Deep-space Optical Terminals

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***Abstract* - We report on engineering trades that led to the conceptual design of a laser communications terminal for spacecraft probing Mars. The flight terminal, the ground receiver and the ground transmitter subsystems are described. The flight terminal point design has 0.25 Gb/s downlink data-rate capability from the Mars close distance (0.42 AU). Capability for uplink data-rate of 0.3 Mb/s and ranging with 30 cm precision are also addressed.**

Keywords: Free space optical communications, laser communications, lasercom, large diameter telescope, modulation, coding, PPM

1. INTRODUCTION

The *Deep-space Optical terminals* (DOT) concept design's intent is to retire the major risks perceived for operational planetary lasercom and to demonstrate a communications system that is scalable to multi-Gb/s data-rates and range of at least 5 AU (Jupiter) from the Earth. The tracking concept assumes availability of an earth-emanated uplink laser beacon source. At ranges above 5-AU, beaconless tracking based on, for example, Earth-image or star tracking will likely be employed.

There are sufficient differences between the assembly level technology requirements for an Earth-orbiting lasercom system and one for deep space communications that at least one demonstration from space of these technologies is warranted prior to operational use. Key differences include: large point-ahead angles, round-trip light times preventing closed-loop beacon tracking, and simultaneous low *Sun-Probe-Earth* (SPE) and *Sun-Earth-Probe* (SEP) angles leading to low signal-to-noise ratio conditions at both ends of the link. Additionally, operations under the photon-starved regime, as a result of large interplanetary distances, requires highly efficient (high bits/photon) modulation and coding strategies that result in requiring high peak-to-average power laser transmitters that are unproven in the space environment.

The DOT system is composed of four major subsystems: The *Flight Laser Transceiver* (FLT); The *Ground Laser Receiver* (GLR); The *Ground Laser Transmitter* (GLT); and The *DOT Mission Operations Center* (MOC).

2. SYSTEMS ENGINEERING

Since a host platform has not been baselined yet, reasonable assumptions were made for the platform disturbance, a key driver influencing the design of the challenging laser beam pointing control assembly, based on disturbance power spectral densities of past spacecraft. The assumed angular *power spectral density* (PSD) is 1E-7 rad^2/Hz at and below 0.1 Hz; 1E-15 rad^2/Hz at 1 kHz with a 20 dB/decade slope beyond 0.1 Hz. The RMS angular disturbance resulting from this assumed PSD is 140 μrad [1].

Downlink signaling primary functions are to provide a variety of downlink data-rates, and to support downlink temporal acquisition. The major signaling selection decisions, to achieve maximum power efficiency (bits/photon), were: the detection method; range of slot-widths; modulation; error-correction-code; and synchronization markers. *Direct detection in conjunction with photon-counting* (DD-PC) data reception was regarded more efficient than other viable options for DOT's operating conditions. *Pulse position modulation* (PPM) was selected due to its near-optimum power efficiency [2]. The *serially concatenated PPM* (SCPPM) encoding was baselined for the optical downlink, since SCPPM in combination with photon-counting direct-detection receiver can achieve communications performance within 1 dB of channel capacity [3].

Uplink signaling primary functions are: transmitting high-rate uplink data; supporting a low-rate command capability: providing a reference beacon; aiding synchronization; and supporting ranging. Again, direct-detection along with photon counting is selected for its photon-efficiency and the relatively high bandwidth capability. Given a detector array sensor with adequate field-of-view to cover the range of point-ahead angles, a single sensor will be sufficient for implementation of beam-pointing, high bandwidth communications/ranging, and synchronization. A Reed-Solomon (255,191) code was selected for the uplink due to its low complexity and efficiency.

Transmit/receive signal isolation at the flight terminal drives wavelength selection considerations. High power (multi-kW average power) 1550-nm lasers for uplink are unavailable commercially at this time, but that is not the case for 1030 nm lasers. This supports the choice of 1550 nm for downlink and 1030 nm for uplink to enhance transmit/receive wavelength isolation. The selection of uplink wavelength is driven by the availability and characteristics of uplink photon counting detectors, while the selection of the uplink laser beam divergence (40μrad) is driven by the requirement to deliver the required irradiance at the entrance aperture of flight terminal telescope.

Figure 2 summarizes the downlink budget assuming 4-W transmit laser power through a 22-cm flight terminal aperture.

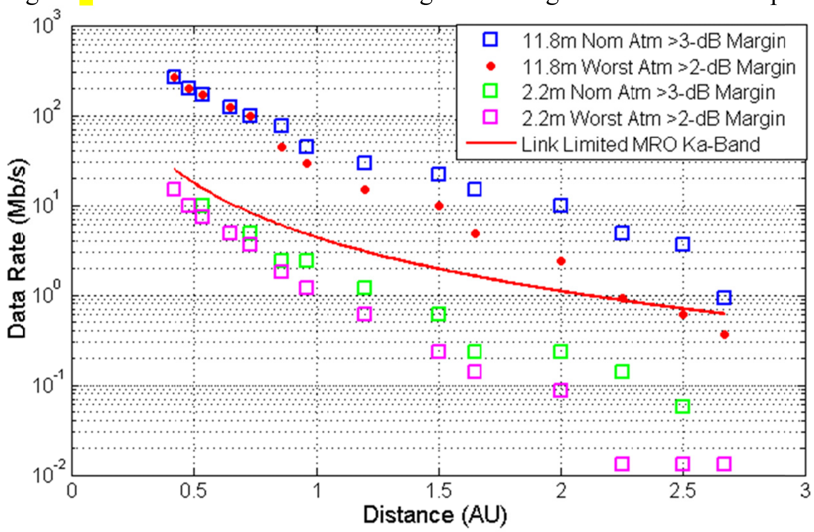

Figure 2. Downlink performance summary for nominal and worst conditions

2. FLT – FLIGHT LASER TRANSCEIVER

The flight terminal is comprised of the three major assemblies:

1. The optical assembly houses transmit/receive telescope, aft optics, acquisition/tracking/data sensors, and a point-ahead mirror sub-assemblies.

2. To facilitate meeting the precision leaser beam pointing requirements, a vibration-reduction assembly called *low-frequency vibration-isolation platform* (LVP) largely attenuates (isolates) the optical assembly from the host spacecraft angular disturbances. The LVP is designed to mitigate the majority of host-platform-induced angular disturbances, using a hybrid of passive and active isolators, controlled by the processor sub-assembly.

3. The opto-electronic assembly houses the laser transmitter, modems, controllers, processors and power converters. These sub-assemblies which generate heat are located away from the optical assembly and do not need to be isolated from the host platform vibrations. An umbilical cord containing soft copper and fiberoptic cables connects the optoelectronic assembly to the optical assembly in a fashion that does not interfere with LVP's function [4].

The *Pointing, Acquisition, and Tracking* (PAT) subassembly has to derive sub-micro-radian (1-σ) transmit beam pointing in the presence of greater than 0.1 mrad of angular disturbance from the spacecraft. Accommodation of the large point-ahead angular range of ±400 micro-rad is another major PAT design driver. A common transmit/receive optical aperture provides the highest pointing stability since closed-loop tracking of transmit beam pointing across the long (up to 10s of minutes) light propagation times at deep space ranges is impractical.

The *laser transmitter* sub-assembly modulates the input encoded electrical signal onto the transmit optical beam. PPM symbols with 16 to 128 slots per symbol were selected [5]. This modulation scheme sets a set of requirements on peak-to-average power ratios ranging from 20:1 to 160:1 from the laser transmitter, and laser pulse-widths ranging from 0.5-ns to 8-ns. Today's commercial *Erbium-doped fiber-amplifier* (EDFA) 1550 nm sources deliver significantly lower peak-to-average power ratios than required. But, today's technology allows the development of laser meeting the requirement.

The *uplink sensor* subassembly is used to track uplink beacon, detect the uplink data, and to simultaneously track the downlink beam to verify the point-ahead angle. An uplink wavelength of 1030-nm was selected for two reasons: availability of low-noise silicon detectors (e.g. resonant cavity enhanced Geiger mode or negative avalanche photodiode). Additionally, use of the Silicon (a non-1550 nm) sensitive detector then becomes advantageous affording inherent transmit-receive isolation.

A 22-cm diameter off-axis Gregorian telescope configuration was selected due to its excellent rejection of the thermal load from the background sunlight during operation at small sun angles. Silicon carbide was selected for the primary mirror substrate and telescope structure to minimize mass and thermal distortion [Fig. 2].

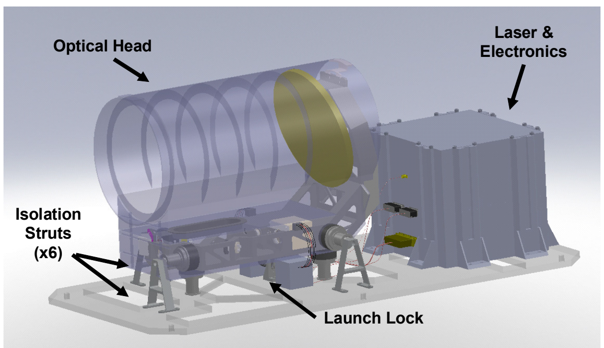

Fig. 2. Schematic of the FLT

3. GLR – GROUND LASER RECEIVER

GLR subsystem's key design drivers include:

1. High antenna gain obtained from large collecting area and highly efficient optics
   - The required GLR telescope aperture gain of 142 dB (at data-rate of 250 Mb/s) translates to 110 m^2 aperture (11.8-m in diameter);
2. Operation during daytime and at low SEP angles;
3. Operation in the photon-starved regime due to reception of extremely faint signal from deep space
   - This necessitates use of highly efficient (photon counting or single photon sensitive) detectors and use of efficient modulation and error-correcting codes at the transmitter to maximize the bits per photon [3]; and
4. Operation at high background to signal ratio since the detected rate of background photons may exceed the rate of signal photons by as much as 18 dB during low SEP operations. Efficient optical filtering helps in this regard [6].

The *Detector Assembly*'s driving requirements are: array format with several hundred elements, detection efficiency >50%; dark count rate <0.33 MHz; and timing jitter <120 ps. Array of *superconducting nanowire single photon detectors* (SNSPDs) was baselined. The *intensified photo-diode* (IPD) meets nearly all requirements, but suffers from relatively low detection efficiency of 30% at 1550 nm [7].

The *Electronics Assembly*'s function is to process the photodetector signal and determine the number of photons received in each temporal slot in each region, synchronizes to the downlink signal, estimates the rate of signal and background photons, and controls the acquisition and tracking of the downlink. This assembly has to able to process variable data-rates, PPM orders, code rates, slot widths, symbol repetitions, and background photon rates.

3. GLT – GROUND LASER TRANSMITTER

GLT subsystem's key design drivers include:

1. To deliver a pre-set power density at the entrance aperture of the flight terminal
   - This derives the uplink laser power (~2.5 kW), beam divergence (~40 urad), and the number of beams (~9 beam separated by at least 10cm) required to effectively mitigate the atmospheric turbulence effects;
2. Meeting the blind pointing accuracy requirement (~16 urad); and
3. Operation during daytime and at low SEP angles.

The *Uplink Telescope*'s options include: a single telescope, distributed (arrayed) telescopes, and flat-mirror beam directors. The existing JPL 1-m diameter coudé path OCTL telescope is selected based on its capability to meet the required pointing, availability, cost and complexity [8].

The *Uplink Laser*'s key requirements include: 1030 nm wavelength, 0.5 nm line-width and ±0.1nm wavelength tunability, 2.5 kW average and 370 kW of peak power with M^2 <1.2 beam quality, pulse repetition rates in the 4 to 500 kHz range, 128 ns pulse-width, random polarization, and 20 dB pulse extinction ratio. Today's technology can meet these requirements.

5. CONCLUSION

Flight and ground terminals were conceptually designed to meet pre-set requirements. This system enables downlink transmission of over 0.25 Gb/s from Mars close distance (0.42 AU) while estimated flight terminal mass power are comparable to the state of practice of existing Mars spacecraft telecommunication systems. Currently, the highest risk items are the technology maturity of the flight isolation platform, the flight laser, and the flight and the ground single photon-sensitive data detectors. These specific technologies are now being addressed in a focused technology development program.

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