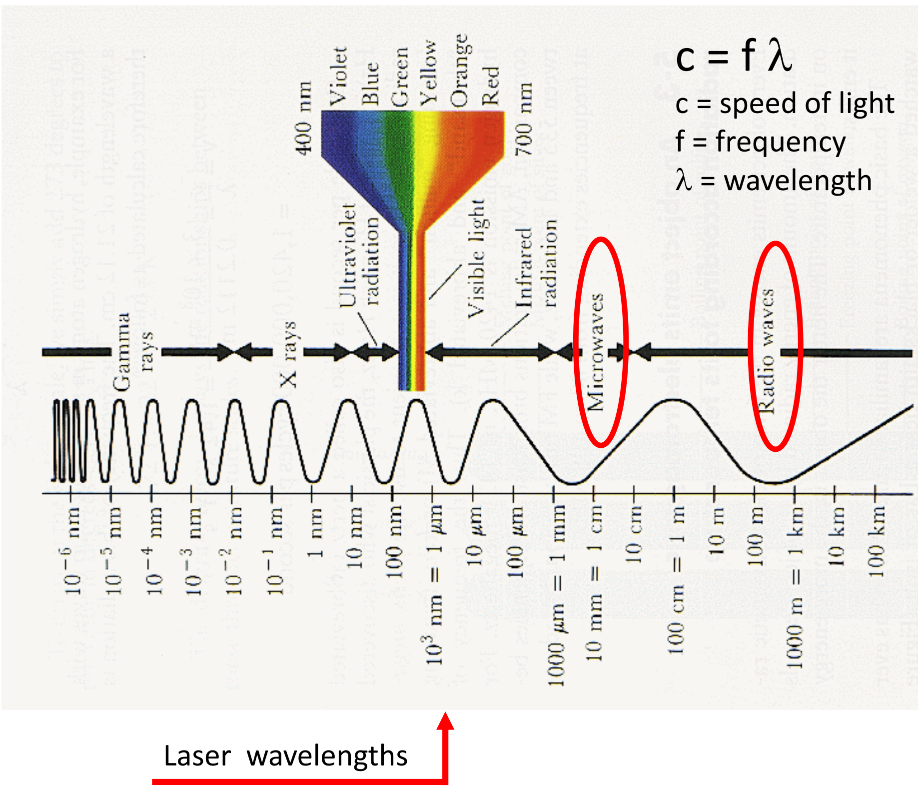
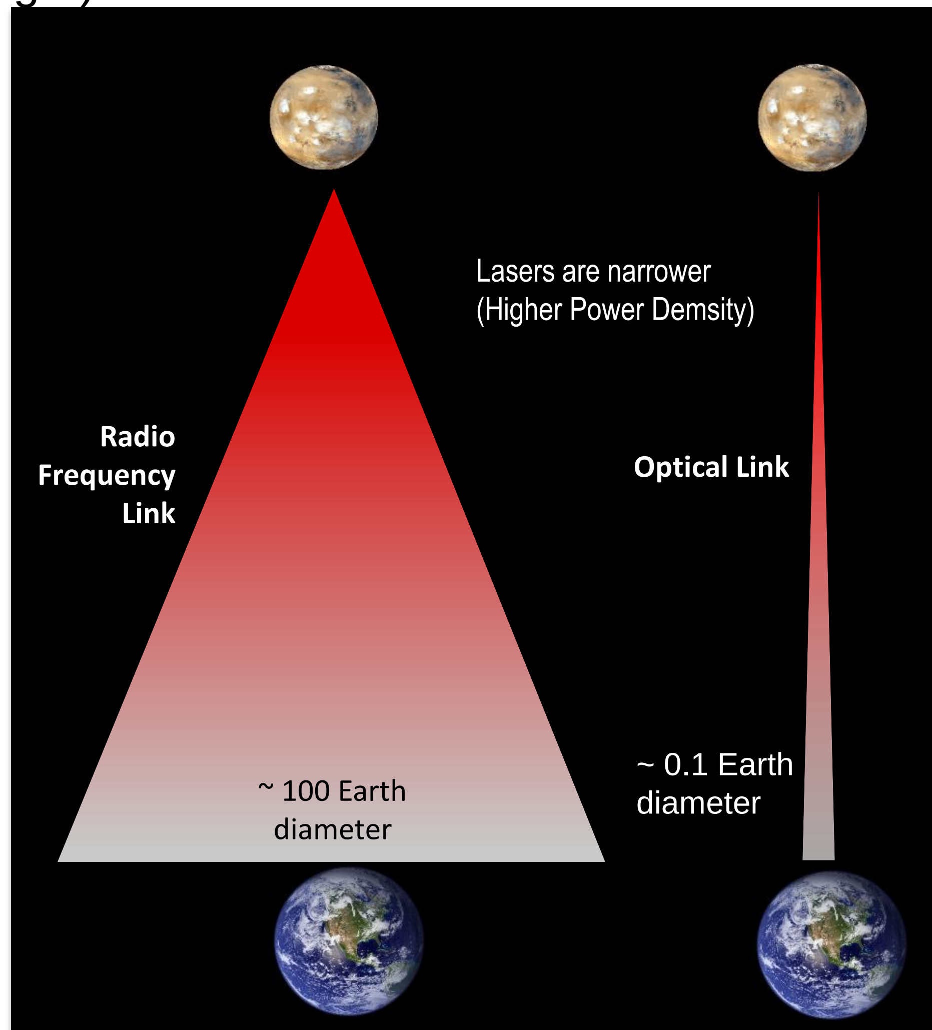
Outline

- Introduction: Why Lasers for Telecommunications
- Laser communications from space
- Past space laser communications demonstrations
- Deep Space Optical Communications (DSOC) Project
- Future Systems for deep space
- Summary

Motivation

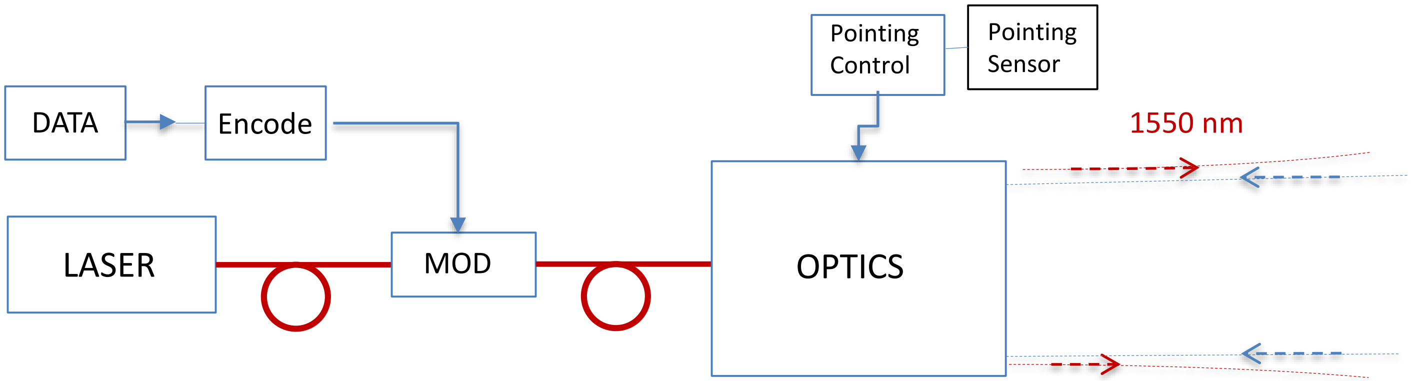
- Why do we want to change to lasers from radio transmitters?
  - Higher carrier frequency (shorter wavelength)
    - Supports higher modulation rates

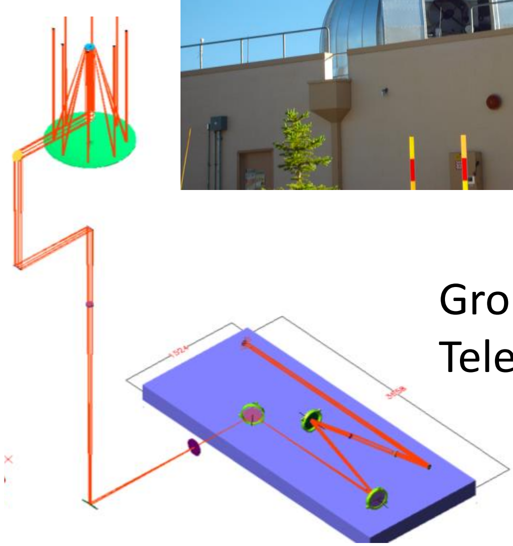




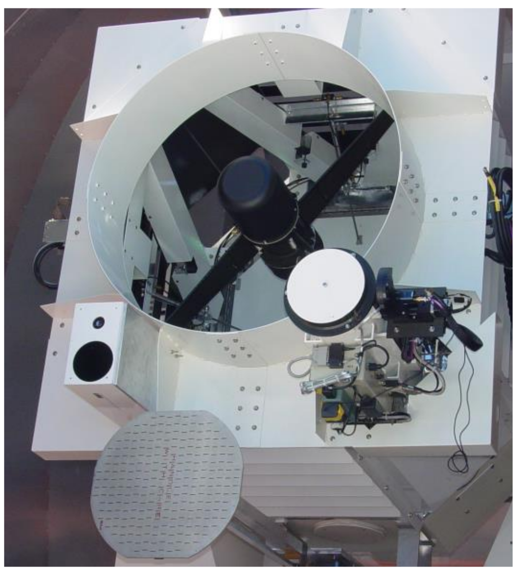
Laser Communications Systems

Generic Transceiver Block Diagram

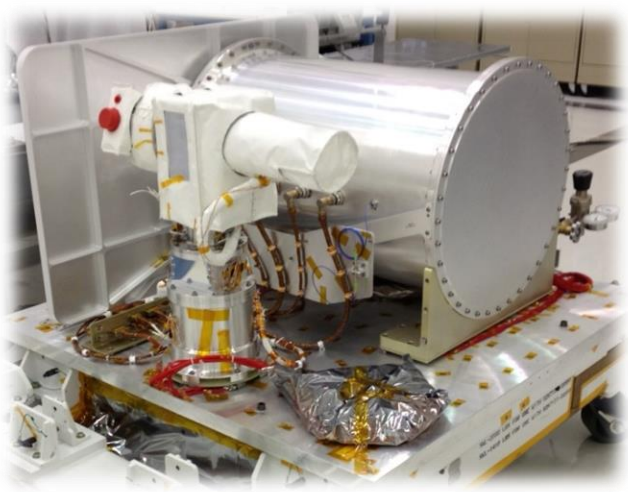




Ground Telescope

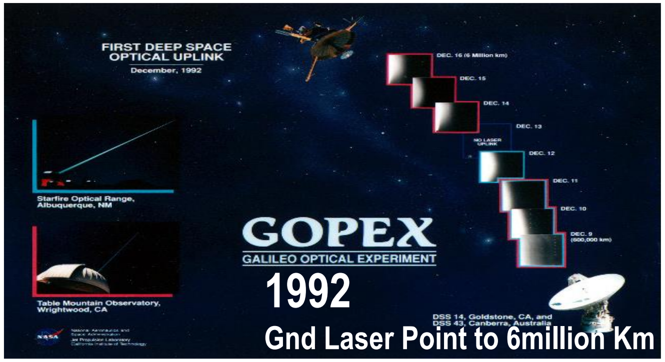


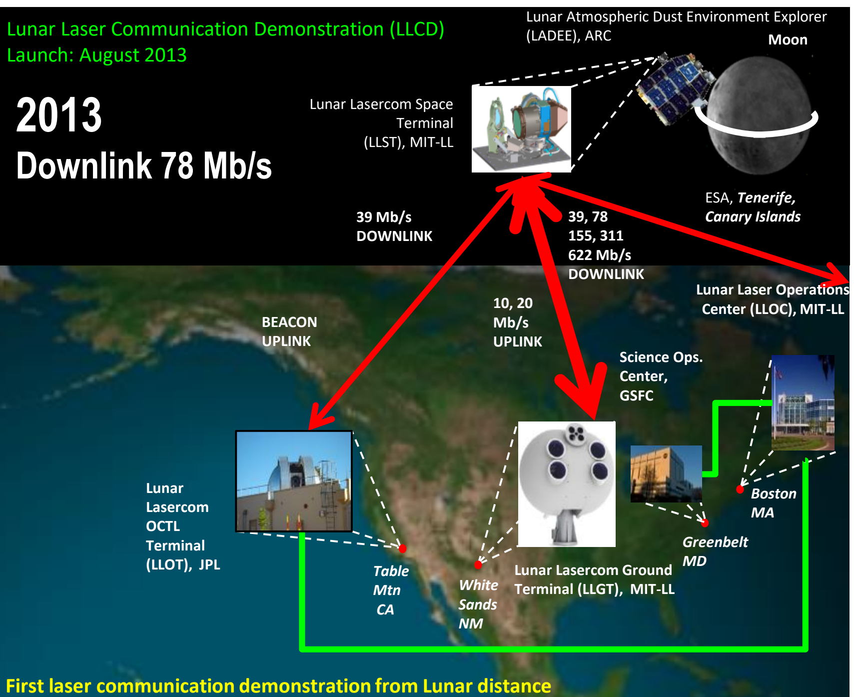
Flight Transceiver

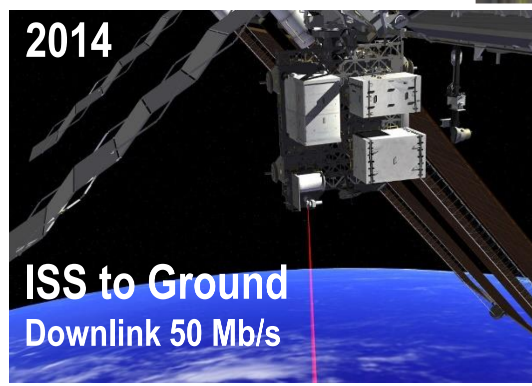


Laser Communications Systems

Technology advancing through incremental demonstrations

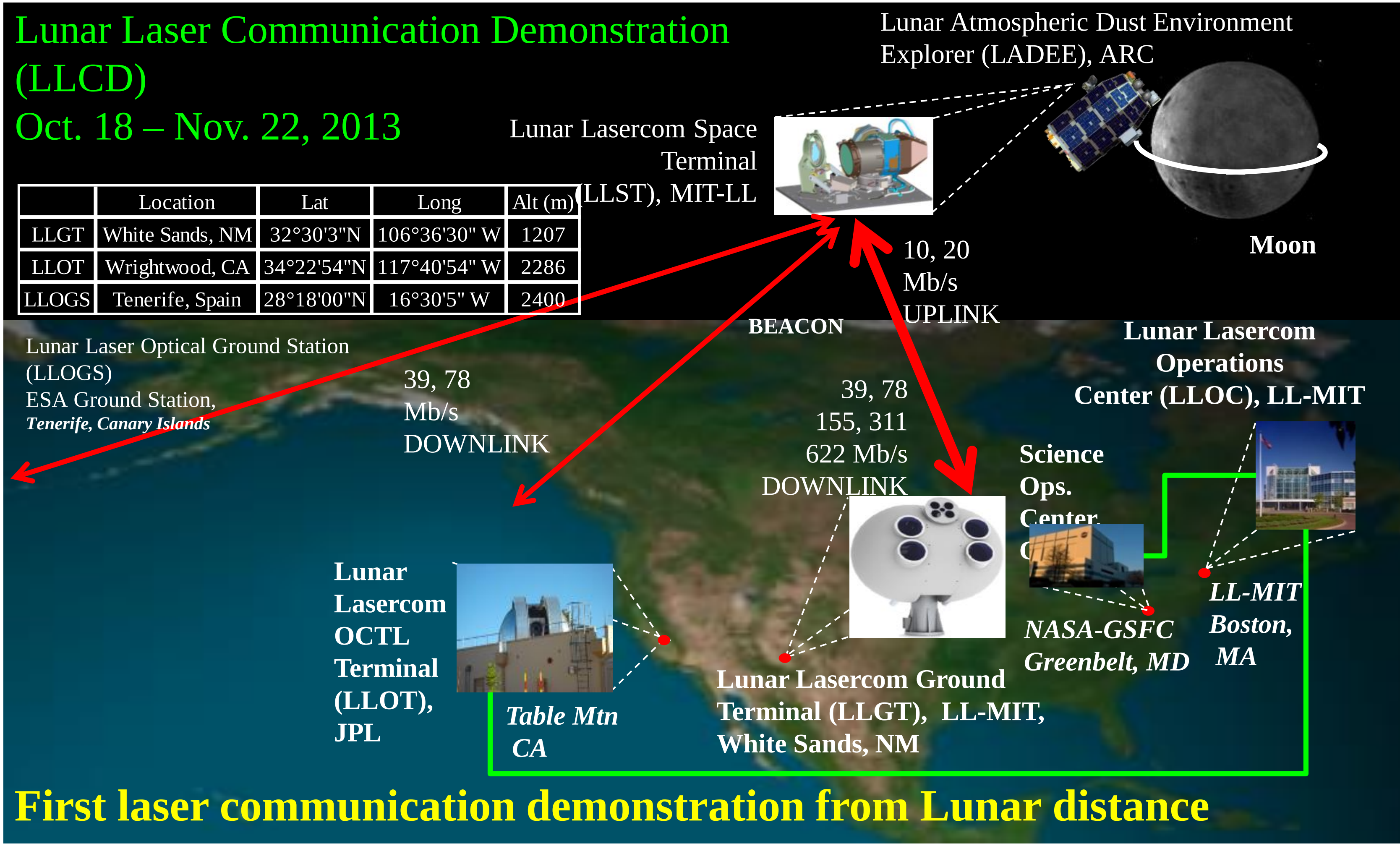






Atmospheric Channel Monitor & Analysis

LLCD & Lunar Lasercom OCTL Terminal (LLOT)



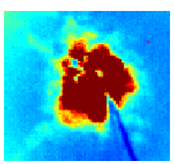
	Location	Lat	Long	Alt (m)
LLGT	White Sands, NM	32°30'3"N	106°36'30" W	1207
LLOT	Wrightwood, CA	34°22'54"N	117°40'54" W	2286
LLOGS	Tenerife, Spain	28°18'00"N	16°30'5" W	2400

Beacon Performance

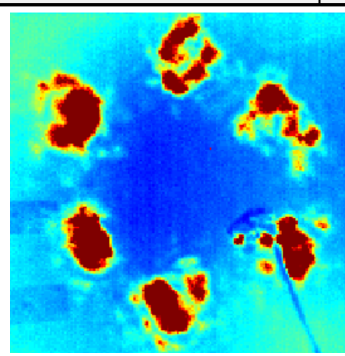
- **Predicted beacon power on LLST quadrant sensor was verified**
- **Varied beam divergence and power**
  - **Compared predicts with average power measured by LLST quadrant**

Average Tx Pwr @ telescope Focus with 5-lasers	14.36	dBW
Tx Gain @ 111.5 mrad	94.1	dB
Telescope Loss	-4.3	dB
Mispointing Loss	-0.26	dB
Atmospheric Loss @ 59 deg El.	-0.54	dB
Atmospheric Strehl Loss @ 3cm r0	-0.34	dB
Range Loss @ 391,125 km	-309.96	dB
Estimated LLST Net Gain	103.7	dB
Power @ LLST Quad	-73.24	dBm
Power Required at LLST	-77	dBm
Margin	3.76	dB

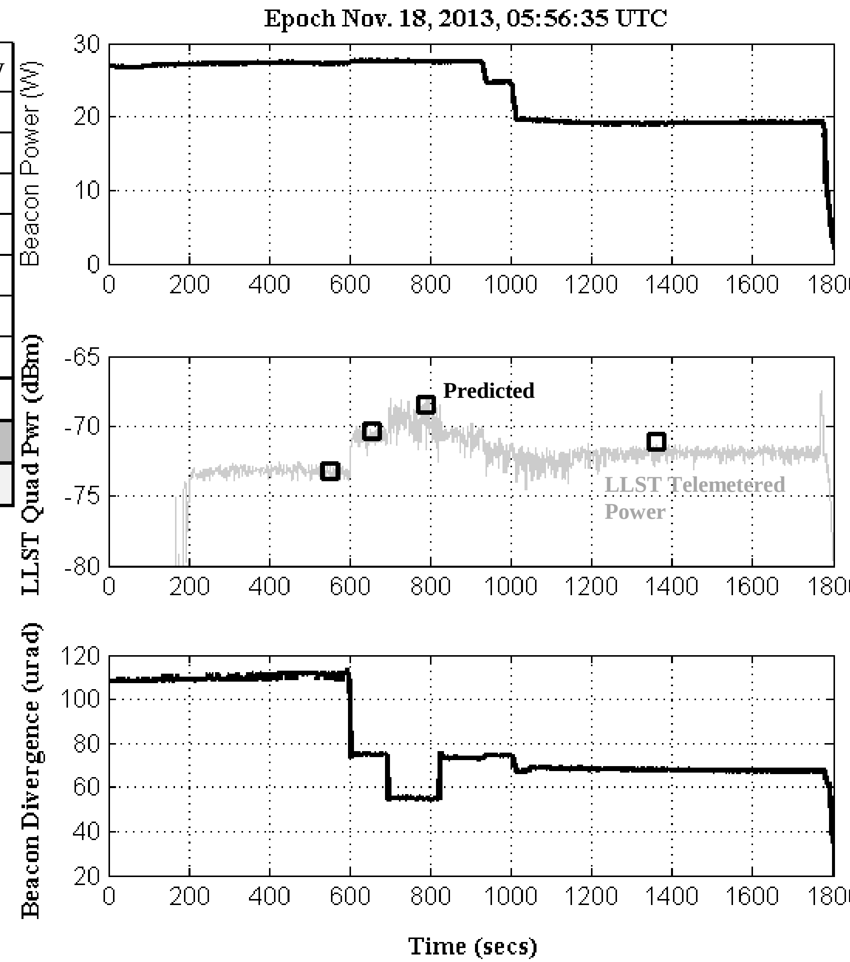
45 x 45 cm



Beams superimposed
By focusing telescope



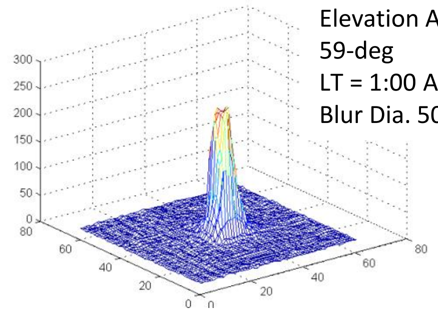
Short exposure of 6-beams (narrow zoom)
1.6 km from telescope exit aperture,



Very good agreement observed

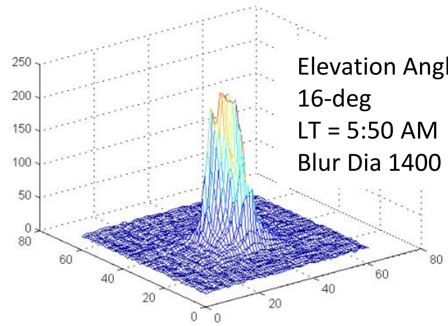
Downlink Atmospheric Blurring

- **Varying downlink spot sizes measured corresponding to diverse atmospheric conditions**

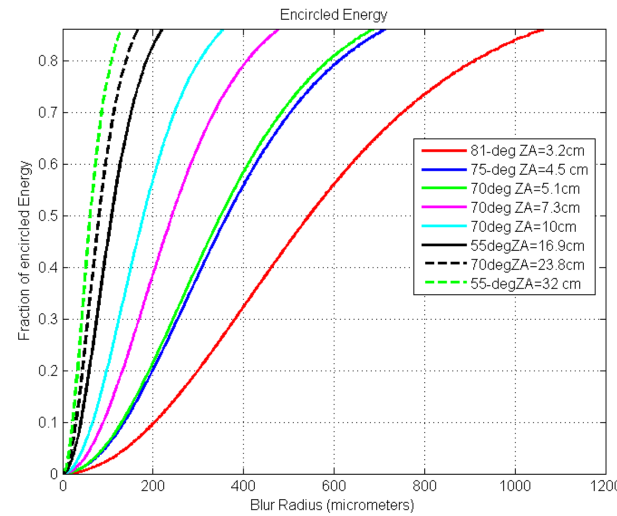


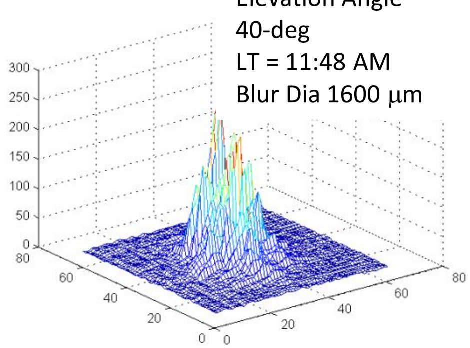
Elevation Angle
59-deg
LT = 1:00 AM
Blur Dia. 500 µm

- **Performed preliminary analysis of blur diameters**
  – Observed diameters are bounded by analytic estimates using Kolmogorov turbulence spectrum*

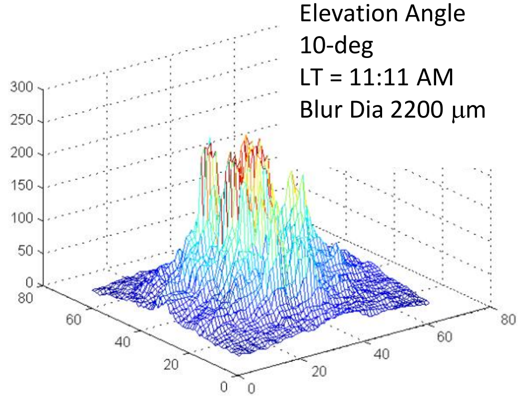


Elevation Angle
16-deg
LT = 5:50 AM
Blur Dia 1400 µm





Elevation Angle
40-deg
LT = 11:48 AM
Blur Dia 1600 µm

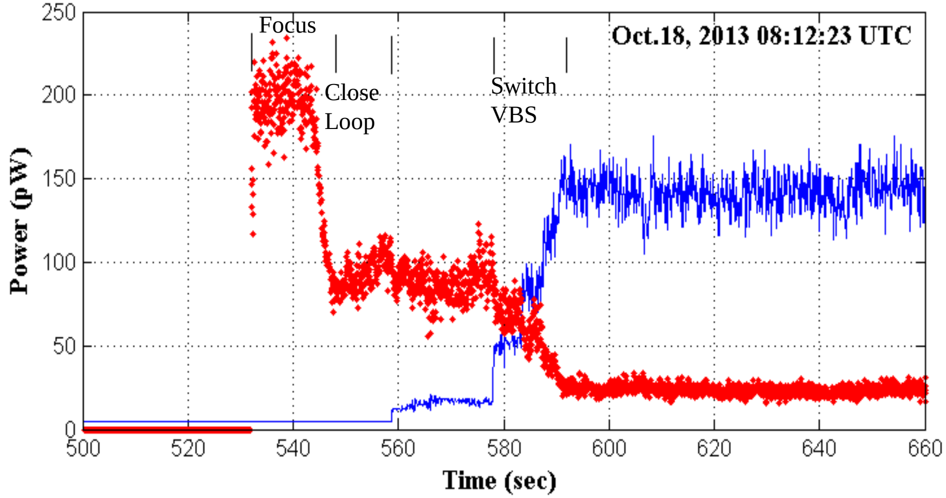


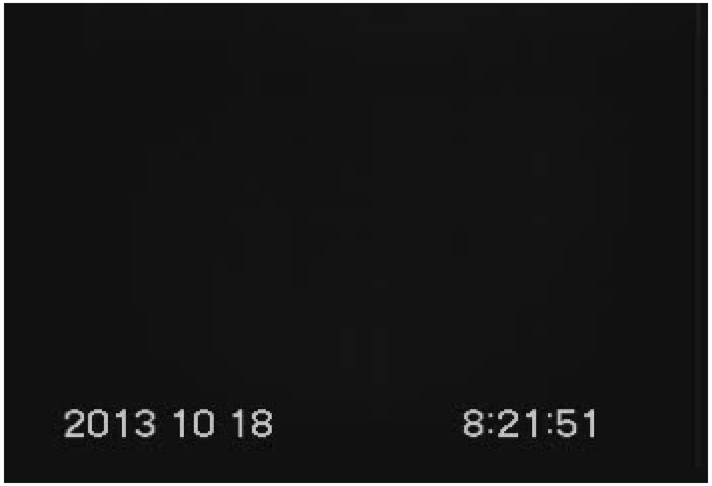
Elevation Angle
10-deg
LT = 11:11 AM
Blur Dia 2200 µm

*Mahajan, V. N., "Aberration Theory Made Simple," Chapter 11, p. 135-147, SPIE, Bellingham, Washington, 1991.

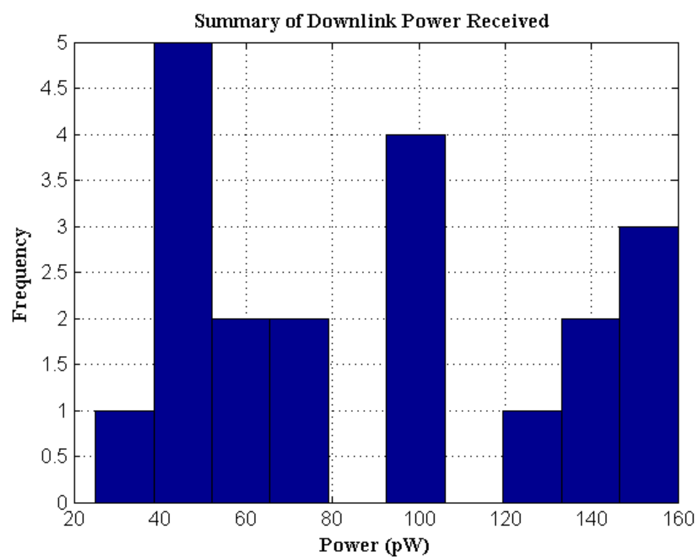
Downlink Acquisition

- **Downlink average power falls within the predicted bounds**
  - Link analysis
  - Current best estimates during testing of LLOT



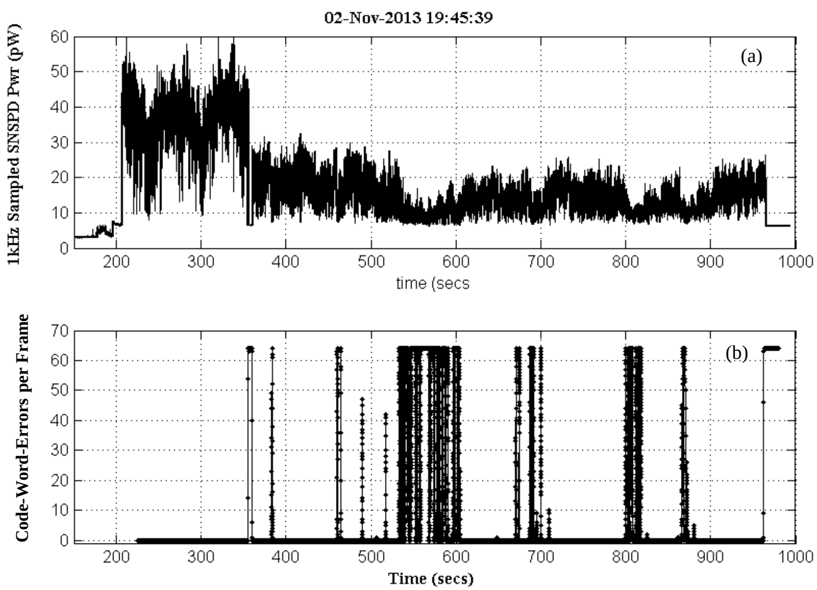


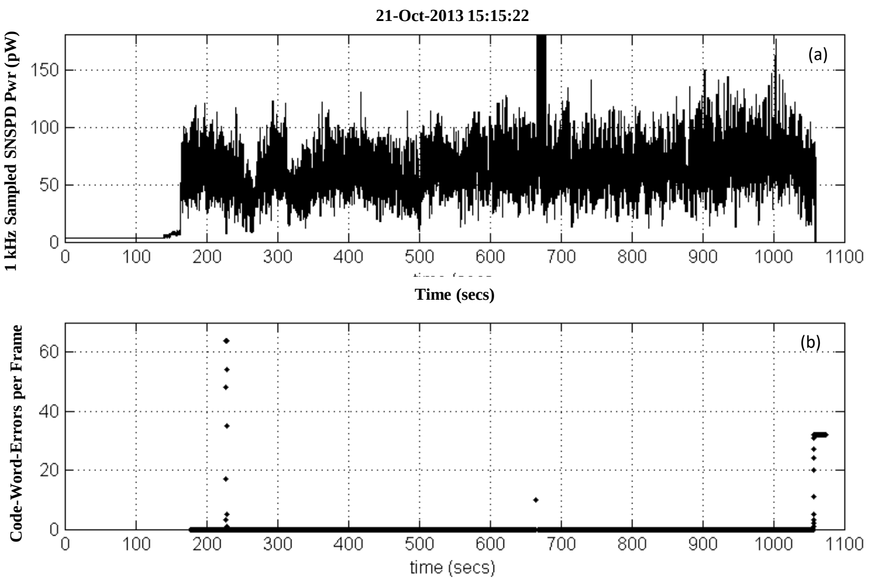
	Nominal	Worst	Best
LLST EIRP transmiting 0.5 W (dBW)	99.1	99.1	99.1
LLST Pointing Loss (dB)	-0.6	-1.5	-0.4
Space Loss (dB)	-310.7	-310.9	-310.0
Atmospheric Loss (dB)	-0.5	-3.1	-0.3
Ground Net gain (dB)	114.4	113.4	115.4
Net Received Power (dBW)	-98.3	-102.9	-96.2
Power in pW	148.7	51.0	242.2



Link Performance

- **Typically link performance was very good with 0 code-word error rate (CWER)**
  - Show one of the marginal links at lowest SEP angle (high background)
    - At full 0.5 W power from LLST 0 CWER
    - When power is halved the performance becomes marginal
  - Link through thin clouds shows zero CWER except for when data-rate switched



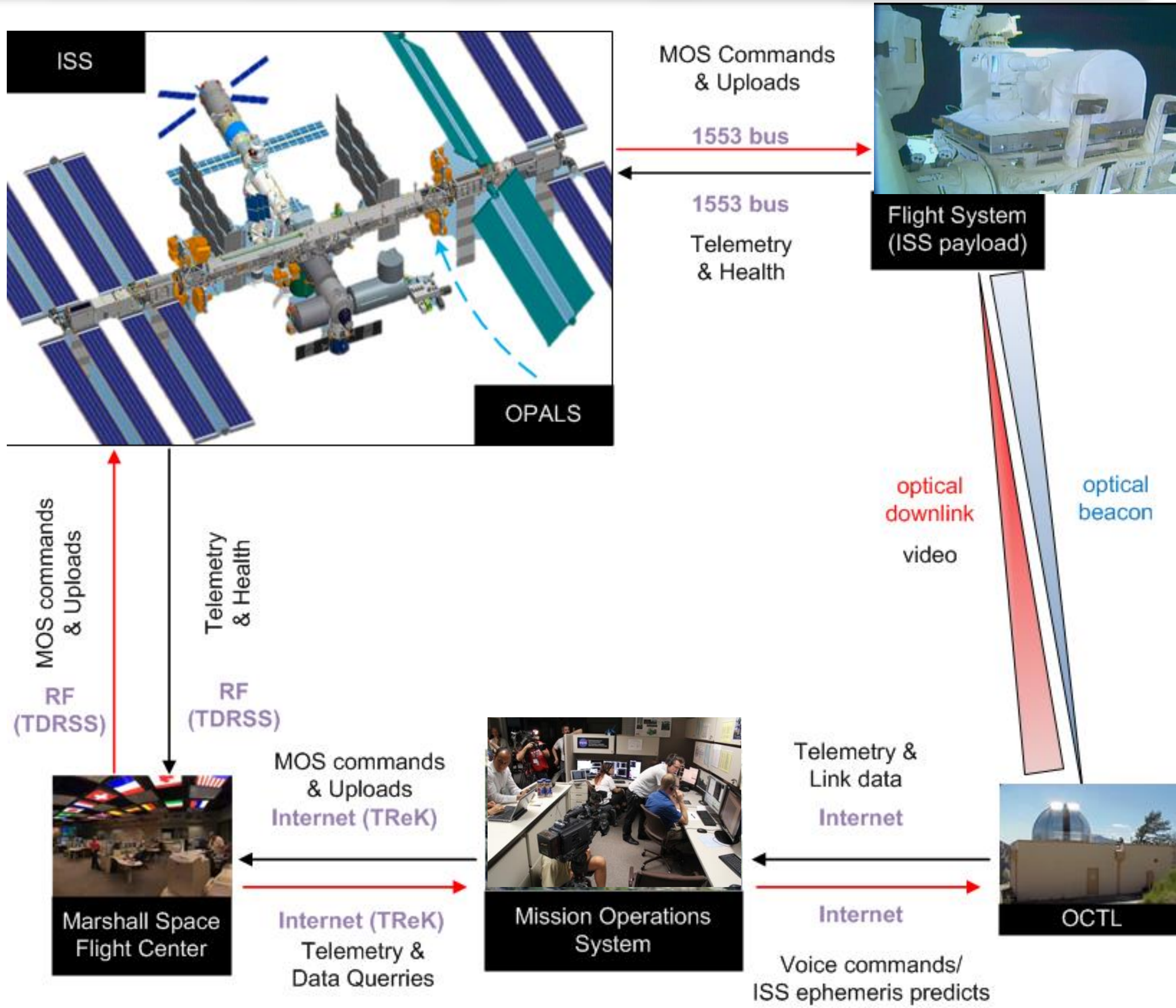


OVERVIEW Optical Payload for Lasercomm Science (OPALS)

Robotic transfer to ELC-1

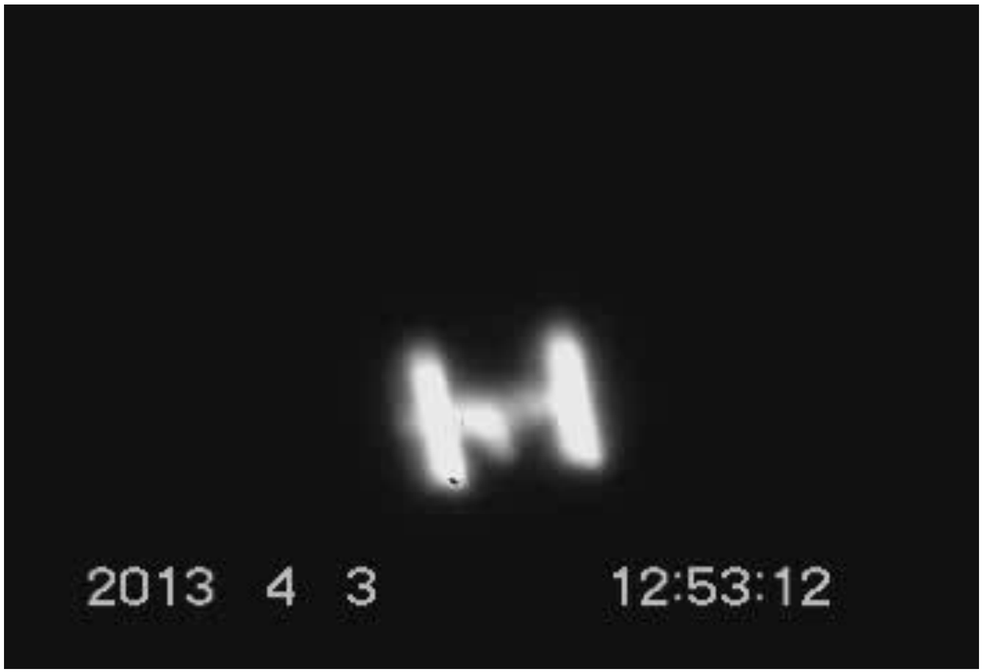
OPALS in Dragon trunk post separation

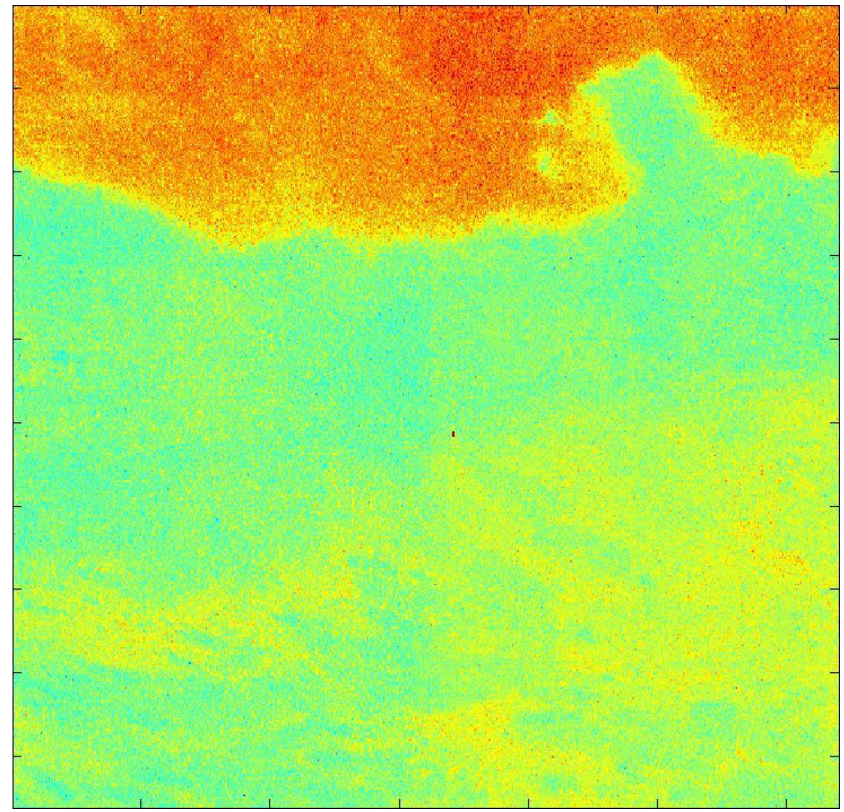
SpaceX CRS-3 Launch April 18, 2014



OPALS – Low-Earth Orbiting (LEO) Satellite

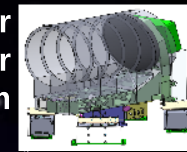
- **LEO satellites have fast slew rates (deg/s) versus (deg/hr)**
  - For communications links good tracking is required at both ends of the link
  - Since tracks literally go from horizon to horizon the air-mass changes rapidly too

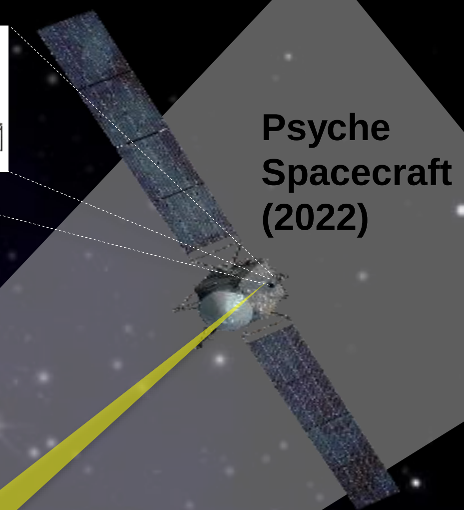




Deep Space Optical Communications

Deep-Space Optical Communications (DSOC) Concept





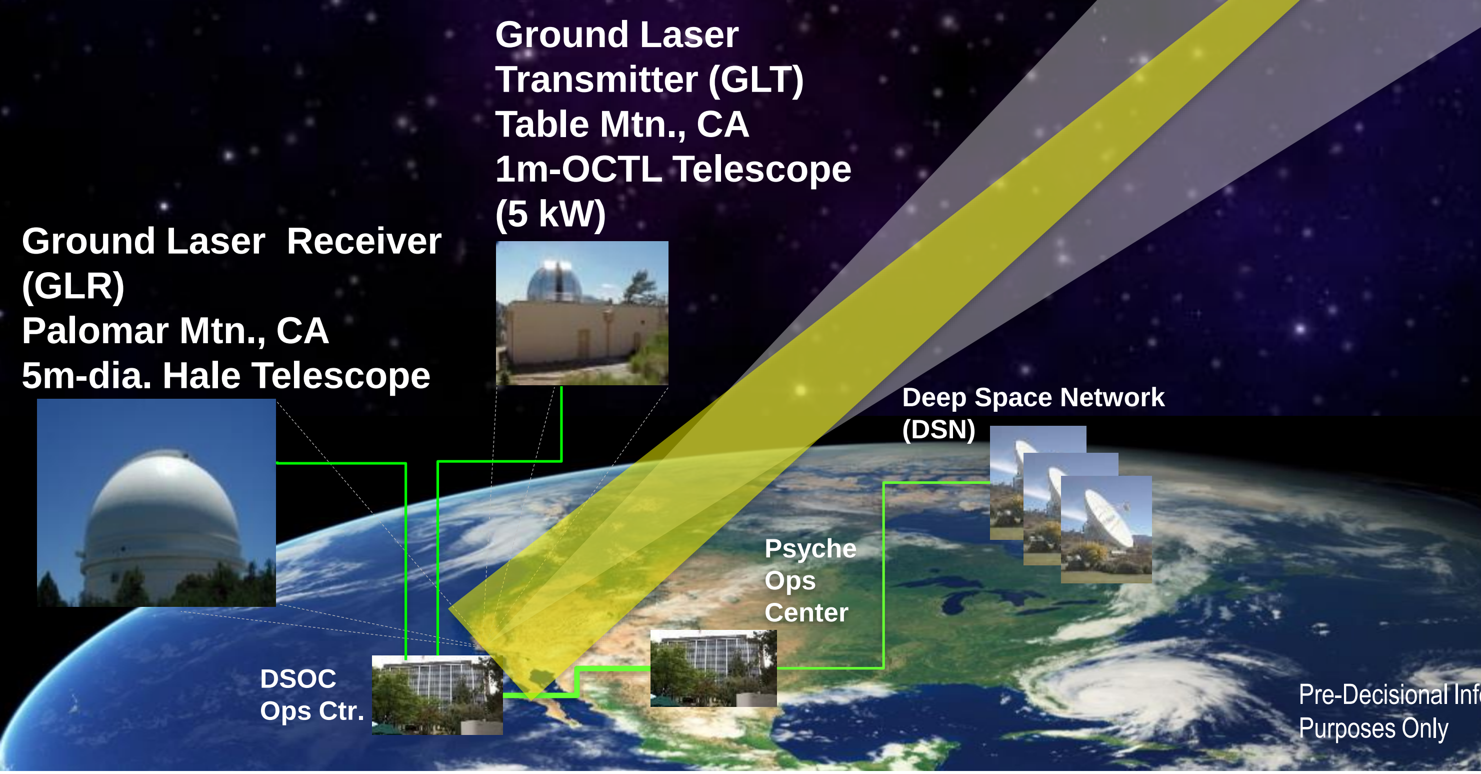
– ***OBJECTIVES:***

Advance NASA's enhanced communication goals by:

- *Demonstrate optical communications from deep space to validate:*
  - *Link acquisition/re-acquisition and laser pointing control*
  - *High photon efficiency signaling (implement emerging CCSDS standard)*

1550 nm downlink

Data-rate (Mb/s)	Distance (AU)
132	< 0.25
14	> 0.25 <1.0
2	> 1 < 2.0
0.2	> 2 <2.6

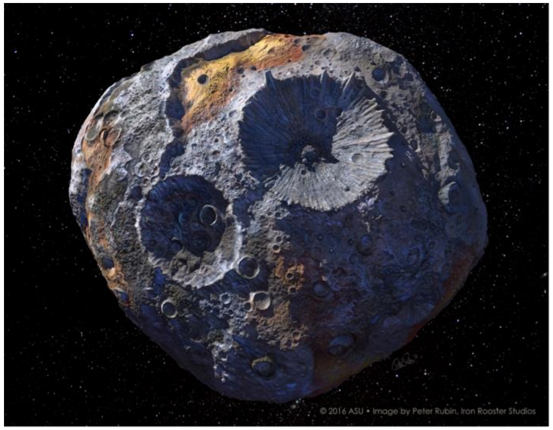


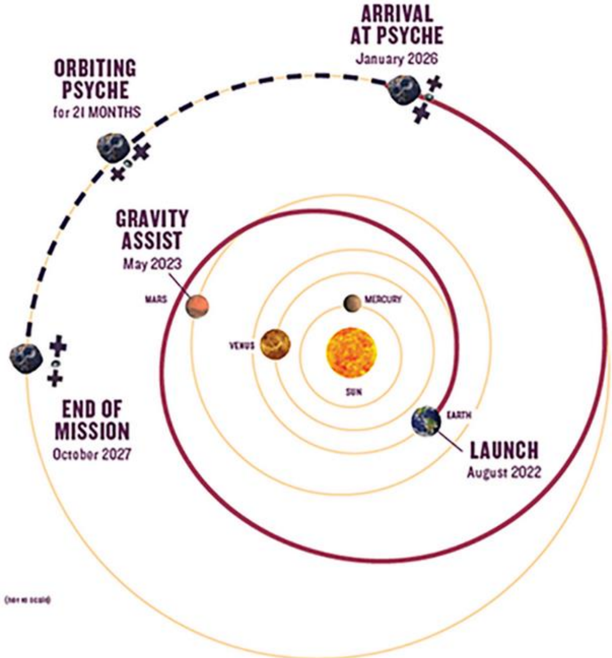
Pre-Decisional Information -- For Planning and Discussion Purposes Only

DSOC Technology Demonstration

- **DSOC tech demo planned to be hosted by Psyche Mission**
  - Selected by NASA/Discovery Program to explore the asteroid Psyche-16
  - Primary science objective is to determine whether Psyche-16 is a core or if it is un-melted material
  - Psyche scheduled for launch in summer of 2022 with a 21-day launch window
    - Trajectory uses a Mars Gravity Assist
    - 21-day launch window around August 2022

- **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 54% joint availability with seasonal variations
  - Limitations of Palomar telescope to operate in the daytime
  - Psyche trajectory

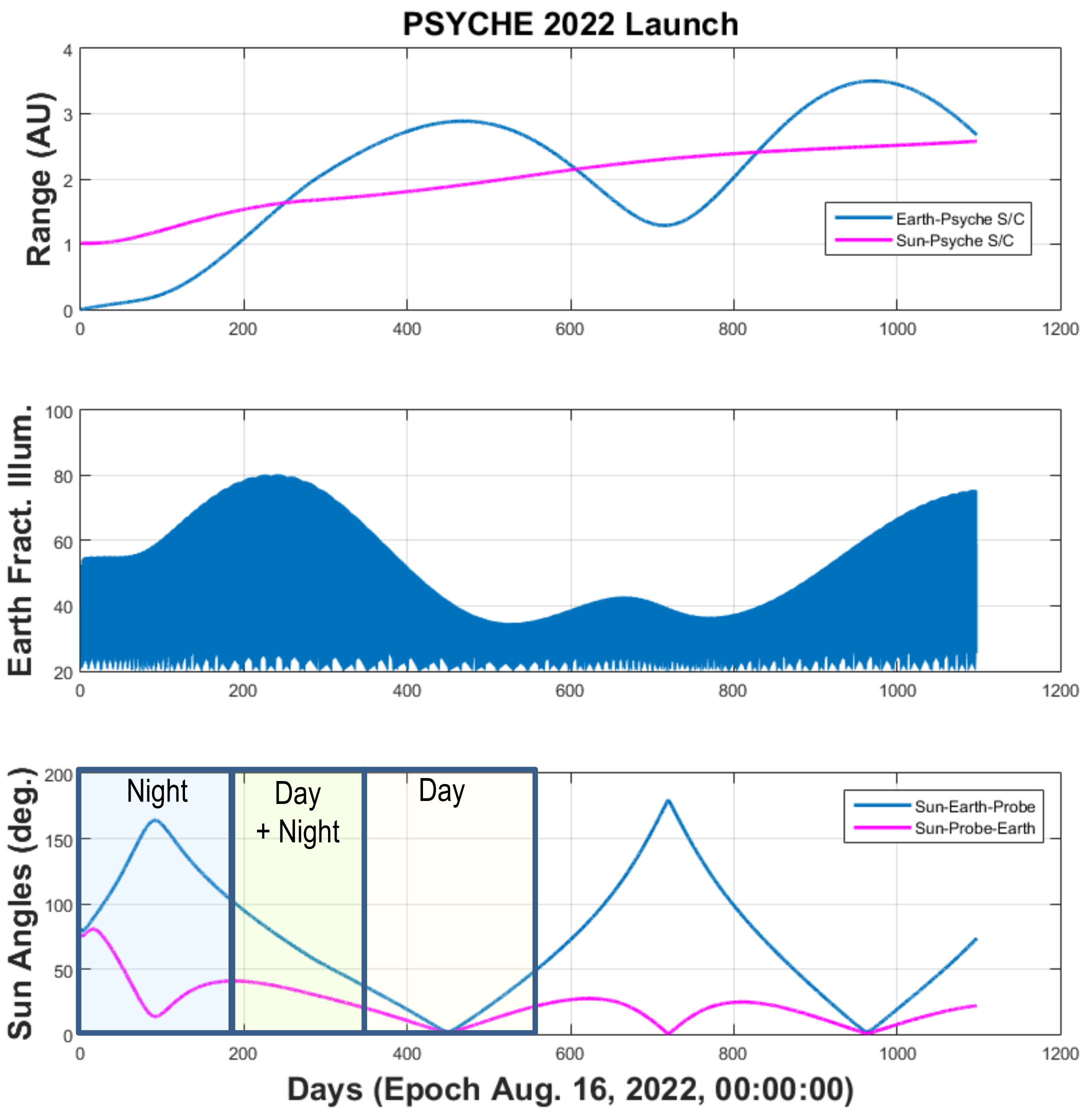




https://medium.com/the-nasa-psyche-mission-journey-to-a-metal-worldSchedule constraint

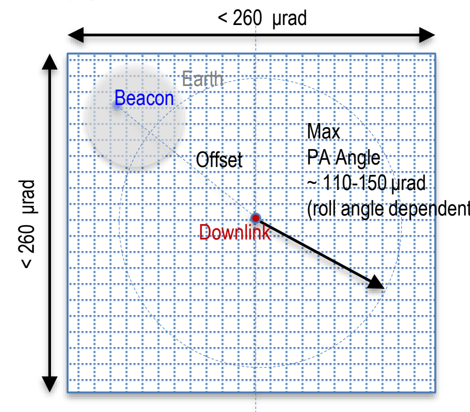
Link Conditions

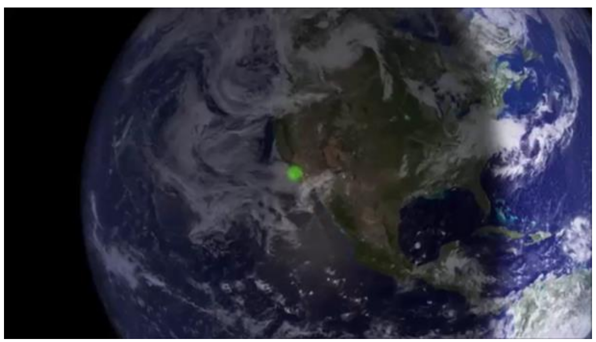
- **Psyche trajectory for observer at Palomar**:
  - Range
  - Air-mass
  - Sun angles
- **“Night” operations for nearly 250 days after launch**
- **“Day” operations restricted to TBD SEP angle**
- **Possible to meet Level 1 requirements within year from launch**
  - Likely would require two contacts per month
  - Frequency of contacts needs further analysis

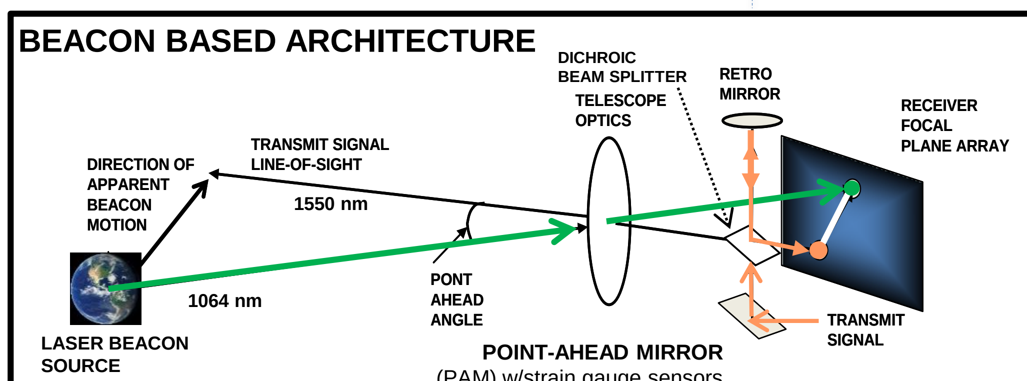


Concept of Operations

- **DSOC tech demo operations concept is under formulation**
  - Following commissioning and calibration a typical day-in-the life will involve: A
    - Transmit ground laser beacon using predicts while Psyche powers FLT and “**coarse poi**nts” to Earth
    - DSOC searches out 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 Receiver 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 may be available



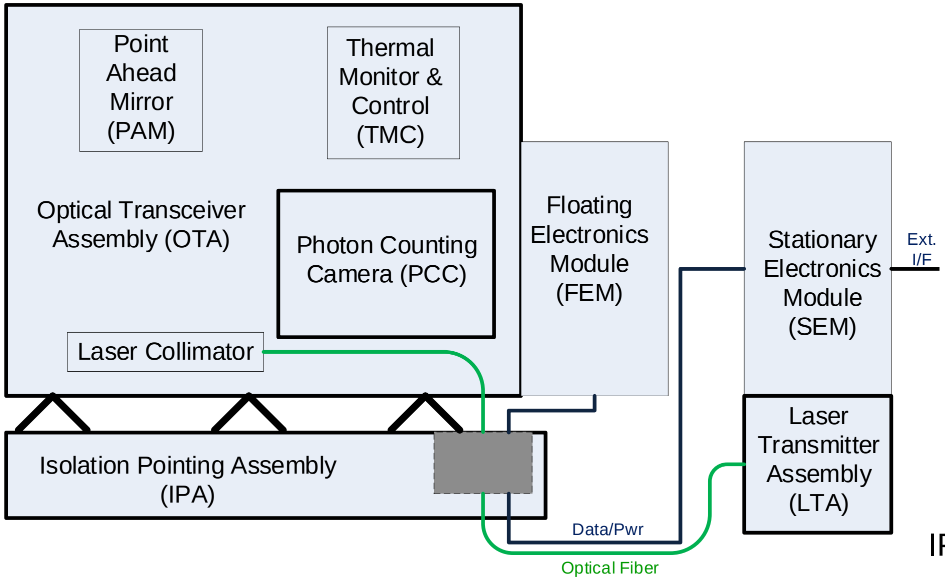


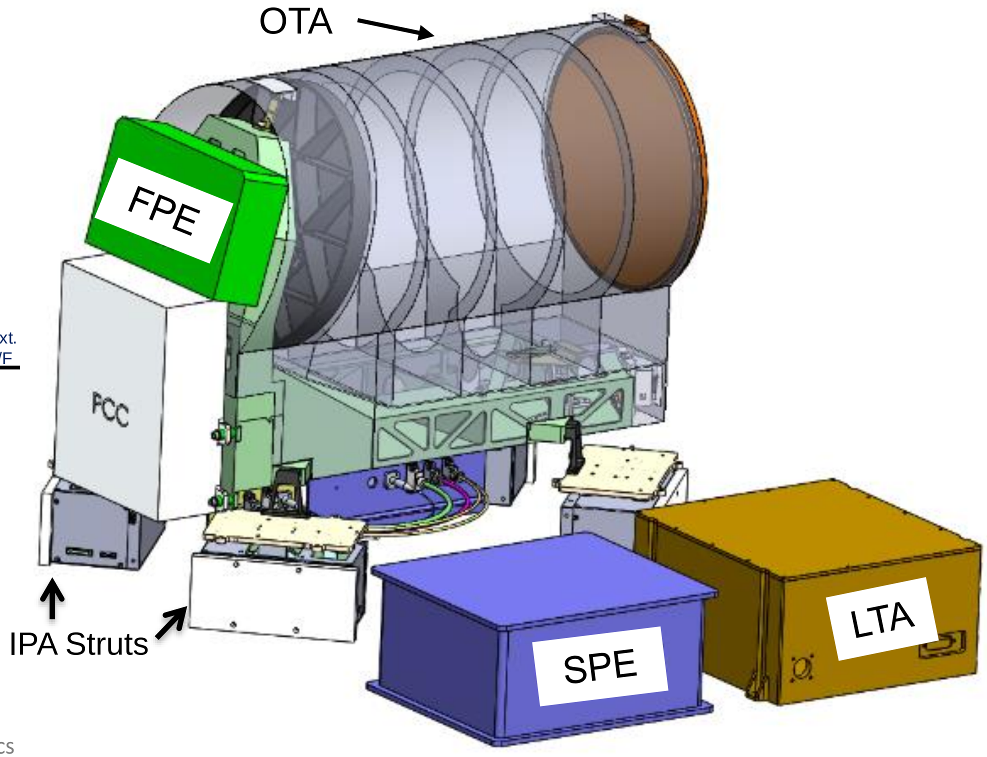


Spot offset is PAA
(For PAA > FOV
– PAM strain gauge tracks PAA
– Strain gauge calibrated with Tx spot

DSOC Flight Laser Transceiver (FLT)

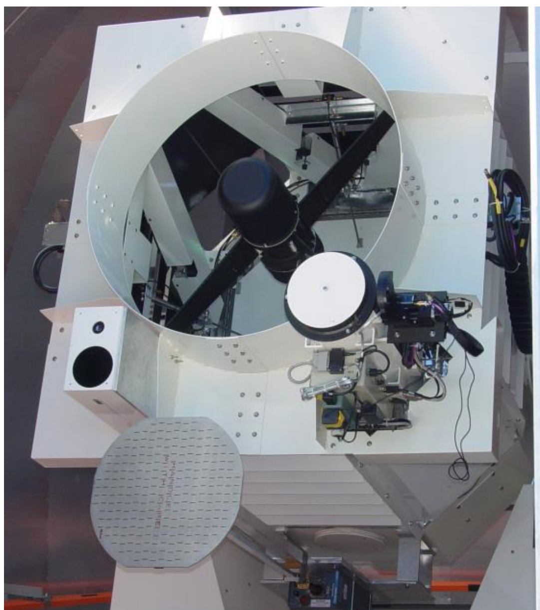
- **The Flight Laser Transceiver (FLT) makes up the flight subsystem**
  - **Silicon carbide (SiC)** Optical Telescope Assembly (OTA) receives beacon and transmits downlink
  - **Photon Counting Camera (PCC)** detects "dim" 1064 nm laser beacon transmitted from Earth
  - **Isolation Pointing Assembly (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



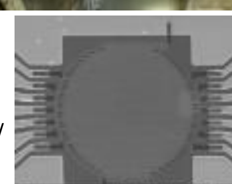


DSOC Ground Data System (GDS)

- **DSOC technology demonstration would utilize**
  - Ground Laser Transmitter at OCTL telescope near Wrightwood, CA
    - Retrofit high power (5 kW) laser transmitter @ 1064 nm
  - Ground Laser Receiver at Hale telescope at Palomar Mountain, CA
    - Tungsten silicide (WSi) superconducting nanowire single-photon detector (SNSPD) array w/signal processing electronics
  - Mission ops center for coordinating ops (not shown)



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



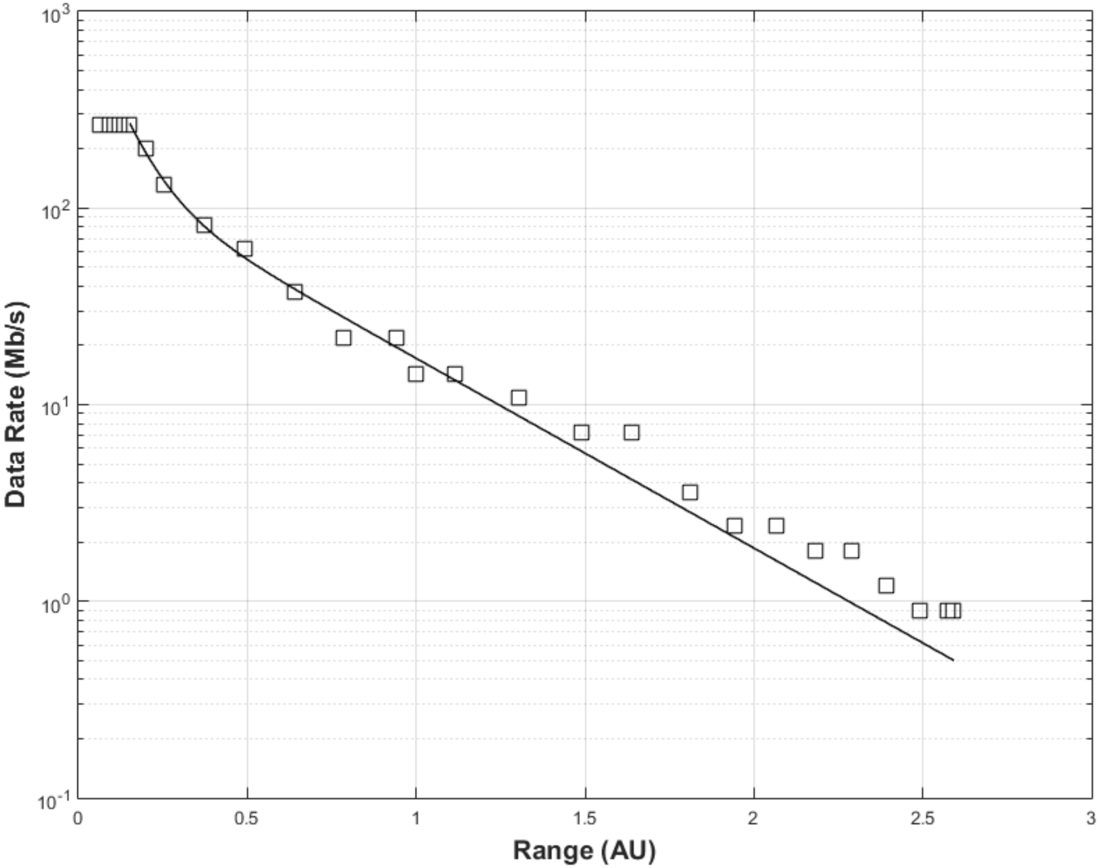
SNSPD array
(~ 320 μm
dia.)

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

Predicted Nominal Link Performance

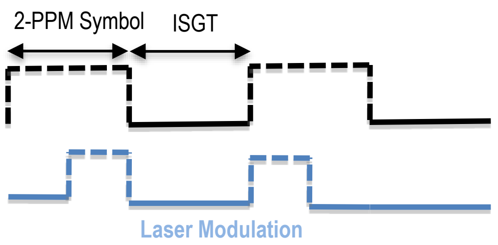
- 4 W average power laser with 22 cm diameter FLT
- Received with 5m diameter Hale Telescope and SNSPD based

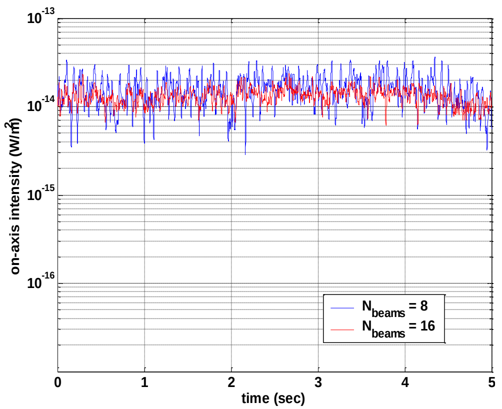
Predicted Nominal Downlink Performance



Uplink

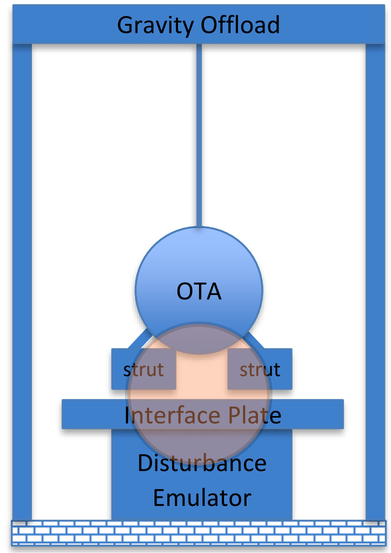
- 1.6 kb/s @ 1 AU
- ~ 4 pW/m² irradiance at FLT aperture

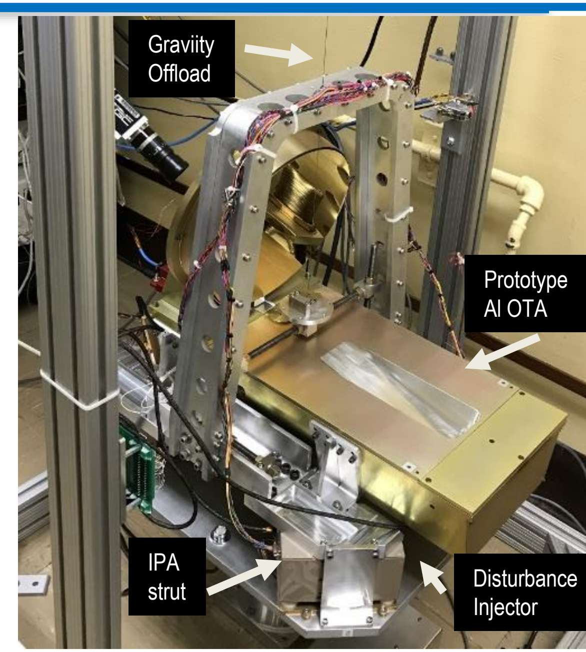


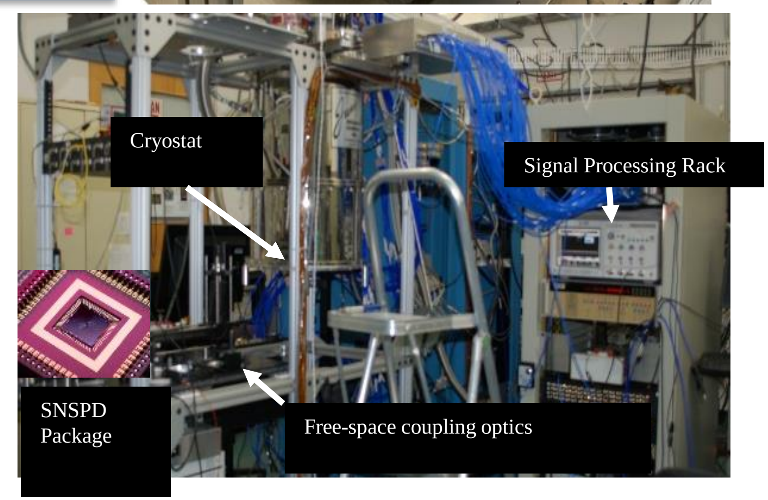


Testbed Activity Summary

- **In preliminary design phase DSOC maintains two end-to-end testbeds**
  - **Pointing and tracking testbed**
    - Gravity off-loaded OTA
    - Integrated to IPA struts
    - Overfilled with 1064 nm beacon
    - Inject base disturbance
    - Tested tracking in presence of disturbance
    - Achieved ~ 1 μrad per axis rms error
  - **Signaling testbed**
    - Generate encoded PPM signal in representative SEM
    - Modulate test fiber laser
    - Free-space couple fiber output to cryostat with SNSPD array
    - Calibrate/Attenuate incident average power to representative signal flux
    - Add background flux
    - Verified operating points including
      - 267 Mb/s, 16-PPM, 0.5 ns slot, 0.66 code rate
    - Adding fading and Doppler shifts pending



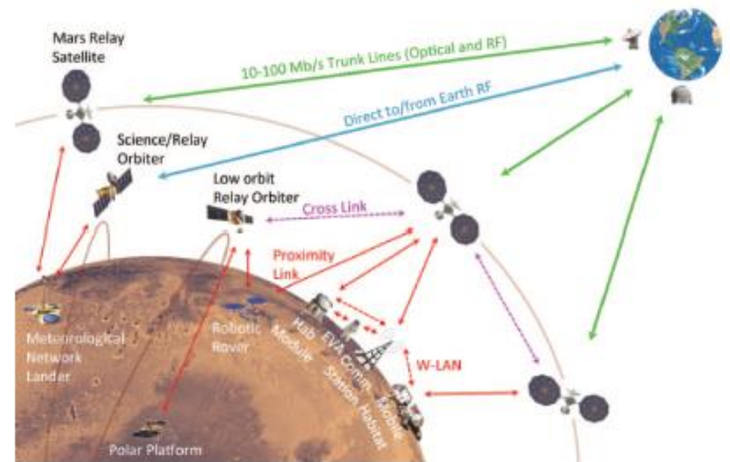




Future Systems

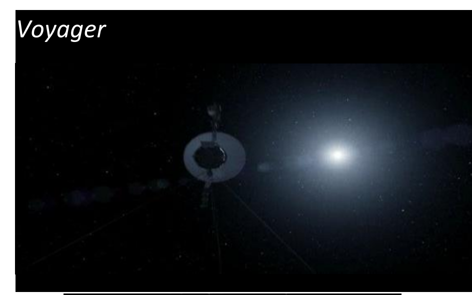
Future Deep-Space Flight Transceivers (FLT)

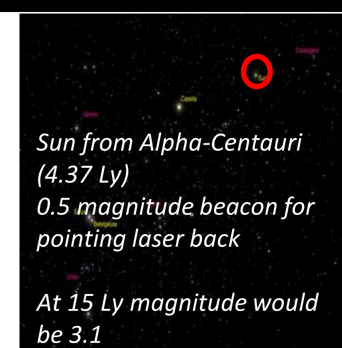
- **Enhanced longer term reliability and scaling of FLT's in post DSOC tech. demo era**
- **Mars telecommunication orbiter would likely be a near-term Infusion of technology validated by DSOC tech demo**
  - Data rates would drive for higher emitted isotropically radiated power (EIRP)
  - Relatively low-risk considered to be
    - 50 cm and 20-50 W
    - Higher effective laser power could be achieved by multiplexing >1 wavelength channel
    - Pointing and thermal challenges of operating pointing close to sun



Robert E. Lock, Charles D. Edwards Jr., Austin K. Nicholas, Ryan Woolley, David J. Bell, "Small Areostationary Telecommunications Orbiter Concepts for Mars in the 2020s," IEEE Aersospace Conference, 1-12, 2016.

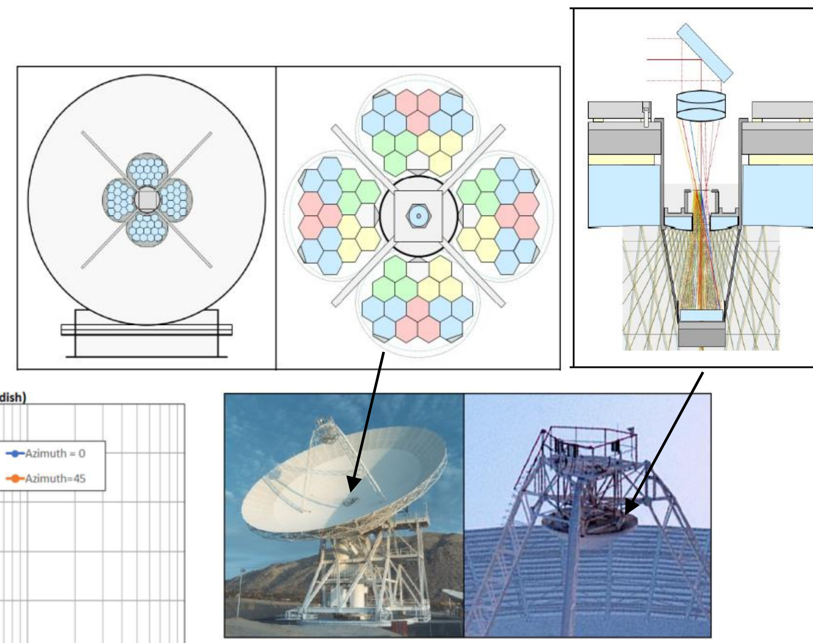
- **Even higher EIRP demands expected for farther missions**
  - For inter-stellar missions (100's of AU) – 50 cm, 100's of W average power
  - Exoplanet missions (5-15 Ly) 2.5 m aperture with 1000's of watt transmitters
  - New challenges
    - Beaconless architecture
    - Pointing, thermal, lifetime (at least 50 years for exoplanet)
    - Light time of 5-15 years???
    - Huge Doppler shifts



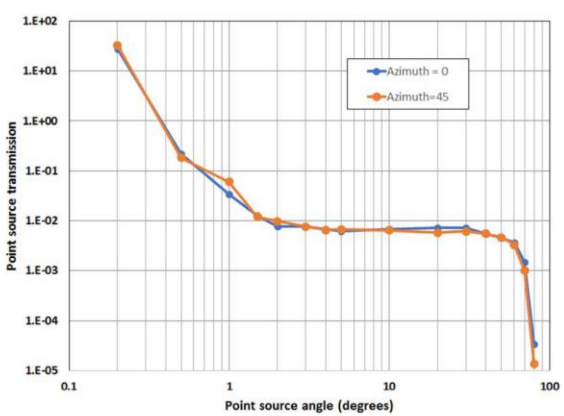


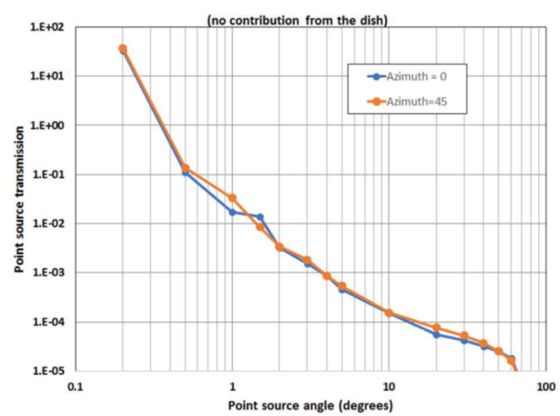
Future Ground Assets

- **Ground infrastructure for deep space optical communications is lacking**
  - Severe impediment to operations even from Mars ranges
  - Astronomical assets not the right answer beyond tech. demos
- **For relatively low investment retrofitting optical surface to existing RF antennae being studied at JPL**
  - ~ 8 m aperture with spherical figure (actively maintained with edge sensors)
  - Recently studies stray light for dome-less concept
  - Stray light analysis
    - Surfaces in vicinity of mirror pods contribute worst stray light
    - Eliminating this surface provides acceptable stray light
  - Possible solution is use of a specially designed Lyot stop
    - 75% reduction in effective aperture from practical implementation constraints
    - Reduced aperture of ~ 6 m at shallow sun-earth-probe (SEP) angles of TBD –to-10 degrees



DSN 34-m antenna





Summary

- **Advances in space laser communications over past two decades**
- **JPL has participated in these demonstrations with important lessons learned**
- **Reported status of DSOC technology demonstration**
- **Pointers to future developments driven by likely near and longer term demands**
- **Near Term**
  - Enhanced longer term reliability flight transceivers
  - Larger EIRP achievable by relatively low-risk scaling for Mars and outer planets
  - Possible low investment RF-Optical Hybrid systems
- **Long term**
  - Orders of magnitude higher EIRP flight transceivers
    - Lasers challenged, lifetime, high power, power and thermal management
  - Earth receiving apertures not addressed