Optical Communications

Presentation to NAC Technology & Innovation Committee

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• Introduction
• Technology Status & Development Approach
• Summary
10 X to 100X increased deep space data returns over present RF communications

- Increased science data return
- “Virtual Presence”
- Public engagement

Future Advanced Instruments

10X Increased Imaging Resolution for Astrophysics

Human Exploration Beyond Low-Earth Orbit

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": \(\text{beam width} = \frac{\text{wavelength}}{\text{antenna diameter}}\)
  
  - Example: Beam width from 30 cm optical antenna at 1550 nm is \(\sim 600X\) narrower than the beam width from a 300 cm RF antenna at 9.2 mm (32 GHz, Ka band)
Different Domains – Different Solutions

- Just like RF, “one size” does not fit all applications...
  - Different domains requires different solutions
Space Optical Communications Status

• **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

No deep space optical communications has yet been demonstrated
• Lasercom from Earth-orbit is well-proven and is transitioning to operations
Present technology space optical transceivers do not provide a performance advantage over existing RF systems in deep space. Technology advancements are required.
Deep Space

- 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 much larger than 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
Deep Space Optical Scenario

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

Earth at \( T_1 + R T L T \)

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

Space Transceiver (ST)
- Large distance
  - Large \( 1/R^2 \) range loss
  - Large \( 2R/c \) round-trip light time (RTLT)

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

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

Earth at \( T_1 \)

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

Point-Ahead Angle
• Introduction
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Deep Space Challenges

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 mm²) photon counting detector arrays behind telescope due to atmospheric blurring (> 50% detection efficiency desired).
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 will not perform 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
• 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”

<table>
<thead>
<tr>
<th>Assembly or Sub-Assembly</th>
<th>Savings with Technology Development</th>
<th>Comment</th>
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<tbody>
<tr>
<td>Space Telescope</td>
<td>minimal</td>
<td>Unless apertures &gt; 50 cm required (multi-Gb/s at Mars far range)</td>
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<tr>
<td>Space Electronics</td>
<td>minimal</td>
<td>Some mass and power savings with ASIC development ($$$)</td>
</tr>
<tr>
<td>1550 nm PPM space laser transmitter</td>
<td>Reduce transmitter mass 1/3, power by 1/2</td>
<td>Similar mass/power gains presently achievable if downlink wavelength shifted to 1070 nm</td>
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<tr>
<td>Spacecraft Disturbance Isolation</td>
<td>~20% of space transceiver mass</td>
<td>Existing disturbance isolation systems not optimized for low mass (&lt;~20 kg) payloads</td>
</tr>
<tr>
<td>Space Receiver Detector Array</td>
<td>10X reduction in uplink irradiance</td>
<td>Also enables &gt;10 Mb/s Earth to deep space optical links</td>
</tr>
<tr>
<td>Pointing Mechanisms</td>
<td>minimal</td>
<td>Multiple commercial solutions exist</td>
</tr>
<tr>
<td>Ground Telescope</td>
<td>~$50M per deep space optical site</td>
<td>Existing assets sufficient for deep space tech demo mission; &gt; $50M to develop first dedicated deep space optical site</td>
</tr>
<tr>
<td>Ground Electronics</td>
<td>minimal</td>
<td>Existing solutions operate within 2 dB of theoretical performance</td>
</tr>
<tr>
<td>Ground Receiver Detector Array</td>
<td>Reduce space transmitter mass and power by 1/2</td>
<td>Doubles deep space to Earth date rate with no change to space transmitter laser power</td>
</tr>
<tr>
<td>Ground laser transmitter</td>
<td>minimal</td>
<td>But ground laser NRE investment needed for &gt; 1 kb/s Earth to deep space optical rates</td>
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</table>
Key Technologies Objectives versus State of the Art (SotA)

- **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
Spacecraft Disturbance Isolation

- **INNOVATION**: Disturbance 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

- **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

- **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

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*
1550 nm PPM Space Laser

- **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
• **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 WSiₓ 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
# Technology Development Goals versus State of the Art

<table>
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<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Goal</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td><strong>Space Receiver</strong> sensitivity</td>
<td>~ -13 dBm 40 Gb/s</td>
<td>~ -90 dBm 1 Mb/s</td>
<td>Reduces deep space uplink laser power from MW to kW</td>
</tr>
<tr>
<td><strong>Space Receiver</strong> array size</td>
<td>2x2</td>
<td>32x32 to 128x128</td>
<td>Near-Earth does not require single photon sensitive detectors</td>
</tr>
<tr>
<td><strong>Space Laser</strong> transmitter bandwidth</td>
<td>&gt; 10 GHz</td>
<td>5 GHz</td>
<td>Deep space requirement is met by SOTA performance</td>
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<tr>
<td><strong>Space Laser</strong> DC-Optical Power Efficiency</td>
<td>&lt; 10% is acceptable</td>
<td>&gt; 20%</td>
<td>Driver is to reduce power and mass burden on spacecraft</td>
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<tr>
<td><strong>Spacecraft Disturbance Isolation</strong> below ~3 Hz</td>
<td>-</td>
<td>&gt; 20 dB</td>
<td>Must achieve this isolation with low mass/power assembly when using a dim uplink laser beacon</td>
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<tr>
<td><strong>Spacecraft Disturbance Isolation</strong> break frequency</td>
<td>~ 5 Hz</td>
<td>&lt; 0.3 Hz</td>
<td>Driver is dim beacon; low payload mass makes isolation difficult</td>
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<tr>
<td><strong>Ground Receiver</strong> photon counting detector efficiency</td>
<td>~ 30%</td>
<td>50%</td>
<td>Must maintain this sensitivity at Gb/s data rates when coupled to large ground apertures</td>
</tr>
<tr>
<td><strong>Ground Receiver</strong> array size (units of spatial modes)</td>
<td>1 to few</td>
<td>&gt; 4000</td>
<td>To match large apertures that collect maximum receive power</td>
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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
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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
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<th>2012</th>
<th>2013</th>
<th>2014</th>
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<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
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<tr>
<td><strong>Q1</strong></td>
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<td>J F M</td>
<td>M A M</td>
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<td><strong>Q2</strong></td>
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**Spacecraft Disturbance Isolation**
- 8-DOF control platform
- 10-DOF control platform
- Integrate BsB PAM

**Space Receiver**
- InGaAs Flight Detector Development
- HgCdTe Flight Detector Development
- Beacon & Point, Ahead tracking
- Space Detector Down-select
- Integrated 32x32 detector & ROIC
- 32x32 development & test
- Extended array testing

**1550 nm PPM Space Laser Transmitter**
- 1530 nm pumped PPM fiber amplifier
- 1530 pumped Er Fiber Amplifier Development
- Crystal Waveguide Amp. Develop
- End-to-end testbed with bi-directional signaling
- 2-axis coarse pointing testbed
- Transceiver I&T
- Deliver PPM laser transmitter (TRL 5)
- PPM Laser Develop.

**Deep-Space Optical Transceiver**
- Integrated nanowire array / 48 pixel ROIC
- Modeling & Testbed Development
- Transceiver I&T
- Deliver deep space optical transceiver (TRL 5)

**Ground Receiver Detector Array**
- ROIC ICD complete
- Prototype low-jitter InGaAs arrays
- InGas Ground Detector Development
- Deliver kilomode ground detector assy. (TRL 5)

**Ground Detector**
- KDP-D
- KDP-E
- KDP-F
Other Benefits of Technology to NASA

- **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

- **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**