End-to-End Information System Concept for the Mars Telecommunications Orbiter

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Abstract—The Mars Telecommunications Orbiter (MTO) was intended to provide high-performance deep space relay links to landers, orbiters, sample-return missions, and approaching spacecraft in the vicinity of Mars, to demonstrate interplanetary laser communications, to demonstrate autonomous navigation, and to carry out its own science investigations. These goals led to a need for an array of end-to-end information system (EEIS) capabilities unprecedented for a deep space mission, performed cooperatively by many system elements. We describe here the EEIS concept for provision of six major types of services by the MTO: relay, open-loop recording, Marscraft tracking, timing, payload data transport, and Earthlink data transport. We also discuss the key design drivers and strategies employed in the EEIS design, and possible extensions of the MTO EEIS concept to accommodate scenarios beyond the original MTO mission requirements.

INTRODUCTION

The Mars Telecommunications Orbiter was originally conceived as a key part of NASA's Mars Exploration Program, contributing to the robustness and overall science data return of other missions in the program by providing high-performance proximity (near-Mars) and deep space links. MTO's proximity link capability was sized such that it was relatively energy-efficient compared to other alternatives, allowing customer missions to reduce their telecommunications power and hardware requirements. This advantage would allow them to apply more of their limited mass, power, and volume budgets to science instruments. MTO was also suited to provide access to telemetry from near-Mars critical events such as entry, descent, and landing (EDL), Mars orbit insertion (MOI), or ascent from Mars. Additionally, MTO was to provide an independent measurement capability for navigation of approaching Marscraft. These latter two features were to contribute to the safety of individual missions, as well as to the overall robustness of the program in feeding lessons learned forward to later missions.

MTO was also conceived as a high-level component within a larger Mars telecommunications network, encompassing multiple Mars-orbiting, landed, and Earth-based assets. The advancement of this network as an evolving communications infrastructure around Mars led to a need for an array of end-to-end information system (EEIS) capabilities unprecedented for deep space missions. To be effective, telecommunications needed to be performed cooperatively by many system elements. We describe here the EEIS concept for provision of six major types of services provided to users of the Mars Network EEIS: relay data and control message transfer, open-loop recording, Marscraft tracking, timing, payload data transport, and Earthlink data transport.

A need to restructure programs within NASA to facilitate manned space exploration eventually led to the July, 2005 cancellation of MTO. However, the mission team had by that time completed a great deal of the mission and spacecraft design, selected the spacecraft contractor, and defined the large-scale and medium-scale features of MTO's EEIS. The EEIS was called on to handle a wide range of challenges pertaining to relay services, open-loop recording, Marscraft tracking, timing services, payload data transport, and Earthlink data transport over multiple RF data links, and over an experimental optical space data link. It is likely that these challenges will be faced, in whole or in part, by the new missions of the restructured Mars Exploration Program. Therefore we are reporting the MTO EEIS conceptual design as a reference for future mission designers.

Overview of the Physical Systems

Figure 1 provides an overview of the MTO physical systems. MTO was planned to have three space links for the long haul to Earth. There was to be a Ka-band link with a redundant operational transmitter power of 35W. An experimental 100W Ka-band transmitter was also planned. Redundant 15W X-band transmitters were included, with consideration of an upgrade to 25W. Both of these links used a 2.5 m high-gain antenna (HGA), and would be completed by the 34-meter beam waveguide class of antennas within NASA's Deep Space Network.

The third space link was to be provided by an experimental 5W laser with 30 cm optics. This two-way link was to be completed by a variety of ground-based optical observatories within what came to be known as the Mars Laser Communications Demonstration (MLCD) Ground Network (MGN). The optical stations included very large apertures, new medium-size apertures, and arrayed apertures. From an EEIS perspective, the key feature of the MGN was its geographical, technological, and organizational diversity. These factors

A two-way UHF link was to be provided with a steerable medium-gain UHF antenna, connected to redundant Electra transceivers. A receive-only X-band link was also planned with an extra down converter in the Electras, the X-band antenna steerable along with the UHF antenna. Various science and engineering payloads were also planned as enhancements to the basic telecommunications mission.

The MTO was planned to have substantial onboard storage, likely greater than 350 gigabits. Power would be supplied entirely from solar arrays totaling 14 square meters.

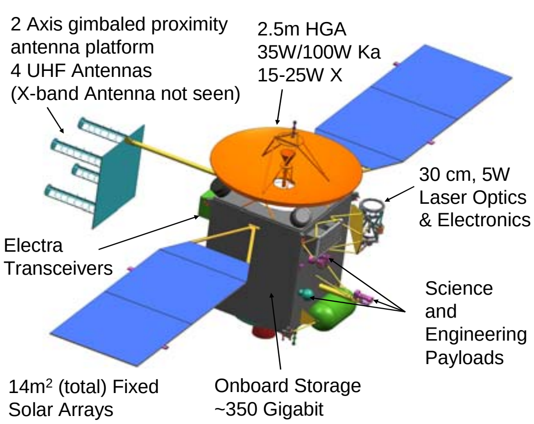

Figure 1. MTO Physical Configuration

Figure 2 summarizes the typical applications contemplated for MTO: routine telemetry, command, and tracking support of large landers, small landers, or aerobots; critical event communications to orbiters, landers, or ascending vehicles; relays from other orbiters; and long-range approach navigation. Typical proximity data rates were expected to be in the range of 1-64 kbps at UHF, and up to 4 Mbps at X, although the Electras were capable of up to 4 Mbps at UHF as well. The Earthlink data rates were expected to be in the range of 50 to 500 kbps at X-band, 350 kbps to 6 Mbps at Ka-band, and 1 to 30 Mbps at optical wavelengths.

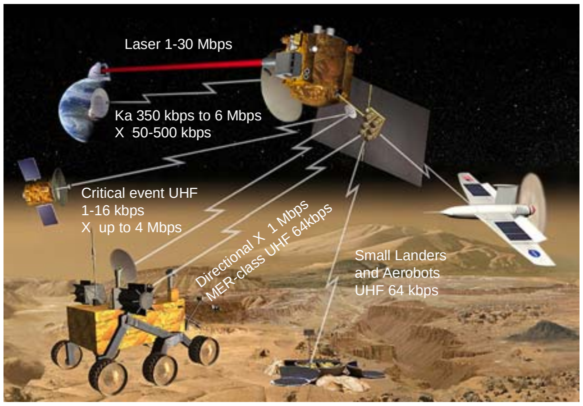

Figure 2. Typical MTO Operational Applications

KEY DESIGN DRIVERS

The key design drivers were requirements for short turn-around time capability for monitoring and commanding of Marscraft, the ability to deliver complete and error-free files in both the forward and return relay link directions, data accountability at each major network node to facilitate anomaly recovery and operations, autonomous function of routine services (e.g., scheduling, command delivery), prioritized transfer of data to and from a Marscraft, the capability of transferring data and control messages between orbiter and Mars bound assets, and accurate time and Marscraft Doppler measurements. These are discussed in more detail below.

Short Turn-Around Time Capability

In situ exploration of the surface of Mars is an operationally-challenging endeavor. The round-trip light time between Earth and Mars, ranging from under 10 minutes to more than 40 minutes over the course of the Earth-Mars synodic period, precludes “joy sticking” of landed spacecraft; Martian landers and rovers must be equipped with sufficient autonomy to operate on their own over these periods. On longer time scales, however, Earth-based science and engineering teams need the ability to close planning loops on a regular basis to evaluate the most recent spacecraft status and *in situ* environment, and to establish goals for the upcoming operational cycle. The efficiency of surface operations is directly tied to the ability to close this Earth-Mars planning loop in a timely manner. Current missions typically desire once-per-sol planning cycles, with data collected at the end of the Martian day used to support overnight (Mars time) planning activities on Earth, leading to a command load that can be delivered to the spacecraft by early morning the next sol. In this regard, the end-to-end latency of communications between operators on Earth and the Mars surface spacecraft must be minimized so that these latencies do not significantly curtail the time available for planning. Future operational scenarios could benefit from even shorter sub-sol planning cycles to further increase productivity of life-limited *in situ* spacecraft. Finally, low end-to-end communications latency becomes critical in the event of a mission anomaly, supporting rapid diagnosis and recovery activities.

Complete and Error-Free Files

The ability of the end-to-end information system to support delivery of complete and error free data products allows for more robust operations and provides high-quality science products. The proximity link between lander and orbiter is particularly vulnerable to significant channel variation during the course of a given contact opportunity, due to large changes in slant range and antenna gain as well as the effects of multipath scattering. The short round-trip light time of the proximity link allows straightforward use of ARQ-schemes to retransmit lost frames; other approaches are needed for the long round-trip delays associated with the deep space link.

Data Accountability

Customers, operations teams, and management teams must from time to time make decisions that require knowledge of the performance and state of telecommunications services. Therefore the EEIS had to provide accountability reports, realtime visibility into the progression of customer data through the system, and system performance and status reports.

Autonomous Function of Routine Services

A long service life was contemplated for MTO, six years required of the hardware along with a reserve of consumables for an additional four years. The projected operations cost was a substantial portion of the entire budget, and automation of routine services was an effective approach to controlling the long-term operating cost. Full automation of anomaly response is usually expensive, expensive per use, and risky. Therefore the goal of autonomy in the EEIS was limited to routine operation, lower levels of fault detection and isolation, and graceful degradation in the event of a fault.

Prioritized Data

Not all Marscraft data are created equal, and as a result, the EEIS needed to include the ability to assign a range of priorities to individual data products. Products that support time-critical planning activities can be assigned high-priority, allowing them to move to the front of the queue for store-and-forward relay, and potentially driving the deep space link configuration (e.g., choice of frequency band or link margin) to maximize the probability of successful product delivery without need for retransmission. Similarly, bulk science products can be assigned lower priority, allowing delivery of these products with higher latency as resources allow.

Data and Control Messages

Several of the foregoing drivers lead to a derived need for routing of control and status messages. The delivery of complete and error-free files requires that the MTO flight system, ground system, and Marscraft keep each other informed as to delivery specifications, the need to correct gaps in received data, the need for actions to be carried out elsewhere in the system (e.g. send a file directory), and the intent of any given transaction. Prioritization requires the ability to inform all parties along the line of the priority of a data file, and the ability to account for data requires the transfer of status information to the accounting parties. All of these need to be tolerant to the possibility that any single message may be lost or corrupted during transport.

Time and Radio Metric Measurements

In addition to supporting telecommunications services, proximity radio links also enable timing and radio metric measurement. Timing services allow a Marscraft to accurately synchronize its time base with UTC; in a relay scenario this involves a multi-hop transfer of time from the DSN's highly accurate time standards to a relay orbiter, and then correlation of the orbiter's clock epoch with the Marscraft's clock over the proximity link.

Measurement of the Doppler shift and/or propagation delay of radio signals between a relay orbiter and a Marscraft provide radio metric information that can be used to support precise *in situ* navigation. Because the orbiter's trajectory is gravitationally tied to the planet, these tracking observables have the advantage of directly tying the Marscraft into an inertial Mars reference frame. Representative navigation scenarios include precision approach navigation, surface position determination, and orbital rendezvous operations.

Flexibility for Future Customers

Because MTO has a lifetime longer than the planning cycle for its future customers, it needed to be adaptable to a wide range of operating conditions. From the performance perspective, the future operating conditions will be characterized by fluctuations in Earthlink capacity, proximity link capacity, and a varying mix of customer needs for completeness, latency, and data volume. For this reason the EEIS needed to allow users to select the required latency of their data, to specify the priority of data, and to choose between incomplete (single transmission) and complete (retransmission) delivery as the system capacity and their needs change from time to time. Realistic performance of the space links would vary over a wide range due to distance changes, and in some cases due to weather, so the ability to adapt data rates to actual conditions was needed.

From a protocol perspective, future customers were likely to have varying degrees of compatibility with the international standards for data transport. For this reason the EEIS needed to be fully compatible with CCSDS Proximity-1 Link Protocols and the CCSDS File Delivery Protocol. It also needed to be capable of providing service with or without CFDP, and with or without Proximity-1.

From a scheduling perspective, it was highly desirable that MTO be capable of providing continuity of service across interruptions in mutual view between MTO and the Marscraft, and that proximity operations be possible with or without a concurrent Earthlink. Also, some future mission scenarios include up to six Marscraft in the vicinity of MTO, contemporaneously. The system needed to be capable of handling them in a serial fashion, one link at a time, but with as little coupling between them as could be arranged.

The performance of the services included many fundamental tradeoffs between data completeness, volume, continuity, and latency. Also, the services possess some sensitivity to factors outside its control such as customer data input characteristics, weather, and occasional loss of system components. Furthermore, the management of space data systems involving long round-trip light times is still in its infancy, so operational experience was expected to be important to guide the system optimization. For these reasons, the EEIS needed the ability to adjust its data management and prioritization rules on an occasional basis.

Variations in the Performance of Mars-Proximity and Earth Data Links

A key feature of the Mars telecommunications environment is the variability of link data rate. On the Earth link, well over 10 dB variability arises from the predictable variation in range between Earth and Mars, and for the Ka-band Earth link another 6 dB or more arises from weather uncertainty. On the proximity link, the variations in slant range, antenna gain, and multipath introduce variations of well over 10 dB. The EEIS needed the ability to provide good quality services in the face of these variations without either undue operational burden or wasted capacity when available.

Optimization among Service Characteristics

The performance of telecom links includes many fundamental tradeoffs between data completeness, volume, continuity, and latency. The MTO mission was expected to provide a substantial increase in the total data volume to a Marscraft, compared to what they could do with a DTE link of their own. This created a demand for high data rate. However, all other factors being equal, data rate is obtained at the expense of signal-to-noise ratio. With a fluctuating channel, losses therefore increase at higher data rate. To some extent this tradeoff can be improved by retransmission, at the expense of increased latency. The customer's operational needs dictated that at least some data be transported with both low latency and high reliability, ruling out retransmission as a solution in some cases.

The MTO mission also needed to provide a high utilization of the RF Earthlinks, partly because of the cost of tracking time, but perhaps more importantly because of the drive to increase total data return for science purposes. The Ka-band DTE link, in particular, provided an opportunity to increase the total data transported as the reliability of single transmission is relaxed, with a flat peak between 80% and 90%. The benefit was expected to be about a factor of four compared to a link designed with 95% to 98% reliability. The X-band Earthlinks had a similar but milder character, with the best data volume around 95% reliability and about factor of 1.2 benefit compared to a 98% reliable design. The EEIS needed to be designed to take advantage of the gains offered by a range of reliabilities depending on customer needs.

A final driver was the degree of completeness needed for the "complete" delivery of customer data. Of course, any real system would not in principle be capable of providing perfectly complete data, though it might conceivably provide completeness so high that data loss would not be observed within a finite mission lifetime. However such a system could be very expensive. A more modest goal was set for MTO, merely to provide data that was complete enough that a customer would not need to have a substantial system of their own for data completeness. An occasional replay under customer's manual direction would be allowed, when MTO did not provide completeness.

MTO EEIS SERVICES

A service approach was selected to simplify the interactions between MTO and its customers. The activities of MTO were divided into six types of service: relay, open-loop recording, Marscraft tracking, timing, payload data transport, and Earthlink data transport. The first five services all rely on the Earthlink data transport service.

All of the services have essentially the same physical characteristics. In the return direction, data originates at the Marscraft and is received by Electra and is either recorded or forwarded to Earth by the MTO command and data handling computer. Alternatively the data may originate at a payload in a similar role to Electra. The telecom or Mars Lasercom Terminal (MLT) subsystem forwards the data to Earth where it is received by the DSN or the MGN. These are connected to the MTO Central mission operations system (MOS) via a combination of WANs and LANs, and thence to the Customer MOSs via a flight LAN. The forward services proceed in the reverse of the above.

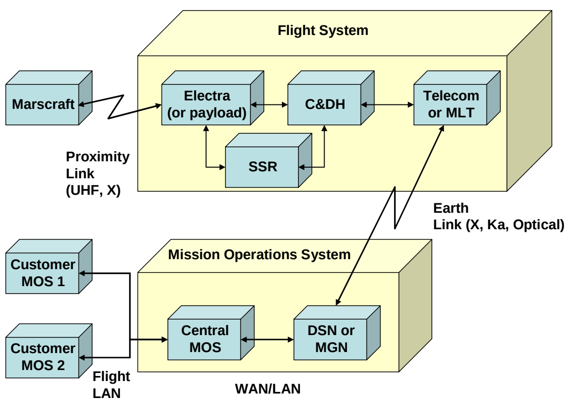

Figure 3. Physical view of MTO services.

Relay

The relay service would transport customer data in the form of files or time-bounded segments of data streams, between sources located in either the Marscraft or the customer's mission operations system (MOS). In the return direction, the data would be provided in incomplete form (single transmission), incremental form (best data available at the end of each gap-filling retransmission), or complete form (either when complete, or best data available at the end of a specified time window). In the forward direction, both incomplete and complete form would be provided. Transmission and retention prioritization would be provided in both directions.

Open-Loop Recording

The open-loop recording service would be provided for critical event coverage. The MTO Flight System would receive X-band or UHF carriers, possibly modulated by "semaphore" tones, from a Marscraft. The Electra would convert these signals to baseband and sample the resulting voltage. A file of the voltages would then be forwarded to Earth. The customer would be responsible for processing the recording to extract information of interest to them.

Marscraft Tracking

For Marscraft tracking service, the MTO Flight System would generate a UHF carrier, which can be transponded by the Marscraft to an X-band carrier, a UHF carrier, or both. The Electra would measure the two-way Doppler frequency of the carriers received at MTO, and forward a file of the resulting measurements to Earth. Ancillary data concerning link status and quality is included in the file. Light time delay would be provided by exchanging time tag information between MTO and the Marscraft.

MTO could provide the Doppler and time delay measurements in closed loop tracking of the proximity link. However the radio metric measurements could not be made during open-loop recording services.

Timing

Two timing services would be provided: a time correlation service and a time distribution service. In both services, the proximity link would be used to exchange timing information between the MTO flight system and the Marscraft, while the MTO flight system would report its own timing information to the ground system. The ground system would measure its timing offsets relative to the National Institute of Standards in Boulder, Colorado, using Global Positioning Satellite (GPS) signals.

In the time correlation service, MTO would determine the offsets between all its internal clocks relative to UTC as realized by NIST at Boulder, Colorado. These offsets would be analyzed by MTO using a combination of manual and computerized calculations, to provide predicted and reconstructed offsets as a function of date. The resulting files would be available for use by the customer MOS, would be maintained onboard the MTO flight system, and could be forwarded to the Marscraft using the relay services if desired. MTO will also measure the offsets between the Marscraft clock and one of the MTO clocks, specifically the timebase in the Electra onboard MTO, using the Prox-1 Time Tag Capture Method. This method results in the offset between the Electra clock and the Marscraft clock being known to both Electra and the Marscraft. MTO would forward the measured offset to the Marscraft MOS. Further action such as reconstructing or predicting the Marscraft clock, or commanding Marscraft clock adjustments, was to be the responsibility of the Marscraft MOS.

In the time distribution service, MTO would also transfer time to the Marscraft using the Prox-1 Time Distribution directive. This directive would contain the correlation between UTC as realized at NIST, Boulder, Colorado, and the Marscraft clock. The latest available data onboard MTO resulting from the time correlation service would be used in the directive.

For both services, MTO was to provide all necessary project system interactions with NIST and GPS, and between the MTO flight system and MOS time management functions.

Payload Data Transport

MTO planned to provide all the same services for payloads as Earthlink data services described in the next paragraph. Additionally, storage of forward and return data was to be provided. The same qualities of service were to be available for payload data services as for relay services.

Earthlink Data Transport

Four basic services were to be provided on the Earthlink to support the other services. These were forward and return services, each over the RF or the optical space data links respectively.

For RF Forward services, the functions provided were to be file transport or command link transmission unit (CLTU) services. Either file transport or CLTU could be used contemporaneously.

For RF Return services, the functions provided were to be file transport, packet transport, or frame transport. Any of file transport, packet transport, or frame transport could be used contemporaneously.

For optical services, the functions provided are the same as RF, plus bitstream transport in both the forward and return directions.

A rule-based routing function was planned to direct any of the above functions except bitstream transport to be carried out using any of the available physical Earthlinks. Bitstream was planned to be provided over the optical Earthlinks.

Data accountability was to be provided for all functions except bitstream transport.

DESIGN STRATEGIES

Interoperability and cross-support is designed into the MTO EEIS for future mission users with varying degrees of compatibility with CCSDS international standards for data transport, for variable numbers of customers, for adaptation to realistic variations in the performance of Mars-proximity and Earth data links, and for optimization among competing characteristics of data completeness, volume, continuity, and latency. The key strategies employed in the EEIS concept are product-based data transport, inheritance of existing international protocols and their corresponding implementations, adaptive proximity data rate control, scheduled autonomous operation of the relay for demand access activities, automated execution of complete data transport, automated generation of accountability reports, routing of data and control messages to physical or logical entities, automated target tracking, high margin on spacecraft storage and throughput in normal operation, graceful degradation under stress, and minimization of the need for complex control evaluations and routine simulations of operation. These are described in more detail below.

Product-Based Data Transport

MTO was to support three kinds of products: files, stream segments, and messages.

Files were to be formed by the customer at the Marscraft, payloads, or the MTO command and data handling subsystem (C&DH). File transport was to be carried out using the CCSDS File Delivery Protocol (CFDP). The customer also had the option of choosing to use ordinary file transfer protocol (FTP) for the last hop from the MTO ground system to their MOS.

MTO was to use a store-and-forward style of CFDP, in which the file was to be reconstructed at each waypoint. The data rates available with MTO were to be high enough that the latency introduced with this approach was insignificant for the intended applications. MTO was also to support CFDP proxy operations described in the CFDP specification.

A stream segment, either a frame or packet stream segment, was to be treated as a product bounded by start and stop times. For the return direction, MTO was to create a file containing a stream segment at either the MTO spacecraft or the MTO ground system, at customer option. The resulting file was to be available as either a CFDP transaction (either end-to-end or nearest neighbor), or an FTP transaction.

Stream segments were not planned to be directly supported in the forward direction. If a customer had a forward frame stream, it would have to be converted to a file before provision to the MTO GS.

Messages were to be handled by MTO as CFDP "message to user" File Directive protocol data units (PDUs). The content was to be at the discretion of the customer.

MTO planned to use a delivery specification for each product. The content of the delivery specification was still under discussion at the end of the project, but was likely to contain information similar to the following: name, associated customer activity, destination, quality of service (low-latency/bulk, complete/incomplete), priority, delivery deadline, disposal date, custody transfer rule (when complete, disposal date, when directed), deletion rule (when custody transferred, disposal date, when directed), CFDP transaction type (none, end-to-end, nearest-neighbor), precedence of delivery specifications in case of multiples received. The mechanism for communicating the delivery specification was to be the CFDP metadata PDUs for CFDP transactions, or a service request from the customer. In cases where a customer supplies a delivery request by both CFDP metadata and by a service request, the precedence indicated in the service request was to be used.

Protocols

Table 1 lists the protocols planned for use on MTO.

Table 1: Mars Layered Protocol Stack

OSI Layer	Protocol Features
Physical	DFE/DTE Links and Proximity Links *RF & Mod* *Prox-1*; Electra extras Convolutional Code
Data Link	DFE/DTE Links and Proximity Links *TC, AOS* *Prox-1* *R-S, Turbo, LDPC codes*
Network	*Encapsulation Packet* *SCPS, IPV4, IPV6, CFDP, Bytestream(CLTUs),others*
Transport	*CFDP*
Session	N/A
Presentation	N/A
Application	Product, Message, H/W cmd, Byte stream, one of a kind data type (e.g., EDL)

Adaptive Proximity Data Rates

To date, relay operations have been sequenced in advance: the data rate for a given pass is selected based on *a priori* modeling of the telecommunications link. Typically a single data rate is selected for the entire pass, necessarily with an ample link margin to account for the variations in link performance over the pass due to changing geometry and multipath effects.

A better option for the short-distance proximity link, however, is to allow the transceivers at each end of the link continuously negotiate the optimal data rate over the course of the pass, based on actual measurement of the link performance. This adaptive data rate strategy maximizes the data return over the pass by allowing the transmitted data rate to track the actual physical channel's link capability over the pass without unnecessary margin. For passes with significant variation in slant range, antenna gain, and multipath, such a strategy can significantly increase data return. It also increases robustness to adverse link conditions by automatically reducing data rate in this case to the maximum supportable. Finally, and perhaps most importantly, it significantly simplifies relay operations by eliminating the need for detailed *a priori* link modeling of every relay pass.

The adaptive data rate capability is currently being developed under the Mars Technology Program as an upgrade to the Electra proximity link UHF transceiver. The orbiter transceiver will continuously monitor the return link signal-to-noise ratio and, based on those measurements, transmit commands on the forward link to direct the lander to raise or lower its data rate (in powers of 2) as the channel characteristics evolve over a pass. Given Electra's software radio architecture, this capability can be uploaded post-launch to the 2005 Mars Reconnaissance Orbiter, and will be available for all subsequent Mars orbiters and landers.

Low-Cost and Simple Operations

Part of the strategy for maintaining low operating cost and simple customer interfaces was to design the orbiter to be capable of scheduled, autonomous operations. This strategy took advantage of the fact that the Proximity-1 protocol has the capability of achieving reliable communication (i.e., data transferred that is in-order without duplicates or gaps) within a communication session between the Relay Orbiter and the Rovers. The orbiter was then designed to be able to carry out these sessions without real time intervention, and even without precise commanding, from Earth.

The role of each element in this scenario can be expressed in three parts:

1. Orbiter establishes communication with the Marscrafts by hailing and relays/forwards commands sent from Earth typically received by the Orbiter before the over flight. The forward Proximity-1 link was capable of handling the one-to-many situation possible with multiple customers. (Figure 4). Alternatively, the hailing could have been initiated by the Marscraft individually, although this would have needed to be carefully scheduled; no provision was made for simultaneous hailing from the Marscraft. Establishing communication included pointing the proximity antenna based on stored ephemerides, and detailed onboard procedures for responding to the proximity link activities.

2. Each Marscraft responds separately to the hail by telemetering data to the Orbiter to be relayed/returned to Earth, stored onboard if needed until a direct-to-Earth link becomes available. Note that forwarding commands and receiving telemetry over the proximity link could be done concurrently. (Figure 5).

The MTO also planned to provide additional services (time correlation, time transfer, resource sharing) enabled via proximity-1 messaging between orbiter and Marscraft applications. Note that relaying is not a required function of Proximity-1, and in particular the data exchanged across the Proximity-1 data link could be consumed (in the "final destination" sense) by application entities at both endpoints.

The Proximity-1 recommendation facilitates a standard approach to messaging by assigning well-know Port IDs (See CCSDS 135.0-B-2, Space Link Identifiers) to proximity message types. On the forward link (Orbit to Surface), hardware commands are assigned to port ID 1, so that once validated they can be routed directly from the proximity transceiver to the addressed hardware unit minimizing latency and by-passing the flight computer. For both forward and return links (Surface to Orbit), CCSDS Space Packets are assigned to port ID 2, so that these self-delimiting data units, i.e., packets containing application data (data, status or control messages) can be transferred and immediately interpreted by the receiving node.

Spacecraft Storage and Throughput Margin

A high margin, greater than 500%, was selected for the spacecraft storage and throughput for the RF links (the optical links probably had about 100% margin). This was done to allow an easy, automated solution to obtaining the required quality of service, and added little to the cost. If either a proximity or an Earth contact was missed, the data could simply be retained onboard and forwarded later

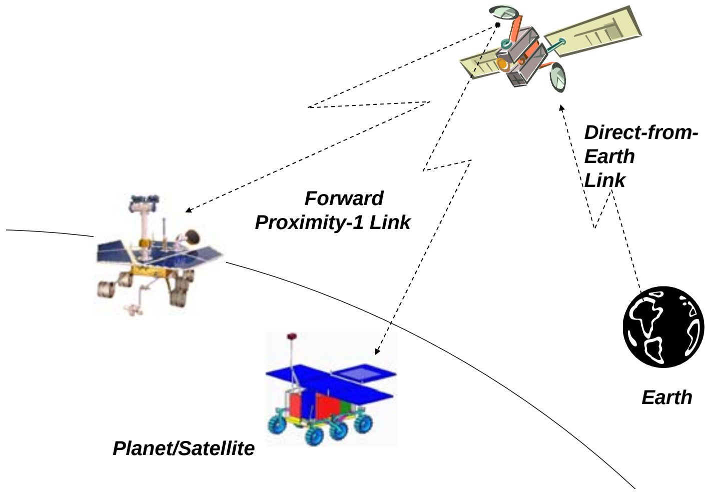

Figure 4. Relay Command Link

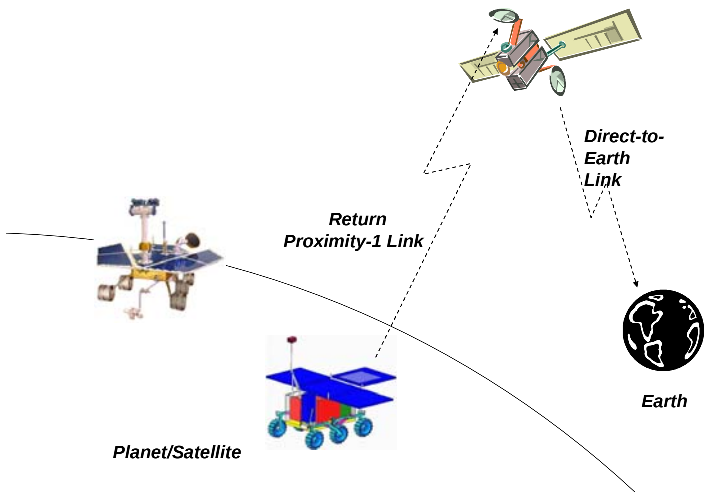

Figure 5. Relay Telemetry Link

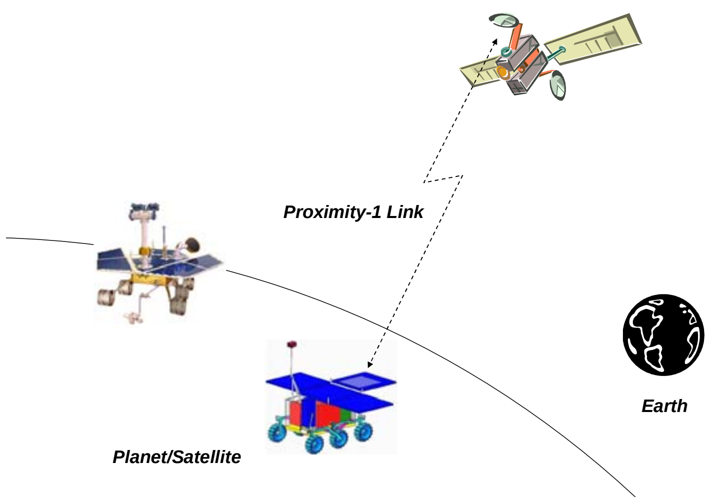

Figure 6. Proximity-1 Messaging

with little risk of service degradation. In the event of a protracted outage, a graceful degradation of service was planned, in which lower priority or stale data (decided based on information in the delivery specification) would be discarded. The high margin also minimized the need for detailed control evaluation and simulation in operation to only customer-critical events. Even for these situations simple scheduling strategies could be used instead of simulation, such as extra Earth tracking or a moratorium on service to other customers for a sufficient period before the critical event to ensure that the MTO storage would not be taxed by a realistic set of outages after the critical event.

Optimization of Quality of Service

A simple array of service qualities was planned, that encompassed the full range of qualities needed by the customers. These are listed in Table 2. These were planned to be implemented with a simple combination of X-band for the low-latency services, and Ka-band for the bulk services under routine conditions. The flexibility to use other routing arrangements was discussed but needed more investigation as to feasibility for the particular spacecraft vendor selected.

FUTURE EXTENSIONS

A number of opportunities were identified during the development of the MTO EEIS concept, in which the capabilities of the Mars network could be increased with a modest change to the concept. These opportunities were generalized messaging services, streaming video and audio, disruption tolerant networking, multiple relay providers, and higher-precision timing.

Generalized Messaging Services

We noticed that the system planned contained a substantial internal messaging capability for service operation. Since a full CFDP implementation was planned, the customer would as a by-product already have had general messaging capability within CFDP. It would have been a small modification to wrap the CFDP messaging capability within MTO, to allow customers to reliably transport messages without having to use CFDP directly.

Streaming Video and Audio

Since MTO internally used a frame stream service, and since there was substantial margin on the C&DH throughput, it would have been feasible to support streaming audio and video. Careful attention would have needed to be paid to the detailed timing characteristics of onboard transport, but the selected spacecraft appeared well suited to the regular cadence needed for streaming services.

Disruption Tolerant Networking

Disruption tolerant networking (DTN), the high-level extension of reliable delivery concepts to networks with multiple nodes and spotty connectivity, could be installed as an alternative for CFDP in the MTO protocol stack. The feasibility of this change would depend on the degree of congruence between the actual interfaces for both CFDP and DTN, and the availability of reference implementations for both. The maturity of this option was still relatively low at the time our work was done, but future missions should watch these capabilities closely and consider including them at an appropriate phase. A by-product of including DTN would be the straightforward addition of multiple relay providers to provide improved throughput, improved connectivity (e.g. multi-hop relays from behind a planet), simplicity of operation, and decreased intervals between customer contacts.

Higher-Precision Timing

Two major factors limited the precision of MTO timing services. The first factor was the selected vendor's software-based approach to binding time tags to messages arriving or departing the spacecraft on the Earthlink. This is a common practice, and typically sets a limit in the range of a few to tens of milliseconds on the ultimate accuracy achievable. In contrast, the Electra used a hardware approach to binding time tags to proximity timing messages, with a precision in the tenths of microseconds range. This approach is also simpler to implement and test in the laboratory, although inheritance of flight software that already has the timing function may argue against this benefit. Future missions should consider the balance between benefits and risks in changing to a hardware approach, and seek simple changes that improve accuracy.

The second factor limiting the precision of MTO timing services was a manual calibration approach to processing of timing data. Our plan was to have occasional time correlation sessions, which would be analyzed on the Earth to reconstruct past clock deviations and forecast future ones. Manually determined commands could then be used to adjust clocks, although this practice was strongly discouraged for sequencing and fault-protection reasons; typically commands would only be used to load timing coefficients to the orbiter for distribution purposes. The long intervals between correlation sessions expected to be imposed by workforce constraints increased our system's sensitivity to clock drift, primarily in quadratic and higher terms (these receive the weakest determination in our approach). This is in contrast to the practice for

Table 2. Planned Qualities of Service for MTO.

Delivery Type	Quality	Quantity	Continuity	Latency
1. Forward Service - incomplete	Single transmission. May have gaps	60 Mb per Sol shared with line 2 [10 Mb] max file size	95% of transmitted files	After a file is received on MTO, 5 minutes plus transmission time to send the file from MTO to the user when a relay pass to the user Marscraft is available. Total latency less than 20 minutes plus OWLT.
2. Forward Service - complete	All files delivered error free	60 Mb per Sol shared with line 1 [10 Mb] max file size	[99.99]% of transmitted files	After a file is received on MTO, 5 minutes plus transmission time to send the file from MTO to the user when a relay pass to the user Marscraft is available. Total latency less than 20 minutes plus OWLT.
3. Return Service - Low Latency - Incomplete	Single Transmission. May have gaps	[1] Gbit/Sol shared with line 4. [10 Mb] max file size	95% of transmitted files	The MTO spacecraft will transmit each file within 5 minutes of receipt if a contact with Earth is available and the relay allocation for the Earth link is not over subscribed. Total latency less than 20 minutes plus OWLT.
4. Return Service Low Latency - Complete	All files delivered error free	[1] Gbit/Sol shared with line 3 [10 Mb] max file size	[99.99]% of transmitted files	The MTO spacecraft will transmit each file within 5 minutes of receipt if a contact with Earth is available and the relay allocation for the Earth link is not over subscribed. Total latency depends on number of retransmissions required to obtain completeness
5. Return Service - Bulk - Incomplete	Single Transmission. May have gaps	[10] Gbit/Sol shared with line 6	80% of files for initial delivery	Staged by priority of file type or specific identification.
6. Return Service - Bulk - Complete	All files delivered error free	[10] Gbit/Sol shared with line 5.	[99.99]% of transmitted files	Staged by priority of file type or specific identification. Total latency depends on number of retransmissions required to obtain completeness, typically less than 5 sols.

terrestrial networks, in which a strategy of continuous measurement is enabled by fully automated measurements, with all system clocks disciplined to UTC in realtime. The resulting small, continuous corrections are nearly always undetectable to all but the most stringent realtime control applications, and even then can usually be conditioned in such a way as to protect the control loop function. Future missions should consider using a disciplined-clock approach instead of the manually-calibrated approach both for accuracy and operating cost benefits.

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