RELAY COMMUNICATIONS STRATEGIES FOR MARS EXPLORATION THROUGH 2020

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Abstract

Mars exploration poses significant telecommunications challenges, including the return of large data volumes from high-resolution surface instruments, highly constrained mass, power, and energy for surface spacecraft, frequent telemetry and command sessions for supporting complex surface operations, and high-risk mission events such as entry, descent, and landing for which the capture of engineering telemetry is deemed critical. Relay telecommunication via Mars-orbiting spacecraft offers significant advantages in meeting these challenges, relative to conventional direct-to-Earth communications. NASA's Mars Global Surveyor and Mars Odyssey orbiters, along with ESA's Mars Express orbiter, represent an initial relay telecommunications infrastructure that has successfully supported the Spirit and Opporutnity rovers. With the arrival of the Mars Reconnaissance Orbiter in 2006, this expanded relay network will provide key support to the 2007 Phoenix Lander and 2009 Mars Science Laboratory missions later this decade. Second-decade mission concepts will introduce new communications challenges; the provision of relay payloads on science orbiters provides a cost-effective means to sustain and evolve the Mars relay network.

1 Introduction

Over the past decade, NASA and ESA have delivered a series of orbital and landed payloads to Mars which have provided fresh insights into the red planet and at the same time raised new questions for future missions to answer. For these current and future robotic investigations, telecommunication represents a key enabling capability that will, in a very real way, define the quality and quantity of data that we can return from the Martian surface. The success of the Spirit and Opportunity rovers has demonstrated the potential for orbiting satellites to significantly augment data return by offering high-rate, energy-efficient relay communications to highly resource-limited landers.

In this paper we will examine NASA's strategy for relay communications support of missions planned for this decade, and discuss options for longer-term relay network evolution in support of second-decade missions. In Section 2, we will summarize telecommunications needs in terms of key figures of merit such as data volume, contact opportunities, and energy efficiency. Section 3 will describe the current suite of relay orbiters at or en route to Mars, contrasting their relay characteristics and capabilities. In Section 4, we will describe detailed telecommunications relay support scenarios for specific current and planned missions, including the 2003 Mars Exploration Rovers, the 2007 Phoenix Lander, and the 2009 Mars Science Laboratory. Finally, in Section 5, we will look ahead to options for further relay network evolution in support of second-decade exploration. The recent cancellation of the Mars Telecommunications Orbiter, originally slated for launch in 2009, and other NASA Mars programmatic updates have resulted in more uncertainty regarding the content of the second decade; we will outline current program planning efforts aimed at defining second-decade science exploration strategies and, from these, deriving robust yet cost-effective strategies for telecommunications support of the resulting mission set.

2 Key Telecommunications Needs for Mars Exploration

The robotic exploration of Mars demands robust and capable telecommunications services. Ultimately, the end-to-end communications architecture must support the ability of earth-bound mission operations teams to command and control assets on the surface of Mars and to retrieve science and engineering telemetry in support of mission goals. Specific telecommunications challenges for Mars surface spacecraft include:

- **Data return:** With increasing spectral and spatial resolution, rover-based remote sensing instruments demand high-bandwidth data return. Pancam imagery from the Mars Exploration Rovers represented data volumes of up to 100-500 Mbits for full-resolution 360 deg panoramas. The MastCam planned for the 2009 Mars Science Laboratory mission will augment this with a capability to acquire high-definition full-color video, amassing a data volume of 2 Gbits of MPEG_compressed video in just 4 minutes.
- **Mass and energy constraints:** Martian landers are typically highly constrained in terms of mass and power. Minimizing the mass and energy consumption of Mars landers/rovers frees up spacecraft resources for science payload mass, instrument operations, and mobility.
- **Contact opportunities:** Frequent contact with surface assets provides science and mission operations teams on Earth with the ability to maximize science acquisition as function of time, providing timely telemetry to drive science planning and engineering assessment as well as timely opportunities to deliver updated commands and goals to the Marscraft.
- **Critical Event Communications:** During mission-critical events such as entry, descent, and landing (EDL), it is imperative that engineering telemetry be collected, sufficient to allow reconstruction and diagnosis of any mission anomaly that might occur during that time period, in order to feed potential lessons learned into future mission designs.

Mars relay communications offers significant advantages with respect to direct-to-Earth communications in terms of meeting these needs. Compared to the long distance for a link back to Earth (up to 400,000,000 km or more), relay links from the Martian surface to a Mars orbiter represent link distances of only hundreds or thousands of km, allowing even simple omnidirectional links to achieve much higher data rates. The orbiters, with large high-gain antennas and ample power from large solar arrays, can then take on the job of relaying those data back to Earth. Relay links also typically require much less lander mass and power, as the rover no longer needs a large, gimbaled high-gain antenna for communications to Earth, and the high-instantaneous data rates on the relay link allow large data transfer in short communications sessions. And relay orbiters can offer contact opportunities at times when direct-to-Earth communication is not possible, such as during the Martian night or at high-latitude sites during seasons when Earth is never in view. Finally, relay communications enables capture of high-rate engineering telemetry during critical events such as EDL, when highly directional direct-to-Earth links are not possible.

3 Mars Relay Network

Based on these considerations, NASA and ESA have launched a series of relay-equipped orbiters that establish an initial telecommunications relay network at Mars. NASA's Mars Global Surveyor and Odyssey spacecraft, and ESA's Mars Express spacecraft, include UHF relay communications payloads in addition to their primary science instrument suites. They will soon be joined by the Mars Reconnaissance Orbiter, currently en route to Mars. We summarize here the key relay telecommunications characteristics of each of these missions.

	Mars Global Surveyor	Mars Odyssey	Mars Express	Mars Reconnaissnace Orbiter
Agency:	NASA	NASA	ESA	NASA
Launch:	Nov. 8, 1996	April 7, 2001	June 2, 2003	Aug, 2005
Mars Orbit Insertion:	Sep. 11, 1997	Oct. 24, 2001	Dec. 24, 2003	Mar, 2006
Orbit Characteristics:	~400 km circular sun-synch ~2 PM asc node 93 deg inclination	~400 km circular sun-synch ~5 AM asc node 93 deg inclination	258 x 11,560 km elliptical non-sun-synch 86.3 deg inclination	255 x 320 km sun-synch ~3 PM asc node 93 deg inclination
UHF Radio:	Mars Relay (CNES)	CE-505	Melacom	Electra
Link Protocol:	Mars Balloon Relay (MBR)	CCSDS Proximity-1	CCSDS Proximity-1	CCSDS Proximity-1
Forward Link:				
- *Frequency*	437.1 MHz	437.1 MHz	437.1	435-450
- *Data Rates*	n/a (MBR tones only)	8 kbps	2, 8 kbps	1,2,4, É , 1024 kbps
- *Coding*	n/a	uncoded	uncoded	uncoded or 7,1/2
Return Link:				
- *Frequency*	401.528711 MHz	401.585625 MHz	401.585625 MHz	390-405
- *Data Rates*	8, 128 kbps	8, 32, 128, 256 kbps	2,4, É ,128 kbps	1,2,4, É , 1024 kbps
- *Coding*	(7,1/2) Convolutional	(7,1/2) Convolutional	(7,1/2) Convolutional	(7,1/2) Convolutional

Table 1: Comparison of Mars relay orbiter key telecommunications characteristics

3.1 Mars Global Surveyor

Launched in 1996, MGS [Albee, et al., 1998] includes a single-string UHF Mars Relay payload. The orbiter aerobraked into a 400-km, near-polar, sun-synchronous science mapping orbit, with an ascending node at roughly 1-2 PM Local Mean Solar Time (LMST). The payload supports only return link (lander-to-orbiter) telemetry with no ability to deliver commands to the lander on the forward link. (Tones are broadcast on the forward link to control the flow of data from the lander.) The forward link tones are transmitted at 437.1 MHz, while return-link data are modulated onto a 401.528711 MHz carrier at data rates of 8 or 128 kbps, with (7,1/2) convolutional coding. Communications with Earth is at X-band via a 1.5 m high gain antenna fed by a 25 W TWTA. MGS continues in good health as it approaches nearly a decade of flight operations, although component failures have eliminated redundancy in gyro and reaction wheel systems. Current orbit operations have achieved very efficient fuel usage at the level of 1-2 kg/yr; with over 8 kg of usable propellant available, operation through the time frame of the Phoenix 2007 mission is very likely; operations through the 2009 Mars Science Laboratory is possible but less certain.

3.2 Mars Odyssey

The 2001 Mars Odyssey orbiter [Spencer, et al., 2002], like MGS, is in a 400 km sun-synchronous polar orbit, but with a different orbit plane: its ascending node is at roughly 5 AM LMST. Odyssey was the first Mars relay satellite conforming to the CCSDS Proximity-1 Space Link Protocol [CCSDS], a link-layer telecommunications standard established to provide interoperability between NASA, ESA, and other potential Mars spacecraft. Odyssey carries redundant Cincinnati Electronics CE-505 UHF transceivers as its relay payload. The CE-505 supports both forward link (command) and return link (telemetry) services for surface missions, with a 437.1 MHz forward link frequency and a return link frequency of 401.585625 MHz (slightly different from MGS). With the Proximity-1 protocol, reliable link layer communications is achieved based on an ARQ scheme to retransmit any incomplete data frames. The CE-505 supports data rates of 8, 32, 128, and 256 kbps, with optional (7,1/2) convolutional coding. On its link to Earth, Odyssey utilizes a 15 W X-band SSPA transmitted through a 1.3 m high gain antenna. The Odyssey mission is in excellent health, with none of its avionics redundancy yet exercised.

With 37 kg of fuel remaining and fuel use at a level of less than 1 kg/year, it is possible that Odyssey could continue to provide relay services well into the next decade.

3.3 Mars Express

Launched in 2003, ESA's Mars Express orbiter includes the Melacom UHF radio in addition to its primary science instruments [Schmidt, 2003]. Like Odyssey's CE-505 UHF trasnceiver, Melacom also complies to the CCSDS Proximity-1 Space Link Protocol. Unlike Odyssey, however, Mars Express is in a highly elliptical, 250 x 10,142 km orbit. As a result, Mars Express has very different contact statistics than NASA's low-altitude circular orbiters. Telecom sessions occur with a wide range of link distance and resulting data rate capability. While the higher-altitude contacts suffer in terms of space loss, they offer a much larger footprint on the surface, resulting in longer contacts and greater coverage for critical events. The Melacom radio supports data rates in powers of two from 2-128 kbps. Mars Express's link to Earth employs a 65 W X-band TWTA and a 1.65 m high gain antenna.

3.4 Mars Reconaissance Orbiter

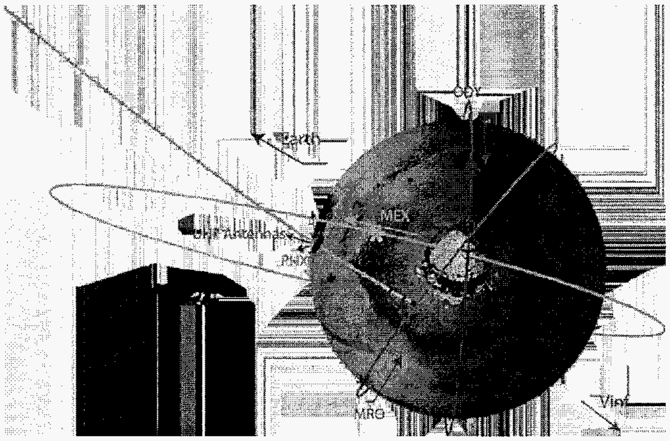
Launched on August 12, 2005, MRO represents NASA's next Mars science orbiter [Graf, et al., 2004]. Currently in cruise, MRO will arrive at Mars in March, 2006 and, after initial insertion into a 35-km elliptical orbit, begin aerobraking down to its final 255x320 km polar sun-synchronous orbit, with a 3 PM LMST ascending node. Based on its high-rate science instruments, MRO is outfitted with a highly-capable earth link, utilizing a 100 W TWTA and 3 m high gain antenna, as well as a demonstration 35 W Ka-band downlink. For its relay link, MRO carries a new generation of relay radio: the Electra Proximity Payload [Edwards, et al., 2003]. Utilizing a reprogrammable software radio architecture, Electra will enable upgrades during the life of the mission to support enhanced performance, new protocols, and unforeseen mission scenarios.

As launched, MRO's Proximity-1 compliant Electra radio will support data rates from 1 kbps to 1 Mbps, with (7,1/2) convolutional coding, and offers tunable transmission over the 390-450 MHz frequency range. Several post-launch upgrades are being considered, including adaptive data rates, higher-rate modulation, and improved coding. With adaptive data rates, the MRO Electra radio would monitor the signal-to-noise ratio of the lander signal and send directives to the lander radio to adjust its data rate to take full advantage of the link capacity over the duration of the pass. In addition to increasing data return, this would also simplify relay operations by eliminating the need to select a fixed data rate based on pre-pass analysis. The addition of QPSK modulation and suppressed-carrier modulation will improve performance while supporting symbol rates as high as 4 Msps. And implementation of Reed-Solomon coding will offer additional performance enhancements. Preliminary analysis suggests that these post-launch upgrades could offer roughly 5 dB of increased data return for a mission like the 2009 Mars Science Laboratory.

Table 1 summarizes the key telecommunications characteristics of the MGS, Odyssey, Mars Express, and MRO. This set of NASA and ESA orbiters effectively represents an international relay network at Mars that will support landed missions through the end of this decade and into the next. We turn next to examine several specific current and planned missions that are customers for these relay services.

4 Mission Support Scenarios

4.1 Relay Support to Spirit and Opportunity



- *LD: 24 Aug, 2007*
- *AD: 05 Jun, 2008*
- *Landing Site: B1 (67.5 N, 130E)*
- *Entry Š 5 min*
- *View from Mars North Pole*
- *1 min ticks*
- *ODY, MRO, MEX phased for maximum EDL coverage*

Figure N: Phoenix arrival geometry.

The 2003 Mars Exploration Rovers have far surpassed their original 90-sol design lifetime. At the time of writing, Spirit and Opportunity continue to operate and collect science at the Gusev Crater and Meridiani landing sites, respectively. The rovers include both X-band direct-to-Earth and UHF relay communications [Edwards, 2004]. During EDL, both rovers transmitted critical event telemetry to Earth at X-band, but were limited to an effective data rate of only 1 bps based on the low-gain rover antenna, large Earth-Mars distance, and high dynamics of entry. After backshell seperation, however, both rovers were able to communicate directly to MGS at 8 kbps over a low-gain UHF antenna, providing nearly four orders of magnitude higher data rate. Fortunately, both rovers successfully completed EDL, but this experience demonstrated the value of relay communications to significantly increase engineering data capture during critical events.

Once on the surface, the UHF relay links have supported the bulk of the science data return for the two rovers. As of July, 2005, the rovers had returned over 135 Gb of data. Of this data volume, 97% has been returned via UHF relay, with 92% via Odyssey and 5% via MGS. The X-band direct-from-Earth link is typically used for command uplinks to the rovers after they wake up each Martian morning, as it offers a direct, minimum-latency path for delivering commands. In current extended mission operations, nearly all telemetry return is via the Odyssey relay path, based on the energy efficiency of the UHF proximity link relative to the X-band direct-to-Earth link, and on the gap-free performance of the Odyssey Proximity-1 reliable protocol, relative to the earlier MGS relay protocol.

In addition to nominal relay support through Odyssey and MGS, NASA and ESA have conducted several demonstration relay passes between the rovers and the Mars Express orbiter, successfully demonstrating the interoperability of these assets and validating the command and telemetry services of the Mars Express Melacom UHF transceiver.

4.2 2007 Phoenix Lander

The 2007 Phoenix Lander mission is the first of NASA's Scout missions. These competitively selected, PI-led, cost-capped missions are intended to increase the breadth of Mars exploration, provide opportunities for innovative mission concepts, and enable rapid response to prior mission discoveries. The Phoenix mission proposes to leverage much of the hardware and instruments that were originally developed for the 2001 Mars Lander, which was cancelled after the failure of the 1998 Mars Polar Lander. Launched in August, 2007, Phoenix will arrive at Mars around May, 2008 and land in the northern plains at a latitude of 65-72 deg N, targeting the presumptive deposits of subsurface water ice that were detected by the Odyssey spacecraft. The stationary, solar-powered lander has a nominal mission lifetime of 90 sols.

Based on MER's successful experience with relay communications, Phoenix will solely utilize UHF relay telecommunications for all of its communications needs after separation from the cruise stage, eliminating the cost and mass of the X-band telecommunications systems on the lander. Phoenix will employ the same CE-505 UHF transceiver that is deployed on Spirit and Opportunity. The most significant change in operations concept for Phoenix relative to MER will be the exclusive use of the UHF link for delivering commands to the lander.

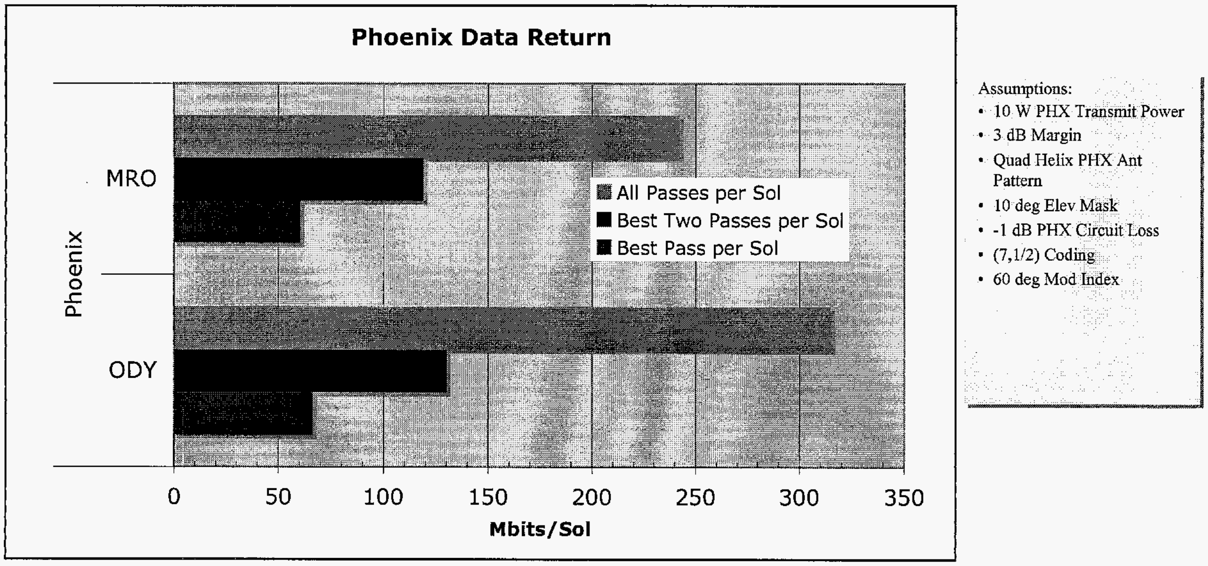


Figure N: Phoenix data return via UHF relay through MOR and Odyssey.

For critical event communications during EDL, the high latitude landing site for Phoenix results in good coverage of the EDL trajectory. Figure N depicts the arrival geometry; by properly phasing the Odyssey and MRO orbiters within their orbit planes, both orbiters will be able to collect critical event telemetry throughout EDL. Mars Express, if available, could also be phased to provide an additional redundant asset for EDL telemetry capture. (Because the MGS return link operates at a slightly different UHF frequency, it cannot acquire the Phoenix lander while it is communicating with the other orbiters.)

Once Phoenix separates from the cruise stage shortly before entry, it will no longer have an X-band direct-to-Earth communications capability, so capture of critical event telemetry during entry, descent and landing will be accomplished via UHF transmission to relay orbiters during the 6-7 min of descent. Due to the high latitude target point, the polar-orbiting relay satellites will provide good coverage of the EDL trajectory. Figure N depicts the arrival geometry; by properly phasing the Odyssey and MRO orbiters within their orbit planes, both orbiters will be able to collect critical event telemetry throughout EDL. Mars Express, if available, could also be phased to provide an additional redundant asset for EDL telemetry capture. (Because the MGS return link operates at a slightly different UHF frequency, it cannot acquire the Phoenix lander while it is communicating with the other orbiters.)

Once Phoenix is on the surface, MRO and Odyssey will serve as primary relay assets for landed operations. MGS offers an additional backup bath for telemetry return, but cannot support forward-link command delivery. Finally, Mars Express could potentially offer another backup path for forward and return link data, should ESA continue orbiter operations into the Phoenix time frame.

Again, because of the Phoenix lander's high latitude and the near-polar orientation of the various relay spacecraft orbit planes, the lander will have many contact opportunities per sol. On a typical sol, Phoenix will upload commands to the lander during an early morning pass via Odyssey or MRO. Queued lander science data can also be played back on the return link relay path. The lander will then conduct primary science operations during the sunlit portion of the sol. Later in the Martian afternoon, Phoenix will relay data back to Earth, again via a relay opportunity with Odyssey or MRO, with priority given to science and engineering data required for planning the next sol's activity. To the extent that the lander energy budget permits, additional passes could be utilized to augment science return.

Figure N illustrates that data volume per sol that Phoenix can return via MRO and Odyssey, based on a) selection of the best pass per sol for each orbiter; b) selection of the two best passes per sol for each orbiter; or c) utilization of all available passes. Both MRO and Odyssey offer in excess of 50 Mb/sol from a single pass, and between 100-150 Mb/sol for two passes per sol; significantly more data can be returned if lander energy allows use of additional passes. Odyssey offers slightly better performance than MRO due to its slightly higher altitude orbit, resulting in longer contact times. While MRO carries the more capable Electra radio, the fact that Phoenix is using the older CE-505, and plans to limit its use to a maximium data rate of 128 kbps, precludes taking advantage of some of the potential Electra performance enhancements.

4.3 2009 Mars Science Laboratory

The 2009 Mars Science Laboratory (MSL) will carry out investigations to assess the habitability of Mars and its potential for harboring past, or even current, life. With significantly larger landed mass and science payload mass, with entry and power systems capable of targeting sites over a wide range of latitude and operating for a full Martian year on the surface, with greater mobility and more precise landing, MSL represents a step beyond MER in terms of rover capability. MSL will carry a complex suite of science instruments, including an analytical laboratory to characterize the chemical composition of selected samples and search for organic compounds; supporting these activities will be a several high-bandwidth instruments, including a Mast Camera, capable of full-color stereo imagery and high-definition video, a Mars Hand Lens Imager for microsopy, and a number of spectroscopic instruments for sample investigation. The complexity of planned surface operations will drive the need for low-latency, high-bandwidth communications support, ideally with multiple communications opportunities spaced throughout the sol.

MSL's communications links to relay orbiters will utilize the Electra-Lite UHF transceiver, a smaller, lighter version of the Electra transceiver that is on MRO, tailored for use by more mass-constrained landers. A full-duplex configuration of Electra-Lite will have a mass of roughly 3 kg, 40% less than the orbiter radio configuration. To achieve this mass reduction for Electra-Lite, some RF flexibility is descoped (namely, the ability to switch between half- and full-duplex modes, and the ability to swap the transmit and receive bands at 390-405 and 435-450 MHz), but the flexible software architecture of the Electra transceiver is fully retained.

MSL's UHF relay communications is likely to be augmented with some level of X-band radio system for direct communications to the DSN, but the capabilities of this system are still an open area of trade. Options include a low-gain X-band system, capable of receiving small command loads each Martian morning as well as limited emergency downlink to Earth for response to lander anomalies, or a system with a gimbaled high-gain directional antenna, with downlink capability comparable to or greater than MER. In either scenario, both X-band and UHF would provide nominal paths for delivering commands to the rover, while UHF would serve as the primary path for telemetry return, based on its potential for greater data volume and much less energy use.

Because MSL will utilize a new EDL system, including guided entry, powered descent, and a "skycrane" system that will set the rover down softly on the surface via a tether from the descent stage, the capture of high-rate engineering telemetry during EDL is essential. Current mission studies suggest that with appropriate selection of launch and arrival dates over an acceptable range of launch vehicle performance, MSL can arrive near the 3 PM local time of the MRO orbit plane over the full

+-45 deg range of targeted latitude, enabling MRO to acquire MSL's critical event communications from entry through landing at 1 kbps or higher data rate.

During surface operations, the MSL-MRO relay path offers the highest performance, due to the fact that both ends of the link would be equipped with the more capable Electra-class transceivers. Figure N summarizes the data return per sol that MSL can achieve through each of the available relay orbiters, as a function of latitude. Performance is calculated for a bit error rate of 10^{-6}, assumes a 10 deg elevation mask for the rover, and includes a 3 dB link margin. The MRO link utilizes adaptive data rates, suppressed carrier QPSK modulation, and concatenated Reed-Solomon and convolutional (7,1/2) coding, while the other orbiters are limited to fixed rate, residual carrier modulation, and convolutional coding only.

The MSL-MRO link offers average return of 500 Mb/sol for equatorial landers, with performance increasing to roughly 1 Gb/sol near the poles. One impact of MRO's very low altitude orbit, and resulting small footprint, is that equatorial sites can experience occasional sols with poor performance due to the lack of any high-elevation passes. NASA's other relay orbiters offer performance in the 50-200 Mb/sol range; their slightly higher orbits result in somewhat less sol-to-sol variability. Finally, Mars Express if available could support data return in the 50-250 Mb/sol range; its elliptical orbit results in significant latitudinal and sol-to-sol variability in performance.

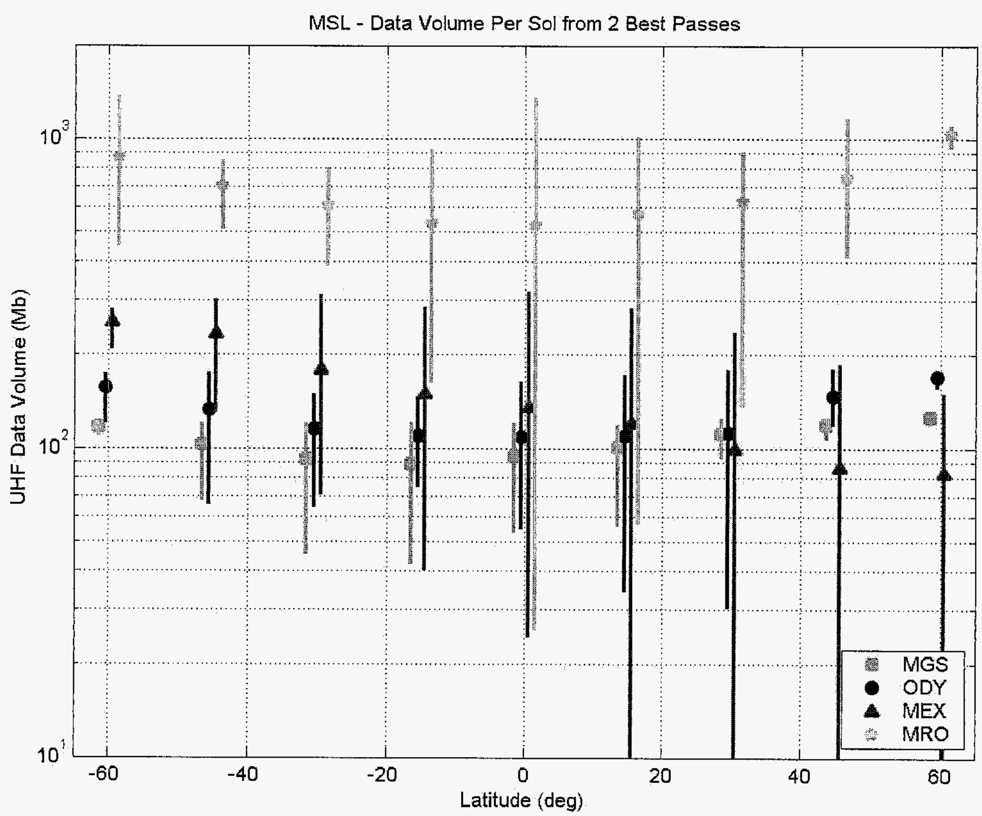


Figure N: MSL data return via MGS, Odyssey, Mars Express, and MRO as a function of latitude, based on two relay contacts per sol. Markers indicate mean performance, while the vertical bar for each data point reflects the range of sol-to-sol variability in performance over the course of the simulation.

5 Second-Decade Strategy

Looking beyond MSL, NASA is in the process of establishing a roadmap for second-decade Mars exploration. Driven by a science strategy of exploring the possibility of past or present life on Mars in the context of an evolving planetary system, the planning process aims to lay out candidate mission queues or "pathways" which represent logical sequences of investigation, with discoveries at each point in time influencing future mission details (e.g., instrument suites, targeted landing sites) and/or leading to decision to jump from one pathway to another.

While results of this roadmapping activity will not be available until later this year, several general mission concepts serve as pathway building blocks; their characteristics serve as a guide for the relay communications needs through 2020. Mission concepts include:

- **Landers and rovers for *in situ* science:** Large rovers and landers, based on heritage from the 2009 MSL mission, could be used to deliver sophisticated instrument packages for *in situ* investigations. Options include highly mobile rovers with astrobiological payloads, or static landers with deep drilling capabilities to sample sub-surface aquifers. These missions will likely have telecommunications requirements similar to MSL, with mobile rovers probably making greater demands than static landers on data volume and contact statistics. Smaller mid-size rovers, with landed mass and surface operations more in the class of MER, represent a lower-cost alternative that could allow deployment of more rovers within current budget constraints, if site diversity is a driver.
- **Network Landers:** In this concept, a number of small landers would be delivered to multiple sites on the Martian surface, forming a network over which correlated meteorological and seismological measurements could be made. Precise measurements of the motion of the network in inertial space would also provide data on planetary rotation, yielding information on the Martian interior. The CNES Netlander mission concept, once envisioned for launch in 2007, represents a good example of this mission class [Marsal, et al., 2002]. Network landers are typically very small, highly energy-constrained assets. Data volume and contact frequency requirements are typically much less demanding than for large lander and rovers; instead, these missions put a premium on meeting their telecommunications needs with low-power transmitters and minimum contact time.
- **Sample return:** Returning a Martian sample to Earth would allow applying the full range of current (and future) ground-based laboratory capabilities towards sample analysis. The leading architecture for a sample return mission would deploy a lander, possibly with a small rover, to select and provide context characterization of ~500 g of rock, soil, and atmospheric samples, launch these into Mars orbit with a Mars Ascent Vehicle (MAV), locate the orbiting samples using optical or radio techniques, rendezvous with and capture the orbiting sample with an Earth return vehicle (ERV), which would then inject into an interplanetary transfer trajectory from Mars to Earth, where an Earth entry vehicle would carry the sample to a safe landing. Such a mission includes a large number of first-time challenges for which critical event communications will be crucial. It should be noted that the ERV can also serve as a relay satellite for the lander during surface operations.
- **Science orbiters:** A variety of orbital science missions are candidates for second-decade launch, including a remote sensing orbiter to monitor trace gases such as methane, an aeronomy orbiter to directly sample atmospheric constituents, and a synthetic aperture radar orbiter to investigate shallow subsurface features.

Given the cancellation of the 2009 Mars Telecommunications Orbiter, a key part of NASA's second-decade strategy will be to include the Electra relay payload on any science orbiters in order to repopulate the Mars relay network as older orbiters reach their mission end. Such a strategy has important implications for spacecraft design, driving the need for long spacecraft lifetime, as the long-term relay network population will be a function of orbiter lifetime and frequency of launch. For instance, if a science orbiter, augmented with relay functionality, were launched every third 26-month Mars launch opportunity, each orbiter would have to achieve a lifetime of over 13 years in order for the steady-state relay network population to remain at or above two, ensuring redundant relay assets at all times.

Propulsive ΔV capability is another important consideration for a combined science-relay orbiter. Different science mission objectives will drive the choice of different initial orbits. For instance, a radar mapping mission will typically operate in low polar orbit for high-resolution global mapping, a trace gas orbiter in low inclined orbit for frequent solar limb occultations at a range of latitudes, and an aeronomy mission in an elliptical orbit with very low periapsis to support *in situ* atmospheric measurements, with apoapsis altitude and inclination designed to allow the periapsis to "walk" over local time and latitude. Each of these initial orbits will have implications for relay coverage and performance. After the primary science goals are completed, the mission may budget additional ΔV to transition into a more optimal orbit for extended relay operations. In addition, ΔV allocations may be made to support orbit phasing or orbit node adjustments.

Several capabilities originally planned for the 2009 Mars Telecommunications Orbiter, could improve the capabilities offered by second-decade relay satellites. Increased orbiter UHF antenna gain would allow more data return while reducing lander resource requirements. The addition of a higher-frequency directional relay link would allow even greater link capability for landers that could support a small gimbaled (or electronically-steered) antenna. Introduction of higher-level protocols such as the CCSDS File Delivery Protocol [CFDP] and the emerging concepts of Delay Tolerant Networking [DTN] would provide assured product delivery and improved data accountability over multi-hop relay paths.

6 Summary

Relay communications offers significant benefits for Mars exploration, providing a higher-bandwidth, energy-efficient alternative to direct-to-Earth communications. An international network of relay orbiters is currently providing relay services to the Spirit and Opportunity rovers, and will play a key role for the planned 2007 Phoenix Lander and 2009 Mars Science Laboratory missions. New capabilities of the Electra UHF transceiver (and its Electra-Lite lander configuration) will allow significant increased in data return relative to current MER levels. While the second-decade mission plan is currently under study, it is likely that continued near-term evolution of the Mars relay network will utilize hybrid science-relay orbiters as a cost-effective means of supporting Mars science and derived telecommunications goals.

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