Status of Free-Space Optical Communications Program at JPL

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Abstract - Optical communications is a rapidly developing technology applicable to future NASA and commercial space missions that desire a communications terminal that provides a higher data rate with lower mass and power. An experimental transmitter that will downlink data at the rate of 2.5 Gbps from the International Space Station is being constructed now. Under its X2000 program, JPL plans to develop a deep space optical communications transceiver for micro-spacecrafts that would, in an early demonstration, support 10's of Kbps data-rate from the Mars range. NASA is currently building a 1-m R&D telescope laboratory at its Table Mountain Facility in southern California to answer key implementation questions of this technology. The telescope is designed with fast tracking capability and will act as a testbed for development of ground acquisition, tracking and communications strategies applicable to future operational stations. These and other programs currently under development are described below.

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1. INTRODUCTION

Future missions will fly smaller spacecraft with instruments that will generate greater data volumes than current spacecraft. Synthetic aperture radar (SAR), multispectral imagers and high-rate sensors are driving this requirement. Conventional deep-space RF communication systems (particularly X-band) will have difficulty satisfying these needs due to limited bandwidth allocations, over-subscription of the ground receiver network, and technology limitations. At the same time, the trend towards smaller spacecraft will dictate that the communication system relaying those data be much smaller in size. Free-space optical communications is an emerging technology under development for addressing the increased communication capacity and reduced size requirements. Optical Communications is seen as the technology that will meet these needs for future near-earth, solar system and interstellar missions. Free-space laser-communications has the promise of delivering as much as 10 times higher data-rate with 10 times reduced size and lower mass, relative to the conventional spacecraft communication technology (assuming the same input DC power). The technical merit of laser communications is derived from the fact that it offers a much higher collimated signal than conventional microwave. This super-collimated beam, can result in a terminal design with greatly reduced size, mass, and power requirements. Furthermore, laser communication systems are not susceptible to radio-frequency interference and are not subject to bandwidth regulation. Additionally, the higher data return rates afforded by optical communications reduce the required ground coverage time that is needed to recover the science data. This results in a reduced ground operations cost.

An optical diagram of a typical deep-space transceiver is shown in Figure 1. It consist of a 10 to 30 cm transmit/receive aperture, a diode-pumped solid-state laser transmitter with 1 to 5 W average output power for downlink, 1 to 2 focal-plane arrays (such as Active Pixel Sensors) for acquisition and tracking, a single-element photodiode for uplink command and ranging reception, and a fine-pointing mirror to remove the spacecraft platform jitter.

The top-level requirements for a typical deep space transceiver are:

- Downlink capability of several 100's of Kbits/s (Kbps) and uplink reception capability of at least 2 Kbps
- Acquisition, tracking and reception of uplink command while transmitting a strong downlink signal through the same aperture
- Proper pointing of the highly collimated laser beam to earth while the host spacecraft is oscillating, jittering, contracting and expanding. Maintaining pointing of the transmit signal during daytime reception with an absolute accuracy on the order of micro-radians.
- Acquisition and tracking of the ground receiver locations, from deep space, for a wide range of Sun-Earth-Probe (SEP) angles.
- Simultaneous two-way ranging and communication

support.

- Adequate level of built-in reliability to survive the targeted mission period and to remain opto-mechanically and thermo-mechanically stable during launch, cruise and intense operation phases of the mission.

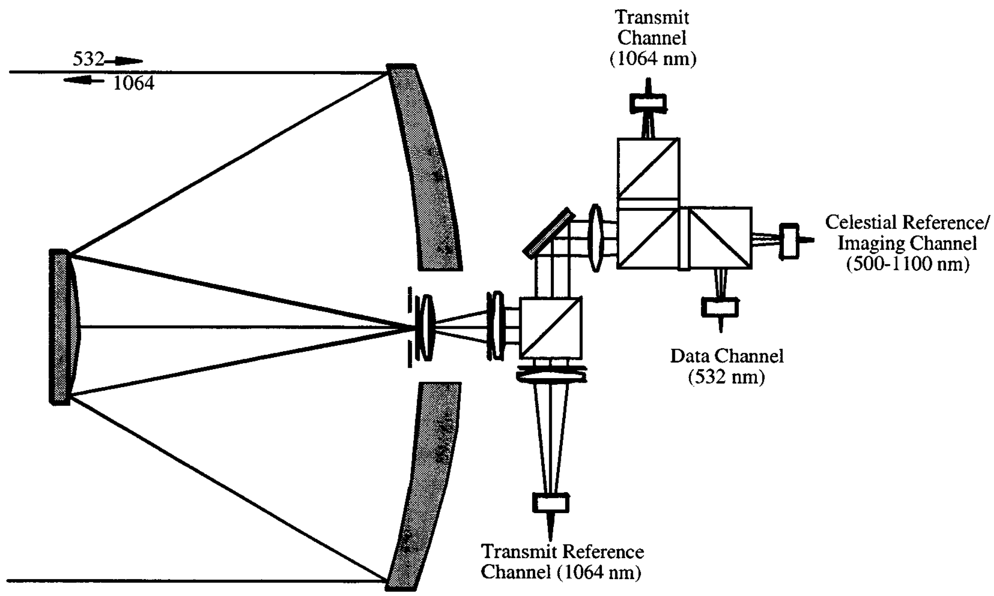

Figure 1 Conceptual Optical Diagram for the Transceiver

1. APPROACH

Both component and subsystem technology development efforts are now underway to enable future operational optical communications from deep space and to more fully realize the potential of this technology. A brief description of some of these efforts is summarized below.

High Efficiency Component and Subsystem Technology Development:

The aim of these tasks is to substantially improve the efficiency and performance of components and subsystems for laser-communication terminals. Mass and the required DC power for the flight instrument are both very expensive commodities, particularly in deep-space missions. Efficiency of high-data-rate (Gbps level) transmitters and low data-rate (Kbps level) diode-pumped solid-state lasers are being improved. Modulated diode lasers or amplified diode lasers with moderate average power are adequate for communications from the earth orbit to ground. Implementation of the pulse-position-modulation (PPM) scheme in deep-space laser transmitters will reduce the required average power but requires high peak powers. Thus, Q-switched solid-state lasers are necessary for deep-space communications. Recent analysis indicates that an overall efficiency of 25% for diode-pumped pulsed lasers transmitters is possible (compared with current value of about 7%). When the optical communications telescope looks back at earth for acquisition and tracking and downlink, the Sun is generally in the background and at times partially within its field-of-view. This causes a number of challenges (such as signal-to-noise deterioration and heating of the telescope) that have to be addressed effectively. For this purpose, low mass, very low thermal expansion optical systems with very effective background filtering are being investigated.

Acquisition, Tracking and Pointing (ATP) Algorithms and Testbed:

ATP is a critical element of optical communication whose implementation strategy is determined primarily by range. Acquisition and tracking for fine beam pointing is the most challenging aspect of free-space laser-communications. ATP is an area that requires technology development while it could be claimed that all other component technologies for a laser-communication terminal are mature enough for operation in space. A typical RF communication system relies on the spacecraft acquiring the Earth and maintaining a pointing knowledge of about 0.1° (~ 2 mrad). This is an adequate level of pointing due to the relatively wide beam-width of the RF systems. In comparison, the laser beam has to be pointed to better than 1 μrad levels. The narrower transmit beamwidth poses a major technical challenge for optical communicationwhich is the acquisition, tracking and pointing process. The lasercomm transceiver must be capable of tracking the receiving station to maintain a residual pointing error that is small (about 1/10) compared with the transmit beamwidth. Laboratory demonstrations and a successful lasercomm demonstration from GEO to ground indicate that solutions for these challenges are at hand, although significant additional work remains [1]. To point the narrow beam-divergence laser beam to Earth, the flight terminal requires a beacon signal from the receiver location. The beacon signal could be either a laser emanating from the Earth (a point source), Sun-illuminated Earth itself (an extended source) or precision star tracking. When the distance from the Earth to the spacecraft is less than 1 AU (1 AU is the mean distance from the Sun to the Earth), an uplink laser beacon signal will be received and tracked. However, as the spacecraft moves beyond 1 AU distance, the system will revert to tracking the solar-illuminated Earth image. In this case outage periods may occur, for example when the Earth is in front of the Sun. Finally, the optical communications system must have the ability to track out base platform motions from the spacecraft in order to keep the downlink beam on the Earth receiver. The tracking loop sensor must have an update rate that is high enough to allow the loop to compensate for the highest frequency jitter components. The current baseline for the update rate is 2 kHz. Currently, concepts that address links up to 0.5 AU have been demonstrated using FPA centroiding accuracy of only $1/10^{th}$ of a pixel, leaving only micro-radians of pointing error [2]. Extended link ranges will require up to five time more centroiding accuracy. The objective of the on-going research effort is to reduce pointing error to the sub-micro-radian level by developing and demonstrating in a simulated space environment, algorithms capable of achieving high-bandwidth, high-accuracy centroiding ($1/50^{th}$ of a pixel). We expect to achieve such an improvement using state-of-the-art Focal-Plane-Arrays (FPAs) together with innovative ATP concepts which combine extended-source-tracking, sensor feedback, and isolators. To experimentally evaluate these algorithms, an acquisition and tracking testbed was developed where spacecraft vibration, both point source and extended-source beacon, and background light can be simulated. Compact, low power consumption (< 0.1 W), large area (1024 x 1024 pixels), high update-rate acquisition and tracking FPAs including active-pixel-sensors and new generations of CCDs are being developed and are characterized in the testbed. High bandwidth, low-mass fine-pointing mirrors (both mechanical and non-mechanical) is also being evaluated in the acquisition and tracking testbed.

Transmitter and Receiver Testbed (for flight and ground):

A testbed for extensive characterization of a variety of laser transmitters and receivers is under development at JPL. This testbed will serve the needs of various on-going programs and could serve programs external to JPL in the near future. A goal of this testbed is to identify highest quantum-efficiency and lowest noise avalanche photodiodes for both ground and in space reception of the lasercomm signals. A goal of this program is identification of detectors and amplifiers for (direct) detection of communication signals down to the level of a few photons per bit.

Optical Communication Demonstrator (OCD):

OCD is a laboratory-based lasercomm demonstration terminal designed to validate several key technologies, including beacon acquisition, high bandwidth tracking, precision beam-pointing and point-ahead compensation functions [3-4]. The instrument has a 10-cm diameter aperture, uses a CCD array for both spatial acquisition and high bandwidth tracking, and a fiber-coupled laser transmitter. Figure 2 shows a picture of the 10-cm aperture OCD hardware where the box containing the

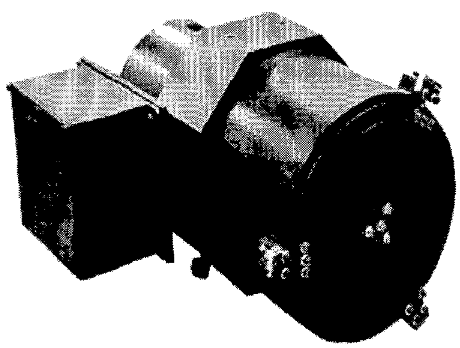

Figure 2 Picture of the OCD assembly (electronics are not shown)

Near-Earth Laser-Communication Transmitter:

The International Space Station (ISS) Engineering Research and Technology Development program (ISSERT) is sponsoring the development of a high data rate (up to 2.5 Gbps) lasercomm transmitter from the LEO range (on board the ISS) [5]. The terminal design is based on the OCD instrument. The transmit aperture for the flight terminal and the ground receiver aperture are 10 cm and 100 cm, respectively. It utilizes an eye-safe transmitter wavelength of 1550 nm (compared with 844 nm for OCD).

Deep-Space Laser-Communication Transceiver:

A new program called the ATTI (Advanced Technology Transfer and Infusion, AKA X2000), has been initiated to develop new cutting-edge technologies for NASA's deep-space missions in an overall flight project environment [6]. The ATTI system is a (50-kg class) micro-spacecraft with highly limited mass and power allocation for the subsystems. The transceiver under investigation for this technology development spacecraft is a multi-functional instrument with capability for narrow-angle (high-resolution) science imaging, optical navigation and ranging in addition to communication. The current baseline is 10's of Kbps data-rate from a range of 2 AU. A mechanical model of such a design is shown in Figure 3. An optics bench follows the telescope where the beam-sizing optics, the focal plane arrays, the fine-pointing mirror and the laser's optical head are located. The laser head is thermally isolated from this plane. The drive electronics and controller and processors for the final segment of this assembly.

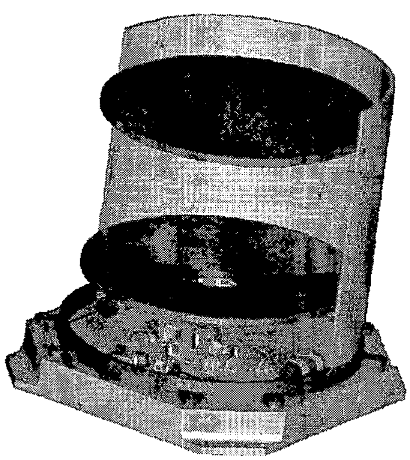

Figure 3 Mechanical concept model for the deep space Optical Communications transceiver

Laser-Communication Test and Evaluation Station Laser-Communication Test and Evaluation Station (LTES):

LTES is a high quality optical system that measures the key characteristics of lasercomm terminals operating over the visible and near-infrared spectral region [7]. LTES can accommodate terminal apertures up to 20-cm in diameter. LTES has six optical channels and can measure far-field beam pattern, divergence, data-rates up to 1.4 Gbps and bit-error rates as low as 1E-9. It also measures the output power of the laser-terminal's beacon and communication channels, and the point-ahead angle with a resolution of 1 μrad. A picture of the LTES setup is shown in Figure 4.

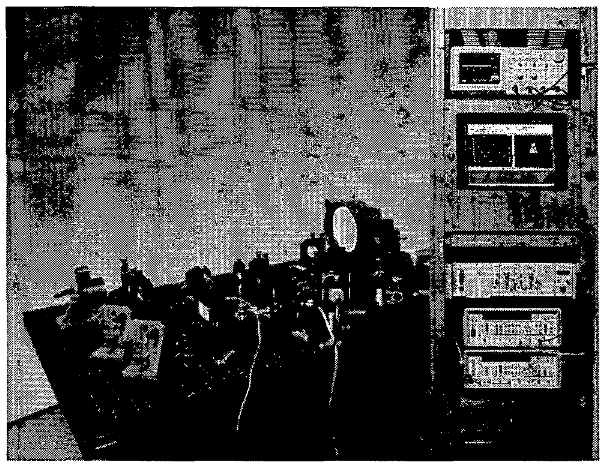

Figure 4 Picture of the ground companion terminal, constructed to evaluate terminals intended for flight

Ground Receivers and Ground Reception Technologies:

Current NASA plans call for building the first of three 10-m-class ground receiving telescopes by year 2008. NASA is currently building a 1-m R&D telescope laboratory at its Table Mountain Facility in Wrightwood, CA, to answer key implementation questions of this technology [8]. The telescope is designed with fast tracking capability to allow JPL engineers to use corner-cube reflector, and laser bearing satellites as testbed for developing acquisition tracking and communications strategies applicable to future operational stations. The expected date for readiness of this telescope is May of 2001. Improved receivers for ground reception, definition of requirements and cost-estimates for larger aperture ($\geq$ 10 m) photon-buckets, schemes for implementing near-earth acquisition and communication with the spacecraft, and recovery from spacecraft emergency scenarios are among the ground reception technologies that are being investigated.

3. CONCLUSION

Technology advances have enabled reliable communications from Earth orbit to ground receivers. Components and systems required to communicate from deep space have matured to the level that demonstrations are feasible. Reliable operation would require further technology development of the efficiency of components and more robust acquisition, tracking and pointing algorithms.

4. ACKNOWLEDGMENTS

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6. BIOGRAPHY

H. Hemmati is the Supervisor of the Optical Communications Group at JPL. He received a Ph.D. in Physics from Colorado State University in 1981 and a Masters degree in Physics from the University of Southern California in 1977. His graduate work was on lasers and laser spectroscopy. From 1981-83 he worked on laser cooling of trapped ions at the National Institute of Standards and Technology as a Post-doctoral associate. From 1983-86 he worked at the NASA-Goddard Space Flight Center conducting research on an instrument for the COBE spacecraft, and also on optical communications technology. In 1996 he joined the Optical Communications Group at JPL. His research interests include: efficient laser transmitters for deep space, flight terminal breadboard development, system engineering, and development of the components and system technologies to enable deployment of optical communication systems in space.