Coding, Modulation, and Relays for Deep Space Communication Mars Rovers Case Study

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Abstract

Over the years, the National Aeronautics and Space Administration (NASA) has supported unmanned deep space missions through point-to-point communications links between the spacecraft and the Deep Space Network (DSN). The DSN is developed and operated by the Jet Propulsion Laboratory (JPL) and subcontractors on behalf of NASA.

The deep space communications environment is unique because of the large distances that create extremely difficult link budgets (dominated by the $1/R^2$ space loss) and long response times (dominated by the round-trip-light-time, RTLT). Over the years, the DSN has employed techniques such as very large steerable antennas, cryogenic low-noise amplifiers, multi-KW transmitters, powerful modulation and coding techniques, and minimal-loss digital processors to maximize the telemetry and command data volume in the point-to-point communication links between the spacecraft and the DSN.

A traditional deep-space spacecraft flies on a largely-predictable trajectory, governed by the celestial mechanics of the surrounding bodies. Such a spacecraft must point its communications antenna at Earth, and then make slow pointing adjustments as the spacecraft flies through its slowly-changing trajectory, a well-understood process. In contrast, the Mars Exploration Rovers (MER) presented a much more complex environment both during the Entry-Descent-Landing (EDL) phase, where antenna pointing was unpredictable and uncontrolled, and during surface operations where the antenna size and steering requirements conflicted with the requirements for a power-limited, mobile, remotely controlled vehicle.

The solution, successfully deployed during the recently-completed MER prime mission, was to augment the point-to-point direct-to-Earth (DTE) link with relays through two other spacecraft, using standard protocols (including coding and modulation), with minimal impact to the EDL and surface operations. Use of relays is continuing during the extended MER mission.

This paper presents the communications challenges for the MER mission, the use of DSN and MER tools to maximize the science return, and the application of standards-based relays to the problem. To date, more than 90% of the data returned from MER has been returned via relays, not DTE.

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1. Introduction

Over the last 45 years, the DSN has provided communication and navigation services to the spacecraft (S/C) of NASA and its partner agencies. The most visible component of the DSN is the set of large - 34-m and 70-m in diameter - steerable antennas employed for telemetry, tracking, and command (TT&C).

Closing the deep space communications link poses unique challenges because of the vast distances between spacecraft and Earth. For a spacecraft orbiting Mars, the distance to Earth varies from 0.4 to 2.7 Astronomical Units (AU), where an AU is the average distance between Earth and the Sun, or roughly 150,000,000 km. These distances have two key effects. First, closing the link is much more challenging than closing terrestrial links or links to Earth-orbiting S/C. For example, Mars at its nearest approach is 2500 times farther than a geostationary satellite. Second, the long RTLT makes joy-stick operations and internet-type close-loop communications protocols difficult or impossible. The average RTLT to Mars is 6-40 minutes!

2. Closing the Link – Point-to-point and Relay

Over the years, the DSN has developed a toolkit of techniques to close the point-to-point and relay communications links with deep space S/C. In this Section, we describe the key elements in this toolkit. In Section 4 we describe its application their the Mars Exploration Rover (MER) mission. Detailed information is available in the DSN Telecommunications Handbook, accessible at http://eis.jpl.nasa.gov/deepspace/dsndocs/810-5/.

2.1 Large Steerable Antennas

The DSN uses large steerable antennas – 34-m and 70m in diameter, that are located approximately 120^0 apart in longitude. Two of the sites are in the northern hemisphere (near Goldstone, California and Madrid, Spain) while the third site is in the southern hemisphere (near Canberra, Australia). With these locations, the DSN has the ability to provide 24x7 support to all the deep space S/C (and many nearer S/C) of NASA and its partner agencies.

2.2 Cryogenic Low Noise Amplifiers

The DSN uses cryogenically-cooled low-noise front-ends based on Microwave Amplification by Stimulated Emission of Radiation (MASER) and High Mobility Electron Transistor (HEMT) technologies. The typical overall system noise temperature (SNT) at X-band is under 25^0K. Thus, the very weak signal (relative to the background noise) is more likely to be detected.

3 Multi-KW Transmitters

The DSN uses high power transmitters to compensate for the space loss when sending commands to the remote S/C. Currently, most commanding is with 20 kW X-band transmitters on the 34-m and 70-m antennas

2.4 Higher Frequencies

Over the years, the DSN has migrated from S-band (downlink: 2200-2300 MHz) to X-band (downlink: 8400-8500 MHz). Currently, the DSN is migrating further to Ka-band (32000-32500 MHz). The higher frequencies result in narrower antenna beams, again increasing the effective power received at the receiver.

2.5 Modulation

The DSN uses, exclusively, coherent digital modulation. Historically, the data rates for deep space S/C are power-limited, not bandwidth-limited; hence, the DSN selected modulation methods that allow capture of all the power, from a rather broad bandwidth. The most common modulation used for deep space S/C is Bi-phase Phase Shift Modulation (BPSK) modulation on a subcarrier. More recently, other modulation types that are more bandwidth efficient were added, e.g. Quadrature Phase Shift Keying (QPSK) and Offset QPSK (OQPSK). Gaussian Minimal-Shift Keying (GMSK) will be added for missions that require highly bandwidth-efficient modulation.

2.6 Error-Correcting Coding

The DSN uses several types of powerful error-correcting codes. The most common coding is the (7, 1/2) convolutional code, concatenated with a frame-based (223, 255) Reed-Solomon code. However, the DSN also supports decoding of (15, 1/6) convolutional code and of Turbo codes. Figure 1 shows the error-correcting codes processed by the DSN.

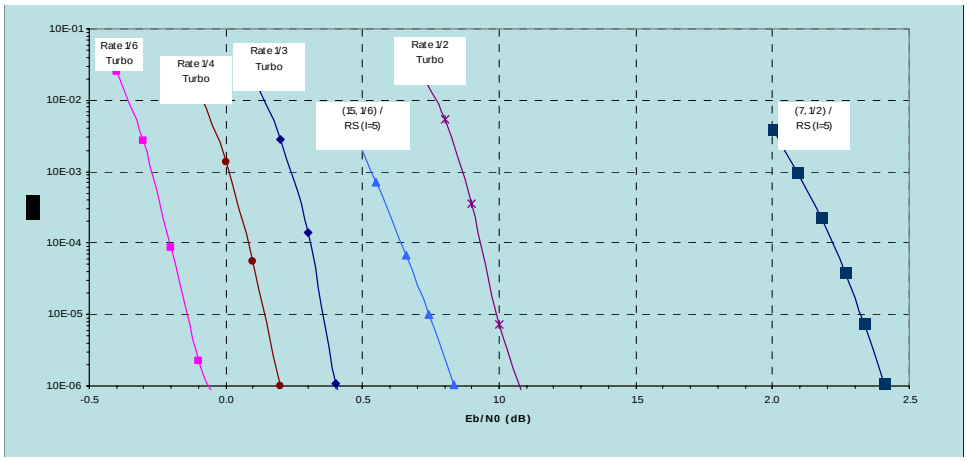


Figure 1 – Coding gain for Error-Correcting Codes Used by the DSN

2.8 Minimal-Loss Digital Processors

The DSN employs a fully-digital Downlink Telemetry and Tracking (DTT) processor. The DTT is designed to minimize processing losses by (for example) using sub-Hz tracking loops, multi-bit sampling, and matched filtering.

2.9 Relays

Relays are especially effective in closing the link when:

1. the S/C antenna cannot be effectively pointed, e.g. during EDL or surface vehicle traverse, and/or

2. the communicating object (e.g. rover) cannot accommodate a relatively large antenna and transmitter.

To minimize the initial investment costs of establishing on-orbit telecommunications relay capabilities, Ultra-high Frequency (UHF) relay payloads were added to already-planned Mars science orbiters. The Mars Global Surveyor (MGS) orbiter, launched in 1996, and the Mars Odyssey orbiter (ODY), launched in 2001, each carry a UHF radio for communications with landed assets. Both of these orbiters are in low (400-km), near-polar, sun-synchronous orbits, based on science considerations for their primary mission goal of global high-resolution mapping; the MGS orbit plane is near 1-2 PM Local Mean Solar Time (LMST) while ODY's is near 4-5 PM LMST. The low-altitude orbits significantly limit contact time for low-latitude users to typically one short daytime pass and one short nighttime pass, each only about 10 min in duration, for each orbiter. Nonetheless, the low incremental cost of adding a UHF payload to a planned science orbiter made this an attractive way to begin to implement an initial Mars Network infrastructure.

The European Space Agency (ESA) Mars Express Orbiter, also launched during the 2003 Mars launch opportunity, provided yet another science orbiter which could host a UHF comm payload. Because ESA chose not to employ aerobraking, the Mars Express spacecraft is in an elliptical mapping orbit, resulting in highly variable contact times and geometries and relatively poorer relay performance. For this reason, MER did not plan to use Mars Express on an operational basis, but did design and test to insure interoperability with Mars Express as a potential backup relay asset, and successfully conducted one relay pass with Mars Express.

Based on this network of orbiters, shown in Figure 2, Spirit and Opportunity (as the Mars rovers were named) benefited from a very robust communications architecture, with each rover having its own DTE comm capability, as well as options for UHF relay comm via any of three on-orbit relay spacecraft. Current Mars program plans call for continued evolution of the Mars Network, first with another Mars science orbiter, the 2005 Mars Reconnaissance Orbiter (MRO), and then with the first Mars Telecommunications Orbiter (MTO) in 2009. MTO, as a dedicated telecommunications satellite, will select a higher-altitude orbit optimized for its telecom role, and will deploy a more capable proximity link comm payload.

3. The MER Communications Challenge

Landers, in general, and rovers in particular, pose unique challenges to meeting of the communications objectives. The objective for EDL communications was to return engineering data, primarily to understand the dynamics of EDL, and to enable forensic analysis, if EDL fails. The objective for surface operations communications was to maximize the return of science data.

Ironically, a secondary challenge was posed by the proliferation of S/C in the Mars view period. Around Mars, at some times, there were five operational S/C: the two MER vehicles (Spirit and Opportunity) ODY, MGS, and ESA's Mars Express, all vying for the unique 70-m antennas. The period from November 2003 to March 2004 was named the Asset Contention Period (ACP); NASA has used special procedures to resolve asset conflicts during the ACP period.

3.1 Entry-Descent-Landing Environment

MER landed on Mars after a dramatic 6-minute EDL phase, shown in Figure 3. During EDL, DTE communication over a coherent digital link was virtually impossible because of the unpredictable antenna pattern.

3.2 Surface Operations Environment – Antenna Size

The rover, roughly the size of a golf cart, included antennas for both relay and DTE communications. However, due to size limitations, the HGA, used for DTE, was only 28 cm in diameter. As reference, the Cassini HGA antenna is 400 cm in diameter.

3.3 Surface Operations Environment – Antenna Pointing

Use of the directional X-band HGA required two-axis pointing to Earth. The UHF relay link, by contrast, utilized a low-gain monopole antenna, requiring no pointing. The layout of the rover deck included structures (e.g., the Pancam mast) that generated significant multipath effects and significantly distorted the monopole UHF pattern. As a result the MER pattern was measured and modeled for each relay pass to understand the expected antenna gain based on overflight geometry.

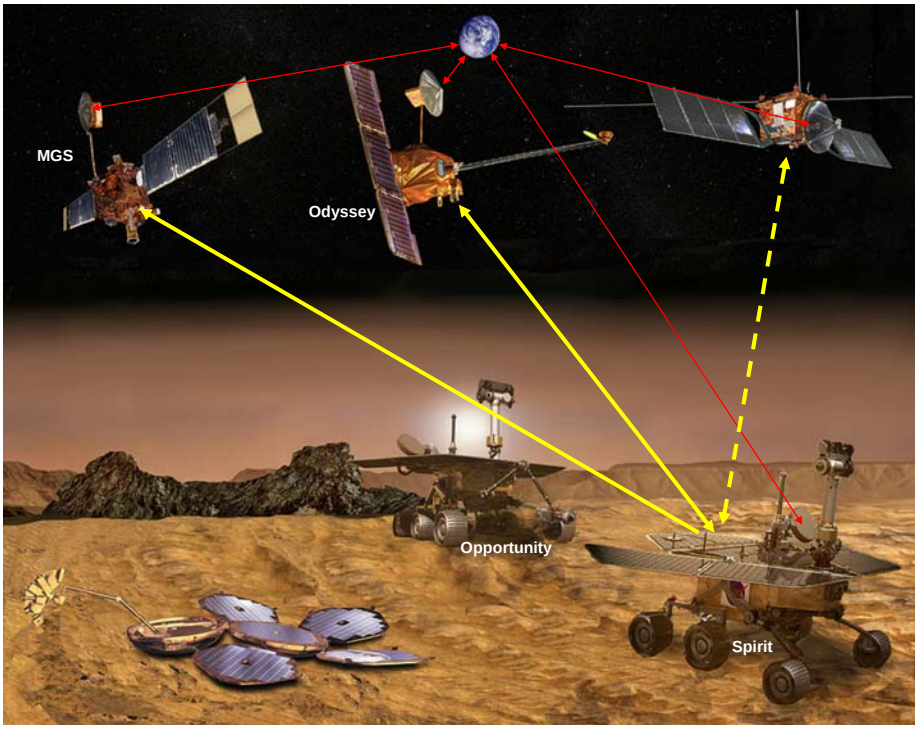


Figure 2 – The MER Relay Options

4. The MER Communications Solution

JPL has approached the MER communications challenge by designing two separate links, both to be used during EDL and surface operations:

1. A very effective point-to-point (or DTE) link. This link would return less science, but was perceived as less risky.

2. A very effective relay link. This link could provide more science, but at a perceived higher risk, requiring more components to interface and function well to complete the link. Note that because MGS and ODY were launched long before the MER system was completed, there was no end-to-end test of the actual operational systems until MER arrived to Mars orbit!

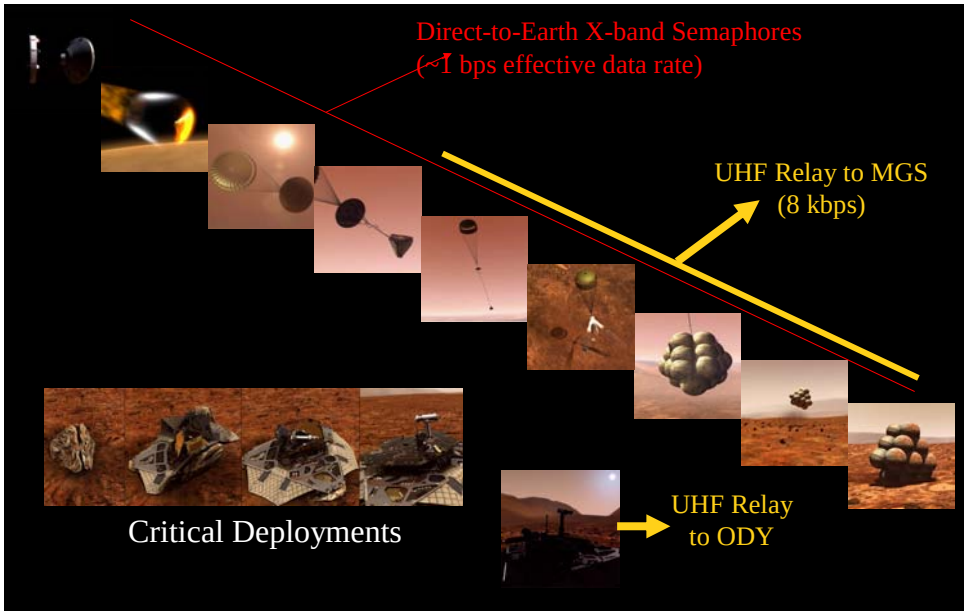


Figure 3 – The MER EDL Environment

The EDL phase was supported by point-to-point "semaphore" communications with the following parameters:

- Large Steerable Antennas. EDL was supported by two 70-m antennas (the event occurred, by design, during a coverage overlap between the Goldstone and Canberra sites). In addition, several 34-m antennas tracked the event as well.

- Cryogenic Low Noise Amplifiers. EDL was supported with the MASER front-end on the 70-m antennas, with SNT of xx^0K

- Multi-KW Transmitters. There was no uplink during EDL.

- Higher Frequencies. EDL (MER in general) operated at X-band.

- Modulation. Because coherent digital modulation was not possible, EDL was supported with non-coherent "semaphore" tones. These were created by varying the subcarrier

frequency to a discrete set of frequencies. This modulation approach is equivalent to M-ary Frequency Shift Keying. The effective data rate for the semaphores was approximately 1 bps.

- Error-Correcting Coding. There was no error-correcting coding for the EDL "semaphore" tones.

- Minimal-Loss Digital Processors. EDL "semaphore" tones were captured with existing sensitive open-loop receivers, with specialized software.

The surface operations were supported by point-to-point communications with following parameters:

- Large Steerable Antennas. Surface Operations were supported primarily by the three 70-m antennas, and occasionally by the 34-m antennas. The DSN made extensive use of the Multiple-Spacecraft-per-Antenna (MSPA) capability to track simultaneously the several S/C around Mars (Spirit and Opportunity, ODY, MGS and Mars Express). To accommodate the needs of the ACP, the DSN has constructed one new 34-m antenna in the Madrid facility and automated the MSPA process.

- Cryogenic Low Noise Amplifiers. Surface operations were supported with the MASER and HEMT X-band front-end on the 34-m and 70-m antennas

- Multi-KW Transmitters. Surface operations were supported with 20 kW X-band transmitters. To accommodate the needs of the ACP, the DSN has upgraded five transmitters on the 34-m antennas from 4 kW to 20 kW.

- Higher Frequencies. Surface Operations communications for MER operated at X-band.

- Modulation. While the DSN has upgraded the telemetry and command processors in preparations for ACP, there was no change in the modulation format. Surface operations telemetry was send using BPSK modulation, on a square-wave subcarrier. The subcarrier frequency was xxx KHz and the data rates were xxx-xxx Kbits/s.

- Error-Correcting Coding. Surface operations were supported mostly with (15, 1/6) convolutional code, concatenated with a (223, 255) Reed-Solomon code.

- Minimal-Loss Digital Processors. Surface operations were supported by the DSN's fully-digital DTT's.

Relay Operations and Results for EDL

Since the loss of the 1998 Mars Polar Lander, which occurred during the critical entry, descent, and landing (EDL) phase and without any communications, the program has established a policy of requiring real time telemetry during all critical mission events, in order to support fault reconstruction and diagnosis in the event of a mission anomaly. For MER, an X-band signal was transmitted via a low-gain antenna throughout EDL and detected at the DSN's 70m antennas. The very weak X-band signal limited this link to an effective data rate of only about 1 bps.

Fortunately, both MER rovers landed in the early afternoon at Mars, consistent with the MGS orbit plane. In-orbit phasing maneuvers allowed MGS to have visibility to each rover during EDL. After back shell separation and descent on the bridle, each rover began transmissions at 8 kbps over the UHF link to MGS. Thus, for this latter phase of EDL, the relay link offered well over three orders of magnitude increase in the critical event telemetry rate, vastly increasing the

quantity of diagnostic engineering data that was available in the event a spacecraft failure had occurred.

While the UHF critical event telemetry collection was totally successful, MER was clearly very fortunate that its mission design was compatible with the MGS orbit plane and the limited footprint of MGS's low-altitude orbit. Having a higher-altitude orbit with larger footprint and increased coverage for critical events is one of the driving factors motivating the program plans for launch of a dedicated Mars Telesat in 2009.

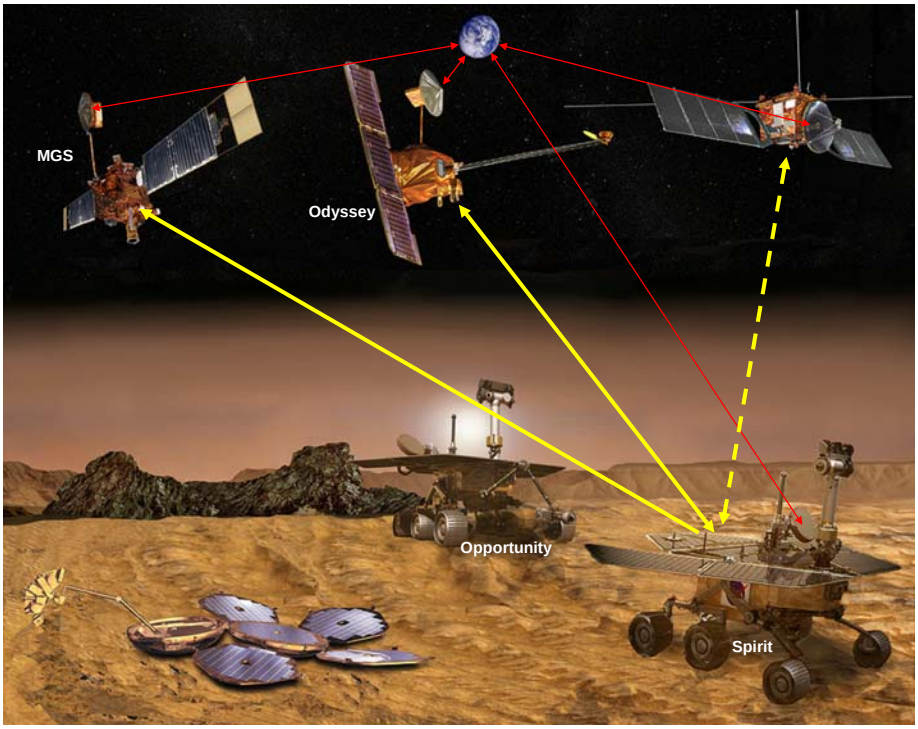


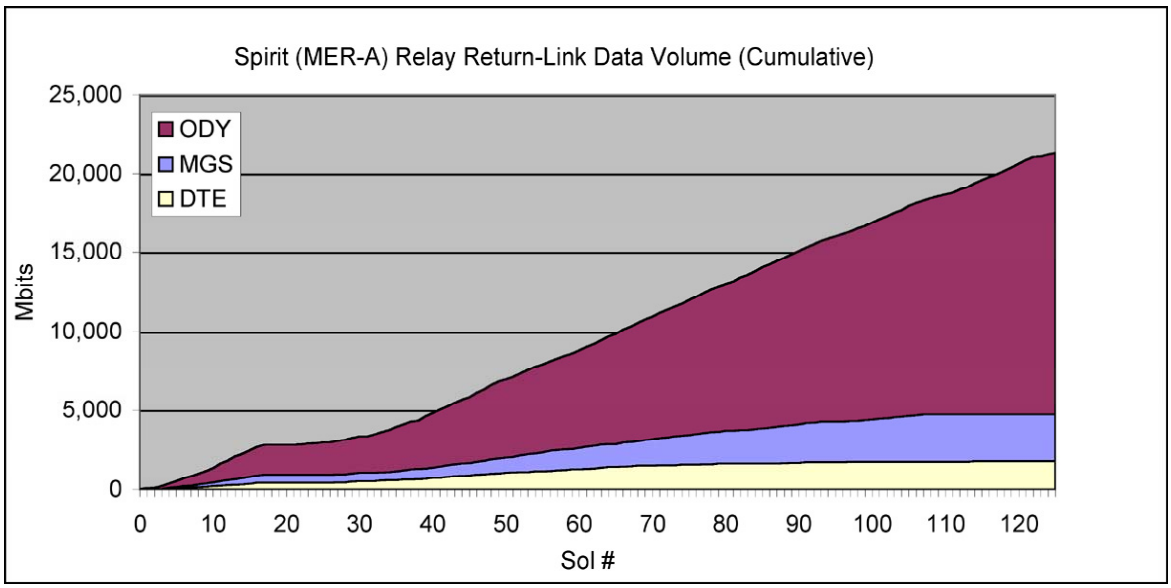
Figure 2 – The MER Relay Options

Relay Operations and Results for Surface Operations

In spite of the short contact times offered by the science orbiters, their proximity to the landers allows for very high-rate, energy-efficient relay links. MER's X-band DTE link could only achieve ~10-20 kbps to a DSN 70m antenna using its directional high-gain antenna at the time of landing, and this value has steadily declined as Earth-Mars distance has increased. By contrast, the UHF relay links operate routinely at 128 kbps, and the MER-ODY link has been successfully operated up to 256 kbps. As a result, the vast majority of the Spirit and Opportunity data return has been achieved over the relay links. Figure 4 summarizes the cumulative data return from each rover, for the X-band DTE link and for the UHF relay links through MGS and ODY. As of May 13, 2004, more than 40 Gbits of rover data have been returned to Earth, with 78% of that data via the ODY UHF link, 14% via the MGS UHF link, and only 8% via the X-band DTE link. Per sol data return from each rover is well over 150 Mb, greatly increased from the 30 Mb/sol average return from the 1996 Mars Pathfinder lander, which had only DTE comm capability. The increased return has allowed much more frequent downlink of data-rich products such as high-resolution, three-color panoramas (representing data volumes of many hundreds of Mbits per product).

In addition to the increase in data volume, the higher instantaneous data rate also implies a much more energy-efficient link; for an energy-constrained solar-powered rover, this is a very important consideration. The rovers' X-band link requires more than 1 Watt-hr to return 1 Mbit of data directly to the DSN; that same Watt-hr of rover energy can support the transfer of more than 10 Mbit of data via the relay link to MGS or ODY.

UHF and DTE communications were used in a complementary fashion during surface operations. The DTE link was used as the primary command path, as it offered the lowest latency. Typically, commands were transmitted to the rover in the morning (Mars time) based on analysis of the previous sol's science and engineering data. Early in the mission, the DTE path was also used extensively in the early afternoon to return critical data for planning purposes. This data return was then augmented by relay opportunities in the late afternoon through ODY and overnight passes through both orbiters. Later in the mission, based on increasing confidence in the relay performance and recognition of the high energy efficiency of the UHF link, the rovers have transitioned to returning nearly all of their data via the relay orbiters.



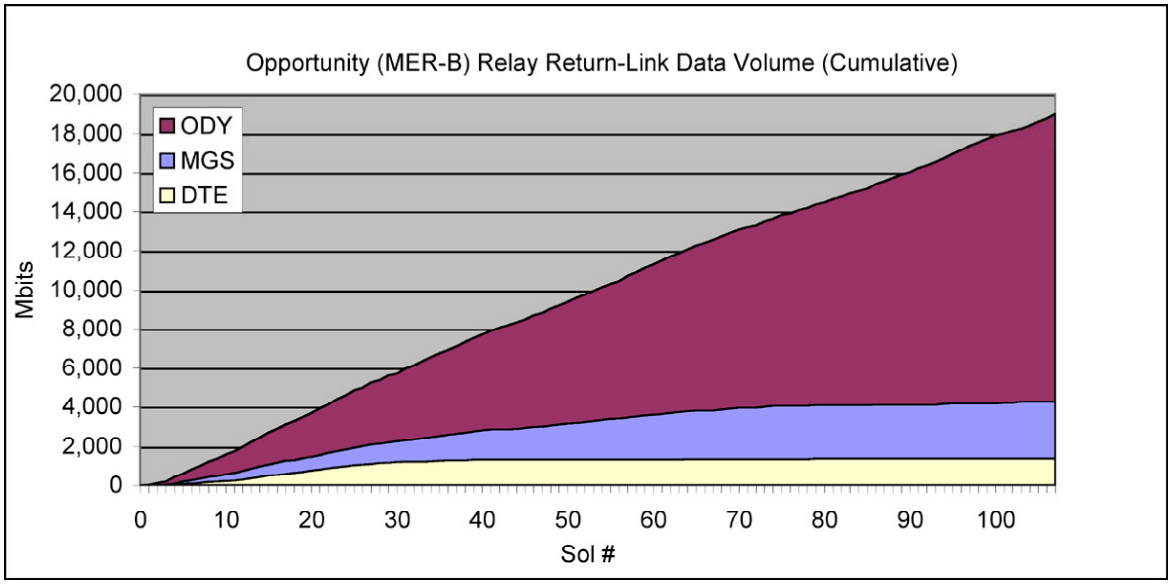


Figure 4 – Data Volume, by Method of Communications

5. Conclusions

The results of the MER operations demonstrate that relay communications with deep space S/C, under the right circumstances, can significantly augment DTE communications. The relay services provided by the MGS and ODY spacecraft have drastically increased the science return from the Spirit and Opportunity rovers. Over 90% of the rover data has been returned via the relay orbiters, while the energy efficiency of the relay links has also benefited these power-limited landers. Establishment of telecommunications protocols and standards has been essential for ensuring interoperability among orbiter and landers, and has enabled interagency cross-support, further increasing the Mars Network robustness, as shown in Figure 5. Future NASA programs can apply these same strategies at any target of sustained robotic and/or human exploration, deploying feed-forward telecommunications infrastructure to enable and enhance subsequent in situ exploration missions.

However, reaping the benefits of relay operations requires the right circumstances. Primarily, there has to be careful planning to have multiple relay resources to assure redundancy, and compatibility in the physical in-situ links and the relay protocols. Relays are especially effective (relative to DTE) for space vehicles that cannot provide cost-effective accurate antenna pointing, and/or large antenna, and/or large transmitter.

There are a large number of missions that cannot benefit from relays, primarily where there is no cost-effective way to place a nearby relay. To support these S/C, NASA and its partner agencies will continue to invest in advancing the cost-effective state-of-the-art in the point-to-point links including large steerable antennas, cryogenic low-noise front-ends, multi-kW transmitters, modulation, error-correcting coding, and low-loss digital.

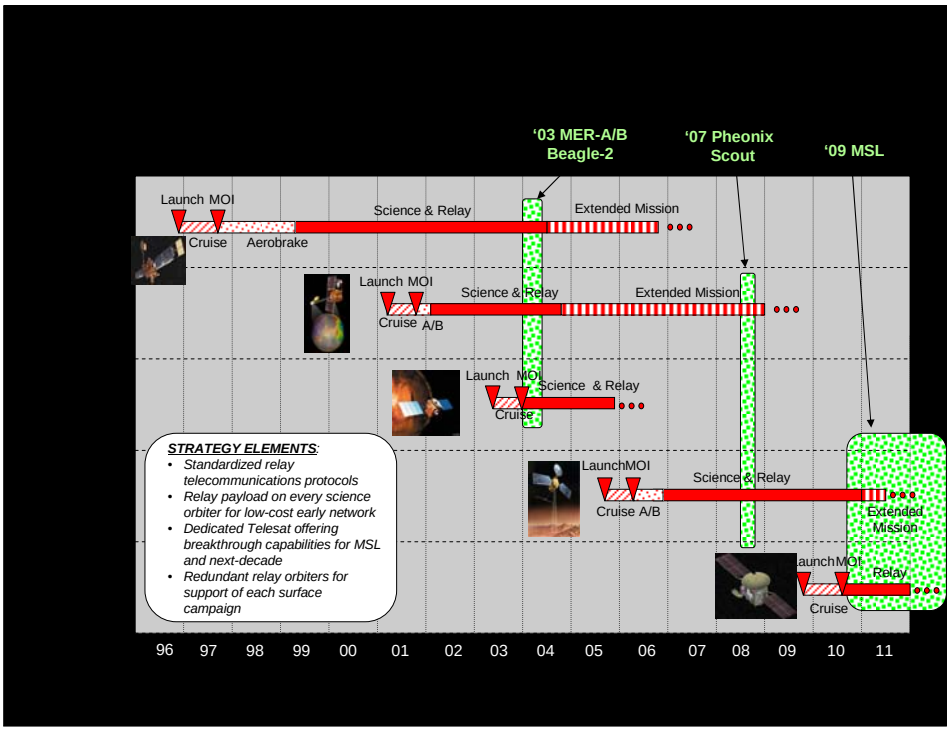


Figure 5 – Plans for Mars Relay Communications

REFERENCES

[1] URL: http://eis.jpl.nasa.gov/deepspace/dsndocs/810-5/.

[2] DTT paper

ACRONYMS

AU	Astronomical Unit
ACP	Asset Contention Period
BPSK	Bi-Phase Phase Shift Keying
DSN	Deep Space Network
DTE	Direct to Earth
DTT	Downlink Tracking and Telemetry
EDL	Entry, Descent, Landing
ESA	European Space Agency
GMSK	Gaussian Minimal Shift Keying
HEMT	High Electron Mobility Transistor
HGA	High Gain Antenna
JPL	Jet Propulsion Laboratory
LMST	Local Mean Solar Time
kbps	Kilo Bits Per Second
MASER	Microwave Amplification by Stimulated Emission of Radiation
mbps	Mega Bits Per Second
MER	Mars Exploration Rover
MGS	Mars Global Surveyor
MRO	Mars Reconnaissance Order
MSPA	Multiple Spacecraft per Antenna
MTO	Mars Telecom Orbiter
NASA	National Aeronautics and Space Administrations
ODY	Mars Odyssey
OQPSK	Offset Quadrature Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
S/C	Spacecraft
SNT	System Noise Temperature
TT&C	Tracking, Telemetry and Command
RTLT	Round Trip Light Time
UHF	Ultra High Frequency