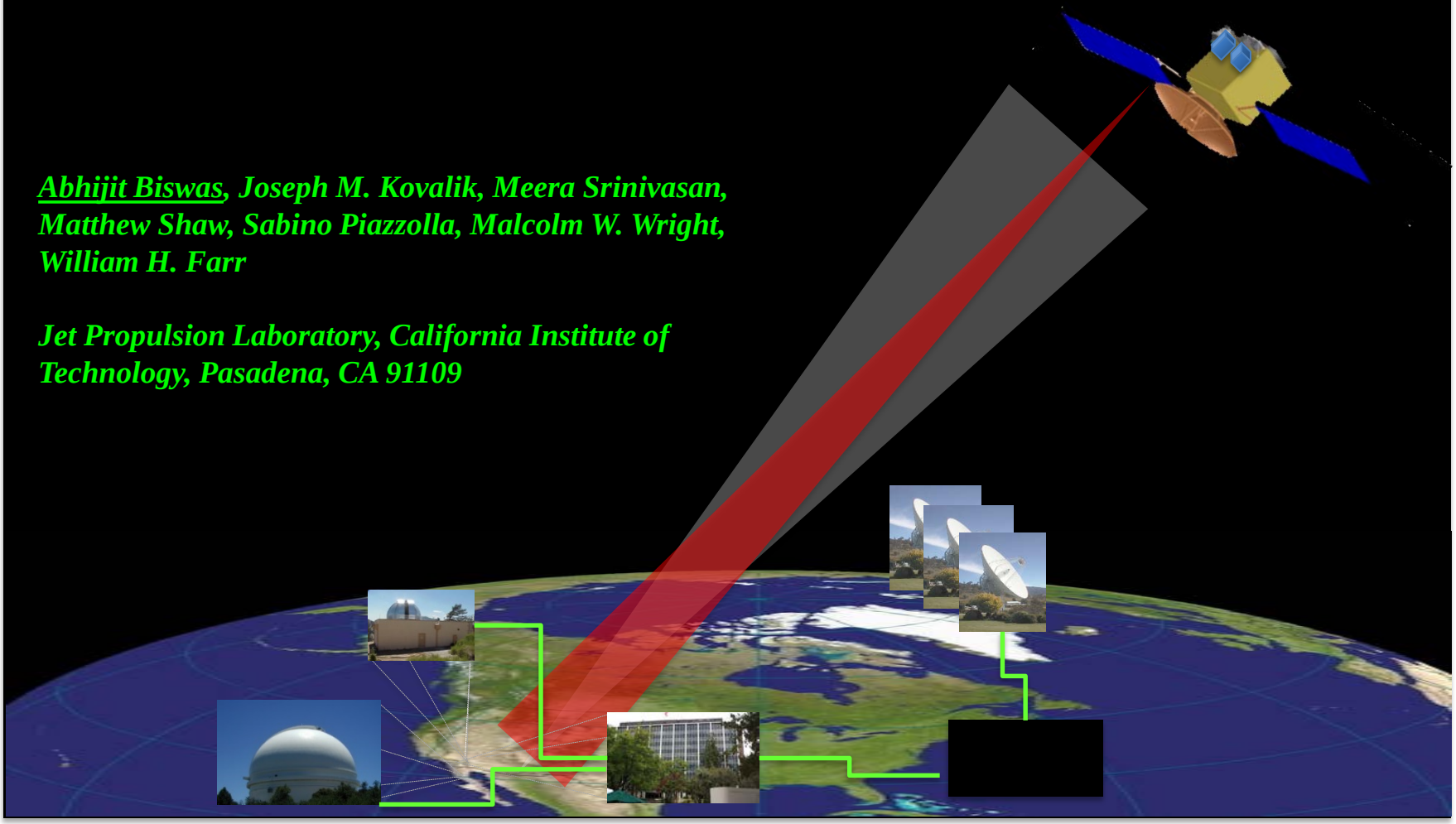
DEEP SPACE OPTICAL COMMUNICATIONS

Abhijit Biswas, Joseph M. Kovalik, Meera Srinivasan, Matthew Shaw, Sabino Piazzolla, Malcolm W. Wright, William H. Farr

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109



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Outline

- Introduction
- System architecture
- System performance
- Flight technology Development
- Ground technology development
- Discussions and conclusion

Introduction

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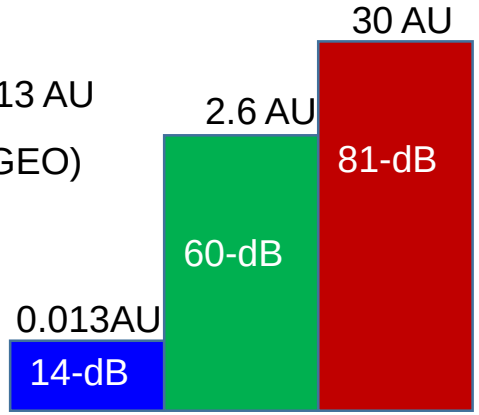
- **Successful space-to-ground technology demonstrations have been completed**
  - Past two decades
- **A number are planned toward the latter part of this decade**
- **The farthest range has been lunar with the Lunar Laser Communication Demonstration (LLCD)**
- **NASA is planning a deep-space technology demonstration of laser communication**
  - In radio frequency** communications deep-space is considered to be 0.013 AU
  - The Deep-space network services missions beyond geostationary orbit (GEO)
  - Link difficulty (Mb/s per AU^2) increases with increasing distance
  - Pursuing technologies to address link-difficulty out to approximately 3 AU
    - Progress report on sub-set of these technologies
      - Other papers will cover some other technology development
  - Extension to farther ranges beyond 3 AU will be pursued in the future
    - Inclusion of *laser ranging* and *light science* (optical equivalent of radio science) is also anticipated



Link difficulty per Mb/s relative to Lunar range

** *Radio Frequency and Modulations Systems – PART 1 EARTH STATIONS AND SPACECRAFT, Consultative Committee for Space Data Systems (CCSDS), Blue Book, September 2005.*

System Architecture

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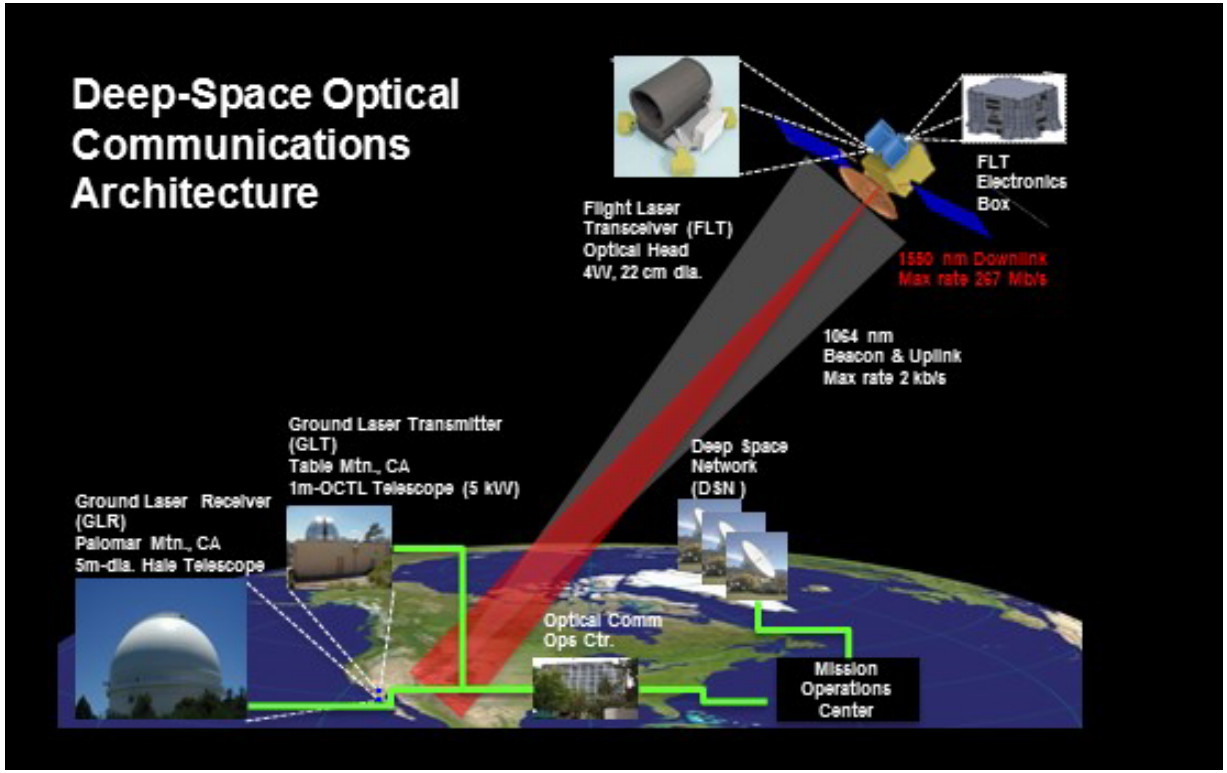
- **Beacon based architecture using existing ground assets for cost-effectiveness**
  - Beacon laser beam serves as
    - A pointing reference
    - Low-rate uplink data carrier
    - Requires sensitive detector to detect dim beacon from deep-space range
  - Downlink is serially concatenated pulse position modulation (SCPPM)
    - Received with a photon-counting detector array retrofitted to 5 m diameter Hale telescope
- **Link demonstration constraints**
  - Ground Laser Receiver restricted to approx. 12° sun-earth-probe (SEP) angle
    - Can result in long link outages
- **Likely target missions for deep-space laser comm technology demo**
  - Venus
  - Asteroids
  - Sun-Earth Lagrange



System Performance (Downlink)

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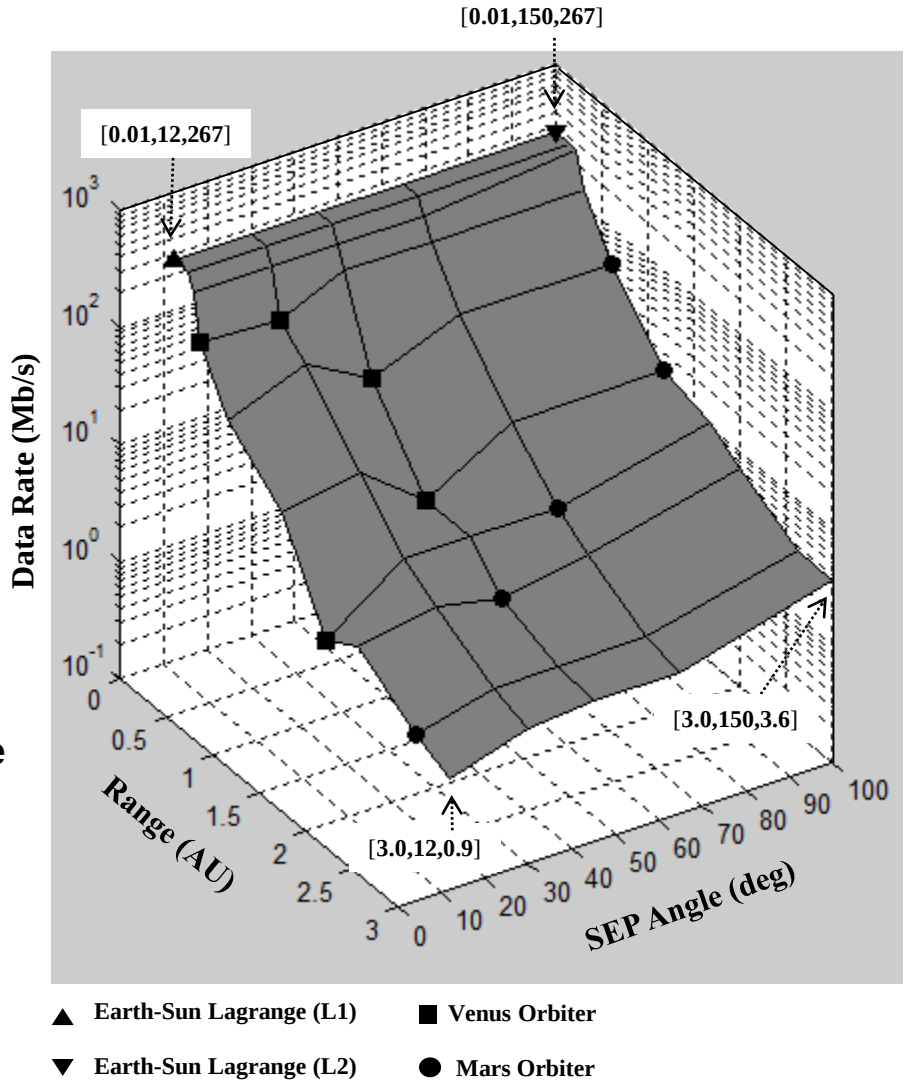
- **A summary of expected optical performance was derived**
  - Max range 3 AU
  - 1550 nm
  - 4 W laser average power
  - 22-cm aperture diameter
  - Serially concatenated pulse position modulation (SC-PPM)
  - Inter-symbol guard time (ISGT) 25%
  - Discrete code-rates 0.33,0.5,0.66
  - 1.18 dB pointing loss
  - Nominal atmospheric conditions
  - 60° zenith angle
  - r0 (day) = 3.6 cm
  - r0 (night) = 5 cm
  - Min Sep 12°
  - 5 m dia. ground collector
  - 70% photo-detection efficiency
  - Detector dia. 320 μm
  - Detector FOV < 50 μrad
  - Night operating points shown as SEP = 100°
  - At 0.01 AU 25-30 dB link margin
  - At all other ranges 3-4.5 dB margin
- **Subset of the grid points notional for particular space destinations**
  - Marked on plot
  - Unmarked points can be considered to be cruise to these or other destinations
- **6-dB penalty from 12° SEP to night time**
  - If FOV for collecting signal were reduced most or all of this penalty could be recovered



	RANGE (AU)			
SEP (deg)	0.01	0.158	0.228	0.3
12	267	267	200	82
30	267	267	200	76
45	267	267	200	132
65	267	267	200	132
150	267	267	267	132

	RANGE (AU)					
SEP (deg)	0.6	1.18	1.7	2	2.62	3
12	28	10.9	1.8	2.7	1.2	0.9
30	50	14.4	5.4	3.6	1.8	1.4
45	25	5.4	5.4	2.7	1.8	1.6
65	50	14.4	5.4	3.6	1.8	1.6
150	50	14.4	11	7.2	3.6	3.6

System Performance (Uplink)

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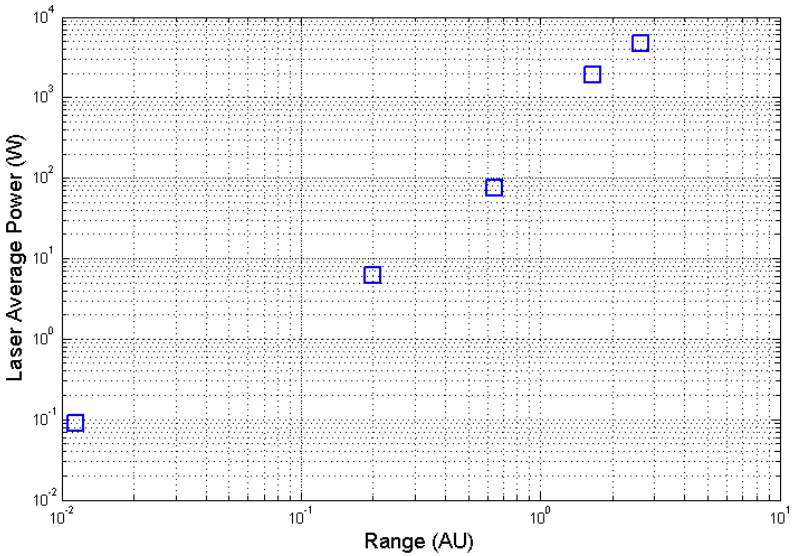
- **Beacon laser must deliver irradiance at Flight Laser Transceiver (FLT) aperture**
  - Acquisition and tracking
  - Low density parity check (LDPC) coded uplink @ ~ 2 kb/s
  - 1 – 4 pw/m^2 is required including 3-dB margin for the uplink data-rate
  - Derived average ground laser power @ 1064 nm required to satisfy the irradiance



  - Estimate as high as 5 kW of laser power is required to satisfy irradiance at 3 AU
    - Also depends on the accompanying sun-probe-earth angle (SPE)

FLT Technology Maturation

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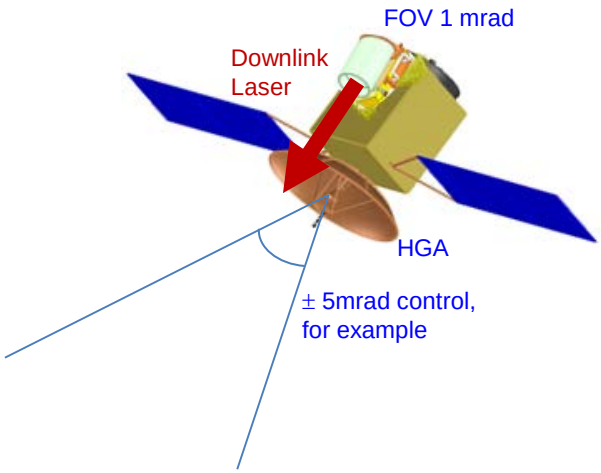
- **Concept of operations (CONOPS) assumes spacecraft body mounted FLT**
  - Spacecraft pointing for radio frequency High Gain Antenna (HGA)
    - Serves as coarse pointing for FLT
    - FLT must search for beacon
    - Acquire and track beacon
    - Point ahead to GLR using on-board ephemeris



- **Key enabling technologies for deep-space CONOPS**
  - Isolation & Pointing Assembly
    - Reject high frequency vibrational disturbance
  - Space Photon Counting Camera
    - Sensitive to dim beacon at pW/m2 level irradiance at aperture
  - Laser Transmitter Assembly
    - High peak-to-average power ratio
  - Single Photon-counting ground detectors
    - Detect faint signal collected by large apertures (> 5m) on ground
- **Technologies integrated with optics, electronics and Ground Support Equipment**
  - TRL-6 FLT to be tested in representative environment, topic of future paper
- **In this presentation we report on progress for the following:**
  - Laboratory tests of acquisition/tracking/pointing to validate the architecture at TRL-4
  - Ground photon-counting detectors
  - Ground signal processing
  - Future developments and technology drivers

Acquisition Tracking and Pointing Emulation

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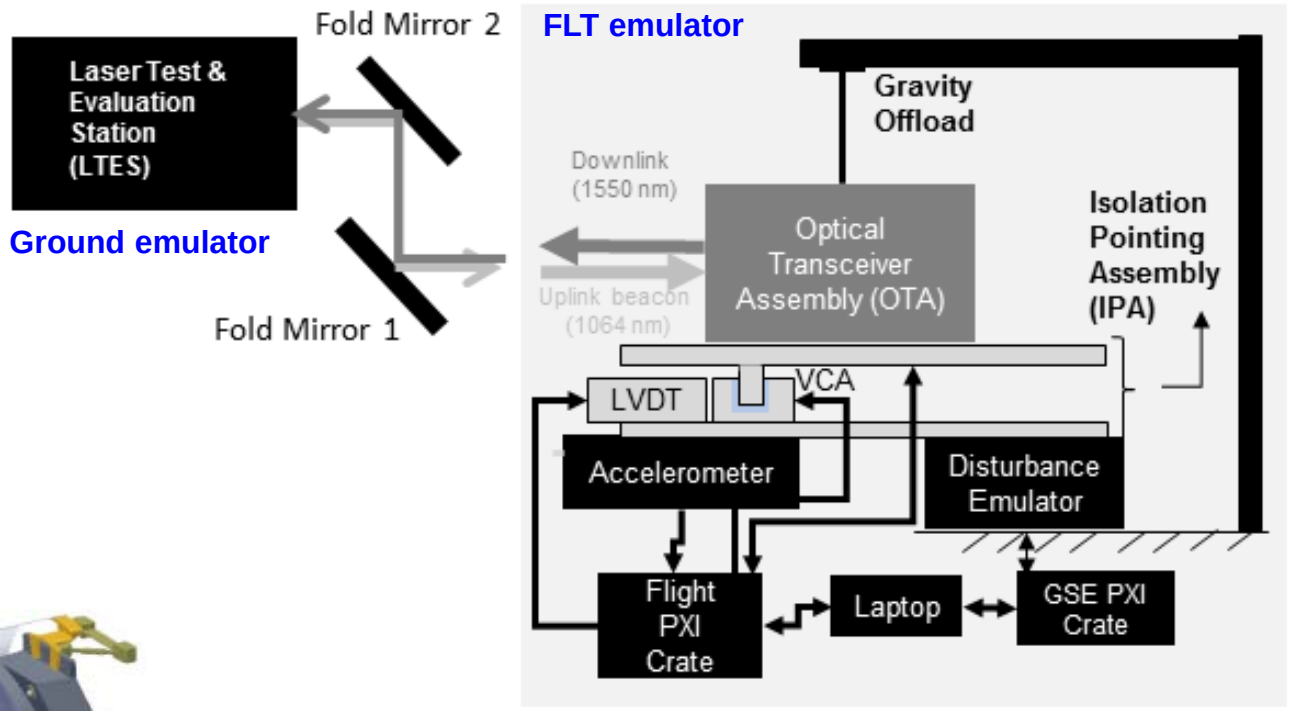
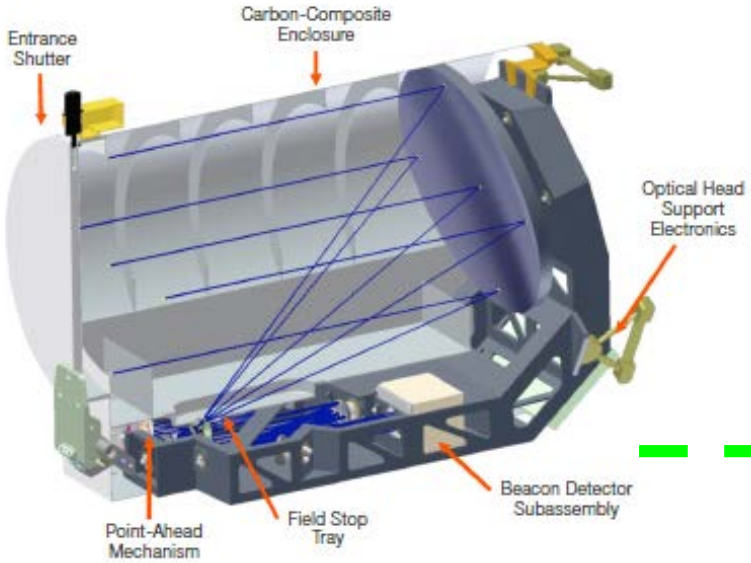
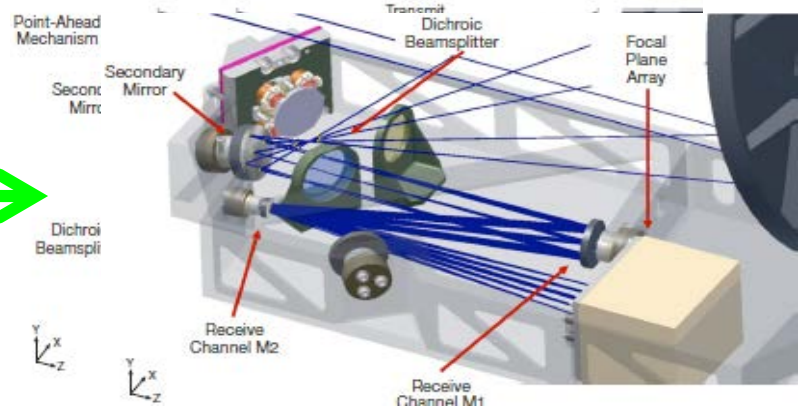
- FLT emulator consist of the OTA integrated to voice coil actuator (VCA) and linear variable voltage transformer (LVDT) sensor based IPA
- A gravity off-load is used
- The Ground emulator delivers a 1064 nm beacon
- The FLT steers itself to acquire and lock to the beacon
- Points downlink with point-ahead



Optical Transceiver Assembly





Video Description

FLT Test Results

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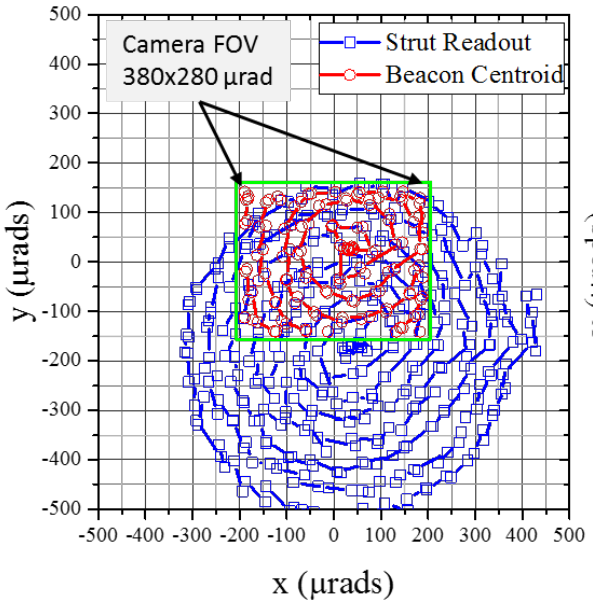
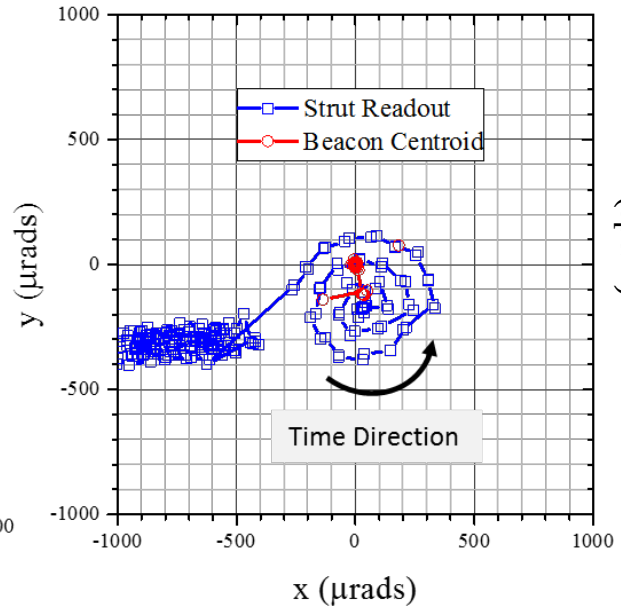
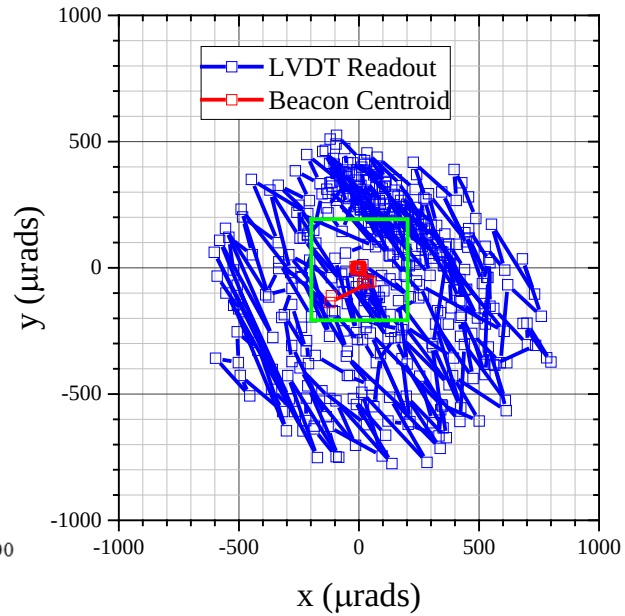
- **Hexagonal spiral step stare scan without excitation**
  - Start scan in LVDT mode, switch to beacon tracking
  - Engage low frequency servo boost
  - FLT focal plan FOV is shown relative to IPA FOR
  - Beacon tracking with and without excitation shows the large motion in LVDT relative to beacon



NO EXCITATION
SCANNING
(50-µrad steps)



NO EXCITATION
SCANNING/TRACKING
(100-µrad steps)



EXCITATION
BEACON TRACKING
(100-µrad steps)

First order validation IPA assisted search, acquisition and beacon tracking

FLT Test Results (cont.)

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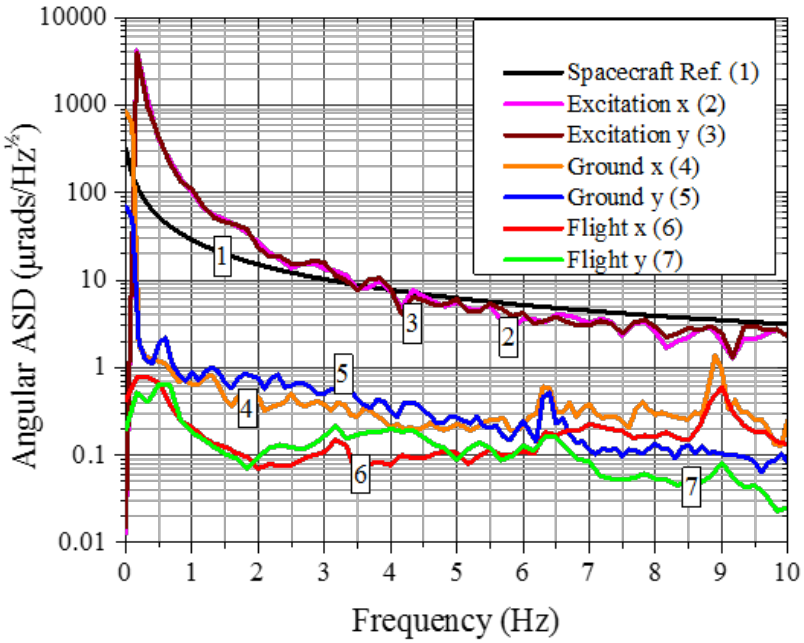
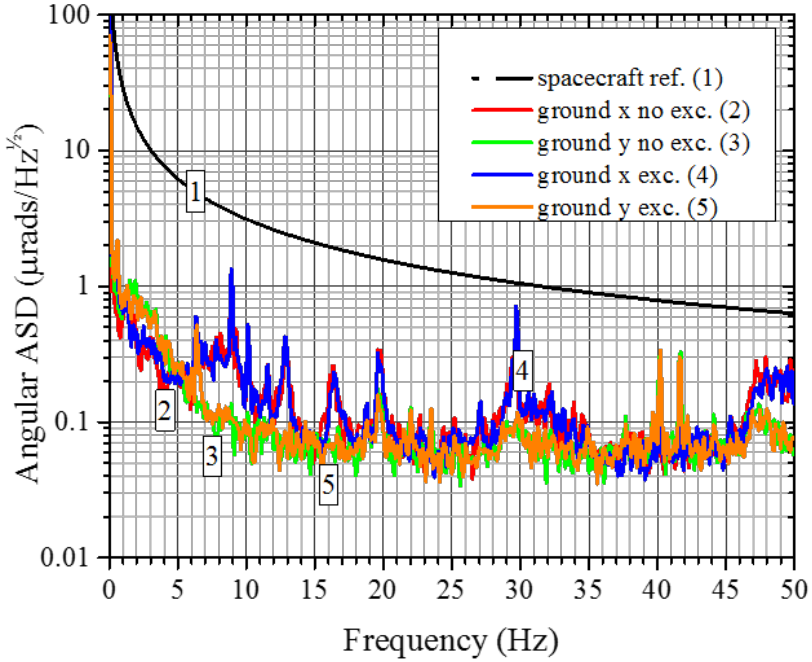
- **Compared allocated spacecraft disturbance spectral density to excitation**
  - Excitation measured with accelerometers
  - Centroid motion of beacon on FLT focal plane
  - Centroid motion of downlink on ground emulator focal plane
  - Note that spot motion on ground emulator nosier than beacon on FLT focal plane
  - 70 dB @ 250 mHz; 30 dB < 10 Hz





Disturbance suppression with IPA

FLT Test Results (cont.)

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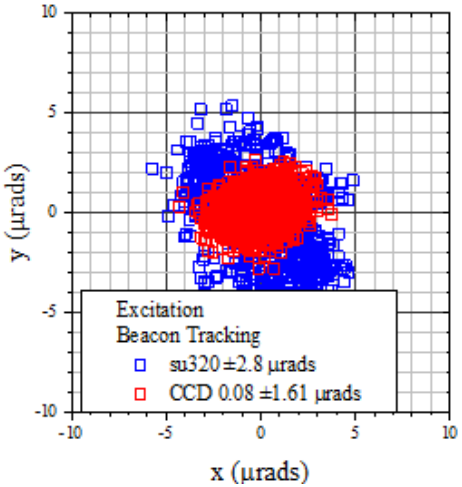
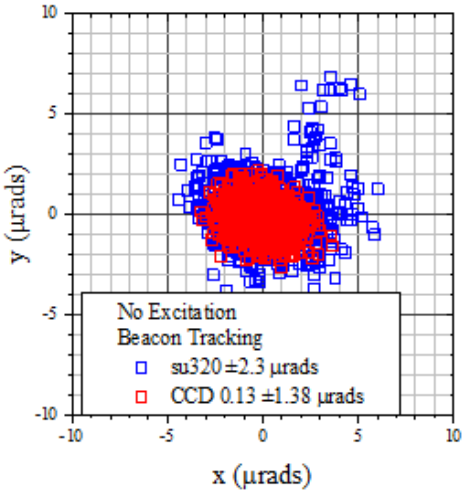
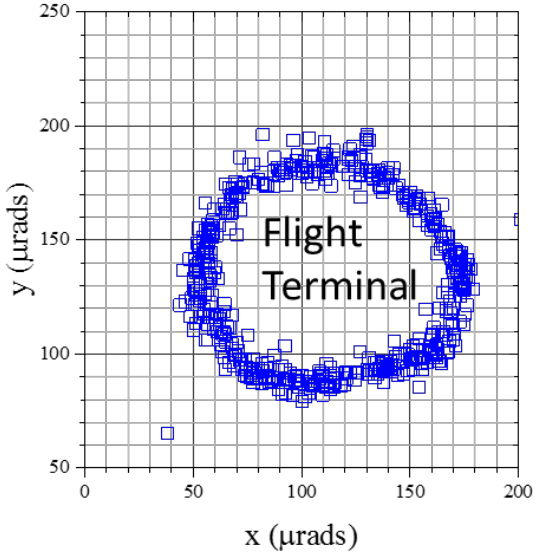
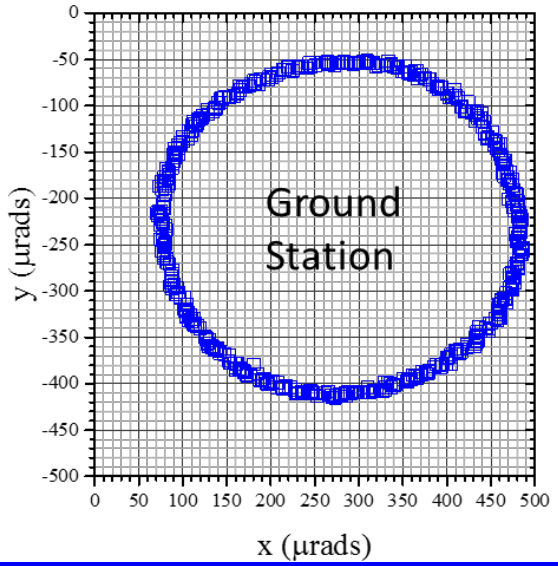
- **Scatter plots comparing the residual jitter:**
  - Beacon motion on FLT focal plane
    - 1.6 μrad rms with excitation & 1.4 μrad rms without excitation
  - Downlink motion on ground emulator focal plane
    - 2.8 μrad rms with excitation & 2.3 μrad rms without excitation
  - Systematic environmental noise (air-currents, seismic, gravity off-load) limit floor
- **Demonstrated ability to point downlink**
  - Used Si photon-counting camera
  - Retro-reflected split fraction of 1550 nm downlink on FLT FPA
  - Downlink spot on ground emulator FPA
  - Driving point ahead mirror in circular motion





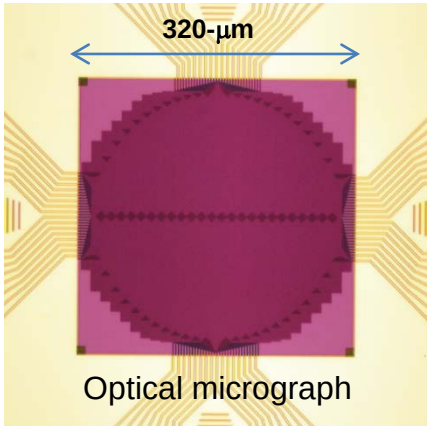


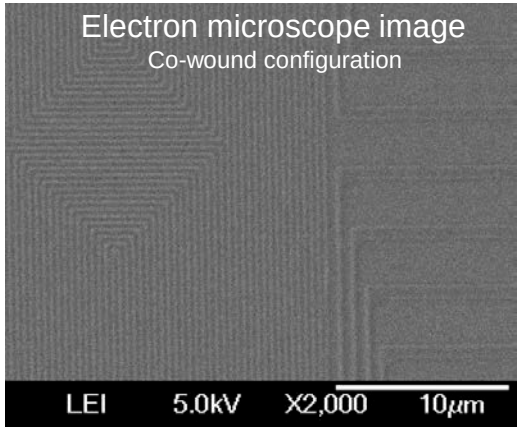


Initial verification of tracking and pointing, ongoing efforts to improve noise

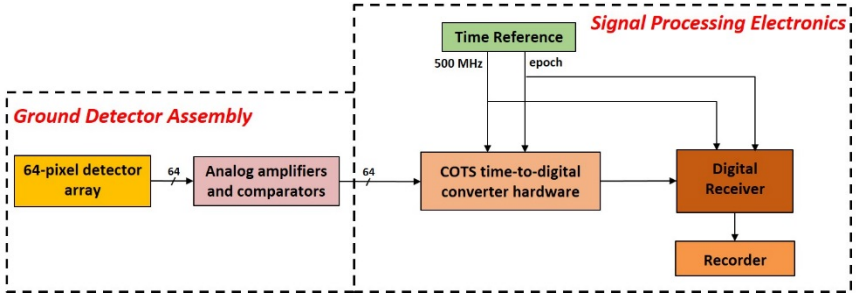
Ground Development

- **Tungsten silicide (WSi) superconducting nanowire single photon detectors (SNSPD)**
  - Under development for detecting faint deep-space signal
  - Operate at **780 mK** counting photons by transition from and to super-conducting state
  - Single pixels (single mode fiber coupled) have demonstrated **93%** detection efficiency (DE)
  - 12-pixel array was used to support Lunar Laser Communication Demonstration downlink at NASA's alternate ground station located at Table Mountain, CA
  - For 5m Hale telescope **320 μm** diameter detector is required
    - Targeted DE **70%** with free-space coupling
    - 150 ps jitter
    - Count rates of 15 Mcps per wire
    - Quad configuration to aid spatial tracking
  - Analog signal transfer to 40K stage
    - Digitized or routed out of cryostat using flex circuits





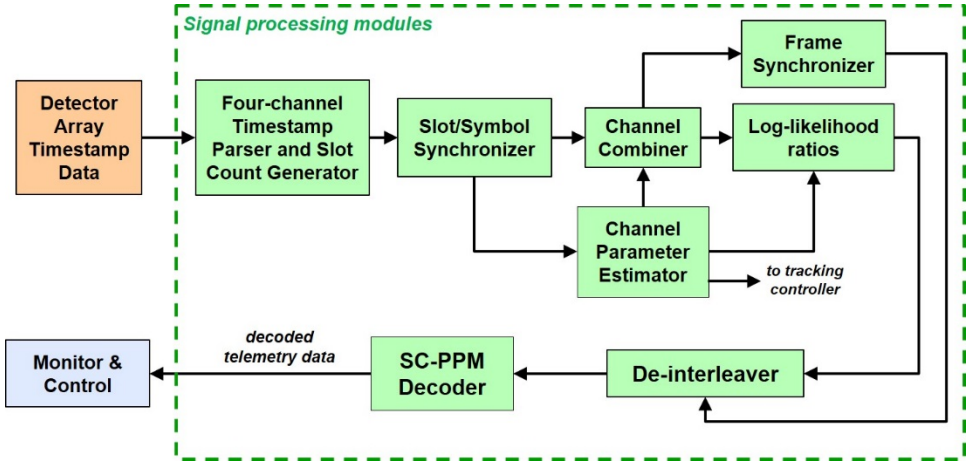
- **Developing signal processing electronics**
  - Conventional detector readout architecture demanding in bandwidth
  - Pursuing commercial multi-channel time-to-digital converter that outputs photon-arrival timestamps
    - 166 ps resolution
    - 3 samples per slot at highest downlink rate
    - 1.5 Gcounts per second, adequate for downlink

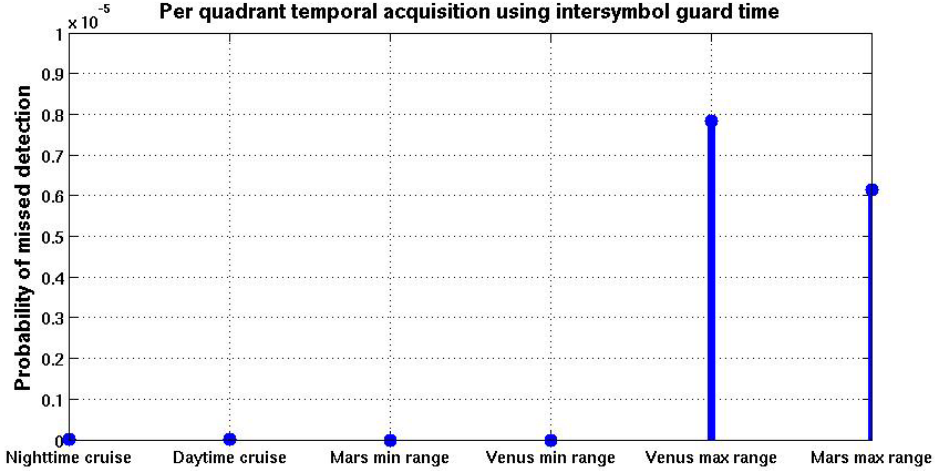


Ground detector and signal processing implementation plans are base lined

Ground Development (cont.)

- **Signal processing functions**
  - Synchronize PPM slots, symbols, codeword frames
  - Produce channel parameter estimates
  - Deliver log-likelihood ratios
  - De-interleave, decode
  - Use software post-processing receiver initial laboratory validation
  - Real-time receiver to be developed for flight demonstration using FPGA's and GPUs
  - Functions are in various stages of verification through simulation
    - Example, probability of missed detection analysis
    - Signal can be acquired > 99.9% of the cases





Signal processing algorithms being verified through simulation

Conclusions with closing thoughts

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- **Progress report on JPL developments targeting flight technology demonstration of deep-space laser communications**
  - Retires major risks for deep-space mission implementation
- **Scope of mission limited by use of existing ground astronomy assets**
  - Compete for time with astronomers
  - Not designed for extended periods of operating at small sun-angles
  - Ideally 8-12 m diameter effective apertures can provide a robust deep-space optical service
- **Distances beyond 3 AU especially beyond Saturn need further study**
  - Re-visit the architecture
  - Celestial beacons, how close to the sun can these be used effectively
  - Laser lifetimes and powers need to be considered
  - Develop reliable lasers to operate for 40-years?
  - Multi-kW peak powers without detrimental effects – fiber-based, hybrid, other?
- **State-of-art deep-space telecom systems provide tracking products**
  - Expect future optical communication to provide this as well
  - Possible to explore “new-physics” with light science (optical equivalent of radio science)
- **Optical-only telecom systems need to handle safe mode operations when spacecraft does not or cannot assist in laser pointing**
- **A number of developments pending for laser communications to embrace the scope of deep-space operations**
  - The transition to optical from data-rate and lower burden standpoint is compelling !

The work described was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology under contract with the National Aeronautics and Space Administration (NASA).