MARS COMMUNICATION PROTOCOLS

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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. [1]. This paper in particular focuses on two CCSDS recommendations for that infrastructure: CCSDS Proximity-1 Space Link Protocol [2] and CCSDS File Delivery Protocol (CFDP) [3]. A key aspect of Mars exploration will be the ability of future missions to interoperate. These protocols establish a framework for interoperability by providing standard communication, navigation, and timing services. In addition, these services include strategies to recover gracefully from communication interruptions and interference while ensuring backward compatibility with previous missions from previous phases of exploration. [4].

NEED FOR STANDARDIZATION

The diversity of communication links within the future potential Mars environment creates challenging engineering problems. Problems such as frequency coordination, link operations, standard data transfer, product accountability, link performance, scheduling vs demand access of services, and network-wide data prioritization need to be addressed. See Figure 1, Future Potential Mars Network.

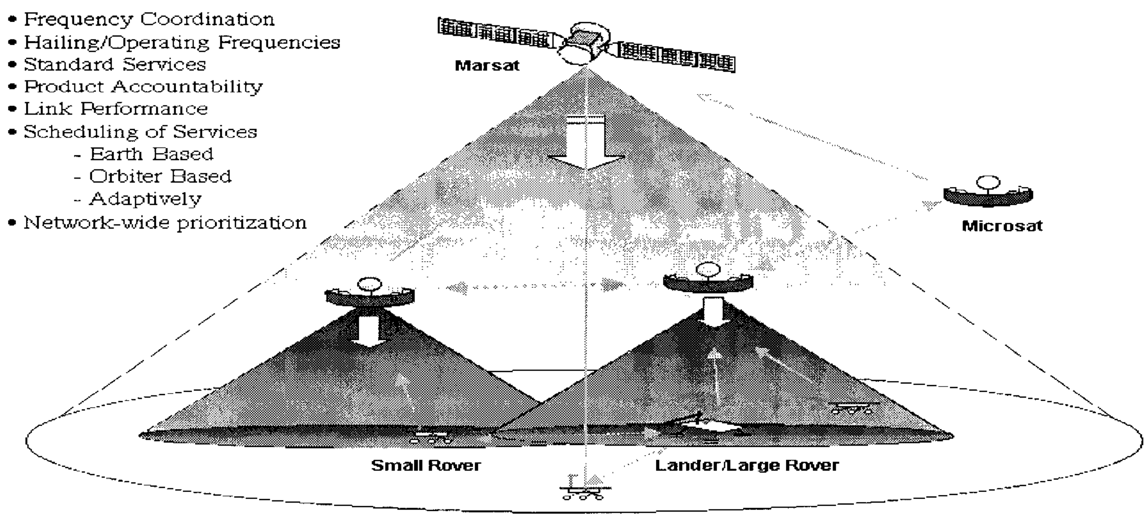

Figure 1: Future Potential Mars Network

The CCSDS Proximity-1 Space Link Protocol provides recommendations for dealing with the components of these issues in the physical and data link layers. These include frequency allocation, coding, data rates, link establishment, maintenance, and termination procedures, reliable or expedited data transfer, ranging and time transfer. On top of Proximity-1, the CCSDS File Delivery Protocol at the transport layer provides applications the capability of transporting their data products end to end across the entire space link either expedited or reliably.

PROXIMITY-1 KEY CHARACTERISTICS

The Proximity-1 protocol contains both data link and physical layer functionality for point to point as well as point to multi-point in-situ communication. A layered model of the protocol is provided in Figure 2. This model describes the interactions of the data link sublayers and physical layer in terms of data and control flow. The key characteristics of the protocol are:

Physical Layer Characteristics

- Defines the functional requirements on the radio equipment. These requirements include the definition of UHF frequencies for hailing and working channels, polarization, modulation, acquisition and idle sequences, data rates, and convolutional coding.
- Defines the performance requirements on the radio equipment. These requirements include allowable bit error rate, carrier frequency stability, residual amplitude modulation, carrier phase noise, out of band spurs, and Doppler tracking and acquisition.

Data Link Layer Characteristics

- Provides a modular link layer that can run on top of different RF frequency bands without impacting the link layer. Proximity-1 has provision for UHF, S, X, and Ka band frequencies.
- Proximity-1 provides standard services for transferring command, telemetry, and radiometric data products across the In-Situ link.
- The protocol was mainly envisioned for use in a high to moderate SNR environment. This drove the design of the protocol to use a simple error detection coding scheme (32-bit CRC) for asynchronous, variable length frame links. Provision for weaker signal environments is supported for synchronous links via the R-S(255,223) code or the Concatenated (7,1/2) R-S code with fixed length frames.
- Coupled with minimal coding, is the use of an ARQ scheme, the Command Operations Procedure - Proximity (COP-P) which is the mechanism behind the reliable Quality of Service (QoS). It operates on the principle of sequential frame acceptance and retransmission with frame sequence numbering (a go back n process).
- The protocol is bi-directional. The same protocol is used for both forward and return links.
- The protocol supports two QoS: Reliable and Expedited. The reliable QoS guarantees that the service data units (SDUs) transferred are error free, in-order, with no duplicates or gaps. The expedited QoS only guarantees that SDUs delivered will be error free.
- Based upon the fact that current in-situ spacecraft are limited to a fixed single channel receive and transmit capability, Proximity-1 is mainly envisioned for point-to-point communication. However, it also supports one to many on the forward link. See Scenario 3 under Operational Scenarios.
- The input/output sublayer supports one input port (to receive SDUs and routing information from the vehicle or transceiver controller) and eight output ports per Virtual Channel (to route SDUs received via the proximity link to logical or physical entities within or exterior to the vehicle).
- The data types transferable over the proximity link are byte streams, messages, packets, segments and user data.
- The protocol is truly modeless meaning all of the services provided do not require that the caller or responder be configured into a particular mode for operations. This feature provides for enhanced

operational flexibility. The two QoS can be multiplexed into the same data transfer along with minimal restrictions on multiplexing data types e.g., a transponding mode is not required for ranging.

- The medium access control sublayer supports full duplex, half duplex, and simplex links.
- In addition, techniques for link establishment, maintenance, and termination onto the hail or working channel frequencies are also provided.
- In order to avoid contention in a non-scheduled link environment, three link contention mitigation strategies are provided. These involve resolution of contention of frequencies already in use.
- The protocol provides a coupled non-coherent ranging and timing service. These services are required for proximity operations in order to provide on-board clock correlation, setting remote spacecraft time and time-derived ranging measurements e.g.,round trip light time (RTLT) calculation.
- Provides a mechanism for rapid data rate and frequency control between nodes. Used during link establishment as a demand action from one node to set the working frequency and data rate of the other. It can also be applied to rate profiling, in which the data rates during a session are ramped upward and then downward to take advantage of the G/T profile of the link.
- Provides a rich set of supervisory protocol directives used to control or report status to the remote transceiver acting as the communication partner over the in-situ link.
- It uses a data driven technique i.e., the data field construction ID (DFC ID) to identify data content as opposed to a managed approach for on-board data processing.
- Provides the necessary routing information in support of the transport layer protocol, CFDP.

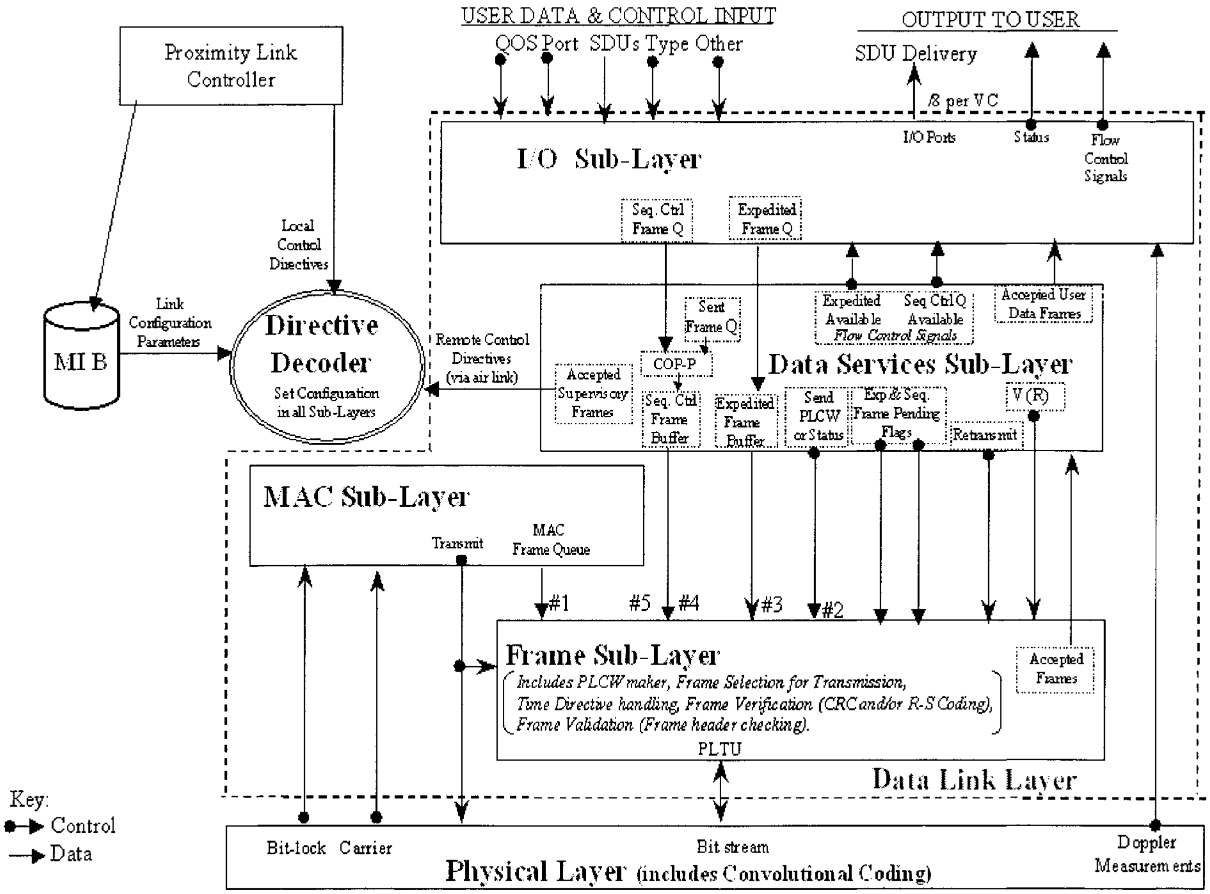

Figure 2. Proximity-1 Protocol Layered Model

CFDP KEY CHARACTERISTICS

CFDP is an international standard for automatic, reliable or expedited bi-directional file transfer between spacecraft or spacecraft and ground, built on top of the CCSDS data link layer. Unlike TCP/IP, it requires no handshaking and is datagram and transaction based to deal with space link characteristics e.g., long RTLT and non-persistent links but is adaptable to fit the proximity link as well. Metadata associated with each transaction describes the data transfer including data processing once the file arrives.

Key characteristics of CFDP are:

- It provides a single end-to-end protocol between data source and sink. Transaction state is tracked end to end by use of the extended procedures. In effect it can span low planetary orbit through deep space.
- It copies files across interplanetary distances between file systems.
- It carries out remote filestore operations such as delete, move, make directory.
- It provides both a Reliable (via a selective repeat mechanism) and Expedited QoS.
- It has provision for Metadata associated with each file.
- It is connectionless and transaction based.
- It supports structured or byte stream files as well as bounded or unbounded files.
- It supports file transfer across multiple hops utilizing the concept of custody transfer i.e., the sender is informed by the receiver that after successful reception and validation of the file, custody of the file can be relinquished by the sender.
- Supports deferred transmission: the application can request a file transfer at any time, without apriori knowledge of when the communication link will be available.
- It supports end-to-end accountability even through multiple intermediaries.
- Automatic store and forward operations are carried out amongst nodes in a multi-hop file transfer.
- It allows for store and forward initiation to occur before the file is completely received at the forwarding entity.
- It has provision through the message to user capability of notifying the user that the transferred file has been received.
- It provides for efficient operation (via the selective repeat mechanism) over simplex, half duplex, and full duplex links.
- Since it is transaction based, it supports file transfers that span multiple ground station or spacecraft contacts.
- It's negative acknowledgement modes (immediate, deferred, prompted, asynchronous) can be configured by the user to best fit the operational environment to deal with highly unbalanced link bandwidths if necessary.
- CFDP utilizes a selective repeat mechanism for retransmission which uses the minimum amount of additional data traffic to fill in gaps and signal completeness of transfer.
- An additional copy of the file is not required on board in order to transfer it thereby minimizing onboard memory requirements.

PROXIMITY-1/CFDP INTERFACE

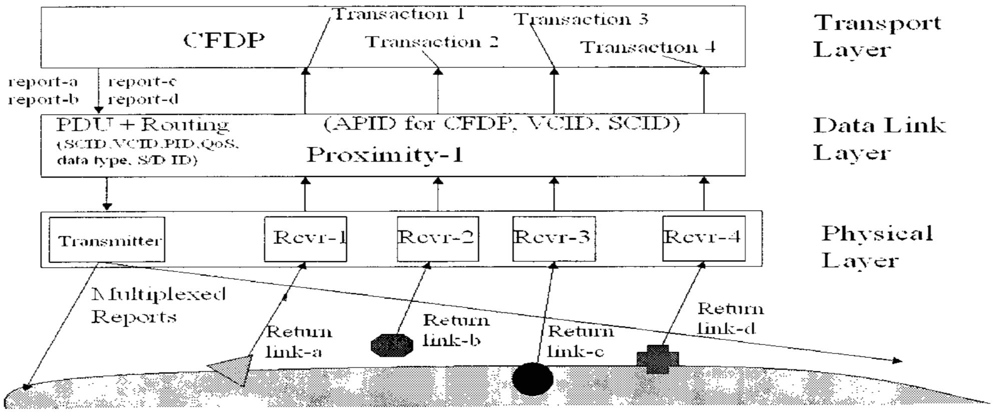

Figure 3. Efficient Use Of Protocols in a Multi-link Environment

Figure 3 depicts an operational scenario in which multiple planetary bound assets are transferring files to an orbiter. This scenario demonstrates the efficient use of CFDP running on top of Proximity-1 in a multi-link environment. Data throughput is enhanced and latency is reduced by using the selective repeat mechanism of CFDP instead of operating four separate full duplex point to point Proximity-1 sequence controlled links between each asset and the orbiter. On the return link, each asset transmits its data file to its associated receiver. The receiver acquires, demodulates, and passes containing candidate Proximity-1 frames to the data link layer for verification and validation. This occurs for each file transfer per receiver. Upon successful validation, valid CFDP Protocol Data Units (PDUs) extracted from the frames are output on a dedicated Proximity-1 port to the CFDP entity on-board. CFDP builds each file based upon the transaction ID within each PDU. CFDP using parameters within the Metadata determines which parts of the file have been received and which parts are missing. It generates a report summarizing the file transaction status and sends this information to the data link layer. The link layer's job is to take the CFDP report PDUs and create Proximity-1 transfer frames. Frame creation requires a specific spacecraft ID, virtual channel, port ID, QoS, data type, and source/destination ID. These fields provide both routing and data processing information used by both transmitter and remote receiver.

OPERATIONAL SCENARIOS

The following scenarios examine operations across two separate links: proximity (landed assets to orbiters) and deep space (orbiters to Earth). The proximity link is characterized by short distance (within 400,000 km), moderate signal strength, and single sessions. The deep space link is characterized by long delays, weak signals, and station overlap. The following five scenarios generically demonstrate operations between Mars landed assets, orbiter relays, and Earth ground stations.

Scenario 1: Simple Relay. The objective is to transfer to/from a landed asset by means of an orbital relay. A file may be transferred from a landed asset to Earth or visa versa. 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 landed asset, 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.

Scenario 2:Multi-Hop Relay (Rover to lander to orbiter to Earth) 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 of Proximity-1. 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.

Scenario 3:Point-to-Multi-point (forward 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 Mars 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 Mars 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 frame verification rules specify that only data marked with the called asset's spacecraft ID or multicast address will be accepted by the asset.

Scenario 4:Time-Sequenced Point-to-Point (return link) Again assuming the orbiter has only one transceiver, it can time share the return link with multiple Mars assets based upon a priority scheme. It does this by establishing communications with a specific asset by hailing it, limiting the period of the data contact to a subset of the total pass time, terminating the link with that asset before hailing the next asset and repeating the process.

Scenario 5:Point-to-Point Network 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). End-to-End file transfers through a point-to-point network will require the use of CFDP to route the data to the correct end destination.

TRANSITION PLAN FOR PROTOCOL INFUSION

The NASA/JPL Mars 2001 Odyssey orbiter and ESA Mars Express/Beagle II project will be the first Mars missions to implement a subset of Proximity-1 for the In-Situ Martian UHF link. In order for these and future Mars missions to benefit from all the advantages of file transfer, a step wise transition from the current state of on-board protocol development to a complete implementation of Proximity-1 and CFDP is envisioned. A three phased approach below describes how the bi-directional file transfer concept can be infused into future Mars missions. The description below uses a simple communications model of a landed asset, an orbiter relay, and Earth stations as illustrative only.

Phase 1:Reliable Proximity-1 (In-Situ) and Expedited CFDP (Deep Space Link)

The objective of this phase is to relay data collected by the landed asset via a reliable Proximity-1 link to an orbiter, store the data on-board, and later transmit that data as a file to Earth using the expedited features of CFDP. This phase does not require the landed asset to transmit nor store its data as a file. In this case, CFDP does not include the automated selective repeat (report) feature. See Figure 4.

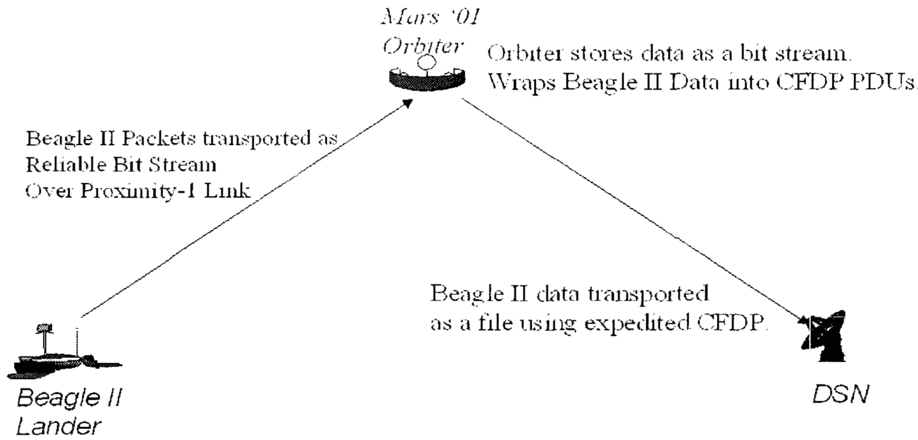

Figure 4: Reliable Proximity-1(In-Situ)/Expedited CFDP(Deep Space)

Phase 2: Expedited CFDP (In-Situ)/Reliable or Expedited CFDP(Deep Space Link)

The objective here is to move the functionality of building the file into the landed asset. The orbiter is provided with the functionality of receiving the file and storing it in the on-board data management system. As in Phase 1, the orbiter transmits the data as a file to Earth using either reliable or expedited CFDP depending upon the data latency and completeness requirements. See Figure 5.

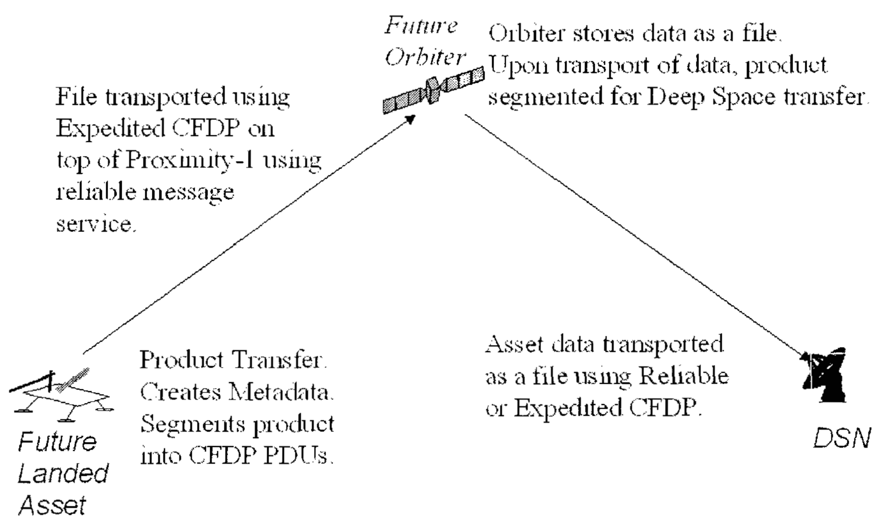

Figure 5: Expedited CFDP(In-Situ)/Reliable or Expedited CFDP (Deep Space)

Phase 3: Reliable CFDP End-to-End

Here the landed asset uses the more efficient and reliable QoS (selective repeat methodology) of CFDP to transfer a file to the orbiter using the expedited QoS of the Proximity-1 link. Similarly, for the Deep Space link, CFDP can be run reliably on top of either CCSDS Packet Telemetry [5] to Earth or CCSDS Telecommand [6] Standard from Earth.

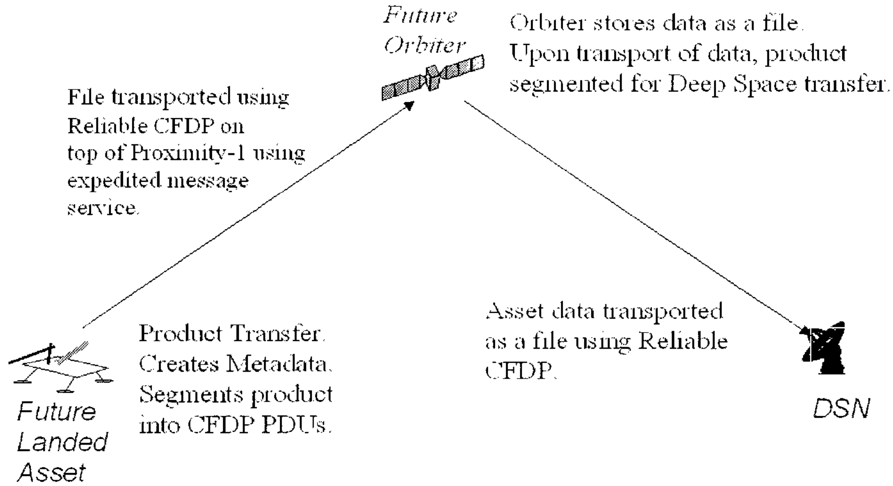

Figure 6: Reliable CFDP End-to-End

ACKNOWLEDGEMENT

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