Optical Ground Station Site Diversity For Deep Space Optical Communications: The Mars Telecom Orbiter Optical Link

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Abstract

Future NASA deep space missions will fly advanced high resolution imaging instruments that will require high bandwidth links to return the huge data volumes generated by these instruments. Optical communications is a key technology for returning these large data volumes from deep space probes. Yet to cost effectively realize the high bandwidth potential of the optical link will require deployment of ground receivers in diverse locations to provide high link availability. A recent analysis of GOES weather satellite data showed that a network of ground stations located in Hawaii and the Southwest continental US can provide an average of 90% availability for the deep space optical link. JPL and AFRL are exploring the use of large telescopes in Hawaii, California, and Albuquerque to support the Mars Telesat laser communications demonstration. Designed to demonstrate multi-Mbps communications from Mars, the mission will investigate key operational strategies of future deep space optical communications network.

1. Introduction

Over the years studies have shown that optical communications offers higher communications bandwidths in a telecommunications subsystem of smaller size and lower mass and power consumption that do RF systems [1]. The unconstrained optical bandwidth makes the technology appealing, even with advances in bandwidth efficient modulation techniques in the RF. In addition, recent optical communications demonstrations have elevated the technology readiness level and hence the acceptance of laser communications system. To meet its growing need for high bandwidth support of its deep space links NASA plans to demonstrate a Mars-to-Earth. laser communications link in 2010.

The Mars Telecommunications Orbiter (MTO) spacecraft is planned for launch on October 6, 2009 and will:

- Serve as a communications relay for Mars surface laboratory, scouts, and Mars surface and orbital missions of the next-decade.
- Provide critical event coverage, for entry and descent landing and Mars orbit insertion (MOI)
- Demonstrate a deep-space optical communications link from Mars
- Detect and track the Orbital Sample Canister

The spacecraft's payload list includes:

- The Optical Comm Demonstration Flight Terminal
- The RF Telecom (100 W X-band, 35 W Ka-band)
- The Electra (UHF, X) communications link
- The Orbiting Sample Canister (OSC) and Ejector
- The OSC Finder Camera

In this paper we explore how the AFRL optical stations in Albuquerque and Maui could be integrated into a ground station network that could support the Mars-Telecommunications-Orbiter Laser Communications Demonstration (MLCD). In particular, we look at how these optical ground stations can, in conjunction with the Optical Communications Telescope Laboratory (OCTL) and Mt. Palomar ground stations, provide site diversity to mitigate possible outages caused by cloud cover and by predictive avoidance

2. The Mars Laser Communications Demonstration

The MLCD will be the first demonstration of an interplanetary deep space laser communications link [2]. The Project will be managed by Goddard Space Flight Center. Massachusetts Lincoln Laboratories has been assigned the responsibility for the spacecraft terminal and JPL the responsibility for the ground terminals. MLCD mission plans call for a two-year demonstration, one year of which is on orbit at Mars. With the October 2009 launch, the MTO spacecraft will be in interplanetary cruise for eleven months with insertion into Mars in August 2010. The objectives of the optical communications demonstration are to:

- Demonstrate downlink rates from Mars of at least 10 Mbps with a goal of 30 Mbps at 10E-6 BER.
- A minimum link rate of 1 Mbps at solar conjunction
- Demonstrate a forward-Link of at least 10 bps at 10E-6 BER to Mars
- Measure and characterize the system performance over a variety of conditions during cruise and over ½ Mars year on orbit
- Characterize system performance near the Sun such that the maximum outage due to solar exclusion is less than thirty days
- Demonstrate weather mitigation techniques
- Demonstrate station handover strategies

The MLCD optical link will use a 5-W average power 1064-nm laser pulse position modulated and coupled to a 30-cm aperture telescope. Current project guidelines stipulate that existing ground terminals be used for the demonstration, and JPL has baselined the NASA/JPL 1-m OCTL in Wrightwood CA as the primary uplink facility, and the 5-m Hale telescope at Mt. Palomar CA as the primary downlink receiver facility. Yet, our past experience with an optical uplink to the Galileo spacecraft has shown that ground station site diversity will be required to achieve a high availability optical link [3].

The site diversity concept is shown in Figure 1.1. The figure shows a multi-station ground terminal network that includes the Palomar, OCTL, the Starfire Optical Range (SOR), and Air Force Maui Optical Station (AMOS) facilities. This network of stations offers several advantages to the MLCD, viz:

- Support site diversity to mitigate cloud-cover effects
- Mitigate predictive avoidance outages imposed by the Laser Clearinghouse
- Enable the demonstration of uplink/downlink site hand off strategies of an operational ground station network. Strategies that would be needed to mitigate cloud cover and satellite predictive avoidance effects.
- Enable the demonstration of expanded tracking coverage as stations hand off from one to the next (CONUS-Continental US- to Hawaii and vice versa).

Figure 1.1: Concept of Mars laser communications demonstration using AMOS, SOR OCTL and Palomar facilities.

2. Ground Telescopes

The SOR and AMOS facilities are shown in Figure 2.1 (a) and (b), respectively. Seen in the foreground of the figure are the large 3.5-m and 3.67-m telescopes. The telescopes are open framed structures with Nasmyth, and coude′ foci. The interest in the SOR and AMOS as potential ground sites is due to several factors, namely:

- The large telescopes at these facilities can support high rate downlink transmissions.
- Both facilities have several coude′ rooms that would allow long-term experiments to coexist with other telescope users without having to tear down their set ups.

- Their experience in laser beam propagation. Government agencies impose several restrictions on laser beam transmission. These facilities have and continue to meet these requirements.
- The adaptive optics capability. Daytime optical communications will require the use of adaptive optics techniques to reduce the background noise for the sky.

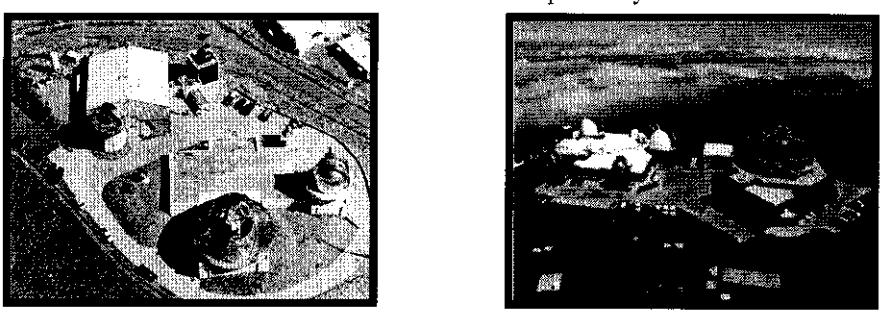
Table 2.1 itemizes some of the key features of the OCTL, Starfire Optical Range (SOR), (Advanced Electro-Optic System) AEOS and the Hale Mt. Palomar facilities. The SOR, AEOS and Mt. Palomar receiver telescopes have adaptive optics systems in place, a capability that is needed to reduce the receiver field of view and hence the sky background noise during daytime operations [4]. The adaptive optics systems at the AEOS and SOR telescopes use a tip/tilt mirror and 900-actuator deformable mirrors to correct the atmospheric-turbulence-induced wavefront distortion in the beam. Both of these facilities are equipped with high power doubled YAG (532-nm) lasers that can generate a Rayleigh guidestar approximately 15-km into the atmosphere for higher order wavefront correction. In addition, the SOR has a 20-W 588-nm that can generate a guide star in the 90-km high sodium layer that will mitigate the cone-error effects and allow for greater wavefront error correction. Currently, the Hale telescope uses natural guidestars for wavefront correction. Because it is unlikely that there will be an adequate number of bright stars within the isoplanatic angle to support wavefront correction, the Hale AO system will need to be upgraded to support the MLCD.

Table 2.1: A listing of some of the key characteristics of the transmitter and receiver telescope facilities.

	Transmitter			**Receiver**	
	OCTL	**SOR**	**Hale**	**SOR**	**AEOS**
Aperture, m	1	1.5	5.1	3.5	3.67
% Obscuration of primary area	5.6		9		4
Focus type	coude′	coude′	prime, cassegrain	coude′, Nasmyth	coude′
Site altitude, km	2	1.86	1.5	1.86	3
AO capability in 2009	Yes	Yes	Yes	Yes	Yes
Telescope transmission @ 1um	60%	45%	90% (cassegrain focus)	45%	79%
Maximum energy density, J/sqcm	0.1	1	N/A	N/A	N/A
Min sun pointing angle, degrees	10	60	13	60	60
Typical nighttime atmospheric seeing, arc sec	1.5 - 2	1.5 - 2	0.75	1.5 - 2	1

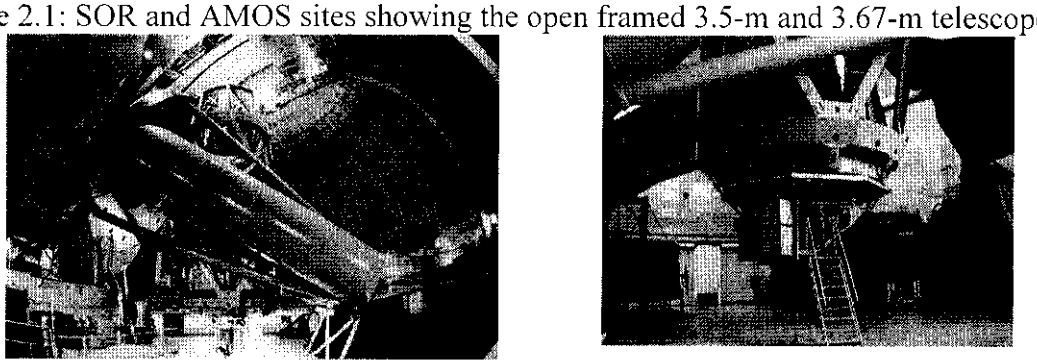
The large point-ahead angles between the downlink beam or the Mars image (if a correlation tracking approach is used) and the uplink make adaptive optics unattractive for the uplink. The baseline uplink strategy calls for using the multi-beam uplink strategy to mitigate uplink beam scintillation [5].

The AFRL telescopes are enclosed in a telescoping dome structure that can be raised and lowered, as needed, to protect the primary mirrors from direct sun illumination during daytime operation. Using this approach these telescopes can point as close to the sun as 60-degrees. The Hale telescope shown in Figure 2.2 is also an open framed structure, and by using the dome to shield the primary, the telescope can point to approximately 13-degrees of the sun before the sun is incident on the primary mirror.



(a) (b)

Figure 2.1: SOR and AMOS sites showing the open framed 3.5-m and 3.67-m telescopes.



(a) (b)

Figure 2.2: (a) Web picture of Hale Observatory at Mt. Palomar CA [6]. (b) The cassegrain cage that houses the adaptive optics system for this 5-m telescope is shown in the expanded view on the right.

Designed for daytime and nighttime operations the OCTL shown in Figure 2.3 is designed to point to as low as 10-degrees to the sun. The telescope is enclosed in louvers and the secondary mirror spider supports are reinforced to prevent wave front aberrations due to secondary mirror tilt should the sun be imaged on these spiders. OCTL has a coude′ focus and is designed to propagate high power laser beams in to space.

Figures 2.4 and 2.5 show how these four telescopes could support the MLCD given their sun-Earth-probe (SEP) pointing angle constraints. Figure 2.4 shows that the AFRL telescopes could support the critical early check out of the space terminal, and ten of the eleven months of the interplanetary cruise phase when the SEP angle is greater than 60-

degrees. Because of their ability to point closer to the sun both the Palomar and OCTL telescopes can support the demonstration for the entire interplanetary cruise including Mars orbit Insertion (MOI).

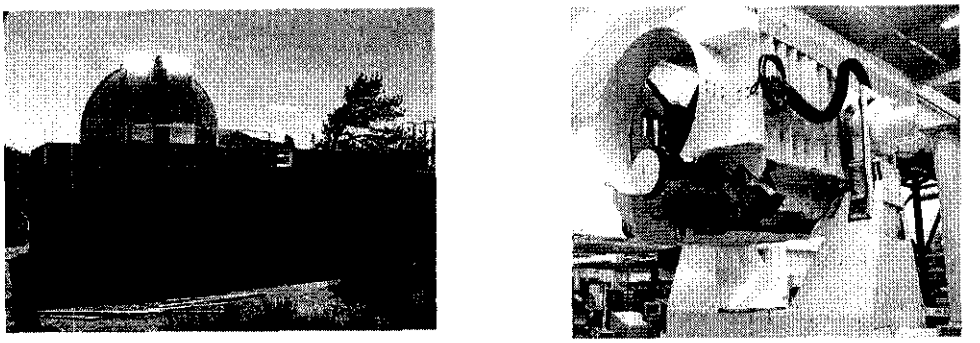


Figure 2.3: OCTL building and telescope identified as primary uplink facility.

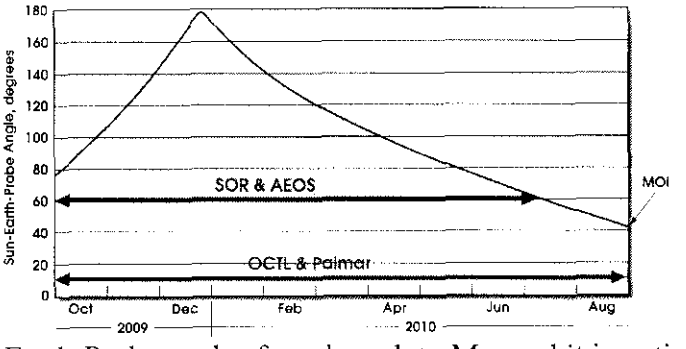


Figure 2.4: Sun-Earth-Probe angles from launch to Mars orbit insertion (MOI).

The support that these telescopes with the current constraints could provide post-MOI is shown in Figure 2.5. For the twelve months following MOI, of the four telescopes only the OCTL and the Hale telescopes could support the MLCD. In the first five months following MOI, the Mars-Earth distance increases and the SEP angle decreases reaching a minimum at conjunction in January 2011. The respective constraints of ten and thirteen degrees minimum SEP angles correspond to eighty-nine and one hundred and fifteen days outage at the OCTL and Palomar telescopes.

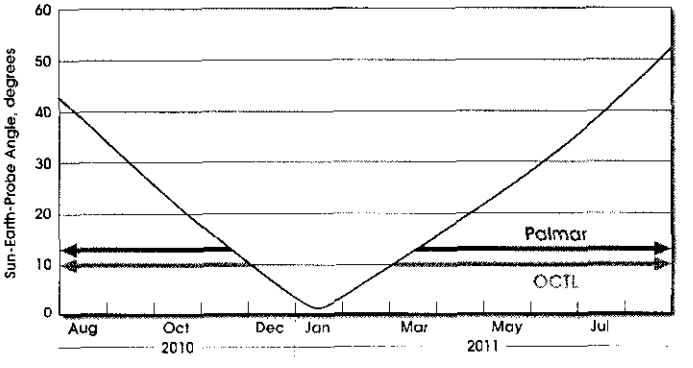


Figure 2.5: SEP angles for twelve months after MOI. OCTL and Palomar ground stations can support the link as low as SEP angles of 10 and 13 degrees, respectively.

3. Mitigating The Effects Of Outages On The Deep Space Optical Link

Cloud cover and predictive avoidance are the two principal causes of outages on an optical space to ground link that relies on uplink beacon tracking. Predictive avoidances are prescribed outage periods that are imposed by the Laser Clearinghouse to prevent illumination of sensitive satellite assets by the uplink laser beam transmission. In current operating scenarios, laser uplink facilities register their sites with the Laser Clearinghouse and provide a schedule of transmissions times and targets. Twenty-four hours prior to transmission the Clearinghouse responds with a list of times when uplinks are prohibited. These outages can last from a few minutes to tens of minutes. Since spacecraft sequence of events are written checked and uploaded as commands several days before execution, a diversity of uplink sites could enable the development of strategies to support continuous communication with the spacecraft. Strategies which that operationally would appear no different from those used to mitigate cloud cover effects.

To identify locations for a global deep space optical network, JPL in fiscal year 2003 initiated a multi-year study to develop cloud-free line-of-sight (CFLOS) statistics for locations of interest for locating deep space optical communications stations [7]. The study began with the analysis of GOES satellite data over CONUS, Hawaii and Peru and Chile, and in particular used archived GOES data from the six year period 1997 to 2003 to develop CFLOS statistics for selected sites in sub-regions of interest. The CFLOS statistics are given in Figure 3.1 (a) the for the AMOS, SOR, OCTL, and Palomar four station network in Figure 3.1 (b). The analysis shows an average availability of approximately 91% over this six-year period. Where the availability is defined as that period of time when the spacecraft at Mars is above 20 degrees elevation and has a cloud free line of sight to one of the four ground stations. The data show that there were thirty-one months during this period when the availability was below 90%. In particular the months in 1998, 2000, and 2002 when the planet is in a southern declination and the availability at these northern stations is less than 80%.

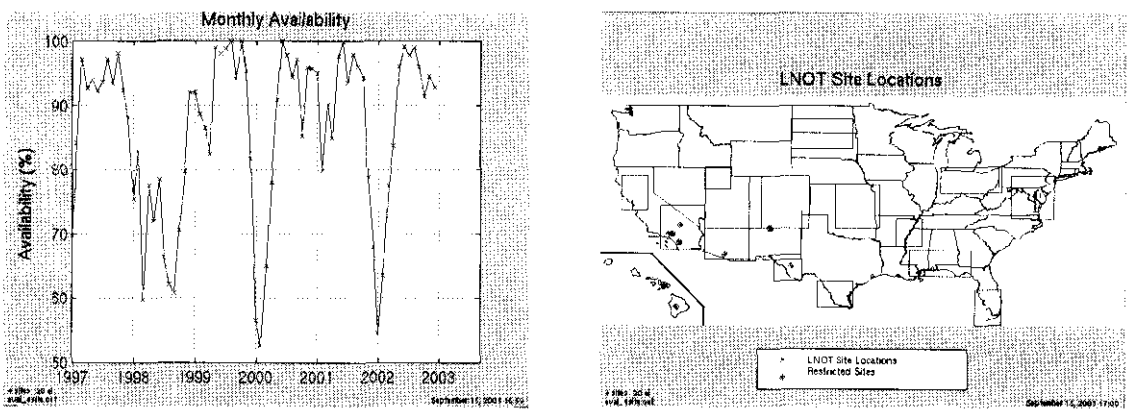


Figure 3.1: (a) Monthly availability average for four-station network sites AMOS, OCTL, Mt. Palomar and SOR in (b). Analysis was done by Northrop-Grumman-TASC using their laser network operations tool (LNOT).

4. Summary

We have described a network of ground stations that consists of AFRL's AEOS and SOR and the JPL OCTL and Palomar telescopes, and have shown how the SOR and AMOS ground stations could support the MCLD. Our analysis shows that the stations can support the MLCD during most of the interplanetary cruise phase, allowing for early demonstrations of key operational scenarios, such as agile downlink beam pointing, to prevent outages caused by cloud cover and predictive avoidance. We have also presented an analysis of six-years of satellite data that show that on average the four station network will provide an availability in excess of 90%..

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