Interstellar Optical Communications

Study for KISS Workshop (January 12, 2015)

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Interstellar Optical Communications

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

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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 *reasonable extrapolation* 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
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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°
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 \(\mu\)m\(^2\)) 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 Reconnaissance 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)

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• 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

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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

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

Bar chart showing data-rate (kb/s) for different conditions and power levels.
Option 1: Single 4 mrad focal plane for acquiring and tracking Sun from 250 AU
- 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

Option 2: Use separate focal planes for imaging Sun and Earth (4 mrad and 0.4 mrad)
- 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
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: ~4x10^-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
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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 time

- 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
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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
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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
• 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
Initial estimate of mass and power

<table>
<thead>
<tr>
<th></th>
<th>Mass</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
<td>58</td>
<td>5</td>
</tr>
<tr>
<td>Laser</td>
<td>25</td>
<td>500</td>
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<tr>
<td>Electronics</td>
<td>15</td>
<td>20</td>
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<tr>
<td>Cables</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>110</strong></td>
<td><strong>530</strong></td>
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</tbody>
</table>