Relay Support for the Mars Science Laboratory and the Coming Decade of Mars Relay Network Evolution

Charles D. Edwards, Jr, Bradford W. Arnold, David J. Bell,
Kristoffer N. Bruvold, Roy E. Gladden, Peter A. Ilott, Charles H. Lee
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-4408
chad.edwards@jpl.nasa.gov

Abstract—**In the past decade, an evolving network of Mars relay orbiters has provided telecommunication relay services to the Mars Exploration Rovers, Spirit and Opportunity, and to the Mars Phoenix Lander, enabling high-bandwidth, energy-efficient data transfer and greatly increasing the volume of science data that can be returned from the Martian surface, compared to conventional direct-to-Earth links. The current relay network, consisting of NASA's Odyssey and Mars Reconnaissance Orbiter and augmented by ESA's Mars Express Orbiter, stands ready to support the Mars Science Laboratory, scheduled to arrive at Mars on Aug 6, 2012, with new capabilities enabled by the Electra and Electra-Lite transceivers carried by MRO and MSL, respectively. The MAVEN orbiter, planned for launch in 2013, and the ExoMars/Trace Gas Orbiter, planned for launch in 2016, will replenish the on-orbit relay network as the current orbiter approach their end of life. Currently planned support scenarios for this future relay network include an ESA EDL Demonstrator Module deployed by the 2016 ExoMars/TGO orbiter, and the 2018 NASA/ESA Joint Rover, representing the first step in a multimission Mars Sample Return campaign.**

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1. INTRODUCTION

Over the past decade, an international network of Mars relay orbiters has established in situ telecommunications capabilities that have enabled greatly enhanced data return from the Martian surface [1,2], including the 2003 Mars Exploration Rovers [3] and the 2007 Phoenix Lander [4]. A standardized telecommunications protocol, the CCSDS Proximity-1 Space Link Protocol [5], establishes a framework for interoperability and inter-agency cross-support for this evolving relay network.

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Currently the Mars 2001 Odyssey, Mars Express, and Mars Reconnaissance Orbiter spacecraft are in place to support the 2011 Mars Science Laboratory, providing critical event telemetry capture during the first use of the new MSL skycrane landing system and offering significant growth in data return for MSL surface operations prior to previous Mars landers.

Over the coming decade, this orbital relay infrastructure will continue to evolve. In 2013 NASA plans the launch of the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft in 2013. A competitively selected Scout mission with focused science objectives, MAVEN will also carry an Electra relay payload provided by the Mars Exploration Program, augmenting the relay network at a time when the prior orbiters are well into their extended mission lifetimes. While the MAVEN spacecraft is formally only designed to meet a one-year science mission lifetime, the Electra payload is designed for a 5-yr on-orbit lifetime, supporting a possible extended science/relay mission. With a highly elliptical orbit and a body-fixed high-gain antenna, MAVEN's relay characteristics are quite different from NASA's prior relay orbiters, sharing instead some of the geometric coverage and operational characteristics of ESA's Mars Express Orbiter.

In 2016, ESA and NASA jointly propose to launch the ExoMars/Trace Gas Orbiter (EMTGO) mission. This hybrid science/relay orbiter represents the next strategic relay element of the Mars relay network, being designed to provide relay telecommunication, tracking, and timing services through at least the end of 2022. While EMTGO would operate from a low-altitude orbit comparable to Odyssey and MRO, its orbital inclination would result in a non-sun-synchronous orbit (motivated by the proposed mission science requirements), with important implications for relay coverage.

We illustrate the planned operational capabilities of this next-decade relay network by considering planned support scenarios for a) the 2011 Mars Science Laboratory; b) a planned EDL Demonstrator Module (EDM) that would be deployed by the proposed EMTGO orbiter on approach to Mars; and c) a proposed NASA/ESA 2018 Joint Mars Rover mission.

2. Relay Support Plans for the Mars Science Laboratory Mission

EDL Support

The Mars Science Laboratory (MSL) mission will land at Gale Crater (4.5 deg S Latitude, 137.4 deg East Longitude), where MSL's Curiosity rover will carry out a program of exploration aimed at studying the past and present habitability of the Red Planet.

MSL is scheduled to launch during a 24-day launch period which opens on Nov 25, 2011, arriving at Mars on Aug 6, 2012. MSL will employ a new Entry, Descent, and Landing (EDL) system to safely deliver the 900 kg Curiosity Rover to the surface. New features of the MSL EDL system include:

- Guided entry during the hypersonic entry phase of the mission, where the entry vehicle will utilize a non-zero angle of attach to achieve lift and hence aerodynamic control. Prior Mars entries have all used ballistic (zero-lift) entry vehicles. The non-zero angle of attack is achieve by ejection of 150 kg of ballast mass prior to entry to invoke an offset of the entry vehicle's center-of-gravity. This guided entry allows the entry vehicle to fly out a large portion of the delivery errors, enabling a much more precise landing error ellipse relative to prior ballistic entries.

- Ejection of an additional 150 kg of ballast mass to re-align the entry vehicle center of gravity just prior to parachute deployment, to reduce off-axis "jerk".

- Use of a larger parachute (21 m diameter) than on any prior Mars mission.

- A new terminal descent strategy, using a "skycrane" descent stage mounted above the rover to propulsively descelerate and then hover while gently lowering the rover to the surface.

- Delivery of a much larger landed mass (900 kg rover) to the Mars surface, relative to prior Mars missions.

Figure 1 shows a timeline of key events during MSL EDL. Given the large number of new aspects of the MSL EDL system, it is imperative that the Mars program be able to capture engineering telemetry during EDL that would enable accurate fault reconstruction in the event of a mission-loss anomaly. As a result, considerable effort has been invested in the MSL communications strategy during EDL.

Figure 2 shows the geometry at Mars on Aug 6, 2012 at the time of MSL arrival. Earth is in view of MSL when the entry vehicle first enters the atmosphere, and for most of the descent trajectory, but falls below (or, for the last two days of the launch period, falls within 1 deg of) the Martian

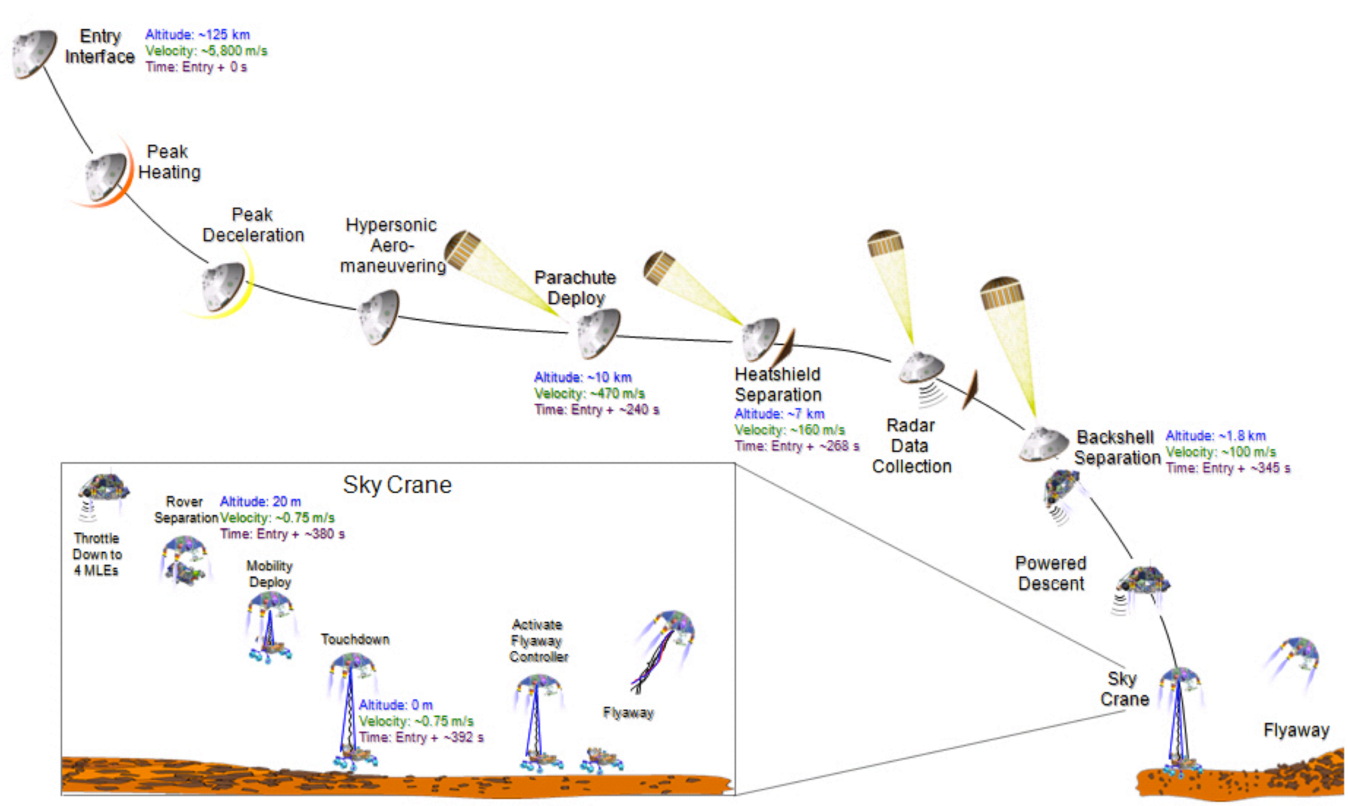

Figure 1 – Timeline of events during MSL Entry, Descent, and Landing

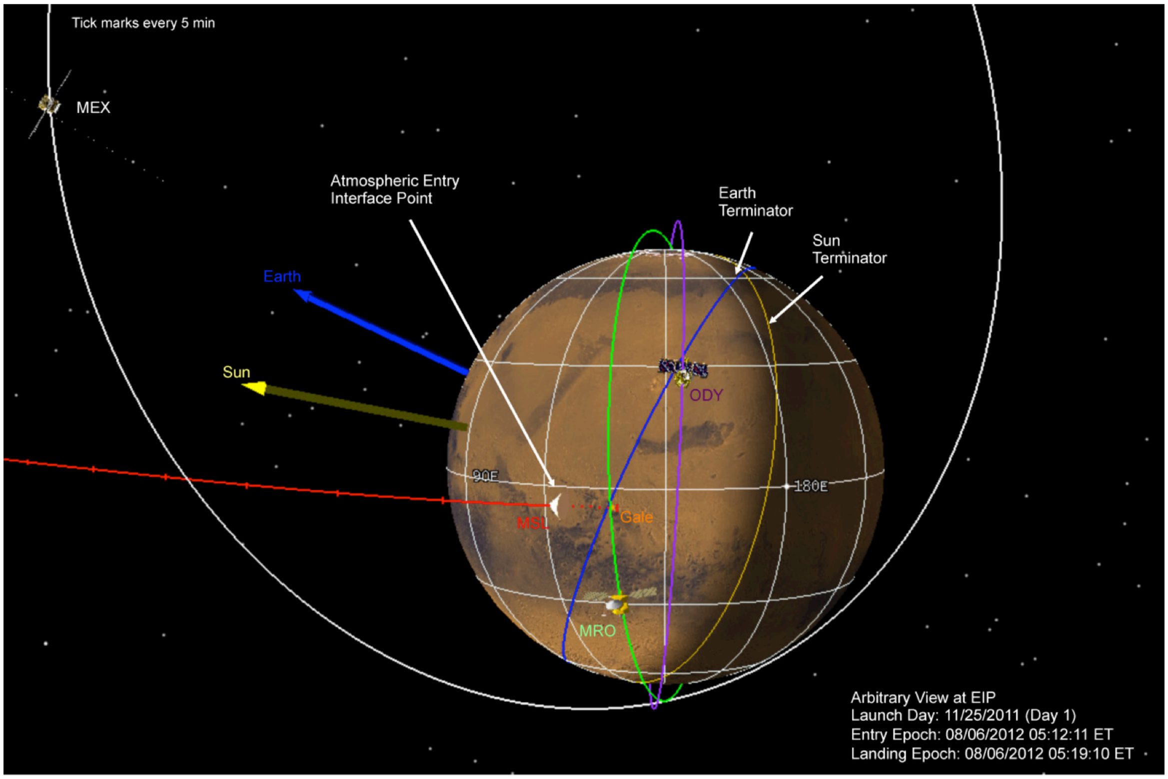

Figure 2 – MSL Entry Geometry

horizon by the time of landing. Hence the DTE link cannot provide full EDL coverage. Nonetheless, MSL will transmit continuously on an X-band Direct-to-Earth (DTE) link during EDL in order to provide diagnostic information while Earth remains in view. The X-band link will utilize a 100 W TWTA on the descent stage, but the large attitude dispersions during EDL will require the use of a very wide beamwidth, low gain antenna, such that even with reception by a 70m DSN antenna, the received signal will be very weak, requiring many seconds of integration to ensure reliable detection.

A low-rate information stream will be encoded on the X-band downlink utilizing Multiple Frequency Shift Keying (MFSK) modulation, with one of 256 possible subcarrier tones modulated at any point in time, similar to the "semaphore" signaling scheme used during MER's EDL. Each MFSK symbol (or subcarrier tone) will be transmitted for 10 s to ensure reliable detection. Given that each MFSK symbol can encode $\log_2 256 = 8$ bits of information, this downlink provides just under 1 bps of telemetry rate, along with measurement of the received Doppler profile, which provides observability of some key events during EDL. While this ~1 bps information rate is adequate to communicate a small amount of status information during EDL, it is not sufficient to characterize the high-bandwidth activities during terminal descent and landing.

Instead, high-rate UHF links will allow the capture of a much higher quantity of critical event telemetry during MSL's EDL. As depicted in Figure 2, MRO, ODY, and MEX are all in orbits which provide geometric visibility of some or all of the MSL EDL trajectory. MRO, with a ~3 PM Local Mean Solar Time (LMST) ascending node, and ODY, with a ~4 PM LMST descending node, each offer full visibility of the MSL EDL trajectory. MEX, by contrast, provides visibility for most of the EDL trajectory but is out of view by the time of rover touchdown.

The MSL EDL UHF communications strategy will take advantage of unique capabilities of each orbiter's relay payload and draws on experience gained from the successful EDL communication strategy executed for the Phoenix Lander [6]. Throughout EDL, MSL will transmit telemetry at 8 kbps, convolutionally encoded, with a residual carrier based on a 60 deg telemetry modulation index. The transmitted telemetry will nominally be sent as a raw bitsteream, without any CCSDS Proximity-1 encoding.

MRO's Electra payload will be configured to collect an open-loop recording of the received UHF signal, sampling a frequency band around the MSL carrier frequency. (To minimize degradation in link performance due to EMI from MRO science instruments, all of the MRO instruments will be powered off for MSL EDL, with the exception of HiRISE, which will be configured to attempt to image the entry vehicle during descent.) Electra acquires in-phase and quadrature samples, with a sampling depth of 8 bits/sample, at a rate of 150 kHz. The recorded MSL signal will be downlinked to Earth after EDL is complete, where ground processing will demodulate the MSL carrier and telemetry in non-realtime. This provides a very robust approach

S/C	Configuration
MSL	X-band: 10-sec MFSK "semaphore" tones UHF: Electra-Lite 8 kbps (7,1/2) code, 69 deg mod index, raw bitstream mode
MRO	Electra Open-Loop Recording, 150 kHz I&Q samples, 8 bitsample; ground post-processsing to recover MSL carrier and telemetry stream
ODY	CE-505 8 kbps demodulation; bent-pipe relay to Earth during EDL
MEX	Nominal: Melacom Open-Loop Recording, 1 bit/sample, ground post processing to recover MSL carrier; Option: Melacom 8 kbps demodulation (requires MSL to change transmission format to Prox-1 frames)

Table 1: Spacecraft configurations for MSL critical event communications during EDL

towards critical event telemetry capture. In the event of an MSL anomaly, a conventional closed-loop demodulation on the relay orbiter might lose lock due to sudden unexpected signal dynamics; with MRO's open-loop recording strategy, the open-loop data set can be analyzed in great detail in non-real time, allowing the use of optimized tracking loop bandwidths, non-causal signal processing, and other techniques to extract the maximum amount of information from the recorded data set.

ODY open-loop recording capability only captures 1 bit per sample, which allows recovery of the carrier signal but not reconstruction of the received telemetry stream, so instead ODY will be configured to demodulate the received 8 kbps MSL bitstream and immediately transmit the MSL telemetry to Earth in a "bent-pipe" mode. This will provide very low latency visibility into the state of the MSL entry vehicle during EDL.

MEX will nominally be configured to acquire an open-loop recording using its Melacom UHF transceiver, which, like ODY, only captures 1 bit per sample. Like MRO, MEX will downlink its open-loop recording to Earth after EDL is complete. Post-processing on the ground of the Melecom open-loop recording will reconstruct the power and frequency of the MSL UHF carrier signal as received on MEX. This is the same manner in which MEX was employed for support of the PHX EDL.

However, to address the risk that either or both of the NASA relay assets were to become unavailable, an alternative MEX configuration mode is being developed. ESA is modifying the MEX Melacom software to allow it to demodulate a simplex receive-only signal (previously, Melacom could only demodulate the return link after completion of a Proximity-1 hailing cycle and establishment of a full-duplex link with a user spacecraft.) One constraint of this new Melacom simplex mode is that it would require the MSL transmission to be formatted as a CCSDS Proximity-1 Expedited Service: the transmitted MSL bitstream would need to be inserted into Proximity-1 frames. Should MRO and/or ODY relay service be deemed at risk, MSL could choose to make this change to its transmission format and allow recovery of MSL telemetry on the MSL-MEX link.

Table 1 summarizes the configuration of the various spacecraft during EDL.

Surface Relay Support

Once on the surface, the Curiosity rover – depicted in Figure 3 – will utilize both X-band communications with Earth and UHF communications via Mars relay orbiters to support its operations. The X-band link, with a 28 cm gimbaled high-gain antenna and a 15 W SSPA, can only achieve a relatively modest data rate of ~275 bps to a DSN 34m antenna at maximum Earth-Mars distance. As a result the X-band downlink will typically only be used for limited telemetry return or contingency operations. However, the X-band uplink will be used routinely each sol, given its operational simplicity and the availability of X-band communication windows every morning, to deliver daily command products to the rover. In addition, an X-band low-gain antenna provides a capability for low-rate emergency communications, without the need of rover antenna pointing.

The vast bulk of telemetry return, however, will be performed using the UHF relay links to MRO and ODY, with MEX providing a backup relay capability. We address each orbiter link in turn.

MRO—The MSL-MRO link, with an Electra-Lite UHF transceiver on MSL and an Electra UHF transceiver on MRO, will be capable of taking full advantage of the new functionality of these software-defined radios for relay communications. Unlike the CE-505 transceiver flown on prior NASA missions and the Melacom transceiver flown on MEX, Electra and Electra-Lite support a number of new features that will enable increased data return [7]:

- Higher data rates: MRO's Electra and MSL's Electra-Lite transceivers will support coded data rates of up to 2048 kbps, compared to the 256 kbps max rate of the CE-505 transceiver and the 128 kbps max rate of the Melacom transceiver.

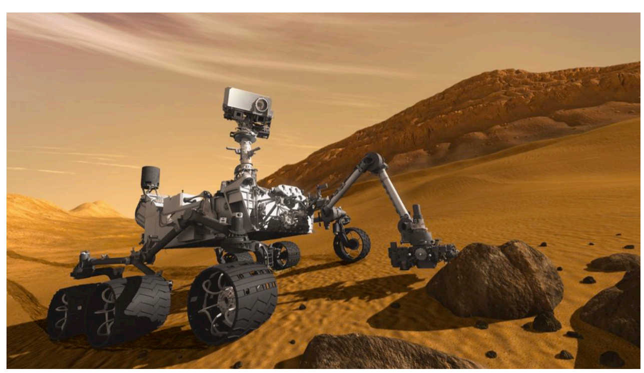

Figure 3 – MSL's Curiosity Rover

- MRO's Electra and MSL's Electra-Lite transceivers support frequency-agile operations, with forward link channels between 435-450 MHz and return link channels between 390-405 MHz. The CE-505 and Melacom operate at fixed frequencies of 437.1 MHz forward and 401.585265 MHz.

- The MSL-MRO link will utilize an adaptive data rate mode to continuously optimize the return link data rate throughout the pass based on observed channel characteristics. MRO's Electra transceiver will monitor the signal-to-noise ratio of the return link signal and, when conditions warrant, will transmit CCSDS Proximity-1 Comm Change Directives to MSL's Electra-Lite Transceiver to invoke a change in the return link data rate. The adaptive data rate functionality will allow the two transceivers to maximize the data volume over the pass, with data rate tracking the variations in slant range and antenna gain. Prior transceivers were constrained to fixed-rate operations for any given pass.

MRO has a capability to roll-steer the spacecraft to a fixed roll angle, up to 30 deg off-nadir, for any given relay overflight. This roll-steering capability can be invoked to reduce the UHF antenna off-boresight angles and hence increase the antenna gain profile for a given pass. (During certain periods, spacecraft engineering constraints will limit the allowed roll angle to less than 30 deg.)

Several of the science instruments on MRO are known to generate electromagnetic interference (EMI) in the UHF band in which the Electra transceiver operates. On the PHX Lander mission, for which PHX operated at a fixed return link frequency of 401.585625 MHz, the EMI led to a degradation in the MRO Electra receiver thresholds of approximately 7 dB. One of the largest EMI contributors is a spurious signal at 400 MHz generated by a harmonic of one of the CRISM clock signals. For MSL, we plan to utilize the frequency agility of Electra and Electra-Lite to operated the return link at 391 MHz, well separated from this large spurious signal. Based on preliminary testing, we have allocated a 4 dB EMI degradation for operation at this 391 MHz channel. More detailed testing is currently planned for MRO, utilizing Electra's "loopback" test capability in which a small, well-calibrated portion of Electra's transmitted signal can be leaked back into the receive chain, providing a mechanism to directly measure receiver thresholds as a function of data rate and channel frequency in flight.

ADR On? (Y/N)	Roll Steer (+-deg)	EMI Loss (dB)	Freq (MHz)	Data Vol (Mb/sol)	
				Nominal (0 dB Margin)	2-Sigma Margin (-2.3 dB)
Y	30	-4.0	391	439	303
N	30	-4.0	391	305	206
Y	0	-4.0	391	352	249
Y	30	-0.5	401.585	788	656

Table 2: MSL-MRO data return for best AM + best PM pass, for various support scenarios. Highlighted scenario represents mission baseline. Last scenario, for reference only, reflects reduced EMI by turning off MRO science instruments.

Table 2 summarizes the predicted average MSL data return per sol, assuming selection of the best AM and best PM pass each sol, for a number of different support scenarios. The baseline case assumes use of ADR, roll steering, and operation at 391 MHz with 4 dB of EMI degradation, which results in a nominal data return of 439 Mb/sol, or 303 Mb/sol with a 2-sigma (2.3 dB) link margin. This meets the MRO requirement of 250 Mb/sol average data return. Other cases show the reduction in data volume without ADR or roll steering, to illustrate the benefits of those functions. Finally, the last case represents a scenario where the MRO science instruments are turned off, significantly reducing the level of EMI affecting the UHF link. This is not envisioned for routine surface operations and is included for reference only.

ODY—Relay operations between MSL and ODY will be limited by the functional capabilities of ODY's CE-505 UHF transceiver, which operates a fixed data rates of 8, 32, 128, and 256 kbps. ODY will be operated in a fixed "quasi-nadir" orientation. (In fact, ODY's nadir deck is pointed in the orbit plane, but 17 deg aft of the local nadir direction.) The predicted relay data volume that MSL can transmit via ODY, again assuming use of the best AM and best PM contact opportunity, is 217 Mb/sol nominal, or 180 Mb/sol with a 2-sigma (1.8 dB) link margin. While offering less data volume that MRO, ODY provides additional contact opportunities as well as important redundancy of NASA relay assets.

MEX—NASA has requested, and ESA has agreed to provide, backup relay support from the MEX spacecraft during the MSL surface mission should MRO and/or ODY become unavailable as relay assets. With its 320 x 10,100 km elliptical orbit, MEX's relay contacts are much more variable than for the low circular, sun-synchronous orbits of MRO and ODY. Based on nodal and apsidal precession, both the local time of day and the slant range of MEX relay overflights will evolve over time. Melacom's transceiver is limited to fixed data rate operations at a maximum coded data rate of 128 kbps. As a result of all these factors, average data return via MEX will be less than for MRO and ODY. Nonetheless, the availability of MEX provides a second layer of redundancy in relay assets to increase the robustness of the overall MSL relay support plan.

3. 2013 MAVEN ORBITER

By the end of the MSL primary mission in 2014, the existing ODY/MEX/MRO relay network will be operating well into the extended mission phase of each orbiter. ODY will have been in flight for 13 years, MEX for 11 years, and MRO for 9 years. To address this situation, the Mars Exploration Program (MEP) will deploy an Electra UHF Transceiver on the 2013 Mars Atmosphere and Volatile Evolution Mission (MAVEN), depicted in Figure 4. MAVEN was selected through a competitive Scout mission Announcement of Opportunity (AO) as a PI-led, cost-capped, focused science mission. However, to address the need for replenishing the Mars relay network, the Scout AO stipulated that any Mars orbiter concept would be required to carry an MEP-provided single-string Electra UHF relay payload, allowing the Scout mission to serve as a relay asset after completion of its primary science mission.

The MAVEN Scout mission has the science objective of directly measuring Mars atmospheric loss processes. To support this objective, the mission will propulsively insert into an elliptical orbit, with a low periapsis of ~150 km and an apoapsis of ~6200 km, enabling observations over a wide altitude range. Coupled with its 75 deg inclination, the orbit node and line of apsides will precess (similar to MEX), resulting in highly variable relay contact statistics.

MAVEN's launch period extends from Nov 18 – Dec 7, 2013, with Mars Orbit Insertion scheduled for Sep 16-24, 2014. After a short commissioning period, the spacecraft will carry out a one-Earth-year primary science mission. During the primary science mission, nominal relay operations are not planned, but the mission will be capable of supporting up to one pass per sol for any required contingency relay operations in support of an extended MSL mission, should MRO and ODY become unavailable. Once the primary science mission is completed, the mission will provide a capability for up to four relay passes per sol during a possible extended mission.

MAVEN will be launched with a full propellant load, and while the spacecraft design lifetime is only required to meet the one-year-on-orbit primary science mission, the onboard propellant will be managed to enable flight operations through 2023 should the spacecraft allow. Part of this strategy includes a raise of the orbit periapsis to 250 km at some point following completion of the primary science mission to reduce the rate of propellant utilization.

MAVEN will fly an Electra UHF transceiver with high heritage to the MRO Electra, but with several differences. These include use of the more recent Xilinx Virtex 3 FPGA, compared with the Virtex 1 on MRO, offering significantly more gates for signal processing firmware, and inclusion of an internal TCXO oscillator, instead of the external ultra-stable oscillator flown on MRO.

To partially compensate for the longer slant ranges over which MAVEN's relay link will operate, MAVEN's Electra payload will implement a new class of error correcting codes for the relay link, increasing the achievable data rate for a given level of received UHF signal. Specifically, MAVEN will support decoding of return link signals employing the AR4JA Low-Density Parity Check code with rate ½ and with a block size of 1024 bits [8]. This LDPC code is being brought forward as a proposed extension of the CCSDS Proximity-1 Coding and Synchronization Sublayer specification. Analysis and initial testing indicates that the LDPC code offers ~3 dB in coding gain relative to the current (7,½) convolutional code.

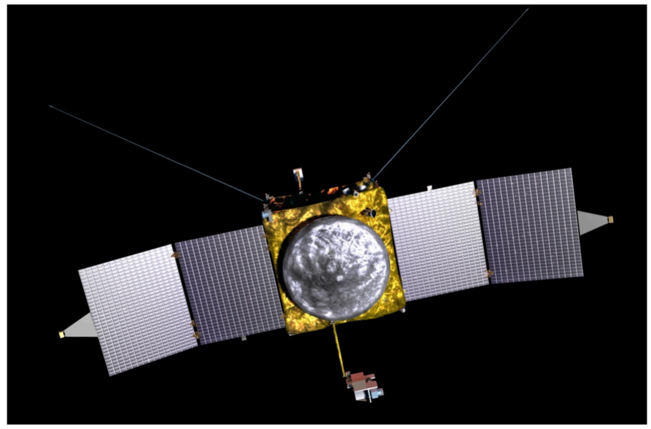

Figure 4 – MAVEN Orbiter

MAVEN's elliptical orbit results in highly variable contact statistics for a given surface user location. The combination of nodal and apsidal rotation leads the latitude and local time of periapsis to vary throughout the mission. (This orbit evolution is in fact driven by the science goals of the mission, enabling the mission to sample the atmosphere below the heliopause over a wide range of latitude and solar angles.) Over the +-30 deg latitude range, a given user on the surface will have anywhere from one to four geometric contacts with MAVEN above a 10 deg local horizon mask. Pass durations can vary widely, with average pass duration varying from 20 min to 2 hrs, depending on latitude and orbit orientation. Slant ranges can also vary widely, with passes near periapsis occuring at ranges of under 1000 km, and passes near apoapsis at ranges of over 6000 km. The elliptical orbit can also result in significant time-varying coverage asymmetries. For instance, when periapsis is at high northern latitudes, southern hemisphere users will have extended periods of relay contact at larger slant ranges, with very low data rates resulting. Similarly, day-night asymmetries can occur, resulting in extended periods where all high-performing, low-slant range passes are on the night side of the planet. In spite of these drawbacks, MAVEN can still provide valuable relay service for an extended MSL mission should MRO and ODY become unavailable.

4. 2016 EXOMARS/TRACE GAS ORBITER

The 2016 ExoMars/Trace Gas Orbiter (EMTGO, depicted in Figure 5) mission is the first of a proposed series of joint NASA/ESA Mars missions. The ESA-led EMTGO mission

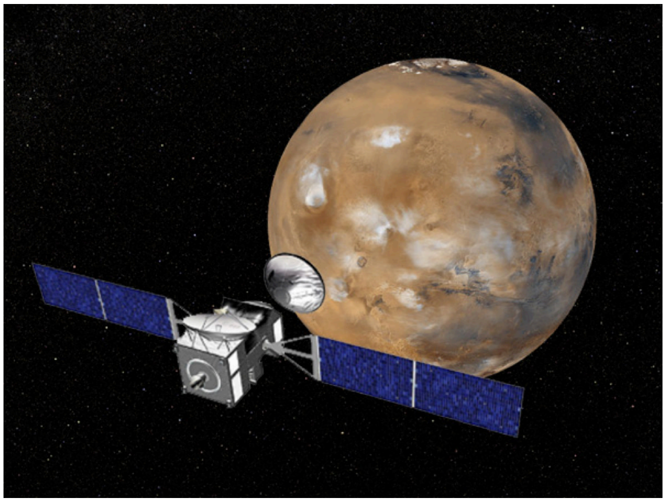

Figure 5 – ExoMars/Trace Gas Orbiter on Approach to Mars

is a hybrid science/telecom orbiter, with a science payload suite aimed at understanding the spatial and temporal distribution of Martian trace gases such as methane, whose putative discovery in recent years points to the possibility of active geological, or perhaps even biological, sources on Mars. ESA will provide the orbiter spacecraft, along with an EDL Demonstrator Module (EDM) to demonstrate ESA EDL technologies. NASA will provide redundant Electra UHF transceivers, identical to the payload on MAVEN, as well as four of the five science instruments, with the fifth instrument provide by Europe. Originally NASA planned to also provide the launch vehicle; however, at the time of writing there is programmatic uncertainty in this aspect of the mission, and alternative launch vehicle provider options are being explored.

The science objectives of EMTGO call for a low-circular orbit in a non-sun-synchronous inclination, enabling the science payload suite to acquire high-sensitivity solar occulation measurements through the Martian atmosphere over a wide range of latitudes. The selected science orbit has an altitude of 400 km and an inclination of 74 deg.

Planned for launch in January, 2016, EMTGO is scheduled to arrive at Mars in October, 2016. The mission will deploy the EDM on approach to Mars, 3-5 days prior to arrival. The orbiter will then overfly the EDM landing site and, while performing its Mars Orbit Insertion burn, will acquire critical event telemetry from the EDM, using the Electra payload's open-loop recording capability (in a similar manner as MRO plans to for MSL's EDL). The EDM itself is battery powered and only designed to survive for 8 sols on the surface. EMTGO's initial post-MOI orbit period is roughly 4 sols, but dispersions in the MOI burn imply that the next periapsis passage at 4 sols after landing may not be properly aligned to overfly the EDM landing site; hence EDM surface relay support will primarily be provided by MAVEN, MRO, and/or ODY, depending on which relay assets are still operational in 2017. After the EDM mission is complete, the orbiter will transition to the desired 74 deg inclination and then begin a 3- to 6-month period of aerobraking to achieve it final 400 km circular orbit. The spacecraft will then carry out its primary science mission of one Mars year in duration (approximately two Earth years), followed by extended relay operations through the year 2022.

Given its low altitude circular orbit, EMTGO will have short relay contacts (~10 min in duration) similar to ODY and MRO. However, unlike those earlier orbiters, the non-sun-synchronous nature of EMTGO's orbit implies that over time, the local Mars time of relay contacts for a given surface user will drift. This will have implications for surface operations of a user mission. Typically, a Mars lander/rover mission prefers to have a high-volume relay contact opportunity available each Martian afternoon, soon after completion of that sol's science activities. Return of data at that local time can then support planning activities on Earth for the upcoming sol, during the rover's local nighttime, with generation of the next sol's command sequence available for uplink on an X-band link the next Martian morning. Both ODY and MRO are well-aligned to support this operations concept. However EMTGO's orbit will drift 13.5 min earlier each day, resulting in periods where no afternoon relay pass is available.

5. Relay Support for the Proposed 2018 Mars Joint Rover Mission

The second mission in the NASA/ESA program of exploration is an ambitious Mars Joint Rover, proposed for launch in May-June, 2018. This NASA-led mission would land an MSL-class rover using the MSL skycrane concept to a landing site in the latitude range of 15 deg S to 25 deg N. The rover would carry ESA's Pasteur astrobiology science payload, performing in situ analysis of samples acquired at depths of up to 2 m using a sub-surface drilling capability. In addition, the rover would incorporate NASA's Sample Acquisition and Caching system to acquire and encapsulate approximately 0.5 kg of scientifically-selected Mars samples, which would be stored in a sample cache that to be placed on the Martian surface, for retrieval and return to Earth by subsequent Mars Sample Return Lander and Orbiter missions. Thus the 2018 Mars Joint Rover represents the first element of a proposed multimission Mars Sample Return campaign.

The EMTGO orbiter represents the primary relay asset for support of the 2018 Mars Joint Rover. EMTGO will phase its orbit parameters to ensure that it overflies the 2018 Rover landing site during EDL, in order to acquire critical event telecommunications from the entry vehicle. The nominal mission design calls for landing in January, 2019 at around 11 AM – 12 Noon LMST on Mars, which precludes use of MRO or ODY for EDL coverage, even if they are still operational in the 2019 time frame. MAVEN could potentially be in view of 2018's EDL, but this will be dependent on yet-to-be-finalized details of the MAVEN and 2018 mission design.

Item	Parameter	
Landing site	24 deg N Lat, 352 deg E Long	
Horizon mask	10 deg	
UHF Transceiver	**QinetiQ (Baseline)**	**Electra-Lite (Option)**
Transmit Power	6.0 W	8.5 W
Transmit Circuit Loss	1.7 dB	1.7 dB
Supportable data rates	8 – 1024 kbps	1-2048 kbps
Surface antenna	MSL Quadrifilar Helix	MSL Quadrifilar Helix
Coding	(7, ½)	LDPC (3 dB coding gain)

Table 3: Key model assumptions for the 2018 Joint Rover

Once on the surface, EMTGO will again be the primary relay asset for the 2018 Rover, while MAVEN, MRO, and ODY offer potential redundant coverage to enhance contact opportunities and overall data return. We have carried out a detailed analysis of the potential relay performance of each of these relay assets for support of the 2018 Rover.

Table 3 summarizes the key assumptions for the 2018 Rover, while Table 4 summarizes the key assumptions for EMTGO, MAVEN, and MRO. Key items to note include:

- The Electra-Lite UHF transceiver offers several advantages relative to the baseline QinetiQ UHF transceiver currently baselined for the 2018 rover. These include 42% higher transmit power, support for LDPC encoding to achieve a 3 dB coding advantage over the baseline (7,½) convolutional code, and support for a higher maximum symbol rate. However, the Electra-Lite does result in larger mass than the QinetiQ transceiver (3.0 kg per unit for the as-built Electra-Lite on MSL, vs. a 1.1-kg per-unit design specification for the 2018 QinetiQ transceiver) and higher DC power (69 W for Electra-Lite vs. 33 W for QinetiQ).

- The MRO UHF antenna suffers a rather large 4.1 dB system loss, primarily due to the relatively narrow frequency bandwidth of that implementation and resulting poor impedence match at the 390-405 return link sub-band. MAVEN and EMTGO are assumed to implement an improved quad helix design, based on or comparable to the UHF antenna developed for MSL.

- EMI due to MRO science instruments leads to a relatively large 4 dB degradation in Electra threshold performance. For the other orbiters, a 0.5 dB EMI degradation is assumed, based on the relatively low levels of EMI generated by MRO's core avionics. It will be very important for MAVEN and EMTGO to address EMI issues early

<table>
<tr><th>Item</th><th>MRO</th><th>MAVEN</th><th>EMTGO</th></tr>
<tr><td>Orbit</td><td>255 x 320 km
Incl = 92.6 deg (Sun-Synch)
3 PM LMST Asc Node</td><td>250 x 6200 km
Incl = 75 deg</td><td>400 km circular
Incl = 74 deg
(Non-Sun-Synch)</td></tr>
<tr><td>UHF Antenna</td><td>Litton Quad Helix
4.1 dB Ant Sys Loss</td><td>3 dB Quad Helix
1.5 dB Ant Sys Loss</td><td>3 dB Quad Helix
1.5 dB Ant Sys Loss</td></tr>
<tr><td>Antenna Pointing</td><td>+-30 deg Roll Steering</td><td>Nadir</td><td>Nadir</td></tr>
<tr><td>Polarization Loss</td><td>0.8 dB</td><td>0.8 dB</td><td>0.8 dB</td></tr>
<tr><td>EMI Degradation</td><td>4.0 dB</td><td>0.5 dB</td><td>0.5 dB</td></tr>
<tr><td>Electra UHF Configuration
(Referenced to (7,½) convolutional code, 10^{-6} BER, w/out EMI losses, measured at Electra input connector)</td><td colspan="3">
<table>
<tr><th>Data Rate (kbps)</th><th>Modulation</th><th>Threshold Power (dBm)</th><th>ADR Switching Time (s)</th><th>Prox-1 Link Efficiency (Return)</th><th>Prox-1 Link Efficiency (Forward)</th></tr>
<tr><td>1</td><td rowspan="5">Residual carrier Mod Index = 60 deg</td><td>-133.3</td><td>5</td><td>0.8111</td><td>0.8347</td></tr>
<tr><td>2</td><td>-130.3</td><td>5</td><td>0.8111</td><td>0.8347</td></tr>
<tr><td>4</td><td>-127.2</td><td>5</td><td>0.8111</td><td>0.8347</td></tr>
<tr><td>8</td><td>-124.2</td><td>5</td><td>0.9500</td><td>0.8347</td></tr>
<tr><td>16</td><td>-121.2</td><td>5</td><td>0.9500</td><td>0.8347</td></tr>
<tr><td>32</td><td rowspan="7">Suppressed carrier Mod Index = 90 deg</td><td>-119.5</td><td>5</td><td>0.9730</td><td>0.8347</td></tr>
<tr><td>64</td><td>-116.5</td><td>5</td><td>0.9890</td><td>0.8290</td></tr>
<tr><td>128</td><td>-113.5</td><td>4.5</td><td>0.9940</td><td>0.8175</td></tr>
<tr><td>256</td><td>-110.5</td><td>4</td><td>0.9713</td><td>0.7946</td></tr>
<tr><td>512</td><td>-107.3</td><td>3.5</td><td>0.9880</td><td>0.7487</td></tr>
<tr><td>1024</td><td>-104.2</td><td>3</td><td>0.9450</td><td>0.6570</td></tr>
<tr><td>2048</td><td>-101.0</td><td>2.5</td><td>0.8180</td><td>0.4735</td></tr>
</table>
</td></tr>
<tr><td>Link Margin</td><td>2.3 dB</td><td>3.0 dB</td><td>3.0 dB</td></tr>
</table>

Table 4: Key model parameters for Mars relay orbiters

		UHF Data Volume (Mb/Sol)	
Orbiter	Lat (deg)	QinetiQ	Electra-Lite
MRO 250X320 93-incl	25	236	342
	0	214	304
	-15	219	318
MAVEN 250X6200 75-incl	25	190	513
	0	170	489
	-15	178	527
EMTGO 400X400 74-incl	25	458	1036
	0	425	963
	-15	434	990

Table 5: Returned data volume from Mars 2018 Rover via MRO, EMTGO, and MAVEN.

in development in order to achieve this goal.

- The Electra performance parameters, assumed to be common to all three orbiters, include efficiency factors for ADR timeout periods (the re-acquisition time required to reestablish the return link after each commanded adaptive data rate change) as well as for Proximity-1 protocol performance (assuming fixed frame size and Go-Back-N parameters).
- For the MRO link, we carry a statistical link margin of 2.3 dB, reflecting the as-built orbiter performance; a higher, nominal 3.0 dB margin is carried for the MAVEN and EMTGO links.

Based on these assumptions, we have calculated the data volume that the 2018 Rover can return via each of these relay orbiters, under several different assumptions, as reported in Table 5. Rover latitudes of 25 deg N, 0 deg, and 15 deg S were considered, reflecting the latitude band currently being considered for the 2018 Rover mission. To reflect typical rover operational and energy constraints, we have limited the rover to use no more than 3 relay passes/sol, and have constrained each pass to no more than 1 hr in duration. (We note that these constraints had only very minor effects on the total returned data volume, relative to a case where all relay contact time was utilized.) We quantify the potential data volume/sol performance assuming either the baseline QinetiQ UHF transceiver or the Electra-Lite UHF transceiver on the 2018 Rover. For the MAVEN case, we evaluated relay performance over a range of apsidal orientations (specifically, with the argument of periapsis set of 0, 45, 90, 135, and 180 deg). The reported MAVEN data volumes represent the average over apsidal orientation; data volumes varied by roughly 20% over the considered range of apsidal orientations.

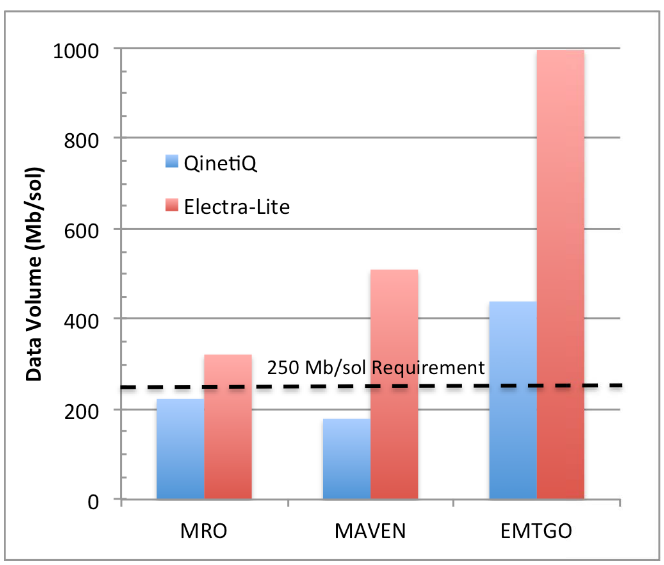

Figure 6: Comparison of returned data volume via relay through MRO, EMTGO, and MAVEN

The data volumes are also presented in graphical form in Figure 6, averaged across the landing site latitudes. We also indiciate on Figure 6 the data return requirement of 250 Mb/sol that the 2018 Rover mission is currently carrying to support its surface operations concept. We see from this analysis that the EMTGO mission can comfortably meet this requirement with the baseline QinetiQ UHF transceiver; however, MRO and MAVEN fall short. The enhanced capabilities of the Electra-Lite UHF transceiver would allow the 2018 Rover to meet this 250 Mb/sol requirement on any of the three orbiters, albeit with an impact on transceiver mass, volume, and power.

SUMMARY

Advances in orbital and lander UHF telecommunications subsystems offer significant growth in Mars data return relative to the current return from the Opportunity Mars Exploration Rover. Improved UHF antennas as well as new capabilities of the Electra and Electra-Lite transceivers on MRO and MSL, respectively, will enable the Curiosity Rover to return over 250 Mb/sol after its landing at Gale Crater on Aug 6, 2010. All three currently operational orbiters (ODY, MRO, and ESA's Mars Express) will be configured to acquire tracking and/or telemetry signals from MSL during its EDL.

Later this decade, the MAVEN and EMTGO orbiters will provide opportunities to replenish the orbital relay infrastructure. Both orbiters are slated to carry the Electra UHF transceiver, with a single-sting configuration on MAVEN and a redundant dual-string configuration on EMTGO. The addition of LDPC decoding capabilities on the Electra payloads on MAVEN and EMTGO offers significant performance enhancements for landers supporting this new code.

The 2018 Rover mission would leverage this relay infrastructure to support its ambitious proposed surface mission. With its baseline low-mass/low-power QinetiQ transceiver, the 2018 Rover would still easily meet its 250 Mb/sol data volume requirement via the EMTGO mission, although it falls short on lins via MRO and MAVEN. With the higher-power (and higher-mass) Electra-Lite, the 2018 Rover can meet its data volume requirement via all three orbiters, and approaches a data return of 1 Gbit/sol on the

EMTGO link. This evolving Mars relay network will enable increased science data return for the coming decade of Mars exploration.

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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.*

Bradford W Arnold *is the Payload Delivery Manager for the two Electra transceivers that will fly on the ExoMars 2016 Trace Gas Orbiter (TGO). Prior to his current assignment, he managed the delivery of the RF payload for the twin GRAIL spacecraft, and supported UFH telecommunication engineering on MER, MRO, Phoenix, and MSL. Prior to JPL, he worked for 10 years in aerospace telecommunications. He received a BSEE and MSEE from California State University, Northridge, and an MBA from California Lutheran University.*

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.*

Kristoffer N. Bruvold *is the Project Element Manager for the Electra Payload for NASA's Scout 2013 MAVEN Mission to Mars. Prior to this assignment he was the Phoenix EDL Open Loop lead, and has been with the Electra Project since its inception 9 years ago doing detailed analysis, design and simulation of the Electra UHF Transceiver. He received his B.S. in Electrical & Computer Engineering from The Ohio State University, and his Ph.D. in Electrical & Computer Engineering from the University of California, Santa Barbara.*

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 (launching 2011) 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 Université de Montréal.*

Charles H. Lee *is a Professor of Applied Mathematics at the California State University Fullerton and a faculty part time staff member in the Communications Architectures and Research Section (332) at the Jet Propulsion Laboratory. He received his Doctor of Philosophy degree in Applied Mathematics in 1996 from the University of California at Irvine. Before becoming a faculty member in 1999, he spent three years as a Post-Doctorate fellow at the Center for Research in Scientific Computation, Raleigh, North Carolina, where he was the recipient of the 1997-1999 National Science Foundation Industrial Post-Doctorate Fellowship. His research has been Computational Applied Mathematics with emphases in Control, Fluid Dynamics, Smart Material Structures and Telecommunications and Biomedical Engineering.*