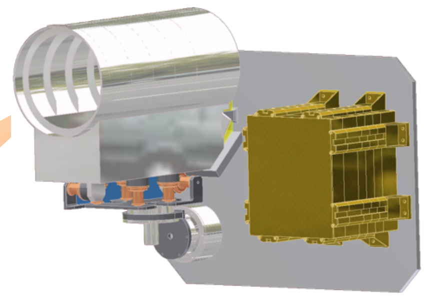


Optical Communications

Presentation to NAC Technology & Innovation Committee

2-August-2011

William H. Farr

Jet Propulsion Laboratory • California Institute of Technology

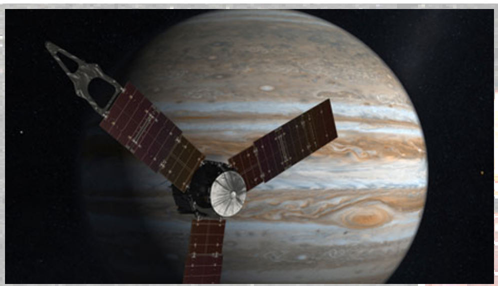
- **Introduction**
- **Technology Status & Development Approach**
- **Summary**

Why Optical Communications?

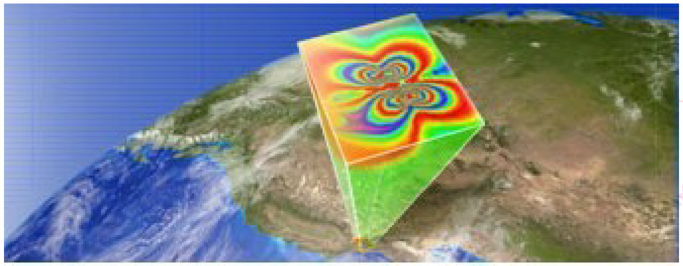
- **10 X to 100X increased deep space data returns over present RF communications**
  - ***Increased science data return***
  - ***"Virtual Presence"***
  - ***Public engagement***

10X Increased Imaging Resolution for Astrophysics

Human Exploration Beyond Low-Earth Orbit



Future Advanced Instruments



10X Increased Resolution Imaging for Earth Science

Tele-Presence with Live HiDef Video

How Optical Improves Over RF

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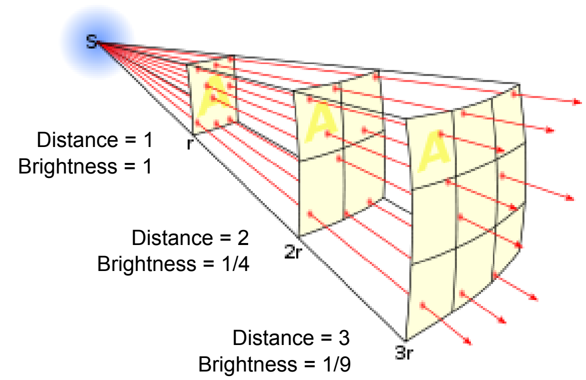
- **As a beam (RF or optical) propagates from transmitter to receiver it illuminates an area proportional to the distance-squared**
  - "Range-Squared Loss" or "Inverse-Square Loss"



- **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)

$$\theta = \lambda / D$$

Different Domains – Different Solutions

- **Just like RF, "one size" does not fit all applications...**
  - Different domains requires different solutions

Space Optical Communications Status

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- **Near Earth**
  - Successful flight demonstration missions by US DoD, ESA, and JAXA
  - ESA is going operational for LEO/GEO missions
- **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 orbital
- **Earth-Sun L1 & L2 Points**
  - Cis-Lunar technologies are sufficient for 10X to 100X improvement in data return volumes
  - Deep-space enhanced technologies would provide for similar data return volumes as cis-lunar technologies with ~1/2 the mass and power burden to the spacecraft

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 and LRO
9. (planned LLCD)

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

Space Propagation Range-Squared Loss

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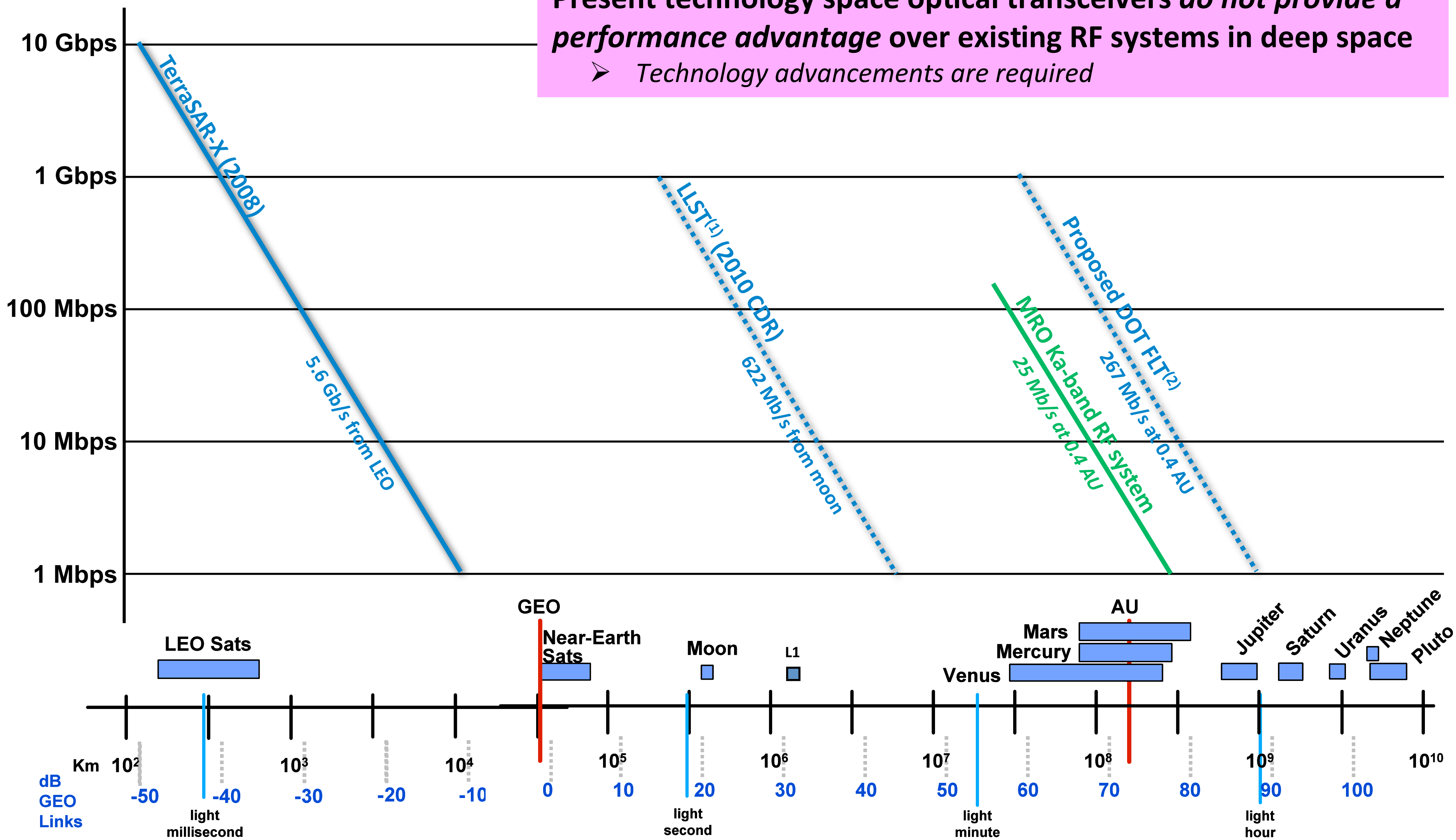
Present technology space optical transceivers *do not provide a performance advantage* over existing RF systems in deep space

- *Technology advancements are required*

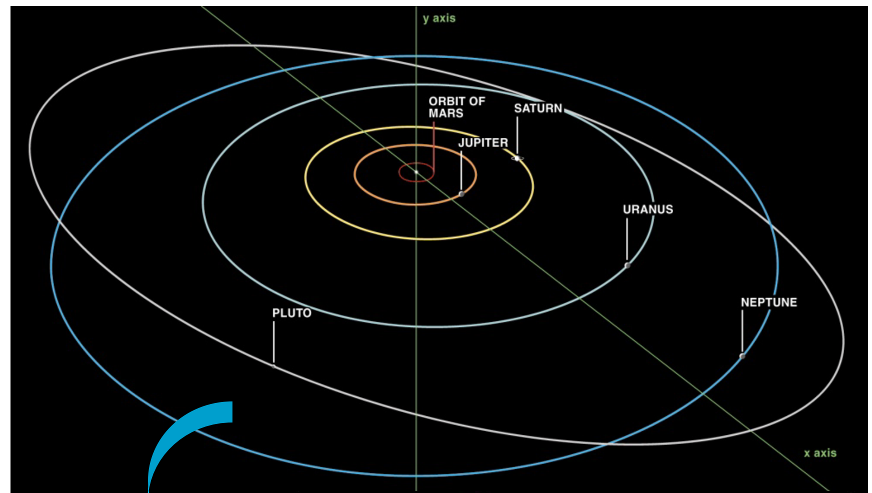


[1]LLCD: MIT-LL Lunar LaserCom Space Terminal, July 2010 CDR

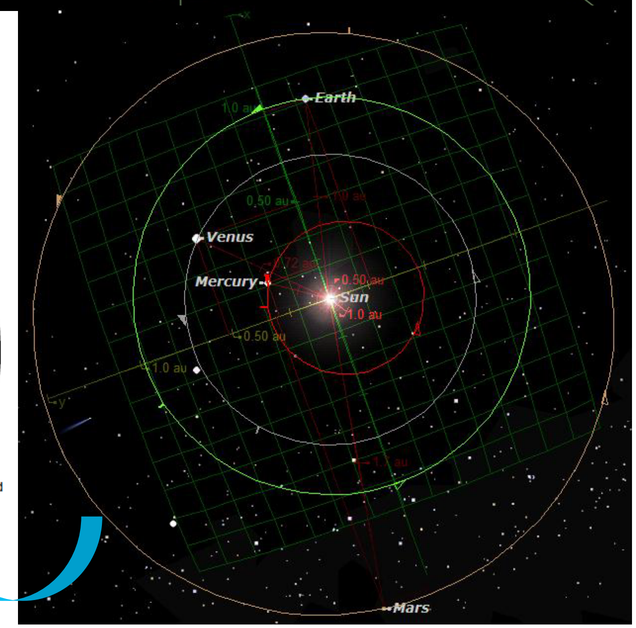
[2]DOT FLT: JPL Deep-space Optical Terminals Flight Laser Transceiver, August 2010 Concept Review

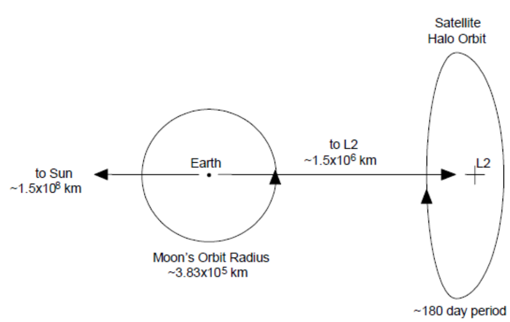
- **International Telecommunication Union definition of deep space for RF spectrum allocation purposes is 2 million km**
  – The moon is about 0.4 million km away
  – The Earth-Sun L1 and L2 points are about 1.5 million km away

- ***However*, interplanetary distances are <u>much larger</u> that that**
  – Mars at typical closest range is about 60 million km
    - 22,500X larger signal loss due to range-squared
  – Venus at typical closest range is about 40 million km
    - 10,000X larger signal loss due to range-squared



~15X





~67X

Deep Space Optical Scenario

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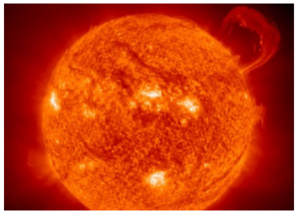
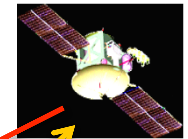


Sun

Can be in field of view

Primary source of optical noise

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



Space Transceiver (ST)

Large distance

Large $1/R^2$ range loss

Large 2R/c round-trip light time (RTLT)

Point-Ahead Angle

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

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

Earth at T_1+RTLT

Earth at T_1

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

Deep space optical communications improves over RF performance by:

- **Pointing:** Narrow beams from small transmit apertures deliver more power "on target"
  - *Requires pointing ~500 times more precise than Ka band RF on the Mars Reconnaissance Orbiter*
- **Modulation:** Pulse Position Modulation (PPM) for more "bits-per-photon" than RF
  - *Requires high peak-to-average power lasers with high DC-to-optical power efficiency*
- **Detection:** Efficient and high rate photon counting both in space an on ground "makes every photon count"
  - *The optical channel is not thermal noise limited*
  - *Requires counting single photons even when pointing multi-meter telescopes near the sun*

- Introduction
- **Technology Status & Development Approach**
- Summary

Deep Space Challenges

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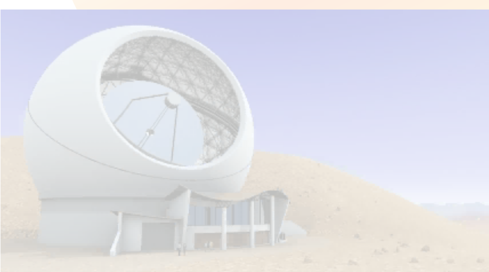
➢ **There is a significant *performance gap* between optical communications solutions developed for commercial and DoD customers and the innovative solutions *required* by NASA for operations across the solar system, especially at interplanetary ranges**

- Large $1/R^2$ losses require NASA unique innovative solutions for ultra-efficient detectors, lasers, and beam pointing
- Launch vehicle delta-V limits require NASA unique innovative solutions for very low mass and power spacecraft assemblies for deep space optical transceivers



Challenges of deep space optical over demonstrated near-Earth solutions:

- **Pointing: Must point downlink using a ~10,000X** dimmer uplink beacon and 100X greater round-trip light time (RTLT)
  - *Requires improved spacecraft disturbance isolation, ultra-sensitive ST detector arrays and point-ahead confirmation without handshaking*
- **Modulation:** Need high order Pulse Position Modulation (PPM 16..128) and multi-Watt lasers to help overcome huge signal loss
  - *~10,000,000X greater loss at Mars far range than moon requires new solutions for kW peak power laser with 5 to > 20 W average powers*
  - *Laser amplifier is largest power consumer on ST*
- **Detection:** Must shift burden from ST by using > 10 m diameter telescope on Earth
  - *Requires large (~1 mm^2) photon counting detector arrays behind telescope due to atmospheric blurring (> 50% detection efficiency desired)*

Technology Development Approach

- ***Objective:*** **Develop a deep space optical transceiver that will deliver greater than 10X data rate of state of the art RF system (Ka-band) for similar spacecraft burden**
  - ***No deep space optical system has yet been built!***
    - Near-Earth optical transceiver designs <u>will not perform</u> at interplanetary ranges due to large range-squared losses

- ***Approach:***
  - ***Develop key technologies*** **for a < 35 kg / < 80W deep space optical transceiver with >250 Mb/s downlink rates at 0.4 AU**
    - *Compare to MRO Ka-band:* 37 kg, 100W, 25 Mb/s @ 0.4 AU
  - ***Integrate and validate technology performance*** **using end-to-end emulated deep space optical links**

Key Technologies for Deep Space Optical Communications

- **Development of four key technologies will enable a deep space optical transceiver with performance greater than 10X data rate of a state-of-the-art Ka band telecom system with similar mass and power burden on spacecraft and similar cost**
  - Although a deep space optical transceiver *could* be built with existing technologies, the mass & power performance is not competitive with existing deep space RF telecommunications systems
  - Key technologies have been identified as offering highest "return on investment"

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 1/3, power by 1/2	Similar mass/power gains presently acheivable 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 1/2	Doubles deep space to Earth date 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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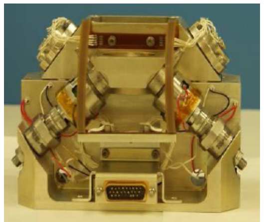
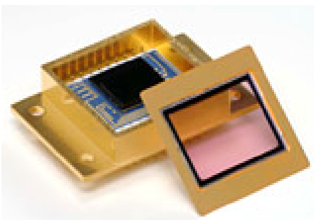


Isolator bipod with 20 dB isolation at 5 Hz (TRL 6)



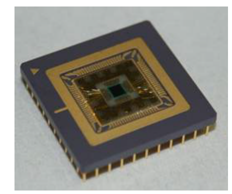
InGaAs array, 10 pW/m^2 for 0.02 pixel centroiding error (TRL 6)

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

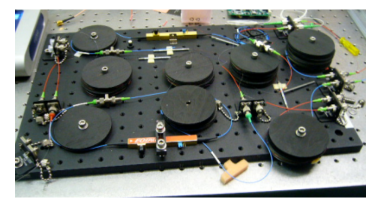
Intensified photodiode for 5 to 12 m apetures (30% efficient, TRL 6)

- **Spacecraft disturbance isolation system with sub-Hertz break frequency**
  - Development will provide 10,000X greater disturbance rejection than SotA for a 1000X reduction in uplink beacon power with a 20% mass reduction of the optical space transceiver
- **Space receiver using a photon counting detector array**
  - 10X higher sensitivity over SotA for a 10X reduction in uplink beacon laser power and enables a > 1000X increase in uplink data rate
- **1550 nm PPM space laser transmitter with > 20% DC-optical efficiency**
  - 2X efficiency improvement over SotA will reduce assembly mass by > 30% and enables doubling of downlink data rate with no increase in required spacecraft power
- **Ground receiver detector array and read-out with greater than 60% efficiency for 5 to 12 meter diameter ground telescopes**
  - 2X efficiency improvement over SotA enables doubling of downlink data rate with no increase in required spacecraft mass or power

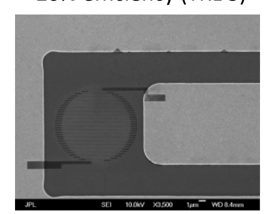
JPL hybrid active/passive strut with 50 dB isolation at 5 Hz (TRL 4)



Photon counting array, 1 pW/m^2 for 0.02 pixel centroiding error (TRL 3)



Part of JPL prototype laser transmitter for >20% efficiency (TRL 3)



JPL superconducting nanowire pixel (> 60% efficient, arrays are TRL 3)

Spacecraft Disturbance Isolation

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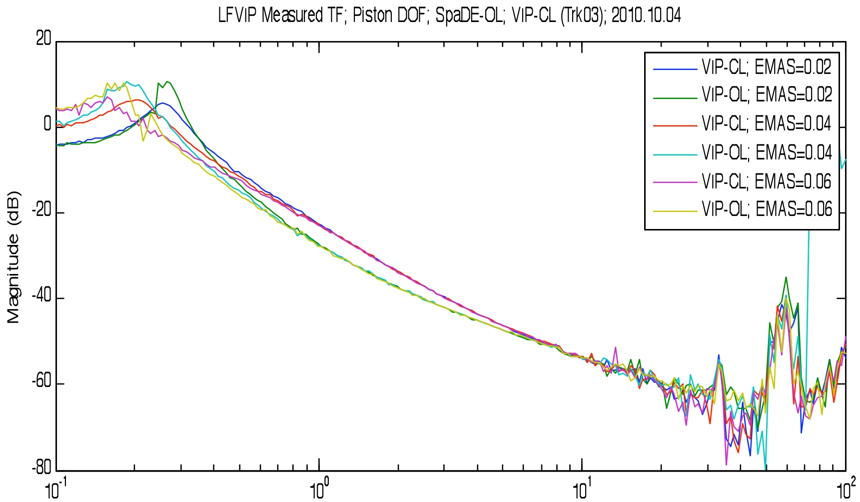
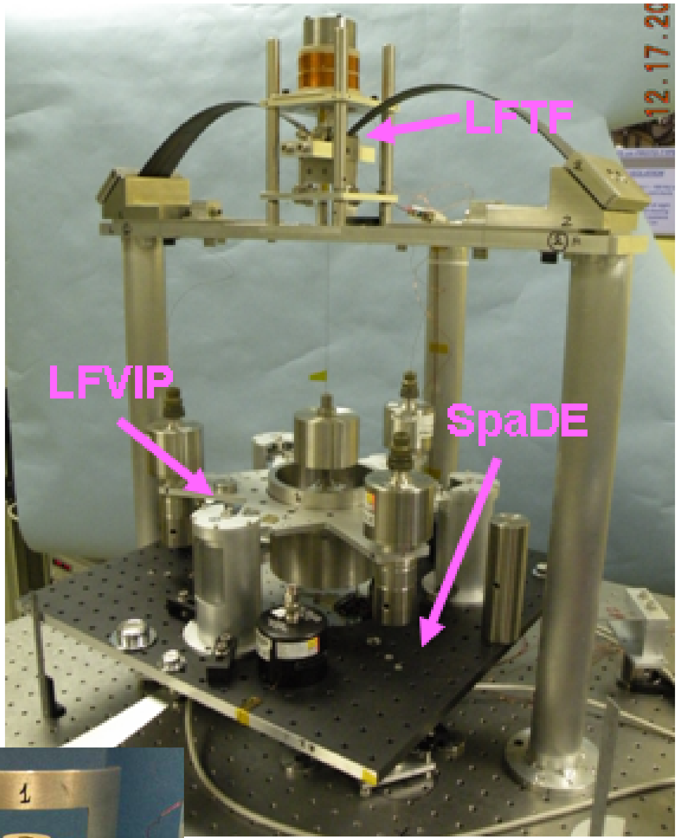
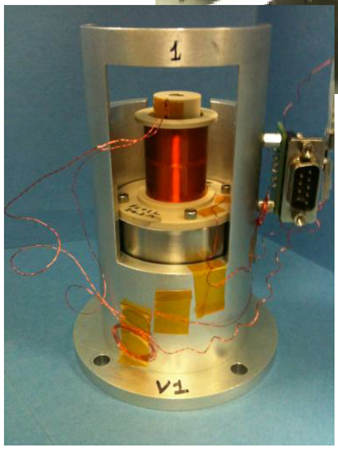
- **INNOVATION: Disturnbance isolation *optimized for operation in microgravity space environment* with a 10X lower passive resonant frequency than SotA for 10,000X better rejection of low frequency vibrations**
  - JPL developed design concept enabled by infusion from Caltech and Columbia University of technology developed for the Laser Interferometer Gravitational Wave Observatory (LIGO)
  - Isolation problem is difficult for low mass payloads
- **CURRENT STATUS:**
  - Prototype Low-Frequency Vibration Isolation Platform (TRL 3-4)
- **IMPACT: Downlink beam pointing using a "dim" beacon and without "hand-shaking" point-ahead verification**







Caltech/JPL developed sub-Hertz disturbance rejection platform can isolate a lasercom payload with greater than 10,000X better isolation than existing low mass / power commercial isolation systems

LFTF – Low Frequency Test Facility
LFVIP – Low Frequency Vibration Isolation Platform
SpaDE – Spacecraft Disturbance Emulator

Space Receiver

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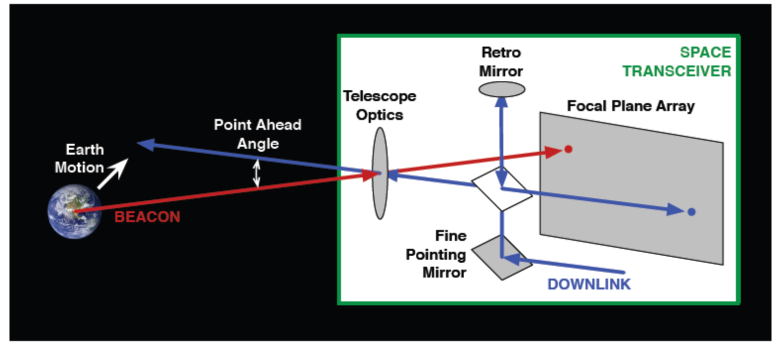
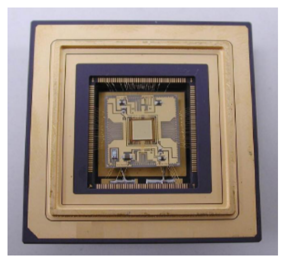
- **INNOVATION: A focal plane array of single photon detectors (SPD) can acquire and track an uplink beacon 10X to 100X better than existing analog focal plane arrays**
  - A focal plane array of single photon detectors (SPD) can achieve optimum (shot noise limited) performance
    - An analog focal plane array performs 10 to 100 times poorer than the shot noise limit due to readout noise

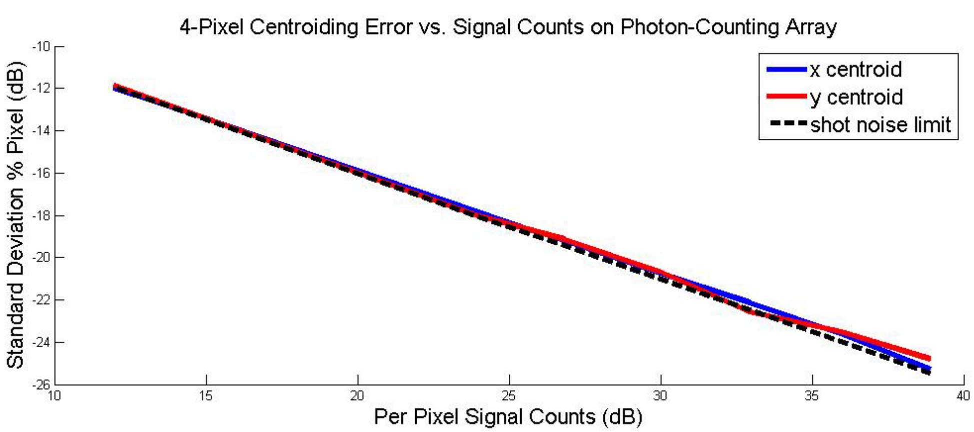


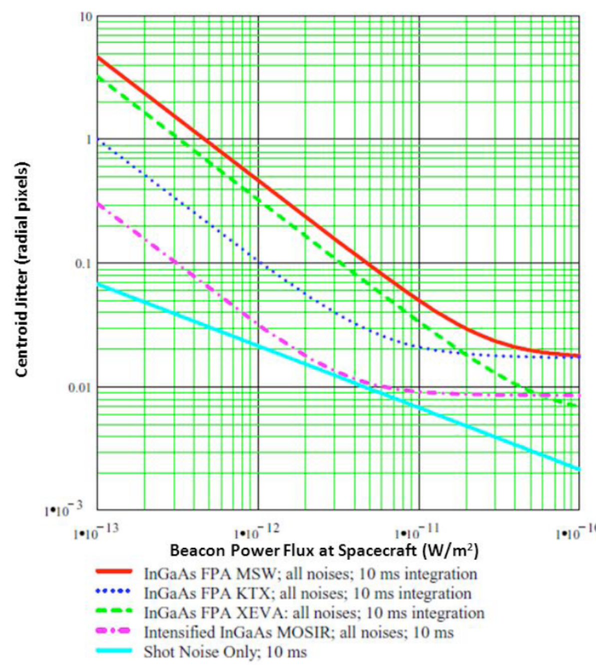
Photon counting array tracks beacon laser, Earth image, and transmit point-ahead with only one optical channel

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

- **CURRENT STATUS:**
  - 6x6 photon counting array demonstrating uplink demodulation plus beacon acquisition and tracking
- **IMPACT:**
  - Increases uplink sensitivity 10X
  - Simplifies space receiver architecture
  - increases uplink rate from < 100 b/s (Si CCD or InGaAs array) to multi-Mb/s
  - Enables cm to mm level ranging







1550 nm PPM Space Laser

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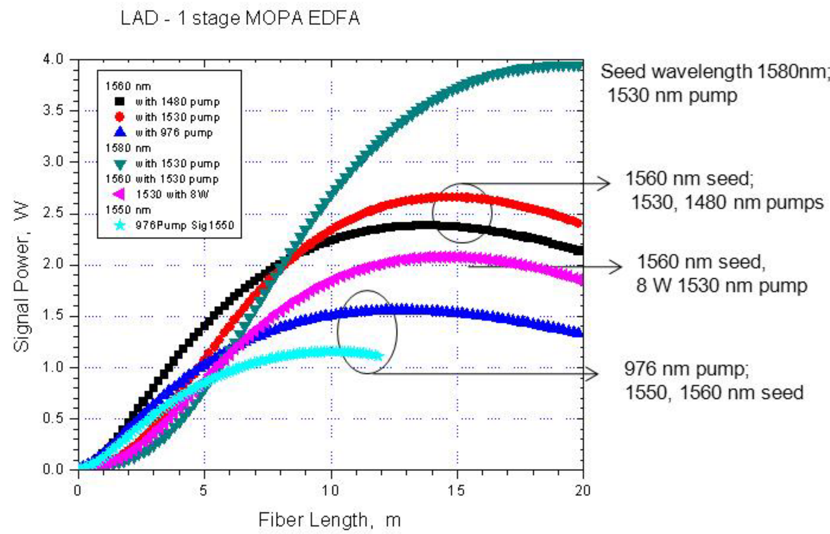
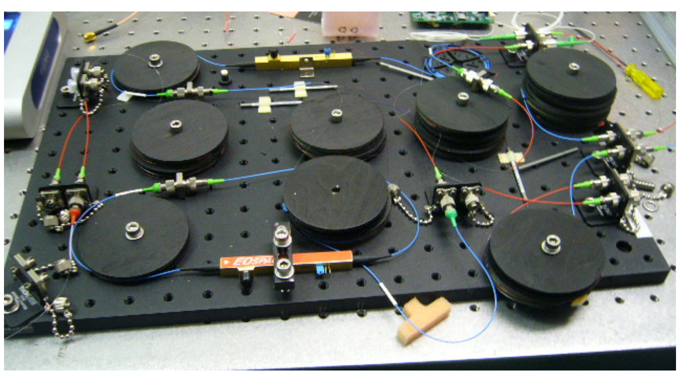
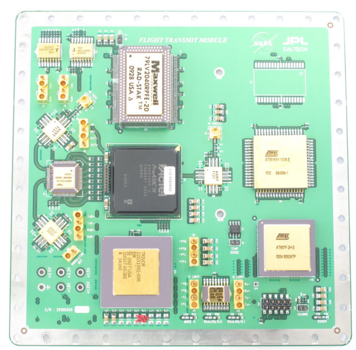
- **INNOVATION: Increase the DC-to-optical efficiency of a 1550 nm PPM laser transmitter by "in-band" pumping of the Erbium fiber laser**
  - Present high power 1550 nm laser amplifier based upon a 976 nm pumped Er-Yb fiber is limited by *63% quantum efficiency*
  - 1470/1530 nm pumped 1550 nm laser amplifier has *93% quantum efficiency*
- **CURRENT STATUS: 1 Watt optical output PPM laser transmitter breadboard**
  - 1530 nm pumped with the potential for > 20% efficiency
- **IMPACT: *Double* the power efficiency with 2/3 mass of present 1550 nm pulse-position modulation (PPM) laser amplifiers**



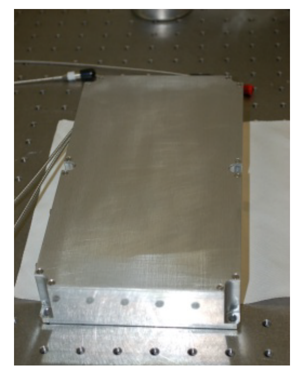
In-band pumped PPM Erbium fiber laser modeling
1530 nm is preferred pump wavelength



Prototype 1550 nm Laser Transmitter



Space Grade PPM Encoder
Enables 267 Mb/s from Mars



976 nm PPM Laser Amplifier
1550 nm, 2W, TRL-5

Ground Receiver Detector Array

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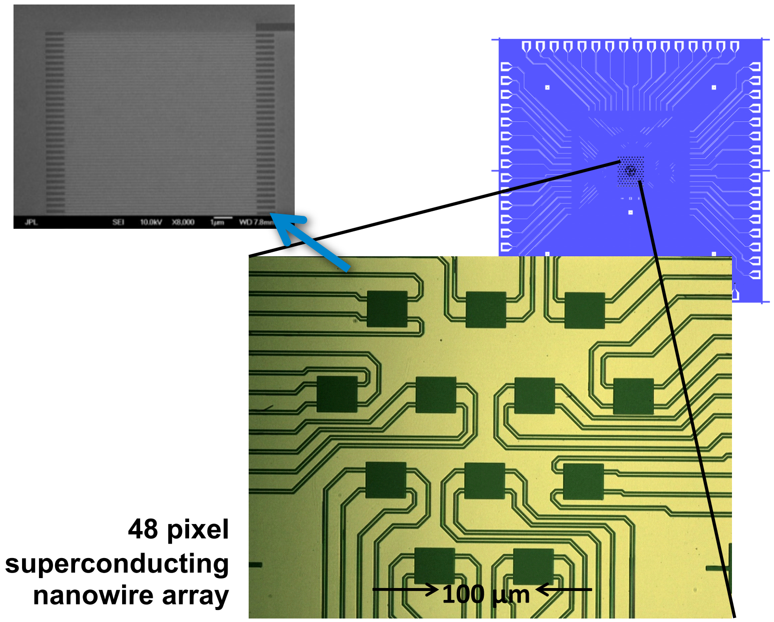
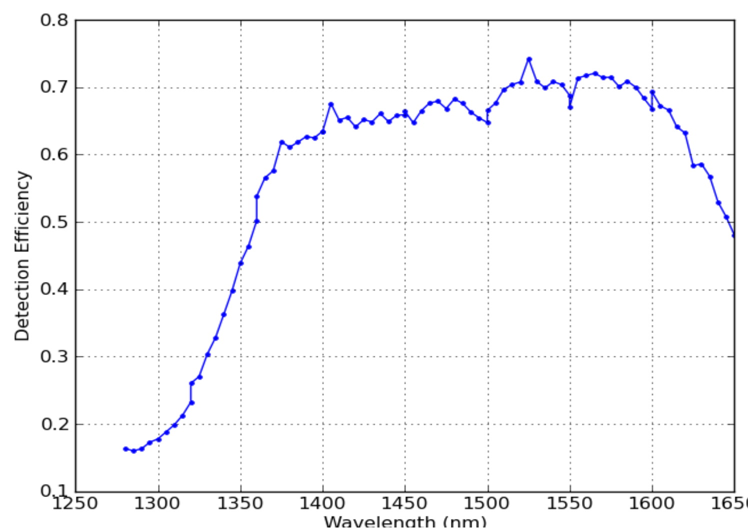
- **INNOVATION: A ground receiver using superconducting nanowire single photon detectors can achieve > 50% photon counting efficiency**
  - compared to 30% for best commercial photon counting detector, the Intensified PhotoDiode (IPD) from Intevac Corp. (at 1550 nm)
- ***Large arrays of SNSPDs presently have low yield***
  - Arrays of hundreds of pixels are required to detect light behind multi-meter optical receivers
- **CURRENT STATUS:**
  - 8 pixel arrays in NbN material system with ~50% efficiency, but < 50% yield
  - 48 pixel arrays in NbTiN material system with 15-20% efficiency, but < 50% yield
  - Single pixels in new WSi_X material system with > 70% efficiency
    - Very promising because superconducting critical current characteristics indicate potential for high yield
- **IMPACT:**
  - Double the downlink data rate without any increase of optical transceiver mass and power on spacecraft
  - Save over $38M per optical ground station as compared to using present 4 pixel SNSPD arrays



48 pixel superconducting nanowire array



Broad Range high Efficiency Detection with new WSi_x SNSPDs

Technology Development Goals versus State of the Art

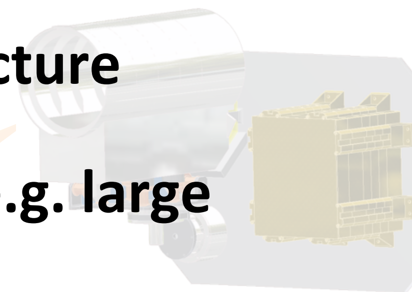
Parameter	Requirement			Goal	Notes
	Near-Earth	*TRL 5-6 SOTA*	*Deep Space*		
Space Receiver sensitivity	~ -13 dBm 40 Gb/s	~ -17 dBm 40 Gb/s	~ -90 dBm 1 Mb/s	~ -90 dBm 1 Mb/s	Reduces deep space uplink laser power from MW to kW
Space Receiver array size	2x2	2x2	32x32 to 128x128	32x32	Near-Earth does not require single photon sensitive detectors
Space Laser transmitter bandwidth	> 10 GHz	10 GHz	5 GHz	-	Deep space requirement is met by SOTA performance
Space Laser DC-Optical Power Efficiency	< 10% is acceptable	~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	Must achieve this isolation with low mass/power assembly when using a dim uplink laser beacon
Spacecraft Disturbance Isolation break frequency	~ 5 Hz	~ 2 Hz	< 0.5Hz	< 0.3 Hz	Driver is dim beacon; low payload mass makes isolation difficult
Ground Receiver photon counting detector efficiency	~ 30%	30%	50%	60%	Must maintain this sensitivity at Gb/s data rates when coupled to large ground apertures
Ground Receiver array size (units of spatial modes)	1 to few	84	> 4000	> 1600	To match large apertures that collect maximum receive power

Achieving requirements with minimal spacecraft burden is an overriding concern

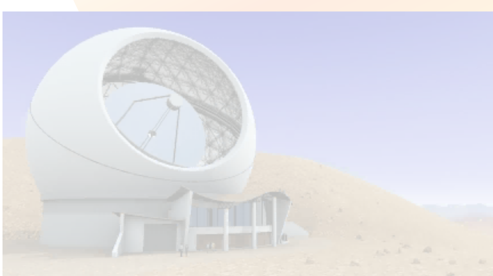
- *Due to mass, power, and delta-V drivers that are critical for deep space missions*

- Introduction
- Technology Status & Development Approach
- **Summary**

Unique NASA Lasercom Needs yet to be Demonstrated



- High-rate, long-delay communications architecture
- Demonstration of NASA-unique subsystems (e.g. large point-ahead, large ground collectors)
- Optical space terminal(s) designs and operations
- Optical ground terminal(s) designs and operations



Proposed GCD Deep Space Optical Communications Technology Development

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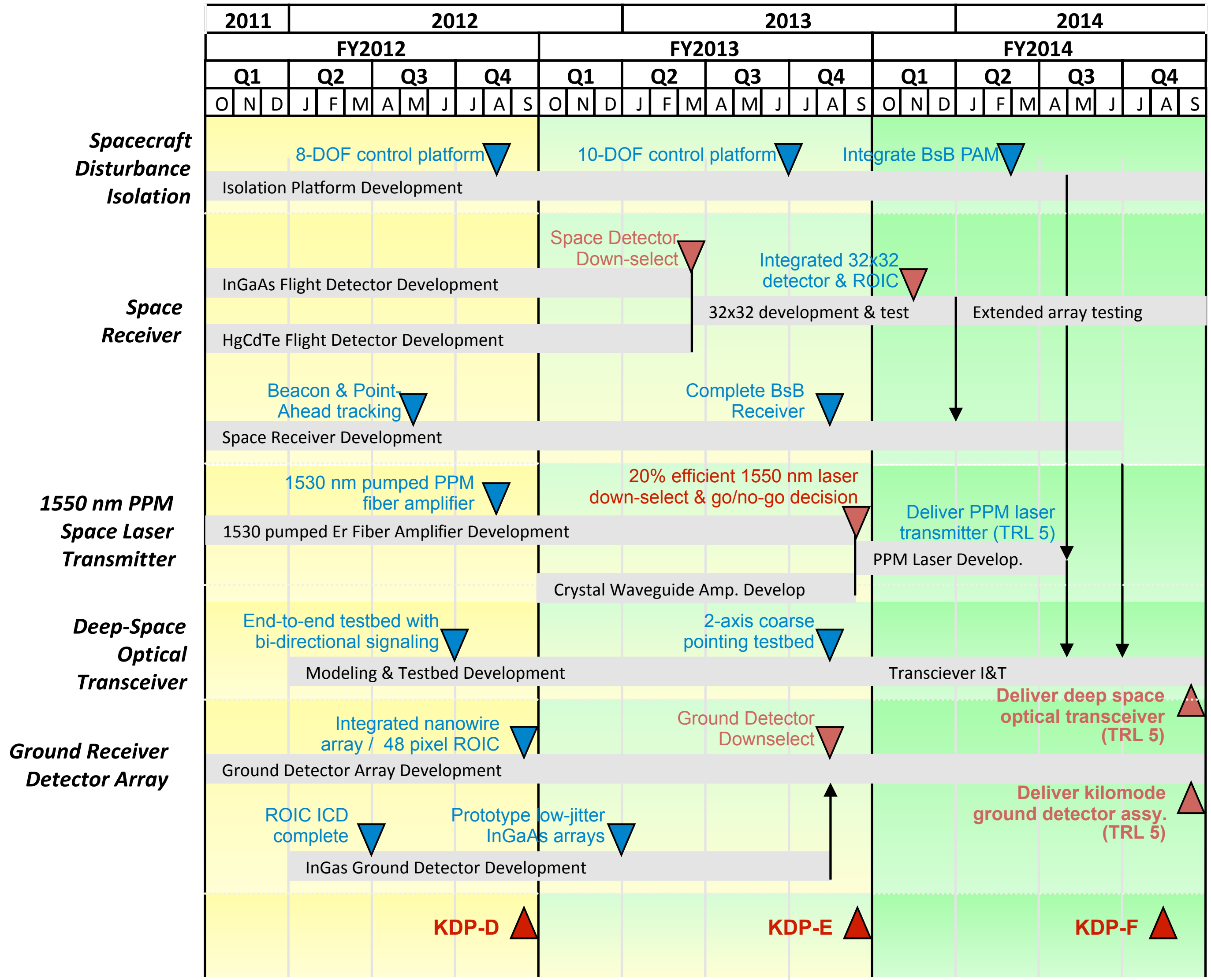

Other Benefits of Technology to NASA

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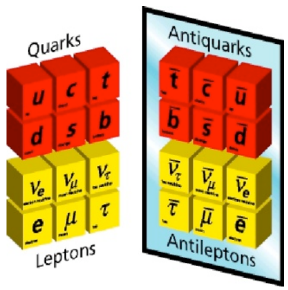
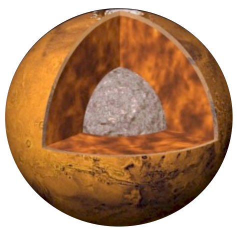
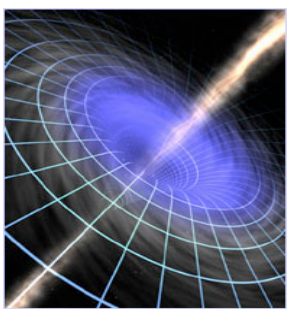


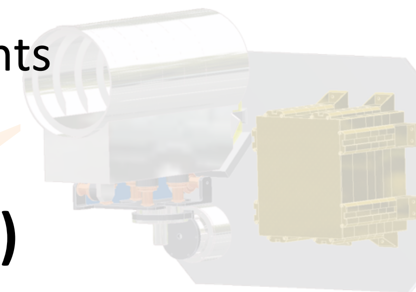




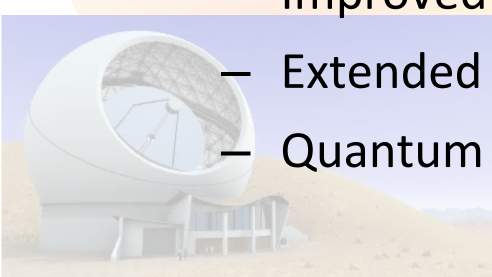
- **Optical Light Science**
  - Tests of physics beyond the standard model
  - Tests of time variation of fundamental physics constants
- **Precision ranging (cm and mm scale) for planetary studies and astrophysics**
  - Determination of planetary interiors
  - Tests of Parametric Post-Newtonian gravitational 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

Other Benefits Beyond NASA

Jet Propulsion Laboratory
California Institute of Technology

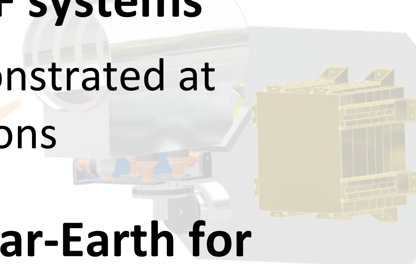


- **Disturbance Isolation**
  - Improved vibration isolation for laboratory instruments
  - Vibration isolation for nanofabrication
- **Single Photon Detector Arrays (semiconductor)**
  - Reduced dose for CAT and PET scans
  - Optical tomography
  - Advanced biosensors for multiplexed detection of biomolecules and detection of radiological, biological, and chemical agents
- **Single Photon Detector Arrays (Superconducting)**
  - Improved defect analysis in semiconductor fabrication processes
  - Extended range quantum key distribution
  - Quantum computing



Conclusions

- **Space optical communications has the potential to deliver 10-100X higher data rates from 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
  - *Innovations in disturbance isolation, photon counting detector arrays for ground and space, and efficient lasers enable this performance improvement*