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RELAY TELECOMMUNICATIONS FOR THE COMING DECADE OF MARS EXPLORATION

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Over the past decade, an evolving network of relay-equipped orbiters has advanced our capabilities for Mars exploration. NASA's Mars Global Surveyor, 2001 Mars Odyssey, and Mars Reconnaissance Orbiter (MRO), as well as ESA's Mars Express Orbiter, have provided telecommunications relay services to the 2003 Mars Exploration Rovers, Spirit and Opportunity, and to the 2007 Phoenix Lander. Based on these successes, a roadmap for continued Mars relay services is in place for the coming decade. MRO and Odyssey will provide key relay support to the 2011 Mars Science Laboratory (MSL) mission, including capture of critical event telemetry during entry, descent, and landing, as well as support for command and telemetry during surface operations, utilizing new capabilities of the Electra relay payload on MRO and the Electra-Lite payload on MSL to allow significant increase in data return relative to earlier missions. Over the remainder of the decade a number of additional orbiter and lander missions are planned, representing new orbital relay service providers and new landed relay users. In this paper we will outline this Mars relay roadmap, quantifying relay performance over time, illustrating planned support scenarios, and identifying key challenges and technology infusion opportunities.

I. INTRODUCTION

The past decade of Mars exploration has benefitted greatly from the development and evolution of an international network of Mars orbiters equipped with relay telecommunications payloads, providing high-rate, energy-efficiency communications services for resource-constrained Mars landers and rovers[1]. Spacecraft delivered to the Martian surface are typically highly constrained in mass, volume, and power; as a result their direct-to-Earth communication payloads have very limited Equivalent Isotropic Radiated Power (EIRP) and correspondingly low data rates on the long communications link back to earth (with slant range of up to 2.7 AU). By constrast, Mars relay orbiters enable Mars landers to achieve much greater data return, at much lower energy-per-bit costs, by providing a short-range proximity link over which the lander can receive commands and transmit science and engineering telemetry at very high instantaneous data rates. The orbiters, with larger high gain antennas and more available power, can then take on the task of relaying those data back to earth on their high-EIRP downlinks.

In this paper we look ahead to the coming decade of Mars exploration and assess plans for future orbiters which would replenish and augment the Mars relay infrastructure, and potential future landed missions which would place new demands on that relay infrastructure. In Section II, we will review the current suite of on-orbit relay spacecraft and briefly summarize their contributions to past and current Mars missions. In Section III, we will preview the proposed sequence of missions envisioned for the coming decade, including NASA's Mars Science Laboratory and Mars Atmosphere and Volatile Evolution (MAVEN) missions, as well as a series of joint NASA-ESA missions involving ambitious orbiter and lander missions. Section IV closes with a summary of the evolution of our relay capability over the coming decade and a look ahead to the decade of the 2020's with the unique relay challenges of a potential Mars Sample Return mission.

II. TODAY'S MARS RELAY INFRASTRUCTURE

Three orbiters are currently operating at Mars: NASA's Mars Odyssey and Mars Reconnaissance Orbiters and ESA's Mars Express Orbiter. These hybrid science/relay orbiters are each equipped with relay communication payloads in addition to their primary remote sensing science instrument suite.

The oldest of these is the Mars Odyssey spacecraft, launched in 2001. Odyssey operates in a 400-km circular, sun-synchronous orbit, with its descending node at roughly 3:45 PM. Odyssey carries a Cincinnati Electronics-505 UHF transceiver, the first flight radio to implement the Proximity-1 Space Link Protocol[2], a standard established under the aegis of the Consultative Committee for Space Data Standards (CCSDS). (All of the relay payloads on subsequent Mars missions – both from NASA and ESA - have adopted the Proximity-1 standard, ensuring interoperability among the various spacecraft.) Odyssey has performed extensive relay operations in support of the 2003 Mars Exploration Rovers - Spirit and Opportunity - and the 2007 Phoenix Lander.

NASA's other currently operational orbiter, the Mars Reconnaissance Orbiter (MRO), was launched in 2005. It features a high-performance X-band deep space link sized to accommodate the high data volumes generated by its remote sensing science payload. MRO's carries the Electra Proximity Link Payload[3], incorporating redundant Electra UHF Transceivers, an Ultra Stable Oscillator, and a quadrifilar helix UHF antenna. Electra is a flight-reconfigurable, software-defined radio with significant new capabilities relative to the earlier CE-505 radio on Odyssey. Electra supports Proximity-1 link protocols at data rates from 1 kbps up to 1024 kbps and can operate over multiple frequency channels, with full duplex operation over forward link frequencies from 435-450 MHz and return link frequencies from 390-405 MHz.

These two orbiters are currently providing operational relay support to the ongoing 2003

	Mars Odyssey	**Mars Express**	**Mars Reconnaissance Orbiter**
Agency	• NASA	• ESA	• NASA
Launch Year	• 2001	• 2003	• 2005
Orbit	• 400 km sun-synch • 93º inclination • ~3:45 AM ascending node	• 250 x 10,142 elliptical • 86º inclination • Non-sun-synch	• 255 x 320 km sun-synch • 93º inclination • ~3 PM asc node
Deep Space Link	• X-band • 1.3 m HGA • 15 W SSPA	• X-band • 1.65 m HGA • 65W TWTA	• X-band • 3 m HGA • 100 W TWTA
Relay Link	• CE-505 UHF Txcvr • 8, 32, 128, 256 kbps • CCSDS Prox-1 Protocol	• Melacom UHF Txcvr • 2, 4, …, 128 kbps • CCSDS Prox-1 Protocol	• Electra UHF Txcvr • 1, 2, 4, …, 1024 kbps • CCSDS Prox-1 Protocol

Table 1: Key characteristics of current Mars relay orbiters.

Mars Exploration Rover (MER) mission. The rovers' X-band link is routinely used to deliver commands directly from Earth each Martian morning, but based on the higher data rates and lower energy cost of the UHF relay link, nearly all MER data have been returned via relay. To date, approximately 98% of the data obtained from Spirit and Opportunity have been returned via relay links provided by Odyssey, MRO, and the earlier Mars Global Surveyor orbiter (no longer operational).

Odyssey and MRO also provided support to the 2007 Phoenix Lander over its 151-sol mission at its high-latitude site[4]. Based on the success of relay support to the Mars Exploration Rovers, the Phoenix project chose to eliminate the X-band direct-to-Earth communications system from the lander, reducing the cost, mass, and power of this low-cost Scout-class mission. During Phoenix's Entry, Descent, and Landing (EDL), Odyssey and MRO were both phased in their orbits to enable reception of the Phoenix UHF signal, which transmitted engineering telemetry that could have been used for fault reconstruction in the event of a mission-ending anomaly. Odyssey was configured to demodulated the Phoenix telemetry stream and relay this in real time to Earth, providing low-latency visibility into the progress of EDL, while MRO was configured to acquire an open-loop recording of the Phoenix signal for subsequent post-processing on Earth to extract the Phoenix telemetry as well as the carrier phase Doppler signature.) Once the lander was on the surface, MRO and Odyssey provided 860 relay contacts, returning 38 Gb of Phoenix data. This corresponds to a per-sol average of 242 Mb/sol, more than four times greater than the Phoenix requirement of 60 Mb/sol.

Completing the current Mars relay network is ESA's Mars Express orbiter, launched in 2003. Mars Express operates in a highly elliptical orbit, which results in more variation in overflight geometry, with periapsis passes having slant ranges as low as 250 km and apoapsis passes operating at much larger slant ranges of over 10,000 km. While not used routinely for surface relay support, NASA and ESA have conducted numerous tests to successfully validate the relay capabilities of the orbiter's Melacom relay payload. Mars Express was also used, along with Odyssey and MRO, to receive the UHF transmission from the Phoenix Lander during its entry, descent and landing. And the availability of Mars Express as an available backup orbiter has been an important element in ensuring robust surface relay support for Spirit, Opportunity, and the Phoenix Lander.

III. FUTURE MARS EXPLORATION MISSION SCENARIOS

III.I Mars Science Laboratory

The first Mars mission of the coming decade is NASA's Mars Science Laboratory (MSL), slated for launch in Nov-Dec, 2011. MSL represents a major step beyond Spirit and Opportunity in terms of scientific and engineering capability. MSL will deliver the 850-kg Curiosity rover to the Martian surface, with a sophisticated science suite focused on evaluating the past and present habitability of Mars[5]. The much larger mass of MSL, compared to the 185-kg Mars Exploration Rovers, calls for a new EDL system[6]. MSL will use a heatshield and parachute, like MER, for initial deceleration, but will then use a propulsive "skycrane" descent stage, mounted above the rover, to gently lower the rover on a tether to the Martian surface.

For the first use of this new EDL system, it is essential to acquire engineering telemetry from MSL during EDL in order to be able to reconstruct any anomaly that might lead to a loss of the spacecraft during this critical mission phase. Accordingly, MRO and Odyssey will be positioned to view the MSL trajectory and receive engineering telemetry from MSL throughout EDL. Current plans call for MSL to transmit information over both its X-band direct-to-Earth link and its UHF link during EDL. On the X-band link, only minimal information can be transmitted via a sequence of "semaphore" tones, with an effective information rate of roughly 1 bps. However, the UHF link will support transmission of engineering telemetry at an 8 kbps data rate.

As with the Phoenix Lander EDL, Odyssey will be configured to demodulate the incoming MSL signal in real time and immediately relay those data to Earth, providing low-latency information on the progress of EDL, and MRO will be configured to acquire an open-loop recording of the MSL UHF signal, which will be played back to Earth after EDL is completed for subsequent post-processing to recover the MSL telemetry stream and carrier phase history. Among the three current relay assets, MRO's Electra payload has a unique capability to acquire a high-fidelity open-loop recording, with quadrature sampling at 8-bit resolution and at sampling rates of up to 150 kHz. This open-loop recording technique is particularly well-suited to acquisition of critical event telemetry; in the event of a mission-ending anomaly, the resulting open-loop recording would provide an effective "forensic" data set which could be exhaustively post-processed to investigate the anomaly and extract all possible information from the link.

In addition to MRO and Odyssey, NASA and ESA are exploring the potential role that Mars Express could also play in providing EDL coverage. One option would be to use Mars Express's "canister mode" recording capability. This mode acquires a 1-bit-per-sample recording of the UHF signal, at a sample rate of 42 kHz. The 1-bit sampling does not support telemetry reconstruction, but does allow generation of a spectrogram – essentially a time series of spectra across the sampled bandwidth – that allows detection of the MSL carrier signal and its frequency

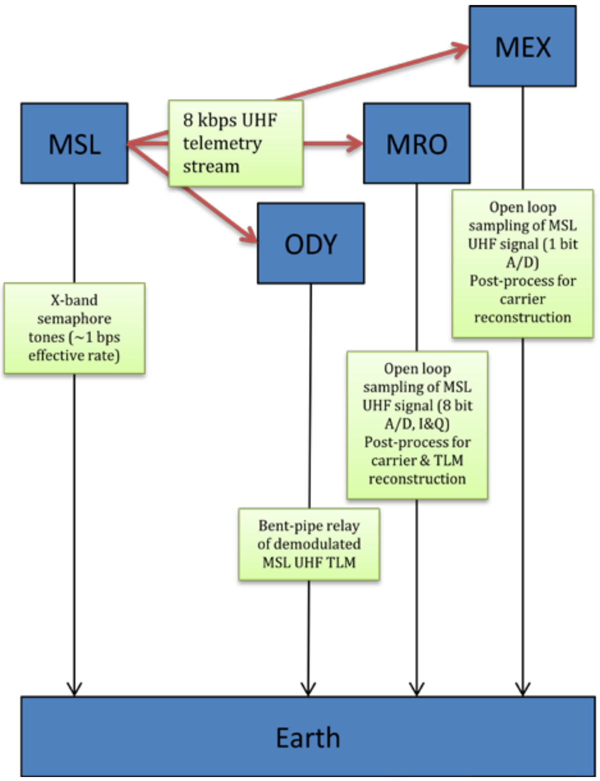

Figure 1: Relay support configuration for MSL Entry, Descent, and Landing.

behavior, which reflects the time variation of the spacecraft's line-of-sight velocity as viewed from MEX. Figure 1 summarizes the multi-orbiter relay support configuration for MSL's EDL.

Once on the surface, MSL – like MER – will utilize a combination of direct X-band links to Earth and UHF relay links via MRO and Odyssey to support its exploration activities. The X-band link will primarily be used to deliver commands to the rover each Martian morning, with instructions for that sol's activities. In the afternoon, the rover will have one or two contacts with MRO, roughly around the 3 PM Local Mean Solar Time (LMST) orientation of that orbiter's node. The MRO link offers the opportunity for large data return, exploiting new capabilities of MRO's Electra transceiver and MSL's Electra-Lite transceiver (a smaller, lower-mass configuration of the Electra technology better-

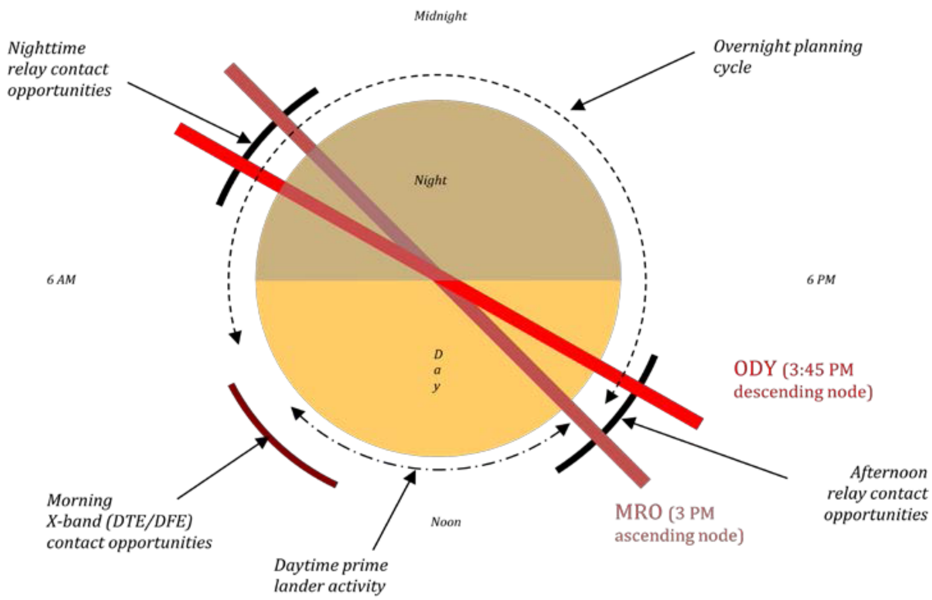

Figure 2: Diurnal cycle of MSL communications.

suited for landed spacecraft). In particular, for favorable overflight geometries, MSL will be able to operate at data rates up to 1024 kbps. Also, the MSL-MRO link will utilize a new Adaptive Data Rate (ADR) algorithm, in which MRO's Electra payload will continuously monitor the UHF return link signal-to-noise ratio and, based on that real-time information, direct MSL's Electra-Lite radio to increase or decrease its return link data rate to the maximum value that the channel can support. ADR will allow increased data return by "filling in" the profile of supportable data rate vs. time over the duration of the pass, accounting for changing slant range and antenna gain patterns. It will also simplify operations by eliminating the need to select the "best" fixed data rate for each pass based on *a priori* analysis of the overflight geometry.

The afternoon MRO pass will provide critical to support planning for the next sol's activities; accordingly, it will be important to ensure DSN coverage for MRO at this time each sol in order to support low-latency delivery of the MSL return link dataset to Earth.

Odyssey will be available to provide an additional relay contact opportunity from its slightly later orbit node of 3:45 PM. With its CE-505 UHF transceiver, Odyssey will be limited to providing only fixed-rate passes and at data rates of only up to 256 kbps. And roughly half a sol later, MRO and Odyssey will be available in the 3 to 4 AM LMST time frame to provide additional overnight relay contact opportunities to augment science return. Figure 2 illustrates the diurnal cycle of communication opportunities for the MSL surface mission.

III.II Mars Atmosphere and Volatile Evolution (MAVEN)

In late 2013, NASA will launch the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft. MAVEN, competitively selected under the Mars Scout Announcement of Opportunity (AO), is an orbiter mission with the science goal of understanding the current and past state of the Martian atmosphere and the loss mechanisms responsible for its evolution[7].

Recognizing the benefits of relay infrastructure and the need to replenish the existing suite of orbiters, the Scout AO called for any proposed orbiters to accommodate an Electra relay payload, provided by the Mars Exploration Program outside of the proposing mission's scout cost-cap. The relay payload is limited to a single-string Electra configuration, in order to minimize impact on the host Scout spacecraft.

Based on its science objectives, MAVEN will operate in a 4.5-hr elliptical orbit, inclined at 75 deg and with an apoapsis altitude of approximately 6200 km. During the one-Earth-year primary science phase, periapsis will be controlled to fly through a fixed atmospheric density, corresponding to an altitude of roughly 150 km. In addition, several "deep dip" campaigns will be conducted, during which the periapsis altitude will be reduced to ~125 km to sample lower layers of the atmosphere.

As is the case for Mars Express, this highly elliptical orbit results in a wide range of overflight geometries, with occasional short overflights near periapsis capable of supporting high data rates, interleaved with long contacts near apoapsis which, due to the much larger slant range, can only support much lower data rates. Figure 3 illustrates the large variation of data rate as a function of slant range for MAVEN relay support to an MSL-class landed asset.

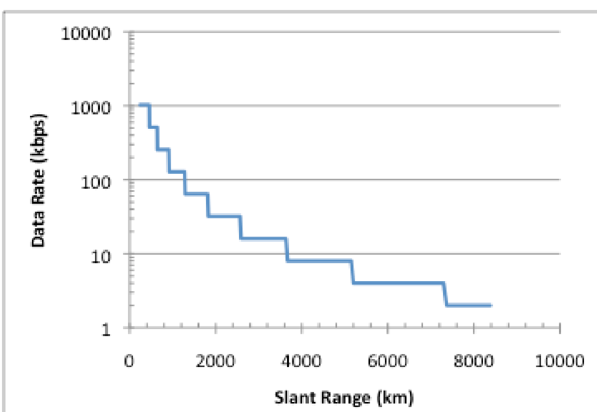

Figure 3: Supportable data rate for a link between an MSL-class lander and the MAVEN orbiter, as a function of slant range.

Preliminary analysis indicates that MAVEN's propellant lifetime could support extended science and relay operations through 2023. At some point during any such extended operations, the periapsis would be raised to 250 km to reduce propellant usage and extend the mission lifetime.

MAVEN's earth communication strategy has important implications for relay services. Unlike MRO and Odyssey, MAVEN's high gain antenna is body mounted rather than gimballed. During nominal science operations, the HGA is sun-pointed, precluding high-rate communications with Earth. Science data return is handled via two 5-hr communication sessions each week, during which the HGA is slewed to Earth to support communications with the Deep Space Network. These infrequent contacts are not adequate for relay support, where DSN contacts shortly before and after a UHF relay pass are necessary to provide low-latency, end-to-end data delivery for forward and return relay products. As a result, it will be necessary for MAVEN to schedule additional deep space communication sessions at the time of any planned relay support.

MSL will be in its extended mission when MAVEN arrives, and in the event that MRO and/or Odyssey are operational, the Mars Exploration Program would refrain from using MAVEN for MSL relay support, allowing MAVEN to focus on its primary science objectives. Only in the event that both Odyssey and MRO are unavailable would MAVEN support be requested during this primary science phase. In a MAVEN extended mission, more frequent MAVEN relay support could be called upon.

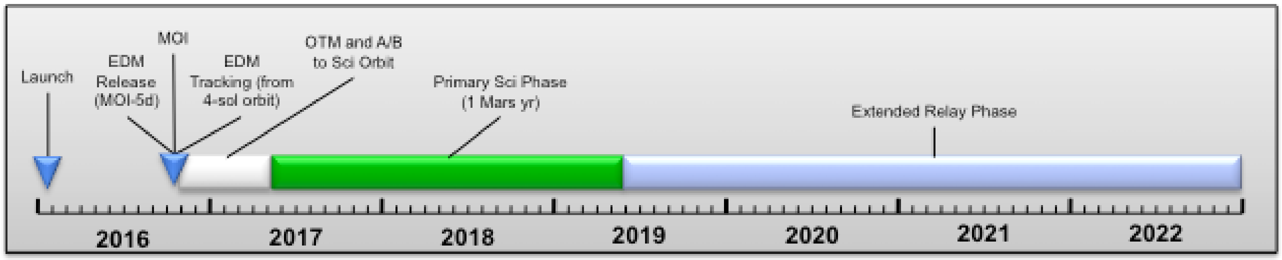

Figure 4: Mission timeline for the ExoMars/Trace Gas Orbiter.

III.III ExoMars/Trace Gas Orbiter

NASA and ESA have recently announced plans for a joint program of Mars exploration, beginning with the proposed ExoMars/Trace Gas Orbiter, slated for launch in early 2016. This ESA-led joint mission would integrate contributions from both agencies. ESA would provide the orbiter bus, an EDL Demonstrator Module (EDM) to validate ESA-developed technologies for landing on Mars, and one instrument for a science payload suite aimed at the measurement of trace gases in the Martian atmosphere[8]. NASA would provide four additional science instruments, the launch vehicle, and a redundant Electra UHF relay payload.

After a Jan 2016 launch, the spacecraft would arrive at Mars in Oct 2016. Several days prior to arrival, the EDM would be release on a trajectory to target its selected landing site. The orbiter would then execute a manuever to target the desired aimpoint for Mars Orbit Insertion (MOI), overflying the EDM during its entry, descent, and landing to acquire critical event engineering telemetry.

The MOI burn would place the orbiter in a 4-sol period orbit, so the next high rate communication opportunity would be 4 sols later. During the intervening period, it might be possible to detect a signal from the EDM, which could be used to convey some limited state information. If other relay assets are available during this time frame, they could also provide contact opportunities to the EDM.

The EDM is planned to have a very short surface lifetime of no more than a few weeks. Once the EDM mission is complete, the orbiter would transition to its primary science orbit, a circular orbit with a 400-km altitude and a 74-deg inclination. This low circular orbit would provide similar relay contact as the current MRO and Odyssey orbiters, but with the important distinction that ExoMars/TGO's orbit would not be sun-synchronous, and hence the local time of day of relay contacts for a surface user would continually drift, with the orbit node moving roughly 14 min earlier each day.

From this orbit, ExoMars/TGO would conduct its one-Mars-year primary science mission, after which it would continue extended relay operations, with spacecraft resources sized for operation through the end of 2022.

III..IV NASA Mars Astrobiology Explorer-Cacher (MAX-C)/ESA ExoMars Rover

The second proposed mission envisioned as part of the joint NASA-ESA program of Mars exploration would deliver a pair of rovers to the Martian surface. Slated for launch in May 2018, the projected NASA-led joint mission would include a NASA-supplied MSL-heritage "skycrane" EDL system to be launched on a NASA-supplied launch vehicle. The entry aeroshell would contain two rovers: NASA's proposed Mars Astrobiology Explorer – Cacher (MAX-C)[9] and ESA's ExoMars Rover[10].

Both rovers would pursue astrobiology science objectives, with differing and complementary capabilities. The proposed MAX-C would have the capability to cache a selected set of samples for subsequent retrieval by a possible future sample return mission, and hence would represent the first step of a potential multi-mission sample return strategy[6]. ExoMars includes a drilling capability that will allow it to acquire samples up to 2 m below the Martian surface for analysis.

With a May 2018 launch, the proposed MAX-C and ExoMars rovers would arrive in Jan 2019, near the end of the primary mission for the projected 2016 ExoMars/TGO orbiter, which would serve as the primary relay asset for the two rovers. The orbiter would acquire critical event telemetry during EDL and then continue to provide relay support for surface operations. MAVEN, MRO, and perhaps even Odyssey could be operational in this time frame and able to augment relay support for the rovers.

The proposed MAX-C rover has a planned surface mission lifetime of 1 Earth year. Like MSL, it would include both an X-band direct-to-Earth link, used primarily for command delivery from Earth, and a UHF relay link, based on an Electra-Lite UHF transceiver. The MAX-C surface operations concept is based on a data return requirement of 250 Mb/sol. By contrast, the ExoMars rover lifetime is specified at 180 sol, and it includes only a UHF communications payload, with no capability for direct X-band communications with Earth. The ExoMars data return requirement is a slightly lower 150 Mb/sol.

The collocated rovers present a new scenario for relay support, as any given orbiter would be simultaneously in view of both rovers during each overflight of the landing site. As the relay payloads on the existing orbiters and the baseline Electra payloads planned for MAVEN and the proposed 2016 ExoMars/TGO orbiter would be single-access radios, capable of supporting only a single user at a time, access to relay services would need to be time-shared between the two rovers. One simple solution would be to allocate alternate overflights to each rover. However, in addition to suffering a 50% reduction in data volume for each rover due to time sharing, this approach has the added drawback of doubling on average the gap time between relay services for each individual rover, which could seriously impact the pace of surface operations. A better solution for single access orbiter radios would be to divide each geometric overflight in half, allocating the first part of the pass to one rover and the second to the other. This strategy, while still suffering a factor of 2 data volume impact for each rover due to time sharing, would at least avoid any increase in gap times between contact opportunities for each rover. If this approach is implemented, it would be important to ensure that the relay radios could terminate the first link and acquire the second link in a very short time, compared to the length of the geometric overflight, to minimize any significant additional loss of data volume during the handoff between rovers.

A better solution, of course, would be to implement a multiple access capability on the proposed ExoMars/TGO and/or MAVEN obiter Electra radios. To this end a study is underway to evaluate the technical feasibility of implementing a Frequency Division Multiple Access (FDMA) capability in the Electra UHF transceiver. The envisioned approach would utilize a single forward link, with individual forward link Proximity-1 frames labelled with spacecraft ID to indicate which forward link frames are intended for which rover. (Forward link data volumes are normally much smaller than return link volumes, and hence the time sharing on the forward link is acceptable.) Each rover would then implement its return link on a unique return link channel frequency. Both return links would need to be received within the Electra IF bandwidth, which is currently limited to 7 MHz in the baseline Electra design. The current study will quantify adjacent channel interference between the two frequency-separated return links, accounting for potential differences in received signal levels from the two rovers. The study will also address how the two rovers would be independently hailed to initiate each pass, how a rover would be re-hailed to re-acquire if that rover drops the link during the pass, and how a multilink adaptive data rate algorithm would operate.

IV. SUMMARY

The current decade of Mars missions has validated the benefit of an orbiting relay network for supporting exploration of the red planet. Ongoing support to the Mars Exploration Rovers, as well as support to the UHF-only Phoenix Lander mission, have demonstrated the capability of orbiting relay spacecraft to provide high-rate telemetry support during critical mission events like EDL, and to return large amounts of science and engineering data from the surface at greatly reduced energy-per-bit costs.

In the coming decade, we plan to build on this success. New capabilities of the Electra UHF transceiver on MRO and the Electra-Lite transceiver on MSL will enable large increases in data return; MSL is baselining 250 Mb/sol return, much larger than the 50 Mb/sol and 60 Mb/sol requirements baselined by MER and Phoenix, respectively.

New orbiters planned for launch in 2013 and 2016 would replenish and augment the on-orbit relay network, incorporating a standardized Electra UHF transceiver to ensure interoperability across all relay assets.

ESA's EDL Demonstrator Module on the proposed 2016 ExoMars/TGO mission represents a first user of that orbiters relay capability. The subsequent proposed MAX-C/ExoMars Rover mission would provide the next unique relay support challenge, with two collocated rovers.

To close, we look beyond this coming decade to the decade of the 2020's, with the possible implementation of a Mars Sample Return (MSR) mission. As noted above, the proposed MAX-C rover could actually represent the first leg of a multimission sample return strategy, with its caching of a scientifically selected sample for subsequent retrieval. This would be followed by another pair of missions: an MSR-Lander mission with a fetch rover to retrieve the MAX-C cache and Mars Ascent Vehicle (MAV) to launch that sample, carried in an Orbiting Sample Canister (OSC), into a 500-km Mars orbit; and an MSR-Orbiter, which would rendezvous with the OSC and return it to Earth in an Earth Return Vehicle.

This proposed MSR mission would introduce a number of new relay communication challenges. First, there would be the possibility of multiple surface assets all requiring relay services, including the MSR lander, its fetch rover, its MAV, and perhaps the earlier MAX-C and ExoMars rovers in extended operations. Next, the launch of the MAV represents a critical event for which it would be essential to acquire tracking and telemetry data to characterize the MAV performance and determine the orbit into which it delivers the OSC. OSC orbit determination might involve a combination of passive optical imaging and active RF tracking; any OSC radio system would need to deal with severe mass and power constraints.

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