

MAVEN Relay Operations Concept

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Abstract—The Mars Atmosphere and Volatile Evolution (MAVEN) mission will launch in late 2013 and, following a 10 month cruise to Mars, will study the upper atmosphere of the planet. In addition to the science instruments, the MAVEN spacecraft is equipped with an Electra UHF transceiver to support relay communication with landed assets. This paper describes how UHF relay service is provisioned by MAVEN. The discussion includes a description of the Electra payload, the process by which relay activities are coordinated and accounted for, the process of a typical relay session, including uplink and downlink, as well as special commands to calibrate and verify relay performance. The operational processes for providing these services are inherited largely from prior Mars missions and take advantage of existing infrastructure and lessons learned from those missions. Preliminary data volume return capabilities using adaptive data rates and low-density parity check channel coding are presented.

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1. INTRODUCTION

The Mars Atmosphere and Volatile Evolution (MAVEN) mission will study the upper atmosphere and ionosphere of Mars and its interaction with the solar wind. The MAVEN payload comprises eight instruments for performing science measurements as well as an Electra proximity radio for communication with landed assets. This paper describes relay operations of the MAVEN Electra radio system.

The Electra UHF Transceiver (EUT) is a software defined radio that is currently operational on the Mars Reconnaissance Orbiter (MRO) and, in a smaller version called Electra Lite, will be deployed on the Mars Science Laboratory (MSL) rover Curiosity. EUT radios have a number of features that make them attractive for relay communications at Mars, including in-situ reconfigurability, in-flight frequency selection to mitigate electromagnetic interference (EMI), and adaptive data rates to optimize data return.

MAVEN is primarily a science mission with a secondary role of supporting relay communications at Mars. MAVEN will be capable of supporting relay operations throughout its Primary Science and Extended Mission Phases. During the Primary Science Phase, MAVEN will be used for relay communications only if the other NASA orbiters, MRO and Odyssey, are unable to support relay operations in that timeframe. The Extended Mission is still being planned, but potentially could include up to 10 years of relay operations.

Each relay activity includes the transfer of any rover forward-link command products from Earth to MAVEN prior to a relay session, slews to and from the relay session attitude, the relay session itself, including the transfer of any forward-link data and the receipt of any return-link data from the rover,; and the transfer of the acquired return-link data to Earth.

Relay planning is coordinated through the Mars Relay Operations Service (MaROS) [2]. MaROS is used by all participants in the Mars relay network to negotiate agreements between relay service users (such as MSL) and relay service providers (such as MAVEN) for ongoing relay support. It consists of a centralized server in which all relay coordination data is correlated and retained. It is also used to transfer forward-link command products, generated by landed asset mission operators, to orbiter mission operators; and to report relay session performance and accountability information.

MAVEN Electra Mission Operations, managed at the Jet Propulsion Laboratory (JPL) in Pasadena, CA; will be responsible for developing uplink files for commanding the MAVEN Electra in support of negotiated relay activities and for monitoring Electra telemetry. In addition to standard uplink products for relay communications, there are a number of special activities of the Electra radio, including a post-launch UHF antenna pattern measurement, loop-back and bit error rate (BER) tests, radio-internal switch exercises, open-loop recording exercises in support of landed assets' entry, descent, and landing (EDL), and cross-link experiments with other orbiters. This paper provides an overview to the foregoing relay operations topics.

2. MISSION DESCRIPTION

MAVEN was selected in 2008 to be the Mars Scout 2013 Mission. The mission is currently in development and is

scheduled to launch in 2013. MAVEN will study Mars' upper atmosphere and how it interacts with the Sun. It will carry instruments to measure characteristics of Mars' atmospheric gases, upper atmosphere, solar wind, and ionosphere [3]. The primary scientific objectives are to:

1. Determine the role that loss of volatiles to space from the Mars atmosphere has played through time.
2. Determine the current state of the upper atmosphere, ionosphere, and interactions with the solar wind.
3. Determine the current rates of escape of neutral gases and ions to space and the processes controlling them.
4. Determine the ratios of stable isotopes in the Martian atmosphere.

The MAVEN spacecraft will also provide relay services to landed assets on the surface of Mars. Relay services are provided via an Electra payload. This payload, comprising an EUT, coaxial cable, and low-gain quadrifilar helix antenna, is currently being developed at JPL.

Relay services will be provided to relay user missions at the direction of the Mars Program Office. It is expected that following the insertion of the spacecraft into its science orbit, no relay services will be provided on a routine basis to relay users throughout the duration of the MAVEN Primary Science Phase. Exceptions to this may be necessary due spacecraft emergencies within other components of the relay network, as directed by the Mars Program Office. Following the MAVEN Primary Science Phase, relay services are expected to be provided as needed to relevant relay user missions, but with MAVEN still acting primarily in a backup role depending on the state of other Mars orbiters. However, MAVEN's role in the Mars relay network may continue in a backup capacity to current and planned orbiting assets.

2.1 Mission Orbit Description

Following its insertion into Mars orbit, the MAVEN spacecraft will be placed into an elliptical orbit with an inclination of 75 degrees and a period of about 4½ hours. This orbit will rotate through a wide range of latitudes, local times, solar seasons, etc. in support of the science objectives of the mission [3]. Figure 1 depicts the frequency and duration of overflights during the Primary Science Phase.

From the perspective of the MSL landing site at Gale Crater on Mars, slant range varies from 400 km to 8600 km and elevation angle varies from 0 to 90 degrees but in many instances is less than 90 degrees (Figure 2). A 10 degree elevation mask is typically applied to link analysis. This orbit is more akin to that of Mars Express, whereas orbiters that have traditionally been used for Mars relay have had much smaller circular orbits (Mars Global Surveyor: 400km circular, Mars Odyssey: 400km circular, Mars Reconnaissance Orbiter: 255 x 320 km [6]).

2.2 Relay System Description

The Electra radio is a software-defined radio that conforms to the CCSDS Proximity-1 communications protocol [1]. Software definition of the underlying baseband signal processing functions enables in-flight reconfigurability. This feature is attractive for deep space missions because it provides flexibility to incorporate new operating modes as they evolve. The MAVEN Electra is essentially a build-to-print version of the Electra radio installed on Mars Reconnaissance Orbiter (MRO), with two notable exceptions. First, MAVEN's Electra is single-string, and has dual low-voltage differential signal (LVDS) interfaces to the redundant spacecraft control and data handling (C&DH) systems. Second, MAVEN Electra is not referenced from a separate ultra-stable oscillator; instead it has an integral temperature compensated crystal oscillator.

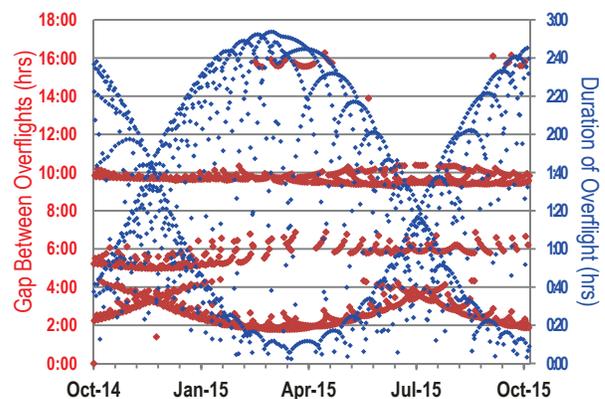


Figure 1. Distribution of overflight durations and gaps between overflights of MSL during the Primary Science Phase.

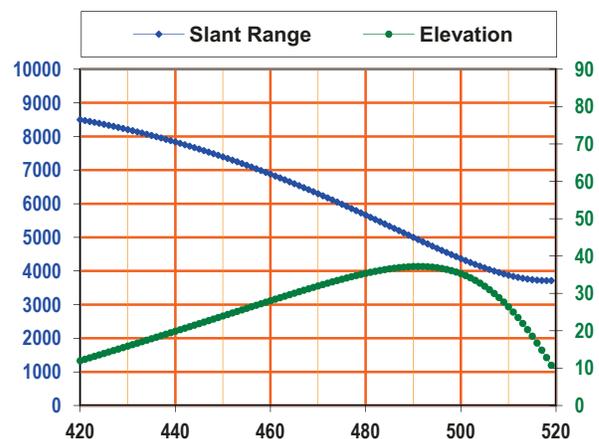


Figure 2. Typical slant range (km) and elevation angle (deg) for MAVEN orbit.

The signal processing core of the Electra radio is implemented in the baseband processing module (BPM, see Figure 3). This module can be married with appropriate RF hardware (e.g. mixers, filters, amplifiers) to produce a radio

system that can operate, in principle, over the entire RF spectrum. To date, Electra radios have been developed at UHF and S-band [4]. Relay operations at Mars, to date, are at UHF. MAVEN’s EUT will be the third radio in the Electra family to be deployed at Mars.

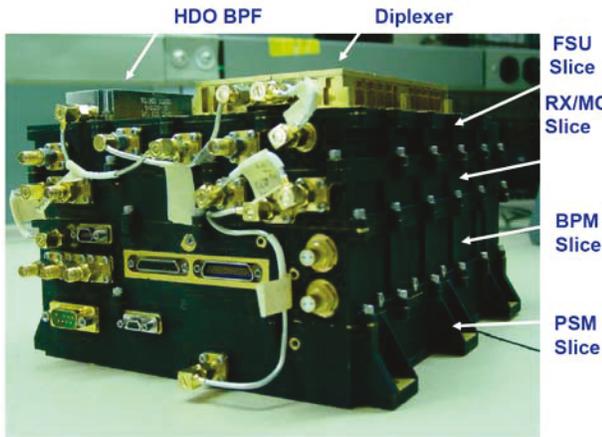


Figure 3. EUT assembly showing bandpass filter (BPF), filtering and switching unit (FSU) slice, receiver/modulator (RX/MOD) slice, baseband processor module (BPM) slice, and power amplifier-power supply module (P/A-PSM) slice.

EUTs can communicate full duplex across a range of frequencies within the UHF spectrum. Frequency agility (in the sense that a range of fixed frequencies can be pre-selected for a given relay link) is an important feature of the relay radio system for mitigating the effects of EMI from various spacecraft sub-systems, as well as compatibility with other Proximity-1 compliant radios in the Mars relay network. Nominally, instruments will not be operating during relay operations, but significant interference can emanate from other systems in the spacecraft that cannot be disabled. These systems emit radio frequency energy that couples into the radio primarily through the low gain antenna. The forward-link transmit frequency range is 435-450 MHz, nominally 437.1 MHz, and return-link receive frequency range is 390-405 MHz, nominally 401.585625 MHz. Additionally, the nominal transmit and receive bands indicated above for relay can be swapped to facilitate orbiter-to-orbiter communication for orbital science. A summary of EUT specifications is provided in Table 1.

MAVEN Electra will feature a new capability, termed *adaptive data rates* (ADR), which will optimize the overall data volume return of a given relay pass. Currently, relay passes involving EUTs are operated at a fixed, pre-selected data rate. The rate must be chosen so that the link can be closed at the point where received signal strength is the lowest (this is typically at the lowest elevation angle). As the link improves and the signal becomes stronger, the radio in principle can support higher data rates, but is limited to the fixed rate predetermined in the hail.

MAVEN Electra will support data rates starting at 1 kbps increasing by powers of two up to 2048 kbps (per the Proximity-1 protocol specification). EUTs with the ADR capability are able to monitor the received signal-to-noise ratio and can adjust the return-link data rate accordingly. The EUT in the orbiter is the arbiter of these data rate changes, commanding the ADR-capable Electra in the landed asset to adjust its return-link data rate.

Table 1. MAVEN EUT Specifications (adapted from [6]).

Parameter	Electra UHF transceiver
Duplex modes	Full-duplex (FD), half-duplex overlay (HDO)
TX frequency	FD: 435–450 MHz; HDO: 390–450 MHz
Operational modes	Sleep, standby, receive, transmit, receive/transmit
RX frequency	FD: 390–405 MHz; HDO: 390–450 MHz
Modulation	Manchester, NRZ-L, BPSK,
TX/RX rate	1, 2, 4, 8, . . . , 2048 kbps
Modulation	QPSK modulation index 60 and 90
Coding/decoding	CC (7,1/2), LDPC ARJA (1024,1/2)
Spectrum record	Open-loop signal sampling ≤128 kSamples/s; 8 bits/sample I&Q
RX noise figure	FD: 4:9 dB; HDO: 3:9 dB
RF TX power	FD: 5:0 W; HDO: 7:0 W
Protocol	Proximity-1
Reconfigurability	Software/firmware in-flight reprogrammable
Doppler Obs	One way/two way
Mass	5 kg
Dimensions (L,W,H)	21:7 cm, 20:1 cm, 11:6 cm
Power – Sleep-mode	7:2 WDC (WC, EOL)
Power – Rx-mode	23:8 WDC (WC, EOL)
Power - Tx/Rx-mode	75:3 WDC (WC, EOL)
Parts	Grade B+
TID	20 krad

The EUT on MRO is being updated with a firmware upload to provide ADR capability. This is in anticipation of the arrival of MSL in 2012, which is equipped with an ADR-capable Electra Lite. This will represent the first field deployment of adaptive relay between Electra radios and is key to meeting MSL’s science data return goals.

MAVEN Electra will also support a new forward error correcting code for relay operations; specifically the ½-rate, block length 1024 bit, low density parity check (LDPC) code. LDPC codes have improved thresholds compared with convolutional codes and Reed Solomon codes, which are presently used with the existing NASA orbiters [9,10]. At a bit error rate of 10⁻⁶, the LDPC code has a 3 dB improvement over a convolutional code. This will help to offset path losses in the very elliptical orbit. MAVEN Electra will also support a half-rate constraint length-7 convolutional code.

The MAVEN UHF low-gain antenna to be used with the Electra payload will be the MSL Rover UHF (RUHF) spare antenna. Like the UHF low gain antennas developed for

MRO and Phoenix, the MAVEN/MSL antenna is a quadrifilar helix producing right circular polarization. However, the MAVEN/MSL antenna is a new design that has lower mass loss as a result of wider bandwidth, as well as lower mass resulting from a composite-based construction technique.

2.4 Ground Data System

A highly simplified block diagram of the MAVEN ground data system is shown in Figure 4.

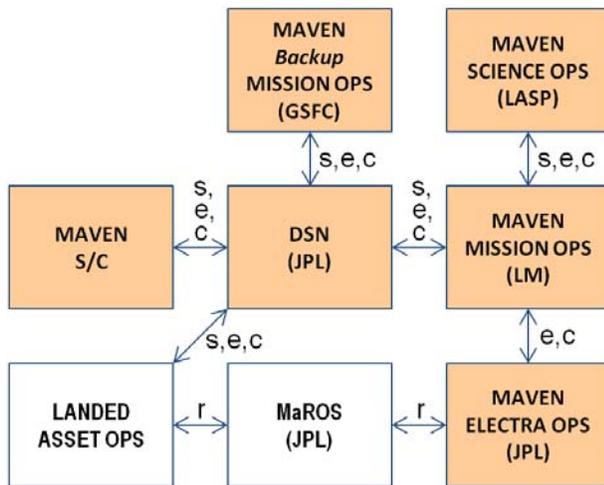


Figure 4. Simplified MAVEN ground data system (shaded boxes), showing flow of science telemetry (s), engineering telemetry (e), commands (c), and relay link reporting (r).

JPL's Deep Space Network (DSN) is the primary gateway for communications between the MAVEN spacecraft and Earth. The mission support area (MSA) for MAVEN is located at Lockheed Martin in Denver, CO. Backup mission operations are provided by Goddard Space Flight Center in Greenbelt, MD. This backup facility is for emergency commanding of the MAVEN spacecraft, through Mars orbital insertion, in the event of an outage at the MSA. The science operations centers communicate with the MAVEN spacecraft via the MSA. MAVEN Electra operations are coordinated at JPL but utilize front-end processing equipment located at the MSA. These activities include the formulation of command sequences and the monitoring of engineering telemetry for MAVEN Electra. In contrast to prior JPL Mars missions, the contractor Lockheed Martin, is taking a leading role in the design and implementation of the ground data system.

Landed asset science operations and mission operations are largely distinct and separate from the MAVEN GDS, but do interact in the following ways. When a landed asset operations team wishes to communicate with their asset, a request is made to the MAVEN project via MaROS. MaROS facilitates the decision-making process as to which

relay orbiter (from the Mars Program Office-approved set) will be exercised for relay. In the event that MAVEN is selected, MaROS passes forward-link command products from the landed assets to the MSA for uplink to MAVEN. Return link data are communicated via MAVEN to the DSN, where landed assets have their telemetry input subsystem interfaces. The MAVEN MSA is not responsible for communicating relay data to landed asset operations centers; that responsibility falls to the DSN under the umbrella of interface agreements that are managed by the MAVEN mission.

2.5 Relay Service Description

The MAVEN project will provide relay services to relay users, consistent with those outlined within the Multimission Relay Operations Plan [7], inclusive of the following services:

Strategic Planning Process: MAVEN will negotiate with landed assets those relay opportunities that are to be implemented during established MAVEN planning periods to establish a baseline plan for relay support.

Tactical Planning Process: MAVEN will provide a mechanism to be responsive to "last minute" changes to the plan established during the Strategic Planning Process. These changes are expected to be minor in nature, as will be outlined later.

Forward-Link Commanding Process: MAVEN will provide a means to transfer a lander mission's forward-link data to the landed asset on the surface of Mars.

Return-Link Data Flow Process: MAVEN will ensure that data acquired from a landed asset during a relay session are transferred to the operators of the landed asset.

Relay Accountability: MAVEN will perform an ongoing analysis of the functionality of the EUT to ensure that its performance meets expectations. Reports will be generated and made available to the operators of the landed assets to report on and account for data transferred in both the forward- and return-link directions.

In addition to supporting these nominal relay functions, other relay-related activities will be accommodated throughout the mission that involve or utilize the EUT. For example, shortly after launch, the pattern of the UHF antenna onboard MAVEN will be measured using a ground-based UHF antenna and transceiver.

In addition, MAVEN will be expected to provide relay support during future lander missions' entry, descent, and landing (EDL) on Mars. Other calibrations, tests, and activities are also expected to be performed, consistent with the MAVEN Baseline Reference Mission [5]. These non-nominal relay activities will require that command sequences be constructed for Electra and that the behavior and health of the radio be monitored.

2.6 Nominal Relay Session

A nominal relay session comprises the major components and timeline shown in Table 2. The actual relay session where the orbiter is communicating to the landed asset via Electra is typically 30 minutes. There is an additional 3 hours and 30 minutes of spacecraft slewing, uplinking of commands, and downlinking of telemetry products associated with each relay pass. A relay pass can acquire upwards of 2 Gbit of data from a landed asset. MAVEN relay operations are designed to downlink relay data as soon as possible after an overflight. However, the MAVEN orbiter has storage capacity for up to 1 Gbyte of relay data, which equivalently would allow storage of approximately 4 such passes. This storage capacity was sized to accommodate open-loop recording, where raw data are recorded during critical events.

Table 2. Nominal relay operations timeline.

Time (min)	Event
10	Slew MAVEN to Earth
60	Uplink via the high-gain antenna (HGA) any forward-link data
10	Slew MAVEN to the sun
20	Slew MAVEN to point the UHF antenna to nadir
30	Perform the relay session
20	Slew MAVEN to the sun
40	Hold attitude to recharge the MAVEN batteries
10	Slew MAVEN to Earth
30	Downlink via the HGA any return-link data
10	Slew to the sun

During the Primary Science Phase, MAVEN may be called upon to perform an emergency relay pass. Such an emergency would probably entail one or both of the other NASA orbiters at Mars being incapacitated, or an emergency from a landed asset (most likely MSL). In this event, a command sequence will be uploaded via the X-band LGA to MAVEN to overlay the ongoing onboard command sequences and interrupt science operations. The MAVEN spacecraft, if necessary, can receive additional uplink configuration information by slewing the high gain antenna (HGA) to Earth. Following the relay pass, the relay data are returned to Earth with high priority.

At the present time, operations have not been defined for the extended mission. Different scenarios are envisioned, ranging from a continuation of science operations in the same manner as in the Primary Science Phase to prioritizing MAVEN as a relay asset with a more optimal orbit for relay coverage and reduced science capacity. The Mars Exploration Program will ultimately make this determination.

Figure 5 displays maximum Prox-1 relay data volumes on a sol-by-sol basis for the first half year of MAVEN's science operations. Open-loop recording modes can result in higher data volumes. The landed asset is assumed to be MSL in the planned landing site of Gale Crater. Equipment performance is based on measurements of MSL Electra Lite and RUHF antenna, as well as predictions (based on MRO) of MAVEN Electra, and measurements of the unaccommodated MSL RUHF antenna.

The analysis assumes that ADR is enabled and that the pass that is capable of transferring the highest data volume is chosen on any given sol. There are typically 2 to 3 relay passes per sol, and it is by no means certain that the best possible pass can be chosen from an operational point of view. Additionally, LDPC channel coding is assumed, along with an operating margin of 0 dB. The utilization of adaptive data rates affords the opportunity to operate at lower threshold margins to mitigate against uncertainties, hence the data in Fig. 5 do not include the typical 3 dB link margin. In summary, Figure 5 is representative of MAVEN's return-link capability with MSL as a relay partner.

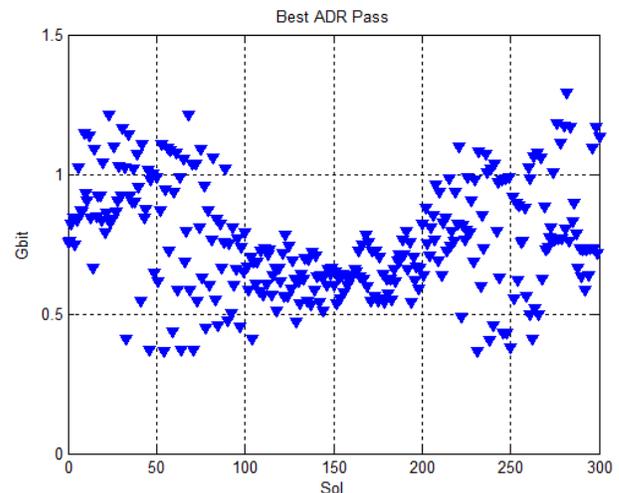


Figure 5. MAVEN capability to return data from MSL located in Gale Crater during the first year of MAVEN science operations.

3. RELAY OPERATIONS PROCESSES

This section describes how the MAVEN project facilitates the 5 relay processes outlined in the Multimission Relay Operations Plan. [7]

3.1 Strategic Planning Process

The Strategic Planning Process will be synchronized with the standard planning process for commanding the MAVEN spacecraft. Nominally, 1 week of MAVEN spacecraft activities will require approximately 2 weeks of lead time to implement. MAVEN navigation predictions will need to be provided to the operators of a landed asset at the beginning

of this 2 week period, which implies that the latest overflight in the planning period may be 3 weeks in the future from the time of delivery of the predictions. These navigation predictions will be used by the operators of the landed assets to determine the periods of time when the MAVEN orbiter will be geometrically visible by the landed asset. The resulting windows of time will be considered “overflights” that are candidate opportunities for relay services to be requested.

The navigation predicts will be produced by the MAVEN Navigation Team at JPL and delivered to a file server as designated by the operators of the landed asset. This interface will be unique for each lander project to which the MAVEN project provides relay services.

The MAVEN project will also provide to the operators of the landed assets other information that will be needed for relay purposes. Specifically, data related to the deep space communications windows, both from MAVEN to Earth (i.e. uplink, or in the forward-link direction) and to MAVEN from Earth (i.e. downlink, or in the return-link direction) will be required. In addition, information related to times when the orbiter will be commandable will be required, as will be data regarding downlink data rates from the orbiter to Earth. There may also be periods of time when the orbiter may be unable to support relay services, for whatever reason; this also must be communicated to the operators of the landed asset. These data will be delivered to a centralized service managed and maintained by the Mars Program Office, namely MaROS, from which the data will be extracted by the operators of the landed asset.

In the forward-link direction, this information will be used to determine how long before a given relay opportunity any forward-link command products destined for a given overflight will need to be delivered to the MAVEN project to ensure they arrive on the orbiter prior to the relay session. This is called the “forward-link latency.” In the return-link direction, this information will be used to determine how long after a given relay opportunity any return-link data products received from the landed asset will be made available to the operators of the landed asset on Earth. This is called the “return-link latency.”

The operators of the landed asset will use all of this information to identify candidate opportunities for relay services and will submit a file that includes requests for relay support to MaROS. Subscribed users on the MAVEN project will then receive a notification that the requests for relay support have been submitted and may then extract them from MaROS.

MAVEN relay service requests may be of two varieties: normal and contingency. Normal relay requests are those which are expected to be implemented and during which it is expected that the orbiter will hail the lander to initiate a communications session. Contingency relay requests are those where the orbiter will be expected to be prepared to

initiate the relay session, but shouldn’t unless additional direction is given during the Tactical Planning Process.

On MAVEN, normal relay requests will be sequenced to occur as requested. Contingency relay requests will also be sequenced in a like manner, but none of the commanding needed to initiate the relay session will occur unless a specific command is received at an appropriate time to initiate it. Further information on the activation of a contingency request will be discussed when outlining the Tactical Planning Process.

The request data will be extracted from MaROS by the MAVEN operators approximately 1 week prior to the beginning of the relevant 1 week commanding period. At the time the data are extracted, the MAVEN operators will also indicate that no additional strategic requests will be accepted for the relevant planning period; MaROS will thereafter reject any additional strategic requests within the planning period.

Representatives from the MAVEN project will then attend a confirmation meeting sponsored by the Mars Program Office to formalize their acceptance of the relay requests.

Afterwards, the relay requests are converted into the appropriate command product(s) to be radiated to the MAVEN spacecraft. Once this has been done, the MAVEN project will return acknowledgements via MaROS to the operators of the landed asset to indicate the features of the relay service to be provided. Ideally, these acknowledgements will precisely echo the original requests for relay services.

The acknowledgement data will be published to MaROS by the MAVEN operators within 1 or 2 days after the extraction of the relay requests from MaROS, generally at the time at which it is too late to accommodate modifications to the generated command products. When the acknowledgements have been submitted to MaROS, the Strategic Planning Process will be considered complete for the designated planning period.

MaROS provides to the orbiter and lander operators a mechanism for negotiating both the relay sessions to be supported and the parameters for each relay session. It is not expected that MAVEN will utilize this capability, but will instead accept and implement authorized relay requests for implementation without negotiation. Relay requests will be considered authorized if they conform to established policies as negotiated with the Mars Program Office (such as being in number no more than the allowed number of requests per day, or should a directive be received from the Mars Program Office regarding the need to provide specific relay support) and if the included parameters for each relay session conform to a pre-negotiated set of parameters.

Once a strategic plan has been implemented as a MAVEN command product, the MAVEN project will follow standard

processes for command approval and uplink to the MAVEN orbiter.

3.2 Tactical Planning Process

The Tactical Planning Process for MAVEN will be utilized for a planning period when the Strategic Planning Process is considered complete. This process will enable last minute changes to the strategic relay plan to be implemented onboard the MAVEN orbiter. There are four types of tactical requests that will be accommodated, as follows:

1. A request to make a minor change in the behavior of an upcoming relay session, such as to change a data rate or other relay session configuration parameter that was implemented during the Strategic Planning Process. This would be utilized if the operators of a landed asset determine that the previously identified parameters for a relay session should be modified to better serve the needs of the landed mission.
2. A request to activate a contingency request, as previously scheduled during the Strategic Planning Process. This would be utilized if the operators of a landed asset determine that it is needful to utilize a relay session that was previously not deemed to be needed, such as if another relay asset suddenly becomes unavailable.
3. A request to de-activate a normal request, as previously scheduled during the Strategic Planning Process. This would be utilized if the operators of a landed asset determine that a relay session should not be initiated by the MAVEN orbiter for whatever reason, such as when multiple orbiters may have been strategically requested concurrently.
4. A request to schedule an emergency relay session that was not previously identified in any form during the Strategic Planning Process. This would be utilized only if the Mars Program Office directs and in accordance with pre-negotiated policies.

The requests to make all of these changes are facilitated via MaROS. Unlike in the Strategic Planning Process, the Tactical Planning Process expects the lander and orbiter missions to negotiate on a set of parameters until an agreement can be met.

To initiate a tactical change to a given overflight or to a set of overflights, the lander project will submit one or more tactical changes via MaROS to be evaluated by the MAVEN project. Subscribed users on the MAVEN project will then receive a notification that one or more tactical requests for relay support have been submitted. The MAVEN project will then evaluate whether the tactical request(s) can be accommodated given any constraints under which the operations team may be operating, including staffing and deep space tracking constraints, and reply with an

acknowledgement to indicate what can or cannot be implemented.

The lander project will then be notified of the orbiter's ability to implement the tactical request, and then may elect to officially request that the tactical request be implemented. This would once again be submitted via MaROS. Subscribed users on the MAVEN project will again receive a notification that one or more tactical requests for relay support have been submitted, will act to implement the request, and will return an acknowledgement when the request has been implemented.

This process will usually be executed within 1 day of the affected relay session. For emergency overflights, it may be longer by 1 or 2 days, or this type of tactical change may be disallowed in favor of implementing requests in the next 1 week planning period.

Once a tactical change has been implemented as a MAVEN command product, the MAVEN project will follow standard processes for command approval and uplink to the MAVEN orbiter.

3.3 Forward-Link Commanding Process

The Forward-Link Commanding Process for MAVEN will be largely automated using MaROS and other MAVEN-specific software automation. Forward-link data can be transferred to MAVEN in one of two manners, as follows:

1. As a "file" where the product is given a unique name and placed in the MAVEN onboard file repository prior to the relay session. With this capability, the MAVEN project will allow the lander project to submit up to 20 forward-link files for each relay session. These must be numbered from 01 to 20, with gaps in numbering allowed, in a manner that allows the lander project to designate the order in which the files are transferred to the lander during the relay session.
2. As a "product" where a particularly large product may be handled as a bulk file. These data are stored in a different memory location onboard the MAVEN orbiter, and only one may be resident onboard the orbiter at any given time. The lander must also designate the relay session for which the product is intended, and these data will be transferred prior and in addition to the 20 named files previously mentioned.

The lander project will submit the forward-link products via MaROS, which in turn transfers them to the MAVEN project file server. MaROS will also store to this file server an additional file which includes any instructions from the lander project that will be necessary to correctly transfer the files to the MAVEN orbiter, including the designation of the files as "files" or as "products", per the above, and, if the former, the file number for the product. These meta-data may also include a time window during which the lander may prefer the product to be transferred – information

especially pertinent when transferring the data in the “product” form.

Upon receipt of the forward-link products from MaROS, the MAVEN project will have automation in place that will immediately convert these products into properly formatted MAVEN command products. In this conversion, the source data will not be modified and the MAVEN project will ensure that the products are made available to transfer to the lander in order, without duplication, and without gaps as a single bit stream during the designated relay session. If a “product” is made available for a given relay session, it will always be sent to the lander before any numbered files that may be designated for the same session, which themselves will be transferred in numbered order; if gaps in numbering exist, the gap will be ignored.

Throughout this process, the MAVEN project will return to MaROS at least two indicators regarding the transfer of the forward-link products. The first will be an indicator that the files have been received from MaROS and have been prepared for uplink to the MAVEN orbiter. The second will be an indicator that the files have actually been transmitted to the MAVEN orbiter. These two indicators provide some insight to the lander operators regarding the handling of their forward-link command products.

The successful transfer of the forward-link command products to the MAVEN orbiter is subject to the same considerations and constraints as is a tactical request. Specifically, if there is insufficient staffing and deep space tracking coverage, it may be impractical or impossible for the MAVEN project to transfer the products if they are received from the lander project too late prior to the desired relay session. The lander project will be made aware of these constraints as part of the Strategic Planning Process, and should be prepared to conform to them.

Once the forward-link products have been received by MaROS, it is tacitly assumed that the lander project desires these products to be transferred in support of the designated relay session. No additional authorization is facilitated, meaning that once the product is received by the MAVEN project, there is no mechanism in place to stall or interrupt the transfer process to the orbiter. The lander project assumes responsibility for ensuring that any forward-link product submitted to MAVEN is “good”.

However, a numbered file may be replaced by “overwriting” one that had previously been submitted for uplink to the orbiter, should a new version be submitted for transfer prior to the designated relay session. This overwrite may occur onboard the orbiter within the orbiter’s file system, or it may be that the earlier version of the product may not be radiated at all. The MAVEN project assumes responsibility for properly managing this scenario, and will do so without interaction with the lander project; this activity is similarly subject to constraints in staffing and deep space tracking time. No similar overwrite mechanism is made available for the “product” uplink method.

Though forward-link command products and tactical changes are subject to the same constraints in time and staffing, the two processes are not assumed to be coupled. The MAVEN command products which contain the necessary data are distinct and separate command products and must be managed so.

Once a forward-link command product has been implemented as a MAVEN command product, the MAVEN project will follow standard processes for command approval and uplink to the MAVEN orbiter.

3.4 Return-Link Data Flow Process

The Return-Link Data Flow Process for MAVEN will be largely handled by the Deep Space Network (DSN). The return-link data received from a landed asset by the MAVEN orbiter during a relay session will be transmitted to the DSN as soon after the relay session occurs as is possible. It is treated as the highest priority data, aside from spacecraft health and safety data, to ensure its rapid transmission to Earth. In this manner, the data are returned with the shortest return-link latency as is practical.

Generally, the data will only be transmitted once from the MAVEN orbiter to Earth. However, the MAVEN project will provide for retransmission of return-link data that may not have been received due to outages in the MAVEN-to-Earth space link; this retransmission may occur days after the relay session. This policy will be negotiated between MAVEN and relay users.

Upon receipt onboard the orbiter, the return-link data are packaged as a CCSDS File Delivery Protocol (CFDP) product. Though the data are packaged thus, the CFDP retransmission protocols to handle incomplete data will not be utilized by the MAVEN project. MAVEN Electra engineering telemetry is not CFDP wrapped; it is treated like any other spacecraft subsystem telemetry stream.

In addition, the operators of the landed asset may choose to retransmit any missing or incomplete return-link data from the source (i.e. the landed asset) during a later relay session, in which case the data would be handled as a separate and distinct return-link data product by the MAVEN project.

The MAVEN spacecraft transmits the return-link data designated as a specific “virtual channel” (VC). At the DSN, this VC is extracted from the balance of the MAVEN telemetry. The DSN assumes the responsibility of reconstructing the return-link CFDP product from these data, and then delivers the return-link data product to the designated landed asset.

The MAVEN project receives the data within their ground telemetry, but does no processing on those data; it does not reconstruct the CFDP product nor does it provide a ready mechanism to provide this return-link data to the landed asset should the DSN fail to do so.

3.5 Relay Accountability

After a relay session has occurred and the return-link data and other related MAVEN telemetry have been returned, the Electra team will process the relevant information to characterize the behavior of the EUT. This information will be used for long-term trending purposes, and also to provide some accountability information to the operators of the landed assets.

Two types of reports will be submitted to MaROS, where the operators of the landed asset will be able to access them. These reports will outline the general performance of the EUT during the relay session and will be of the following nature:

1. One that includes static performance measurements for the relay session, such as the maximum signal strength measured during the relay session or the total return-link data volume acquired.
2. One that includes time-varying measurements for the relay session, such as the measured signal strength throughout the relay session, counters for data transferred in both the forward- and the return-link directions, etc.

These will generally be submitted to MaROS within 1 working day after the relay session has concluded by the EUT operators, with a goal of submitting them as soon after the relay session as is practical. This reporting may be automated. Table 3 shows typical reported data.

Table 3. Time-varying, reported measurements

Event	Units
Measured orbiter received power	dBm
Measured orbiter transmit power	dBm
Acquired return-link data frames	frames
Acquired return-link bits	bits
Successfully transferred forward-link frames	frames
Successfully transferred forward-link bits	bits
Return-link control frames transmitted	frames
Total frames transmitted	frames
Return-link out-of-sequence frame count	frames
Commanded return-link data rate	kbps

The EUT operators will also view other related spacecraft telemetry in order to properly monitor the performance of the EUT. These data will likely include temperature, power, and attitude information, as derived from other spacecraft telemetry.

4. SPECIAL RELAY COMMANDING

Throughout the MAVEN mission, the EUT will need to be exercised to fulfill full verification and validation activities. Most of the activities to verify the functionality of the EUT and its interoperability with the remainder of the MAVEN

spacecraft will occur before launch. The rest, which will focus on the in situ performance of the radio and its ability to interoperate with other vehicles in the Mars relay network, will occur after launch.

4.1 Pre-Launch Activities

Verification of radio functionality, including power draw, bit error rate (BER) testing with relay partner hardware emulators, health and safety testing, open-loop testing, timing and radiometric testing, and EMI susceptibility testing, will be performed on the flight model (FM) EUT prior to delivery to Assembly, Test, and Launch Operations (ATLO). Additionally, the engineering model (EM) version of the EUT will be integrated into the spacecraft test lab (STL) along with associated ground support equipment (GSE) to control and configure the radio. Once integrated into the MAVEN spacecraft at ATLO, the FM EUT will be subjected to a number of tests at the spacecraft level including:

1. Verification of end-to-end command and telemetry flow.
2. UHF compatibility testing against a number of spacecraft subsystem and payload on/off configurations and in a number of different radio operating modes.
3. System verification test (SVT) for nominal relay session.
4. Relay compatibility test with relay partner hardware emulators to exercise Proximity-1 modes, including both forward- and return-link.
5. End-to-end relay data flow with relay partner hardware emulators and a DSN emulator (i.e. a thread test).

4.2 Post-Launch Ground Test Activities

After launch, several different types of tests will be performed with the expected relay service users. These tests will take the following three forms:

1. Compatibility testing will be performed between ground testbeds that include functionally equivalent versions of the UHF radios that are onboard MAVEN and the landed asset. These tests will be performed to ensure that the radios can interoperate using all the expected radio modes. This type of testing will simulate flight-like link conditions and will stress test the radios to characterize their behavior given both favorable and unfavorable environmental conditions and operational scenarios.
2. Thread testing will be performed between the MAVEN project and the landed asset's ground data system, including MaROS, to ensure that the systems can effectively transfer data between them. This type of testing is sometimes called "end-to-end testing" and is intended to ensure that data can flow between the

projects successfully, without data corruption, and with throughput latencies that meet expectations. At times, this testing may also include the UHF radio simulators and simulators of the DSN.

3. Operational readiness tests (ORTs) will be performed between the MAVEN project and the landed asset's operations teams to practice flight-like operational procedures and timelines. These exercises will practice several operational scenarios, inclusive of nominal relay operations that assume a lander is safely on the surface of Mars, off-nominal relay operations, and EDL scenarios. The operations teams for the involved projects will act as if they are performing the actual event involved and, in some cases, anomalies with the software and hardware will be intentionally introduced so that the teams may practice problem resolution processes. Typically, the ground testbeds, which replicate much of the flight hardware and simulate the mission environments, will be utilized during these tests, including the UHF radio simulators.

For all of these tests, efforts will be made to conform to flight-like operational processes, procedures, and policies. Where possible, the actual hardware and software will be utilized to manage relevant data, and the appropriate file formats will be used for data interchanges.

4.3 Post-Launch In-Flight Test Activities

Some post-launch, in-flight tests will need to occur in order to verify the functionality of the EUT onboard the flight system. These include but may not be limited to the following:

1. A post-launch antenna pattern measurement will be performed with an Earth-based UHF antenna. This test will involve transmitting a UHF signal from the Electra antenna while the spacecraft slews to position the antenna in a variety of off-boresite angles. (The lower power Electra transmitter is used to minimize interference with near-earth satellites.) This test will measure the effective gain pattern of the antenna.
2. Loop-back bit error rate tests will be performed to understand the in situ electromagnetic environment of the UHF radio. This self-test mode involves feeding back a highly attenuated transmit signal to the receiver. This testing will involve placing the spacecraft and onboard instruments in a variety of configurations to measure the interference that the flight system causes to the UHF radio. This testing will be utilized to determine the appropriate mode in which the spacecraft may be placed to minimize the amount of electromagnetic interference when relay sessions occur with a landed asset.
3. Internal Electra switch exercises will occur to ensure that the internal switches of the Electra radio remain functional in the space environment. These exercises

will be performed periodically to reduce the likelihood of vacuum welding of the EUT components.

4. Open-loop recording events may be tested with landed assets already on the surface of Mars to practice collecting this type of data, such as would be required to support a new landed asset's EDL events. These are also performed to characterize the EMI environment, like the tests in item 2.
5. Cross-link experiments with other Mars orbiters may be performed once MAVEN is on orbit, which may be used to perform radio science.

Each of these activities are considered to be "unique" in that the spacecraft and EUT commanding required to accomplish them typically cannot be reused from one instance to the next.

In support of these activities, the Electra operators will need to generate unique inputs in order to properly command the radio. Once these inputs are provided and integrated into a full command set that will execute these activities on the MAVEN spacecraft, they will be verified in a spacecraft simulator called the spacecraft test laboratory (STL) that will include an engineering model (EM) of the EUT. These simulations will be used to ensure that the intent of each activity can be met while not risking spacecraft health and safety.

Additional software-only simulations will also occur for many of these activities. These simulations require less time to execute than the full spacecraft simulator and allow for verification of the command execution and timing to occur.

Once all needed products have been implemented and verified as valid and correct MAVEN command products, the MAVEN project will follow standard processes for command approval and uplink to the MAVEN orbiter.

5. SUMMARY

The MAVEN spacecraft, while not an ideal relay platform due to its eccentric and evolving orbit and fixed HGA, will be fully capable of providing relay services to users as directed by the Mars Program Office. These services will be augmented by the introduction of ADR and LDPC, which provide a dramatic improvement on the data volumes that could be achieved in their absence. The operational processes for providing these services are inherited largely from prior Mars missions and takes advantage of lessons learned [8, 11] from those missions and the infrastructure that remains in use today to facilitate the relay coordination processes.

6. REFERENCES

- [1] “Proximity-1 Space Link Protocol—Rationale, Architecture, and Scenarios”, Informational Report CCSDS 210.0-G-1.
- [2] “Mars Relay Operations Service (MaROS): Rationale and Approach”, R. Gladden, AIAA SpaceOps 2010, Huntsville, AL, April 2010.
- [3] <http://lasp.colorado.edu/home/maven/science/>
- [4] <http://trsnew.jpl.nasa.gov/dspace/bitstream/2014/41781/1/11-0046.pdf>
- [5] http://www.nasa.gov/mission_pages/maven/main/index.html
- [6] Relay Communications For Mars Exploration, Charles D. Edwards, International Journal Of Satellite Communications And Networking, Int. J. Satell. Commun. Network. 2007; 25:111–145.
- [7] “Relay Operations Plan Version 3”, Multimission Ground Systems and Services, Doc-0453, JPL D-26272.
- [8] “Mars Relay Coordination Lessons Learned”, R. Gladden et al, IEEE Aerospace Conference, Big Sky, MT 2005.
- [9] “Low Density Parity Check Codes for use in Near-Earth and Deep Space Applications”, CCSDS 121.1-O-2, 2007.
- [10] “The Development of Turbo and LDPC Codes for Deep-Space Applications”, K. Andrews et al, IEEE Proceedings, Vol 95, No. 11, 2007.
- [11] “Mars Reconnaissance Orbiter: The History of Supporting the Phoenix Lander”, R. Gladden, AIAA Space 2009 Conference & Exposition, Pasadena, CA 2009.

7. BIOGRAPHIES



Neil Chamberlain received the BSc. with Honours from Kings College London, UK in 1981. He worked briefly for Marconi Space and Defence Systems, Ltd., Portsmouth, UK before undertaking graduate studies at The Ohio State University, where he received the MS and Ph.D. degrees in Electrical

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Roy Gladden received a Master of Science Degree in Mechanical Engineering from Utah State University in 1999. Since joining the Jet Propulsion Laboratory, he has mostly worked in mission operations, having supported every successful Mars mission since Mars Global

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