Jet Propulsion Laboratory
California Institute of Technology

OPTICAL COMMUNICATIONS NODE IN SPACE
Space Technology

Overview:

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Collaborators:
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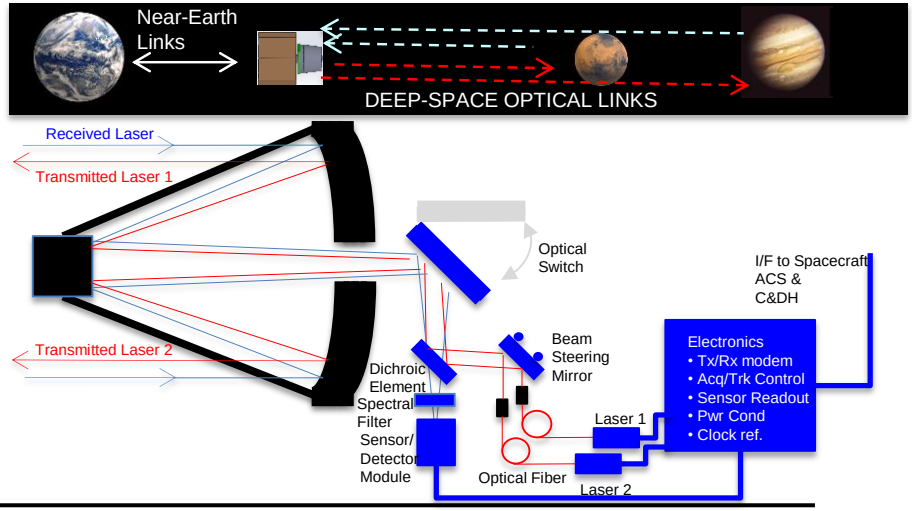
External: Bob Marshalek, Ball Aerospace Corporation

- Design of optical transceiver in space
  - Architecture trades
  - Design trades
- Spacecraft requirements and integration of optical transceiver
- Demonstration Opportunities

Graphic:



Description:

- Study an optical communication node in space to guarantee reliable services to/from deep-space assets throughout the solar system
  - Overcome cloud/weather outages of ground-based receivers
- Design optical transceiver behind large optics deployed at Earth/Sun L2
  - Receive downlink from deep space assets at Mars, asteroids, outer-planets
  - Transmit space-based laser beacon anywhere in solar system (not possible from ground telescope) for communications, navigation and high-precision ranging
  - Explore dual use incoherent and coherent optical receiver
  - Sharing with other instruments not precluded
- Technologies at TRL5-9, except for space-based optical receiver (TRL3-4); being advanced with Office of Chief Technologist funding
- Partner with Ball Aerospace & Technologies Corporation (BATC) and leverage their experience in implementing space optical systems

Value to NASA:

- Future NASA missions will require enhanced communication and navigation services for human exploration and high resolution science instruments. Optical communication has been identified for augmenting the sate-of-the art. This proposal accelerates implementation of optical communication by:
  - Guaranteeing reliable service without a full-blown ground network
  - Extending the reach of optical communication throughout solar system without requiring the development of beaconless communication to ground assets

Large 10m diameter ground telescope (2021) and beaconless pointing from space (2022) are currently called out in NASA's Communication and Navigation Systems Roadmap. Proposed work will augment ground network limiting number of operating nodes and provide a robust alternative for beaconless pointing of deep-space optical communication terminals

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OPTICAL COMMUNICATIONS NODE IN SPACE

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Primary Concept Goal Category:

Space Technology

Abbreviated Concept Summary:

Utilizing large space optics as the front-end for a deep-space optical communications node is proposed. Compared to ground-based optical telescopes an optical transceiver coupled to large space optics can provide highly reliable deep-space optical communication services by completely avoiding link outages due to cloud cover. Furthermore, severe limitations caused by a combination of atmospheric-effects and scattered additive background noise on deep-space links with ground telescopes can be overcome. Transceiver architecture trades combined with orbit selection and spacecraft resources will be studied to design such a system. Optical communication, navigation and high precision laser ranging services with excellent coverage, to the farthest reaches of the solar system will be targeted. Future deep-space human missions and high-resolution science instruments will benefit from this capability. The transceiver design will not preclude adding science instruments to the optical node, thereby, extending functionality.

Goal of the Proposed Application:

The goal of this proposal is to design a transceiver that can be coupled to large space optics in order to serve as an optical communication node in space. The effort will target a design for space-deployment in the 2020 timeframe. Deep-space optical communication assets under consideration for Mars and/or asteroids can avail services provided by the proposed node. Link demonstration opportunities with existing near-Earth-orbiting or ground optical assets will be identified, as a precursor to deep-space operations.

The key goals are:

(i) Design of the optical transceiver with a concept of operations
(ii) Identifying special spacecraft requirements such as thermal design for near sun pointing
(iii) Demonstration opportunities

Orbit Selection

Orbit selection is motivated by accessibility to extended contact time with future deep-space assets. Based on this the optical communications node would be placed in a Halo orbit about the Sun-Earth L2 Lagrange point. This location allows a single node to provide a near continuous communications link with robotic and human planetary spacecraft throughout the Solar System. Communications links would only be limited by Solar Conjunction periods with the communication node being able to point within 2° of the Sun. The 2° limitation will be further analyzed, it is proposed as an allocation now, in order to keep the Sun at the edge of the 1.8° telescope field-of view. The required slew rates at Sun-Earth L2 are minimal compared to what would be required in Low Earth Orbit (LEO) thereby avoiding the complexity of carrying a gimbal for coarse pointing. Either a Falcon 9 or Atlas V 511 class launch vehicle is capable of injecting the spacecraft on trajectory to Earth-Sun L2 (a Falcon 9 could inject 3715 kg to the required C3 of -0.7 km^2/s^2).

Flight System

Incorporation of the available 2.4m telescope hardware into a flight system for the optical communications node has been studied and should be straightforward, requiring comparatively modest spacecraft performance relative to many observatory applications. A baseline spacecraft concept has been developed that would accommodate the Outer Barrel and Forward Optics Assemblies with the optical transceiver into a flight system with

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dry mass of ~3050 kg (~3180 kg wet mass). A monopropellant propulsion system would provide up to 150 m/s total delta-V capability that should be sufficient for a minimum 10 year life at Earth-Sun L2. The spacecraft would use star cameras and reaction wheels with disturbance damping to achieve pointing control of 30 arcsec and stability better than 0.25 arcsec over 10 s. Solar arrays would provide 2500W of power for the baseline concept, but this could be expanded to accommodate additional laser power to enable access to Pluto-type distances. The C&DH subsystem provides ample interfaces for the optical communications system and the ACS, and includes memory capability up to 128 Gb with the baseline card, expandable with additional cards.

Any special thermal design considerations arising due to the desire to point the optics within 2° of the Sun will be a subject of study.

The flight system would relay data to Earth from the Sun-Earth L2 location using a 20W RF transmitter operating in near-Earth Ka band frequencies. Maximum data rate to the DSN (34m BWG) would be 100 Mbps using a 0.5m HGA on the spacecraft. The inclusion of optical terminals for this link building upon near future successful demonstrations of the Lunar Laser Communication demonstration (LLCD) and Laser Communication relay Demonstration (LCRD) may allow further boosting this rate.

Benefits of the Application:

Receiving faint deep-space optical signals reliably and transmitting lasers to the farthest reaches of the solar system are the benefits of an optical node in space that cannot be matched by ground assets.

To further illustrate this Figure 1 compares deep-space downlink from Mars, Europa and Pluto to ground telescopes (5-12m dia.) versus a space telescope (2.37 m dia.). The average laser power and transmitter aperture diameter are indicated in Figure 1. Laser peak power was conservatively limited to 640 W. Identical photon-counting pulse-position modulation (PPM) receivers are presumed in all cases. For ground telescopes decreasing Sun-Earth-Probe (SEP) angle with increasing range, in the presence of atmospheric scattering and

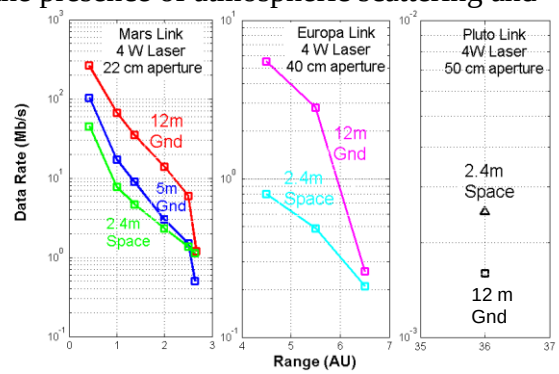

Figure 1

turbulence results in performance loss proportional to $1/R^n$ where R is the range and n can be as high as 4. Negligible additive background noise for space telescopes result in the expected $1/R^2$ link loss dependence. As a result Figure 1 shows that link performance for Mars and Europa with a much smaller diameter space telescope converges at farther ranges. For Pluto at 36 AU and 20-deg SEP angle the space telescope performs slightly better than a 12 m ground telescope. For Mars 40% of the contact time is spent at > 2 AU distances, with 66% of contact time experiencing daytime sky from the ground. For outer planets nearly 50% of the mission will experience daytime sky from the ground.

Approximately 33% coverage from a single ground station due to earth rotation is effectively reduced to 15-20% with typical 50-60% cloud outage. By comparison a space node with nearly 100% availability will return comparable or larger data-volumes from deep-space even though the aperture diameter is much smaller.

Based on considerations of weather outage and contact time limited by Earth rotation a 2.4 m node in space can provide comparable or slightly higher data volumes than a much larger single ground telescope.

The remote terminal in deep-space links requires a laser beacon from Earth for link

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acquisition, and pointing control, especially because of the large point-ahead angles. An optimistic estimate of the distance reachable with a ground laser is 10 AU (Saturn). Once again the atmosphere puts a hard constraint as illustrated by Figure 2. Decreasing laser beam divergence results in increased atmospheric loss so that net transmitted gain stays nearly constant (green line). On the other hand, the irradiance per watt transmitted from the ground to Mars can be extended past Saturn and close to Neptune with 5-10 μrad beam divergence lasers transmitted from space platforms. Pointing control of such laser beams has been demonstrated in space already. With improved technology and narrower laser beams reaching the edge of the solar system will be possible.

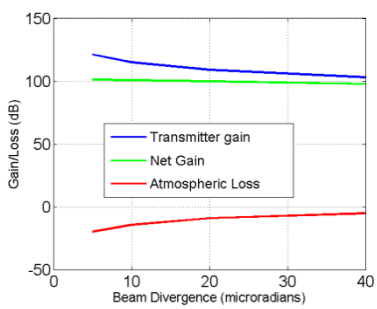

Figure 2

Another advantage with a space based receiver is the ease of implementing coherent communications from deep-space. Coherent receivers can be 2-4 dB worse than photon counting receivers at background noise levels encountered in space. However, homodyne coherent optical receivers are space proven whereas photon-counting receivers for space need development, both in terms of high-performance detectors and the required cryo-engineering.

Top-level Description of the Design, Operation, and Results:

The optical design concept is presented in Figure 3 below. An optical switch will enable sharing the large optics with other instruments. The transceiver electronics will house transmit and receive modem electronics, acquisition and tracking controllers, readouts and controls for sensors and actuators, power conditioning and timing circuitry.

Transmitters will be comprised of fiber coupled lasers with beam-steering for point-ahead. Optical isolation of > 150 dB between transmit/receive paths through wavelength selection and dichroic/spectral filter design is planned.

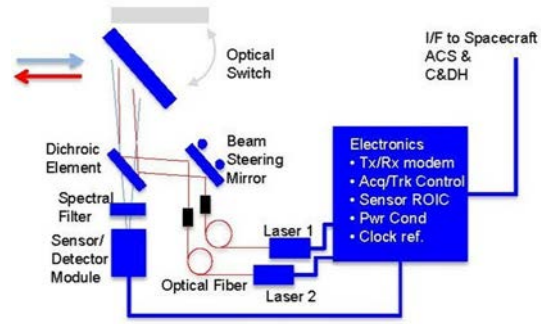

Figure 3

For lasers a current best estimate (CBE) 10 kg/100 Watt with 30% electrical-to-optical efficiency was used. 500 W of transmitter power capable of accessing Jupiter distances is base lined. Increasing transmitter range will drive mass and power.

The implementation of both photon-counting and coherent receivers will be explored for best communication performance and unique light science will be enabled by detecting optical signal phase, intensity and polarization state.

The CBE for the optical transceiver mass and power is 246 kg and 1080 W. Partnering with Ball Aerospace & Technologies Corporation (BATC) will leverage their experience is deploying space optics.

Pointing the laser beacon to the deep-space assets using on-board pointing control and beam-steering will acquire the deep-space link. Using sufficiently bright celestial objects as a pointing reference with the wide-field optics will be explored. Modest uplink data-transfer (0.1-200 kb/s) will be achievable with beacon modulation. High precision ranging can also be achieved with suitable clocks on the remote terminal.

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