Future Planetary Optical Access Links
Mars Rover to Orbiter High-Rate Links

Abhijit Biswas, Joseph Kovalik, Martin W. Regehr
Jet Propulsion Laboratory,
California Institute of Technology
Pasadena, CA 91109, USA
abiswas@jpl.nasa.gov

Abstract— Optical planetary access links to return information from surface assets on Mars to orbiting spacecraft for subsequent relay back to Earth will be discussed. The capabilities that can be realized using such links will be presented for a presumed concept of operations at Mars. Autonomous acquisition and tracking using low-complexity optical terminals will also be discussed.

Keywords-optical planetary access; proximity links; Mars Network

I. INTRODUCTION

Recent Mars missions have returned science and telemetry from surface rovers (Mars Pathfinder, Mars Exploration Rovers, and the Phoenix Lander) utilizing UHF “access” or proximity links to over-flying orbiters [1, 2, 3]. Operating autonomously at instantaneous data rates of 0.25 Mb/s with 2-3 short periodic contacts per Mars day (sol), these links support average data volumes of 150 Mb/pass over average contact periods of 10 minutes. In the upcoming MSL era the maximum data volume per pass will increase to 600 Mb/s [4].

UHF relay communication systems also support entry descent and landing (EDL) at Mars and provide reliable and autonomous surface communications under diverse Mars environmental conditions, including periodic dust storms. This significant UHF access link functionality has operated reliably and efficiently utilizing approximately 40 to 70 W of electrical power and less than 5 kg mass. However, the UHF bandwidth capability for streaming compressed high-definition (HD) video from the Mars surface is marginal. With current and anticipated capability in the upcoming MSL era, at best 10-40 seconds of compressed HD video can be returned per pass. Stimulating public engagement or supporting higher resolution science imagery with such short duration HD video will not prove feasible, prompting the question as to how we can gain this much desired capability.

Using proven radio frequency (RF) technology will require migrating to higher frequencies (X and Ka band) needing larger steerable antennae demanding higher mass and power, similar to the scheme proposed for the Mars Telecommunication Orbiter (MTO) Project [5].

At JPL studies and research toward finding an optical solution to this bandwidth limitation have been conducted and is the subject of this paper. In addition to satisfying high-bandwidth, optical communications technology offers low mass, power and volume sought after by Mars spacecraft. Though high-bandwidth space-to-ground optical communications from near-Earth orbiting satellites has matured significantly in the past decade [6, 7], the size, weight and power (SWAP) of these systems and the concept of operations do not naturally lend themselves to viable Mars relay communication systems. Some of the key constraints as we currently understand them are presented next.

A. Constraints on Planetary Optical Access Link Systems for Mars

The optical systems must provide reasonable link availability under dust-laden Mars-atmospheric conditions, though link outages under severe dust storms may be acceptable, provided current low-data-rate UHF capability is also carried on missions.

Thus optical access link systems will augment the multi-functional and reliable UHF relay capability at Mars and not replace it. As an add-on system aggressively low SWAP is desired. As the SWAP is allowed to increase the advantage of optical technology over RF will diminish.

Low complexity concept of operations that does not place a huge demand on orbiting and surface spacecraft is highly desired. Unlike omni-directional UHF antenna patterns, laser beams used by optical communication systems are directional, requiring efficient yet precise acquisition and tracking.

These are the key constraints addressed in this paper.

B. Optical access link performance

A near term motivation for inserting optical access links into the existing Mars Network will be to enable the capability to return streaming video from the surface. High-definition compressed video with excellent visual imagery can be transmitted over 20-30 Mb/s instantaneous data-rates, however this will require some processing of the raw HD signal output by the HD video cameras. Such imagery will serve science mapping and public engagement functions well. Streaming of uncompressed high-definition imagery on the other hand would require close to 1.5 Gb/s instantaneous data-rates. Note that the data-volume per sol assuming an average of 1500 seconds of contact per sol will vary from 45 Gb/sol to 2.25 Tb/sol, compared to an MSL era capability of an average of 0.7 Gb/sol.
In this paper we target optical systems that can satisfy the 45 Gb/sol requirement. Higher performance into several Tb/sol is well within the optical communications technology capability, and will result as a natural extension of the initial capability targeted in the current discussion.

C. Paper layout

In the remainder of this paper we will briefly present our research findings pertaining to the three constraints presented in Section IB. In Section II we will discuss the Mars atmosphere followed by link analysis considerations in Section III. In Section IV we will present the concept of operations along with a brief summary of emulating this concept using ground to aircraft optical links. Section V will conclude this paper pointing out a notional roadmap for developing planetary access link systems for Mars.

II. MARS ATMOSPHERE

The Mars atmosphere is dust laden and will cause substantial attenuation of propagating laser beams. Figure 1 presents a summary of the expected optical attenuation at 810 nm and 1060 nm, obtained using a Spectral Mars Radiative Transfer (SMART) model [8]. The model computed attenuation assuming mean optical densities at 500 nm of 0.6, 1.0, 1.5 and 2.0 at discrete zenith angles. We tried secant and polynomial fits to the computed data points. At zenith angles larger than 60° the points displayed lower attenuation than a secant fit prediction. The polynomial fits continuous (810 nm) and dashed (1060 nm) are shown in Figure 1.

For this study wavelengths of 810 nm and 1060 nm were provisionally chosen to serve as forward (orbiter to Mars surface) and return (Mars surface to orbiter) links respectively.

In addition to the Mars atmospheric attenuation, choice of wavelength for future optical planetary access links will depend on additive background (upwelling or down-welling radiance) noise, choice of receiver and availability of high wall-plug efficiency space worthy lasers. We will report on these details in future publications.

III. OPTICAL ACCESS LINK ANALYSIS

The optical link analysis for the access link will depend on the range between the orbiter and the Mars landed asset [10]. Typical science spacecraft orbit Mars in circular polar orbits at altitudes of 300-400 km. Telecom orbiters like MTO on the other hand, orbit Mars at altitudes of 4500 km. Mars missions with elliptical orbits which allow science and telecommunication functions have also been studied. Each of these configurations will result in different link characteristics for an optical planetary access link. Some details pertaining to these diverse orbits were presented previously [10].

A. Return Link

The key utility of the optical access link is the ability to return high-rate data from the surface of Mars. It was shown in a previous paper [10] that instantaneous downlink data-rates of 50-100 Mb/s could be supported using previously space-qualified near infra-red enhanced silicon avalanche photodiode receivers. These data rates were established for a science orbiter (300-400 km altitude) or a telecom relay orbiter (4500 km altitude). For the science orbiters 1W of laser power from the surface of Mars utilizing a 50-µrad 3-dB beam-width provided a 100 Mb/s data-rate at the average link range of 862 km. The receiver diameter on the orbiter was assumed to be 10 cm. For the higher altitude orbiters an average of 2 W laser power transmitted with a 21-µrad beam-width from the rover and received by a 20-cm aperture resulted in 50 Mb/s. Extremely conservative estimates presuming half of the predicted contact time indicate data volumes of 35-100 Gb/sol data volumes.

In the previous work summarized above the background additive noise was not explicitly addressed. If use a science orbiter with characteristics similar to the Mars Reconnaissance Orbiter (MRO) with the following reported pointing characteristics [11]:

- 3-sigma attitude knowledge: 0.7 × 1.0 mrad
- Ephemeris 3-sigma Uncertainty:
  - 1.5 km in-track
  - 0.5 km cross-track
  - 0.04 km
- Spacecraft Clock error: 10ms
- Target 3-sigma position uncertainty:
  - 600 m horizontal per axis
  - 500 m surface altitude

The estimated root-sum-square of the errors from the above is 1.7 mrad. We assume that 3 mrad will provide sufficient guard band for tracking the received laser signal. The Mars
The upwelling radiance at 1064 nm from the surface of Mars was estimated using the data taken by the Mars Observer Laser Altimeter (MOLA) and reported to fall between 7.1E-3 – 9.1E-3 W/cm²/st/µm. A 10 cm receiving terminal with a 1 nm band pass spectral filter will receive 3-5 nW of background power which will result in negligible performance degradation given the high thermal noise of these receivers.

The summary above provides a lower bound on performance with “head-room” for improvements by, for example, using efficient but low complexity forward-error-correction codes (2-3 dB gain), advanced receivers with improved sensitivity (2-10 dB) that are not yet space qualified.

B. Forward Link

As will become clearer in the next section describing the concept of operations, the primary function of the beam transmitted from the orbiter is to enable link acquisition and tracking. While this laser can be used for low-rate (10’s-100’s kb/s) data as well the capability will be comparable to UHF. Therefore we will not discuss the optical forward link capability and postpone the discussion of its acquisition tracking functions to the next section. We simply point out that the optical forward link may be useful for some unique needs like supporting two-way ranging, or implementing a protocol for ensuring quality of service over the optical link.

IV. CONCEPT OF OPERATIONS

Unlike many of the demonstrated near-Earth links, optical planetary access links at Mars need to operate autonomously without human in the loop.

Figure 2 shows the basic configuration for the optical access link at Mars.

![Figure 2 Lander Transceiver (LT) and Orbiter Transceiver (OT)](image)

The concept of operations for the Mars optical access link relies on the orbiter having sufficient knowledge of the surface asset’s location so as to allow blind-pointing a laser beam to illuminate the LT. Upon being illuminated a spectrally filtered wide-field-of-view camera on the LT senses the signal on its focal plane. The focal plane which maps a 160° × 360° region of the sky is able to locate the overflying orbiter to within ±1° so that the co-ordinates can be “handed over” to the gimbaled optical head part of the LT. With this knowledge the gimbaled optical head can acquire and track the laser beacon incident from the orbiter and re-transmit a high-rate communication beam to the orbiter. Upon receiving the communication laser from the LT the OT switches from blind-pointing to closed-loop tracking.

A. Wide-Field of View Acquisition

The wide-field of view acquisition was first validated using over-flights of the sun-illuminated International Space Station (ISS) [13]. Here a commercial fish-eye lens with a commercial silicon camera was used. ISS passes were chosen when the spacecraft was reflecting sunlight but the sky background was sufficiently dark to provide good contrast. Other stationary background lights that were fixed were discriminated against using a simple frame-differencing algorithm. The ± 1° acquisition accuracy with subsequent handover to a 2-3° field-of-view two-axis gimbaled camera was verified.

Acquisition of laser beams in the presence of daylight background but without direct Sun illumination of the fish-eye lens was verified next using a static point-to-point links [14]. The wide-field acquisition camera in this case was customized to provide a wide-field and spectral filtering with a band pass of 2 nm. Note that in order to achieve this with a commercial fish-eye lens the effective entrance aperture diameter was constrained to 0.7 mm. In these experiments the wide-angle camera was moved in order to emulate a moving laser source and utilizing the frame differencing.

B. End-to-end validation of concept of operations

The end-to-end optical access link concept of operations was validated by emulating the end-to-end link using an airborne and ground transceiver with the details reported elsewhere [15]. The pair of transceivers developed for this demonstration is shown in Figure 3.

The aircraft circled overhead at altitudes ranging from 8500 - 13000 ft above sea-level. The laser beam transmitted from the aircraft had 10 mrad full beam divergence. Assisted by the combination of an inertial monitoring unit (IMU) and global position system (GPS) feed and known ground GPS coordinates, the airborne system was able to blind point to illuminate the ground transceiver in the presence of a 3-sigma 52 mrad × 180 mrad attitude (pitch and roll) [16]. The residual 3-sigma blind pointing error was about ± 10 mrad. This performance was adequate to achieve illumination of the ground transceiver to enable link acquisition and lock.

Once the link was locked video was streamed from the ground at 270 Mb/s. The video stream was received by the airborne transceiver and recorded on the aircraft. A multi-media video file recorded during the demonstration is included in [15].
The link demonstration was repeated on six different campaigns with half the demonstrations performed at night and the remaining during the day. The nighttime demonstrations worked well as planned. The daytime links also performed reasonably well. At certain sun elevation angles the wide-field-of-view camera was vulnerable to excessive stray light which restricted the parts of the sky at which the link could be acquired. Once acquisition and lock was established the link was robust. On one occasion the acquisition and tracking worked well but the video signal transmitted was intermittent, this occurred during strong wind conditions and the loss of performance was attributed to wind buffeting of the tripod on which the ground transceiver was mounted.

V. CONCLUSIONS

The optical planetary access link emulation using the ground to aircraft link provided an encouraging validation of the low complexity concept of operations. Several important lessons were learned. It was clear that commercial fish-eye lenses used for the wide-field camera were not adequate for robust acquisition over the expected orbital distance at Mars. We estimated that at least a 4 mm entrance aperture diameter with a 2-nm spectral band pass was required for acquisition. With this in mind an optical design for such an optical system was designed [17] but has not been validated yet. It is also clear that daytime acquisition in the presence of the sun should be improved.

The link validation activity has validated the concept of operations for an optical access link at Mars and provided a proof of concept for low-complexity transceiver architecture.

Development toward future optical planetary access links need to identify space-qualified designs that are low mass, power, and volume.

ACKNOWLEDGMENT

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

REFERENCES


