Relay Orbiters for Enhancing and Enabling Mars *In Situ* Exploration

Charles D. Edwards, Jr., William B. Banerdt, David W. Beaty,
Leslie K. Tamppari, Richard W. Zurek

Jet Propulsion Laboratory, California Institute of Technology

A white paper submitted to the National Research Council as input to the 2009 Planetary Decadal Survey*

September 15, 2009

For additional information, please contact:

Charles D. Edwards, Jr.
Jet Propulsion Laboratory, California Institute of Technology

Address: Jet Propulsion Laboratory, M/S 301-345L
4800 Oak Grove Dr.
Pasadena, CA 91109
Phone: 818.354.4408
E-mail: chad.edwards@jpl.nasa.gov

---

* Also posted on the MEPAG web site, and may be referenced as follows:
Edwards, C. D. Jr., W. B. Banerdt, D. W. Beaty, L. K. Tamppari, and R. W. Zurek (2009). "Relay Orbiters for Enhancing and Enabling Mars *In Situ* Exploration", 7 p. white paper posted September 2009 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/decadal/index.html

Relay Orbiters for Enhancing and Enabling Mars *In Situ* Exploration

Introduction[1]

The scientific exploration of Mars has pursued a parallel strategy of remote sensing observations from orbital platforms coupled with *in situ* observations from landers and rovers. Starting with the Viking orbiters and landers in the 1970s, resuming in 1996 with the flights of Mars Global Surveyor and Pathfinder, and followed up with additional orbiters (Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter) and landers (Spirit, Opportunity, Phoenix), this strategy has yielded rich dividends, with landers providing ground truth calibration of orbital data sets, and orbiters providing global context for detailed *in situ* lander measurements.

As an additional dividend of this coupled orbiter/lander strategy, each of these science orbiters has also served as a telecommunications relay asset for landed spacecraft, greatly enhancing and in some cases enabling new surface exploration concepts. In this white paper we quantify the benefits of an orbital relay infrastructure for Mars *in situ* exploration, summarize recent Mars missions which have successfully utilized relay communications, describe the role that relay orbiters could play in the coming decade, and highlight the potential future growth of relay communications capability and the key technologies enabling that growth[2].

Benefits of Mars Relay Telecommunications

Due to the challenges of entry, descent, and landing, Mars landers are highly constrained in mass, volume, and power. For landed missions, this places severe constraints on antenna size and transmission power, which in turn greatly reduce direct-to-earth (DTE) communication capability in comparison to orbital spacecraft. As an example, the DTE downlinks on Spirit and Opportunity have only 1/600th the capability of the MRO downlink. Relay communication addresses this problem by allowing Mars surface spacecraft to communicate using higher data rates over short-range links to nearby Mars orbiters, while the orbiter takes on the task of communicating over the long-distance link back to Earth. This relay strategy offers a variety of key benefits to Mars *in situ* spacecraft (Edwards, 2007):

Increased Data Return: Because the relay link operates over a much shorter range, a Mars lander can achieve a much higher instantaneous rate on a surface-to-orbiter link than it can on the long-distance Mars-to-Earth DTE link, and over the course of a sol (Mars day) can return a far greater volume of data. For MER, the downlink DTE data rate for a 70m DSN

---

[1] All acronyms used in this document are defined in "Compiled Bibliographic Citations and Acronym Glossary for the Mars-Related White Papers Submitted to the NRC's Planetary Decadal Survey", which may be accessed at http://mepag.jpl.nasa.gov/decadal/index.html.

[2] While the focus of this white paper is on relay communications at Mars, we note that similar relay capabilities are applicable to many other planetary mission concepts.

antenna at 2 AU is roughly 2 kbps, while relay links to the ODY and MRO orbiters can operate at up to 256 kbps.

Reduced Energy Requirements: Energy is a precious commodity on the surface of Mars. Relay communication, due once again to the much shorter range over which the links must operate, requires far less energy-per-bit than DTE links. For MER, relay communication requires 10-100 times less energy per bit than a DTE link. This efficiency frees up energy for other activities, such as roving, drilling, thermal control and instrument operations.

Reduced Communications System Mass: Relay communication payloads are typically much smaller and lighter than DTE communication payloads. Achieving even modest data return on the DTE link requires highly directional, gimbaled antennas, whereas relay links can obtain high data rates with simple low-gain, low-mass antennas. These mass reductions free up landed mass for additional science payloads and can be critical for innovative small lander concepts.

Increased Communications Opportunities: Relay communication offers contact opportunities at times when Earth is not in view. For instance, the Spirit and Opportunity rovers routinely use relay passes at times when Earth is below the rovers' local horizon.

Robust Critical Event Communications: During critical mission events such as Entry, Descent, and Landing (EDL), Mars Exploration Program policy calls for acquisition of sufficient telemetry to allow for identification and reconstruction of a potential flight anomaly. Such a strategy, which was implemented after the loss of the Mars Polar Lander during EDL, is essential in order to diagnose and learn from any such loss-of-mission event. Robust critical-event communication calls for use of low-gain, wide beamwidth antennas in order to sustain communications in spite of unanticipated attitude variations. DTE communications via low-gain X-band antennas can only attain data rates of roughly 1 bps; however, a relay link with comparable beamwidth UHF antennas achieves rates of 8 kbps or more, roughly four orders of magnitude higher. This higher rate enables transmission of far more engineering telemetry, supporting fault diagnosis in the event of a mission anomaly.

In Situ Navigation: While the primary driver for relay links is their telecommunications function, the radio links also provide highly accurate *in situ* navigation. Measurement of the Doppler shift on the relay link between a lander and orbiter is very sensitive to the position of the lander relative to the orbiter's trajectory, and analysis of Doppler measurements from several overflights can yield lander position accuracies of 30 m or less. (It is also worth noting that precise Doppler measurements on UHF links *between* orbiters can enable scientifically valuable crosslink occultation measurements, providing a sensitive probe of the Martian atmosphere and ionosphere.)

Recent Mission Experience with Relay Communications

The recent Phoenix mission and the ongoing Mars Exploration Rover mission clearly demonstrate many of the benefits of relay communications cited above.

Mars Exploration Rovers:

The Mars Exploration Rovers, Spirit and Opportunity, carry both X-band DTE and UHF relay communication systems (Estabrook, et al., 2004). During EDL, each rover communicated to Earth at X-band via its low-gain antenna, using a "semaphore" signaling scheme to indicate key events throughout the EDL timeline and transmitting a small amount of spacecraft data, at an effective data rate of only about 1 bps. After backshell separation, however, each rover was able to establish an 8 kbps link to Mars Global Surveyor, increasing the critical-event telemetry bandwidth by roughly four orders of magnitude.

For operations on the martian surface, while use of the DTE link was initially the primary plan, the UHF system quickly demonstrated its advantages in terms of increased data return and energy efficiency, and, by the end of the primary 90-sol surface mission, the project had transitioned to using the UHF relay path almost exclusively for rover telemetry return. To date, 98% of all MER data have been returned via the UHF relay path, with an average data return of 88 Mb/sol for each rover. While ODY has provided the bulk of the relay support to MER, MGS offered frequent relay service while it was operational, and several demonstration passes have been conducted with ESA's Mars Express orbiter to demonstrate interagency interoperability, which is an important byproduct of both agencies formulating and adopting the CCSDS Proximity-1 Space Link Protocol (CCDSS, 2006) for these UHF relay links. More recently MRO, having completed its primary science mission, has begun to provide periodic relay support to the rovers.

Phoenix Lander

Based on the successful UHF relay support to Spirit and Opportunity, the Phoenix lander mission (Lewicke, et al., 2006) chose early in its development phase to eliminate X-band communications from the lander in order to reduce spacecraft mass and cost. The Phoenix project estimates that removal of the X-band telecom system reduced the lander mass by 14.8 kg and saved the mission more than $3M.

As a result, from the time the lander separated from the cruise stage shortly before atmospheric entry, all Phoenix communications for the rest of the mission were conducted via UHF relay links, using ODY, MRO, and MEX. Due to the high latitude of the PHX landing site, all three orbiters (each in a near-polar orbit) were able to view the EDL trajectory, providing the project with critical-event engineering telemetry at rates of 8-32 kbps from entry through landing.

Once on the surface, ODY and MRO provided multiple relay contacts each sol for support of lander commanding and telemetry return. Over the course of the Phoenix surface mission, which ended after 151 sols, the two orbiters supported 852 relay passes, returning a data volume of 37.9 Gb from the lander, corresponding to an average of over 250 Mb/sol of data return, more than four times the Phoenix requirement of 60 Mb/sol. Table 1 summarizes some of the key communications metrics for the MER and PHX missions.

	EDL		**Surface Relay (Through July'09)**	
	DTE (X-band)	***Relay (UHF)***	***DTE (X-band)***	***Relay (UHF)***
MER:	Semaphores **(~1 bps)**	**8 kbps** (after backshell sep)	6.9 Gb total (2.0%) **1.8 Mb/sol avg**	346.8 Gb total (98.0%) **88.0 Mb/sol avg**
PHX:	n/a	**8-32 kbps** (entry through landing)	n/a	25.6 Gb total (100%) **251.2 Mb/sol avg**

Table 1: Key MER and PHX telecommunications metrics.

Relay Communications for Future Mars Missions

Near-Term Mission Plans

Two missions slated for launch early in the next decade will continue to advance Mars relay capabilities, one as a relay user and the other as a relay provider.

- **Mars Science Laboratory:** In 2011, the Mars Science Laboratory (MSL) mission will launch to Mars, carrying the Curiosity Rover with a sophisticated scientific payload suite aimed at investigating past and present habitability at its selected landing site. MSL will offer significant advances beyond MER in terms of both rover engineering and *in situ* science capabilities. MSL's science payload includes a number of high-bandwidth science instruments, including the MastCam, a stereo, multi-wavelength, panoramic camera that is also capable of collecting high-definition video, and the Mars Hand Lens Imager (MAHLI), providing microscopic imaging of rocks and surface features down to a resolution of 12.5 μm. The MastCam's high-definition video represents a particularly large potential data source: just 4 min of MPEG-compressed video will generate 2 Gb of data. Other instruments include various spectrometers, sample analysis instruments, radiation detectors, and environmental sensors. MSL plans to return an average of 250 Mb of science and engineering telemetry each sol, with the vast majority of that data return returned via relay contacts with MRO and ODY.
- **MAVEN:** In 2013, NASA will launch the MAVEN Scout mission, an aeronomy orbiter which will study the evolution of the Martian atmosphere. In addition to its primary science objectives, MAVEN will also carry a UHF relay payload (provide by the Mars Exploration Program, outside of the Scout cost-cap) as a cost-effective means of augmenting the Mars orbital relay infrastructure. Although considered a secondary relay asset while ODY and MRO continue to operate in their extended missions, MAVEN will provide additional redundancy in relay assets, increasing the overall relay network robustness and offering wider coverage for critical event telemetry support.

Longer-Term Mission Options

While the detailed mission queue beyond the MAVEN mission is still uncertain, four specific mission concepts are under consideration, each of which involves important elements of relay communications:

- **Trace Gas Mission**: Like MRO, the Trace Gas Mission(TGM) orbiter would be a hybrid science-telecom orbiter, designed for a long operational lifetime beyond its primary science phase (Smith, et al., 2009). In support of its science objectives, the spacecraft would operate in a 400 km circular orbit, at an inclination of roughly 74 deg (or its complement, 106 deg). From this orbit, relay overflights would be similar in duration and link capability to those from ODY and MRO; however, TGM's orbit would by design not be sun-synchronous, so the local time of relay contacts for a given lander would slowly drift over time.
- **Mars Astrobiology Explorer-Cacher (MAX-C)**: The Mars Astrobiology Explorer-Cacher (MAX-C) mission could serve as a bridge between *in situ* exploration and sample return: MAX-C would carry a highly capable *in situ* science payload suite, following up on discoveries from MSL and/or orbital remote sensing observations, while also providing for caching of a scientifically selected sample for subsequent retrieval and return to Earth (Pratt, et al., 2009). Current instrument concepts would call for

returned data volume capability comparable to MSL, supported predominantly via relay communications.

- **Network Landers**: This mission would deploy four or more small, low-cost landers to the Martian surface, providing network science based on seismological, geodetic, and meteorological measurements from multiple sites (Banerdt, et al., 2004). Relay communications would be essential to minimize per-lander mass and cost; return data bandwidth would be dominated by high-rate sampling of observed seismic signals.
- **Mars Sample Return**: A Mars Sample Return (MSR) mission would return a scientifically selected sample to Earth, where the full spectrum of current – and future – laboratory analysis capabilities could be applied to geochemical and astrobiological investigations well beyond the capability of current *in situ* instruments (Borg, et al., 2009). Typical MSR mission architectures call for orbiter and lander launches in separate, adjacent Mars launch opportunities. (As mentioned above, MSR could also couple with the MAX-C mission to retrieve a previously cached sample.) An on-orbit relay asset would provide communications support for the surface sample collection activity, and would also be available to provide tracking and telemetry coverage for the numerous critical events associated with MSR, including the first launch from the surface of another planet, as well as EDL, sample rendezvous, and trans-Earth injection. (Note that, if launched prior to the MSR Lander, the MSR Orbiter itself can serve as an orbital relay asset to support surface operations.)

While these four mission concepts are the focus of current exploration plans, it is worth noting that relay communications is also an enabling capability for other candidate mission concepts such as balloons, airplanes, and penetrators. Figure 1 provides a summary timeline of recent, current, and future Mars orbiters and landers, illustrating the relay support provided by various orbiters during each lander's or rover's period of Mars operations.

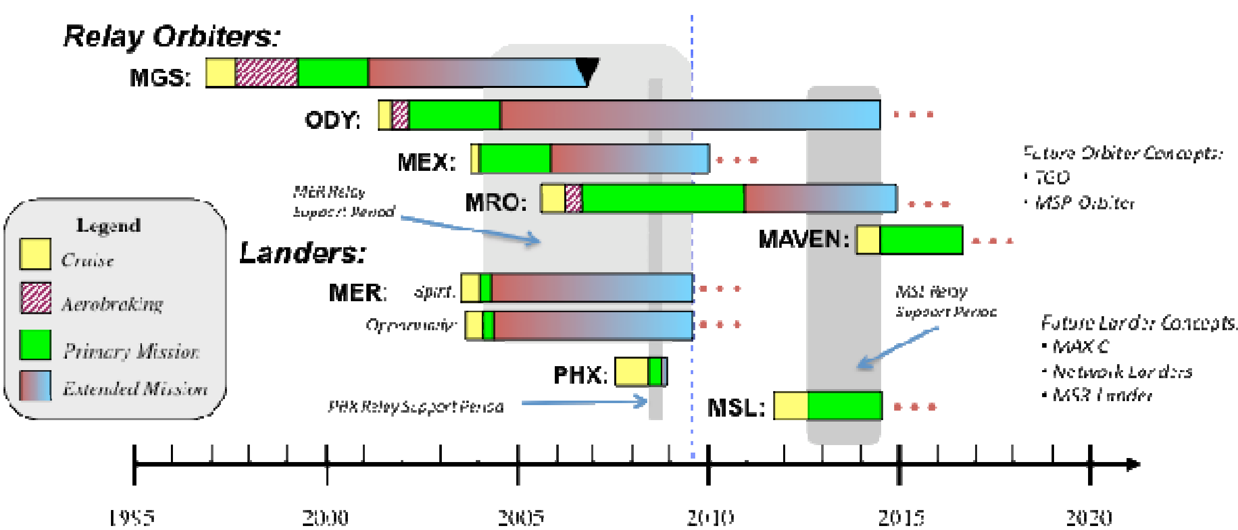

Figure 1: Timeline of past, current, and future Mars missions, showing relay service-providing orbiters and landed relay service users.

Key Technologies for Evolution of Relay Capability[3]

While relay orbiters have already made a significant impact by increasing the data return from Mars landed missions, a number of potential technology advances offer a path towards much higher bandwidth and improved operability. We highlight here several of these areas for growth.

Software-defined radios: The Electra UHF relay payloads now flying on MRO and scheduled for flight on MSL and MAVEN will advance relay capabilities well beyond the levels demonstrated on MER and PHX. While PHX and MER supported maximum relay data rates of only 128 and 256 kbps, respectively, the MSL-MRO link will operate at rates of up to 1024 kbps. These radios also offer a software-reconfigurable architecture that provides greater flexibility and allows the infusion of new capability over the long lifetime of a relay orbiter (Edwards, et al., 2003). As an example, a new Adaptive Data Rate capability developed within the Mars Technology Program after the launch of MRO will be uploaded to the orbiter and allow MSL and MRO to autonomously negotiate the maximum possible data rate throughout each relay contact, increasing data return by 50% and simplifying relay operations.

Improved coding: Current UHF transceivers utilize Viterbi error-correcting codes. Another recent product of the Mars Technology Program is a new class of Low Density Parity Check codes tailored for Mars proximity links. Infusion of these new codes into the Mars relay network could provide roughly a factor-of-two increase in performance.

Directional antennas: Current Mars relay scenarios employ omnidirectional antennas for the lander and orbiter. While this supports a simple operations paradigm, it also fundamentally limits relay performance. Transition to higher-gain antennas on the orbiter and/or lander offers a path for order-of-magnitude performance improvement. Migration of relay communications to higher frequency bands would enable high antenna gain from relatively small, low mass components. For instance, a MER-class X-band radio system – already incorporated into many lander concepts to support DTE communications – could achieve data rates well in excess of 10 Mbps on relay links to a comparably equipped orbiter.

Optical communications: Highly directional optical links provide further potential for improved link performance (Kovalik, et al., 2009; Hemmati, et al., 2007). Small optical payloads with mass and power comparable to current UHF relay payloads could achieve data rates of 100 Mbps. Such very high instantaneous data rates would be well-suited to the short intermittent relay contacts offered by low-altitude hybrid science-telecom orbiters, allowing a lander to burst back tens of gigabits of data in a single relay contact.

Improved Orbiter Deep Space Link Performance: While current relay data return is limited by the lander-orbiter relay link performance and limited contact time, rather than the performance of the orbiter's link back to Earth, significant improvements in relay link performance would ultimately drive the need for commensurate advances in the orbiter deep space link. Options here include: increased transmit power, larger aperture antennas, migration to Ka-band, and ultimately transition to optical downlink capability.

---

[3] These technologies are considered enhancing, and not included the Hayati, et al., 2009 white paper "Strategic Technology Development for Future Mars Missions (2013-2022)".

Network protocols: The current protocol stack for relay communications operates over standardized link layer protocols, but with rather *ad hoc* application layer functionality to implement the store-and-forward two-hop relay path between the lander, orbiter, and Earth. Infusion of Delay Tolerant Networking (DTN), an emerging network and transport layer protocol similar in function to the Internet's TCP/IP protocol suite but tailored for the long-delay, intermittently connected environment of deep space (Burleigh, et al., 2003), will standardize multi-hop relay interfaces and support future, more complex network topologies.

Programmatic Considerations and Conclusions

The past decade of Mars *in situ* exploration has greatly benefitted from the availability of an orbiting relay network, dramatically increasing the data return from the Martian surface. In considering the future strategy for exploring Mars, the following principles should be taken into consideration:

- Next-decade Mars rovers will drive the need for increased data return based on the increasing spatial and spectral resolution of future *in situ* instruments and the increasing traverse distances achieved each sol. Increased data return will also support public engagement by enabling immersive visualization using high-resolution, stereo panoramic imagery. At the same time, relay capabilities will enable new, innovative concepts for small, low-cost landers by providing communications services without requiring DTE communication capability.
- Addition of a relay payload to each science orbiter provides an extremely cost-effective means for establishing a Mars orbiter relay network. While dedicated relay orbiters offer higher performance from orbits optimized for telecommunication considerations, and may ultimately be required for advanced robotic or eventually for human exploration, hybrid science-telecom orbiters offer considerable capability and represent a sensible interim strategy.
- The relay plan for MER and PHX was extremely robust due to the availability of multiple relay assets. MGS, ODY, and MEX were available for support of MER's primary mission, while ODY, MEX, and MRO were on orbit at the time of PHX arrival. Maintaining redundant relay assets whenever relay services are required should be a goal of the Mars exploration strategy. Key to achieving this goal is attaining a long operational lifetime for each orbital relay asset.
- International cooperation is likely to play an important role in the coming decade of Mars exploration. Interagency relay cross-support will be an important element of such cooperation. We should build on the successful cross-support of ESA's MEX to NASA's MER and PHX, and the originally planned support of Beagle-2 by ODY, in future mission scenarios. Standardized relay protocols and coordinated interagency relay processes are key to the success of an international program of exploration.

References

The reference list may be accessed at the following web site:
http://mepag.jpl.nasa.gov/decadal/index.html.