Technology Development for High Efficiency Optical Communications

William H. Farr

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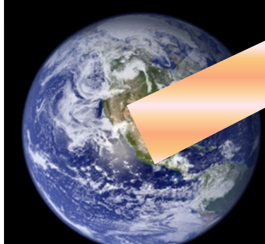
Jet Propulsion Laboratory
California Institute of Technology



Why Space Optical Communications?

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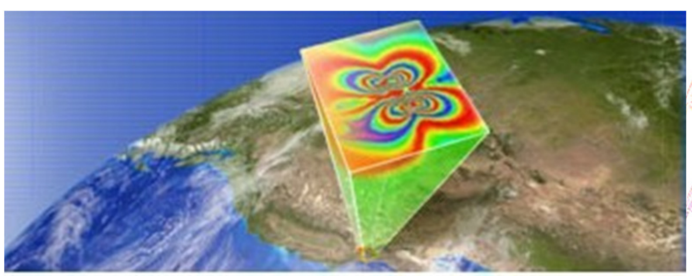
➢10X to 100X increased data returns over present RF communications

- ***Increased science data return***
- ***"Virtual Presence" for public engagement***

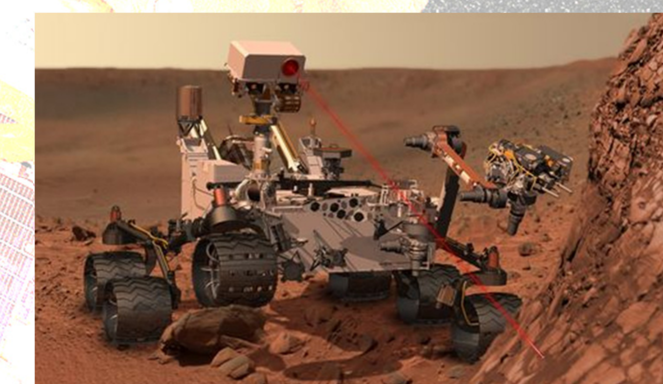
Human Exploration Beyond Low-Earth Orbit

Future Advanced Instruments

10X Increased Imaging Resolution for Astrophysics



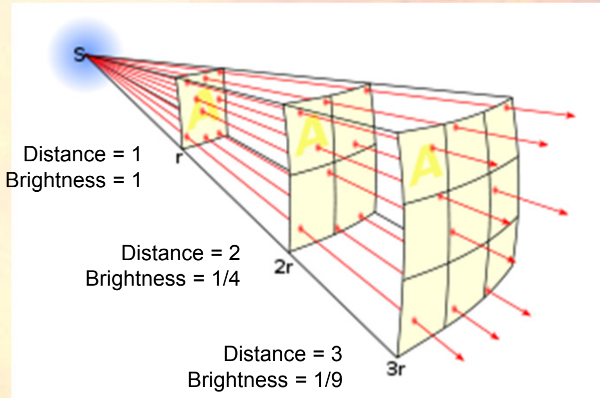
10X Increased Resolution Imaging for Earth Science



Tele-Presence with Live HiDef Video

How Optical Improves Over RF

- As a beam (RF or optical) propagates from transmitter to receiver it illuminates an area proportional to the distance-squared
  - "Range-Squared Loss" or "Inverse-Square Loss"



- Basic telecommunications tenet (RF or optical):

  In a well-designed system data rate is proportional to received power

- Thus, the same data rate at 10X the distance requires either:
  - *100X the area* of the receiver antenna (10X the diameter); or
  - *100X more power* transmitted; or
  - *10X narrower* transmitted beam

- The "optical advantage": beam width = wavelength / antenna diameter
  - Example: Beam width from 30 cm optical antenna at 1550 nm is ~600X narrower than the beam width from a 300 cm RF antenna at 9.2 mm (32 GHz, Ka band)

$$\theta = \lambda / D$$

Space Optical Communications Status

- **Near Earth**
  - Successful flight demonstration missions by US DoD, ESA, and JAXA
  - ESA is going operational for LEO/GEO
    - **One GEO (2 Gb/s) and two LEO (5.6 Gb/s) terminals to be launched in CY2012**
- **Cis-Lunar**
  - Successful beam pointing, but no real communication link
  - *NASA plans to demonstrate Earth-moon optical communications in 2013*
- **Deep Space**
  - *No deep space optical communications*
  - NASA is at the technology forefront for deep space optical

Domain	NASA /JPL	Lincoln Lab	NASA/ GSFC	Europe	Japan
Deep Space	1992[1]		2005[5]		
Cis-Lunar		(2013[9])	2009[8]		
GEO	1995[2]	1999[4]		1999[6]	1995[2]
LEO-GEO				2005[6]	2005[6]
LEO-LEO				2008[7]	
LEO	2009[3]			2006[3] 2010[7]	2006[3]

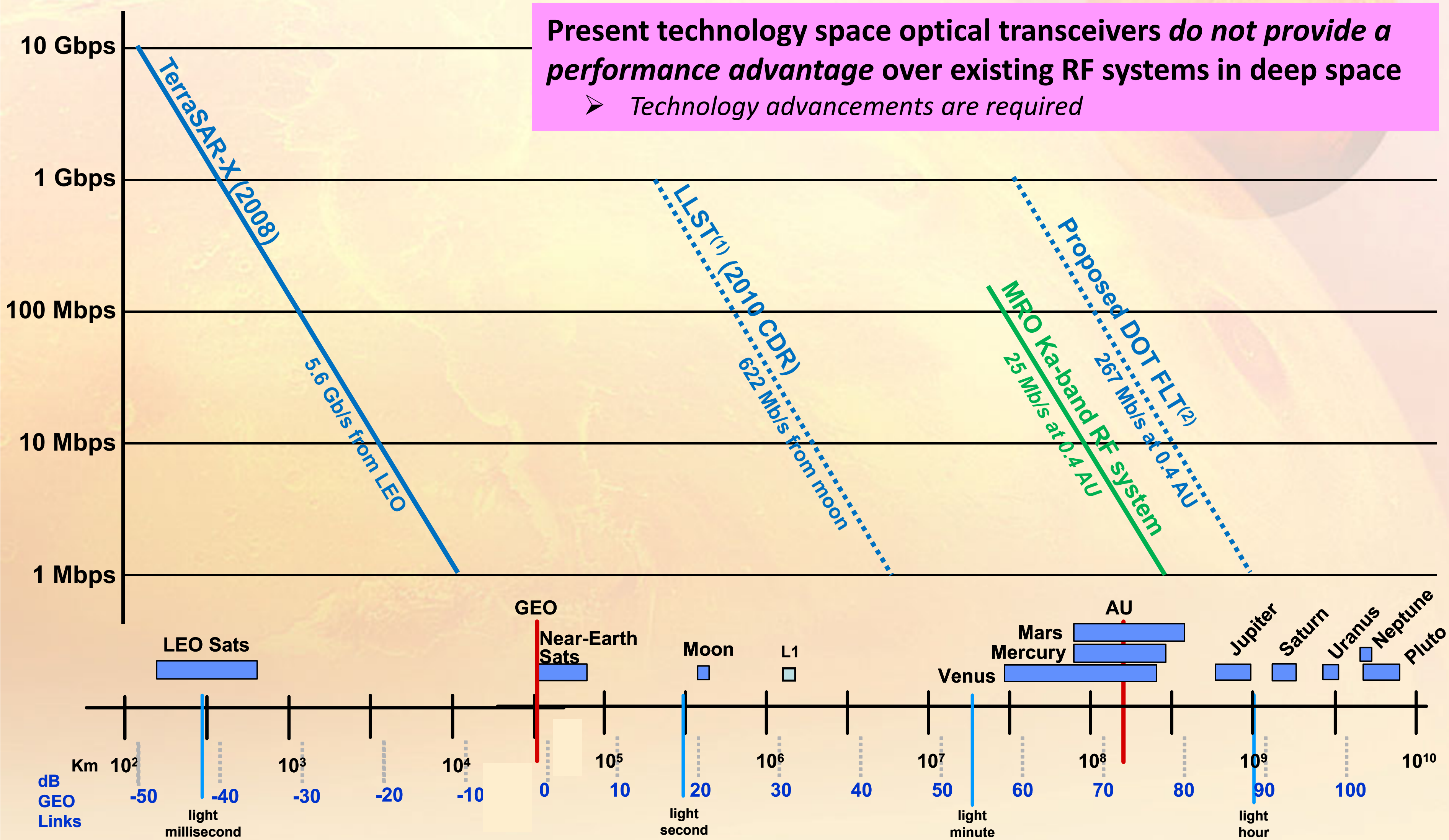
1. Laser pointing to Galileo spacecraft
2. LCE on ETS VI spacecraft
3. OICETS spacecraft
4. GeoLITE
5. Laser pointing from Messenger spacecraft
6. SILEX
7. NFIRE - TerraSAR-X
8. Calibration of LOLA on LRO
9. (planned LLCD)

- ***Lasercom from Earth-orbit is transitioning to operations***
  - *No deep space optical communications has yet been demonstrated*

Space Telecommunications

Present technology space optical transceivers *do not provide a performance advantage* over existing RF systems in deep space

- *Technology advancements are required*



[1]LLCD: MIT-LL Lunar LaserCom Space Terminal, July 2010 CDR
[2]DOT FLT: JPL Deep-space Optical Terminals Flight Laser Transceiver, August 2010 Concept Review

Deep Space Optical Challenges

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Challenges of deep space optical over demonstrated near-Earth solutions

- **Pointing:** Must point downlink from Deep Space transceiver (DST) using a ~10,000X dimmer uplink beacon across 100X greater round-trip light time (RTLT)
  – *Requires improved spacecraft disturbance isolation to be able to acquire the dim beacon*
  – *Requires deep-space focal plane architecture with ultra-sensitive detector arrays for beacon tracking and point-ahead confirmation without handshaking*

- **Modulation:** Use high order Pulse Position Modulation (PPM 16..512) and power-efficient multi-Watt lasers to overcome huge signal loss
  – *~10,000,000X greater loss at Mars far range than moon requires >300 W peak power lasers*
  – *Laser amplifier is largest power consumer on DST*

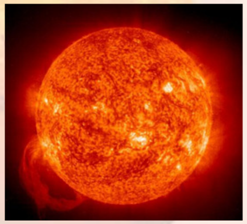
- **Detection:** Must shift burden from DST by using > 10 m diameter telescopes on Earth
  – *Requires large (~1 mm^2) photon counting detector arrays behind telescope due to atmospheric blurring (> 50% detection efficiency desired)*

Deep Space Transceiver

Large distance
Large $1/R^2$ range loss
Large 2R/c round-trip light time (RTLT)

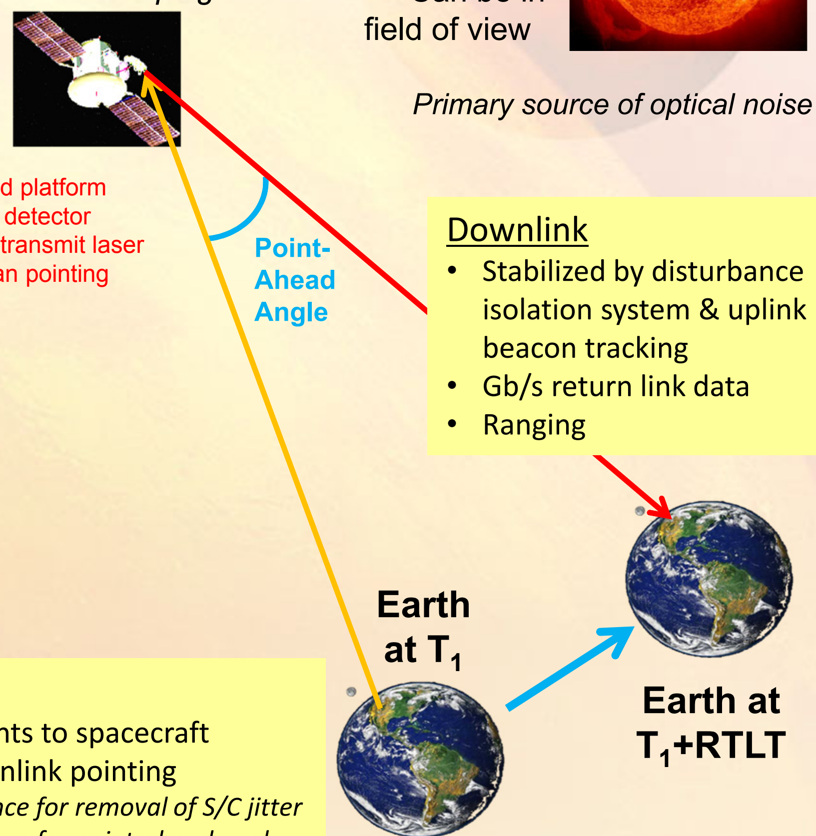
REQUIRES:
- Stable / isolated platform
- Efficient uplink detector
- Efficient PPM transmit laser
- Sub-microradian pointing

Sun



Can be in field of view

Primary source of optical noise



Downlink
- Stabilized by disturbance isolation system & uplink beacon tracking
- Gb/s return link data
- Ranging

Uplink
- Blind points to spacecraft
- Aids downlink pointing
  – *Reference for removal of S/C jitter*
  – *Reference for point-ahead angle*
- Mb/s forward link data
- Ranging

REQUIRES
- Multi-kW power uplink lasers
- > 10 m optical receiver apertures
- Efficient downlink detectors

Key Technologies for *Operational* Deep Space Optical Communications

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- ***Objective***: **Develop key technologies for a deep space optical transceiver with 10X data rate of state of the art (Ka-band) RF system**
  - With similar spacecraft mass & power burden

- **No deep space optical system has yet been built!**
  - Although a deep space optical transceiver *could* be built with existing technologies, the mass & power performance is not competitive with existing deep space RF telecom systems

Assembly or Sub-Assembly	Savings with Technology Development	Comment
Space Telescope	minimal	Unless apertures > 50 cm required (multi-Gb/s at Mars far range)
Space Electronics	minimal	Some mass and power savings with ASIC development ($$$)
1550 nm PPM space laser transmitter	Reduce transmitter mass ⅓, power by ½	Similar mass/power gains presently achievable if downlink wavelength shifted to 1070 nm
Spacecraft Disturbance Isolation	~20% of space transceiver mass	Existing disturbance isolation systems not optimized for low mass (<~20 kg) payloads
Space Receiver Detector Array	10X reduction in uplink irradiance	Also enables >10 Mb/s Earth to deep space optical links
Pointing Mechanisms	minimal	Multiple commercial solutions exist
Ground Telescope	~$50M per deep space optical site	Existing assets sufficient for deep space tech demo mission; > $50M to develop first dedicated deep space optical site
Ground Electronics	minimal	Existing solutions operate within 2 dB of theoretical performance
Ground Receiver Detector Array	Reduce space transmitter mass and power by ½	Doubles deep space to Earth data rate with no change to space transmitter laser power
Ground laser transmitter	minimal	But ground laser NRE investment needed for > 1 kb/s Earth to deep space optical rates

space ↕ ground

Key Technologies Objectives versus State of the Art (SotA)

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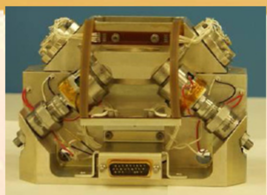
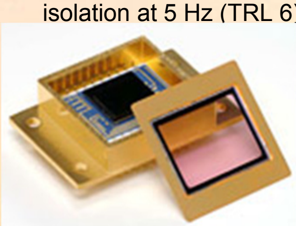


Isolator bipod with 20 dB isolation at 5 Hz (TRL 6)



InGaAs array, 10 pW/m^2 for 0.02 pixel centroiding error (TRL 6)

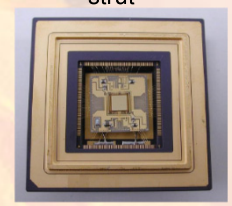
PPM laser transmitter with 10% efficiency (TRL-6)

Intensified photodiode (30% efficient, TRL 6)

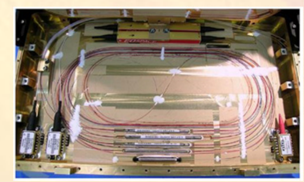
SotA

Parameter	Requirement		Goal	Notes
	TRL 5-6 SOTA	*Deep Space*		
Space Receiver irradiance	~10 pW/m^2	~1 pW/m^2	1 pW/m^2	Reduces laser beacon power from MW to kW
Space Receiver array size	2x2	32x32 to 128x128	32x32	Near-Earth does not require single photon detectors
Space Laser transmitter bandwidth	10 GHz	5 GHz	-	Deep space requirement is met by SOTA performance
Space Laser DC-Optical Power Efficiency	~34% 1064 nm ~13% 1550 nm	> 20%	20% for 1550 nm	Driver is to reduce power and mass burden on spacecraft
Spacecraft Disturbance Isolation below ~3 Hz	-	> 20 dB	> 27 dB	Operate with dim laser beacon; low payload mass makes passive isolation difficult; precision IRU is high mass/power
Ground Receiver detector dia. / efficiency	1 mm / 30% .014 mm / 60%	1 mm / 50%	1 mm / 60%	Must maintain this sensitivity at Gb/s data rates

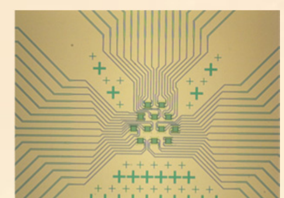
< 1Hz resonant active/passive isolation strut



Photon counting array, 1 pW/m^2 for 0.02 pixel centroiding error



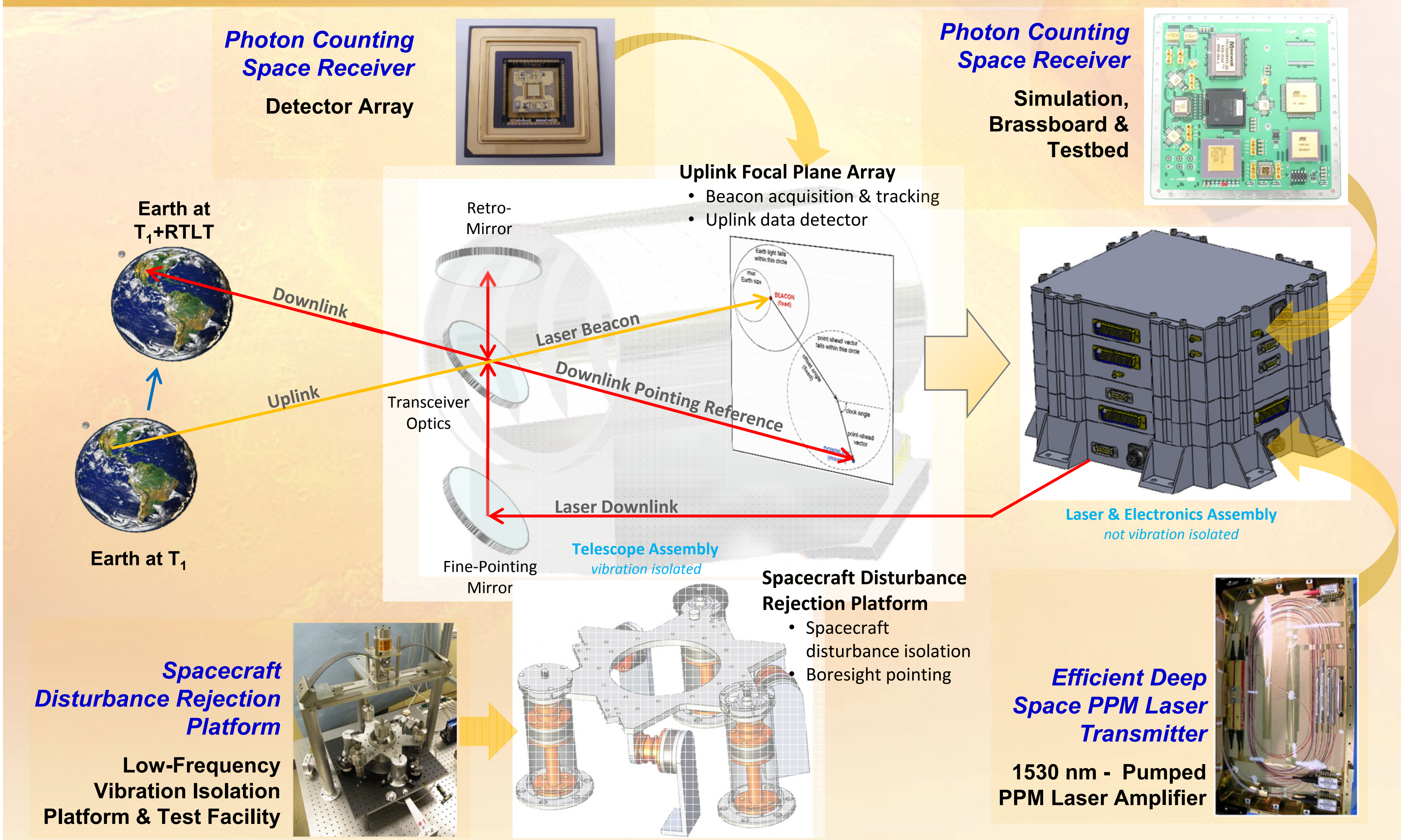
PPM laser transmitter for >20% efficiency



Large superconducting nanowire arrays with > 60% efficiency

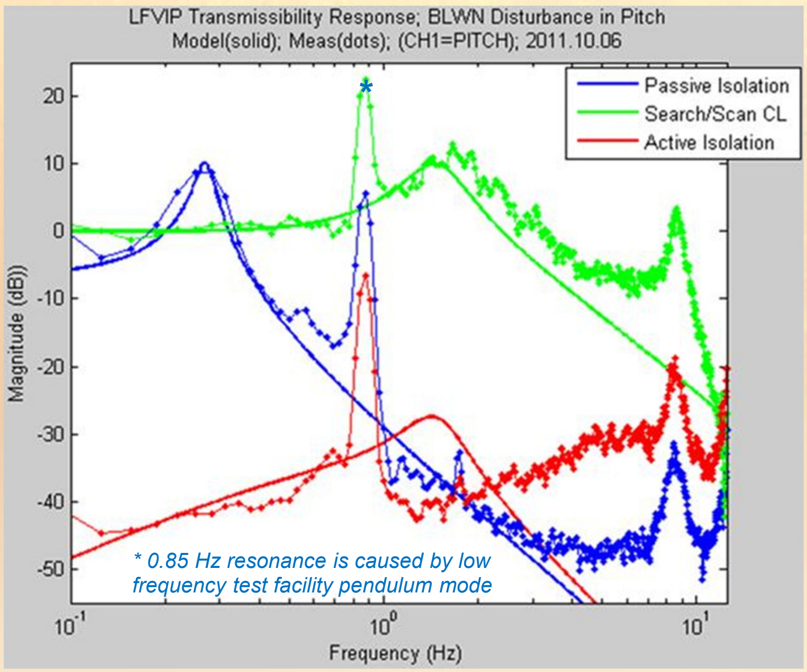
Goal

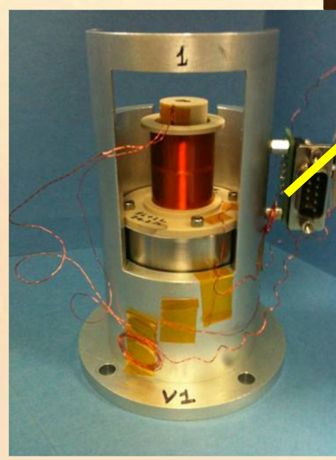
Deep Space Optical Flight Technologies



Spacecraft Disturbance Isolation

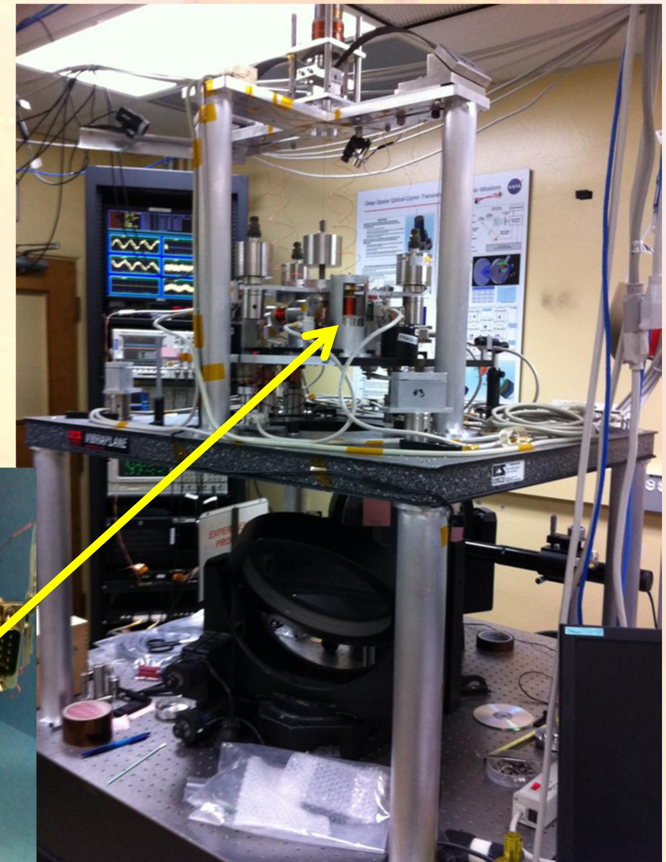
- **Hybrid active-passive disturbance isolation platform has with greater than 25 dB rejection (0.1 – 12.5 Hz) in pitch & yaw**
  - Passively isolates and actively suppresses disturbances
- ***Benefit*: Reduce subsystem mass from 10.2 kg (MLCD[1] 2005 PDR) to 3.5 kg (DOT[2] 2010 ICR)**





Hybrid Active-Passive Isolation Strut

Highly compliant spring + voice coil actuator and LVDT sensor



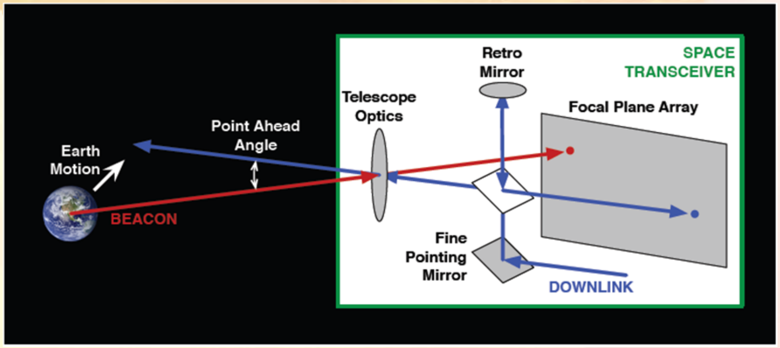
Low Frequency Vibration Isolation Platform & Test Facility

Test facility implements gravity off-load and spacecraft disturbance emulation

[1]Mars Laser Communications Demonstration
[2]Deep-space Optical Terminals

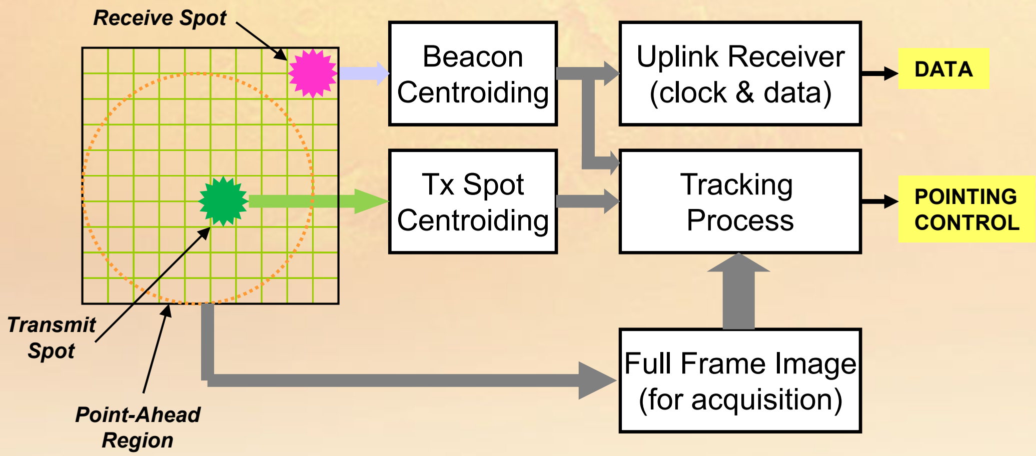
Photon Counting Space Receiver

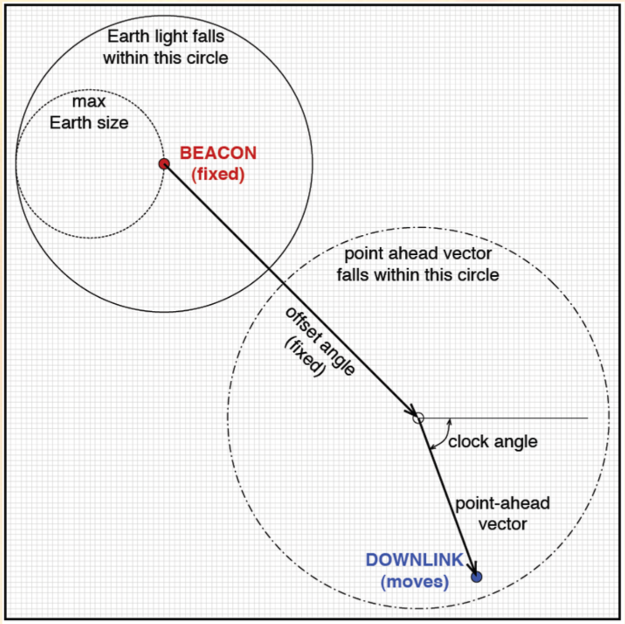
- **Single focal plane array of single photon detectors for acquisition, tracking, communications, and precision ranging**
  - Shot noise limited detection for 10X to 100X better performance than a conventional focal plane array
- ***Benefit*: 10X lower uplink laser power and uplink data rate increases from < 100 b/s (Si CCD or InGaAs FPA) to multi-Mb/s**



Photon counting array tracks beacon laser, Earth image, and transmit point-ahead with only one optical channel

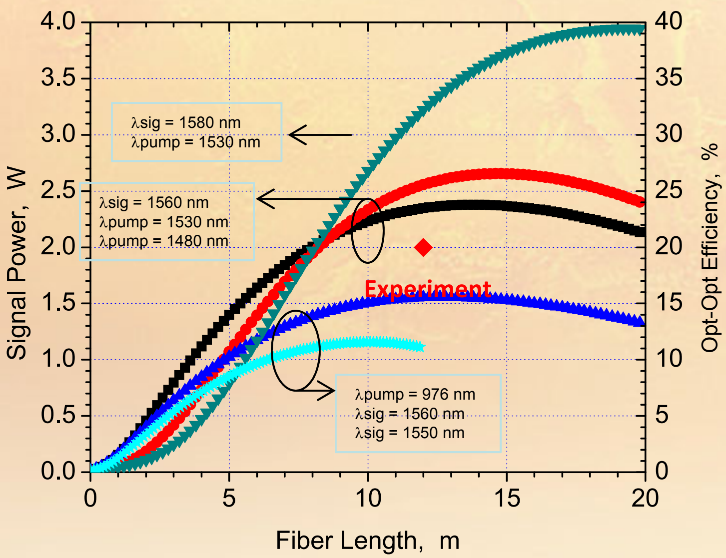
Versus two or three for previous deep-space optical transceiver designs

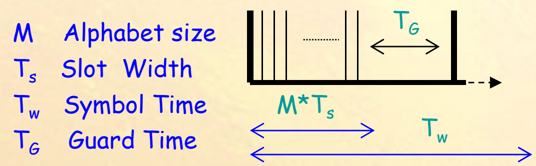




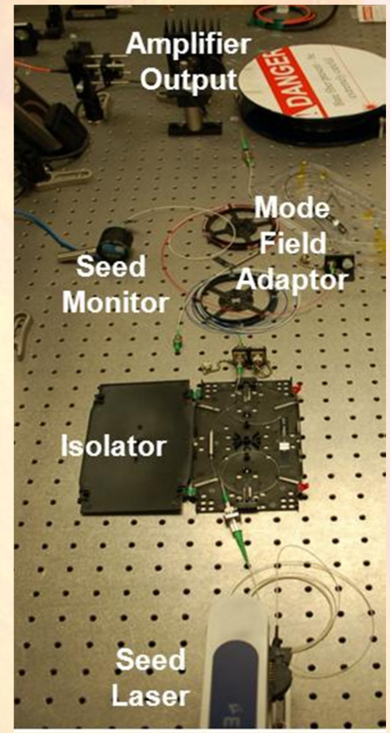
Efficient 1550 nm PPM Transmitter

- **1530 nm pumped laser amplifier suitable for high order (> 64 slots per symbol) deep space Pulse Position Modulation (PPM)**
- ***Benefit*: 2X power efficiency with 2/3 mass of present 976 nm pumped technology**
  - Increase DOT[1] downlink rate 2X to > 500 Mb/s for similar mass & power





PPM Symbol Structure



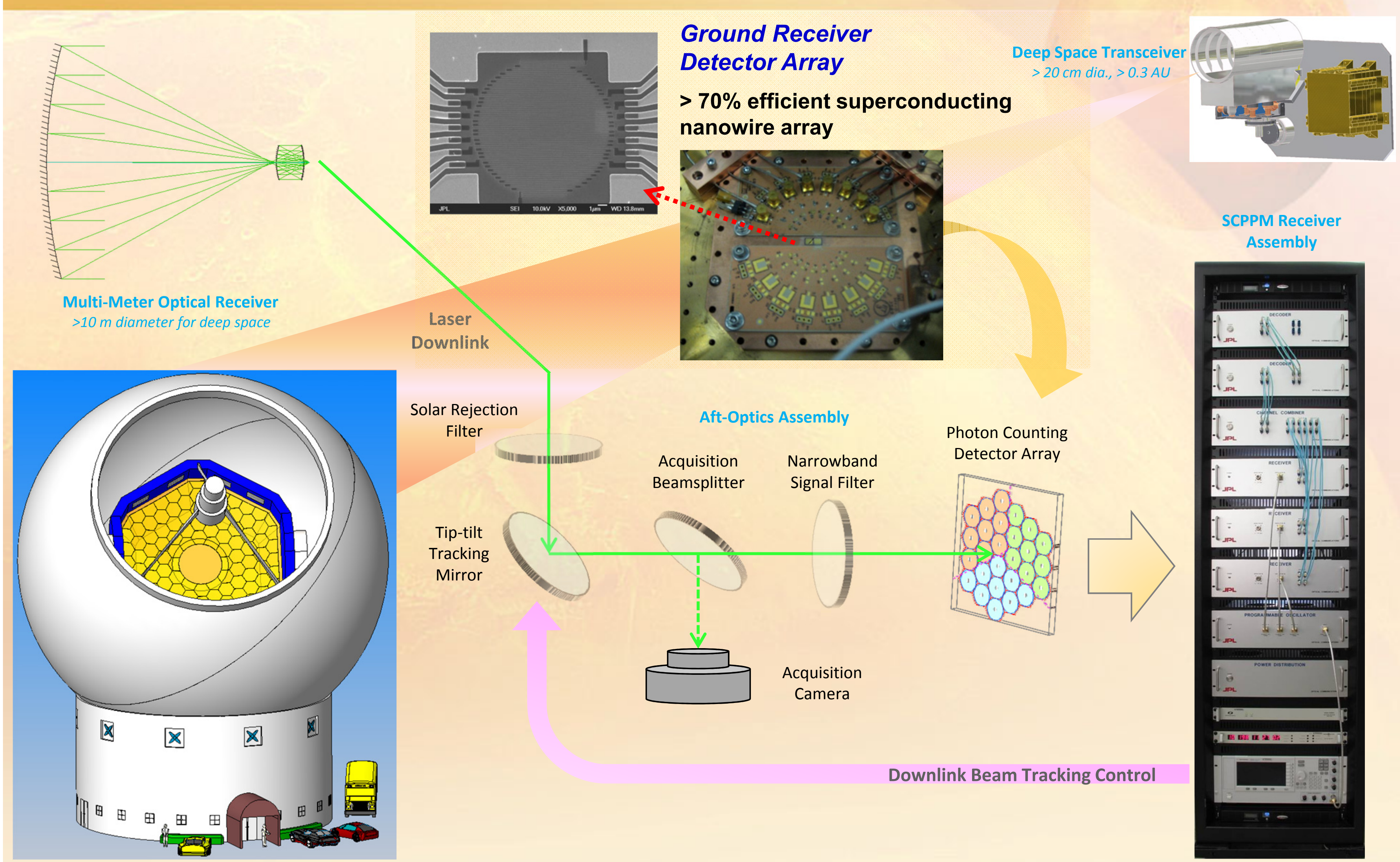
JPL results plus recent AFRL results indicate >25% efficient 1.5 μm PPM deep space laser is viable

Pathway to >20% DC-optical Efficiency

- Incorporate ≥40% efficient wavelength stabilized pump diodes
- Develop comprehensive time-dependent model including non-linearities to optimize PPM fiber amplifier design
- Use single mode fiber with reduced bend sensitivity, increase seed power, and optimize pump orientation

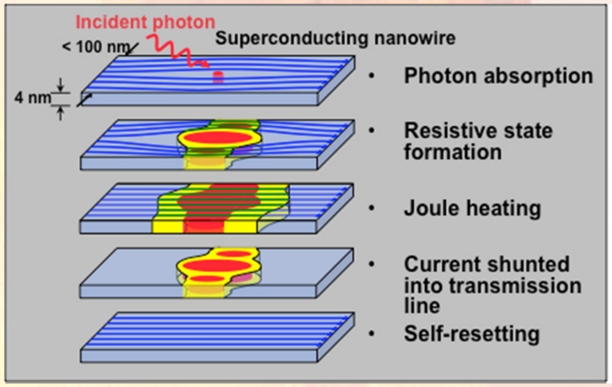
[1]Deep-space Optical Terminals

Deep Space Optical Ground Technologies

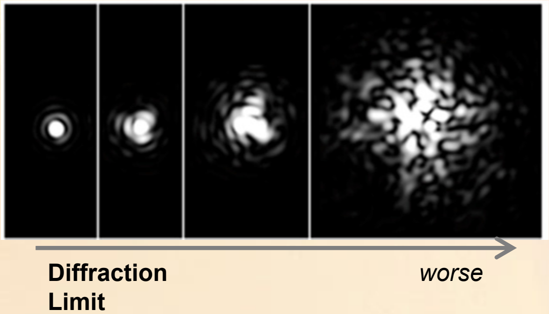


Ground Receiver Detector Array

- **Superconducting nanowire single photon detectors (SNSPD) presently offer the highest performance for photon starved optical communications at near-infrared optical communications wavelengths**
  - ~4 nm thick by ~100 nm wide superconducting wire biased just below the critical current
  - Absorbed photon breaks a large number of quasi-particles
    - *Locally depresses the critical current of the wire*
    - *If the bias current exceeds the critical current, the hot-spot rapidly goes normal*
    - *Drop in current is read out as a voltage across a load*



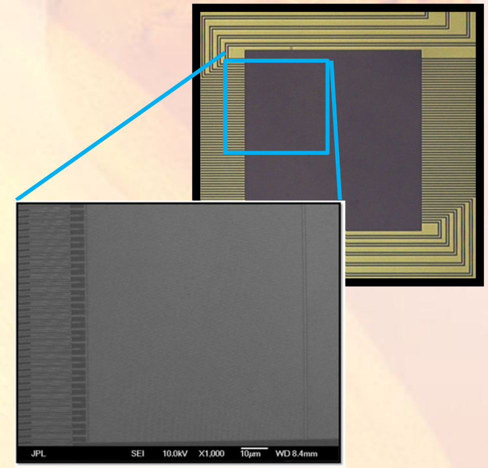
- **Atmospheric "seeing" requires mm² sized arrays coupling to multi-meter optical receivers, versus the μm² size fiber coupled arrays developed to date**
  - Diffraction limit = 2.44 F λ
    - *F is focal ratio, λ is the receive wavelength*
  - Focal spot size ≈ (Diffraction limit) x (D/r_0)
    - *D is telescope aperture* *[F = (focal length) / D]*
    - *r_0 is atmospheric coherence size* *["seeing" = λ/r_0]*



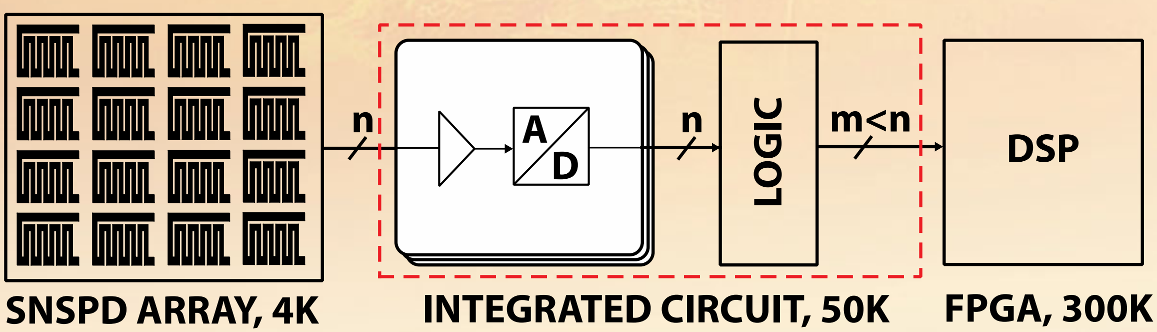
Example: 5 a.s. seeing, 12 m aperture, F1.3 → ~1 mm minimum detector diameter

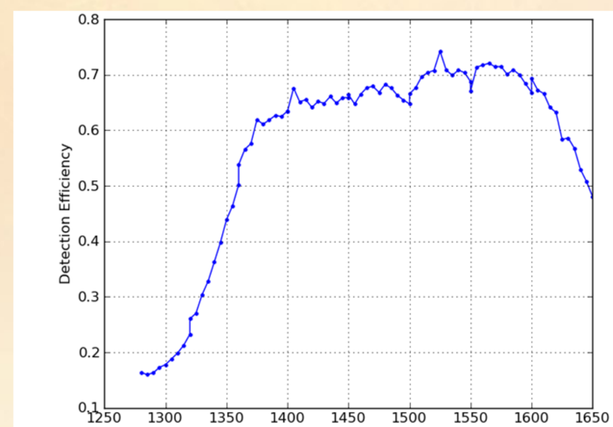
$W_{(1-x)}Si_x$ Nanowire Array Development

- **SNSPDs in new $W_{(1-x)}Si_x$ material system**
  - High efficiency across broad range of bias currents is favorable for tolerance to manufacturing variances versus problems with constrictions in previous Nb(Ti)N SNSPD technology
  - Collaborative development at NIST (Boulder, CO) and JPL
- **Present Status**
  - Fabricating high quality $W_{(1-x)}Si_x$ films at JPL
  - Fabricating single pixel to 64 pixel dense-packed arrays at JPL
  - First tests of $W_{(1-x)}Si_x$ JPL detectors conducted at NIST
  - Multi-pixel tests pending installation ^{3}He insert in the Cryogenic Array Test System at JPL in March
- ***Benefit*: Double downlink data rate with no increase in spacecraft burden**



Optical and SEM image of 64 pixel dense-packed $W_{(1-x)}Si_x$ array
Total array area is 160 x 160 μm^2





Deep Space Communications Capability

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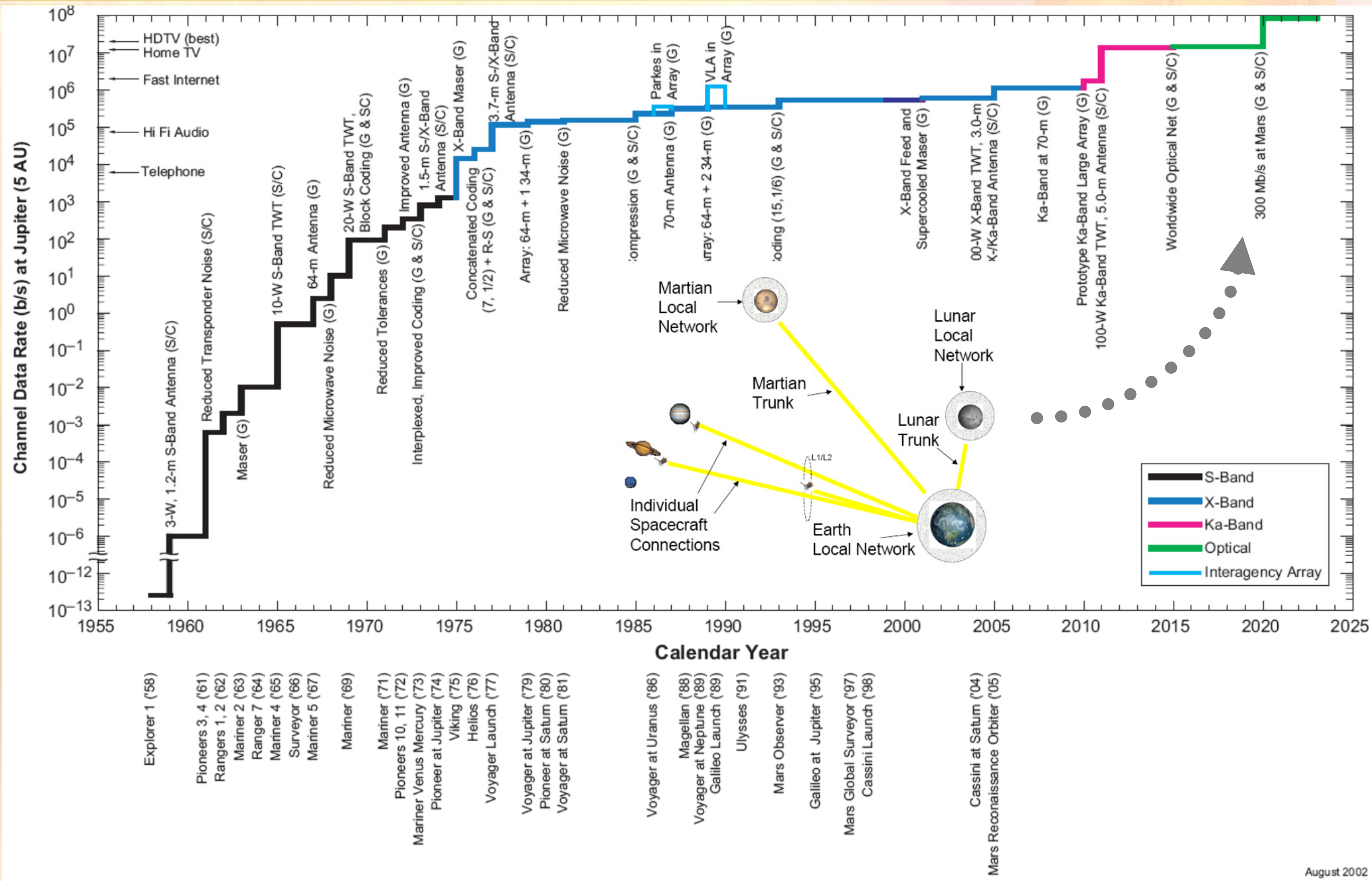

Other Benefits of Technology to NASA

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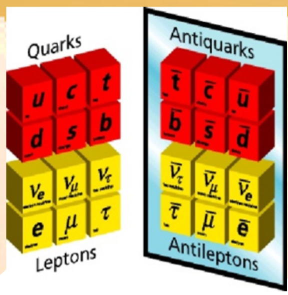
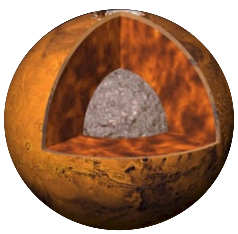
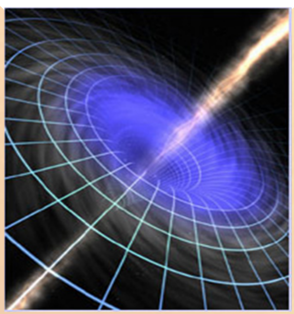


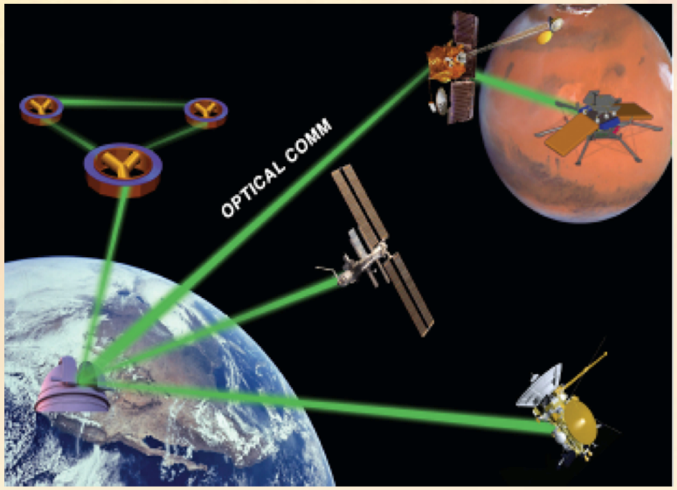




- Optical Light Science
  - Tests of physics beyond the standard model
  - Tests of time variation of fundamental physics constants
- Precision ranging (cm and mm scale) for planetary studies and astrophysics
  - Determination of planetary interiors
  - Tests of Parametric Post-Newtonian gravitational theories
  - Tests of strong and weak equivalence principles
- Improved vibration isolation for high resolution cameras
  - Longer integration times without blurring
- Ultimate sensitivity cameras for near-infrared imaging
  - Smaller apertures for high sensitivity planetary imaging

Summary

- **Space optical communications can deliver 10-100X higher data rates for the same mass and power as present RF systems**
  - Challenges unique to optical communications have been demonstrated at GEO and LEO, but still need validated solutions for NASA missions
- **Deep space is a significantly more difficult domain than Near-Earth for implementation of optical communications**
  - NASA unique solutions are required to close the "performance gap"
- **Advancement of a few key technologies** will enable a Space Optical Transceiver with Size, Weight and Power (SWaP) attractive to missions
  - 10X data rate performance of Ka band RF for similar Size, Weight, and Power



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