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The History of the Use of Orbiter Relay at Mars, 1972 to 2024

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Abstract

Today's Mars Relay Network represents a highly successful international collaboration. Its current architecture is the result of an evolution of capabilities that were first exercised when the twin Mars Exploration Rovers, Spirit and Opportunity, arrived at Mars in early 2004. After landing, the 2001 Mars Odyssey Orbiter and the Mars Global Surveyor relayed data from the rovers on the surface of Mars to Earth. This provision of orbital relay to landed assets has become a fundamental infrastructure that facilitates the exploration of the surface of Mars and its importance has only increased since that time.

However, the current network, operating continuously since 2004, does not represent the first era when relay has been used at Mars. As early as 1971, relay was implemented in support of some of the first explorations of Mars. This paper will summarize the history of the use of relay at Mars, including much that never manifested as flight missions but nevertheless had a significant impact on the way the current network was assembled and operates today. Following this history, a discussion on a possible future for relay at Mars will be presented.

Keywords: Mars, communications, relay, history

1. Introduction

Today's Mars Relay Network (MRN) represents a highly successful international collaboration [1]. Its current architecture is the result of an evolution of capabilities that were first exercised when the twin Mars Exploration Rovers (MER), Spirit and Opportunity, arrived at Mars in early 2004 [2]. The 2001 Odyssey Orbiter and the Mars Global Surveyor (MGS) relayed data from the MERs on the surface of Mars to Earth. This provision of orbital relay to landed assets has become a fundamental infrastructure that facilitates the exploration of the surface of Mars, and its importance has only increased since that time.

However, the current MRN, which has been operating continuously since 2004, does not represent the first era when relay has been used at Mars. As early as 1971, relay was implemented by the Union of Soviet Socialist Republics (USSR, or Soviet Union) and then later by the United States of America (USA or U.S.) in support of some of the first explorations of Mars.

This paper will summarize the history of the use of relay at Mars, including much that never manifested as flight missions but nevertheless had a significant impact on the way that the current MRN was assembled and operates today. This history will be described as five distinct eras: the Viking era of the 1970s (Section 2), the Mars Observer era in the late 1980s and early 1990s (Section 3), the Mars Surveyor era in the late 1990s and early 2000s (Section 4), the Odyssey era in the mid-2000s (Section 5), and finally the modern era of the MRN (Section 6). Following this history, a discussion on a possible future for relay at Mars will be presented (Section 7).

1.1 Definitions

There are several definitions that are useful when discussing relay networks. Herein, we refer to the radio link between an orbiter and a deep space tracking network on the Earth as the "deep space link." The radio link between an orbiter and a surface asset, usually a lander or rover, is referred to as the "proximity link." The transfer of data from Earth to an asset on Mars is referred to as the "forward-link"; this term may refer to an "uplink" from a deep space tracking network to an orbiter, though it typically refers only to the proximity link. The transfer of data from an asset on Mars to Earth is referred to as the "return-link"; this term may refer to a "downlink" from an orbiter to a deep space tracking network on Earth, though it typically refers only to the proximity link. See Figure 1.

The period when a landed asset is within view of an orbiter is referred to as an "overflight" and a communications session that occurs during an overflight is referred to as a "relay session." A landed asset may be referred to more simply as a "lander" (despite its form-factor possible being a "rover", for example) or a "relay service user", and an orbiter may be referred to as a "relay service provider". Depending on the context, the "user" and "provider" terms may also include the operators of the various spacecraft on Earth and their attending ground data systems.

1.1 Why Relay?

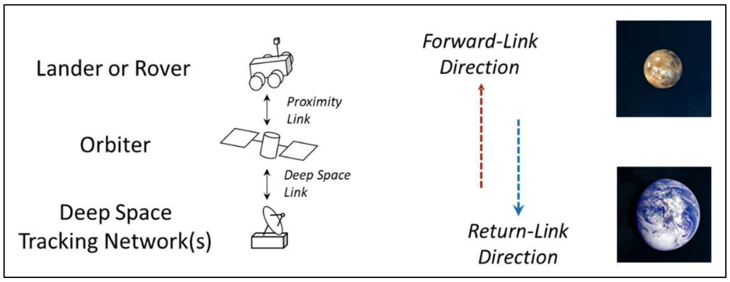

Figure 1: Simple topology illustrating the primary definitions for this discussion.

There are several benefits that orbital relay can provided to landed missions. Once on the surface, Mars landers usually lack line-of-sight to the Earth and the Sun for about 12 hours per day due to Mars's planetary rotation. In addition, the long and variable distance between Earth and Mars (coupled with the power requirements needed to communicate over that long distance) make it necessary for a lander to carry large and power-hungry communications systems, or else suffer with low data rates. In comparison, Mars orbiters tend to have near-continuous access to solar energy and experience generally short or non-existent Earth occultations, depending on their orbits.

From the lander viewpoint, the shorter range to an orbiter, being a small fraction of the range to Earth, makes it possible to achieve high-rate data transfers using low-mass, low-power, and physically smaller telecom systems, relying on the orbiters to carry the burden of transferring the data over the long-leg to Earth.

During critical events, such as when a new lander arrives at Mars, *enters* the Martian atmosphere, *descends* to the surface, and *lands* (a series of events referred to as EDL[1]), orbiters can provide relay services to transfer telemetry from the lander to its operators on Earth. During a lander's descent, high Doppler caused by atmospheric drag; uncontrolled vehicle motion, and power limitations make it difficult to maintain communications. Here again, the shorter range to an orbiter makes it possible to achieve higher rates during this very challenging mission phase.

Radiometric observations (e.g., power and phase) made on these proximity links can also enable precision position and navigation services in the Mars reference frame.

To achieve these benefits, the ground operations for the orbiters are burdened with greater complexity due to the need to interface with the lander operations systems, and the data throughput to and from the orbiters themselves are reduced due to the need to transfer relay data. Ground operations for the landers are also impacted by the introduction of new interfaces that are required for them to access the relay services provided by the orbiters.

2. The Viking Era, 1971-1982

The Soviet Union executed the first Martian relay in 1971 between the Mars 3 Lander and Orbiter. This remarkably ambitious mission featured a lander which parachuted through a planetary dust storm, fired its descent motors, and finally dropped onto the deserts of Mars. While famous as the first controlled landing on another planet, for this discussion what is important is that ninety seconds later the lander began to transmit a weak, Very High Frequency (VHF) signal[2]. The transmission ended after a few tens of seconds, its data containing a single, static-streaked "image" of the surface, as shown in Figure 2 [5].

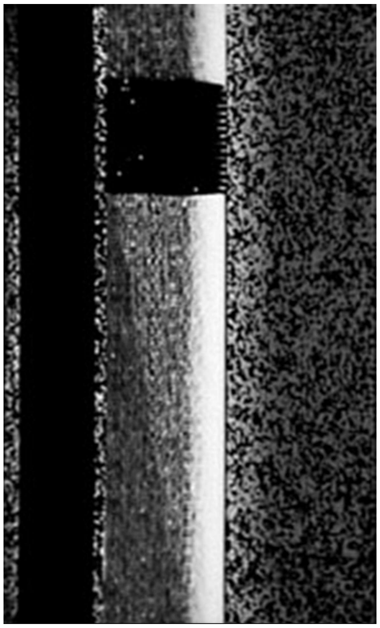

Figure 2: The first "image" returned via relay through the Mars 3 orbiter, which is believed to be mostly static. The image contains the rightmost portion of a panorama.

Waiting high above in an elliptical orbit was the Mars 3 orbiter. The orbiter captured and relayed the lander data back to Earth. No other Mars 3 lander data was received, but in that moment data relay at another planet became a reality. Several other Soviet missions to the surface of

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[1] The investigations into the loss of the Mars Polar Lander and the Deep Space 2 missions were significantly hampered by the lack of relay support during EDL [3]. Since that time, relay coverage has been a critical element of planning for the arrival of new landed missions at Mars [4].

[2] Interestingly, the approach of having the lander initiate the relay session with the orbiter is consistent with modern communications strategies where the "user" initiates communications within a network – a paradigm that contrasts sharply with what has been presently implemented in the MRN, as will be discussed.

Mars also attempted relay but were lost either before or during landing. The Soviets would continue to implement relay systems in other locations around the solar system in partnership with the French, most particularly at Venus during the Venera missions of the 1970s and 1980s [6].

At Mars, from 1976 to 1982, the U.S. Viking Project successfully operated two orbiters and two landers. Each lander was equipped with a one-way Ultra High Frequency (UHF) transmitter which could communicate with either orbiter as they circled Mars in 12-hour elliptical orbits [7]. The Viking orbiters recorded the critical telemetry transmitted from the Viking landers during their EDLs. After landing safely on Mars, the landers' science data was returned preferentially via relay [8].

The Viking missions were operated out of NASA's Jet Propulsion Laboratory (JPL). There, during routine operations, the navigation team provided overflight times to the mission sequencers[3], allowing them to schedule about two relay sessions per week per lander on each of the orbiters. The landers were then separately sequenced to broadcast during these scheduled relay opportunities. In this way, the landers transmitted their data "in the blind" while the orbiters were simultaneously in view and receptive to the independently controlled broadcast from the surface. This scheduling process was almost completely manual. This network operated for 4 years until the Viking 1 orbiter ran out of propellant in 1980.

The topology of this network (see Figure 3) was simple compared to the present MRN. Both landers could transmit to either orbiter, but only in simplex[4] mode. There was no means of commanding the landers via the orbiters, meaning there was no forward-link. The ground planning and sequencing for each spacecraft was essentially independent once the relay sessions were scheduled.

While the Viking Project built the first fully operational deep space relay network, it was operated within a single project and almost all knowledge of how it was implemented and operated has been lost. Even so, the Viking Project demonstrated the value of using relay for critical operations (i.e. EDL) and to enhance data return from surface assets (see Figure 4). The Soviets never built a multi-node relay network but they and their international partners gained relay experience at Venus over the next two decades that would ultimately shape the modern MRN.

After the loss of the Viking 1 orbiter in 1980, it would be decades before a new relay network would operate at Mars.

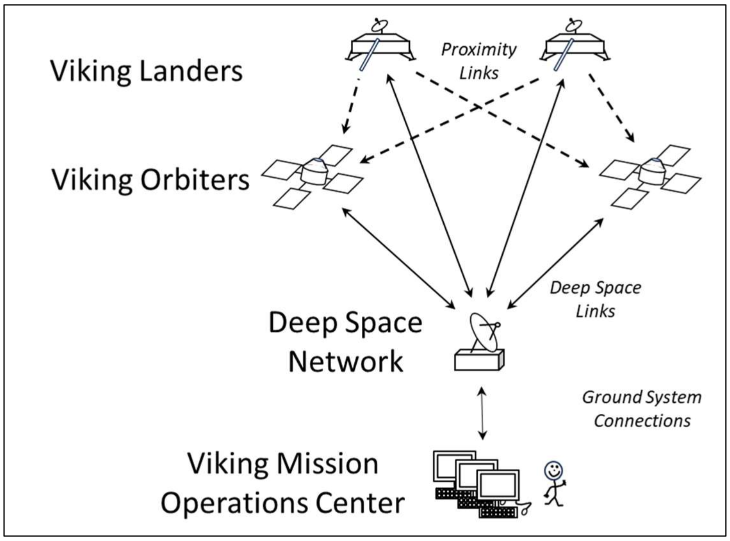

Figure 3: The topology of the relay network during the Viking missions.

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[3] "Sequencer" is a term for a person who constructs long-duration command "sequences", necessary for operating far-distant spacecraft where the two-way light time prohibits highly interactive commanding.

[4] "Simplex" communication is a one-way method of communication where data is sent from one device to another, but the receiving device cannot send data back. The sender does not know if the data was received or the quality of the received data.

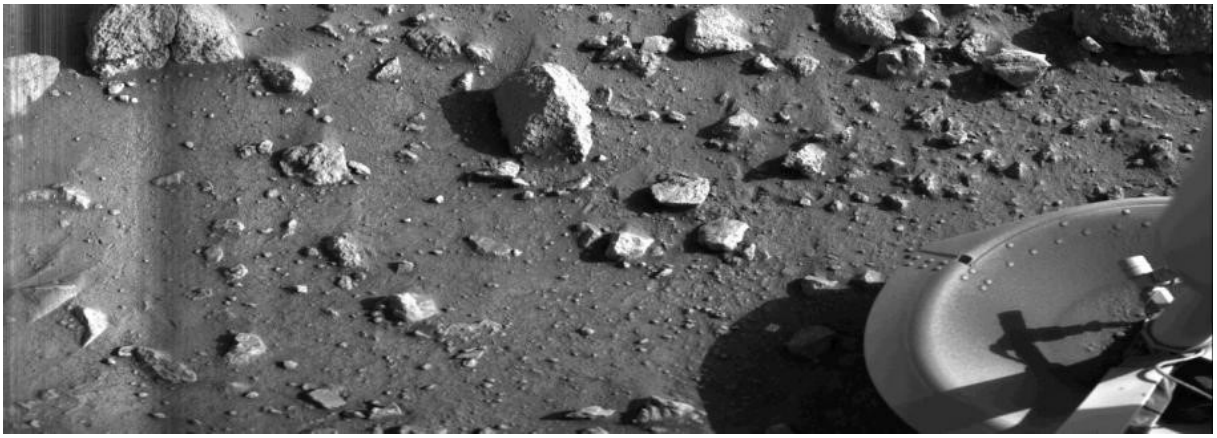

Figure 4: The first successful photograph taken from the surface of Mars, acquired by the Viking 1 lander just minutes after its successful landing on 20 July 1976. Credit: NASA.

3. The Mars Observer Era, 1986-1992

Starting in the 1970s there was a long interval of Franco-Soviet cooperation that continued into the 1990s. The United States was approached several times to participate in joint missions but declined, mostly for political reasons. In time, the Soviet-led Phobos missions of the 1980s, an international effort that planned to relay data from the Phobos landers via the orbiters, were both lost [9].

After these losses, the Soviet Union and the French space agency, the Centre National d'Etudes Spatiales (CNES), jointly proposed ambitious, multi-spacecraft Mars missions for launch in 1992. CNES would contribute several instrumented balloons and develop the Mars Balloon Relay (MBR) hardware to provide UHF relay between the balloons and the orbiters [10]. As conceived, the Soviet Union would construct two orbiters, each of which would carry a rover, a surface penetrator, and a CNES-provided balloon.

The MBR used a communications scheme called the Basic Telemetry Time Sequence (BTTS) communications protocol [11] which enabled an orbiter radio to instigate return-link only transmissions from the balloons by transmitting a subcarrier. This was intended to allow great autonomy on the balloons and maximize power savings if an orbiter was unable to support a relay session. In this architecture, if no relay session was initiated by the orbiter, the balloons would not transmit any data.

At the same time, Mars Observer (MO) was in development in the United States (see Figure 5). The spacecraft was derived from a General Electric Defense Meteorological Satellite bus [12] [13] with the scientific goal of operating as the first interplanetary meteorological satellite. The MO ground system was a tremendous advance over previous NASA deep space operations systems in every way: data-driven software enabled the automated construction of command sequences, software was used to model subsystem performance, the nascent internet enabled data exchanges between mission operators, and new Unix workstations provided greater computational power. The MO operational strategy was also unique in that the science teams would independently construct commands for their instruments assuming pre-defined power, data, and pointing envelopes, without the involvement and oversight of the primary MO operations team, an approach later called "non-interactive payload commanding" (NIPC) [14]. These advances would provide the foundation for future ground system enhancements that would enable relay operations.

In 1987, Jacques Blamont, the founder and director of CNES, recommended that an MBR antenna be added to MO to enhance data collection from the French balloons on the Soviet Union's Mars '92 Mission [15]. The proposal was considered but the MO data system had already been built featuring fixed data allocations for the mapping instruments; the data system was simply incompatible with the highly variable data acquisition rate of the MBR that was the natural result of sporadic MO overflights of the balloons and their power-limited broadcasts.

Figure 5: An artist's rendition of Mars Observer. Credit: NASA.

Michael Malin, the Principal Investigator of the Mars Observer Camera (MOC) [16], offered to use the MOC as a data buffer for the MBR. Since MOC imaging presented similar data production variations (hence the need for its own buffer) this was an ideal, low-impact solution. The only downside was that the MOC would need to sacrifice some of its imaging bandwidth when relay support was required. The agreements were settled and signed and two MBRs, a flight and a spare unit, were delivered by CNES to NASA. In the years ahead, these actions by Jacques Blamont and Michael Malin had long-lasting impacts on the design of the future MRN.

As the MO operations team pondered how to use the MBR in flight, they realized that MO's intended orbit would change their relay's operational characteristics relative to their prior experience – Mars 3 and the Viking orbiters were all in elliptical orbits that provided long overflights but were not Sun synchronous. In comparison, MO would be in a low, circular, Sun-synchronous orbit that would provide short contacts several times a day, regularly clustered near the plane of the orbit in the late afternoon and early morning of any relay users on Mars (assuming the intended 3 to 5 pm orbit). In analysis, both types of orbits were recognized to have strengths and weaknesses from a relay perspective[5], but MO's science mission was to be performed in a low altitude orbit.

The MOC consisted of three cameras – one narrow angle and two wide angle – which exported data to the MOC memory. Images were taken by enabling the desired camera while commanding data collection to commence. Collection continued until a stop command was issued. While the image was being taken, the data was quickly moved to MOC memory. Once in memory, the images were read out from the MOC memory to the MO tape recorder at a much lower, fixed rate. During transmission to Earth, data was played back from the MO tape recorder at a fixed rate that was compatible with the direct-to-Earth downlink rate.

In the end, relay data acquisition via the MBR was designed to behave exactly like a fourth camera. The MBR was to be commanded by the MO sequencing team (via the NIPC process, as mentioned above) to hail with a pre-assigned subcarrier and, at the same time, the camera team would command the MOC to "take a picture" (again, via the NIPC process), meaning it would be configured to accept data from the MBR and place that data in its memory stores. The data produced from the MBR would consist of any relay data the balloon radio transmitted in response to the hail. Once the relay session was complete, the MO sequencing team would command the MBR to stop hailing.

Because of this unusual implementation, the MBR could not be used to forward command data to a spacecraft on Mars; it could only issue the hail and acquire any return-link data transmitted from a relay user spacecraft.

After the MOC data was to be returned to Earth (which could include either actual MOC images or the MBR relay data), the MO ground system was to send the MOC data to Malin's operations facility in San Diego, California, USA. Once there, the MBR data would be assembled and exported to CNES.

Mars Observer launched in 1992. The MBR was checked out during MO's cruise to Mars, including a successful transmission of its UHF subcarrier to Earth-based antennas. Unfortunately, MO vanished three days before orbit insertion on 21 August 1993 [17].

Returning our attention to the Soviet/CNES Mars '92 missions, the dissolution of the Soviet Union in December 1991 resulted in setbacks for the two Mars '92 orbiters. A launch slip from 1992 first delayed the mission to 1994, resulting in a name change to Mars '94. Around this time, CNES withdrew from the project due to cost overruns, taking the balloons with them. The mission was delayed yet again to launch in 1996 and reduced in scope to a single spacecraft. Ultimately, what came to be called the Mars '96 mission was lost in a launch failure on 16 November 1996 [18] [19].

Though these networks never manifested, the topology of the NASA-side implementation is worth examining, as shown in Figure 6. Several distinct features can be noted:

- A balloon would have only returned data to Earth through the MO MBR.
- A balloon would have only received forward-link commands directly from Earth.
- The MO MBR would have completely controlled the proximity link.
- The relay function of MO would have operated in partial isolation from the rest of the MO mission, per the NIPC process.
- The MO mission operations system would have included extra and unique interfaces because of the involvement of the MOC in both the commanding of the MBR and in the return-link data flow.

With the loss of these ambitious missions, a decade of mission design was spent (not wasted!) along with the French dream of ballooning on Mars. The only relics of this network were the single MBR flight spare and the MO operations concepts, both of which would direct JPL's operational path forward for future Mars missions in the coming decades. Leaning into this MO/MBR architecture of the relay system being reliant on a science payload, future relay

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[5] Low-altitude, circular, Sun synchronous orbits can provide high data rate, regular relay opportunities at generally fixed times of day, whereas elliptical orbits can provide variable time-of-day, variable data rate relay opportunities, often with longer view periods.

architectures would similarly treat landed assets as if they were, in many ways, orbiter science instruments, even as they were sponsored by external organizations. The relay transceivers on the orbiters were subsequently designed to operate as a "non-interactive" payload, mostly allowed to freely operate independent of the rest of the host spacecraft if they stayed within their predefined operational box. This allowed the operators of the landers the same access to orbiter resources – principally onboard data storage and direct-to-Earth data bandwidth – as an instrument scientist.

This philosophy of treating the relay capabilities of an orbiter much like a science payload had some long-lasting side effects. Relay radios were accommodated by future orbiter missions as "just another payload," and sometimes the balance of the orbiter's science mission came in direct conflict with relay operations. This sometimes necessitated the integration and deconfliction of relay activities with other science activities. This approach further reinforced the notion of having the orbiters control the proximity link (i.e. always initiating relay sessions with a hail by the orbiter), a paradigm that can be directly traced back to the operational scenarios developed to accommodate the MBR.

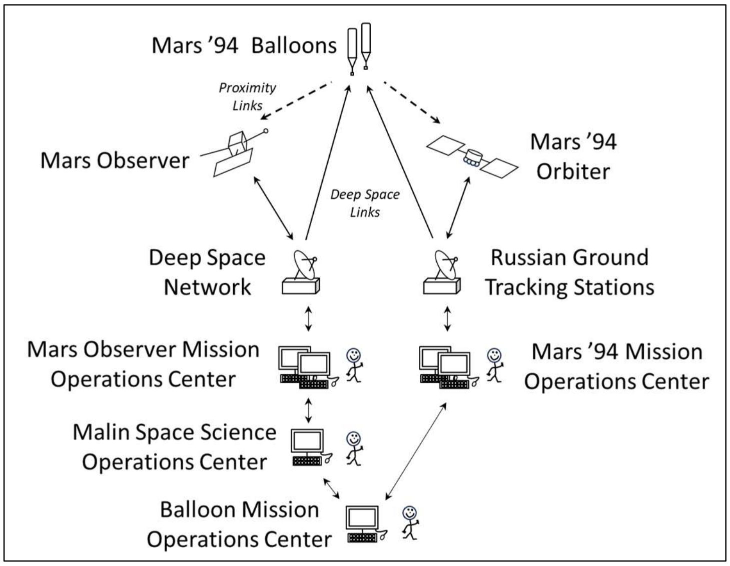

Figure 6: The topology of the Mars Observer relay network for the CNES Mars balloons. Note the parallel paths for data transfer, one via U.S. assets and the other via Soviet assets; no coordination or collaboration had been pursued between these two data paths prior to the termination of the Mars '94 missions.

4. The Surveyor Era, 1997-2001

With the loss of MO in 1993, two smaller missions, Mars Pathfinder [20] and the Mars Global Surveyor (MGS) [21], were quickly set in motion, with both launching in late 1996. Mars Pathfinder was to demonstrate a set of innovative technologies for landing on and exploring Mars. On 4 July 1997, Pathfinder successfully landed and shortly thereafter deployed the Sojourner rover (see Figure 7), the first successful mobile platform on Mars. MGS arrived a few months later on 12 September 1997.

With both missions operating at Mars simultaneously, NASA's Deep Space Network (DSN) demonstrated a new capability to track two spacecraft at the same time with a single antenna aperture, a capability later referred to as "multiple spacecraft per aperture", or MSPA [22]. This capability effectively doubled the DSN's 34-meter station tracking coverage and would prove very useful in increasing the throughput of the future flotilla of orbiters at Mars.

While not important to the direct development of the relay network, there was one aspect of the Pathfinder mission that would be important to relay in the future: the first two-way relay. The Pathfinder lander and Sojourner rover used very low power radios to communicate with each other, with Sojourner being fully reliant on Pathfinder for communicating with its Earth operators. Each radio used a half-duplex protocol and could either transmit or receive packets at any given time. The Sojourner rover usually initiated the telecommunication sessions with the lander. Pathfinder itself would communicate directly with the DSN, not having a relay orbiter available to it. After Pathfinder's short mission (the lander survived 83 days, longer than the planned 7-day mission) the UHF band at Mars fell silent once again.

After the loss of MO, there remained a complete set of flight spare instruments and engineering components. Lockheed Martin, fresh from their pioneering aerobraking experience with the Magellan orbiter at Venus [23], acquired General Electric Aerospace and the MO flight spares. Teaming with JPL, they proposed MGS as a less expensive path to recapturing the lost science of some of the MO payload. The spacecraft would use aerobraking instead of propulsive maneuvers to reach its science orbit, the tape recorder was replaced by a solid-state recorder, and, most important to this discussion, the spare MBR, renamed simply as the Mars Relay (MR), was included in the payload and connected

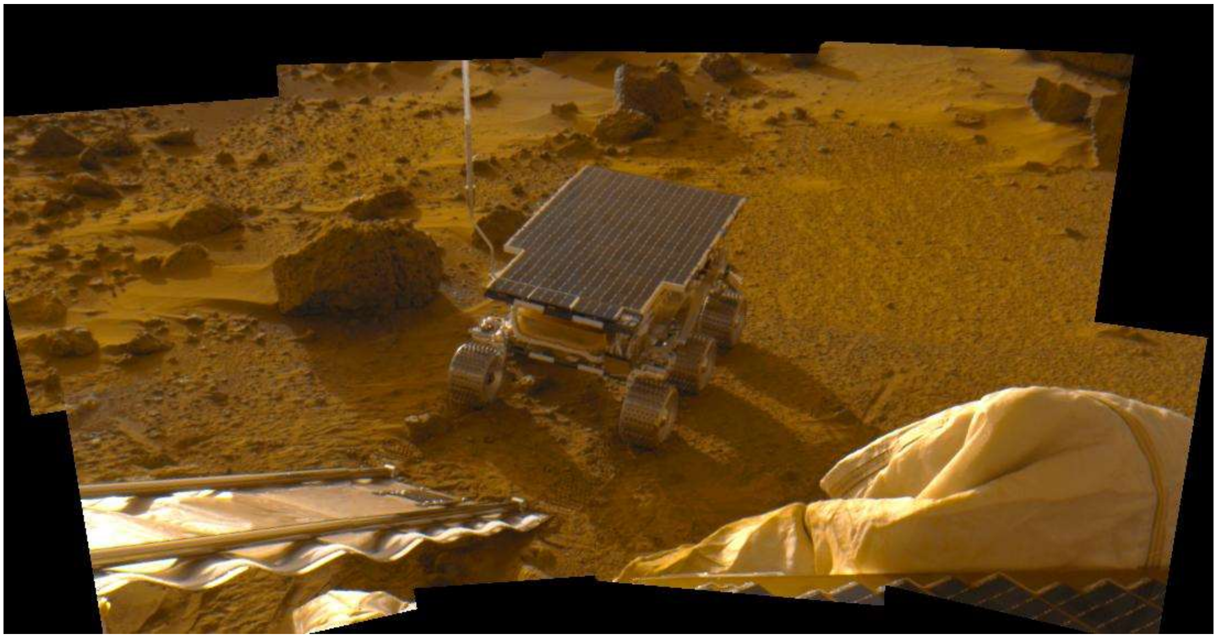

Figure 7: An eight-image mosaic from the Pathfinder lander that includes the Sojourner rover on 5 July 1997, 1 day after landing after just egressing from the lander's top. The rover's UHF antenna, which it used to communicate with the lander, can be seen to the upper left of the rover. Credit: NASA/JPL.

to the MGS MOC just as it had been on MO. Following a lengthy two-phase aerobraking campaign [24], MGS entered its final science orbit in February 1999. NASA now had a relay asset in place for the first time in almost 20 years.

Given the success of the Pathfinder and MGS missions, NASA initiated the Mars Surveyor Program (MSP) [25]. The Mars Surveyor '98 missions (or Mars '98) would consist of the Mars Climate Orbiter (MCO), the Mars Polar Lander (MPL), and the twin Deep Space 2 (DS2) impactors [26] [27].

MCO launched first on 11 December 1998 and arrived several months ahead of MPL/DS2 (which were launched together on 3 January 1999) and, like MGS, was also to aerobrake into its science/relay orbit. MCO was to serve as the prime relay for MPL; both carried Cincinnati Electronics UHF radios. The protocol used by these radios was called the Cincinnati Electronics Telemetry Broadcast Protocol (CETBP) [28] which acknowledged frames using a stop-and-wait scheme. This was the first full-duplex system ever flown in deep space.

MGS, meanwhile, was to be tasked with receiving data transmitted by the DS2 probes during their expected lifetime of several days and to provide supplementary data return for MPL once the DS2 batteries depleted. This new network's topology is shown in Figure 8.

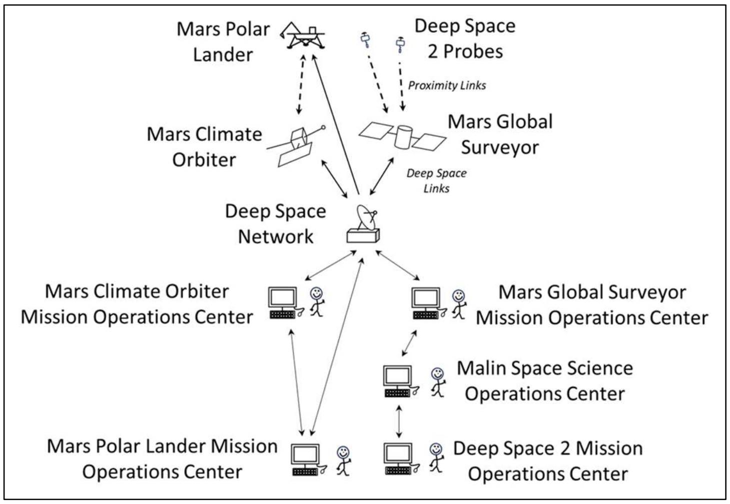

Figure 8: The intended topology of the Mars Climate Orbiter and Mars Global Surveyor network for the Mars Polar Lander and the Deep Space 2 probes.

4.1 Early Ground Coordination

This was the first time that a relay network needed to be operated across more than three organizational boundaries, which introduced a new challenge to ground coordination.

The entire relay operations system was developed by the MSP multi-mission flight team, several members of which had MO operations experience. This was done without any dedicated funding or external management – it was an unplanned job that just needed doing. The multi-mission nature of the teams provided an environment in which the organic development of the relay ground system could occur, especially for the Mission Planning and Sequence Team (MPST) at JPL which led the development.

By this time, the multi-mission Navigation Team traditionally generated data files for the orbiters called Orbit Propagation and Timing Geometry (OPTG) files which contained a time-ordered listing of orbital events, such as the times of periapsis, descending equator crossings, etc. For relay purposes, the team developed a similar file which contained view period information from a lander's perspective and called it the Landed Orbit Propagation and Timing Geometry (LOPTG) file. The LOPTG contained a time-ordered listing of view period events, such as when an orbiter would rise over the horizon, be at its maximum elevation, and set below the horizon. Though now obsolete, this standardized file format finally formalized the *ad hoc* data deliveries by the navigation team from the Viking era.

To sequence relay activities, MPST and the Spacecraft Team[6] at Lockheed Martin used the JPL-developed Activity Plan Generator (APGEN) [29], a tool first developed to support Cassini activities during its cruise to Saturn. APGEN was employed here to construct relay sequences for MCO simultaneously with matching MPL wake, sleep, and relay sequences, all while checking for UHF cross-talk[7] conflicts. To do this, the LOPTG file was ingested into APGEN along with an OPTG and other files that specified DSN tracking times. With MCO planned to operate in a sun-synchronous polar orbit with an equator crossing at around 4 am/pm local Mars time, it would pass over the landing sites 2 to 4 times per Martian day at roughly the same times of day at both 4 am and 4 pm.

MPL's commands and sequences were to be submitted to the MCO ground system by the MPL ground operators. The MCO ground operators would then process these "forward-link" command products into MCO command products using their Automated Sequence Processor (ASP) [30] in the same manner as the MGS and MCO science teams would submit their "non-interactive" instrument commands.

One of the key problems the team had to solve was how to allocate the relay opportunities given that all the landed assets would be in essentially the same area on Mars and operate on the same frequencies. In early 1999, the initial understanding was that the MGS hails would sort out which lander was to be contacted. However, late in the cruise phase, the DS2 team realized that the impactors would power on if they detected *any* UHF carrier signal, regardless of whether MGS was specifically hailing the DS2 probes or not. Because the probes had very limited battery life, this was a serious complication.

Like the Mars '94 balloons, UHF pinging was effectively the only method to control the impactors. Ultimately, the MPST resolved the issue by building a very complex series of overlapping sequences for MGS which alternated attempts to listen to the impactors every 2.5 minutes. These overlapping sequences were to be loaded onto MGS and then activated or deactivated via ground command based on which impactors were still functional during the few days of their missions.

4.2 Managing the Unexpected

Three months before MPL's EDL, MCO exploded in the Martian atmosphere due to a commanding error which placed it too close to the planet during orbit insertion [31]. MPST suddenly had to rework the entire relay operations concept while simultaneously continuing preparations for the EDL and surface operations of MPL and the DS2 impactors. In a moment, the network topology shifted to that shown in Figure 9.

The operations team immediately recognized that MGS would have to relay all data for MPL in addition to DS2; none of the landed assets had the ability to transmit directly to Earth and therefore the burden for returning data from these landed assets had fallen completely to MGS. Since MGS did not have a forward-link capability, the MPL Project was also forced to shift their commanding paradigm to be direct-from-earth (DFE) only, whereas before they had intended to rely upon MCO. In three months, the entire landed operations scenarios had to be reworked. The already complicated DS2 scheme became an interwoven sampling scheme, trying to contact all three landed assets during a single overflight while protecting the DS2's battery lives.

By design, UHF relay was not required during EDL. As a result, first contact with each of the landed assets would be after their EDLs, meaning that landing occurred in the blind. The relay architecture had become something quite different than what was intended when MPL and DS2 were launched.

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[6] While MPST was responsible for the proper construction of spacecraft commands and sequences, the Spacecraft Team was responsible for the analysis and operations of the spacecraft systems and subsystems. They would have the principal responsibility for generating command sequences, with the MPST acting as a check to confirm the safety and viability of those sequences.

[7] Cross-talk is a destructive phenomenon whereby the electric or magnetic fields of one telecommunications system may interfere with another. In this context, cross-talk conflicts exist when more than one radio transmits on similar or identical frequencies to those being used by another radio.

4.3 Lessons Learned from A Bad Day at Mars

Following the EDL of MPL and the DS2 impactors, there was no response to MGS MR hails from any of the landers. The flight team conducted search and rescue operations for 3 months. Ultimately, all three landed vehicles and MCO were declared lost, ultimately leading to the demise of the Mars Surveyor Program. A definitive MPL or DS2 failure root cause was never identified due to the lack of EDL data [32].[8]

After all these events, not a single bit of data had been relayed between a lander and an orbiter at Mars since the loss of the Viking 1 orbiter in 1980. Most Mars missions had been a failure over that 20-year span. However, there were several key lessons learned from the losses.

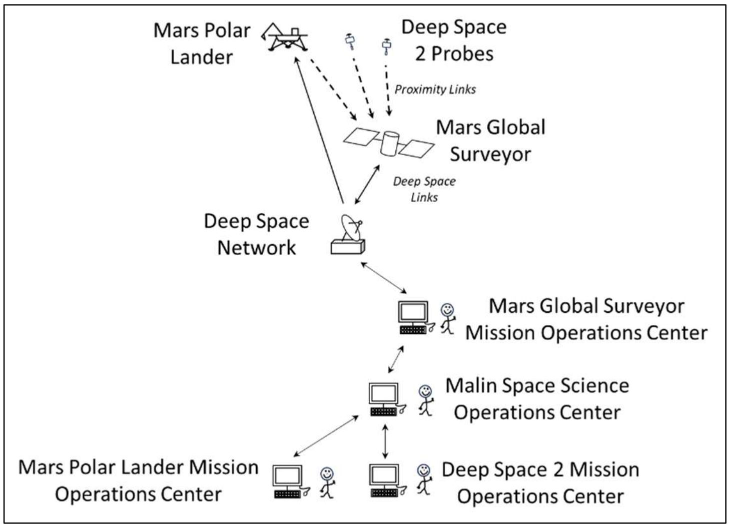

Figure 9: The intended topology of the Mars Global Surveyor network for the Mars Polar Lander and the Deep Space 2 probes following the loss of the Mars Climate Orbiter.

NASA would soon insist that future Mars landing systems must transmit data during EDL, to be captured either by relay orbiters or directly by Earth-based antennas. The operations team gained valuable experience operating the MGS MR, which remained operational in Mars orbit aboard MGS. The use of MSPA at the DSN and full-duplex protocols in the UHF proximity radios were also advancing based on flight experience.

Additionally, the Mars ’98 vehicles used an early version of Virtual Machine Language (VML) [35] to sequence MPL and MCO. The MPST gained valuable experience building spacecraft-expanded blocks[9] which could be controlled using input parameters and global variables, a feature that would enable future Mars orbiters and landers.

The relay ground infrastructure as a multi-mission architecture was developed for the first time. It was substantially more capable than the Viking system that preceded it (based on what little we know about it) and proved to be a very important stepping stone for what was to follow.

Even with the Mars ’98 failures, there was little doubt that the orbiters should be considered network trunk lines in the future. Managing these trunk lines was expected to be key to enabling and enhancing future data return from the surface of Mars.

5. The Odyssey Era, 2001-2009

The Mars Surveyor Program was restructured after the loss of the Mars ’98 missions into the Mars Surveyor Operations Program (MSOP). MSOP was itself soon reorganized into the Mission Management Office (MMO) at JPL, partly because not all the missions it was operating were Mars missions[10]. The MSP-planned Mars ’01 orbiter was rechristened as the Mars 2001 Odyssey orbiter, a rebuild of MCO which again carried some of the spare instruments

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[8] In the years to come, the lack of EDL coverage would hinder the investigation into the loss of the United Kingdom’s Beagle 2 lander in 2004 [33], but the provision of EDL coverage would be quite helpful in analyzing the fate of ESA’s ExoMars Entry, Descent, and Landing Module (EDM), the Schiaparelli lander, in 2016 [34].

[9] In this context, a “block” is a series of commands that persisted within a spacecraft’s command system which could be initiated with a single command perhaps accompanied by parameters. Functioning much like a computer subroutine, these blocks, implemented via VML, included many modern control features to simplify spacecraft commanding, such as “if” branches that could respond to external stimuli, “while” loops, etc. The use of these blocks dramatically reduced the size of command products that needed to be sent to spacecraft, improved command reliability, expanded operational flexibility, and enhanced efforts to verify and validate command sequences.

[10] MSOP would go on to operate not only MGS, MCO, MPL, and DS2, but also Stardust (launched on 7 February 1999), Genesis (launched on 8 August 2001), and Spitzer (launched on 25 August 2003) within a single multi-mission flight team at JPL that included all operations areas of expertise.

from MO. There was also a planned Mars ’01 lander, but it was delayed after the Mars ’98 failures and would later become the Phoenix lander[11] launched in 2007.

Cincinnati Electronics provided another UHF radio for Odyssey. This was the first radio to use the new Proximity-1 protocol [36]. This protocol supports the establishment of a full-duplex link, the acknowledgement of transfer frames, and the mid-session adjustment of relay session attributes, such as the data rate. The Odyssey UHF relay blocks were constructed using VML, which allowed the ground operators to set global variables onboard the orbiter that would effect tactical changes[12] after sequence uplink, a new feature of the network that would be extensively used in the years to come.

After launch and cruise, Odyssey joined MGS at Mars, aerobraking into its science orbit in early 2002. The network now had two operational trunk lines for the first time.

5.1 The 2003-2004 Armada

At the end of 2003, ESA’s Mars Express Orbiter arrived at Mars, carrying the Beagle 2 lander that was operated from the UK. Mars Express entered into a relatively large, elliptical orbit and expected to provided relay support to Beagle 2 after it landed on 25 December 2003. MGS and Odyssey, in their lower-altitude orbits, were also tasked to support Beagle 2 using their more rapid overflight cadence.

The Spirit and Opportunity rovers arrived on 3 January 2004 and 24 January 2004, respectively. The rovers were each equipped with a medium gain antenna that could communicate directly with Earth, and the missions were designed to be achievable with only that method of communication (the Pathfinder experience formed the basis of the operations scheme). They also carried UHF radios to supplement data return through MGS and Odyssey, with Mars Express intended as an additional backup. The two rovers were built and operated as a unified project at JPL (separate from MMO) called the Mars Exploration Rover (MER) Project. This new network would cross national borders for the first time. See Figure 10 for the intended network topology.

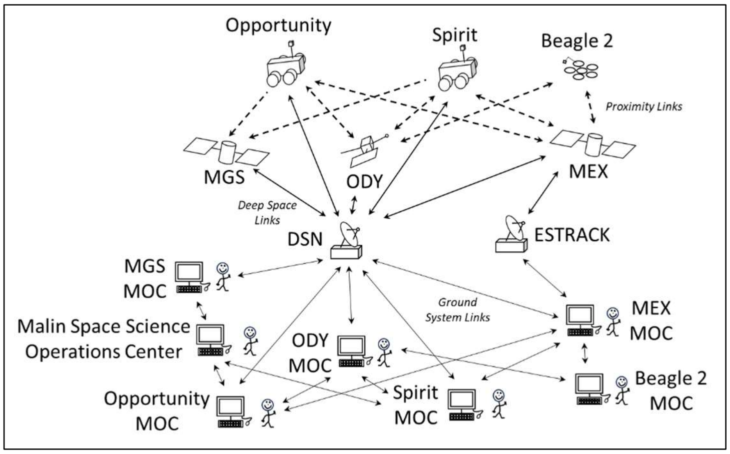

Figure 10: The intended topology to support the missions arriving at Mars in 2003/2004.

The new network would feature a wide variety of organizations, relay hardware, and spacecraft configurations. The network topology finally appears to look like a network, with a wide assortment of connections between almost every entity. This web of connections complicated the cross-project relay planning efforts, requiring the MPST to be mindful of the operational nuances of each spacecraft and ground system. In addition, every connection between spacecraft, ground systems, and mission operations centers (MOCs) represented an interface that had to be built, tested, and verified as a reliable, operational interface.[13] This integration effort represented a significant, non-recurring effort. However, once built, each interface then had to be operated indefinitely, which was a recurring effort that would test the resiliency of the ground planning systems and their operators in the years to come.

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[11] Phoenix remains the only NASA mission to Mars to-date (excepting the Sojourner rover) that has successfully landed on Mars without the ability to communicate directly with Earth. It was completely dependent on relay to perform its mission.

[12] “Tactical” changes are minor changes made externally to longer-length sequences. Some tactical changes to a scheduled relay session might include the adjustment of a commanded return-link data rate, the delay of the hail start time, or a shift from a coherent to a noncoherent relay session.

[13] Odyssey transmits its data to the DSN using a frame-based transmission scheme [37], with certain data types tagged in what are called “virtual channels” (VCs). Relay data collected from its onboard proximity radio are tagged with a unique VC that are recognized by the DSN during downlink. The DSN extracts the relay data with this unique VC and directly transfers it to the MOCs of the landed missions, circumventing the Odyssey MOC. This represents an exception to all topologies shown from Figure 10 and forward. This historic artifact has been persisted through the addition of each new orbiter mission, who each use this DSN-provided service in various ways. A MaROS-based method (see Section 6) of transferring return-link data from an orbiter MOC to a lander MOC stands ready, but at this writing has not been used operationally.

5.2 Ground Planning and Coordination

To address these issues, the Mars UHF Relay Operations (MURO) team was formed by MMO as a loose organization to include all the relay partners. It focused on managing these variances. As best as possible, the lead sequencers from Odyssey and MGS worked with each relay partner to consider every possible complication.

One of the biggest planning issues was that the sequencing timelines for the rovers, measured in hours, was completely inconsistent with the sequencing timelines for the orbiters, measured in weeks. MPST had to find ways to bridge these timelines in a cost-effective way, without drastically altering the operations paradigms of any mission. The use of Global Variables to effect tactical changes in the VML-based relay sequences on Odyssey was one of the solutions in this area.

Additionally, the rover teams needed estimates of when their return-link data would be available, necessary information to implement their daily commanding. These return-link "latency" estimates depended on (among other things) how much data volume was expected to be transferred, the one-way light time to Earth, the timing of when DSN tracking time was allocated to Odyssey and MGS, and the presence of occultations that might interrupt the transmission. APGEN was again deployed to account for all these data and estimate these latencies weeks ahead of time.

Perhaps the most surprising aspect of the relay network development was that it was never initially "conceived" by any organization – the development of its ground tools and processes was completely *ad hoc*. Though people had previously proposed fully enabled, autonomous networks to be implemented at Mars, the actual network just emerged from the evolving mission set, just as it had in the Viking and Surveyor eras. There was no direct funding provided to assemble the network; all the work occurred through the teams supporting the various participating missions. This was especially true for the MPST (which had members who had been associated with relay operations since MO) which provided the cross-organization coordination.

JPL and the MER Program's management hadn't been exposed to the past work of the MPST, and they assumed the landers should drive the design and operation of the relay network. However, for them, relay wasn't a priority since the main data return was planned to be DTE. External parties also lacked appreciation of the complexity of sequencing MGS and Odyssey and the importance of their ongoing science missions. It fell to MPST to educate these external parties as to why network coordination was vital. Fortunately, formal responsibility for network development was given to MMO and the MPST several months prior to the arrival of Spirit and Opportunity at Mars.

As the last component of the network, support from MMO's multi-mission Ground Data System (GDS) Team enhanced data tracking, which helped to pinpoint return-link anomalies. This development task was added and developed just in time for Beagle 2's EDL.

The APGEN development work proved to be critical as a network planning tool. It was used to track all overflights, the relay session configurations for all three orbiters, cross-talk conflicts, MER shift timing and uplink opportunities, MGS and Odyssey occultations, details of MGS's and Odyssey's onboard data management, DSN allocations to MGS and Odyssey, ground system latencies, periods of time during which each orbiter could not support relay activities (i.e. "non-relay periods"), etc. It was also used to directly construct the MGS and Odyssey relay sequences, delivered to the projects as inputs to be integrated with the balance of their spacecraft sequences.

From a mission planning and uplink perspective, APGEN was used to coordinate operations among all the various mission operations teams. Similarly, on the downlink side, the multi-mission GDS served as the common data distribution system. Fault tables and extensively developed "playbook" responses were developed to allowed MPST to instantly respond to single and double failures anywhere in the network.

5.3 Things Get Real

The true test of all this preparation [38] [39] was the arrival of Mars Express and Beagle 2. As with MPL, no radio coverage was planned to record the events of Beagle 2's EDL. First contact was to be shortly after landing, and that first contact came and went with no hint of a signal from the lander. In the weeks to come, Mars Express, MGS, and Odyssey each attempted to hail the lander and failed to elicit a response [40]. This was not an auspicious beginning, though it was unfortunately familiar.

However, in the following days, Spirit and Opportunity both had a successful EDL. Spirit's landing had been monitored using ground-based antennas, which were listening for radio "beeps" from the rover to indicate its progress during landing. These beeps indicated a successful landing, but did not include much other data from the rover after touchdown. A few hours later, Odyssey performed the first relay session with the rover and returned the first images. Data had finally been relayed by the network!

It bears mentioning that until this point in time, relay via the orbiters was still considered a "nice-to-have" for the mission, a capability that was unnecessary for the rovers to achieve their mission objectives. However, when this

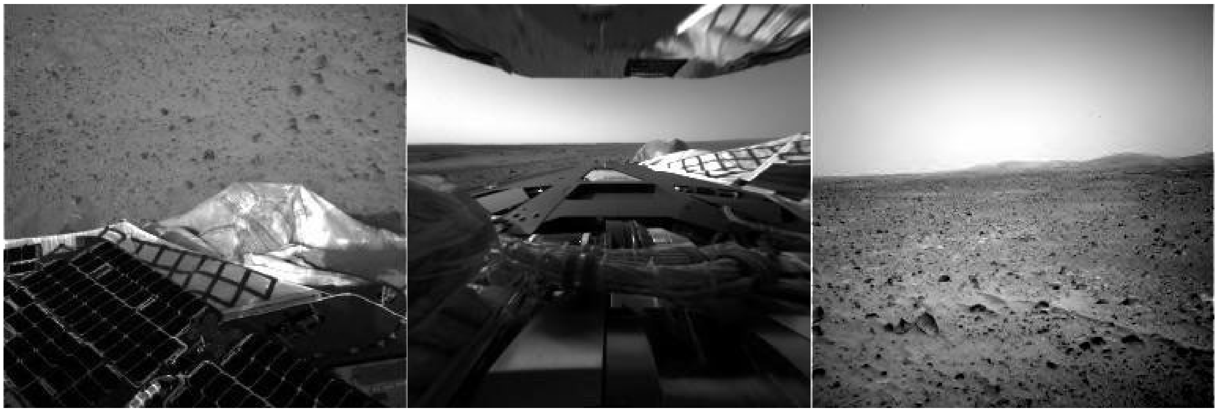

Figure 11: Some of the first images returned from the Spirit rover via the Odyssey orbiter shortly after landing on 4 January 2004. Credit: NASA/JPL.

Odyssey pass occurred and pictures from the rover shortly thereafter appeared on the monitors of the Spirit operations consoles (see Figures 11 and 12), a significant mental shift occurred. In that moment, the use of orbital relay very suddenly went from a technology demonstration to an enabling infrastructure.

Subsequently, almost all MER planned and executed relay sessions worked as expected [41] [42]. Relay tactical changes via the UHF blocks worked perfectly. After a week, the MER Project contacted MPST to express their amazement on how much data had been returned. The rover teams began to ramp up their use of the network and pivoted away from the Pathfinder-inherited DTE baseline. The importance of the orbiters as trunk lines was confirmed.

This network proved so successful from first use and thereafter largely because of the heavy emphasis on network ground coordination, which eliminated most issues before actual sequencing began. APGEN made the entire relay planning process efficient by integrating inputs from a wide variety of sources so that they could be scheduled against

Figure 12: MER Principal Investigator Steve Squyres (in blue) points to the first images returned via the Odyssey orbiter just hours after landing. Credit: Bill Ingalls, Associated Press with permission from NASA.

in a single process, a methodology that, by design, eliminated the likelihood of scheduling conflicts between the various missions. The ability to predict the arrival of relay data through the network assumed much greater importance as the rovers came to rely almost exclusively on relay for their data return. The recognition of the network's benefits cemented the orbiter-centric network topology[14] into place for the decades to follow.

The concept of treating surface assets operationally like science instruments also proved to work well for both forward- and return-link operations. With the inclusion of Mars Express and Beagle 2, despite ITAR restrictions[15], collaboration worked well and forced the JPL-developed relay coordination system to be better than it would have been without it.

This was the genesis of this highly successful collaboration across project and national boundaries. Mars Express became a functioning node in the network after initial demonstrations with MER, which paved the way for future international cooperation and highlighted the usefulness of mixed orbit types.

5.4 The Nascent Mars Relay Network

Since 2004, the network has continued to operate through both the addition and occasional loss of nodes – both relay service users and relay service providers.

The Mars Reconnaissance Orbiter (MRO) joined the network in 2006 and carried the first Electra UHF Transceiver (EUT, or simply Electra) [43]. The EUT is a software-defined radio (see Figure 13), and was later updated, post-launch, with a capability that could optimize relay session throughput by evaluating the instantaneous signal-to-noise ratio during a relay session and use the Proximity-1 "communications change" directive to adjust the return-link data rate, a capability called "adaptive data rate" (ADR) [44].

MRO was designed to roll from its preferred nadir orientation to perform targeted imaging, and this capability was additionally deployed during relay sessions to enhance the returned data volume. MRO operations were conducted via MMO and relay operations were blended into the MRO science planning process. When MRO reached its science orbit in 2006, four orbiters were available to provide relay.

Around this time, relay network management shifted from MMO to NASA's Mars Exploration Program (MEP) Office, the direct organizational successor to MSOP. MEP had been formed in 2002 with the objective of managing future robotic missions at Mars [45][45], but it did not take ownership of the relay coordination activities at that time, partly because it wasn't recognized as an activity that needed to be actively managed. When relay coordination was eventually shifted from MMO to MEP, the intent was to centralize and formalize these activities, a decision that would prove key to the implementation of the modern architecture for ground coordination.


Figure 13: A pre-flight image of the EUT which later flew on MRO. Credit NASA/JPL.

Eventually, a commanding error caused the loss of MGS in 2006 [46], which ended the long history of the last MBR unit 20 years after it was developed. Looking back, the MBRs ultimately were the "north stars"[16] of the modern relay operations philosophy even though they were products of the French and Soviet space programs.

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[14] One key example of this paradigm shift is that during the EDLs of future missions, DSN 70-meter tracking time would be allocated to the orbiters to optimize their data return rather than to the landers. The use of MSPA would also prove critically important in this area.

[15] ITAR, or International Traffic in Arms Regulations, are the U.S. regulations that control the manufacture, sale, and distribution of defense and space-related articles and services as defined in the United States Munitions List (USML). ITAR and the USML have evolved since the arrival of Mars Express and Beagle 2 at Mars in late 2003, but at the time these greatly restricted the exchange of information with ESA and the UK when assembling this nascent network.

[16] The use of the term "north star" symbolizes the notion of a constant direction and stable guidance through difficult times, due to its fixed position relative to other stars.

Figure 14: MRO's HiRISE camera was able to capture the Phoenix lander on its parachute during its descent, a feat that was the result of both good engineering and good luck. The pointing of MRO was optimized to acquire the radio signal transmitted from Phoenix assuming a wide variety of possible landing trajectories, and the time when the image was taken was estimated based on these trajectories in an attempt to capture the lander as it passed through the imager's field of view. It worked! It is noted that Phoenix did not land in the crater in this image (Heimdall crater), but instead in Vastitas Borealis. This was the first time a vehicle's descent onto a non-terrestrial body was captured in an image. Credit: NASA/JPL.

Arriving at Mars in 2008, the Phoenix mission was built on the mothballed Mars '01 lander from the then-defunct Mars Surveyor Program to recapture MPL's science goals. MMO, which had been restructured into the Multimission Ground Systems and Service (MGSS) Program, was given responsibility for the lander's operations, which, by that time, was considered an unusual choice since Spirit and Opportunity were operated by standalone (i.e. not multi-mission) teams.

The Phoenix lander was the first successful mission (the Sojourner rover notwithstanding) with no DTE capability [47]. During the Phoenix EDL, both MRO and Odyssey were tasked with recording the critical event telemetry transmitted from the lander. During descent, MRO also used its HiRISE camera to take an image of the lander, as shown in Figure 14.

During the Phoenix mission, the network topology was, for lack of a better word, "busy", especially in the ground connections as shown in Figure 15. This topology illustrates a situation that was becoming untenable for the operators of the relay network, namely that the sheer number of interfaces, especially the ground interfaces, multiplied with each new mission that arrived at Mars. In addition, requiring science orbiters (whose primary purpose was to perform science investigations) to provide relay services was sometimes directly at odds with their scientific investigations.

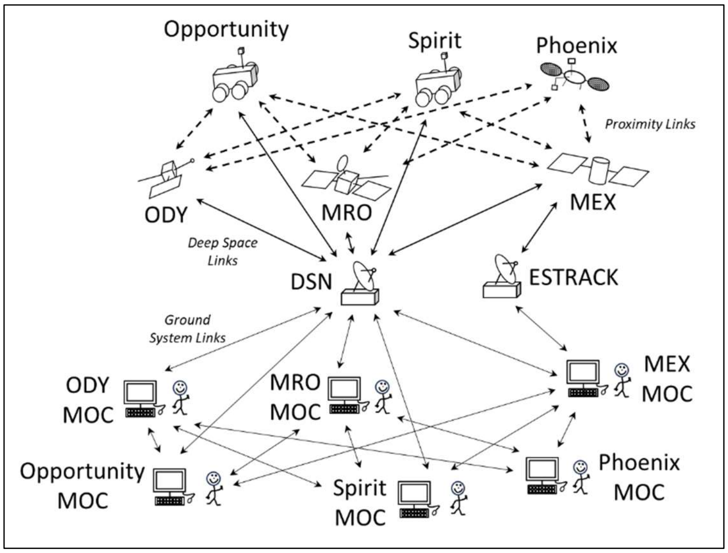

Figure 15: The relay network topology during the Phoenix mission in late 2008. Note the inclusion of ESA's tracking station network, ESTRACK.

6. The Modern Mars Relay Network, 2010-Today

To date, NASA's and ESA's Mars orbiters have never been dedicated exclusively to relay operations. However, recognizing the need for a more robust communications infrastructure at Mars, several orbiters have been proposed over the years to act as high-bandwidth, dedicated relay trunk lines with Earth. Though there have been many variations on the theme, the two most prominent examples are the Mars Telecommunications Orbiter (MTO) [48], with an intended launch in 2009; and the Next Mars Orbiter (NeMO) [49], with an intended launch in 2022. Both would have carried hardware to demonstrate an optical deep space link.

In their times, both MTO and NeMO were cancelled due to a lack of funds. Historically, unless a U.S. orbiter carries a scientific payload and directly responds to objectives outlined in The National Academies of Sciences, Engineering, and Medicine's Planetary Science and Astrobiology Decadal Survey [50] [51], it has been impossible to muster the political and financial backing to be implemented, even in the face of its obvious engineering utility.

MTO, however, indirectly led to the MarCO project [52], which provided critical event coverage for the InSight lander in 2018 [53]; and the Deep Space Optical Communications (DSOC) project [54], which was launched with the Psyche spacecraft [55] in late 2023 and demonstrated the ability to use high-rate laser communication technology in a deep space application. Both projects suggested capabilities that could be leveraged at Mars in the future, namely the implementation of communications services in a small form factor and the application of optical communications technologies to enhance data throughput.

Despite the headwinds in implementing a dedicated relay infrastructure at Mars, some better success has been achieved in addressing the complexities of the ground planning and coordination systems. During the Phoenix mission [56], many deficiencies in the ground relay systems and processes were exposed. The ground tools, including the APGEN-based planning system, having never been designed to be extensible, were showing their age and it became obvious that something different should be done.

Faced with the lessons learned from the Phoenix experience and the prospect of even more missions going to Mars, MEP partnered with MGSS to manage the situation in a more deliberate way. This partnership yielded the Mars Relay Operations Service (MaROS) [57], a ground system that acts as a central point of coordination between lander and orbiter operations teams for scheduling relay activities, a portal via which to exchange forward- and return-link data, and a clearinghouse for relay session performance data. The service utilizes standardized interfaces[17] for data exchanges and provides a streamlined mechanism to add new assets to the ground planning systems of the MRN. Going online in 2010, MaROS was used as the baseline relay planning system for the Curiosity rover [58] which arrived at Mars in 2011.

In the flight domain, MEP also made the decision to ensure that every science orbiter that it sent to Mars should thereafter carry a relay payload. Following the successful implementation of the Electra on MRO, additional models were built for the MAVEN orbiter (launched in 2013) [59] and, in another win for international collaboration, for ESA's ExoMars Trace Gas Orbiter (TGO, launched in 2016) [60]. By design and consistent with the MRO Electra's capabilities, these Electra radios supported the Proximity-1 protocol with ADR, key features that would be useful for existing and future surface missions.

TGO carried with it the Schiaparelli lander, also called the EDL Demonstrator Module (EDM) [61]. Its purpose was to demonstrate an ESA capability to land on Mars. Though the landing itself did not fully succeed [62], preparations for its arrival [63] proved the wisdom of both of MEP's decisions to construct the MaROS-based ground planning infrastructure and to implement the Electra radios as a standard payload.

In the following years, the InSight lander [64] arrived at Mars in 2018 and the Perseverance rover [65] arrived in 2021. In each case, the addition of these new surface missions (and the loss of older ones) was handled gracefully in both the ground and flight domains. Today, the network topology for the ground interfaces has more connections but is simpler in the aggregate, as shown in Figure 16. The use of both flight (i.e. Proximity-1) and ground interface standards (i.e. the MaROS-based interfaces) eased the integration and operations of the network even as it evolved.

At the proximity link, all orbiters communicate with the surface assets using the Proximity-1 protocol. In the ground system, it is notable that the number of interfaces for relay coordination collapsed from what was an "X times Y" problem, where every lander MOC had to construct a unique interface to every orbiter MOC, to an "X plus Y" scenario, where each mission only needed to construct a ground system interface to MaROS. By doing so, a lander project can perform relay planning activities with every orbiter using only a single interface and, inversely, an orbiter project can support relay planning activities with every lander project using their single interface. In the case of Figure

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[17] It is noted that The Consultative Committee for Space Data Systems (CCSDS) now offers internationally recognized standards for cross-organizational data exchanges that can be used in this domain. However, these standards did not exist or were not mature when MaROS first went online in 2010, and are only now maturing. However, it is notable that CCSDS, with key participation by NASA and ESA, developed the Proximity-1 standard, as discussed, enabling cross-agency interoperability.

16, the ground interfaces for relay planning number only 8 instead of the original approach of 15, saving time, money, and operational complexity.[18]

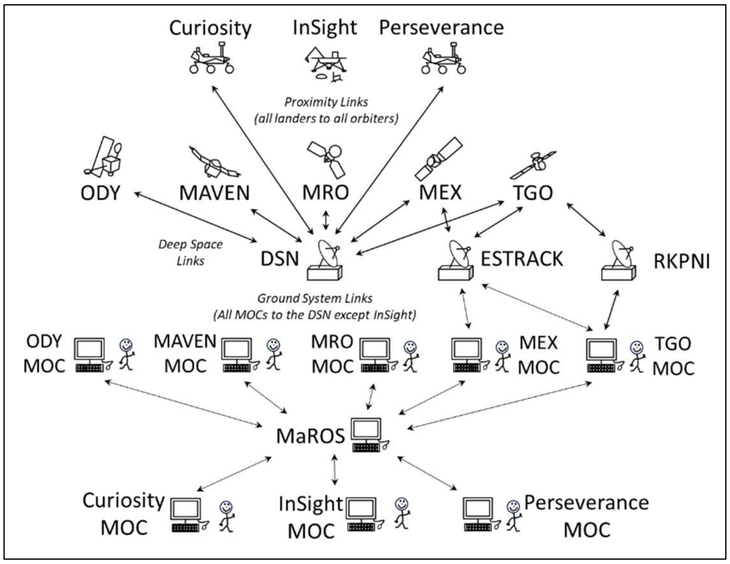

Figure 16: The relay network topology after the arrival of Perseverance at Mars in 2021. To simplify the diagram, the proximity links and the MOC links to the DSN are not shown. Note the inclusion of the Russian ground tracking stations, the Russian Complex for Receiving Scientific Information (RKPNI), which provides deep space tracking support to TGO.

6.1 Network Evolution

The MRN did not come to maturity as the result of a decades-long master plan; it was assembled piecemeal based on the evolving mission set. The success of the network over the past two decades was the result of three evolutionary pressures:

1. Heritable characteristics: the introduction of a multi-mission sequencing architecture, as represented by VML; the introduction of a multimission ground system and architecture, relay radios designed to be flown on several missions, and the concept of non-interactive payload commanding.
2. Unexpected characteristics: the introduction of distributed science operations, the development of the MBR, and the unpredictable nature of the as-flown mission sets.
3. Characteristics driven by resource limitation: non-relay-dedicated orbiters, the introduction of MSPA at the DSN, and the implementation of a consolidated relay planning process for scheduling the scarce resources of the network.

However, the evolution of the network was also directly influenced by technological improvements, such as the maturation of the CCSDS communications protocols (Proximity-1), the development of the Electra radio, the application of VML in key systems, and the evolving ground systems that leveraged innovations in computer science, leading to the development of MaROS.

6.2 Other Considerations

Given the historic rarity of orbiters being sent to Mars, there is not yet a great need to closely coordinate the orbits of each spacecraft for the purpose of avoiding in-orbit collisions. Even so, NASA supports the Multimission Automated Deepspace Conjunction Assessment Process (MADCAP) [67], which analyzes the predicted trajectories for each of the Mars orbiters, calculates the likelihood of collisions, and identifies times when the orbiters pass close to each other. This process is mostly automated, can readily include additional orbiters, and is expected to continue to be applied in future years.

As at Earth, the allocation of the radio spectrum to various users at Mars needs to be carefully managed. Today, the Space Frequency Coordination Group (SFCG) [68] is tasked with performing that allocation, and historically all national and private entities have been compliant with decisions made by that body. As more spacecraft arrive at Mars, the spectrum is expected to get more congested and the SFCG will continue to play a key role in allocating it.

Both of these considerations, namely the possibility of in-orbit collisions and frequency assignments, were brought to the forefront of multi-agency coordination efforts prior to the launch of the China National Space Administration's (CNSA) Tianwen-1 orbiter, which arrived at Mars on 10 February 2021 carrying with it the Zhurong rover [69]. Due to sociopolitical considerations, direct coordination between CNSA and NASA/ESA (which by that time had been collaboratively operating the MRN for over 15 years) proved difficult. Two primary concerns manifested: 1) the Tianwen-1 orbiter was designed to operate in a highly elliptical orbit that would rotate about Mars and cross the orbits of the other spacecraft in the MRN, introducing a possibility for an in-orbit collision, and 2) CNSA implemented the

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[18] It is noted that ESA, for their own reasons, constructed what is called the "European Relay Coordination Office" (ERCO) [66], which interfaces with MaROS, aggregates all ESA-related data, and performs data transformations as necessary between ESA-crafted mission planning data types to the MaROS-standard data types.

proximity link between the orbiter and the rover to utilize the Proximity-1 protocol with its specified frequencies, several frequencies of which were already being robustly used by the MRN.

Regarding this last point, the common protocol and frequencies implemented by CNSA might have suggested that some interoperability would be possible, but this was not pursued by any party. Instead, a two-fold agreement was achieved with the aid of the IMRCWG: 1) CNSA would make available predicted trajectories for Tianwen-1 that could be used in the MADCAP process, and 2) certain frequencies were allocated to CNSA for use that did not conflict with the frequencies already in use by the MRN.

On paper, it seemed the issues had been resolved. However, during operations, radio frequency interference was occasionally observed by NASA (on UHF and X-band frequencies) and the delivery of trajectories for use in the MADCAP process was not always reliable – both situations that could have been better and more quickly addressed if CNSA and NASA/ESA had more directly interacted. Though the Zhurong rover's mission came to an end in 2022, these issues are expected to remain concerns as new missions from these agencies (and others) manifest in the future.

7. Discussion and Conclusion

The MRN in its present form remains a small network, characterized by unique elements that are each aging and brittle. Given this condition, there is a great desire to move to a next-generation architecture, one characterized by relay orbiters that are dedicated to the task [70].

The implementation and operation of the current MRN over the last 20 years has yielded many lessons that can be applied [71] when considering how to evolve to a new architecture. Chief among these findings is the continued need for a centralized body to manage the integration and ongoing operations of the network, employed across the whole life cycle of each element in the network.

In the future, without the implementation of a dedicated relay infrastructure, one could expect that the network would continue to be populated by orbiters that serve both relay and science objectives, and these orbiters could come from a variety of national space agencies. This would introduce complications in both the governance and the physical integration of the network. Today, the NASA/ESA collaboration that is the MRN is managed quite effectively via a cross-agency working group called the International Mars Relay Coordination Working Group (IMRCWG) [72], with NASA's participation in the IMRCWG led by MEP. This working group stands ready to interface with other national players.

However, there remain many questions about how dedicated relay orbiters or other related assets (such as new ground stations) would be integrated into the network should it be sponsored and/or operated by a private entity, though it is expected that the IMRCWG would prove key to guiding this integration.

Even if new players provide or use relay services using different frequencies or protocols, it is still expected that a ground planning and coordination infrastructure will be needed. Thus, it is anticipated that MaROS (or a successor) would continue to have a role in the short- and medium-term as a centralized system with which to schedule time on the relay service provider spacecraft. It is expected that this service would be retired only when the network scales up in size and capability, with a richness of connections that can be dynamically asserted without human intervention[19]. Such a scaling might prove coincident with the arrival of human explorers at Mars, though this is not assured.

In the meantime, much effort is being spent on the implementation of a relay network around the Moon [75]. In principle, lessons learned from assembling the MRN should be applied at the Moon, with lessons learned at the Moon then further applied at Mars. However, the political and financial environment for NASA and other players remains complex, and the future is uncertain.

Given these challenges, it is important to remember that the MRN was assembled as an interoperable system not by a master design but rather by the engineers who were faced with an immediate challenge and rose to the occasion. The non-recurring costs of identifying the frequencies, protocols, and orbits to be used in a future network tend to dominate the discussion regarding future relay networks in most forums. However, the MRN is a case study of success by those who glued together the heterogeneous elements of the network as part of the recurring costs related to actually operating the network at Mars.

Today's MRN functions successfully today only by the grace of the participating organizations, who altruistically share the objective of exploring Mars. In practice, the multi-organization nature of the MRN has proven to be quite collegial, with all parties bringing their best to the table. The relationships formed between missions stretch beyond the relay network to collaborations in other areas, including in their various science investigations. This case demonstrates that the exploration of Mars is best achieved when all participants cooperate with intent.

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[19] Such a network could be part of the solar system internetwork, as described in [73]. It may also implement delay tolerant networking protocols, as referenced in [74].

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