Relay Support for the Mars Science Laboratory Mission

Charles D. Edwards, Jr, David J. Bell, Roy E. Gladden, Peter A. Ilott, Thomas C. Jedrey, M. Daniel Johnston, Jennifer L. Maxwell, Ricardo Mendoza, Gaylon W. McSmith, Christopher L. Potts, Brian C. Schratz, Mazen M. Shihabi, Jeffrey M. Srinivasan, Phillip Varghese
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr., Pasadena, CA 91109
818-354-4408
chad.edwards@jpl.nasa.gov

Stephen S. Sanders
Lockheed Martin Astronautics
Littleton, CO

Michel Denis
European Space Operations Centre
Robert-Bosch-Str. 5, 64293 Darmstadt, Germany

Abstract— **The Mars Science Laboratory (MSL) mission landed the Curiosity Rover on the surface of Mars on August 6, 2012, beginning a one-Martian-year primary science mission. An international network of Mars relay orbiters, including NASA's 2001 Mars Odyssey Orbiter (ODY) and Mars Reconnaissance Orbiter (MRO), and ESA's Mars Express Orbiter (MEX), were positioned to provide critical event coverage of MSL's Entry, Descent, and Landing (EDL). The EDL communication plan took advantage of unique and complementary capabilities of each orbiter to provide robust information capture during this critical event while also providing low-latency information during the landing. Once on the surface, ODY and MRO have provided effectively all of Curiosity's data return from the Martian surface. The link from Curiosity to MRO incorporates a number of new features enabled by the Electra and Electra-Lite software-defined radios on MRO and Curiosity, respectively. Specifically, the Curiosity-MRO link has for the first time on Mars relay links utilized frequency-agile operations, data rates up to 2.048 Mb/s, suppressed carrier modulation, and a new Adaptive Data Rate algorithm in which the return link data rate is optimally varied throughout the relay pass based on the actual observed link channel characteristics. In addition to the baseline surface relay support by ODY and MRO, the MEX relay service has been verified in several successful surface relay passes, and MEX now stands ready to provide backup relay support should NASA's orbiters become unavailable for some period of time.**

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INTRODUCTION

The Mars Science Laboratory (MSL) mission and its Curiosity rover represent the most ambitious robotic explorer ever delivered to the surface of the Red Planet. Combining a novel Entry, Descent, and Landing (EDL) system capable of delivering nearly a metric ton safely to a wide range of potential landing sites, a robust mobility system designed for 20 km of traverse, a nuclear power system allowing years of surface lifetime, and a sophisticated suite of science instruments including remote sensing, sampling, and analytical capabilities, MSL will investigate the past habitability of Mars during the course of a one-Martian-year (roughly two-Earth-year) journey through the layered deposits of Gale Crater and Mount Sharp.

Key to the success of the mission is the availability of robust, high-bandwidth, energy-efficient telecommunication capabilities provided by a network of relay-equipped Mars orbiters, including NASA's 2001 Mars Odyssey Orbiter (ODY) and Mars Reconnaissance Orbiter (MRO), and ESA's Mars Express Orbiter (MEX). During EDL, all three orbiters provided coverage of this critical event, acquiring telemetry and tracking data from MSL that would have been used for fault reconstruction in the event that an anomaly had led to a loss of mission on landing day. And once on the surface, the Mars telecommunications relay network is enabling greatly increased data return from Curiosity, compared to all prior Mars landers, essential for supporting the rover's highly capable instrument suite and complex surface operations.

In Section 2, we provide an overview of the three relay orbiters currently in operation at Mars, summarizing their key capabilities and differences. We summarize the MSL mission in Section 3, with a focus on telecommunication requirements and telecommunication subsystem capabilities. In Section 4, we describe the strategy for providing critical event communications during MSL's EDL, while in Section 5 we present quantitative metrics on relay performance during the Curiosity surface mission, including several new capabilities being demonstrated for the first time at Mars on the Curiosity-MRO relay link. With an eye towards future

proximity relay networks being contemplated/planned by NASA and ESA, Section 6 will offer a number of preliminary lessons-learned related to relay communications, based on our experiences through the first few months of Curiosity surface operations, with some final conclusions in Section 7.

1. MARS NETWORK OVERVIEW

Mars-orbiting relay satellites offer a number of advantages to *in situ* Mars spacecraft, relative to direct-to-Earth communications, including greatly increased data return, reduced energy-per-bit communication costs, ability to communicate at times when Earth is not in view, and precise navigation and timing information derived from the radio link [1,2]. Relay communications has been used very successfully by the Spirit and Opportunity rovers, launched in 2004, with over 98% of the rovers' returned data transmitted via relay links through relay-equipped Mars science orbiters [3]. The 2007 Phoenix Lander mission arrived at Mars with no direct-to-Earth communication capability, carrying out its entire *in situ* mission using exclusively UHF relay links [4].

Today we have an international Mars relay network composed of NASA's 2001 Mars Odyssey Orbiter (ODY) and Mars Reconnaissance Orbiter (MRO), and ESA's Mars Express Orbiter (MEX). Table 1 provides a summary of the key features of each of these orbiters.

Odyssey

ODY operates in a low-altitude, near-circular, near-polar, sun-synchronous orbit. At the time of MSL arrival, ODY's ascending node was oriented at ~4 AM Local Mean Solar Time (LMST). For low-latitude landing sites, this implies contact opportunities at roughly 4 AM and 4 PM each Martian day, or sol. ODY's relay communications are provided by a CE-505 UHF transceiver built by L-3 Cincinnati Electronics. Like all of the Mars relay orbiters currently operating, the CE-505 implements the Consultative Committee on Space Data Systems (CCSDS) Proximity-1 Space Link Protocol (referred to as "Prox-1") [5]. This link layer protocol supports reliable bi-directional communications, using frame-level error detection and retransmission to ensure complete and gap-free data transfer on the proximity link, while also establishing an interoperable standard for inter-agency Mars relay cross-support. The transceiver also supports an unreliable, raw data mode that bypasses the Prox-1 protocol and simply operates as a bitstream modem. (This raw data mode is useful for special events such as critical event communications, where a simple, low-latency telemetry bitstream is needed, and where a link layer process that discards frames with errors would not be desirable.) The CE-505 operates at fixed frequencies of 437.1 MHz on the forward link (from orbiter to lander) and 401.585625 MHz on the return link (from lander to orbiter). Return link data rates of 8, 32, 128, and 256 kbps are supported, with optional (7,1/2) convolutional coding. In addition to these modem capabilities, the CE-505 is capable of making an open-loop recording of a received UHF signal for subsequent ground processing. The signal is sampled at 83.6 kHz with 1-bit-per-sample resolution. This mode of recording does not support full demodulation of a high-rate telemetry stream, but can be used to reconstruct the signal spectrum, making it useful to track the amplitude and

	Mars Odyssey	**Mars Express**	**Mars Reconnaissance Orbiter**
Agency:	NASA	ESA	NASA
Launch:	Apr 7, 2001	June 2, 2003	Aug 12, 2005
Orbit:	400 km circular 93 deg inclination Sun-synchronous ~4 AM LMST ascending node	330 x 10,530 km elliptical 86.9 deg inclination Non sun-synchronous	255 x 320 km 93 deg inclination Sun-synchronous ~3 PM LMST ascending node
Deep Space Link:			
Band	X-band	X-band	X-band
Power Amplifier	15 W SSPA	65 W TWTA	100 W TWTA
High Gain Antenna	1.3 m HGA	1.65 m HGA	3 m HGA
Proximity Link:			
Transceiver	CE-505 UHF Transceiver	Melacom UHF Transceiver	Electra UHF Transceiver
Protocol	CCSDS Proximity-1	CCSDS Proximity-1	CCSDS Proximity-1
Antenna	Quadrifilar Helix	Patch Antennas (2)	Quadrifilar Helix
Forward Link			
- *Frequency*	437.1 MHz	437.1 MHz	435-450 MHz
- *Data Rate*	8, 32 kbps	8 kbps	8, 32, 128 kbps
- *Coding*	Uncoded	Uncoded	(7,1/2) Convolutional
Return Link			
- *Frequency*	401.585625 MHz	401.585625 MHz	390-405 MHz
- *Data Rate*	8, 32, 128, 256 kbps	2, 4., …, 128 kbps	1, 2, 4, …, 2048 kbps
- *Coding*	(7,1/2) Convolutional	(7,1/2) Convolutional	(7,1/2) Convolutional
- *Other*	1 bit-per-sample open loop recording	1 bit-per-sample open loop recording	8-bit I/8-bit Q open loop recording Suppressed Carrier Modulation Adaptive Data Rates

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frequency of a carrier signal.

Mars Express

In contrast to ODY's low, near-circular orbit, MEX operates in a highly elliptical orbit, inclined at 86.9 deg, and with an apoapsis altitude of 10,530 km and a periapsis altitude of 330 km. Both the orbit plane and the line of apsides precess, leading to much more variable relay contacts, with significant variation in the local time of relay opportunities as well as the slant range and resulting data rates that can be achieved on any given contact. MEX relay services are provided by the Melacom UHF transceiver, built by QinetiQ. Like ODY's CE-505, it operates at the same fixed forward and return link frequencies. Melacom supports return link data rates of 2, 4, 8, 16, 32, 64, and 128 kbps. Like ODY, MEX can also acquire an open-loop recording of a received UHF signal, with 1-bit-per-sample resolution at a 40 kHz sampling rate.

Mars Reconnaissance Orbiter

MRO, like ODY, operates in a low-altitude, sun-synchronous orbit; it's ascending node is oriented at ~3 PM LMST. MRO incorporates the newer Electra UHF Transceiver (EUT) for providing its relay services [6]. It supports the CCSDS Proximity-1 protocol and, like ODY's CE-505 transceiver, also supports an unreliable raw data mode that bypasses the Prox-1 protocol. Electra is a software-defined radio, in which effectively all of the radio's functionality is implemented in flight-reprogrammable software and firmware [7]. Electra features a number of new capabilities, relative to prior proximity link radios:

- *Higher Data Rates*: Electra can operate at data rates in all powers of 2 from 1 kbps up to 2,048 kbps.

- *Frequency-Agility*: Instead of operating at a fixed forward and return link frequency, Electra can operate its forward link anywhere within the 435-450 MHz sub-band, and the return link anywhere within the 390-405 MHz sub-band.

- *Suppressed-Carrier Modulation*: In addition to the conventional residual-carrier, bi-phase modulation implemented by the CE-505 and Melacom, Electra also supports fully suppressed carrier modulation, making all the transmitted power available for the data channel.

- *Adaptive Data Rates*: All prior Mars relay operations have utilized fixed data rates, requiring *a priori* analysis to select the best fixed rate that would maximize data return on any given relay pass, after accounting for the highly variable received signal level on the link over the duration of the relay contact due to time-varying slant range and antenna angles. By contrast, Electra supports an Adaptive Data Rate mode in which the transceiver monitors the signal-to-noise ratio of the return link symbol-tracking loop and uses these real-time observations of the actual channel performance to make decisions about when the data rate can be increased or needs to be decreased. The orbiter then sends directives on the forward link to the lander to execute those data rate changes, using standardized CCSDS Proximity-1 "COMM_CHANGE" directives, allowing the link to operate at the highest possible data rate at all times throughout the pass.

- *Full-Spectrum Recording:* Electra can acquire a high-fidelity recording of a received UHF signal, over a Nyquist-sampled bandwidth at rates up to 150 kHz. Unlike ODY's and MEX's 1-bit-per-sample recording capability, Electra acquires 8-bit-in-phase (I)/8-bit-quadature (Q) samples of the complex baseband signal, as well as 6-bit samples of the Automatic Gain Control value, enabling ground post-processing to reconstruct the observed spectrum and also to demodulate a high-rate telemetry signal.

Mars Relay Operations Service

Complementing these various Mars relay orbiters, the Mars Exploration Program has implemented a suite of web-based tools, known as the Mars Relay Operations Service (MaROS), to facilitate multimission relay operations [8]. MaROS provides standard interfaces for each lander and orbiter participating in Mars relay operations, and supports all aspects of relay planning and scheduling, as well as post-pass relay performance assessment and data accountability. Implemented after completion of the Phoenix Lander mission, and incorporating lessons learned in relay support to Phoenix as well as to the Spirit and Opportunity rovers, MaROS allows each mission – lander or orbiter - to establish a single standardized ground data system interface for all relay services, rather than having to implement separate bilateral interfaces with each individual relay partner, and provides full visibility of all relay planning and performance data to each mission throughout the lifecycle of every relay pass.

2. MARS SCIENCE LABORATORY MISSION OVERVIEW

The fundamental science objective of the MSL mission is to explore the habitability of Mars, determining whether the past or present Martian environment could have supported microbial life [9]. To carry this out, MSL delivered the highly capable Curiosity rover to Gale Crater. The rover, as depicted in Figure 1, carries a number of remote sensing imaging cameras and spectrometers, and is also equipped with the capability to acquire *in situ* samples and deliver

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Figure 1: Illustration of MSL's Curiosity Rover

them to a pair of analytical instruments within the rover. Table 2 lists the full MSL science instrument suite.

Many of these instruments are capable of generating large quantities of data, driving the need for high-bandwidth relay communications. For instance, the Mastcam is a high-resolution stereo camera mounted on the rover's mast, capable of acquiring multispectral images and even short High Definition videos. Mastcam can acquire panoramic color mosaics with data volumes of several hundred megabits. Other cameras include a Mars Hand Lens Imager (MAHLI) on the rover's robotic arm, for close-up, high-resolution imaging of selected targets, as well as multiple engineering navigation cameras (navcams) and hazard avoidance cameras (hazcams).

MSL's entry, descent, and landing (EDL) system involved a number of new technologies driven by the large rover mass (the largest spacecraft ever delivered to the Martian surface) and the greatly improved landing accuracy (allowing access to scientifically more compelling landing sites). These included a 4.5 m heat shield, a 19.7 m diameter disk-band-gap parachute, a guided entry trajectory during the

Table 2: MSL Science Instrument Suite

Cameras	• Mast Camera (Mastcam) • Mars Hand Lens Imager (MAHLI) • Mars Descent Imager (MARDI)
Spectrometers	• Alpha Particle X-Ray Spectrometer (APXS) • Chemistry & Camera (ChemCam)
Analytical Instruments	• Chemistry & Mineralogy X-Ray Diffraction/X-Ray Fluorescence Instrument (CheMin) • Sample Analysis at Mars (SAM) Instrument Suite
Radiation Detectors	• Radiation Assessment Detector (RAD) • Dynamic Albedo of Neutrons (DAN)
Environmental Sensors	• Rover Environmental Monitoring Station (REMS)
Atmospheric Sensors	• Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI)

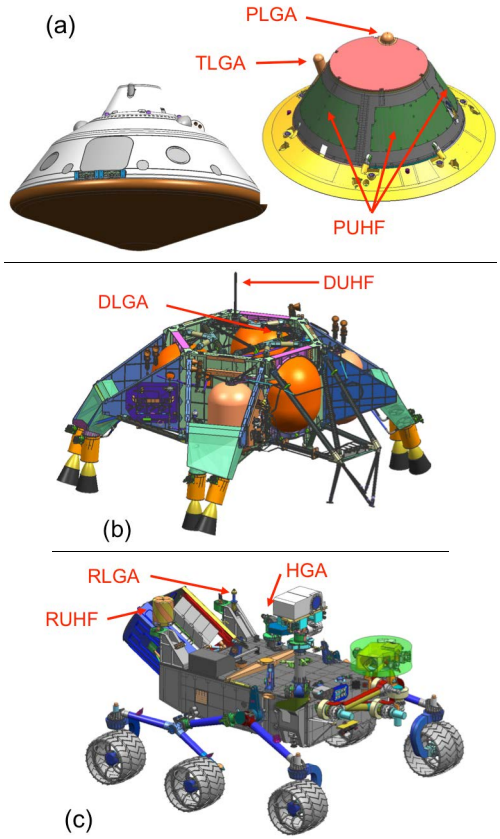

Figure 2: MSL telecommunications antenna configurations for a) entry, b) powered descent, and c) surface operations

hypersonic phase of EDL, and a powered-descent stage that used eight monopropellant hydrazine rocket thrusters to decelerate and then acted as a "skycrane" by hovering while it lowered Curiosity gently to the surface on a 7.6 m tether. Details of the MSL EDL system are described in [10].

MSL employs a combination of X-band direct-to-Earth links and UHF relay links to accomplish its mission goals [11]. X-band communication is accomplished with a Small Deep Space Transponder, paired with a 100 W Traveling Wave Tube Amplifier on the descent stage for use during cruise and EDL, and a 15 W Solid State Power Amplifier on the rover for surface operations. UHF communication uses the Electra-Lite UHF Transceiver (ELT), a reduced mass/volume version of the Electra UHF Transceiver on MRO.

Figure 2 illustrates the various X-band and UHF antennas used during EDL and on the surface. The entry vehicle had two X-band low-gain antennas (LGAs) on the aeroshell: a Parachute LGA (PLGA) pointed parallel to the symmetry axis of the spacecraft, and a Tilted LGA (TLGA) that was canted to point along the anti-velocity vector during the guided entry phase when the spacecraft was flying with a non-zero angle of attack. The entry vehicle also had a wrap-around UHF antenna on the parachute cone called the Parachute UHF (PUHF) antenna. Once the rover and the attached powered descent stage dropped out of the aeroshell,

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X-band transmission was via a Descent LGA (DLGA) on the descent stage, while UHF transmission utilized a Descent UHF antenna (DUHF). UHF transmission switched to the Rover UHF (RUHF) antenna during the skycrane phase and after touchdown. For subsequent surface operations, Curiosity's X-band communications can use a Rover LGA (RLGA) or a gimbaled High Gain Antenna (HGA) based on a planar 48-element microstrip patch array with 25.5 dBi peak gain at 8.4 GHz transmit frequency.

3. Critical Event Communications Support for Entry, Descent, and Landing

MSL was launched from Cape Canaveral, FL, on Nov 26, 2011. After an Earth-Mars cruise of just over 8 months, the spacecraft arrived at Mars on Aug 6, 2012. Ten minutes prior to arrival at the atmospheric entry interface, the MSL entry vehicle separated from the cruise stage. Major elements of the entry vehicle include the 900-kg Curiosity rover, a powered descent stage, a heat shield and an aeroshell.

Due to the large number of new technologies and first-of-a-kind activities during EDL, the Mars Exploration Program placed an extremely high priority on capturing tracking and telemetry information from MSL during this critical mission phase. A combination of X-band direct-to-Earth communications and UHF relay communications to all three Mars orbiters was employed to maximize the information acquired and provide redundant communication paths.

On the X-band DTE link, MSL transmitted very low-rate information via its low-gain antenna. These data were received by the 70m Canberra Deep Space Network antenna. The transmission used a multiple frequency shift keying (MFSK) modulation scheme, sometimes referred to as "semaphores", transmitting a carrier along with one of 256 subcarrier frequencies, thereby conveying 8 bits of information during each symbol, with a typical symbol period of 10 s. The resulting signal thus provided roughly a 1 bps effective information rate, while also providing additional diagnostic data based on the amplitude and frequency of the carrier. Unfortunately the X-band signal path was only available until approximately 2 minutes prior to landing, when Mars occulted the signal path (i.e., Earth set below the Mars horizon as viewed from the entry vehicle.)

All three relay orbiters were phased in their orbits to optimize their visibility of the EDL trajectory and allow receipt of MSL's UHF signal. The relay strategy for MSL

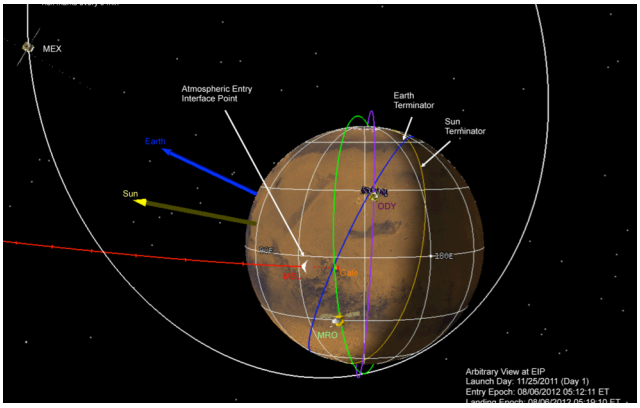

Figure 3: MSL EDL geometry

EDL had strong heritage to the successful EDL communications conducted for the Phoenix Lander mission in 2008 [12]. Figure 3 illustrates the MSL arrival geometry at Mars, along with the orbits and positions of ODY, MRO, and MEX. Each orbiter was configured to leverage the unique capabilities of its relay payload. Throughout EDL, MSL transmitted telemetry at a data rate of 8 kbps. ODY employed its "bent-pipe mode", in which its UHF transceiver was configured to receive and demodulate MSL's telemetry signal, and then immediately downlink that data to Earth on ODY's X-band link, This provided "real-time" visibility of MSL's engineering telemetry (aside from the Earth-Mars signal propagation time of nearly 14 min). Due to the high Doppler shift and low signal strength of the MSL signal received by ODY early in EDL, the ODY link was not expected to acquire until roughly 2 min after atmospheric entry. Geometric visibility on the MSL-ODY link continued until roughly 7 min after landing.

In contrast to ODY, MRO was configured to acquire an open-loop recording of the MSL signal throughout EDL until the end of geometric visibility, roughly 6 min after landing. This product was then downlinked to Earth after EDL was complete, where ground post-processing reconstructed the spectrum of the received MSL UHF signal and subsequently demodulated the signal to recover the MSL telemetry stream.

Finally, MEX was configured to acquire an independent open-loop recording of the MSL UHF. As noted earlier, MEX's Melacom UHF Transceiver open-loop recording function only acquired 1 bit per sample. This supported recovery of the spectrum of the sampled signal, including the time history of the carrier frequency and amplitude, but did not allow full demodulation of the MSL telemetry stream. MEX was in view of MSL throughout most of EDL, but set below the horizon roughly 1 min prior to landing.

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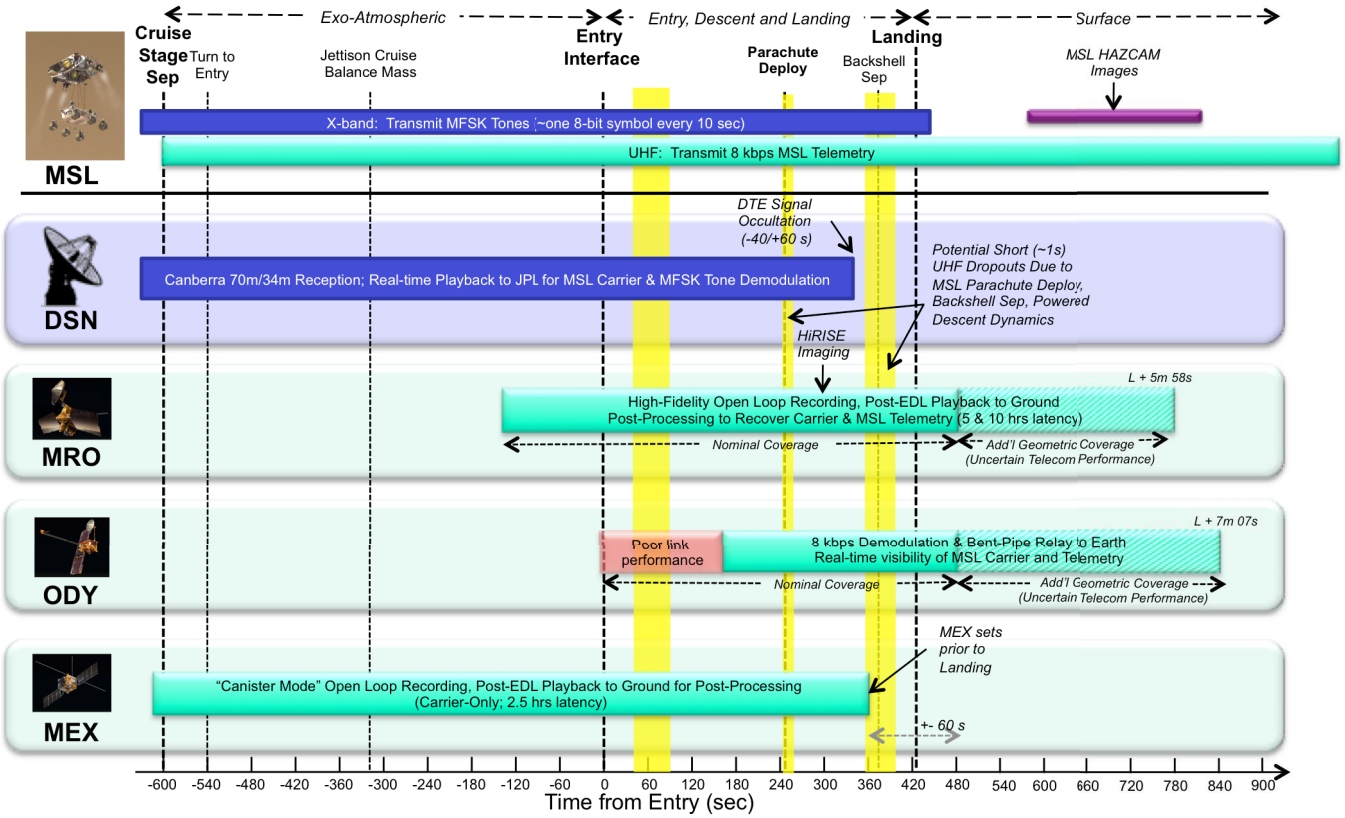

Figure 4: Overview of EDL telecommunications coverage via Direct-to-Earth and Relay paths

Figure 4 summarizes the overall EDL communication strategy and timeline of key events. Actual performance of the various links was excellent. X-band DTE "semaphore" tones provided visibility into the hypersonic phase of EDL, during a period when plasma build-up around the entry vehicle caused a blackout, as predicted, of the longer wavelength UHF links. ODY returned 5.5 Mb of MSL telemetry via its bent-pipe path during EDL, providing real-time visibility into the progress of MSL EDL. MRO's open loop recording was successfully acquired, and the resulting large 7.3 Gb data product was downlinked to Earth, with post-processing to recover the MSL signal spectrum completed ~5 hrs after landing, and full demodulation of the MSL telemetry completed ~12 hrs after landing, consistent with plans. The smaller MEX 1-bit-per-sample open-loop recording was downlinked and processed on the ground, with the reconstructed MSL signal spectrum available roughly 2½ hrs after landing. A more detailed discussion of the EDL communications strategy and performance can be found in references [13] and [14].

4. Surface Relay Support

Less than two hours after landing, ODY once again passed over the Gale Crater landing site after completing an orbit of Mars, shortly before 5 PM LMST. For this pass, ODY was configured to hail Curiosity and establish a full-duplex, reliable Prox-1 link at data rates of 8 kbps on both the forward and return links. The low return link data rate ensured large telecommunication link margin and would have provided optimal data return if the rover had been in safe mode. Over 5 Mb of data were returned during this first surface pass, providing confirmation of Curiosity's safe landing and nominal rover status, as well as initial low-resolution images of the landing site.

During Curiosity's first Martian night, at roughly 3-4 AM LMST on Sol 1, MRO and ODY each provided contact opportunities, with return link rates of 32 kbps. (Note that by MSL convention, the landing sol itself is designated Sol 0.) These two passes provided an additional 42 Mb of data on rover status prior to Curiosity's first sunrise.

Beginning later on Sol 1, Curiosity began the standard cadence of communications that supports the mission's nominal surface operations concept. At ~10 AM LMST each sol, an X-band uplink session supports prompt delivery of commands to the rover via NASA's Deep Space Network. These commands provide Curiosity with the sequence of activities to carry out during that sol, with the bulk of activities conducted mid-day based on illumination and thermal considerations. Then, during the mid- to late-afternoon, Curiosity will typically have one or more relay contact opportunities, with MRO at ~3 PM LMST, and ODY at ~4 PM LMST. These relay passes provide time-critical information on the status of the rover at the end of its working day, information which is used during the

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Martian night by the rover engineering and science teams to plan the next sol's activities. Additional relay pass opportunities during the Martian night, at ~3 AM LMST for MRO and ~4 AM LMST for ODY, provide windows for returning additional non-time-critical data from Curiosity. This completes the daily operations cycle, which begins again after sunrise with the next sol's X-band uplink session.

The MSL project established requirements on relay link performance consistent with Curiosity's surface operations and the anticipated orbiter capabilities. In particular, MSL designed its mission to return an average of 75 Mb/sol via ODY and 250 Mb/sol via MRO, reflecting the higher performance potential of the MRO Electra UHF Transceiver. Both of these data volumes assume that MSL selects the best AM and best PM pass for each orbiter, and assume a local 10 deg elevation mask at the rover site.

Based on ongoing support by ODY to the Opportunity rover, there was relatively high confidence in meeting the MSL-ODY data volume requirement. However, there was greater uncertainty in meeting the higher MSL-MRO data volume, as achieving this higher level required successful use of a variety of new capabilities on the MSL-MRO link, enabled by their Electra-Lite and Electra UHF transceivers.

A particular concern was related to the known Electromagnetic Interference (EMI) generated by several of the MRO science instruments in the UHF return link band, which can degrade UHF link performance. Based on the frequency-agility of the Electra and Electra-Lite transceivers, it was planned to operate the MSL-MRO return link at 391 MHz to mitigate the effects of a large spurious tone generated by MRO's CRISM instrument at 400 MHz. (All prior MRO relay support has used a return link frequency of 401.585625 MHz, the fixed frequency of the CE-505 UHF radios on MER and Phoenix.) In-flight tests in 2011 and early 2012 indicated that the MRO EMI might degrade MSL-MRO link performance to a level that would threaten meeting the 250 Mb/sol requirement, but significant uncertainty remained due to the inherent limitations of those tests.

To account for this uncertainty, an MSL Relay Link Characterization Plan (MRLCP) was established to provide a strategy for introducing and evaluating the new capabilities on the MSL-MRO link while at the same time quantitatively assessing the impact of EMI as a function of MRO spacecraft instrument configuration. The MRLCP included four phases, intended to balance the need to introduce new capabilities and characterize the EMI impacts of each MRO instrument against the need to minimize the risk to the PM relay passes, which provide the time-critical data needed for planning the subsequent sol's activity, while completing the plan expeditiously in order to return MRO to full science operations:

- Phase 1: During the initial relay passes, both the ODY and MRO links were operated conservatively, at only up to 32 kbps return link data rate, providing substantial link margin to maximize the probability of successful data transfer. During this phase MRO operated at the same frequency channel (401.585625 MHz) and modulation (residual carrier) that had been successfully demonstrated previously in relay support to Opportunity. All instruments except HiRISE were powered off during this phase in order to establish a low-EMI performance baseline. (Pre-launch and in-flight tests have not shown any measurable EMI issues with HiRISE.)

- Phase 2: After a minimum of two successful passes in Phase 1, MSL progressed to the use of data rates up to 256 kbps, again using operational configurations that had been previously demonstrated by MRO during Opportunity passes. All MRO instruments except HiRISE remained powered off in this phase.

- Phase 3: After a minimum of two successful passes in Phase 2, MSL entered Phase 3, in which new capabilities on the MRO link were introduced. Passes were configured for the first time on the 391 MHz frequency channel supported by Electra and Electra-Lite, with suppressed-carrier modulation

Table 3: Curiosity data return metrics through Sol 90

	ODY	MRO	Total
Total # Passes	187	152	339
Total Data Return (Gb)	14.1	31.7	45.8
Average # Passes/sol:	2.08	1.69	3.77
Average Return Data Vol/Sol (Mb)	156.61	352.67	509.28
Average Return Data Vol/Pass (Mb)	75.37	208.82	135.21

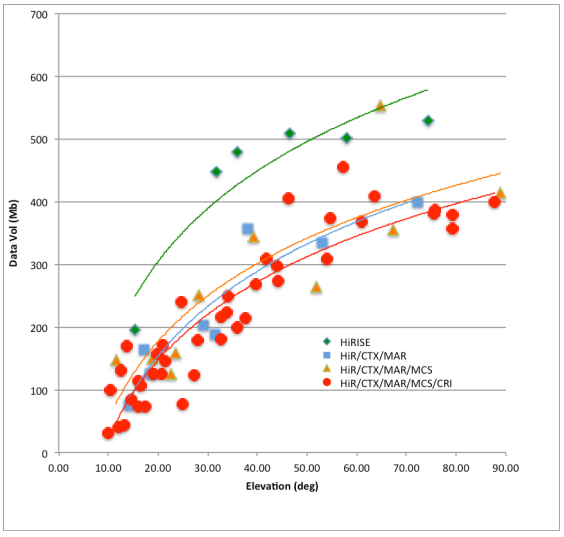

Figure 5: Data volume per pass vs. elevation angle, as a function of which MRO science instruments are powered on (HiRISE, CTX, MARCI, MCS, and CRISM).

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and data rates up to 2048 kbps. These new capabilities were always exercised for the first time on AM relay passes, to minimize risk to the time-critical PM relay passes needed for next-sol rover planning. Individual data rates were selected based on *a priori* link analysis, and all data rates between 32 kbps and 2048 kbps (in powers of 2) were characterized. At the end of this phase, the Adaptive Data Rate capability was exercised for the first time on the MSL-MRO link, with ADR configured to initially establish the link at 32 kbps and then use the measured return link signal-to-noise ratio to direct lander data rate changes throughout the pass, in order to maximize data return. All MRO instruments except HiRISE remained powered off during this phase.

- Finally, in Phase 4, the various MRO science instruments were powered on sequentially. The phase began with powering on of MRO's CTX and MARCI instruments, which were not believed to be the largest EMI emitters, followed by MCS and, finally, CRISM. In each configuration, data were acquired over a full 5-day cycle during which the geometry of the MRO overflights varied over a full range of maximum elevation angles.

In practice, Phase 1 and Phase 2 each lasted only a single sol, as observed pass performance appeared nominal. Phase 3 lasted from Sol 3 through Sol 26, during which time fixed data rates as high as 2048 were successfully demonstrated. The first use of Electra's ADR capability occurred on Sol 18, with a single pass with a relatively modest maximum elevation angle of 36 deg returning 479 Mb of data, by far the largest single-pass data volume ever achieved at Mars to that point in time. Since then, data returns of over 550 Mb have been achieved on individual ADR passes. As a note, the conservative approach of only introducing new capability on the AM MSL-MRO passes ensured that all of the PM passes successfully delivered data to support time-critical planning activities.

During Phase 4, which was carried out from Sol 27 through Sol 62, some reduction in per-pass data volume was observed after powering on CTX and MARCI, with only minor additional degradation after powering on MCS and CRISM. Figure 5 illustrates the observed performance of the link as a function of the various MRO instrument

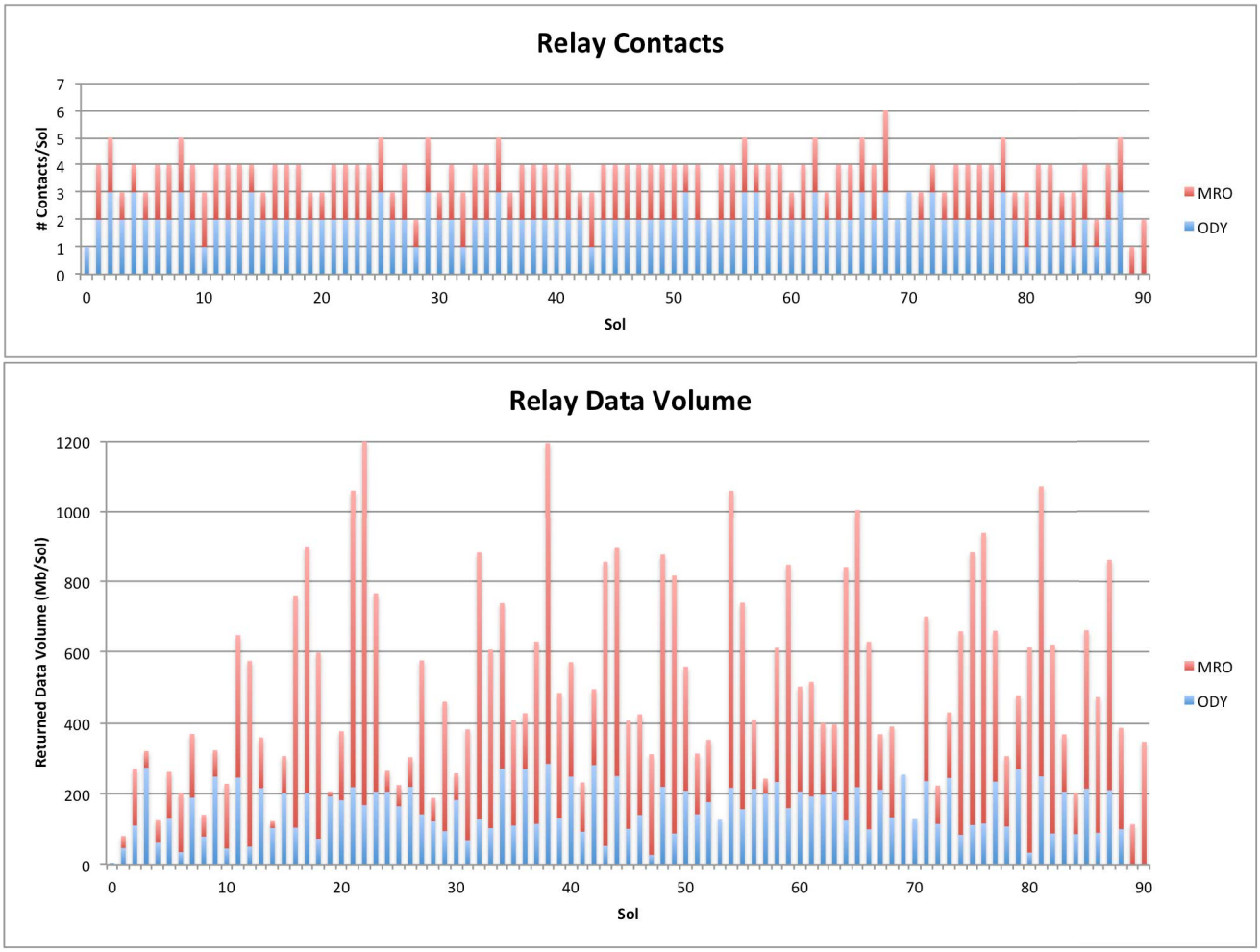

Figure 6: Per-sol metrics for number of Curiosity relay contacts and returned data volume, for MRO and ODY

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Table 4: MSL-MEX demonstration passes conducted during the first 90 sols

Sol	Pass ID	Pass Configuration	Result
13	MEX_MSL_2012_232_02	8k forward link/8k return link	Successful • 7 Mb returned
24	MEX_MSL_2012_244_01	8k forward link/128k return link (Includes MSL command product)	Successful • 55 Mb returned • MSL command product delivered
30	MEX_MSL_2012_250_01	8k forward link/128k return link	Successful • 110 Mb returned
59	MEX_MSL_2012_280_01	8k forward link/128k return link	Successful • 105 Mb returned

configurations. (Note that during this period, the final MRO science instrument, SHARAD, remained powered off, as a result of a re-location of the SHARAD science center in Italy. Based on all testing to date, SHARAD is not expected to contribute any appreciable level of EMI.)

Table 3 summarizes the relay performance metrics through Sol 90. A total of 339 passes had been completed by that date, with over 45 Gb of aggregate data return. An average of 509 Mb per sol of data were returned during this period, with 157 Mb/sol via ODY and 353 Mb/sol via MRO. If we limit the statistics to passes for which all of the MRO instruments (except SHARAD) were powered on and ADR was being used routinely, the data return via MRO averaged 386 Mb/sol. Figure 6 illustrates the per-sol data return metrics for passes via MRO and ODY. One can clearly observe the strong 5-sol modulation in MRO performance due to variations in the overflight geometries. Based on the successful relay performance, well in excess of Curiosity's average per-sol data return requirements, the decision was made on Sol 65 to continue operations in this MRO mode with all science instruments powered on.

To provide additional robustness in the Curiosity surface relay plan, MEX was prepared to provide backup relay support in the event that ODY and/or MRO became unavailable for some period of time. Prior to landing, JPL and QinetiQ conducted ground tests to verify the interoperability of MSL's Electra-Lite and MEX's Melacom UHF transceivers. During the first 90 sols, four demonstration relay passes were performed with Curiosity and MEX to confirm this capability, as summarized in Table 4. These passes confirmed return link performance at rates up to 128 kbps, as well as the capability to deliver MSL command products on the MEX forward link.

5. Preliminary Lessons Learned

Although we are relatively early in the MSL surface mission, there are already a number of preliminary lessons learned, both in terms of things that have worked well and areas where improvements can be made for the future. These build upon, and in some cases reinforce, previous experiences in relay support to the Mars Exploration Rovers and the Phoenix Lander missions [15,16].

Software Defined Radios: The MSL-MRO link is providing unprecedented levels of data return from the Martian surface, based on the advanced functionality of the Electra and Electra-Lite radios on the two spacecraft. These software-defined radios are able to implement more capable and more flexible signal processing algorithms, including support for higher data rates, multiple modulation types, frequency-agility, and adaptive data rates. The fact that the ADR algorithm was delivered to MRO post-launch is a graphic illustration of the benefits of a software-defined radio architecture, which is particularly well-suited to a long-lived relay infrastructure orbiter, enabling evolution of capability and infusion of new software/firmware algorithms over the life of the mission. Having said this, we also observe that the increased Electra capability comes at the cost of increased complexity and increased number of operational parameters and configurations, which can impact testing schedule and cost. As we gain experience with the new Electra operational modes, it will be important to establish a core set of recommended operational configurations, hiding configuration details from the user where possible.

Operational Readiness Testing: Thorough operational readiness tests (ORTs) were crucial in exercising the full range of multimission processes involved in successful relay operations. These ORTs, which included participation by the MSL, ODY, and MRO project teams, were effective in uncovering a number of design anomalies and process issues, allowing them to be resolved prior to MSL arrival at Mars. All future missions incorporating relay operations should plan a full set of ORTs, including nominal and off-nominal operational scenarios, executed as early in the project life cycle as practical.

MaROS: The Mars Relay Operations Service (MaROS) system proved to be very effective in providing a central database of *a priori* planning and *a posteriori* performance information for all the orbiters and landers engaged in relay operations. However, early ORTs revealed that the lander

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mission personnel - MSL in this case - required more thorough training to fully master the MaROS user interface. A contributing factor here was the large amount of new MaROS functionality that was implemented and used for the first time for MSL relay support. To address this, specific MaROS training was implemented after the ORTs, prior to MSL arrival at Mars, and will be a standard part of future lander mission preparations. In addition, the next delivery of MaROS will introduce new features aimed at improved operability, and the MaROS customer working group will be surveyed for longer-term potential updates that could further simplify operations.

End-to-End Information System: Compatibility of the orbiter and lander relay transceivers is a necessary but not sufficient condition for end-to-end relay data flow. In particular, on MSL there were several idiosyncrasies in the interface between the MSL flight computer and the Electra-Lite UHF Transceiver that resulted in constraints on allowable command data product size and development of a complex buffer management system to avoid truncating downlink frames. While operational workarounds were ultimately identified, these idiosyncrasies resulted in more complex ground processes and delayed other critical relay tests. Future missions should ensure early and thorough documentation and validation of the end-to-end relay data path.

Verification & Validation (V&V) Test Schedule: Several relay issues were discovered relatively late in the MSL lifecycle, including during the cruise phase of the mission. While these were addressed prior to arrival at Mars, and actual surface operations have proceeded smoothly, it would have been desirable to identify these issues earlier. The challenge here, which is common to the previous experiences with MER and PHX, is that the testing timeline is dictated by the lander mission's V&V test program and testbed accessibility. The Mars Exploration Program may need to establish more formal guidelines for the scope and schedule of testing related to verification and validation of relay services, and ensure that all missions develop their test schedules and corresponding resource profiles to meet those guidelines.

End-to-End Relay Testbeds: The fidelity of the end-to-end testbeds for relay system testing can play a significant role in the overall success of the V&V test campaign. For the MSL-MRO link, both the orbiter and lander projects had high fidelity spacecraft testbeds resident at JPL, with Engineering Models of the Electra and Electra-Lite transceivers, and with flight-like representations of the spacecraft Command & Data Handling (C&DH) subsystem. While these testbeds were located at separate sites within the JPL campus, fiber optic links supported signal flow between them, as well as integration of a high-fidelity link channel simulator capable of emulating realistic time variation of link amplitude, frequency, and delay, enabling thorough end-to-end data flow testing over a range of flight-like signal conditions. For ODY and MEX, however, each orbiter project had only a portable test set available at JPL to support cross-project testing with MSL, each with a flight-like UHF transceiver but with lower fidelity representations of the orbiter C&DH. This limited the scope of ground testing possible on the MSL-ODY and MSL-MEX links. This, combined with some non-flight-like aspects of the ODY test set that were discovered late in the V&V test campaign, resulted in the deferral of full validation and use of the MSL-ODY forward link capability until well after landing. The conclusions here are that high-fidelity testbeds increase the robustness of end-to-end relay testing; when programmatic considerations limit the test hardware fidelity, it is essential to clearly document and assess any non-flight-like aspects of the testbed infrastructure.

Electromagnetic Interference: Uncertainty in the MRO EMI environment resulted in significant concern prior to MSL arrival as to whether Curiosity would be able to achieve the desired 250 Mb/sol data return via the MRO relay path. This resulted in a large amount of MRO flight and ground testing to attempt to better quantify the EMI impacts as a function of Electra return link frequency. It also drove the need for a lengthy commissioning phase during the first few months of MSL surface operations, to carefully monitor performance as each MRO science instrument was powered on. Electra's frequency-agility turned out to be an important tool in mitigating the EMI impacts. In hindsight, earlier and more thorough flight testing could have provided more confidence in the predicted MRO relay performance; however, such testing would have required interruption of ongoing MRO science observations. Ultimately, future missions will want to address EMI issues earlier in the spacecraft/instrument development cycle to identify and mitigate any spurious emissions prior to launch.

6. CONCLUSIONS

NASA's ODY and MRO orbiters and ESA's MEX orbiter embody an international network of Mars relay orbiters, providing essential telecommunication services to the Mars Science Laboratory mission. All three orbiters provided complementary coverage of MSL's EDL, acquiring tracking and telemetry data from MSL's UHF transmission that could have provided essential information for fault reconstruction had a mission-ending anomaly occurred during EDL. Since landing, ODY and MRO are providing the highest levels of data return yet achieved for a Mars lander, with over 45 Gb of Curiosity data returned over the first 90 sols of the surface mission. Key to this level of performance are a number of new capabilities in the Electra and Electra-Lite UHF Transceivers on MRO and MSL, respectively, including higher data rates, frequency-agile operations, and adaptive data rates, as well as the dedication of the operations teams on each mission and the MaROS multimission relay operations tools and processes supporting them.

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BIOGRAPHIES

Charles (Chad) Edwards, Jr. *is the Chief Telecommunications Engineer for the Mars Exploration Program and acting Chief Technologist for the Mars Exploration Directorate at the Jet Propulsion Laboratory. Prior to this current assignment he managed the research and development program for NASA's Deep Space Network. He received an A.B. in Physics from Princeton University and a Ph. D. in Physics from the California Institute of Technology.*

David J. Bell *is the supervisor of the Communications Systems & Operations group, 337H at the Jet Propulsion laboratory and has over 30 years experience in all aspects of flight and ground radio system design including modulation, coding, antennas, propagation and interference mitigation. Mr. Bell has published numerous telecom technical papers and holds several patents related to antennas and coding systems for telecom operations in difficult propagation and signal environments. In addition, Mr. Bell was the system engineer for all aspects of the development, flight build and test of the Electra Software defined radio subsystem that is now flying on the MRO spacecraft.*

Roy Gladden *is the Multimission Relay Operations Lead for the Mars Program Office and the Multimission Ground Systems and Services organization at the Jet Propulsion Laboratory. Prior to this current assignment, he led the Mission Planning and Sequencing Team for the Mars Reconnaissance Orbiter Project. He received both a B.S. and M.S. in Mechanical Engineering from Utah State University.*

Peter Ilott *is the Telecom Lead for Mars Science Laboratory at JPL. Peter previously worked on Phoenix, and was the UHF relay engineer for the MER mission. Other JPL projects include Odyssey, MRO, Deep Impact, and Cloud Sat. Prior to JPL he worked for 12 years on commercial spacecraft. Peter received his BSc in physics, and PhD in Elec. Eng. at McGill University, and his MSc in Plasmas Physics at the*

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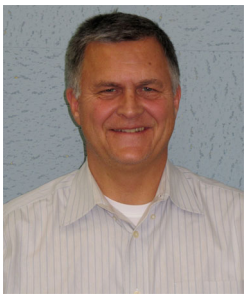
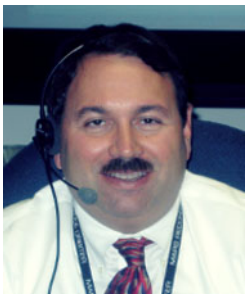


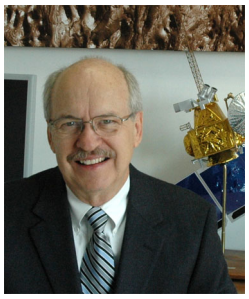
Thomas Jedrey *received his BS in Mathematics from the University of Maryland, College Park Maryland, in 1979, his MA in Probability and Statistics from the University of Maryland in 1982, and his MS in Electrical Engineering from the University of Southern California in 1990. He is the author of over thirty papers in the communications field. He has also served as a special editor for the International Journal of Satellite Communications. Mr. Jedrey has been at the Jet Propulsion Laboratory since 1986. He has worked on and managed multiple NASA, DOD, and private industry based projects. He is the technical lead for the various Electra Software Defined Radio developments and was the manager of the JPL Wireless Communications Group. The UHF Relay communications payload for the Mars Reconnaissance Orbiter was developed under his cognizance and he is currently managing the Flight Communications Systems Section at JPL, the section responsible for flight communications on the majority of JPL missions.*



Dan Johnston *received a B.S. in Aerospace Engineering from the University of Texas in 1984 and an MSE from the University of Texas in 1989. Since joining JPL in 1989, he has participated in the development and flight operations phases of the Mars Observer and Mars Global Surveyor missions. Prior to joining JPL, he was employed with McDonnell Douglas Astronautics in Houston, TX, in support of STS (Shuttle) rendezvous flight planning. Currently, Mr. Johnston is the Deputy Project Manager (and as additional duty the Mission Manager) of the Mars Reconnaissance Orbiter Project.*

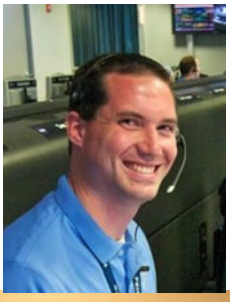
Jennifer Maxwell *is the Lead Relay V&V Engineer on the Mars Science Laboratory Project at the Jet Propulsion Laboratory. Prior to this current assignment, she worked on End-to-End Information System and Mission System testing on MSL. Other missions include the Cassini-Huygens Mission to Saturn and Titan. She received her B.S. in Aeronautics and Astronautics from Massachusetts Institute of Technology and two M.S. degrees in Aerospace and Systems Engineering from University of Southern California.*

Ricardo Mendoza *has over 10 years of flight operations experience including Cassini, the Mars Exploration Rovers, the Mars Reconnaissance Orbiter and the Mars Science Laboratory. He earned his bachelor's degree in electrical engineering from Cal Poly Pomona in 2001 and his MSEE with an emphasis in microwave communications in 2004.*



Gaylon McSmith *is currently the 2001 Mars Odyssey Project Manager. McSmith has worked at JPL since 1985. During that period he has additionally worked on projects such as Galileo, Deep Space One and Outer Planets – Solar Probe. Areas of expertise include Developmental System Engineering, Assembly Test and Launch Operations, Payload Integration & Flight Operations and Project Management. .*

Christopher L. Potts *is the Mission Manager for the Mars 2001 Odyssey Project at the Jet Propulsion Laboratory. He has 28 years of experience at JPL including Deputy Navigation Team Chief for the Mars Exploration Rovers Project and a technical group supervisor. He received a B.S. in Aero/Astro Engineering from the University of Illinois and a M.S. in Aerospace Engineering from the University of Southern California..*



Brian Schratz *is the lead engineer for the EDL telecommunications on the Mars Science Laboratory mission and a member of JPL's Communications Systems and Operations group. He joined JPL three years ago with a B.S.E.E. and M.S.E.E. from The Pennsylvania State University.*

Mazen Shihabi *is the operation lead for MRO UHF radio. Prior JPL assignments included modem design and modulation algorithm development. Prior to JPL, he worked for 10 years in aerospace, cellular telecommunications, and remote patient monitoring . Dr.*

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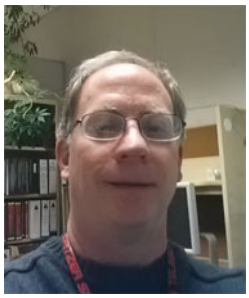
Shihabi is a senior member of IEEE and has published several technical papers and holds several patents related to synchronization algorithms, interference mitigation and physiological alarm notification systems. He received a BS and MS from University of Southern California, and PhD from University of California at Irvine, all in Electrical engineering.

Jeff Srinivasan *is currently the Deputy Manager for the Communications, Tracking and Radar Division at NASA's Jet Propulsion Laboratory, where he has worked for 29 years. He previously managed of Flight Communications Systems Section (337) and was the Supervisor of the Advanced Radio Metric Instrument Development Group. In addition, he has provided leadership and key contributions to some of JPL's most challenging flight implementations. He was one of the early key developers of the BlackJack family of flight GPS receivers for precision tracking and science that flew on the successful GRACE and COSMIC spacecraft launched the early/mid 2000's. More recently he has had key roles on MSL's CheMin X-ray Source and Landing Radar development teams and co-led the final push to prepare relay communications for MSL's arrival at Mars. He has authored or co-authored more than 30 publications and holds a Bachelors degree from Harvard College and a Masters degree from USC..*

Phil Varghese *currently manages NASA's Mars Reconnaissance Orbiter (MRO) Mission. MRO provides UHF data relay support to MSL and MER. Previously he was Project Manager for NASA's 2001 Mars Odyssey (ODY) Mission, ODY also has been providing UHF data relay support to both MSL and MER.*



Steve Sanders *Stephen S. Sanders is the Odyssey spacecraft team lead at Lockheed Martin Space Systems Company. He has worked on Odyssey since 2005 and its relay support of the Mars Exploration Rovers, Phoenix, and now the Mars Science Laboratory. His previous Mission Operations experience was on Magellan, the Venus Radar Mapper. He holds a B.S. in Computer Science and Applied Mathematics from Colorado State University and an MCIS with Software Engineering emphasis from University College at the University of Denver.*

Michel Denis *is the Spacecraft Operations Manager for Mars Express and has covered all phases of this ESA science mission from preparation through routine operation in orbit, including relay support to the NASA landers on Mars. He joined the European Space Agency as a flight control team engineer for Meteosat, and then worked on Cluster, Huygens and XMM-Newton. Before joining ESA he was employed in the aerospace industry in France, where he developed embedded software systems. He graduated as an engineer in the Ecole Centrale de Paris, and later obtained a master's degree in Space Engineering.*

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