MARS PROXIMITY LINK OPERATIONS

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ABSTRACT - *Given the recent setbacks of the Mars 98 missions, the Jet Propulsion Laboratory (JPL) is reassessing its approach and architecture for future Mars exploration. One of the preliminary focuses of rearchitecting the Mars Program is to first establish an infrastructure at Mars that will extend key ground network services of the existing earth-based Deep Space Network, (DSN), managed by the Telecommunications and Mission Operations Directorate, (TMOD), at the JPL. Missions in the 2003 to 2005 time frame that plan to extend these network services are: NASA/JPL Mars Surveyor Project 2001, ESA Mars Express, and NASA/JPL Mars Network. For all of these missions, extending reliable communication, navigation, and time management to inbound Mars assets creates unique and challenging issues for operations. This paper addresses three of these key issues. First, it describes the operational scenarios involved in operating point to point, point to multipoint, and multipoint to multipoint links between orbiting relays and Mars based assets. Secondly, it examines mechanisms that help transform the current schedule/manual based mode of operations into a more autonomous demand driven approach. Last, it presents a plan to transition to file transfer services using Consultative Committee for Space Data Systems (CCSDS) Proximity Space Link Protocol* [Ccsd 00] *and File Delivery Protocol (CFDP)* [Ccsd 99] *recommendations for these missions.*

1 - INTRODUCTION

Over the next decade, international plans and commitments are underway to develop an infrastructure at Mars to support future exploration of the red planet. The purpose of this infrastructure is to provide reliable global communication and navigation coverage for on-approach, landed, roving, and in-flight assets at Mars. The claim is that this infrastructure will: 1) eliminate the need of these assets to carry Direct to Earth (DTE) communications equipment, 2) significantly increase data return and connectivity, 3) enable small mission exploration of Mars without DTE equipment, 4) provide precision navigation i.e., 10 to 100m position resolution, 5) supply timing reference accurate to 10ms. [Bell 00, Hast 00] This paper in particular focuses on the **operability** of that infrastructure. [Cesa 00, Kuo 00] Operability in this context means flight and ground system visibility, controllability, and accountability of data products managed and transported across the local proximity and long haul deep space links.

The second key aspect of this infrastructure is **interoperability** with the future international armada that is planned for robotic exploration of Mars culminating with a man presence. Interoperability in this context means providing for standard communication, navigation, and time services including strategies to recover gracefully from interruptions and interference while ensuring backward compatibility with previous missions from previous phases of exploration. [Kazz 98]

This paper describes proximity link operations for the Mars environment. First, the mechanism for link negotiation between a caller and a responder for communication services is described. Once the link is established, link maintenance including real-time link dynamics (frequency and data rate changes) takes place. A summary of link termination options follows. The possibility of having more than one Mars asset simultaneously in view raises issues of contention. Although studies have shown that through the 2005 period contention is rare (highest probability of an orbiter simultaneously in view of two landed assets limited to 7% of the planned contacts), it will become an increasingly important issue as the infrastructure expands. [Bell 99] In order to understand the applicability of the protocols to future mission contexts, a set of four operational scenarios in terms of increasing complexity is provided. Another aspect of operations is to enhance operability and lower cost by enabling automation. A set of automation enablers is proposed. Finally, in order to benefit from the rich set of capabilities of the CFDP, the existing ground and flight systems must establish three proposed mechanisms to monitor, account, and manage files end-to-end.

2 - PROXIMITY ENVIRONMENT FOR ESTABLISHMENT, MAINTENANCE, TERMINATION OF COMMUNICATION SERVICES

For the purposes of discussion, this section assumes communication is to be established between an orbiting relay (caller) and a landed asset (responder) during a session. A session is the period of time over which the proximity link is operational. It consists of three phases: link establishment, data service, and link termination.

2.1 - Link Establishment

Operations at the Earth schedule the deep space link between the orbiter and Earth. The proximity link between the relay and landed asset is demand driven. The orbiter knows where the landed assets are located. The orbiter is the master and will hail to alert the asset that it is in view and available for telemetry or command relay. The asset can refuse a proximity link session for numerous reasons including: lack of data, power limitations, or instrument operational constraints. The orbiter command and data handling system (C&DH) knows what asset to address and supplies the known spacecraft ID to the Ultra High Frequency (UHF) radio. If more than one asset is within the field of view of the orbiter, the orbiter can poll for the assets it desires to communicate with by cycling through the potential spacecraft ids until a contact is made. The orbiter can also use this as a technique for gathering initial status and priority from each asset to determine the servicing priorities for the return link (assigning portions of the session to each asset).

During the 2003 time period when the possibility of link contention is not possible, operations will be carried out on the hailing frequency pair. Later, operations will switch as soon as possible from the hailing frequency and onto a working frequency pair based upon the type of data service e.g., Doppler, high or low data rate communications. Since the orbiter has knowledge of where the assets are, it is possible that future assets could be assigned different channels and the orbiter will need to establish contact on those channels instead of on the hailing channel.

2.2 - Data Service

In the data services phase, both user and protocol information is passed using the communications link provided by the transceivers. Two grades of service are provided: expedited service guarantees only that the data units accepted are error free. Sequence controlled service assures that the data units accepted are in order, without gaps or duplications within a session. The orbiter keeps the carrier on throughout the entire session to indicate it's present. If data communication is interrupted during a session, the UHF radio informs the C&DH (via status reports) and awaits instruction whether to terminate the session or reestablish the link by re-hailing. Data rate or frequency changes can also occur during this phase. A data rate/frequency change procedure is defined to minimize data loss during the transition. [Ccsd 00]

2.3 - Link Termination

Since the orbiter knows the ephemeris of the orbit at the expected point of loss of signal, the UHF radio is commanded by the C&DH to the inactive state or the on-board carrier loss timer expires. (This also covers the contention case because the C&DH takes appropriate action after it is notified of the contention.)

2.4 - Considerations

Duplication of data may occur during multiple proximity sessions using sequence-controlled service. Handling of data between sessions is outside of the Proximity-1 protocol. Controlling the sequence number count between sessions or deleting duplicate frames can be dealt with by the C&DH.

CFDP, which works on a transaction basis, provides continuity between proximity sessions. It provides the capability of delivering duplicate free data across multiple sessions and for integrating data collected/relayed from multiple orbiters.

3 – PROXIMITY OPERATIONAL SCENARIOS

The following scenarios examine operations across two separate links: proximity (landed assets to orbiter) and deep space (orbiter to Earth). The proximity link is characterized by short distance (within 400,000 km), moderate signal strength, and single sessions. The CCSDS Proximity-1 Space Link protocol [Ccsd 00] is the specification that defines both the physical and data link layers. The CCSDS File Delivery Protocol (CFDP) [Ccsd 99] is run on top of Proximity-1 at the data transport layer. It utilizes a selective repeat mechanism for retransmission of unacquired portions of a transaction. The deep space link is characterized by long delays, and weak signals. The data link layer in this case is supported by CCSDS

Telecommand (TC) Recommendation in the forward direction [Ccsd 92] and CCSDS Telemetry (TM) Recommendation in the return direction [Ccsd 95].

3.1 – Point-to-Point (Simple Relay)

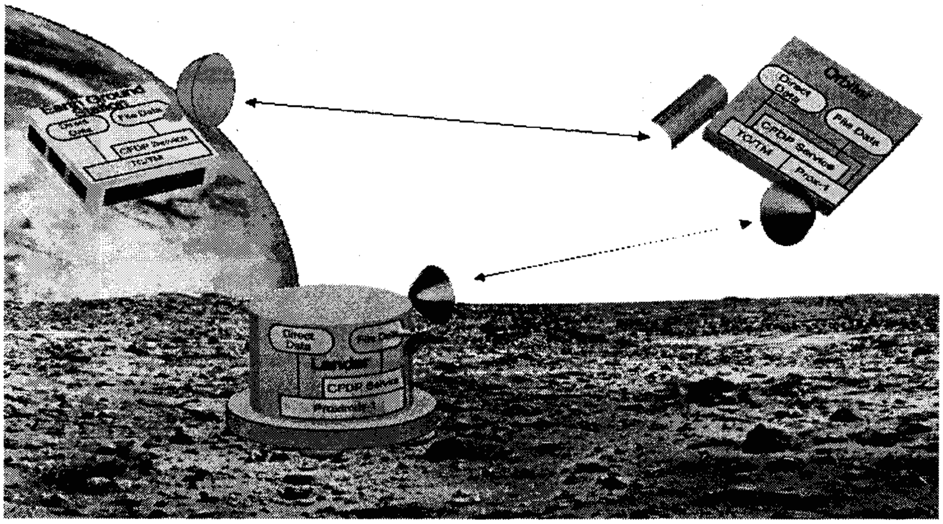

Fig. 1: Point-to-Point (Simple Relay)

The objective is to transfer a file by means of an orbital relay. A file may be transferred from a lander to the Earth or from the Earth to the lander. The orbital relay functions as a store and forward node. The on-board command and data handling system manages the data it receives from Earth or the lander, as a file in it's on-board file management system. In those cases where the lander does not manage data as a file, the relay orbiter can accept data not organized in files e.g., byte streams, CCSDS packet sets, and create one or multiple files from this data on-board. Once the file is successfully transferred to the orbiter, it takes custody of the data (custody transfer), and relays status back to the lander acknowledging its receipt. Given adequate resource margins on-board the orbiter, the lander can now delete this data providing storage space for future data acquisition.

3.2 - Point-to-Point (Multi-hop Relay)

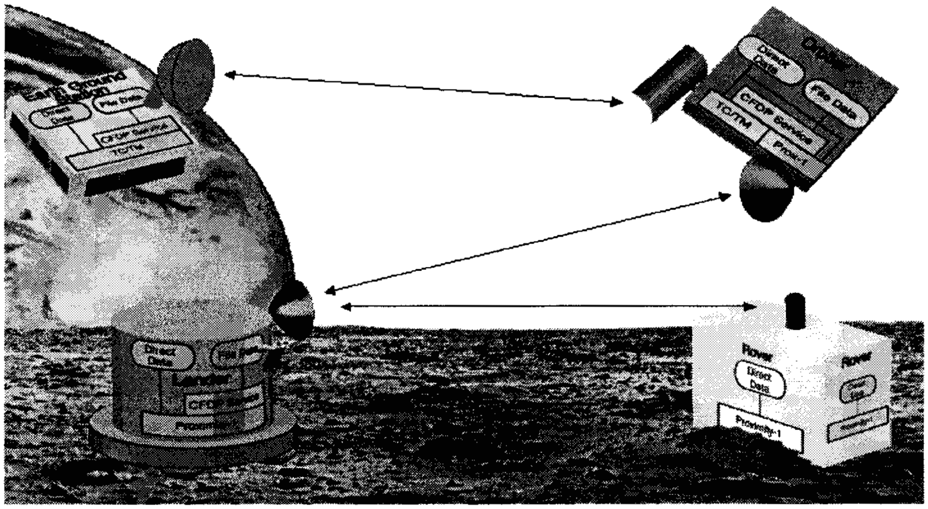

Fig. 2: Point-to-Point (Multi-hop Relay)

Now a rover enters the environment and transfers its data to the lander. The rover having limited computing power and storage does not have the resources to run CFDP. Depending upon the required completeness of the data transfer, the rover utilizes either the expedited or the sequence controlled service. Both the lander and orbiter function as store and forward nodes. Custody transfer occurs first between the lander and the rover and later between the orbiter and the lander.

3.3 - Point-to-Multi-Point (Forward/Return Link)

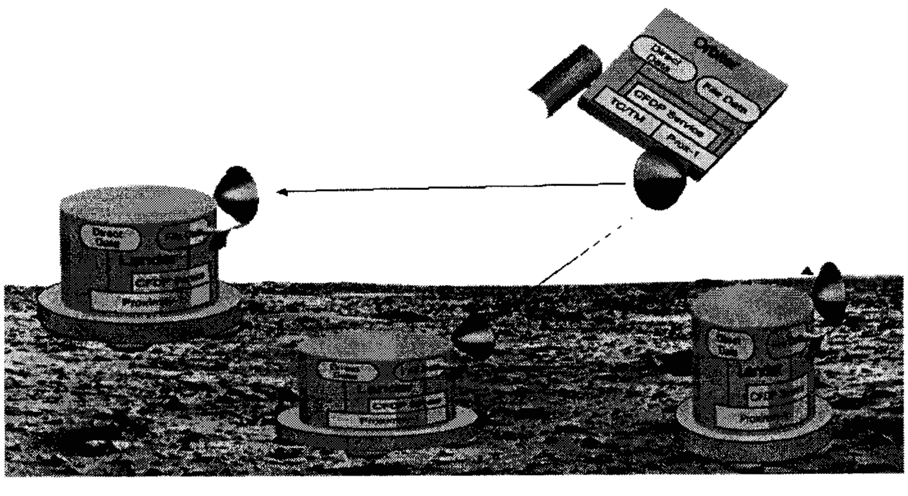

Fig. 3: Point-to-Multi-Point (Forward/Return Link)

Within the proximity link environment, an orbiter encounters multiple landed assets. Assuming the orbiter has only one transceiver, it can simultaneously communicate to all or a subset of the landed assets within its field of view. By cycling through a set of spacecraft IDs during the hailing period, the orbiter can a) broadcast commands for all landed assets, or b) multicast commands to a subset of landed assets e.g., all landers, or c) poll each landed asset to determine the priority of its return link data transfer and once determined choose the asset with the highest priority. The proximity-1 protocol frame verification rules specify that only data marked with the asset's specific spacecraft ID or multicast address will be accepted by the asset.

3.4 - Multi-point to Multi-point

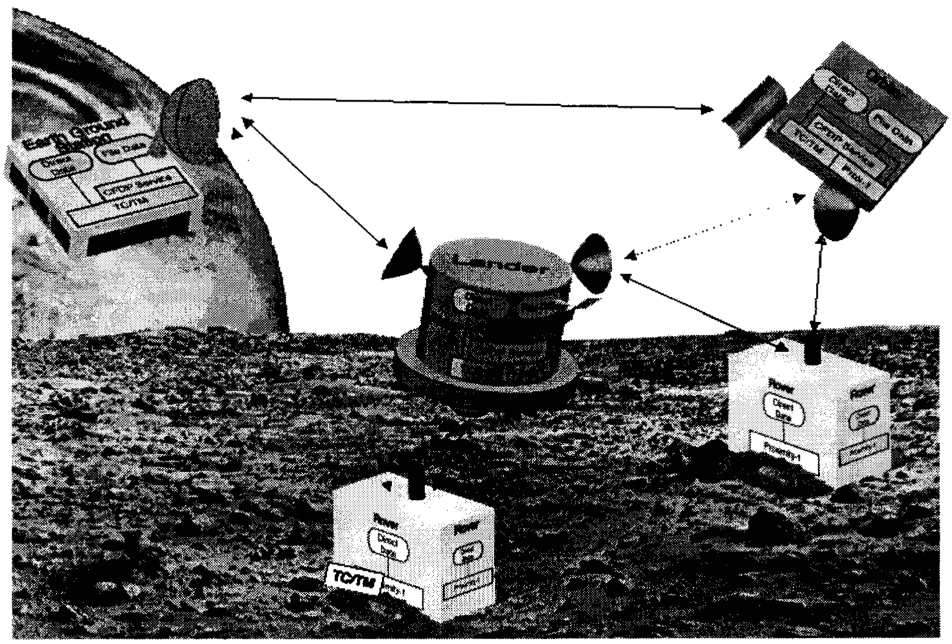

Fig. 4: Multi-point to Multi-point

This scenario will require some form of multiple access scheme. Candidates under study at this time are frequency division multiple access (FDMA), code division multiple access (CDMA), and time division multiple access (TDMA). FDMA has the advantage that spectrum is available on Mars but it forces landed assets to have frequency agile transponders. CDMA is beneficial where ranging is a requirement for navigation however it imposes a power level control problem which results in more complicated hardware on the landed assets. TDMA in the true time slotted approach imposes tight oscillator requirements on the landed assets and time coordination between them and the orbiter relay.

4 - AUTOMATION ENABLERS

4.1 Orbiter shall provide demand access to landed assets.

Nominal proximity link detailed level scheduling for data transfer of navigation, command, telemetry products shall be done without ground intervention. Scheduling of landed asset contacts shall occur by means of the hailing procedure, knowledge of lander position and orbit ephemeris, instrument and power constraints. The orbiter knows when a contact is possible. The lander may reject a contact due to instrument or power constraints.

4.2 The proximity link shall be operated in a modeless fashion.

Data transfer is data driven and is independent of mode. This eliminates the costly testing of operational modes. It enhances operability by multiplexing expedited and sequence controlled data across the link. An infrequent small message that does not require sequence control can be multiplexed into a sequence controlled series of messages. This makes the content of the data transferred transparent to mode.

4.3 Dynamic control of transaction relay

Data quality needs shall be signaled in the data. Each transaction should have a Quality of Service (QOS) indicator and a priority indicator to allow the orbiter to dynamically control relaying of the transaction without intervention from the ground.

4.3 On-board network wide priority scheme

This scheme replaces the timely and costly ground negotiation process of prioritizing data transfer amongst multiple users and moves it to the spacecraft. On-board data prioritization schemes such as the downlink priority table on Mars Pathfinder were used to prioritize the return link for two spacecraft (lander and rover) within the same mission. The challenge is to develop a scheme across multiple missions with multiple applications. Unlike the Mars Pathfinder mission, future missions will require that all data be prioritized at the product level i.e., file level.

5 - TRANSITION STEPS TO FILE TRANSFER

5.1 Use of on-board file directory mirrored by the ground

In order to catalog files end-to-end between the orbiter and the ground, an on-board file directory is required. It shall identify file characteristics e.g., file size, file name, originator, file creation time and transfer status. The ground shall maintain an identical directory so that operations can manage the prioritization, monitor the status, and account for file transfer end to end.

5.2 End-to-End accountability at the file level

End-to-End data accountability shall occur at the file level. This includes all files received or transmitted by the orbiter including those internally generated.

5.3 On-board managers control CFDP protocol

The host (e.g. Orbiter, Mars landed asset, ground station/Project Operations Control Center) system will need to manage its own resources. There are Resource and Data Management functions within the orbiter that manage onboard data storage, assign downlink priorities, and control communications channel availability. There is also a Communications Manager function which has knowledge of space link communications issues such as data rate (which relates to the data volume transfer per pass), one way light time (which is required by CFDP for automated reliable data transfer operations), the network routing issues (which transactions to send on which links, virtual channels, or passes) and handles the delivery of prioritized data that is to be transferred. Thus the Communications Manager must have visibility into the operational status of all CFDP transactions and must be capable of providing the required parameters and external controls to partner with CFDP and the lower level communications elements in providing a complete service.

The Data Transport Manager is the host's agent for the transfer of data between itself and the remote world. It is the exclusive user of CFDP. The Data Transport Manager controls the ordering of transmission of transactions and provides the high level controls needed to prioritize the data transfers and control which transactions occur on a pass or link. The CFDP Put directive enables the Data Transport Manager to initiate a transaction. The suspend and resume directives enable the Data Transport Manager to stop and restart transactions on the proper link after a transaction is initiated. It must also be capable of terminating a transaction when required or preventing the acceptance/continuation of a transaction being received. Thus the Data Transport Manager can provide the high level control of CFDP operations by controlling which transactions occur on which links, and the ordering of their transfer on the link. The Data Transport Manager controls the logical transfer of data between the host and external delivery points.

The internal operations of CFDP, for reliable transaction operations, requires that CFDP know the round trip communications delay time. This time is required for control of retransmissions; when to expect reports and when to re-send unacknowledged transmissions. This delay time is an ever-changing value that can be significantly different on different links associated with a node. The delay time for a Mars orbiter with Earth could be the round trip light time (between 10 to 25 minutes) or may be substantially increased because of occultation or ground station scheduling factors. CFDP must also have awareness of the state of underlying data link and physical communication channel elements. It must know when a link has been established and when it is lost. The Communications Manager works with these protocol layers, and with external elements that provide operating schedules, ephemeredes, and estimated round trip light time to establish and control the link and physical aspects of data transfer.

REFERENCES:

[Ccsd 00] Consultative Committee on Space Data Systems Proximity-1 Space Link Protocol, CCSDS 211.0-R-2, Red Book Issue 2, Jan. 2000. Available at http://www.ccsds.org/

[Ccsd 99] Consultative Committee on Space Data Systems File Delivery Protocol, CCSDS 727.0-R-3, Red Book Issue 3, May 1999. Available at http://www.ccsds.org/

[Bell 00] Bell, David J. "Mars Network: A Mars Orbiting Communications & Navigation Satellite Constellation," IEEE Aerospace 2000 Conference ,IEEE publication 0-7803-5846-5/00, Big Sky MT, March 18-25, 2000.

[Hast 00] Hastrup, R.C. "Mars Network for Enabling Low-Cost Missions," Fourth IAA International Conference on Low-Cost Planetary Missions," IAA-L-0509, Laurel, Maryland, 2-5 May 2000.

[Cesa 00] Cesarone, R.J. "Design Considerations for the Mars Network Operations Concept," Paper No. 211, SpaceOps 2000, Toulouse, France, June 2000.

[Kuo 00] Kuo, N.R. "Mars Network Operations Concept," IEEE Aerospace 2000 Conference ,Paper Id. 163, Big Sky MT, March 18-25, 2000.

[Kazz 98] Kazz, G.J. "Application of an Extended CCSDS Telecommand Standard for all Mars In-Situ Telecommunication Links," First ESA Workshop on Tracking, Telemetry, and Command Systems, ESTEC, Noordwijk, Netherlands, June 24-26, 1998.

[Bell 99] Bell, David J. "Variable Data Rate Analysis for Maximizing Pre-aerobreaking Data Return," Presentation at the Mars Network Meeting, JPL, December, 1999.

[Ccsd 92] Consultative Committee on Space Data Systems Telecommand Part 2 - Data Routing Service. CCSDS 202.0-B-2, Blue Book Issue 2. Nov. 1992. Available at http://www.ccsds.org/

[Ccsd 95] Consultative Committee on Space Data Systems Packet Telemetry , CCSDS 102.0-B-4, Blue Book Issue 4, Nov. 1995. Available at http://www.ccsds.org/

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