Mars Relay Operations Service (MaROS): A Present Service Preparing for the Future

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The Mars Relay Operations Service (MaROS) has been deployed by NASA's Mars Program Office and the Multimission Ground Systems and Services (MGSS) Project into mission operations to aid in the coordination of relay activities at Mars. This live system presents standardized interfaces and a centralized infrastructure to current and future participants in the Mars Relay Network for the purpose of reliably and securely exchanging and storing all relay-related planning and operations data.

The initial development of this system leveraged over eight years of experience performing relay operations between the various spacecraft at Mars. Now, four years after its initial deployment, MaROS continues to undergo further refinement to better meet the needs of the Mars Relay Network. The most substantial, recent update was focused on providing capabilities needed by the Mars Science Laboratory project, which landed on Mars in August of 2012. This paper will describe the nature of that update and describe additional features being added to the system to better serve the needs of current and future Mars missions.

I. A Brief History of the Mars Relay Network

The Mars Relay Network consists of those Mars orbiters that provide relay services to landed assets on the surface of Mars. At this writing, this consists of NASA's Mars 2001 Odyssey Orbiter, NASA's Mars Reconnaissance Orbiter (MRO), and ESA's Mars Express Orbiter. These orbiters "relay" data on behalf of landed assets on the surface of Mars, which presently consists of NASA's Opportunity and Curiosity rovers, from the surface of Mars to Earth-based ground stations. These orbiters each can achieve significantly higher data rates between Mars and Earth than can be achieved by the more power- and mass-constrained vehicles on the surface of Mars, and thus are utilized to transfer nearly all of the science data acquired by these rovers.

In the past decade, this relay network has notably evolved and matured. When ESA's Beagle 2 mission arrived at Mars in late December 2003, Odyssey and NASA's Mars Global Surveyor (MGS) were already on station, and were prepared to provide relay services for that ill-fated mission. Weeks later, with the successful landing of both NASA's Spirit and Opportunity rovers, these two orbiters began providing reliable relay services at Mars for the first time since the Viking missions of the 1970s.

Soon Mars Express was also available for relay services, but was not used for normal relay operations in the aftermath of the loss of Beagle 2. Instead, some relay sessions were performed with the NASA rovers as demonstrations of the capability of Mars Express to perform these services as a backup capability.

After about a year of relay services, MGS was eventually retired from providing active relay support to the rovers, which made Odyssey the primary workhorse for returning the rovers' science data to Earth even while continuing to return meaningful science data of its own. The rovers had far exceeded their design mission lifetime and because they remained healthy, their missions were extended.

In November 2006, MRO entered its operating orbit around the same time as the unfortunate loss of MGS. As MRO was in its primary mission, it performed only a few relay sessions with the Spirit rover to demonstrate its relay capabilities until mid-2008, when the Phoenix lander arrived at Mars. Through the end of 2008, MRO and Odyssey worked together to provide primary relay support to the Phoenix lander, which had no means to communicate directly with its Earth-based operators. During this time, Odyssey still shouldered most of the burden of relay

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support for Spirit and Opportunity, and continued to do so even after the end of the Phoenix mission. Spirit was eventually lost in early 2010.

The relay network continued in this manner until the arrival of the Mars Science Laboratory rover, Curiosity, in August 2012. From that time to the present writing, MRO and Odyssey have been providing primary relay support to Curiosity, with Odyssey also providing primary relay support to Opportunity while MRO serves as a backup to it.

The network will continue to evolve as new missions arrive at Mars. NASA's Mars Atmosphere and Volatile Evolution (MAVEN) orbiter is now en route to Mars and is expected to become available as a primary relay asset after its primary mission is over in November of 2015.

In early 2016, NASA will be launching another Mars lander, which mission is called the Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport; or, more simply, InSight. Around the same time, ESA will be launching the first part of its ExoMars program, consisting of an orbiter called the Trace Gas Orbiter (TGO) and a test vehicle to demonstrate an ESA capability to perform entry, descent, and landing (EDL) at Mars; this vehicle is called the EDL Demonstration Module (EDM). The TGO orbiter will be capable of providing relay services.

In 2018, ESA will launch the second part of its ExoMars program, consisting of a Russian-built lander, which serves as the descent module, and a ride-along ESA-built rover; both of which will require the use of relay services. These missions are expected to be followed in 2020 by another NASA rover, which will also require relay services.

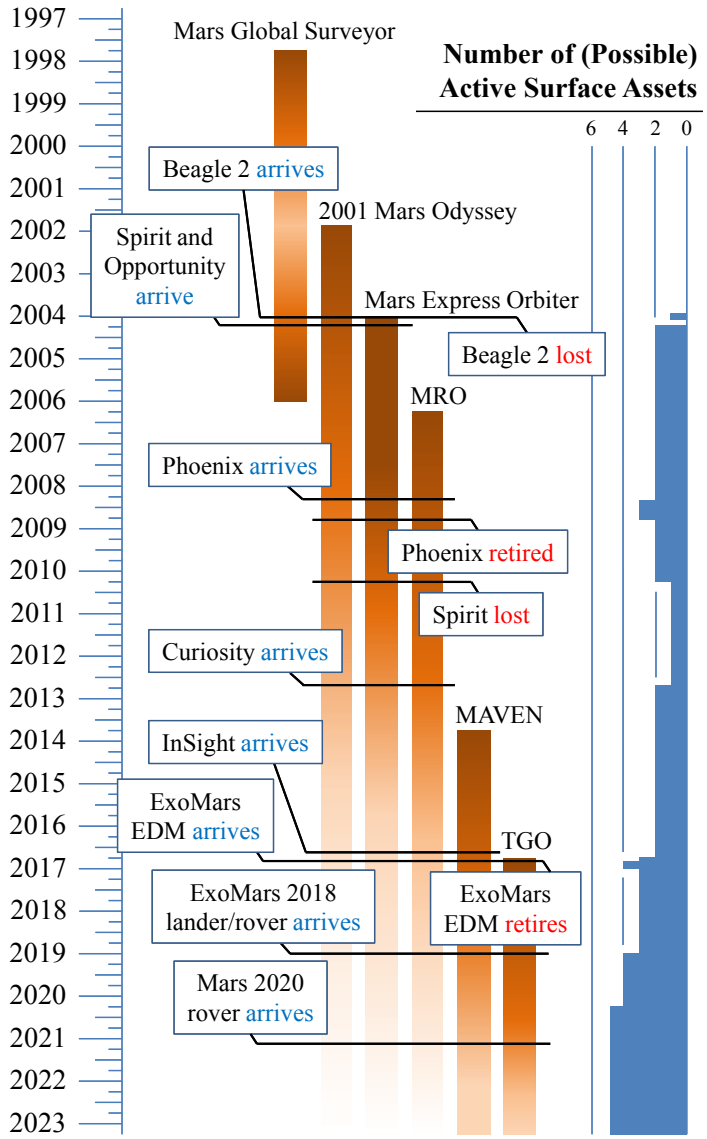

Figure 1. Number of Surface Assets, Both Historically and As Planned. *Exact retirement dates for all ongoing missions are unknown, with each orbiter planning to operate into the next decade and each lander expected to operate until a mission ending event occurs.*

II. Description of the Mars Relay Operations Service (MaROS)

The Mars Relay Operations Service (MaROS) is provided by NASA's Mars Program Office and the Multimission Ground Systems and Services (MGSS) Project at the Jet Propulsion Laboratory in Pasadena, CA. Its maintenance and continued development is funded by these organizations to provide needed capabilities to the various missions participating in the Mars Relay Network.

MaROS functions as a centralized server where all of the data needed to coordinate when and how the orbiters at Mars communicate with the vehicles on the surface of Mars. The service itself was born of lessons learned during the Phoenix landed mission, when it became apparent that the evolving needs of the relay network were not being met by the existing ad-hoc infrastructure that had not been deliberately designed. Of particular concern was the inability to track when changes to long-term plans needed to occur, as these changes were (by design) easy to make and thus no formalized mechanisms were put into place to track them. With

Phoenix, this lack of formality led to some confusion on the part of the lander operators when it came to understanding exactly how any particular relay session had been configured.

With this and other lessons in hand, a deliberate engineering effort began to design a system that would put into place a centralized planning system. Such a system would be required to track the types of changes mentioned. Soon it became apparent that what was previously called "relay" actually had five specific aspects to it, as follows:

1) Strategic Planning, generally consisting of "long term" planning and implementation activities that are required to define a baseline plan for relay service to be provided to landed assets.
2) Tactical Planning, generally consisting of processes that would cause a change to those plans implemented during the strategic planning processes.
3) Forward-Link Data Transfer, consisting of the processes needed to transfer lander command products from the lander operators to an orbiter's operators to the relevant orbiter and then ultimately to the lander itself.
4) Return-Link Data Transfer, consisting of the processes of transferring lander telemetry data from a lander to a designated orbiter to that orbiter's operators and then ultimately to the lander's operators themselves.
5) Accountability, consisting of means provided to both lander and orbiter operators to report on the performance of any particular relay session, both as static reports (for example, the total amount of data that was transferred during a relay session) and as dynamic reports (for example, the amount of data transferred during a relay session as a function of time).

The MaROS development was divided into phases, with continuing efforts being expended to further augment and enhance its capabilities. The first development phase of MaROS was focused on strategic planning and accountability. This phase was first deployed and used by the participants in the Mars relay network in early 2010. The second phase focused on implementing mechanisms to handle the transfer of forward-link files through MaROS. This phase was first used by late 2010 and has been augmented several times since to introduce other needed features. The third phase focused specifically on implementing capabilities needed to support tactical planning. This third phase was implemented on a timeline that would put needed capabilities in place in time to support MSL operations.

The MaROS development itself was somewhat of an experiment. In early 2009, the MaROS design effort began with a very small team of software developers and representatives of the missions that were participating in the relay network at that time. Using agile software development methods, the effort soon produced demonstrable capabilities for strategic planning and accountability.

The original intent was to minimize perturbations to the existing relay processes. This was largely accomplished, but in the act of standardizing the interfaces, particularly the file formats used to exchange relay planning data, some adjustments were required by the participating projects. In addition, some adjustments to the relay processes were required to realign areas of responsibility where there existed some overlap between "multi-mission" functions and "project-specific" functions.

The MaROS development effort continues to this day, mostly with the same participants, with new features being planned and implemented to support the evolving needs of the relay network.

III. Strategic Planning

Each relay function has its own nuances and challenges. The primary challenge of performing strategic planning is in coordinating the various planning timelines for each mission. For example, the Mars 2001 Odyssey Orbiter is commanded using long-duration sequences that span 2 to 4 weeks in duration. Contrast this to the Opportunity rover, which is commanded every day. Thus, the operators of the orbiters tend to favor long-duration planning cycles, whereas the operators of the landed assets tend to favor very short planning cycles.

The lander operators originally desired the orbiters to be responsive on their shorter timeline, which was prohibitively expensive for the orbiter operators. After extensive negotiations, it was decided that the orbiter operators would continue to command their vehicles at their typical pace, but with two adjustments: 1) they would provide a means to make changes to a "strategically" scheduled relay plan (i.e. meaning the use of a "tactical" process would be supported), and 2) they would work to align their planning boundaries with each other (within a few days) to enable the lander operators to schedule relay services with multiple orbiters simultaneously.

Once this was settled, the focus was then shifted to understanding the data that needed to be exchanged between the various spacecraft operators to meaningfully schedule the relay sessions. Some of the data was common, such as the time at which the orbiter should hail the lander, but other data was unique to each orbiter's radio implementation. At the advent of MaROS, an effort was made to understand which parameters could be considered "common" and which should best be handled generically. For the first of these, checking logic could be added to MaROS for the

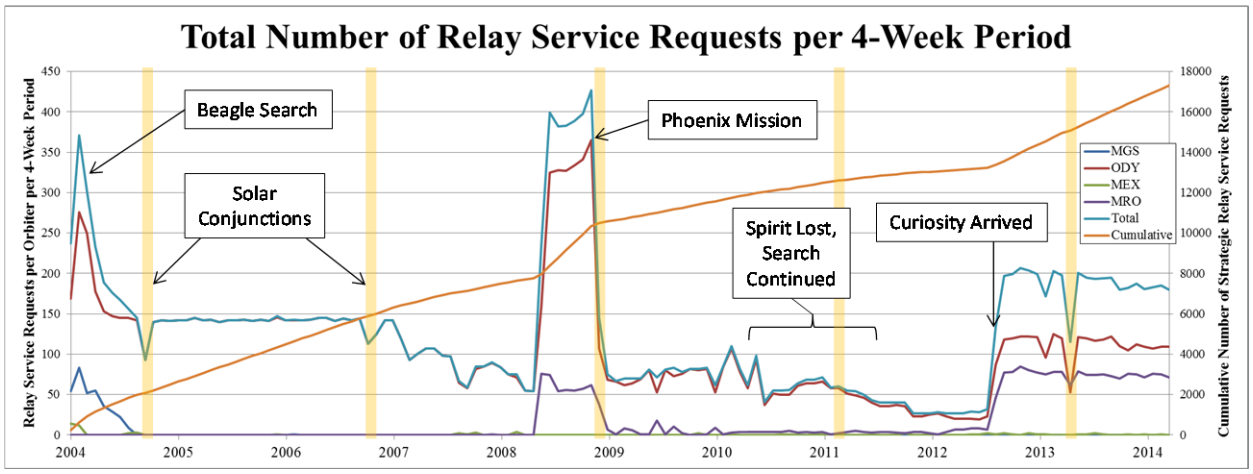

Figure 2. Total Number of Relay Service Requests per 4-Week Period. *Major lander events and solar conjunction periods are marked appropriately.*

intent of seeking for undesirable conditions. In all cases, the lander and orbiter operators must come to an understanding of the parameters and how they are to be utilized.

As MaROS was intended to be a repository to retain a history of all of the relay planning interactions between the operators of the landers and the orbiters, it also became necessary to define different flavors of requests for relay services that could be provided by lander operators. Correspondingly, there was a need to define similar flavors for acknowledgements that could be provided by the orbiter operators to detail their response to those relay service requests. These would all be stored in MaROS and a history kept (see Fig. 2).

An example of a typical request for relay services might specify that a relay session should be configured "normally". Contrast this to a relay session that might be configured as a "contingency" session, whereby the relay session might be scheduled during the strategic planning process, but wouldn't actually cause a relay session with the lander to occur unless a further "tactical" directive was provided by the lander operators to initiate it.

These request and acknowledgement "types" were expanded to handle various scenarios, including the introduction of a relay request where none had been strategically planned, called an "emergency" request. Also included were mechanisms for orbiter operators to decline providing relay support or to tactically specify that support for a relay service request has been cancelled (usually due to an issue with the orbiter).

While these "types" are, strictly speaking, not considered parameters for configuring the relay sessions, they are necessary features of relay service requests to facilitate the interchanges between the various parties during different times in the strategic and tactical planning processes. Once these types were specified, rules were put into place that would highlight if an orbiter acknowledged a request for relay services in a way that was unexpected. This is useful to all the users when coordinating when and how relay sessions are to be configured. These new "types" became the standardized "language" in which relay coordination activities occurred.

IV. Tactical Planning

For tactical activities, there are two primary challenges. The first and arguably more approachable of which is to implement means onboard the orbiters to accept a last minute change in the long-duration sequences that the orbiters implement. Each orbiter handles this problem uniquely, and lessons from one orbiter mission have been effectively applied to subsequent missions.

The second and more challenging problem was to understand the nature of tactical changes, to ensure that there is a short-term (within hours) means of communicating those changes, and to keep a record of all changes that have been implemented. With the addition of "tactical" request and acknowledgement "types" and MaROS acting as a repository of all interactions (especially the "last" state of each relay session), the capabilities of the orbiter project to respond to short-term requests for updates to the relay sessions became the limiting factor.

Within MaROS, these tactical interactions are effectively treated the same as strategic interactions. One related fear that has been alleviated was the possibility that a lander could erroneously make a strategic request after the orbiter operators have already implemented a previously established strategic plan. This fear was mitigated by

adding a means in MaROS to "lock" the strategic requests for designated orbiter planning periods. Once these planning periods have been locked, no further strategic requests are accepted by MaROS – only tactical requests.

V. Accountability

Once a relay session has executed, it is often critical to understand the features of that relay session. Before MaROS, there were often reports provided by the orbiter operators in an ad hoc fashion to limited email distribution lists that indicated the amount of data transferred during a particular relay session. This was historically a manual process, prone to not being sent to key recipients, and often formatted in varying ways so that the information presented therein was not consistent from one report to the next.

MaROS solved each of these problems, in part by providing a means for all interested parties to subscribe to notifications when accountability reports were provided. These reports may now additionally be supplied by both the orbiter and the lander operators, which enables both sides of the relay link to indicate their perspective on how well a relay session performed. The reports include specific information, are formatted in a standardized fashion, and are submitted directly to MaROS.

The reports also have been fragmented into two types, namely one that provides "fixed" values for a relay session, such as total data volumes transferred (see Fig. 3) or maximum signal strengths experienced; and one that provides "dynamic" values for a relay session, such as geometric relationships between the lander and the orbiter, signal strength, and counts of data transferred as a function of time. These two types of data can be viewed via a web-browser application which has a graphical nature to it.

MaROS stores all this information in the same database as all other relay planning information. In doing so, all relay planning data – from the earliest planning stages to the post-relay session reports – are captured in one location and can be directly accessed and correlated by authorized users.

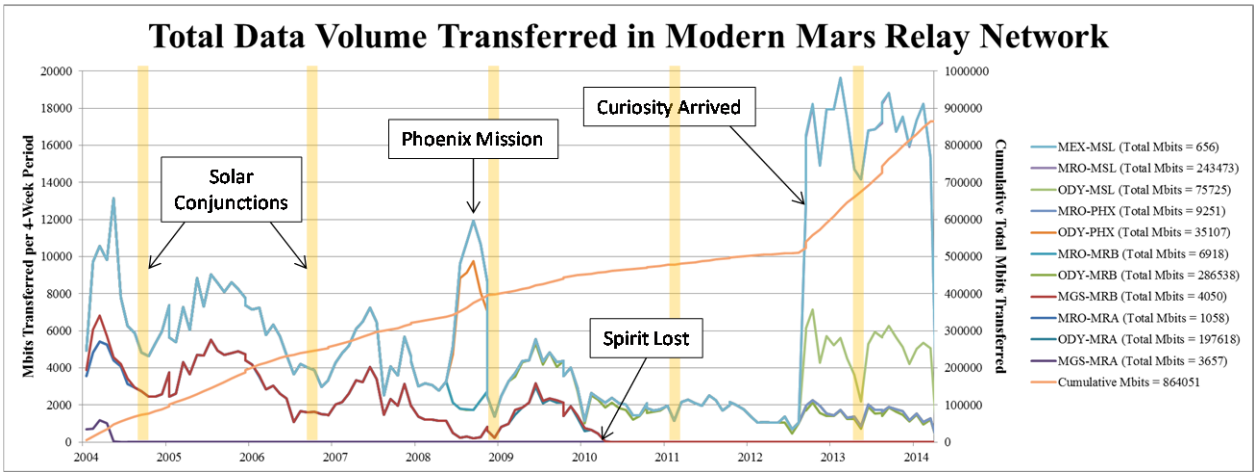

Figure 3. Total Data Volume Transferred per 4-Week Period. *Major lander events and solar conjunction periods are marked appropriately.*

VI. Forward-Link Data Transfer

Prior to the introduction of MaROS, the operators of each lander and each orbiter had different processes and means to exchange forward-link data (command data destined for the lander that is transferred via an orbiter). As the network evolved and more orbiting and landed assets were added to the network, it became clear that a general solution was needed.

MaROS introduced a standardized interface for all participants. What was implemented became a single point to which the operators of each lander could interface and from which they would gain access to the forward-link capabilities of all the orbiters. Similarly, it served as a single point to which the operators of each orbiter could interface and from which they could receive forward-link data from all of the lander operators. The instantiation of these single interfaces for each mission enables them to gain or grant service to new missions added to the network without any additional cost for this interface.

The data that the lander projects submit to the orbiter projects must be delivered to the lander without alteration or otherwise corrupted; this is required to meaningfully command the landers safely. Prior to the orbiter operators

handling the data product, MaROS acts as an intermediary to transfer the data and utilizes certain security features to ensure this handoff occurs without issue. CRC checks are performed on the product at submission (by the lander operators) and extraction (by the orbiter operators) time. This CRC check is in addition to other security features of the service which restricts access both to the network on which MaROS is hosted and additional restrictions on which system users can perform what function within the service.

It is understood, however, that each orbiter project needs to package the forward-link data as if it were orbiter data prior to transferring the data to the orbiter, and then subsequently takes the responsibility to ensure it is de-packaged appropriately at the time it is transferred to the lander. In this manner, the data transmitted to the lander represents the same bit pattern received by the orbiter operators via MaROS.

VII. Return-Link Data Transfer

Return-link data is handled uniquely for each vehicle and MaROS is not involved in this interchange. JPL's Deep Space Network (DSN) Project provides services that predate MaROS to handle this data. In principle, the DSN intercepts all the data that an orbiter transmits, recognizes if any data therein is intended for lander operators, and then extracts and transfers such data to the lander operators. To date, it has been decided not to modify this interface and to continue to leverage these existing services for future missions. Variations on this approach exist for current and future ESA missions, not to be discussed here.

VIII. MaROS Updates for MSL

Prior to the arrival of MSL at Mars, a major update was planned to put into place specific capabilities that could be utilized by the lander operators. In particular, tactical changes were handled exclusively via file interactions. It was greatly desired by the MSL operators to be able to manage tactical requests directly via a web-browser application that was previously available only to view all of the relay planning and coordination data. To implement features of this nature, a major update to the MaROS system was planned and implemented leading up to the landing of MSL at Mars.

This capability proved to be enormously beneficial. Prior processes for performing relay operations relied on the construction of properly formatted data files that needed to be submitted via offline means. By adding a new capability to the MaROS web-browser application to manipulate request and acknowledgement data directly, simplified processes could be put into place by the user missions that focused the work of relay coordination less on the formatting and submission of a data file and more on the nature of the relay requests and their attending parameters.

The web-browser application now allows authorized lander and orbiter users to graphically select lander/orbiter view periods for the purposes of submitting a request or acknowledgement. Once selected, the application automatically presents to the user the options that need to be selected in pull-down menus (see Fig. 4). It further restricts those options to only those that are allowable given the conditions of the relay session in the planning cycle. These new features enable the lander and orbiter operators to very quickly submit and reply to tactical changes.

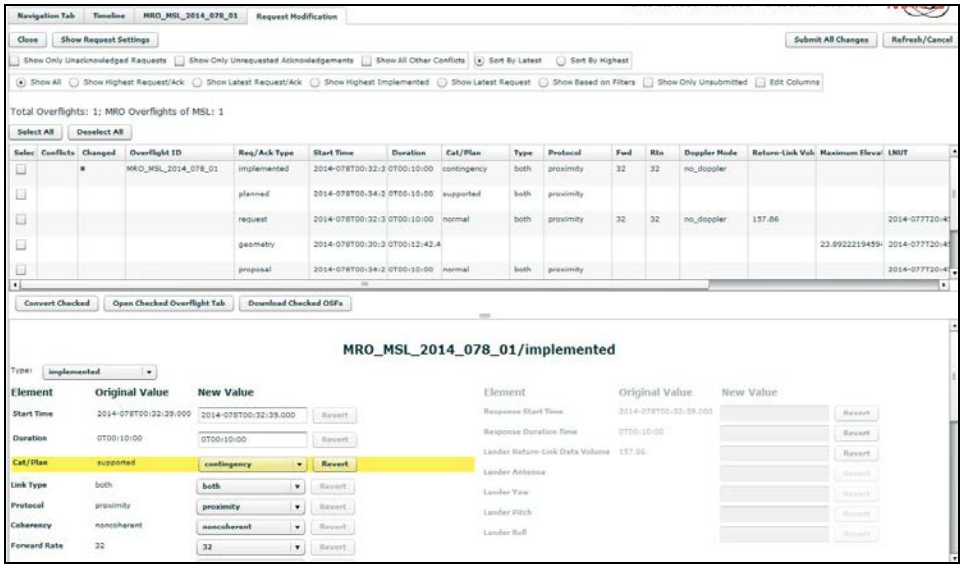

Figure 4. The Request Modification Tab of the MaROS Web-Browser Application. *This tab allows authorized users of the system to make needed changes to requests and acknowledgements with a minimum of effort.*

Other changes were also made to the system to improve the relay coordination workflow. For example, orbiter operators publish to MaROS predictions of when acquired lander data will be returned to Earth. These predictions are a function of the DSN tracking time that each orbiter has available to them, which are generally published to MaROS via data files. Just as lander users desired the ability to modify relay service requests directly through the MaROS web-browser application, the orbiter users also desired an ability to manage their own DSN planning data in a similar manner. An update to MaROS was made to provide this capability via a MaROS view of a timeline. This "timeline editor" greatly augments the ability of an orbiter's operators to update the MaROS database with meaningful data that affects the performance of the relay network.

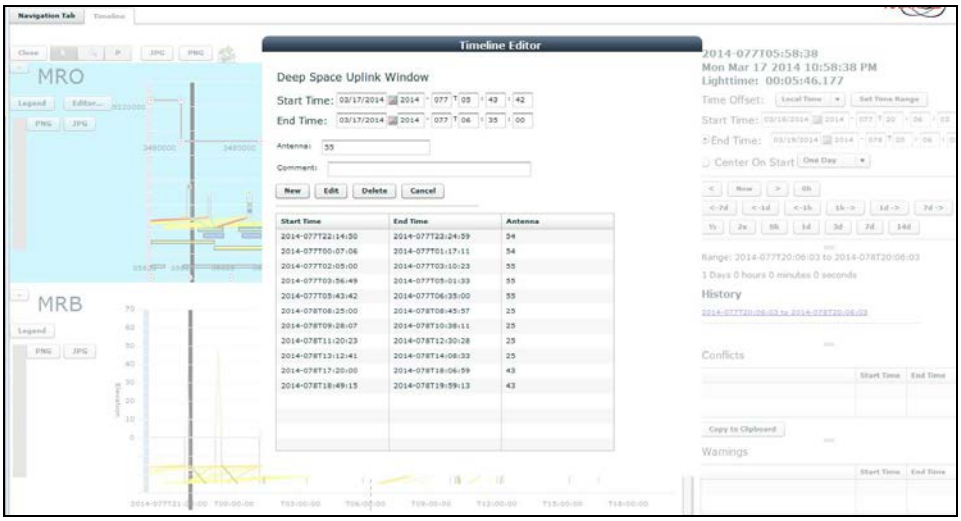

Figure 5. The Timeline Editor of the MaROS Web-Browser Application. *This editor allows authorized users to rapidly make changes to orbiter event data to quickly reflect changes that may affect latencies related to both forward- and return-link data transfers.*

With these changes, nearly everything that could previously be done via a file upload can now also be done via the MaROS web-browser application. This has enabled some user processes to be streamlined and for mission-side cost savings to be realized.

Other minor updates were also added that improved some record-keeping within the MaROS database. For example, prior to MSL's arrival, the system would retain a record of all data files published to the service as part of an "event history". With the move towards more interactive operations via the MaROS web-browser application, it became apparent that a secondary mechanism for record-keeping would be useful, namely by tracking all changes made to a specific relay session. This new mechanism came to be called the "overflight history" and records everything from updates to the geometric characteristics of a relay session to changes made to any parameter at any level of planning. Now, a comprehensive history of a relay session is kept, which has proven to be useful when needing to identify who made what change, when, and why.

Along with this update came a more thorough means of handling "comments" in the system. Before MSL's landing, only comments included in the header of a file were retained by the system. Now, comments can be attributed to most every data field, which allows users to indicate the rationale for why a parameter is being set to a specific value. This is most useful when performing tactical changes, where only a single parameter may need to be adjusted, and further improves the usability of the system and augments the situational awareness of the participants in the relay network.

These updates were put into place along with many other MaROS web-browser application improvements, system-level enhancements, bug fixes, etc.

IX. Continuing Evolution

MaROS will continue to evolve just as the Mars Relay Network does. Planned updates are already in development to further improve the system in anticipation of future missions. First among these new features is the implementation of an interface between MaROS and a DSN service called the Service Preparation System (SPS), which will enable the MaROS to always remain up-to-date with the latest navigation predictions for all of the vehicles at Mars. This interface will leverage existing capabilities within SPS to detect and determine the nature of view periods between the landers and orbiters at Mars.

This change will provide cost savings to all of the participants in the relay network. The lander projects will no longer need to self-determine the view periods of their landers with the orbiters, and the orbiter projects will no longer need to directly interface with each lander project to provide regular updates to their trajectories. This will

result in a net reduction in operational complexity – with the attending cost savings – and a dramatic improvement in the understanding of the actual geometries of the relay sessions at any given point in time.

Next to be implemented is an updated set of algorithms for modeling the onboard storage areas of the orbiter missions. As each orbiter has a different method of handling data onboard, these algorithms need to be flexible enough to support a variety of most-likely scenarios. What was most notably missing from the previous models, which were used to calculate when acquired return-link data would be transferred to Earth, was any understanding of multiple onboard buffers of a fixed size. The previous models within MaROS assumed the presence of a single onboard buffer of unlimited size. Thus, buffer overflow conditions, such as would occur if several relay sessions were scheduled with no attending transfer of the data to Earth, went undetected.

In addition, there was no means of modeling the sharing of bandwidth between multiple buffers when transferring data to Earth, with varying prioritization and bandwidth sharing schemes. Without these nuances, the predictions for when return-link data would be available to the lander operators were flawed. Assuming a single, sufficiently large buffer existed onboard an orbiter, the MaROS models functioned as designed, but this assumption does not stand even for all of the existing missions already at Mars.

One other change that will be implemented is a refactor of the MaROS web-browser application into a more modern architecture. Presently, the system servers up a single Flash application to facilitate much of its graphic-intensive functionality. It is desired to update this interface from the current monolithic and performance-limited application to a more discrete and modern series of applications.

X. Conclusions

MaROS has continued to evolve as the needs of the relay network have demanded. Despite the above-mentioned changes that are planned, there are none that are required to support the spacecraft that will be arriving at Mars in future years. This is a testament to the deliberate effort that was expended to engineer a system that would be flexible and applicable for years to come. Further development will continue to improve the service and will implement desired features or resolve known issues.

With this service now available as a standardized system, new missions can now attune their relay planning processes and architectures to the interfaces that are available via MaROS. New missions can be introduced with minimal cost. For both lander and orbiter missions, relay services can be accessed or granted to multiple parties with the implementation of just the one ground system interface to MaROS. In years past, this approach has been shown to save each participating mission millions of dollars in non-recurring development costs and reduce by millions more those recurring costs associated with ongoing relay operations. As new missions are introduced into the relay network, the overall cost savings will continue to multiply.

Acknowledgments

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