Integrated Network Architecture for Sustained Human and Robotic Exploration

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Abstract—The National Aeronautics and Space Administration (NASA) Exploration Systems Mission Directorate is planning a series of human and robotic missions to the Earth's moon and to Mars. These missions will require telecommunication and navigation services. This paper[1] sets forth presumed requirements for such services and presents strawman lunar and Mars telecommunications network architectures to satisfy the presumed requirements. The paper[2] suggests that a modest ground network would suffice for missions to the near-side of the moon. A constellation of three Lunar Telecommunications Orbiters connected to a modest ground network could provide continuous redundant links to a polar lunar base and its vicinity. For human and robotic missions to Mars, a pair of areostationary satellites could provide continuous redundant links between a mid-latitude Mars base and Deep Space Network antennas augmented by large arrays of 12-m antennas.

TABLE OF CONTENTS

1. INTRODUCTION

The Jet Propulsion Laboratory (JPL) developed and operates the Deep Space Network (DSN), which consists of three complexes of large antennas around Earth that communicate with spacecraft throughout our solar system [1]. JPL also developed and operates a relay network at Mars that uses UHF radios on Mars orbiters to communicate with other Marscraft[3] [2]. This Mars Network was established through a successful NASA policy of adding a relay radio to every science orbiter sent to Mars, including Mars Global Surveyor and Mars Odyssey. Mars Network capabilities were augmented in 2003 by the European Space Agency's Mars Express orbiter, which has a compatible relay radio. Most of the data collected by the two Mars Exploration Rovers now at Mars were relayed to Earth through Mars Global Surveyor and Mars Odyssey [3], and the rovers have also communicated with Earth through Mars Express.

JPL is managing the development of Mars Reconnaissance Orbiter (MRO), which will launch in 2005 [4]. MRO will add a new Electra reprogrammable UHF relay radio [5] and a K_a-band deep space link [6] to the Mars Network. JPL is also managing the development of Mars Telecommunications Orbiter (MTO), the first interplanetary mission whose principal function is to support other missions [7]. MTO will add an X-band relay capability to Electra and will demonstrate deep space laser communications [8] after it is launched in 2009.

In response to the President's Vision for Space Exploration, announced on January 14, 2004, JPL generated presumed telecommunications requirements and strawman telecommunications network architectures to support sustained robotic and human exploration of the moon and Mars. These requirements and architectures were based on JPL's extensive experience with deep space telecommunications and Mars relay links. This paper presents the JPL requirements and architectures and briefly describes Lunar Reconnaissance Orbiter (LRO) communications. The next NASA lunar mission, LRO is expected to establish a lunar relay network.

[1] 0-7803-8870-4/05/$20.00© 2005 IEEE

[2] IEEEAC paper #1378, Version 5, Updated December 28, 2004

[3] A spacecraft, astronaut, rover, base station, lander, orbiter or aerobot in the vicinity of Mars.

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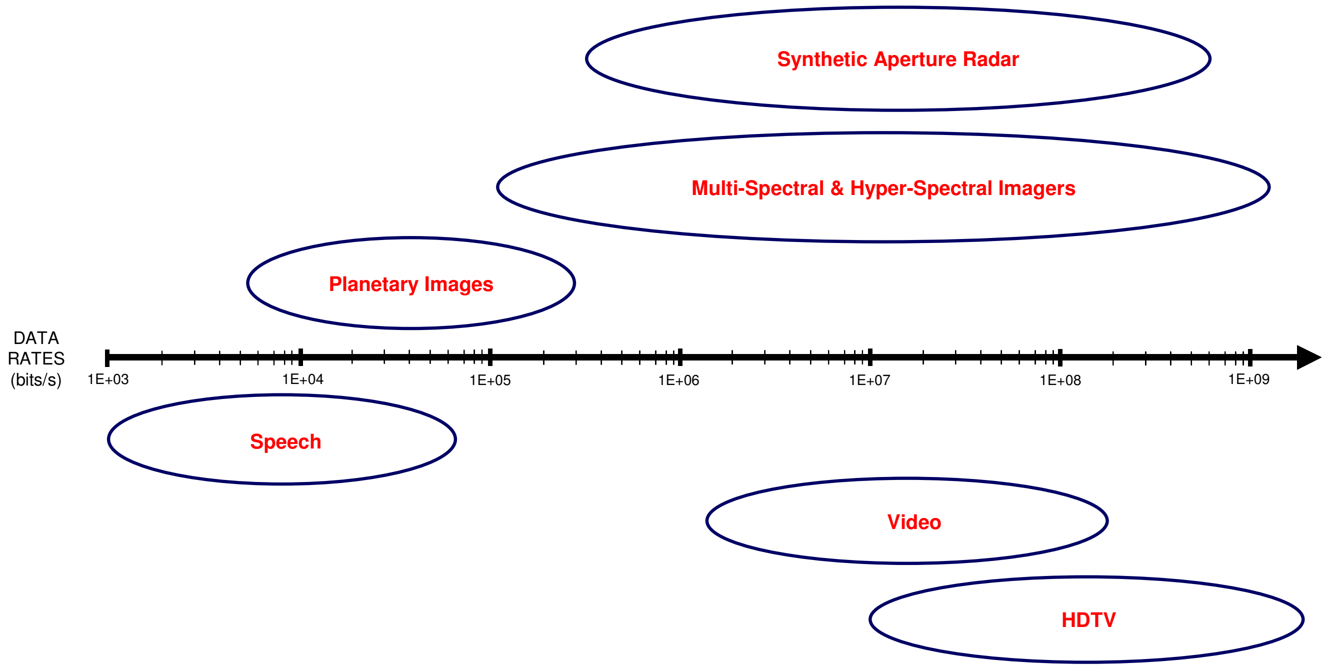

Figure 1. Data Rates for Various Applications

2. Presumed Requirements

To determine the needs of future human missions to the Earth's moon and Mars, we imagined what we would want were we to go on such missions. We took account of lessons learned by JPL from robotic planetary missions, such as the need for reliable communications during critical events.

We would want two basic types of communication channels: high reliability channels and high rate channels. We would use high reliability channels for operational and critical event communications that need to be sent reliably and with minimum latency. Forward (Earth-to-space) high reliability links would include digital commands and digitized speech (to astronauts); return (space-to-Earth) links would carry digitized speech, engineering data, video (if there is sufficient bandwidth), and limited science data. We would want high reliability channels to:

- Operate over near continuous (24/7) redundant links in the vicinity of a base on the surface of the moon or Mars.
- Serve spacecraft en route to the moon or Mars and during descent and ascent.
- Support multiple spacecraft, robots & astronauts simultaneously.
- If there are human occupants, support commands, engineering telemetry and two-way speech at any time from any spacecraft attitude.

Figure 1 shows ranges of data rates required for various applications using current technology [9]. Table 1 shows presumed required data rates based on the ranges in this figure.

Table 1. Presumed Data Rate Requirements

		Data Type	*Data Rates*
Reliable Channel	*Forward*	Speech	10 kbps
		Digital Commands	200 bps astronaut 2 kbps transport/rover/base
	Return	Speech	10 kbps
		Engineering data	2 kbps astronaut, 20 kbps transport/rover/base
		Video	100 kbps helmet cam 1.5 Mbps rover
High Rate Channel	*Forward*	Command loads	100 kbps
		CD-quality audio	128 kbps
		Video (TV, videoconf.)	1.5 Mbps
	Return	High Definition TV	20 Mbps
		Hyperspectral imaging	150 Mbps
		Radar	100 Mbps

High rate forward link channels would be used for videos and digital music for astronauts and for large command loads. On the return link, high rate channels would support high rate science and public outreach applications like hyperspectral imaging, radar and high definition television. We would be satisfied with reduced availability requirements for these high rate channels; interruptions due to adverse weather on Earth or Mars or temporary pointing problems could be tolerated.

We also presumed a customer set including a single base from which astronauts would not venture more than 100 km. The base communications system would support continuous redundant reliable channels and, when available, high rate channels through a steered antenna. We assumed that the lunar base will be near a pole and that the Mars base will be in a mid-latitude region. We assumed the following customers:

- 12 astronauts at or near the base, requiring up to 6 simultaneous two-way voice channels, which would be monitored on Earth. Astronauts would use omnidirectional antennas.

- 4 transports carrying humans, which would need simultaneous reliable channels supporting up to 10 kbps on the forward link and up to 1.5 Mbps on the return link for each transport through omni and steered antennas. High rate channels could be used when available.

- 24 robotic rovers simultaneously using two-way reliable links with up to 100 kbps on the forward link and up to 1.5 Mbps for video on the return link using omni and steered antennas. High rate channels could be used when available.

Table 2 shows how return link data from these users adds up. The aggregate data rate for reliable channels is 44 Mbps, dominated by simultaneous video from 24 robotic rovers (1.5 Mbps from each rover).

We assume high rate channels are shared. The aggregate data rate for high rate channels is 440 Mbps. If additional high rate channels are necessary, there may be a need to support a substantially higher aggregate data rate.

Radio-based navigation will be required en route to the moon and Mars. Also, navigation will be needed for descent and landing, for surface navigation and for ascent. We assume that radionavigation needs to be good enough to ensure that a lander will land within easy walking distance from a base, but far enough away to ensure that the base is not damaged by the lander when landing. We estimate this to require on the order of 100 m accuracy.

We assume that to a first order, telecommunication and navigation requirements are the same for both lunar and Mars missions.

Table 2. Aggregate Return Link Requirements

User	*Channel Content*	*# of Channels*	*Channel Data Rate*	*Total Data Rate*
Reliable Channels				
Base	Speech	6	10 kbps	60 kbps
	Engineering	1	100 kbps	100 kbps
Astronauts	Speech	6	10 kbps	60 kbps
	Helmet-cam	12	100 kbps	1.2 Mbps
	Engineering	6	20 kbps	120 kbps
Transports	Video	4	1.5 Mbps	6 Mbps
	Engineering	4	20 kbps	80 kbps
Rovers	Video	24	1.5 Mbps	36 Mbps
	Engineering	24	20 kbps	480 kbps
			Aggregate	**44 Mbps**
High Rate Channels				
Base	HDTV	1	20 Mbps	20 Mbps
Transports	HDTV	1	20 Mbps	20 Mbps
	Hyper-spectral Imaging	1	150 Mbps	150 Mbps
Rovers	Radar	1	100 Mbps	100 Mbps
	Hyper-spectral Imaging	1	150 Mbps	150 Mbps
			Aggregate	**440 Mbps**

3. LUNAR NETWORK ARCHITECTURE

To generate a strawman lunar network responsive to our presumed needs, we first considered the capabilities of Earth antennas. We found that an inexpensive ground network could meet most of our presumed requirements for near-side lunar missions, though Earth-based antennas could not provide far-side coverage of spacecraft en route to near-side landings. The communication and navigation requirements of a polar base not in view of Earth could be met by a constellation of three Lunar Telecommunications Orbiters (LTOs) in conjunction with an augmented ground network.

Earth-Based Ground Network

The DSN has been planning to construct very large arrays of 12-m diameter antennas to expand the capabilities of the network [10]. These arrays will provide 10 to 100 times the receive performance of existing 70-m DSN stations. Given that these antennas would be built in large quantities, there

Table 3. Data Rates between mooncraft and 12-m Earth Antenna

Spacecraft Antenna	Frequency Band	Return[4] (10 W transmitter)				Forward (200 W transmitter)	
		Allocation	Full moon[5]	½ moon	No moon	Allocation	Rate
1-m High Gain Antenna	S-band	2.2-2.29 GHz	5.2 Mbps	9.4 Mbps	55 Mbps	2.025-2.11 GHz	1 Mbps
	X-band	8.45-8.5 GHz	70 Mbps	100 Mbps	700 Mbps	7.19-7.235 GHz	13 Mbps
	K_a-band	25.5-27 GHz	530 Mbps	820 Mbps	2.1 Gbps	N/A	N/A
Omni	S-band	2.2-2.29 GHz	12.5 kbps	23 kbps	135 kbps	2.025-2.11 GHz	5 kbps

should be beneficial economies of scale from using new 12-m antennas also for lunar network Earth stations.

We thus estimated the performance of a 12-m antenna on the surface of the Earth communicating with a mooncraft[6] through either an omnidirectional antenna or a steered 1-m dish antenna (Table 3)[7].

A 12-m Earth antenna communicating with a 1-m mooncraft antenna appears capable of providing all the required communications for both reliable channels (70 Mbps X-band capability vs. 44 Mbps required) and high rate channels (530 Mbps capability at K_a-band vs. 440 Mbps required). A 12-m Earth antenna could even support two-way speech through a mooncraft omni antenna.

The capabilities of existing DSN stations are considerably better than those of 12-m stations (Table 4). 34-m stations generally have nearly an order of magnitude higher receive performance, enabling reception of voice communications directly from astronauts walking on the moon using omni antennas and less than 1-W transmitter power. 70-m stations have an additional factor of four times better performance.

Table 4. Ground Antenna Performance

Ant. Dia.	*S-Band*				*X-Band*				*K_a-Band*			
	T	*G/T*	*RF Power*	*EIRP*	*T*	*G/T*	*RF Power*	*EIRP*	*T*	*G/T*	*RF Power*	*EIRP*
m	*K*	*dB/K*	*kW*	*dBm*	*K*	*dB/K*	*kW*	*dBm*	*K*	*dB/K*	*kW*	*dBm*
12	30	30.5	0.2	99	30.2	43.6	0.2	110	123	46.8	0.2	123
34	37	40.9	20	128	40.5	52.0	20	140	123	56.0	1	138
70	22	49.8	400	149	33.4	58.6	20	146	70 m not efficient at K_a-band			

A network of 12-m antennas on Earth appears sufficient to communicate with mooncraft on the lunar near-side. Existing DSN stations might support initial near-side missions, but new ground antennas will probably be necessary to provide near-continuous redundant links to a sustained human base.

There is substantial interest in establishing a human base in the vicinity of a permanently shadowed crater near one of the lunar poles. These "cold traps" are believed to be repositories of frozen volatiles. However, these areas are generally not in view of the Earth. We thus considered using lunar relay satellites to support mooncraft in polar regions or placing a repeater atop Malapert Mountain, which is 5 km above the lunar reference radius – the highest point near the lunar South Pole [11].

Analyses [12] assuming a smooth moon horizon in the vicinity of Malapert Mountain indicate that the summit may

[4] Link capability – regulatory bandwidth limits may substantially reduce data rates. Bandwidth efficient modulation can support 2 bps/Hz (Bandwidth-Efficient Modulations: Summary of Definition, Implementation and Performance, CCSDS 413.0-G-1 Green Book, April 2003).

[5] The lunar brightness temperature of 230 K significantly reduces return rates when the moon is in view of the ground antenna. The system noise temperature contribution due to lunar blackbody brightness temperature depends on link frequency. With the moon's linear diameter of about 0.5º, we assume that the full 230 K will be picked up by the 12-m antenna beam at X-band (0.2º Half Power Beam Width, or HPBW) and at K_a-band (0.06º HPBW), for the cases when the antenna boresight aligns with the center of the lunar disk ("full-moon" cases in Table 3). At S-band, the size of the antenna beam for the 12-m dish (about 0.7º HPBW) exceeds the lunar disk, so only a fraction of the 230 K will be picked up when centered on the lunar disk (roughly 50 K). When the antenna beam is pointed to the limb of the lunar disk ("half-moon" cases in Table 3) such as at Malapert Mountain in the southern polar region, about one-half of the "full-moon" contributions of lunar blackbody noise is added to the system noise temperature values in Table 3.

[6] A spacecraft, astronaut, rover, base station, lander or orbiter in the vicinity of the Earth's moon.

[7] Assumptions:
- 384,400 km range (mean Earth-Moon distance)
- 2.2 dB combined losses
- 450 K mooncraft equivalent system noise temperature
- Suppressed carrier
- 1 dB E_b/N_o threshold with 1 dB system implementation loss
- 12-m antenna system noise temperatures are shown in Table 4. Atmospheric loss is based on statistical noise temperature and attenuation values derived from DSN Document 810-5 for Goldstone, California climatic conditions.

have a continuous view of Earth and that there is total darkness at the summit for no more than 7 days at a time 5 times per year. Simulations have shown that gaps in DSN visibility of Malapert Mountain are no greater than 90 minutes at 10° elevation angle, no greater than 30 minutes at 6° elevation angle and no greater than 15 minutes at 5° elevation angle.

We assume that there will be only one lunar base, so there will be a need to provide continuous coverage at just one pole.

Lunar Space Network

We assume that we require continuous redundant links to the vicinity of a lunar polar base. We considered three space-based relay alternatives: relay spacecraft in pole-sitting orbits, in halo orbits about Earth-moon Lagrange points and in lunar orbits. We concluded that the technology necessary to maintain a pole-sitting orbit, in which a spacecraft uses continuous thrust (i.e. from a solar sail) to keep its position over a pole, is insufficiently mature. Halo orbits about Earth-moon Lagrange points would be much further from the pole than lunar orbit alternatives, resulting in inferior relay performance, and would provide poor coverage of polar regions. We thus developed a lunar space network architecture to serve a polar base with relay spacecraft in lunar orbits.

Lunar Orbit

To serve as a relay between Earth and humans near a polar base, it would be desirable to have one or more orbiters that "linger" over the pole. On Earth, Molniya orbits are sometimes used for extended polar coverage. These orbits are inclined at the critical inclination (116.565°) so that the line of apogee does not rotate. This orbit works at Earth because of the large Earth J2. However, at the moon at high altitudes there is no equivalent orbit using effects of the moon's gravity field. Fortunately, we found an elliptical lunar orbit that uses Earth gravity perturbations to keep its apolune over a polar region.

We assume that the relay orbiter constellation will serve a single base near a lunar pole, and that at least two orbiters must be in view of the base at all times to ensure redundant links back to Earth. This could be done with three orbiters in high altitude elliptical orbits phased 120° apart, if their apolunes stay oriented generally over the pole.

The design of high altitude lunar orbits must take into account the unique characteristics of the moon. Earth's gravity is the most significant perturbation on high altitude lunar orbits. As a result, these orbits can possess a multitude of complex motions atypical of lower altitude orbits, which are dominated by non-spherical gravity field perturbations. Indeed, many can exhibit unstable characteristics. However, there exists a class of elliptical orbits which, due to the influence of Earth gravity perturbations, yields a line of apsides that librates in the vicinity of the South (or North) Pole, hence focusing coverage at one of the poles. Furthermore, we found that three spacecraft can be placed in these orbits and maintain a relatively stable formation that meets our requirements (Figure 2). We denote this a Pole Lingering Lunar Orbit (PLLO) [13].

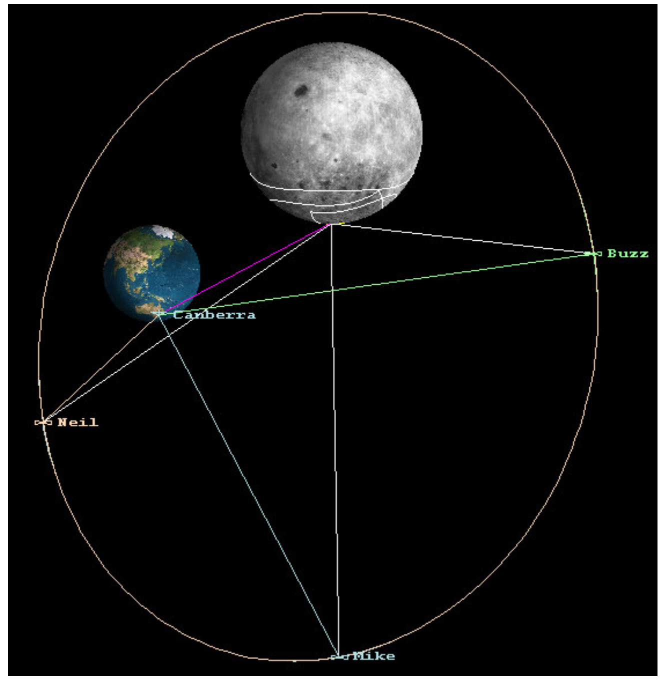

Figure 2. Three orbiters in PLLOs

Lunar Telecommunications Orbiter RF System

We considered three alternative radio systems for the lunar orbiters: bent-pipe linear transponders, regenerative transponders, and store-and-forward radios.

Bent-pipe linear transponders have a great deal of flexibility – they relay whatever is sent through the transponder bandwidth, regardless of how many channels there are or data rate or type of modulation or coding. However, bent-pipe linear transponders require both ends of the link to operate simultaneously. They also amplify the noise as well as the signal received by the transponder, typically reducing the signal-to-noise ratio on the second hop by 3 dB.

Regenerative transponders demodulate and decode the received signal to recover the original data stream, then recode and remodulate it prior to retransmission at a new frequency. In this case, there is minimal degradation between uplink and downlink – data received without error on the uplink are retransmitted without added noise on the downlink. Furthermore, the transmitter can be saturated, a more efficient operating mode. Regenerative transponders thus require less power than linear transponders.

A store-and-forward radio is basically a regenerative transponder in which the data are stored prior to retransmission. Its performance is fundamentally the same as that of a regenerative transponder.

Regenerative transponders and store-and-forward radios have some limitations with respect to bent-pipe linear transponders – they are relatively inflexible and complex: they must demodulate, decode, remodulate and recode each individual received channel.

Bent-pipe linear transponders appear well suited to the LTOs, as they can easily support multiple simultaneous channels, Earth is generally in view of an orbiter whenever a polar base is in view, and there is generally plenty of margin so power is not an issue. We thus selected bent-pipe linear transponders for our strawman orbiter RF payload. We include a store-and-forward relay radio for use when relaying communications from a user on the far side of the moon when Earth is not in view of the orbiter.

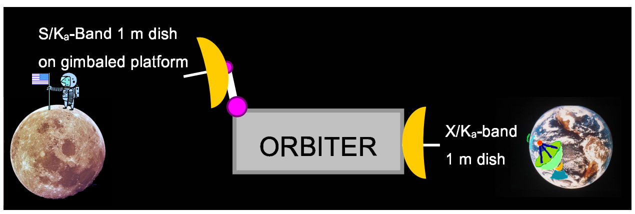

Figure 3. LTO Antenna Configuration

Figure 3 illustrates the strawman LTO antenna configuration. The orbiter has a body-fixed 1-meter X/K_a High Gain Antenna (HGA) for Earth communication and a 1-meter S/K_a gimbaled HGA for lunar communication. The gimbaled antenna will be fully articulated to allow essentially 360° pointing with respect to the Earth-pointed antenna in order to support any moon-spacecraft-Earth angle and to support Earth-based end-to-end testing. Table 5 shows relay data rates that could be supported with a 1-m orbiter antenna.[8]

The LTO RF system must meet the following requirements:

Lunar Relay Communication

- Linearly translate multiple S-band channels for lunar-surface-to-orbiter-to-lunar-surface links using frequency-division multiple access (FDMA). This function provides "over-the-horizon" real-time communications and data transfer between robotics, astronauts, and lunar base stations.
- Linearly translate medium-data-rate (1.5 Mbps or less) bent-pipe S-band transmissions from the moon to the X-band orbiter-to-Earth downlink. This uses FDMA to support reliable real-time data from multiple users on the lunar surface to Earth.
- Relay X-band data from Earth to the lunar surface at S-band with high reliability. This relay link will use FDMA to support multiple users in the S-band beam illumination area.
- Relay high-rate (up to 150 Mbps) data from the lunar surface to Earth at K_a-band. FDMA on this link will support multiple channels if they originate from a single site or in close proximity.
- Store-and-forward data between the lunar surface and Earth. The lunar side of this link will function at S-band using an Electra radio modified to include an S-band upconversion/downconversion stage. The Earth side of this link will use an X-band near-Earth transponder.

Backhaul (Earth-Orbiter) Communications and Navigation

- Single-channel X-band coherent transponding function to support orbiter-to-Earth Doppler measurement using the Deep Space Network or other ground stations.
- Turnaround sequential ranging from Earth.
- Delta Differential One-Way Ranging (Delta-DOR) to Earth ground stations.
- Single-channel direct-from-Earth uplink at data rates from 7.8 bps to 4 kbps for orbiter command and control and for store-and-forward relaying.
- Direct-to-Earth X-band telemetry at up to 10 Mbps for orbiter engineering and science data return and lunar surface store-and-forward data return.

Lunar Navigation

- S-band coherent turnaround with a frequency source derived from an ultra-stable oscillator

Table 5. Lunar Relay Data Rates with 1-m Orbiter Antenna

User Ant.	*Freq. Band*	*Return (User-to-Orbiter)*			*Forward (Orbiter-to-User)*		
		Allocation	*Power*	*Rate*	*Allocation*	*Power*	*Rate*
-3 dB	*S-band*	2.2-2.29 GHz	4 W	10 kbps	2.025-2.11 GHz	4 W	10 kbps
0.25 m			15 W	1.5 Mbps		25 W	1.5 Mbps
	K_a-band	37-37.5 GHz	4 W	100 Mbps			

[8] Table 5 assumes regenerative rather than bent-pipe transponders. Links that specify a 0.25-m user antenna assume gain equivalent to that of a 0.25-m diameter dish; at S-band, the antenna could also be a horn or patch design. 1 dB of circuit losses are assumed for both transmit and receive systems. The data are modulated onto a suppressed carrier using a high performance code with a threshold E_b/N_o of 1 dB and 1 dB of implementation losses. A maximum range of 11,600 km is assumed. 630 K system noise temperature is assumed for both orbiter and user receivers. Margins are about 3 dB.

(USO). This enables a descending or ascending lander not in view of Earth to measure the Doppler shift of its own carrier relative to the known ephemeris or simultaneously measured position of the orbiting RF payload with respect to Earth.

Test Capability

- Simultaneously point both the lunar and Earth antennas at Earth to do full end-to-end relay link testing from Earth.

Figure 4 illustrates the S-band and K_a-band footprints on the moon of 1-m relay HGAs on three LTOs. Note that the S-band footprints cover a very large area in the vicinity of the pole, enabling users over this wide area to simultaneously use an orbiter for reliable S-band channels without repointing the relay HGA. The K_a-band beamwidth is much narrower, so the relay HGA must be pointed at individual users of high rate K_a-band channels unless they are close together.

Figure 5 is a high-level block diagram of the RF payload illustrating the linear transponding and store-and-forward data handling capabilities.

On the lunar side, S-band communications received from the surface are separated by spectral filtering. One region of the spectrum is sent to a modified Electra proximity radio [5], which can receive and store data to spacecraft memory via the Command & Data Handling (C&DH) subsystem. Another region of the received spectrum is downconverted to another region of the S-band spectrum and sent back

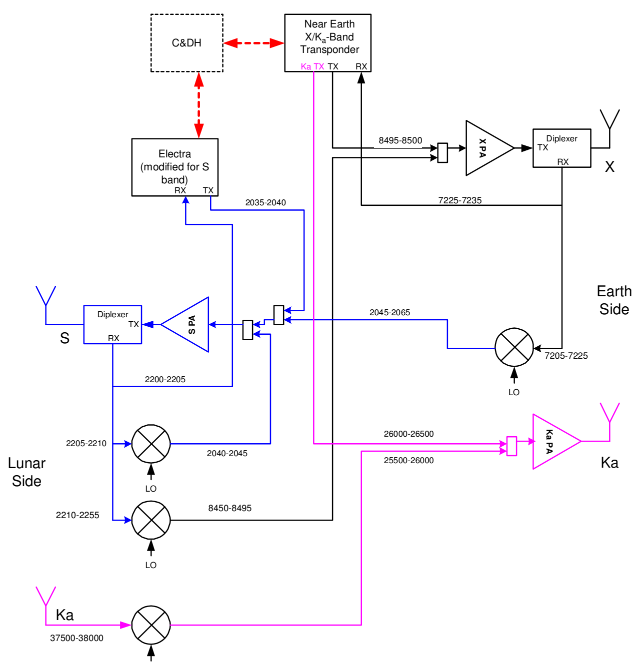

Figure 5. RF Payload High-Level Block

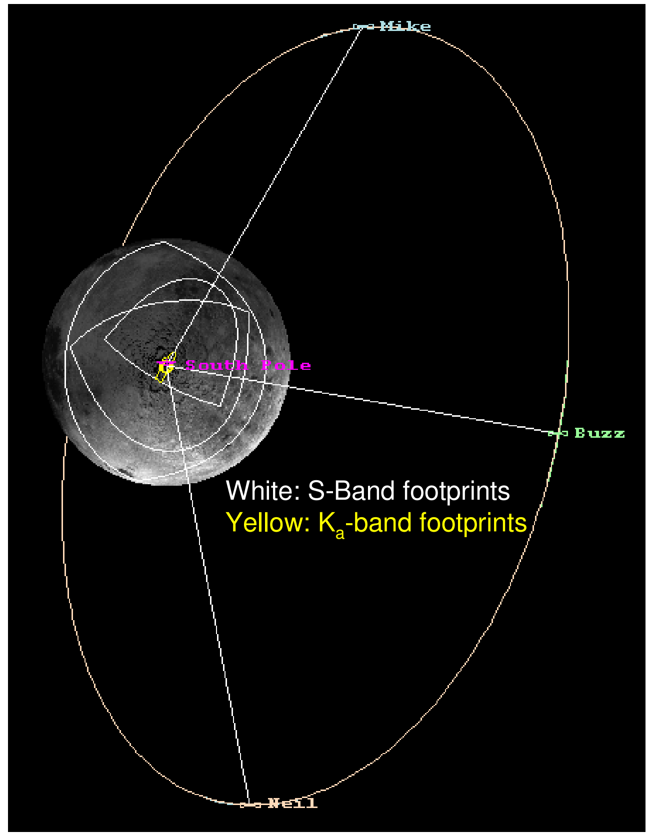

Figure 4. Orbiter Footprints

through the same antenna to the lunar surface to support real-time over-the-horizon communications. The third region of the S-band spectrum is upconverted to X-band and sent to Earth over the high-reliability X-band downlink channel.

Very high-rate data from the lunar surface are transmitted to the orbiter at K_a-band, linearly translated to another region of the K_a-band spectrum and returned to Earth over the K_a-band downlink channel.

In the S-band subsystem, the moon-to-moon S-to-S downconverter is driven by a local oscillator (LO) derived from an ultrastable oscillator (USO) to provide high-stability, low-phase-noise coherent turnaround.

On the Earth side, the X-band uplink is similarly separated by spectral filtering into a band used for orbiter uplink command and control and another band used for forward-link, real-time Earth-to-lunar-surface data flow. An X/K_a-band near-Earth transponder provides the needed orbiter command and telemetry interface to the spacecraft C&DH subsystem, as well as an LTO-Earth radio navigation capability with Doppler turnaround, sequential two-way ranging, and Differential One-way Ranging (DOR).

It may be possible to simplify the RF system by combining the functions of the store & forward proximity radio (Electra) and the Earth TT&C radio (a near-Earth transponder) into a new integrated radio. Currently, the requirements for orbiter navigation (Doppler, ranging, and DOR) and high-rate X and K_a-band downlink require a near-Earth transponder, and the requirements for uplink data rates from the lunar surface in excess of 4 kbps require an Electra radio.

Lunar Frequency Plan

It can be shown that to a first order approximation, the following relationships hold [14]:

- The performance of a link between two omnidirectional antennas increases with the inverse square of frequency.
- The performance of a link between an omni antenna and a steered antenna with fixed aperture is independent of frequency.
- The performance of a link between two steered antennas with fixed apertures improves with the square of frequency.

For example, a link between two astronauts with small whip antennas – effectively omnidirectional – increases with the inverse square of frequency, so we would want the frequency of such links to be as low as possible, such as a 400 MHz UHF link. The performance of a link between a steered antenna on an orbiter and a steered antenna on the ground, whether it be a ground station on Earth or a lunar base station, improves with frequency squared, so we would want to go to a frequency as high as possible – such as a 26 GHz K_a-band link. Links between omni antennas on spacecraft and ground stations on Earth are, to a first approximation, independent of frequency up to X-band, but at higher frequencies (like K_a-band) this relationship does not hold, so frequencies at X-band and below are preferred for links between Earth ground stations and omni antennas.

Lunar communications must deal with some unique restrictions. First of all, from a regulatory perspective the moon is near Earth and thus must use frequencies allocated for Category A. Secondly, there is a shielded zone of the moon on its far side to preserve the possibility of using the far side of the moon for radio astronomy [15]. At this time, only frequencies between 2 and 3 GHz are explicitly allowed on the lunar far side.

Table 6 shows spectrum that could be used for lunar missions. We have separated the frequency bands into "Reliable" bands (S-band and X-band), which are minimally affected by weather when passing through Earth's atmosphere and which work well through omni antennas, and "High Rate" bands (K_a-band), which are affected by adverse weather but which can operate at very high rates when used between steered antennas on both ends of a link.

Table 6. Potential Lunar Spectrum

	Band	Forward GHz	Return GHz	Cat.	Comments
Reliable	S	2.025-2.11	2.2-2.29	A	Shuttle/TDRS & others
	X	7.19-7.235	8.45-8.5	A	Space Research Primary
High Rate	K_a		25.5-27	A	Space Research Primary TDRS/Space Station
		40-40.5	37-37.5	A,B	Space Research Primary
			37.5-38	A,B	Shared users

To select between these bands, we considered the following:

- Users generally wish to use the same frequency bands when they are on their way to their destination (the moon in this case) as when they arrive at the destination.
- Uplink and downlink frequencies of transponded signals must be widely separated to avoid passive intermodulation on relay orbiters.
- Lunar proximity links will generally not be in the Earth direction, enabling reuse of frequency bands that are crowded at Earth for proximity links.

Based on these considerations, we selected the frequency plan illustrated in Figure 6.

The near-Earth S-band allocation is heavily congested. We suggest that it be used for narrowband reliable Direct From Earth/ Direct To Earth (DFE/DTE) and backhaul (i.e. LTO DFE/DTE) links.

We suggest that the near-Earth S-band allocation also be used for reliable proximity links. These may be relatively large bandwidth, but as Earth will rarely (if ever) be in the same direction as lunar proximity relay links, spatial diversity should minimize the potential for conflict.

The K_a-band frequency for lunar proximity uplink and DTE

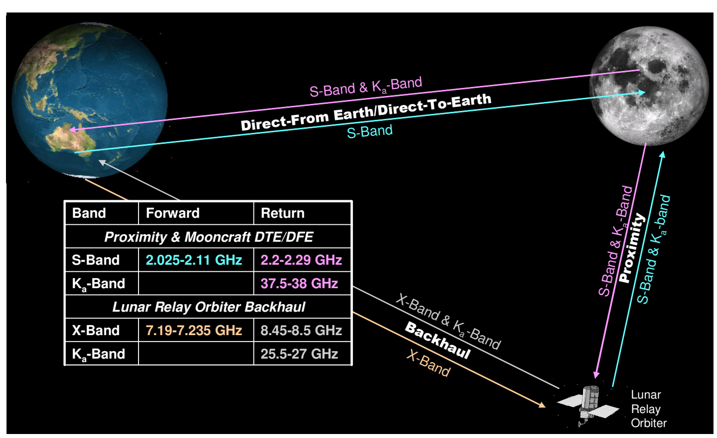

Figure 6. Lunar Frequency Plan

high rate transmissions from mooncraft lies within the Space Research Service allocation at 37 to 38 GHz. JPL proposes that the 37 to 37.5 MHz band be reserved for human Mars missions, so we propose to use the 37.5 to 38 MHz band for lunar missions. This region is yet to be used for deep space missions, which currently operate in the other K_a-band deep space allocation at 31.8 – 32.3 GHz.

For LTO K_a-band direct-to-Earth communications (backhaul downlink), we selected the 25.5 – 26.5 GHz band. This band is allocated for near-Earth operation and for space research, and is used by the Tracking and Data Relay Satellite System (TDRSS). The near-Earth X-band allocation is used for reliable backhaul links.

Figure 7 summarizes the communications frequency plan for the LTO RF payload. Sub-bands at S, X, and K_a-band are allocated for the multi-channel communications support described above. Note that the allocations do not imply that the full spectrum is utilized. Rather, multiple narrow channels will be assigned within this allocation. Since at least two and often three orbiters will be in view of users on the lunar surface, the specific channel assignments for each of the three orbiters will be different in order to avoid interference in areas covered by overlapping antenna footprints.

Lunar Reconnaissance Orbiter / RLEP Communications

NASA established the Robotic Lunar Exploration Program (RLEP) at Goddard Space Flight Center (GSFC) in 2004 to carry out robotic lunar missions in support of the Vision for Space Exploration. Beginning in 2008, RLEP will launch a series of missions to the moon in preparation for the return of human crews to the lunar surface. RLEP includes orbital and landed elements, and will perform a complimentary set of science and exploration oriented measurements, as well as proving necessary technologies and deploying infrastructure to support human exploration. Lunar Reconnaissance Orbiter (LRO) is the first RLEP mission, and is the first robotic precursor mission in the Vision for Space Exploration. LRO is a remote sensing mission intended to study the Moon's topography, radiation environment and resource availability. Knowledge gained by LRO will be used to aid later missions, including the second RLEP mission – a lunar lander to launch in 2009.

The long term, multi-mission nature of RLEP requires that

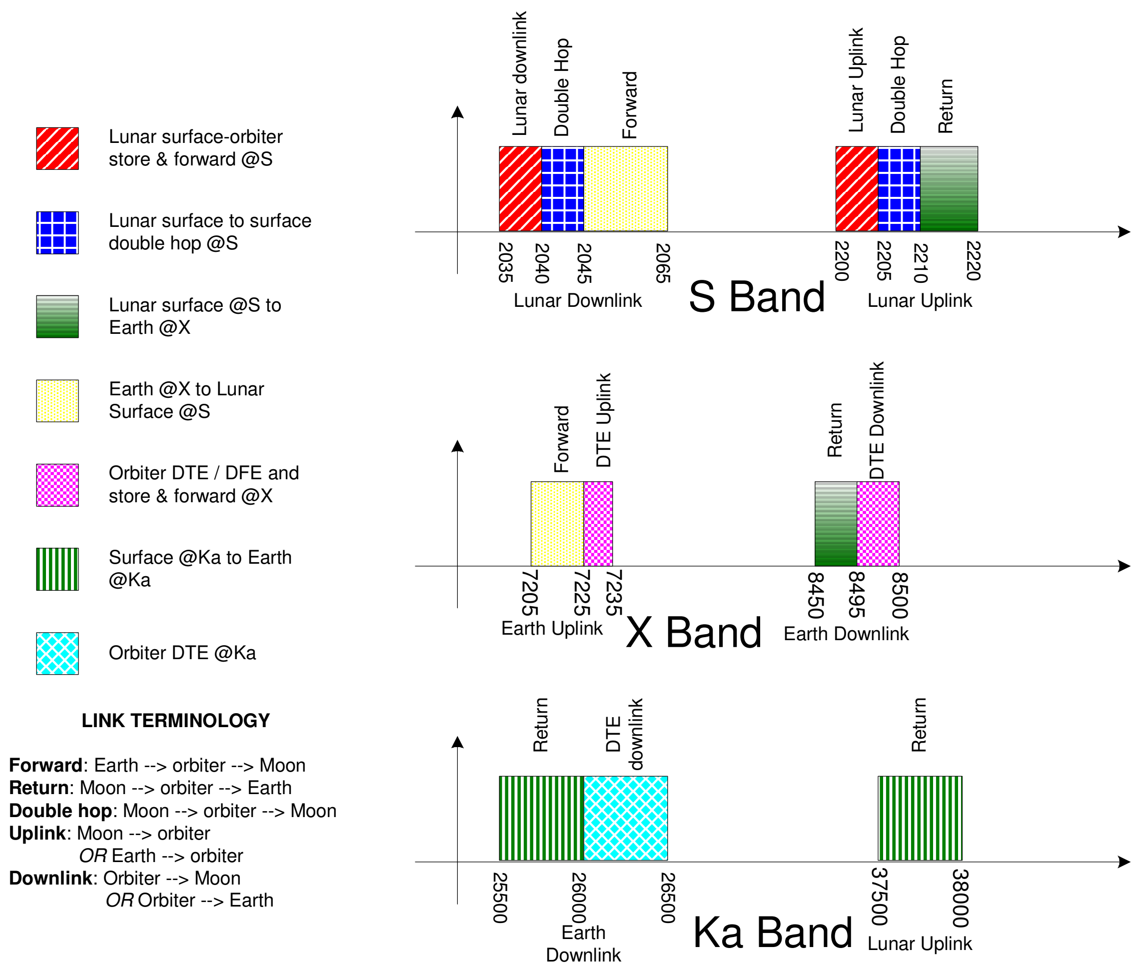

Figure 7. LTO RF Payload Frequency Plan

care be given to the communication architectures of each individual mission as well as the program as a whole. RLEP will place surface elements in locations without direct-to-Earth visibility, such as permanently shadowed craters, and thus requires multi-mission and multi-element communication cross-support. Following the successful Mars Network model, this will be done initially by adding relay radios to orbiting RLEP science orbiters. These may eventually be augmented by dedicated LTOs as described herein.

LRO will employ at least two independent communication systems: a high rate K_a-band system and a medium rate S-band system for TT&C. Proximity relay capability will be provided at S-band and will be either included in the TT&C communication hardware or added as a third independent system.

LRO's K_a-band system will operate in the 25.5-27 GHz band. This high rate system will support downlink rates up to 125 Mbps using QPSK modulation with CCSDS forward error correction methods. Link contact periods are driven by onboard storage capacity, ground network loading and orbit geometry.

The S-band system will operate in the Category A space research band, and will provide nominal and contingency TT&C communication and navigation functions for all phases of the mission. The S-band system will be capable of communicating with TDRSS, the DSN and commercial ground stations. Multi-network interoperability will be provided through reconfigurable, software-defined radio-based transceiver systems. TDRSS will be used during launch and early orbit operations and trans-lunar cruise. Communications will then hand off to the DSN or commercial ground stations, which will support the remainder of the mission.

LRO will provide relay services, including forward and return data communications and radio navigation, to later missions in the RLEP sequence. LRO may also provide relay cross-support to international exploration partners.

The LRO relay capability is modeled on Electra. It integrates an S-band transceiver with error correction and link layer protocol and link management support. Standard lunar proximity links will support data rates up to 1 Mbps, and will employ the CCSDS Proximity-1 protocol. RLEP must support non-standard relays, such as those used on extremely lightweight, short-lived probes where power and mass constraints do not permit higher level protocols. In such cases, software-defined radio techniques will be used to allow the LRO relay transceiver to adapt to non-standard links.

LRO will be placed into a 50 km polar orbit for its science mission. This orbit is not stable – LRO requires substantial fuel for orbit maintenance as long as it is in the science orbit. LRO is expected to be moved into a low-maintenance "stable" orbit optimized for relay communications following the completion of the primary LRO science mission.

4. MARS NETWORK ARCHITECTURE

Mars missions must cope with a range to Mars up to 400 million km – more than a thousand times greater than to the moon. Communications performance will be reduced by range squared, or by over a million. A 12-m ground antenna on Earth is not sufficient for communications with Mars missions.

The distance to Mars typically varies by a factor of about 7 through the Earth-Mars synodic period, making it possible to transmit at data rates nearly 50 times greater when Mars comes closer to Earth (inferior conjunction) than when Mars is at maximum range from Earth (superior conjunction).

The huge variation in distance between Earth and Mars also results in a large variation in the light time between these planets of from 3 to 22 minutes. From a monitor and control perspective with Earth in the loop, two-way light time varies from 6 to 44 minutes. If an astronaut asks a question of Earth controllers when at maximum range from Earth, it will be 44 minutes before the astronaut can hear a reply.

These factors all combine to make Mars communications much more difficult than lunar communications, especially DFE/DTE links. As with the lunar network, we propose a strawman Mars network consisting of ground stations on Earth and relay orbiters at Mars, but with large arrays on Earth rather than single ground antennas.

Earth-Based Ground Network

Large effective apertures are required to communicate with users at Mars. The DSN currently does this with 34-m and 70-m ground stations. DSN antennas are sometimes arrayed to increase receive performance for critical events, such as for the Voyager encounter of Neptune in 1989. Arraying five antennas in 1996-1997 increased data returned from Galileo three-fold over what could have been received from a single 70-m antenna.

The DSN plans to implement arrays of as many as 400 small (perhaps 12-m diameter) antennas at each of its complexes to create at least 10 times the effective receive aperture of a 70-m antenna [10]. The data rates that could be supported between Earth and Mars at maximum Mars range are shown in Table 7 for 70-m DSN antennas and for an Array of Small Antennas (ASA) with receive performance equivalent to ten 70-m stations (10 x 70 ASA).[9] While transmit arrays of

[9] A worst-case Earth-Mars distance of 2.67 Astronomical Units is assumed. The 70-m antenna has cryogenically cooled Low Noise Amplifiers (LNAs) with overall system noise temperature of about 36

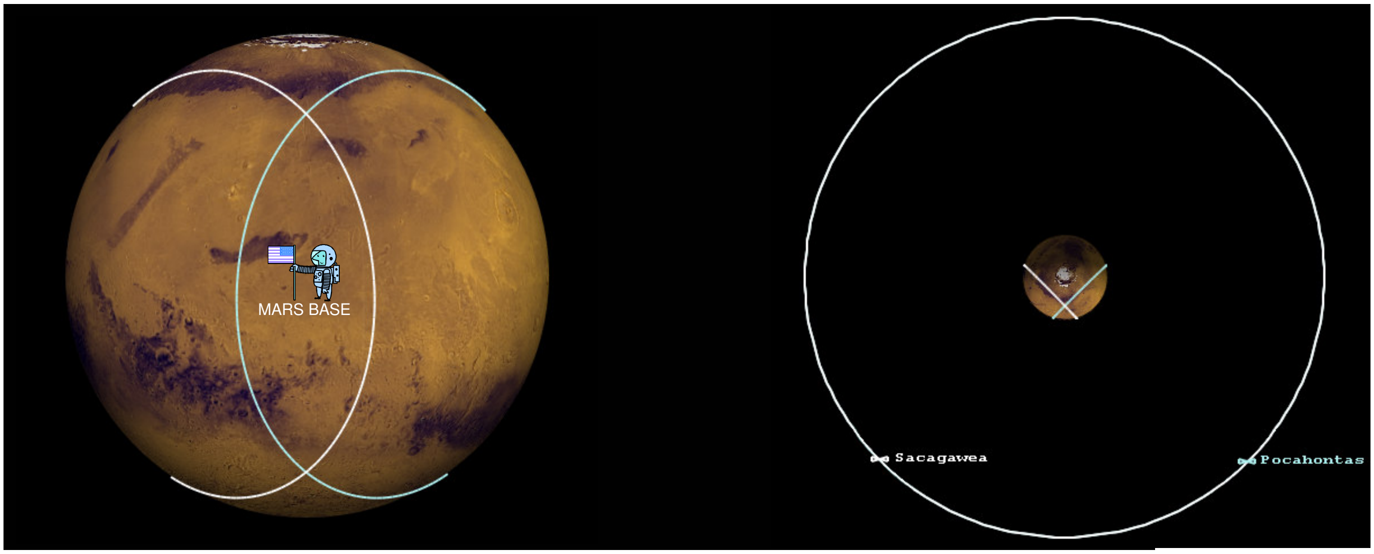

Figure 8. Two areostationary orbiters

small antennas have proposed [16], they have not been demonstrated, so we considered only 70-m antennas for forward links.

Relating Table 7 back to the return link aggregate data rates in Table 2 (44 Mbps for reliable channels and 440 Mbps for high rate channels), we can see that existing 70-m antennas are far from able to meet our presumed requirements. However, our requirements could be met with 10 x 70 ASAs by increasing Marscraft X-band transmitter power to 300 W (reliable channels) and K_a-band transmitter power to 1 kW (high rate channels).

Table 7. Data Rates between Mars and Deep Space Network Antennas

S/C ant.	*Freq. Band*	*Ground Antenna*	*Return (100 W)*		*Forward (20 kW)*[10]	
			Allocation GHz	*Rate*	*Allocation GHz*	*Rate*
Omni[11] *LGA*	X-band	70-m	8.4-8.45	20 bps	7.145-7.19	40 bps
		10 x 70 ASA[12]		200 bps		
3 m HGA	X-band	70-m		1.5 Mbps	7.145-7.19	1.5 Mbps
		10 x 70 ASA[9]		15 Mbps		
	K_a-Band	10 x 70 ASA[9]	31.8-32.3	50 Mbps		

Mars-Based Space Network

We considered a wide range of orbits for Mars communications orbiters [17]. To maintain continuous communications while a mid-latitude base on Mars is not in view of Earth, we selected areostationary orbiters that rotate around Mars once per sol (Martian day). An areostationary orbit at Mars is akin to a geostationary orbit around Earth. Areostationary orbits are equatorial, as at Earth, and have an altitude of 17,074.5 km. A pair of areostationary orbiters with overlapping footprints (Figure 8) would provide redundant continuous links between Earth and a Mars base (except during occultations), and non-redundant links to much of the rest of Mars. There is no shielded zone at Mars, so we can use frequencies other than S-band for reliable relay links. X-band yields similar performance to S-band for links between users with omni antennas and a steered antenna on the orbiter and superior performance if the user has a steered antenna, so we selected X-band for reliable relay links. However, there is only one X-band allocation for deep space; a new X-band relay allocation with separation adequate to avoid passive intermodulation with the X-band reliable backhaul on the orbiter will be necessary (Figure 9).

K at X-band and 81 K at K_a-band, referenced to a 20º elevation angle with Goldstone climate at about 90% weather. Atmospheric attenuation at K_a-band is about 1 dB. We assume a high performance code with threshold E_b/N_o of 1 dB and 1 dB of system losses. Margins of at least 3 dB are assumed.

10 In the uplink direction, the spacecraft receiver has an equivalent system noise temperature of 600 K. The uplink (forward) data (or commands) are assumed to be uncoded. Higher data rates for the forward links than those specified in Table 4 are achievable using error-correcting codes.

11 We assume the LGA has a gain of 0 dB. Circuit losses are about 1 dB.

12 Array of 12-m antennas with receive performance equivalent to ten 70-m stations.

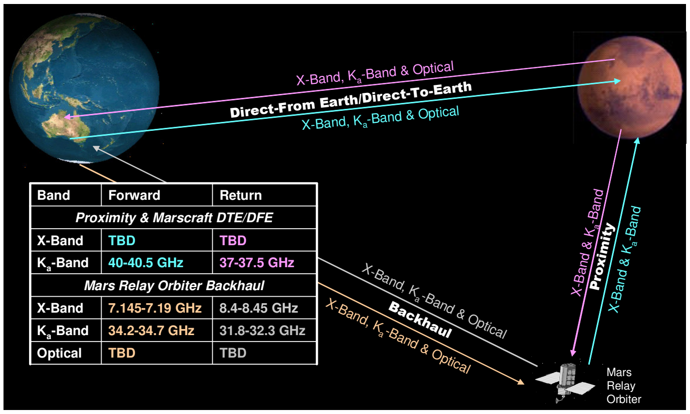

Figure 9. Mars Frequency Plan

Table 8 shows relay data rates that could be supported with such an areostationary orbiter. Due to the critical need for high performance for Mars communications, we assume regenerative rather then bent-pipe transponders.

Table 8. Mars Relay Data Rates

Antenna		*Freq. Band*	*Return*		*Forward*	
Orbiter	*User*		*Power*	*Rate*	*Power*	*Rate*
2.2 m	-3 dB	X	35 W	110 kbps	10 W	25 kbps
	0.25 m	X	90 W	130 Mbps	30 W	31 Mbps
		K_a	35 W	800 Mbps	8 W	210 Mbps
4.5 m	-3 dB	UHF	35 W	110 kbps	10 W	25 kbps

Emergency Communications

Communications with a distressed spacecraft in the vicinity of Mars can be sent through a relay orbiter. Communications with a distressed spacecraft en route to Mars must be sent through deep space links with Earth antennas.

Nominal deep space communication links use a spacecraft HGA pointed at Earth. During spacecraft emergencies in deep space, the spacecraft usually communicates through an LGA with an omnidirectional or hemispherical pattern. Emergency scenarios for deep space missions to the outer planets normally require the spacecraft to go into a state known as safing where the solar panels and one or more antennas maintain Sun-point. Earth is generally in the same hemisphere as the Sun for outer planet missions; the maximum antenna off-point angle between Sun and Earth is accounted for in emergency link budget calculations.

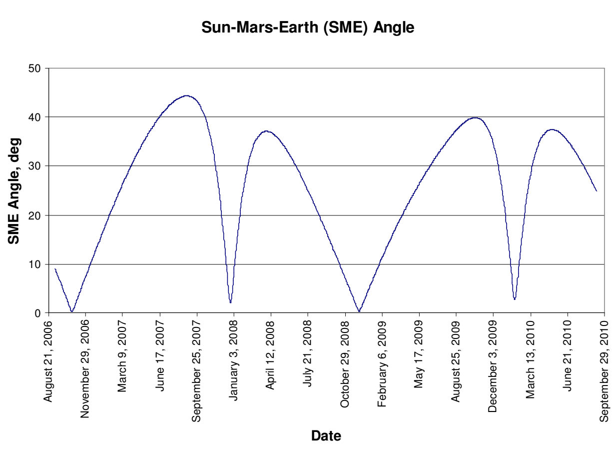

Figure 10. Mars-Earth angle for MRO at Mars

Figure 10 depicts the angle of the Earth off Sun-point as a function of time for the case of the Mars Reconnaissance Orbiter (MRO) mission at Mars during a four year period. Here the angle off boresight of a Sun-pointed antenna reaches a maximum of about 46°. This results in an antenna gain of about 4 dB for the link to Earth, assuming an antenna pattern similar to that of the Mars Exploration Rover cruise LGA (Figure 11). To analyze emergency communications en route to Mars, we assume a worst-case range distance of 2 AU and 42° Sun aspect angle.

In addition to a Sun-pointed safing orientation, in an emergency a spacecraft could go into an uncertain orientation such as an unplanned roll or drift if it loses stabilization. During such events, communications require the use of an omnidirectional LGA, where the direction to Earth relative to LGA boresight could span a considerable angle. The Earth may even drift in and out of the LGA field of view of one hemisphere during such anomalous safing scenarios. The use of an LGA also constrains the amount of RF power that could safely be put into it for communications from the spacecraft to Earth.

Robotic missions to Mars operate with command rates as low as 7.6125 bps and telemetry rates of 10 bps when in safe mode. This is not likely to be acceptable for human missions, which can be expected to require, at a minimum, intelligible 2-way voice communications between humans and Earth under nearly all conditions. Speech compression devices like Mixed-Excitation Linear Predictive (MELP) codecs can send intelligible speech at around 2000 bps. We assume for the purpose of deep space link calculations that

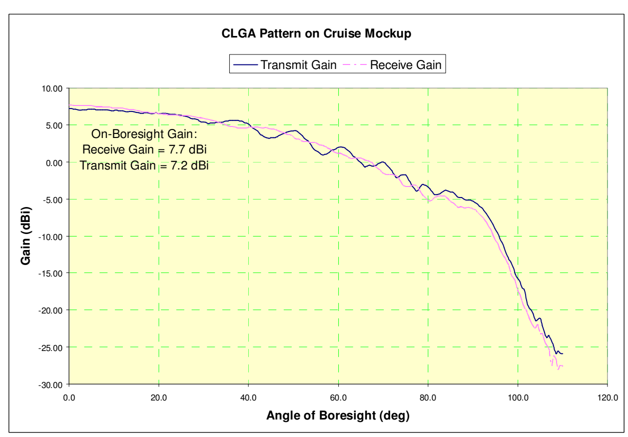

Figure 11. Mars Exploration Rover LGA Pattern

voice transmissions can be encoded using a Turbo or low-density parity check (LDPC) error correcting code that has a typical E_b/N_o threshold of about 1 dB with about 1 dB of implementation loss.

DTE Emergency Communications En Route to Mars

In the spacecraft-to-Earth direction, a 2 kbps digital voice link cannot be closed at X-band using 100 W of RF power out of an omni to a 70-m equivalent antenna on Earth. Such links come up about 20 dB short (Table 7).

A Direct To Earth (DTE) emergency voice link might be feasible if the ground system had 10 times the receive performance of a 70-m diameter antenna and the spacecraft could accommodate 1 kW of RF power input to an open-ended choke LGA. The larger equivalent area of the ground system could be realized in the future in the form of an equivalent large array of small diameter antennas. However, only a limited amount of RF power can be safely put into a spacecraft LGA without inducing problems such as arcing. Open-ended LGA choke designs without dielectric or micro-striping might be able to transmit 1 kW of RF power.

DFE Emergency Communications En Route to Mars

We assume that 70-m DSN antennas will be used for emergency uplink commanding. The current DSN transmit capability includes 20 kW transmitters for use at X-band (7.15 GHz), and 20 kW and 400 kW for use at S-band (2.11 GHz). In the Earth-to-spacecraft direction, at X-band, a digital voice uplink using an MELP codec operating at 2 kbps with an LDPC code could be closed at a range of 2 AU (assumed maximum range en-route to Mars) using a 70-m diameter DSN station with a 100 kW transmit capability (Table 9). For this link, it is assumed that an LGA with an antenna gain pattern equivalent to that of Figure 11 is used, yielding a -5 dB gain at or near 80º off-boresight. Transmitter power could be increased to 400 kW or the spacecraft receiver could be cooled to enable voice links at LGA aspect angles greater than 80º.

Solar Conjunction

The relative positions of Earth and Mars in their orbits around the Sun repeat with a regular “synodic” period of about 780 days. Thus, every 26 months, the two planets lie nearly on opposite sides of the Sun in an orientation known as superior solar conjunction. The angular distance of Mars from the center of the solar disk as observed from Earth is known as the solar elongation angle or the sun-Earth-Mars (SEM) angle. The minimum SEM angle during a superior conjunction can range from about 1.1° (~4 solar radii) to less than 0.26° (Mars is occulted by the solar disk) [18]. For links in which the receive element is at Mars and the transmitter is at Earth, the Sun appears as a disk that subtends an angle of 0.18° as viewed from Mars. From the perspective of the receiver at Mars, the Sun-Mars-Earth (SME) angle (Figure 12) defines the angular separation between the Earth and Sun.

Table 9. Emergency Uplink Budget

Transmit Parameters	
Power (100 kW)	80 dBm
Waveguide Loss	-0.3 dB
Antenna Gain (70-m)	72.83 dB
Pointing Loss	-0.1 dB
EIRP	152.43 dBm
Path Parameters	
Space Loss	-279.05 dB
Atmospheric Attenuation	-0.2 dB
Receive Parameters	
Antenna Gain	7.08 dB
Circuit Loss	-1 dB
Pointing Loss	-12 dB
Polarization Loss	-1 dB
Power Summary	
Received Power	-133.73 dBm
Noise Spectral Density	-172.07 dBm/Hz
P_t/N_o	38.34 dB-Hz
Carrier Performance	
Telemetry Suppression	-10.29 dB
Carrier Loop Noise BW	13.01 dB
Required Detection SNR	12 dB
Carrier Loop Margin	3.04 dB
Data Channel Performance	
Telemetry Data Suppression	-0.43 dB
P_d/N_o	37.91 dB-Hz
Data Rate (2 kbps)	33.01 dB-Hz
Available E_b/N_o	4.9 dB
Implementation Losses	-1 dB
Output E_b/N_o	3.9 dB
Required E_b/N_o	1 dB
Data Margin	2.9 dB

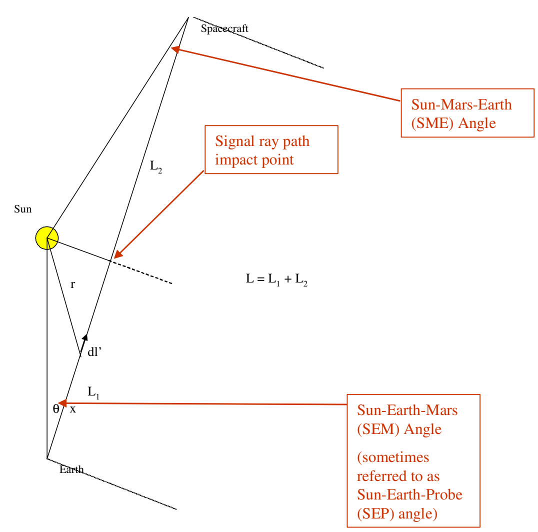

Figure 12. Superior Conjunction Geometry

Table 10 lists minimum SEM and SME angles as well as expected solar cycle phase and solar passage of the signal's impact point for Earth-Mars-Sun superior conjunctions occurring between 2015 and 2030.

Table 10. Superior Conjunction Mars-Sun-Earth Angles

Superior Conjunction Date	Minimum Sun-Earth-Mars Angle	Minimum Sun-Mars-Earth Angle
June 14, 2015	0.62°	0.40°
July 27, 2017	1.10°	0.68°
Sept. 2, 2019	1.08°	0.66°
October 8, 2021	0.65°	0.40°
Nov. 18, 2023	0.11°	0.08°
January 9, 2026	0.94°	0.66°
March 21, 2028	0.81°	0.58°

An example of a northern polar passage for the signal path from Mars to Earth relative to the Sun at a minimum SEP angle of 0.62° is shown in Figure 13 for solar superior conjunction occurring on June 14, 2015.

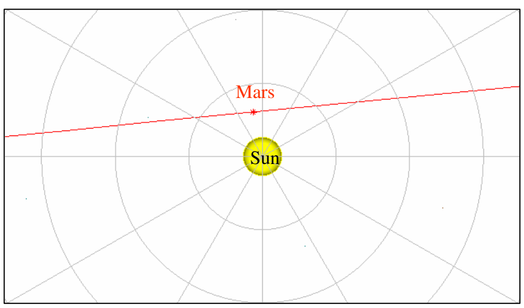

Figure 13. Solar Conjunction Geometry of Mars and Sun as seen from Earth for June 2015

The intervening charged particles of the solar corona can disrupt communications between Mars and Earth. Such effects include amplitude scintillation [19], phase scintillation, spectral broadening [20] and increased thermal noise from the solar disk picked up by the antenna sidelobes. In addition to the communication disruptions, the maximum range distance between Earth and Mars (up to 2.67 AU) occurs near superior conjunction. The received signal strength can be a factor of nearly fifty times weaker during superior conjunction than when Mars is closest to Earth (during opposition).

Robotic missions typically suspend or scale down their operations during periods centered on superior solar conjunctions. Such measures include invoking command moratoria, reducing tracking schedules, progressively lowering data rates, and taking vacations for a couple of weeks. Human missions are likely to require continued communications through as much of the solar conjunction period as possible.

Communications can probably be maintained, albeit at reduced data rates, down to 0.6° SEM angle with K_a-band and Frequency Shift Key (FSK) modulation. This should be sufficient to maintain communications throughout all superior conjunctions between 2015 and 2030 except the 2023 conjunction, which will have an SEM angle below 0.6° for less than 4 days.

Mars Reconnaissance Orbiter K_a-band telemetry performance will be tested with simulated FSK during its 2006 solar conjunction down to SEM angles of 0.4°. Following this test, we may be able to operate confidently somewhat below 0.6° SEM angle.

5. LASER COMMUNICATIONS

During the past decade, three successful laser communication experiments from Earth orbit have demonstrated the viability of laser communication technology. These experiments include LCE/GOLD, a 1 Mbps GEO-to-Ground link performed jointly by NASDA and JPL (1995); SILEX, an ESA 50 Mbps LEO-GEO link, (2001); and a 10 Gbps link from GEO (performed in 2001 by NRO/ Lincoln Laboratory). Extension of this technology to deep space may revolutionize deep space telecommunications technology. JPL, Lincoln Laboratory and GSFC expect to demonstrate the first ever deep space optical communications link using the NASA Mars Laser Communications Demonstration (MLCD) on Mars Telecommunication Orbiter [8]. MLCD should provide, by the end of this decade, much needed engineering insight towards efficiently delivering high data rates (upwards of 30 Mbps from Mars) to Earth. An artist concept of the MLCD flight terminal is shown in Figure 14 [21].

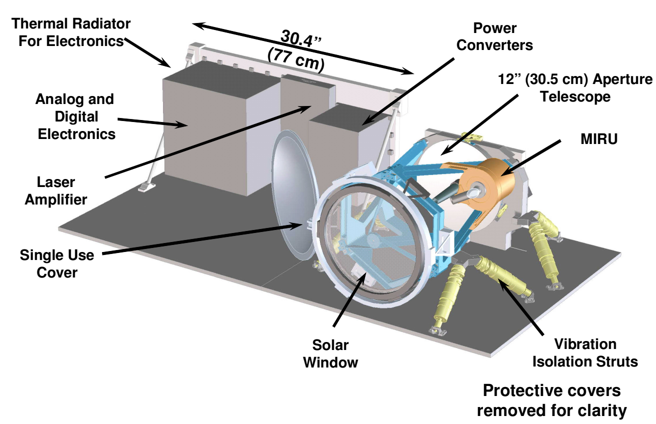

Figure 14. Preliminary MLCD Laser Terminal Configuration

Today's laser communications technology is believed capable of sending up to 10 Mbps at maximum Mars range from Earth. Extension to 1 Gbps data rates and higher is possible once higher-power space-qualified laser transmitters become available.

The primary challenge of laser communication technology is laser beam pointing, due to the very narrow beamwidth of the laser beams used. Modulation and demodulation of the signals at multi-gigabit ranges has been well developed by the fiber optics industry.

Deep space optical transceivers in the vicinity of Mars could support:

- Tens of Mbps to several Gbps downlink
- Uplink on the order of 10s to 100s of Mbps
- Two-way ranging simultaneous with communications

Deep space optical transceivers must surmount a number of challenges:

- Acquire and track a beacon and receive uplink commands while transmitting a strong downlink signal through the same aperture
- Precisely point a highly collimated laser beam to Earth with an absolute accuracy on the order of micro-radians
- Acquire and track ground receiver locations for a wide range of Sun-Earth-Probe (SEP) angles
- Remain opto-mechanically and thermo-mechanically stable during launch, cruise and operation phases of the mission
- Tolerate atmospheric obstructions (clouds at Earth, dust at Mars)

"Ground" receive terminals could be Earth-based, air-based, or space-based. Current technology only supports Earth-based receive terminal stations. Space-based receivers will require spacecraft with adequate platform stability and pointing and light-weight, high reliability, high maturity and long-life optical receiver terminals.

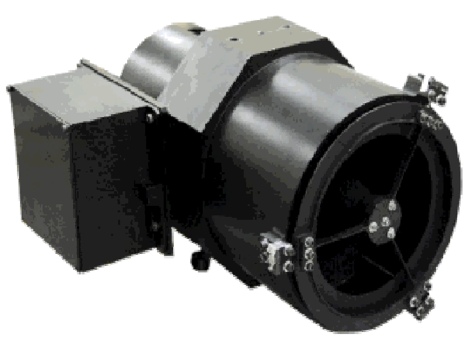

Figure 15. Optical Communications Demonstrator

Figure 15 shows a reduced-complexity laser communications terminal developed at JPL called the Optical Communications Demonstrator (OCD). OCD is a brassboard laser communications demonstration terminal designed to validate several key technologies, including beacon acquisition, high bandwidth tracking, precision beam pointing and point-ahead compensation functions. This terminal consists of data transmit, uplink receive, acquisition and tracking, and boresight channels. All these have to be implemented with high mechanical and thermal stability, be very compact and low mass, and have power consumption as low as possible.

OCD has a 10-cm diameter aperture, uses a CCD array for both spatial acquisition and high bandwidth tracking, and has a fiber-coupled laser transmitter. Two versions with transmit wavelengths at 844-nm and 1550-nm have been constructed. The latter is being prepared for a 2.5 Gbps link from a UAV at a slant range of 20 km to a 1 m ground-based telescope.

Table 11 is summary link budget for laser communications from Mars. A photon-counting detector and no coding were assumed. Coding would increase link performance by about 3 dB. Figures 16 and 17 were generated from Table 11.

Table 11. 10 Mbps Laser Downlink Budget

Transmitter Power	20 W average 1.28 kW peak	61.7 dBm
Optical Transmit Losses	63% transmission	-2 dB
Transmit Gain	30 cm aperture	117.65 dB
Pointing Losses	6 μrad beamwidth	-3 dB
Space Loss	2.67 AU	-373.48 dB
Atmospheric Attenuation	75.32% transmission	-1.23 dB
Receiver Telescope Gain	10 m aperture	149.4 dB
Optical Receiver Losses	60% transmission	-2.21 dB
Bit Sync. Loss		-1 dB
Pulse Amplitude Loss		-1 dB
Received Peak Power at Detector	132 photons/pulse 2.63 nW peak	-55.8 dBm
Average Background Power @ Detector	7.85 photons/slot 0.15 nW	
Received Peak Signal Power at Receiver	37.2 photons/pulse 0.743 nW peak	-61.29 dBm
Link Margin @ 10 Mbps	Pulse Position Modulation (M=64), 10^{-3} BER	5.48 dB

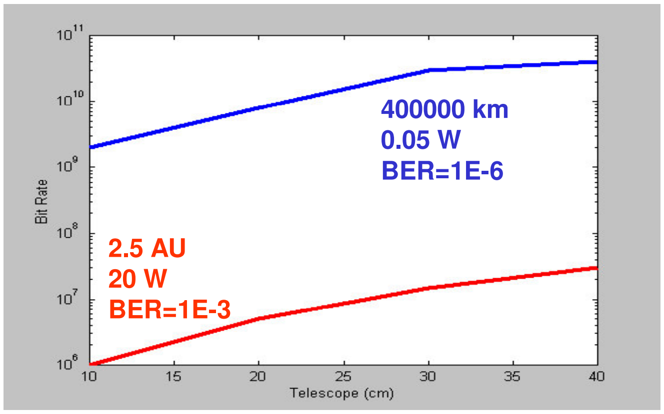

Figure 16. Achievable Data Rate vs. Space-Based Telescope Diameter

Figure 16 shows achievable data rate vs. space-based telescope diameter for low power and for high power laser transmitters.

Figure 17 shows required laser power vs. range assuming a constant data rate of 100 Mbps or 1 Gbps. A 20-cm aperture space-based terminal, daytime viewing, and a link margin of 6 dB were assumed.

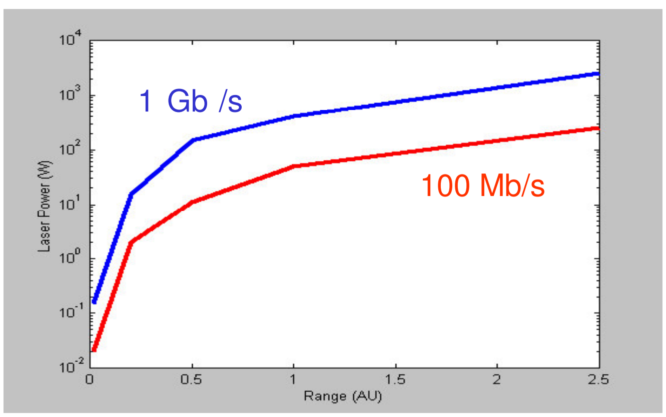

Figure 17. Required Laser Power vs. Range

Table 12 is a link summary for a 100-Mbps uplink from Earth to a 40-cm telescope in the vicinity of Mars. The required laser power is about 5 kW, produced by 50 independent (different coherence lengths to each other) 100 W lasers. Light from all 50 lasers can be sent through the same telescope. Multiple uplink beams can mitigate atmospheric scintillation effects that could result in undesired beam steering.

Optical links are more sensitive to atmospheric obscuration at both Earth and Mars than RF links and require precise pointing. We thus do not recommend the use of optical links for reliable channels, but rather that optical links be used for high rate channels. This avoids the need for a large number of ground receivers to avoid clouds; in the event of disruptions caused by temporary atmospheric obstructions, one could resend lost data at a later time.

Table 12. 100 Mbps Laser Uplink Budget

Transmitter Power (50 100-W lasers)	5 kW average 320.32 kW peak	85.05 dBm
Optical Transmit Losses	68.4% transmission	-1.64 dB
Transmit Gain	1 m aperture	127.19 dB
Pointing Losses	1.89 μrad beamwidth	-3 dB
Space Loss	2.49 AU	-372.9 dB
Atmospheric Attenuation	75.32% transmission	-1.23 dB
Receiver Telescope Gain	40 cm aperture	121.44 dB
Optical Receiver Losses	60% transmission	-2.21 dB
Bit Sync. Loss		-1 dB
Pulse Amplitude Loss		-1 dB
Received Peak Power at Detector	58.82 photons/pulse 11.73 nW peak	-49.3 dBm
Average Back-ground Power @ Detector	0 photons/slot 0 nW	
Received Peak Signal Power at Receiver	17.52 photons/pulse 3.49627 nW peak	-54.56 dBm
Link Margin	Pulse Position Modulation (M=64), 10^{-3} BER	5.25 dB

6. NAVIGATION

Humans going to the moon and Mars must arrive with sufficient accuracy. 'Sufficient' requires some elaboration. For robotic rover missions going to Mars, a key challenge has been reducing landing errors to levels that enable landing at scientifically interesting locations safely. In the case of the Mars Exploration Rovers, safe locations had to be selected within the context of the inherent delivery accuracies that an unguided airbag landing system could deliver: ~80 km. The next generation of rover, Mars Science Laboratory (MSL), will employ an active guidance system during its entry phase through parachute deployment that will reduce landed delivery errors to ~10 km. Indeed, MSL is being designed so that its roving capability extends to the boundary of the landing error, enabling a 'go-to' capability. That is, MSL will be able to rove to a predetermined site given its landing capability. A 'go-to' capability will be needed by any human mission to the moon or Mars as well. Humans will, on first arrival, need to land at a predetermined site that has been selected via prior survey from orbital reconnaissance and/or robotic exploration. Afterwards, humans will need to land at existing sites. In either scenario, the landing should be sufficiently accurate to enable transit to the desired location via foot while also ensuring that the landing is made far enough from the desired site to prevent damage to it or to the lander. Thus the navigation architecture and strategy employed by human missions should enable this 'go-to' capability, where the maximum transit should be on the order of 100 m.

An in-situ network of orbiters capable of tracking an approaching vehicle can improve that vehicle's entry knowledge and targeting. Analysis conducted for the Mars network has shown that 1-way Doppler data, derived from an Ultra Stable Oscillator with 10^{-12} class short term stability, can yield trajectory errors of better than 1 km (1σ) at 1 day prior to entry. This could improve by an order magnitude with 2-way coherent Doppler data. Additionally, network-aided Entry, Descent and Landing (EDL) trajectory updates can be used to augment an entry system that employs active guidance and hazard avoidance. Analysis of a Mars Exploration Rover-like ballistic trajectory that is being tracked continuously during final approach and EDL yields trajectory determination errors on the order of 100 to 500 m during the flight. Coupling network tracking data with on onboard Inertial Measurement Units (IMUs), entry guidance, and a terminal guidance strategy employing optical target recognition could easily achieve 100-m landing accuracies. In this strategy, the Mars network improves performance and robustness. For instance, in the event of an IMU failure, network data can be used to maintain trajectory updates for the guidance system.

There have been extensive studies showing that surface position determination at Mars, using a single orbiter tracking a landed element, achieves 10-m position knowledge – typically within 2 to 4 passes. Of course, a desirable capability would be to get this level of knowledge in near real-time, perhaps over the course of a single pass. To accomplish this typically requires multiple spacecraft in view to get sufficient independent measurements. In order to limit the number of these spacecraft to two, a ground beacon could be used to augment the spacecraft data. For instance, at Mars this could consist of Mars Telecommunications Orbiter, an areostationary satellite and a ground beacon. At the moon, this could be two LTOs and a ground beacon. Near real-time positioning performance with 2 spacecraft and a ground beacon are current topics of investigation.

7. CONCLUSION

This paper derived preliminary requirements for sustained robotic and human exploration of the moon and Mars, including aggregate return link data rates of 44 Mbps for operational communications and 440 Mbps for science.

Three lunar relay satellites in stable elliptical orbits could meet the preliminary lunar requirements in the vicinity of a polar base, with full redundancy, in conjunction with a few 12-m Earth antennas at each DSN complex.

The much greater range of Mars from Earth makes it difficult to support the required data rates. Large arrays of small antennas on Earth will be needed. A pair of areostationary Mars satellites could meet the in-situ Mars telecommunications requirements with near-continuous redundant links. Communications near Mars superior conjunctions can generally be supported (with reduced capacity) by using modulation and coding resistant to solar effects. Emergency communications en route to Mars is problematic if two-way voice is required.

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