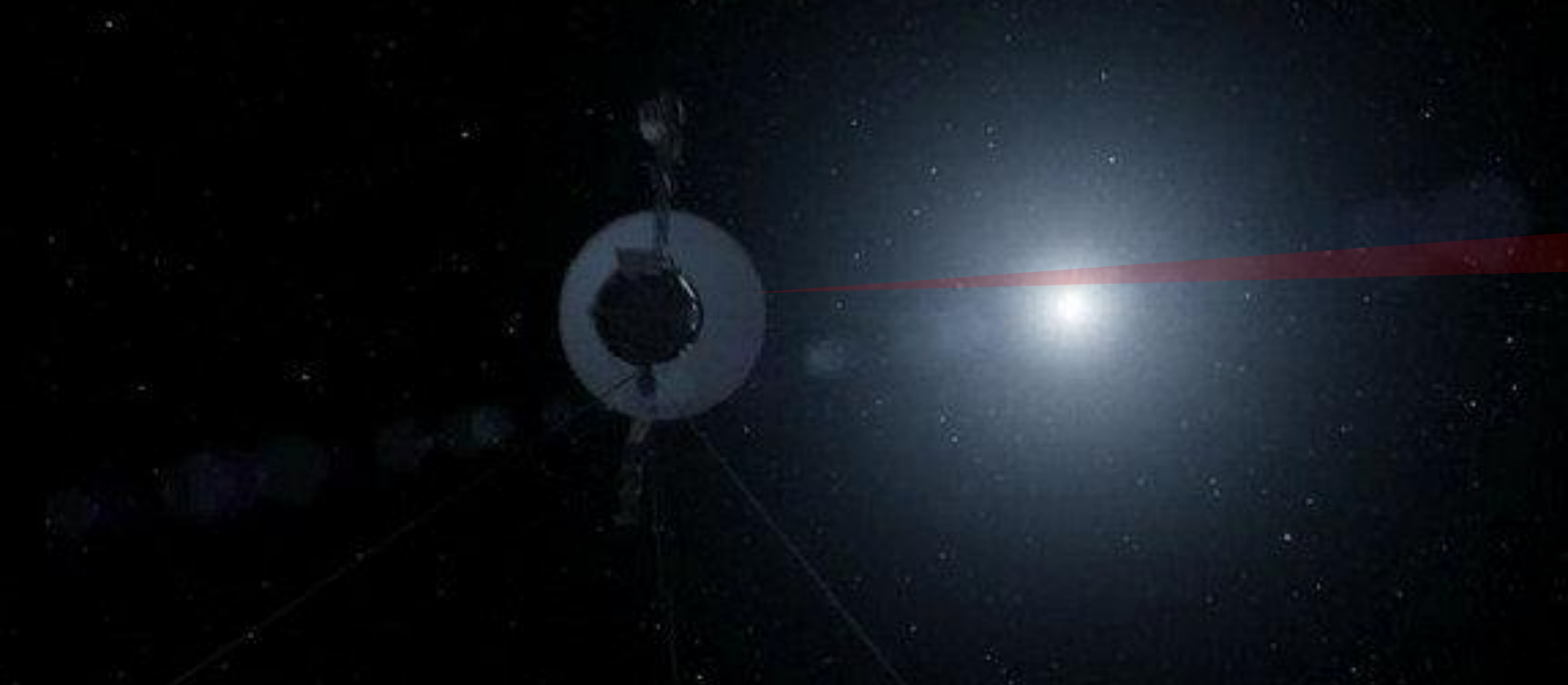
Interstellar Optical Communications

Study for KISS Workshop (January 12, 2015)



Abhijit Biswas, Meera Srinivasan, Malcolm Wright, Sabino Piazzolla

OUTLINE

- Introduction
- Interstellar Mission Parameters
- Interstellar Point Design
- Link Budget
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- Laser Lifetime
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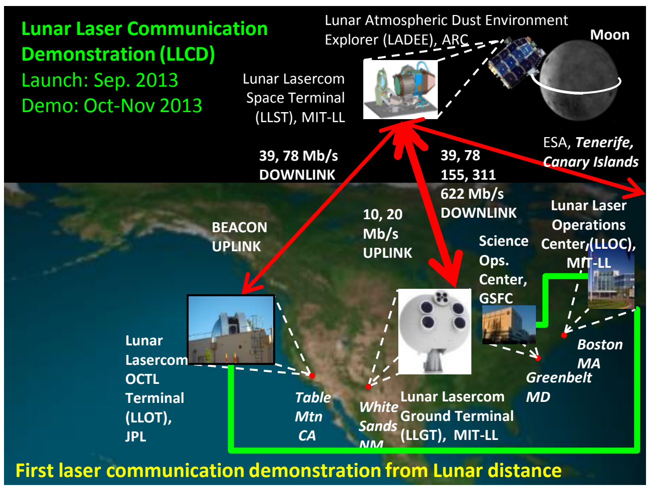
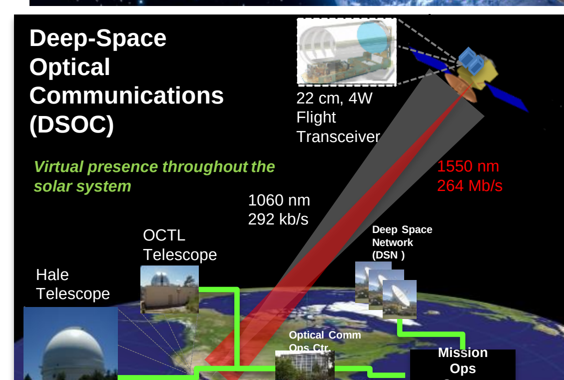
Introduction

- **Optical communications can augment service to future space missions**
  - Enhanced telecommunications capacity for comparable resources
  - Overcoming RF bandwidth allocation constraints
  - Support high precision ranging
  - Allow novel light science
- **NASA funded space demonstrations are retiring key risks for laser communication (lasercom) service**
  - *A few examples of recent and upcoming NASA demonstrations of lasercom*
  - *International Space Agencies also funded lasercom demonstrations and are planning operational service*





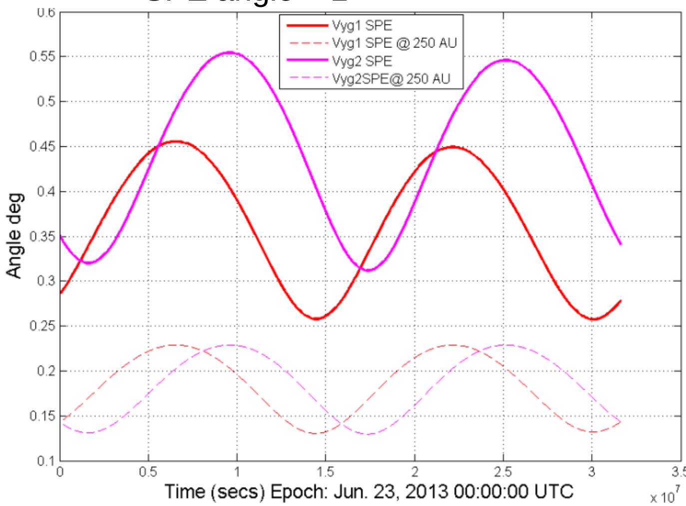
Laser communications emerging as an operational capability through technology maturation

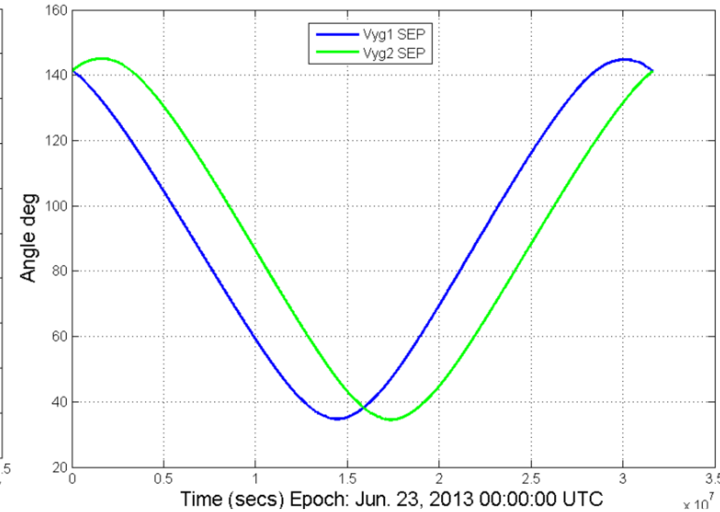
Introduction (cont)

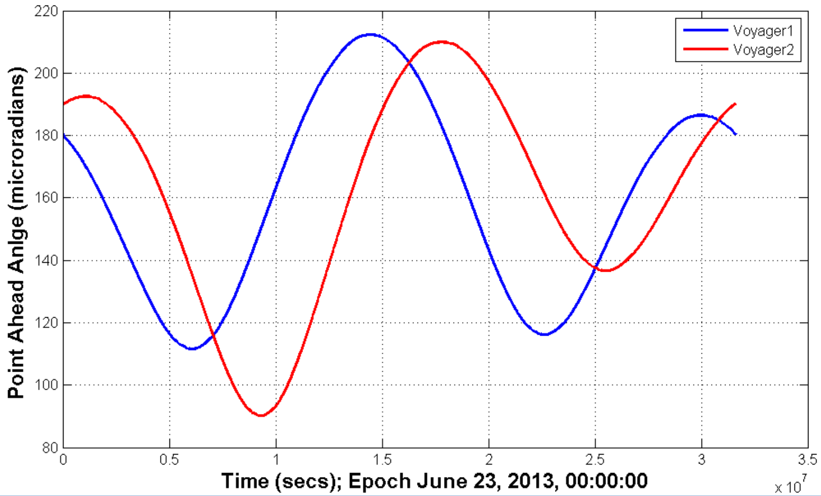
- **Deep-space demonstration, expected early next decade, will retire additional risks**
  - Long round-trip light-times
  - Single photon-counting detector arrays on both ends of link
  - High peak-to-average power lasers
  - Extended operations at variety of link and atmospheric conditions
  - Reliability and lifetime of components/assemblies in space
- **Current study - a point-design based on <u>reasonable extrapolation</u> of technology**
- **Study approach addresses a point design**
  - Downlink performance
    - Rough estimates of mass & power on spacecraft
    - Link and atmospheric conditions for ground-based receiver
    - Initial system trades
  - Link acquisition from space
  - Link acquisition on the ground
- **Not addressed**
  - Concept of operations
  - High precision ranging and other possible light science applications

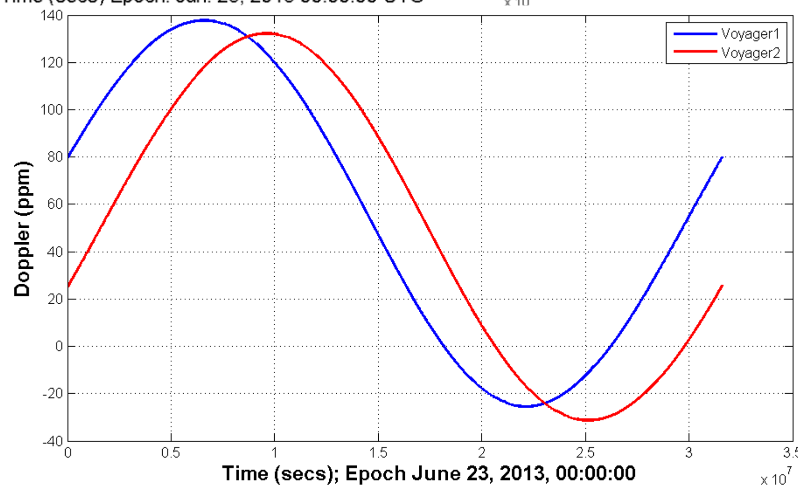
Interstellar Mission Parameters

- **Fix range at 250 AU**
- **Use Voyager 1 & 2 link geometry to guide link conditions**
  - Minimum Sun-Earth-Probe angle ~ 35°
  - SPE angle < 1°



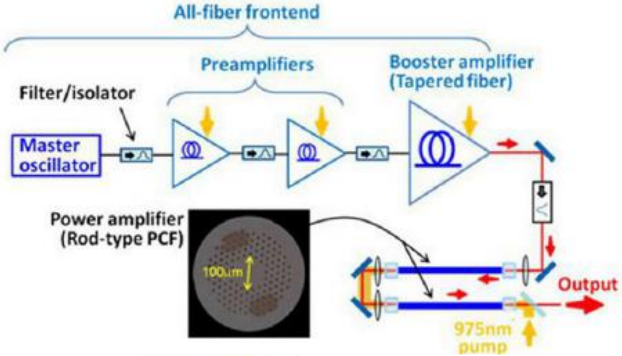


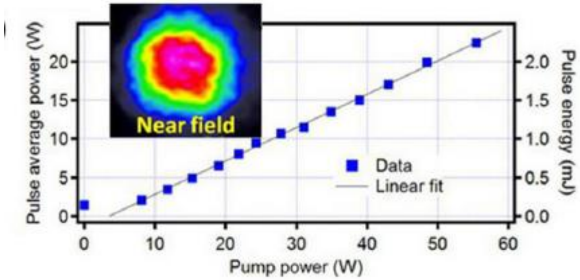




Interstellar Point Design

- **Select fiber laser transmitter**
  - Robust for high average and peak powers[1] ~ 100-150 W
  - Average power ~ 100-150 W
  - Peak powers < 150 kW
  - Narrow linewidth
  - Moderate pulse modulation 10's of kHz
  - Good thermal management
- **Select Ytterbium (Yb):doped fiber laser amplifier @ 1060 nm**
  - Best electrical-optical conversion efficiency ~ 25%
  - Wide-gain bandwidth
  - High average power > 100 W for 100 MHz line-widths
  - Electrical power estimated at 400-600 W
  - Larger area (1000 μm^2) fiber handles peak power
  - Expected improvement in 10-20 years
  - Can handle thermal damage of 150 kW
  - Good beam quality
  - Long lifetime components (Mhrs MTBF demonstrated on pump diodes)
  - 2 dB/yr improvement in power over past
  - Compatible with space-based LIDAR system development
- **Select 50 cm diameter space telescope aperture**
  - Experience with building telescopes exists
    - Mars Observer Laser Altimeter (MOLA) on Mars Global Surveyor (MGS)
    - HiRise on Mars Reconaissance Orbiter (MRO)
    - Mass estimate of light-weighted 50 cm optical transceiver scaled from 22 cm SiC telescope estimate is
      - 48-58 kg
      - For comparison Voyager SXA telecom mass 53 kg (reflector structure, coax and waveguide)





Ref: "High power pulsed fiber lasers for space based remote sensing", F.Di Teodoro, *SPIE newsroom DIO 10.1117/ d.1201310.005059*, 2013

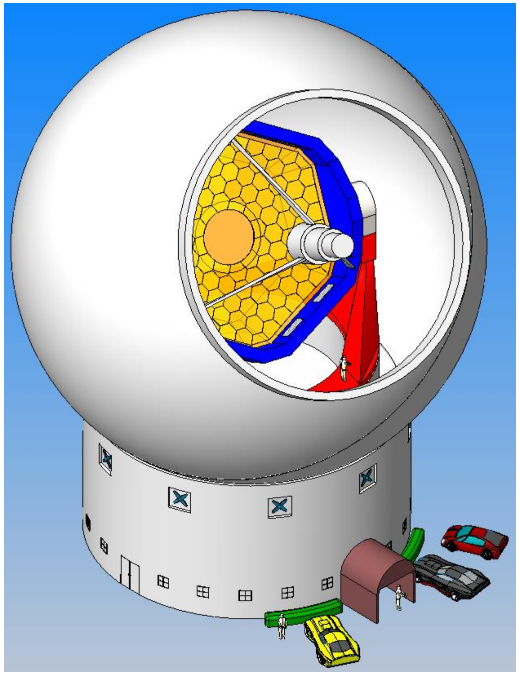
Mars Orbiter Laser Altimeter (MOLA)

HiRise

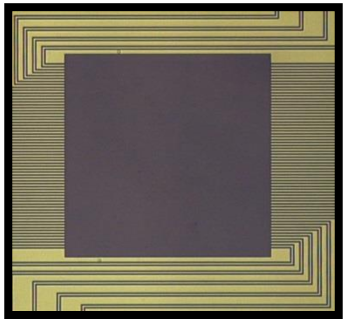
1. *D. J. Richardson, J. Nilsson and W. A. Clarkson, "High Power Fiber Lasers: current status and future perspectives," J. Opt. Soc. Am. B, Vol. 27, No. 11, Nov. 2010, B63-B92.*

Interstellar Downlink Point Design (cont)

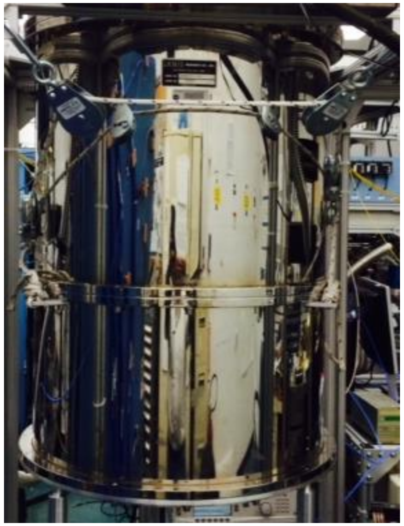
- **Assume a 12 m ground collection telescope**
  - being studied under SCaN funding for deep-space service
- **Superconducting Nanowire Single-photon Photo-detector (SNSPD) arrays 50 x 50 array of 20μm nanowires**
  - 70% detection efficiency with 60 ns recovery time and 100 ps jitter
    - similar to what is being developed for Deep-space Optical Communication (DSOC) Project except that array size is larger



Artists Concept Of 12m Ground telescope*



64-pixel SNSPD Array



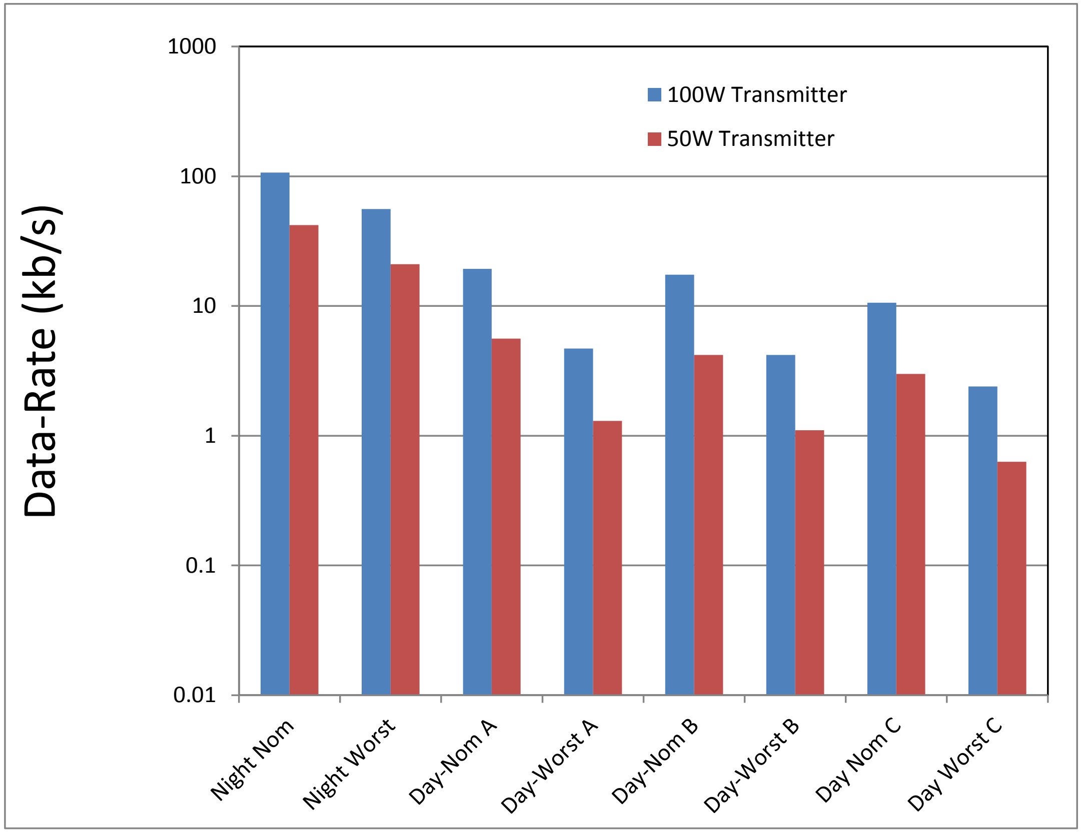
Cryostat

*Hamid Hemmati, Abhijit Biswas and Ivan Djordevic, "Deep-Space Optical Communications: Future Perspectives and Applications," Proceedings of the IEEE, 99(11), 2020-2039, (2011).

Link Performance Summary

- **Evaluated link performance for different day and nighttime conditions**
  - Range 250 AU
  - Detailed link table in backup chart
  - Assumed 5-dB link margin
  - Constrained laser peak power to ~ 100 kW

	Data-Rate (kb/s)			
	Avg. Transmitter Power **100 W**	Avg. Transmitter Power **50 W**	SEP (deg)	r0 @ 500 nm @ zenith (cm)
Night Nom	107	42	140	5
Night Worst	56	21	140	3
Day-Nom A	19.3	5.6	85	5
Day-Worst A	4.7	1.3	85	3
Day-Nom B	17.4	4.2	70	5
Day-Worst B	4.2	1.1	70	3
Day Nom C	10.6	3	34	5
Day Worst C	2.4	0.628	34	3



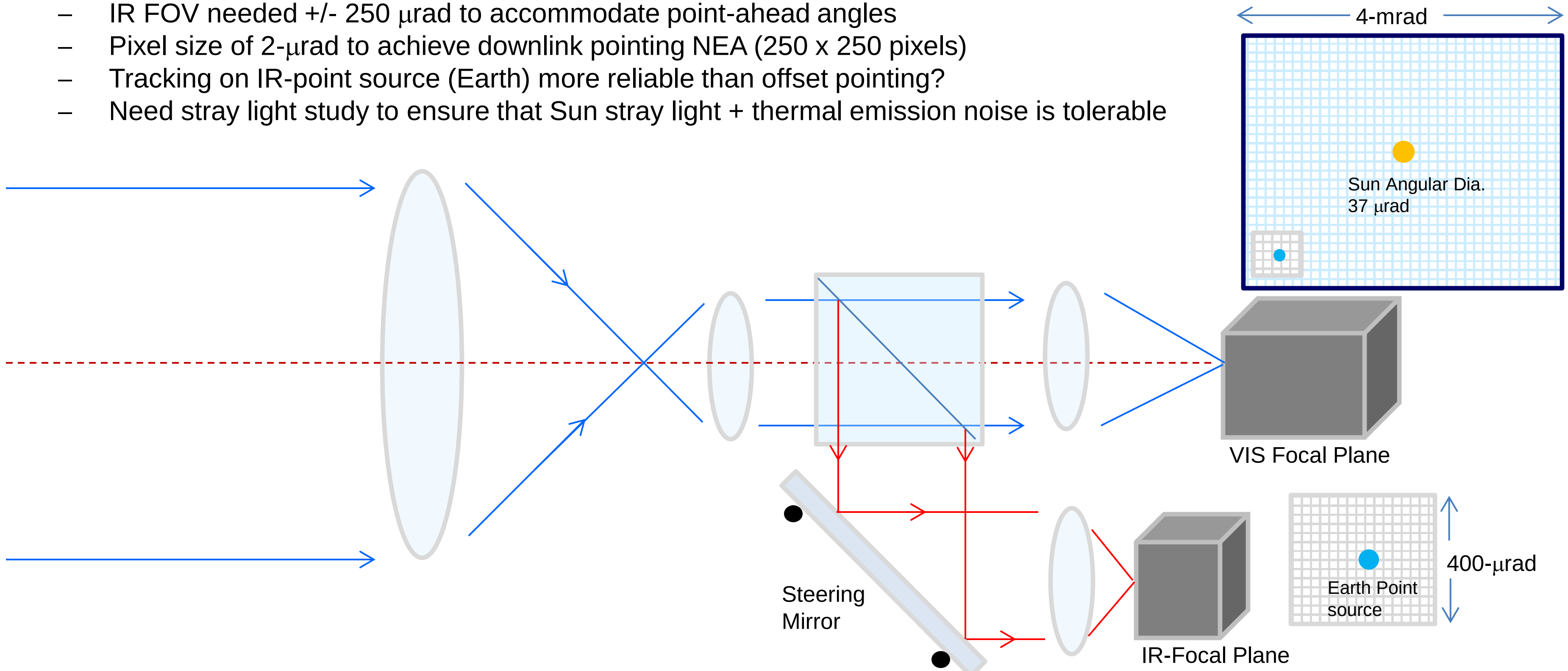
Link Acquisition & Tracking Architecture

<u>Option 1: Single 4 mrad focal plane for acquiring and tracking Sun from 250 AU</u>

- Focal plane sizing becomes challenging
  - To first order array size of +/- 4 mrad required to find Earth
  - Studied 128 x 128 photon-counting array with 39 μrad instantaneous field-of-view (IFOV)
  - High solar photon-flux (VISIBLE band) theoretically allows achieving sufficiently low noise equivalent angle
  - Approach relies on “offset-pointing” and the accuracy of estimating Earth position relative to the Sun

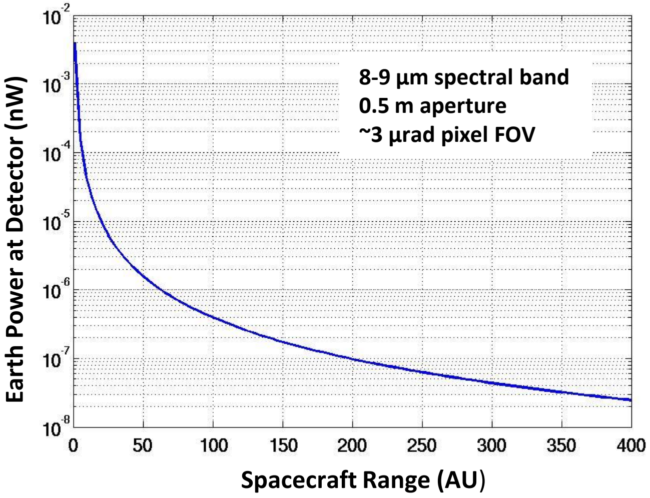
<u>Option 2: Use separate focal planes for imaging Sun and Earth (4 mrad and 0.4 mrad)</u>

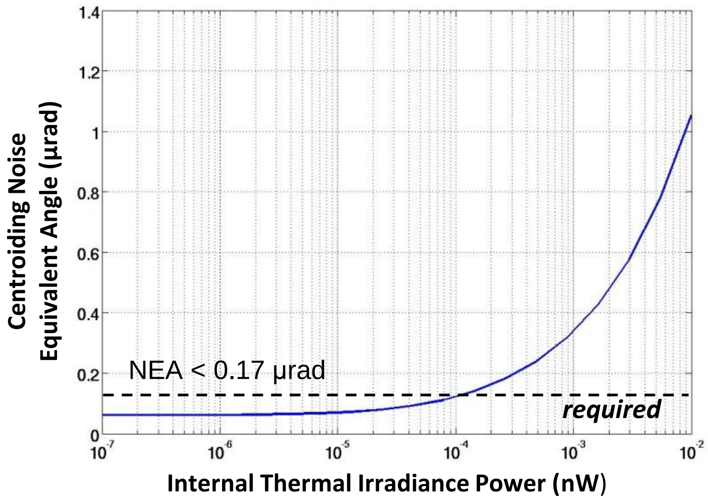
- Have additional thermal IR array for finding Earth
- Thermal IR 8-10μm array for detecting Earth based on knowing Sun position
- IR FOV needed +/- 250 μrad to accommodate point-ahead angles
- Pixel size of 2-μrad to achieve downlink pointing NEA (250 x 250 pixels)
- Tracking on IR-point source (Earth) more reliable than offset pointing?
- Need stray light study to ensure that Sun stray light + thermal emission noise is tolerable



Link Acquisition Tracking & Pointing from 250 AU

- **Two-stage concept for using Sun and Earth as references**
  - Initial use of Sun as a beacon on wide field-of-view detector array (±4 mrad)
    - Plenty of photons available to establish reference position knowledge: ~4×10^{-4} μrad centroid error
  - Handoff to long-wave infrared (8-9 μm) focal plane detector array to sense Earth thermal image for reliable pointing
    - Narrow IR field-of-view to 400 μrad (accommodates downlink point-ahead angle, Sun out of view)
    - Earth thermal image appears as point source on focal plane; assume sufficient pixels and/or optics so Earth image ~ 1 pixel diameter
    - Sufficient photons in 8-9 μm band for centroiding
    - Dominant source of centroiding error is internal thermal irradiance (requires further investigation to quantify)

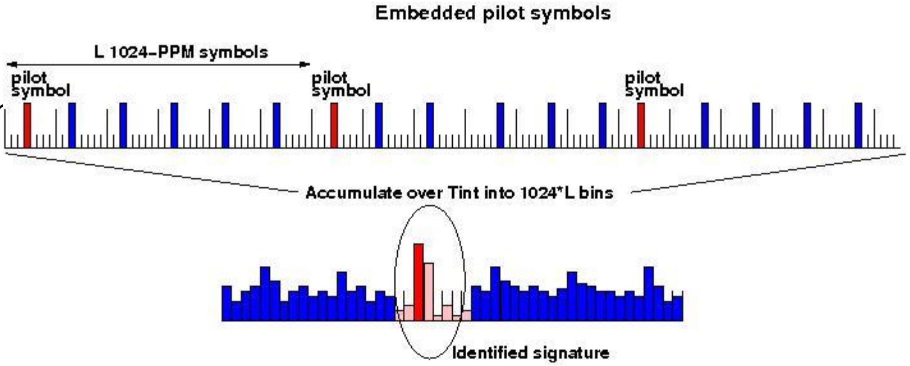




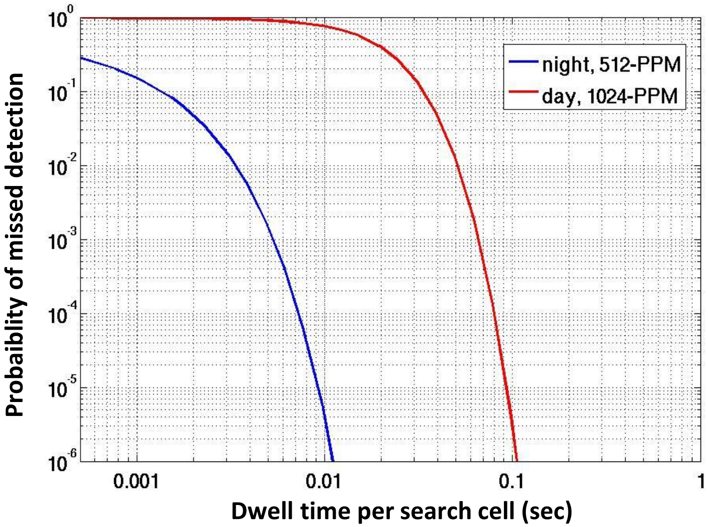
  - Downlink pointing error < 0.8 μrad to achieve < 0.5 dB pointing loss
    - Reference centroiding NEA < 0.17 μrad

Ground Acquisition & Tracking

- Downlink acquisition relies upon detection of periodically inserted pilot synchronization symbols into PPM data stream
  - Assume 5% synchronization overhead
  - Accumulate slot statistics over integration tim



  - At 250 AU daytime conditions, acquisition dwell time is 100 ms for 10^{-6} probability of missed detection
  - May be achieved with 100 parts per billion downlink clock stability



- **25 ns pulse width**
- **5% pilot overhead**

Summary

- Completed initial evaluation of inter-stellar optical communications from 250 AU
- 100 W transmitter with a 50 cm aperture in space
- 12 m ground receiving aperture
  - Data-rates of 10-100 kb/s under nominal day and night conditions
  - Initial estimate of mass and power are 110 Kg and 530 W (*see backup for breakdown*)
  - Acquisition and tracking use Sun in Visible spectral band and Earth image in thermal IR band
  - Acquisition and tracking on ground with pilot tone (5% overhead)
- Future study topics
  - Laser lifetime (*Needs study and technology development to start soon if needed in 20+ years*)
  - Detector array expansion both flight and ground (*flight detectors need near-term/immediate attention*)
  - Concept of operations, especially how the optical terminal will operate over the diverse ranges on its way to 250 AU
    - *How is the terminal operated in early mission phases*
    - *How ephemeris needed for pointing will be obtained*
    - *Long light times of days can result in weather changes by the time the signal reaches Earth*
      - *Need to have a re-transmission scheme of some sort*
  - No uplink was considered, optical uplink from space-borne platforms are an option worth exploring
  - Possibility of ranging and other light science

THANK YOU Joe Lazio, Leon Alkali

BACKUP

Laser Reliability and Lifetime Considerations

- **Issues for reliability**
  - Peak power limited (~ 4 MW for 0.05 – 100 ns) pulses by:
    - Thermal effects on optical coatings
    - Self-focusing in fibers
    - Optical damage limits of glass fibers – larger cores possible
    - Nonlinear effects in fiber
  - Thermal management of high pump powers
  - Pulse energy limited by:
    - Energy storage of metastable states due to amplified spontaneous emission (ASE)
    - Onset of nonlinear processes – stimulated Rayleigh scattering (SRS), Brillouin scattering (SBS)

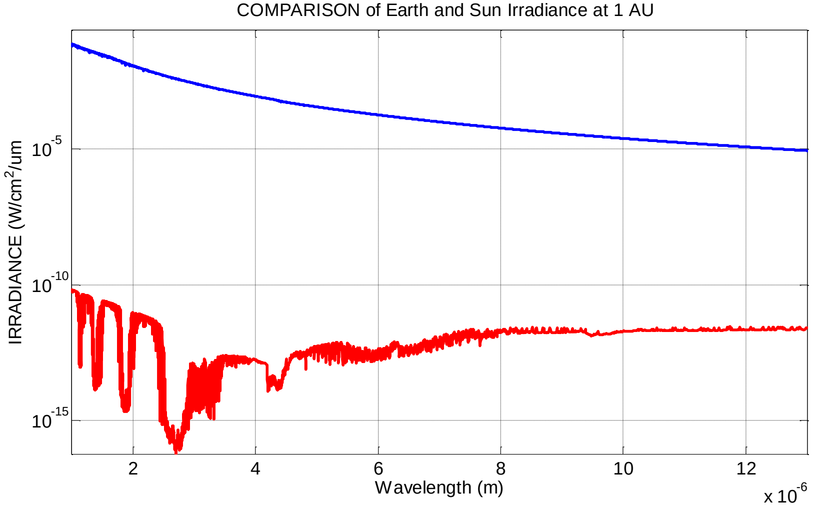
- **Mitigation techniques to address lifetime reliability and power handling**
    - Operate at most efficient wavelength around 1 µm to minimize thermal loading
    - Optimize material - better processing, polishing, impurities, use end caps
    - Need controllable pulse parameters – adaptive pulse shape control, PRFs above reciprocal of upper state lifetime due to stored energy depletion effects
    - Improved fiber nonlinearity management
      - Mode area scaling – air-clad (photonic crystal fibers – PCF), large mode area fibers for reduced NA to give good beam quality with larger core diameters
      - Reduce Kerr nonlinearities with hollow core fiber, multiple apertures
    - Minimize fiber strain – lower pump absorption, longer length fibers
    - Increase laser linewidth through phase modulation, seed pulsing to increase SRS threshold
    - Radiation tolerant fiber designs becoming available

Robust fiber based laser transmitters can be developed to support interstellar optical links with current technology

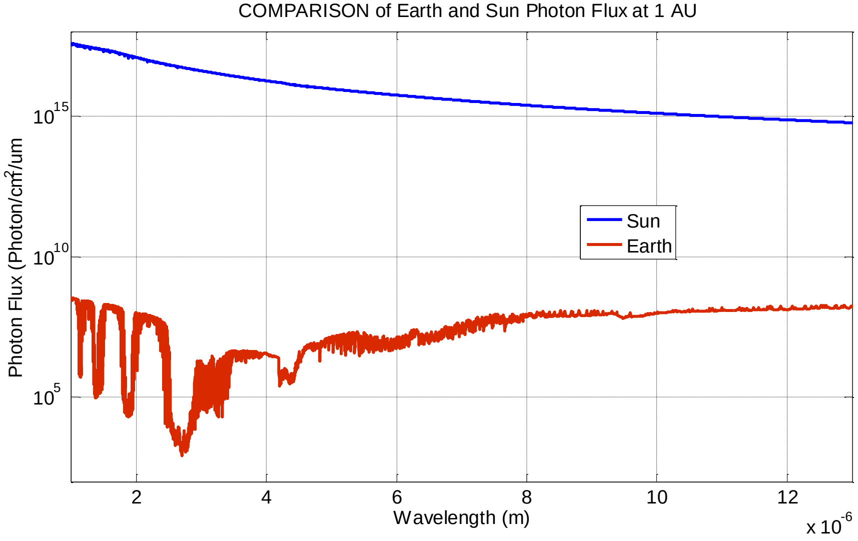
Sun versus Earth Spectral Irradiance

- Comparison of Earth and Sun Irradiance at 1 AU
  - Earth Diameter 12740 Km
  - Sun Diameter 1391684 Km
- Wavelength range 1-13 micron
- Earth: data from MODTRAN, one can assume a 3dB of variation
  - Sun Zenith Angle 52 Degreeq

Irradiance at 1 AU



Photon Flux at 1 AU



Initial estimate of mass and power

	Mass	Power
Telescope	58	5
Laser	25	500
Electronics	15	20
Cables	5	
Thermal	7	5
TOTAL	110	530