Telecommunications Relay Support of the Mars Phoenix Lander Mission

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Abstract— The Phoenix Lander, first of NASA's Mars Scout missions, arrived at the Red Planet on May 25, 2008. From the moment the lander separated from its interplanetary cruise stage shortly before entry, the spacecraft could no longer communicate directly with Earth, and was instead entirely dependent on UHF relay communications via an international network of orbiting Mars spacecraft, including NASA's 2001 Mars Odyssey (ODY) and Mars Reconnaissance Orbiter (MRO) spacecraft, as well as ESA's Mars Express (MEX) spacecraft. All three orbiters captured critical event telemetry and/or tracking data during Phoenix Entry, Descent and Landing. During the Phoenix surface mission, ODY and MRO provided command and telemetry services, far surpassing the original data return requirements. The availability of MEX as a backup relay asset enhanced the robustness of the surface relay plan. In addition to telecommunications services, Doppler tracking observables acquired on the UHF link yielded an accurate position for the Phoenix landing site.

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1. INTRODUCTION

Spanning a period of over three decades, a series of robotic probes have landed on the Martian surface, conducting *in situ* explorations of our neighboring planet. Beginning with the two Viking Landers launched in 1975, and followed by the launch of the Mars Pathfinder Lander in 1996 and the two Mars Exploration Rovers in 2003, these spacecraft have greatly advanced our understanding of the Red Planet. One of the many challenges of these landed Mars mission is the severe mass and power constraints for a spacecraft that must be safely delivered to the Martian surface, and the resulting limitation in telecommunications capability. To mitigate these constraints, these missions have utilized relay communications to increase data return from resource-constrained landers.

As an example, while the two Viking Landers were capable of communicating directly to Earth via S-band deep-space links, they returned much of their data via energy-efficient, short-range relay links to the two Viking Orbiters which carried the landers to Mars. The orbiters could then take on the job of returning those data to Earth, taking advantage of the orbiters' more capable deep space link telecommunications system and more abundant power [Brown, 1974].

While the Pathfinder Lander only returned data over a direct-to-Earth X-band link, the Sojourner Rover that Pathfinder deployed was too small to communicate directly to Earth, and instead returned all its data on a short range surface UHF link to the Pathfinder Lander. Hence the lander served as a relay node for the even more resource-constrained rover. [Matijevic, 1997].

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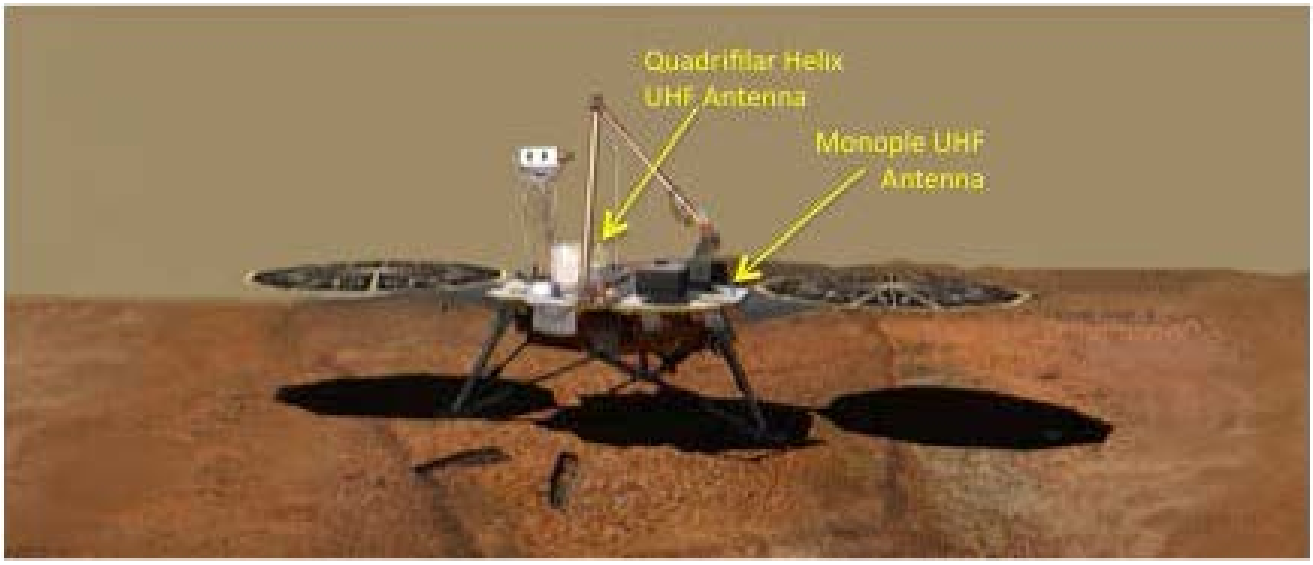

Figure 1: Phoenix Lander Surface Configuration

The Mars Exploration Rovers, Spirit and Opportunity, are equipped with X-band direct-to-Earth telecommunications systems, but have in fact returned nearly all of their data via UHF relay links through an international network of Mars orbiters, including NASA's Odyssey, Mars Global Surveyor, and Mars Reconnaissance Orbiter spacecraft, and ESA's Mars Express Orbiter [Edwards, 2007].

The most recent mission to the Martian surface, the 2007 Phoenix Lander, was selected as the first of NASAs Scout class missions [Smith, 2004; Shotwell, 2004]. Based on the success of MER's relay communications, the Phoenix mission was designed to exclusively use UHF communications once the lander separated from its cruise stage shortly before Mars entry, thereby reducing the cost, mass, and power of the lander [Lewicki, et al., 2006].

In Section 2 we summarize the Phoenix mission and describe the spacecraft, with an emphasis on its telecommunication systems. In Section 3 we outline the relay capabilities of the three Martian orbiters that supported Phoenix relay operations. Section 4 describes the critical event communications support provided during entry, descent, and landing of the Phoenix spacecraft. Section 5 addresses relay operations during the lander's surface mission. Section 6 describes the use of Doppler observations collected during UHF link sessions to determine an accurate lander location. Section 7 closes by summarizing lessons learned and looks ahead to future Mars relay scenarios.

2. Phoenix Mission and Spacecraft Description

The Phoenix Lander mission was the first Scout mission within NASA's Mars Exploration Program. The competitively-selected, cost-capped Scout missions are focused, science-driven concepts that complement the program's core series of interdependent strategic missions. Scouts provide an opportunity to introduce innovative mission concepts and to respond quickly to scientific discoveries from previous missions. Phoenix illustrated both of these characteristics. Its science goal of searching for ice and other volatiles in the upper decimeters of the Martian surface at its high-latitude landing site was motivated by the previous discovery from orbit, by the 2001 Odyssey mission, of enhanced levels of hydrogen – likely in the form of water ice – in the Mars subsurface at these latitudes. And to achieve its ambitious goals within the Scout cost cap, Phoenix proposed to utilize the Mars 2001

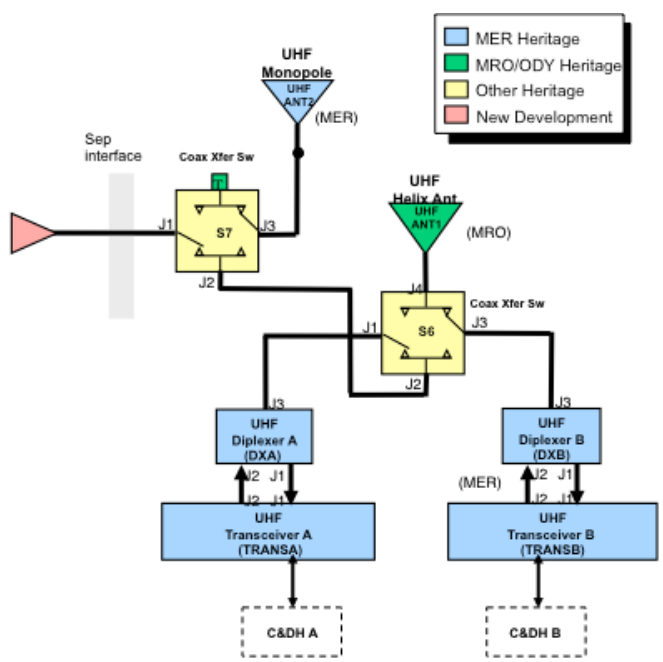

Figure 2: Phoenix Lander Telecommunications Block Diagram

Lander, which had been largely implemented prior to a decision to cancel the launch in the wake of the loss of the Mars 98 Polar Lander.

The surface configuration of the Phoenix Lander is illustrated in Figure 1. A pair of deployable solar panels provide power for surface operations. Key science elements of the lander include the Robotic Arm, capable of trenching and scooping up soil for delivery to the lander's two analytical instruments: the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) and the Thermal and Evolved Gas Analyzer (TEGA). Other instruments include the Surface Stereo Imager (SSI), the Meteorological Station (MET), the Robotic Arm Camera (RAC), and the Mars Descent Imager (MARDI).

While the original Phoenix Lander proposal included an X-band direct-to-Earth communications system for the surface phase of the mission, similar to the X-band capability on the Mars Exploration Rovers, the X-band system was eliminated from the Lander early in development. This decision, which was justified based on the highly successful relay support of the Mars Exploration Rovers and by the ongoing availability of redundant relay orbiters, resulted in significant mass, power, and cost savings for the Phoenix mission. The project estimates that elimination of the X-band system and supporting hardware reduced the lander mass by 14.8 kg, reduced lander energy requirements by 36 W-hrs, and saved the project over $3M.

So while the Phoenix cruise stage incorporated X-band communications for the nearly 10 month transfer orbit from Earth to Mars, once the lander separated from the cruise stage shortly prior to entering the Martian atmosphere, all communications from that point forward were carried out via UHF relay links to the Odyssey, MRO, and Mars Express orbiters. The resulting Phoenix Lander telecommunications system, shown in Figure 2, included block-redundant CE-505 UHF transceivers. The transceivers supported the CCSDS Proximity-1 Space Link Protocol [CCSDS, 2004], providing interoperability with the UHF payloads on all three relay orbiters. The Proximity-1 protocol specifies physical layer, coding and modulation, and link layer standards for communication payloads supporting short distance links, and establishes hailing procedures for link establishment and retransmission protocols that allow reliable full duplex communications, ensuring error-free, gap-free data transfer on Mars relay links. The implementation of the Proximity-1 standard in the Phoenix CE-505 transceiver utilized fixed-frequency operations, receiving on the forward link (orbit-to-surface) at 437.1 MHz and transmitting on the return link (surface-to-orbit) at 401.585625 MHz, supported data rates of 8, 32, 128, and 256 kbps (although the Phoenix mission chose not to utilize the 256 kbps capability), and provided an option for encoding the return link with a (7,1/2) convolutional code.

During atmospheric entry, the lander was enclosed in a protective aeroshell. Communications during this phase utilized a wrap-around antenna on the backshell. Once the lander separated from the backshell to begin its terminal descent, the communications switched to a quadrifilar helix antenna on the lander deck. On the surface, the lander had two UHF antennas available for use in any given relay contact. The quadrifilar helix antenna offered the best gain gain pattern for most overflights; however, in order to support late-morning passes on the surface with the Odyssey orbiter, which would occur with Odyssey at low elevation towards the northwest horizon, a monopole antenna was added. (Because the Phoenix Lander touched down with a controlled azimuthal orientation, it was possible to locate the monopole antenna on the lander deck to optimize the gain pattern for these late morning passes.)

3. MARS RELAY NETWORK

While the three orbiters operating at Mars during the time frame of the Phoenix Lander mission share a common interoperable relay service, each has unique characteristics that impact their performance as relay assets.

Mars Odyssey

The Mars Odyssey spacecraft, launched in 2001, operates in a 400-km circular, sun-synchronous orbit, with an inclination of roughly 93 deg [Spencer, et al., 2002]. At the time of the Phoenix mission, the ascending node of the Odyssey orbit was positioned at roughly 5 AM Local Mean Solar Time (LMST). Communications to Earth is performed at X-band via a 1.3 m high gain antenna and a 15 W solid state power amplifier. Odyssey relay operations were very mature by the time of Phoenix support, based on the fact that Odyssey provided the vast majority of relay support to the Mars Exploration Rovers.

For relay communications, Odyssey is equipped with the same CE-505 UHF transceiver that Phoenix carried (modified to swap the transmit and receive frequency assignments for the orbiter side of the proximity link). The CE-505 transceiver also includes a 1-bit-per-sample open loop recording capability (sometimes referred to as "canister mode", as it was originally included to detect a tone from an orbiting sample canister for a future Mars Sample Return mission); the resulting recording can be post-processed to extract a carrier signal, providing frequency and amplitude information.

Mars Express

Launched in 2003, ESA's Mars Express operated during the Phoenix time frame in a highly elliptical 255 x 10,142 km orbit, with an inclination of 86.35 deg and an orbital period of 6.75 hr. These orbit elements result in continual variation of both the latitude and local time of periapsis. Mars Express communicates to Earth at X-band via a body-fixed

1.65 m high gain antenna and a 65 W TWTA [Schmidt, 2003].

Relay communication is supported by the Melacom UHF transceiver, with separate transmit and receive patch antennas. Melacom supports return link data rates in powers of 2 from 2 kbps to 128 kbps, although support for Phoenix only utilized rates of 8, 32, and 128 kbps. In addition, Melacom supports a 1-bit-per-sample open loop recording capability similar to Odyssey, which can be post-processed to provide carrier tone information.

Mars Express was originally intended to be the primary relay support for the Beagle-2 Lander. Although Beagle-2 was lost during entry, descent, and landing, Mars Express has continued to play an important role as an additional relay asset supporting the Mars Exploration Rovers. While not utilized on a routine basis, Mars Express has conducted a number of relay passes with Spirit and Opportunity, which have successfully validated its Melacom relay payload and demonstrated its capabilities to provide backup relay services in the event of a loss of Odyssey and MRO.

Mars Reconnaissance Orbiter

Launched in 2005, MRO carries a data-intensive set of science payloads, including the HiRISE imager, driving the need for high-rate communications to Earth; accordingly, MRO incorporates a high-performance X-band downlink with a 100 W TWTA and a 3 m high gain antenna Graf, et al., 2005]. To maximize the resolution of MRO's remote sensing instruments, the spacecraft flies in a low altitude orbit of 255 x 320 km, at a sun-synchronous inclination of 93 deg and an ascending node fixed at 3 PM LMST.

MRO incorporates the Electra UHF transceiver, a new design based on a software-defined radio architecture that allows significant evolution of protocols and signal processing capabilities even after launch [Edwards, 2003]. While Electra offers frequency-agile operations and a wider range of data rates, for Phoenix support operations was constrained to the fixed frequencies and limited data rates available in the Phoenix CE-505 transceiver. In addition to its closed-loop demodulation capability, Electra also offers a high-fidelity recording capability, acquiring open-loop in-phase and quadrature samples of a 150 kHz bandwidth with a bit depth of 8 bits per sample. Based on this multi-bit recording capability, post-processing on the ground can be performed to provide both carrier extraction as well as full demodulation of any telemetry modulated within the recorded bandwidth.

A particular challenge for MRO relay operations was the discovery, prior to launch, that several of the orbiter's science instruments generated excessive electromagnetic interference (EMI) in Electra's UHF receive band, leading to large degradations in return link performance and, in some cases, false lock conditions that could completely preclude any data transfer. MRO proceeded to launch with the knowledge that, if required, these instruments would be powered off during relay operations; however, such an approach would impact MRO science return, and the power cycling would pose a risk to the payload lifetime. To avoid these impacts, a new baseband digital filter was developed after launch and uploaded to Electra while in orbit at Mars which attenuated the EMI sufficiently to avoid having to power cycle those instruments. Extensive tests were conducted in flight, using Electra's open loop recording capability and closed-loop self-test capability, to optimize the configuration of the science instruments to minimize EMI degradation and quantify the resulting return link performance. In the end, configurations were identified

	Mars Odyssey	**Mars Express**	**Mars Reconnaissance Orbiter**
Agency:	NASA	ESA	NASA
Launch:	Apr 7, 2001	June 2, 2003	Aug , 2005
Orbit:	400 km circular 93 deg inclination sun-synchronous 5 AM LMST ascending node	255 x 10,142 km elliptical 86.3 deg inclination Non syn-synchronous	255 x 320 km 93 deg inclination sun-synchronous 3 PM LMST ascending node
Deep Space Link:			
Band	X-band	X-band	X-band
Power Amplifier	15 W SSPA	65 W TWTA	100 W TWTA
High Gain Antenna	1.3 m HGA	1.65 m HGA	3 m HGA
Proximity Link:			
Transceiver	CE-505 UHF Transceiver	Melacom UHF Transceiver	Electra UHF Transceiver
Protocol	CCSDS Proximity-1	CCSDS Proximity-1	CCSDS Proximity-1
Antenna	Quadrifilar Helix	Patch Antennas (2)	Quadrifilar Helix
Forward Link			
- *Frequency*	437.1 MHz	437.1 MHz	435-450 MHz
- *Data Rate*	8 kbps	8 kbps	8 kbps
- *Coding*	Uncoded	Uncoded	Uncoded
Return Link			
- *Frequency*	401.585625 MHz	401.585625 MHz	390-405 MHz
- *Data Rate*	8, 32, 128, 256 kbps	2, 4., …, 128 kbps	1, 2, 4, …, 1024 kbps
- *Coding*	(7,1/2) Convolutional	(7,1/2) Convolutional	(7,1/2) Convolutional

Table 1: Key Characteristics of Mars Relay Orbiters During Phoenix Relay Support Period

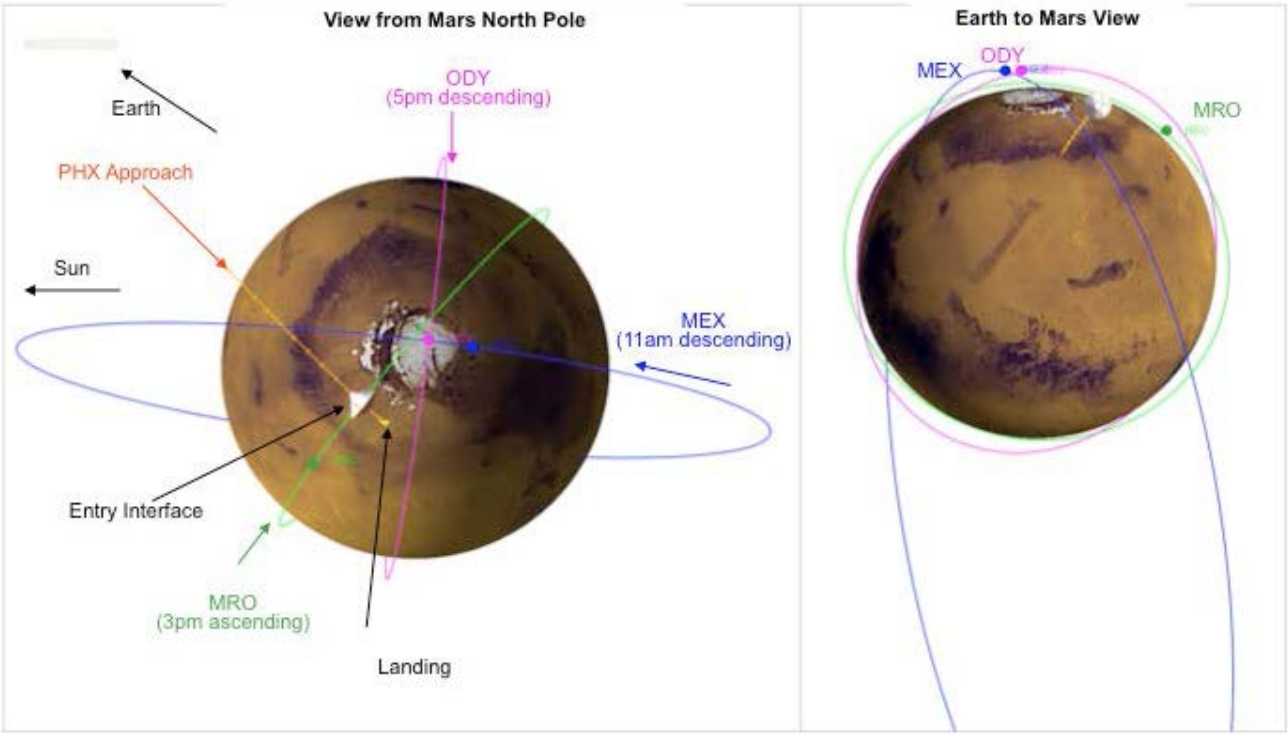

Figure 3: Phoenix Arrival Geometry

which avoided the need for instrument power cycling and reduced the link degradation to the range of 5-7 dB.

4. Critical Event Communications During Entry, Descent and Landing

The Phoenix spacecraft arrived at Mars on May 25, 2008, targeted to a landing site at 68 deg northern latitude. Since the loss of the Mars '98 Polar Lander, NASA's Mars Exploration Program has required each landed mission to acquire sufficient information during the critical period of entry, descent, and landing to enable fault reconstruction in the event of a mission anomaly. To that end, all three orbital assets were utilized to capture information during the Phoenix EDL.

Figure 3 depicts the arrival geometry, showing the orbits of the Odyssey, Mars Express, and MRO spacecraft. Due to the high latitude of the selected landing site and the high inclination of each of the orbiters, it was possible to adjust the true anomaly of each orbiter to allow all three to be in view of Phoenix during EDL.

The overall EDL communications strategy took advantage of unique aspects of each of the relay orbiters. Upon separating from the cruise stage seven minutes prior to atmospheric entry, the Phoenix spacecraft began transmitting a UHF carrier signal through the wrap-around antenna on the backshell of the entry vehicle. Two minutes prior to entry, Phoenix began modulating telemetry information on the UHF carrier at a rate of 8 kbps. This continued throughout the hypersonic entry phase, during

Event	Time	PHX Configuration	Odyssey Configuration	Mars Express Configuration	MRO Configuration
Cruise Stage Separation	E-7 min	Carrier only	Open-loop recording (1 bit-pr-sample) Post-processing provides PHX carrier only	Open-loop recording (1 bit-pr-sample) Post-processing provides PHX carrier only	Open-loop recording (150 ksps, 8 bit-per-sample, I&Q) Post-processing provides PHX carrier and telemetry
Turn-to-Entry	E-6.5 min				
Begin 8 kbps Telemetry	E-2 min	8 kbps			
Entry	E-0 min, L-419 s				
Hypersonic Phase (potential UHF blackout)					
Parachute Deployment	E+224 s; L-195 s	32 kbps	Closed-loop demodulation 32 kbps Bent-pipe playback to Earth		
Heat Shield Jettison	E+239 s; L-180s				
Leg Deployments	E+249 s; L-170 s				
Radar Activated	E+259 s; L-160 s				
Lander Separation	E+382 s; L-37 s				
Throttle Up	E+385s; L-34 s				
Touchdown	E+419 s; L-0 s				

Table 2: Timeline of EDL Events

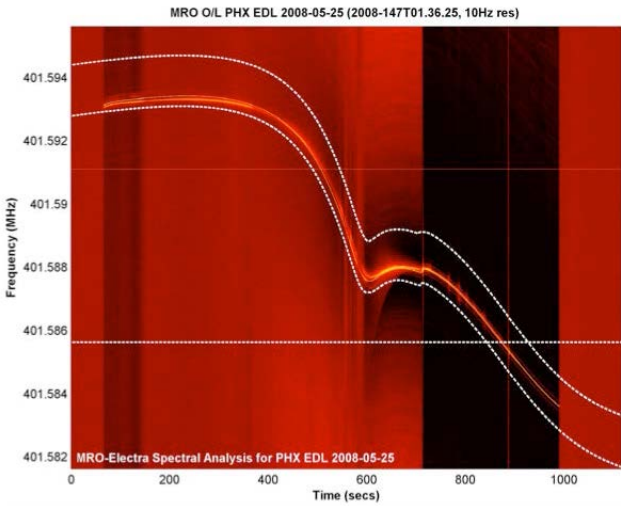

Figure 4: Spectrogram of Phoenix UHF Transmission, Extracted From MRO Open-Loop Recording

which it was predicted that a short blackout period might be experienced due to the buildup of plasma around the entry vehicle. A little less than four minutes after entry, a parachute was deployed. At this point the lander increased its data rate to 32 kbps for the remainder of the descent. (The data rate increase was primarly driven by a desire to reduce the latency between generation of onboard telemetry and transmission of those data.) At an altitude of roughly 700 m, Phoenix throttled up its descent engines and completed a powered descent to the surface, landing roughly 7 min after entry. Table 2 summarizes the timeline of key events during Phoenix EDL.

During this entire period the MRO spacecraft acquired a high-fidelity open-loop recording of the Phoenix UHF signal. This strategy provided the most robust approach to acquiring EDL telemetry. In the event of a mission anomaly, the open-loop recording would provide the best data set for fault identification, allowing extensive post-processing to extract as much information as possible. However, the required post-processing meant that MRO was not able to provide real-time information during EDL. MRO's onboard data architecture does not allow downlinking Electra data products during a relay pass, so the entire Electra open-loop recording was replayed to Earth after Phoenix touchdown. The complete open-loop data set was available on Earth [???] hrs after landing. Initial post-processing to extract the Phoenix carrier phase and amplitude was completed by [???] hrs after landing; subsequent post-processing to demodulate the Phoenix telemetry stream was not completed until [???] hrs after landing. Figure 4 illustrates the observed spectrogram of the Phoenix signal as received on MRO. The Doppler profile of the Phoenix carrier can be seen, consistent with the *a priori* Doppler prediction corridor.

By contrast, the Odyssey spacecraft was configured to provide real-time visibility into the Phoenix EDL. With support from the 70 m antenna at NASA's Goldstone Deep Space Communications Complex, Odyssey was able to maintain a downlink data rate to Earth of 124 kbps during EDL, sufficient to allow "bent-pipe" transmission of the Odyssey CE-505 relay products, including both the open-loop "canister mode" recording prior to Phoenix parachute deployment (representing a data rate of 85 kbps on Odyssey), and the 32 kbps demodulated Phoenix telemetry stream acquired after parachute deployment. During the pre-parachute deployment phase of EDL, ground software was configured to process the received Odyssey/CE-505 open loop samples and generate a spectrogram of Phoenix carrier amplitude and frequency, providing real-time visibility into the status of the Phoenix spacecraft. And after parachute deployment, the Odyssey link provided direct visibility of the 32 kbps Phoenix telemetry stream.

The Mars Express Melacom payload was configured to acquire a 1-bit open loop recording of the Phoenix signal throughout EDL. These data were downlinked to Earth after touchdown, and post-processing was performed within [???] hrs to extract the amplitude and frequency of the Phoenix UHF carrier as received on Mars Express. The availability of this additional relay asset, observing the Phoenix EDL from a different viewing angle, contributed to the overall robustness of the critical event communications plan.

Finally, the 100 m Green Bank Telescope was configured to receive the Phoenix UHF transmission during EDL. The received signal was far too weak to enable extraction of the Phoenix telemetry, but was sufficient to allow real-time detection and monitoring of the Phoenix UHF carrier signal throughout EDL.

5. SURFACE RELAY OPERATIONS

Once on the surface, the Phoenix Lander began its nominal 90-sol science mission. Relay operations were tightly integrated into the overall science operations concept for the lander. With no direct-to-Earth communications capability, Phoenix was solely reliant on UHF communications for delivery of all commands and return of all science and engineering telemetry during the surface mission. The nominal surface relay plan incorporated operational support from Odyssey and MRO, with Mars Express available as a backup relay asset in the event that the NASA orbiters became unavailable for any reason. The Phoenix mission placed the following requirements on the relay communications network:

- Deliver 1 Mb of command data over the forward link to Phoenix during the Martian morning (between 2 AM – 7 AM LMST)

- Acquire 30 Mb of telemetry data over the return link from Phoenix during the Martian afternoon/evening (between 12 Noon – 7 PM LMST)

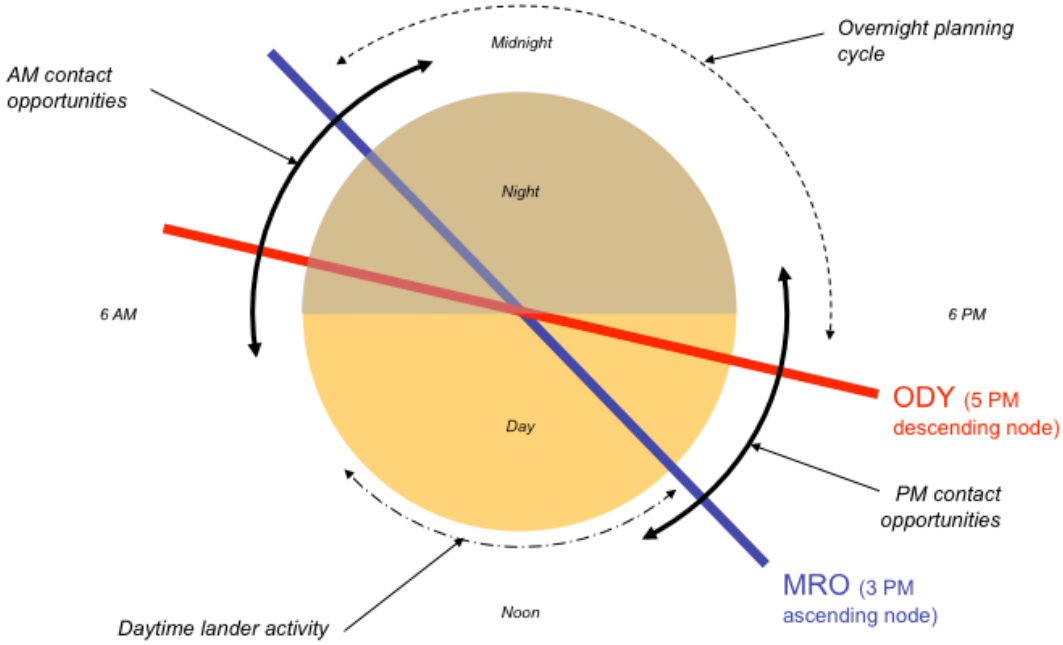

Figure 5: Overview of Phoenix Daily Operations Cycle

- Acquire an aggregate data volume of 60 Mb of telemetry data over the return link from Phoenix, based on two or more passes each sol.

As illustrated in Figure 5, a typical sol would begin with one or more early morning relay contacts to deliver commands to the lander for the upcoming sol's activities. Given its later 5 AM/PM orbit plane, the Odyssey orbiter typically offered the latest opportunity for delivering commands to the lander. Lander science activities were typically conducted in the middle of the day, with the high solar elevation providing maximum power and offering the best illumination of the science workspace. In the afternoon and early evening, science and engineering data gathered during the sol were returned, with MRO – in its earlier 3 AM/PM orbit plane - typically offering the earliest opportunity for afternoon data return.

During the Martian night, data from the prior sol were used to establish the science strategy and, ultimately, the detailed command sequences for the next sol. Because of this, it was critical that the end-to-end latencies for forward and return link data delivery were minimized. Assuming DSN coverage was available for the given orbiter, Phoenix could deliver command products destined for the lander to the Odyssey or MRO ground data system as late as 2 hrs prior to the relay pass during which those products would be transmitted. And, once again assuming DSN coverage, any Phoenix telemetry received on the return link during an Odyssey or MRO relay pass would be returned to Earth and delivered to the Phoenix ground data system within 1 hr, not including any additional delay due to occultation of the orbiter downlink by Mars. During actual operations, latencies well below these were routinely achieved.

	# Passes	Forward Link Data Volume (Mb)	Return Link Data Volume (Mb)
ODY	607	559	30,135
MRO	253	15	7,985
Total	860	574	38,120

Table 3: Cumulative Phoenix Relay Statistics Over the 157-Sol Surface Mission

Several anomalies impacting relay service occurred during Phoenix surface operations. On June 4, the Odyssey spacecraft entered safe mode, due to a radiation-induced memory error, interrupting its ability to provide relay services for two days until nominal operations were restored. During this period MRO successfully provided all relay passes in support of Phoenix command and telemetry.

MRO suffered a series of relay anomalies, beginning with a failed relay pass on May 27, 2008, the second sol of Phoenix surface operations after landing. Over the course of the following weeks additional anomalies occurred. Over the full course of the Phoenix mission, eight anomalous passes were experienced, and while this represented only 3.2% of the total number of MRO relay passes over the Phoenix mission lifetime, it nonetheless had an impact on relay operations. A tiger team was formed and ultimately traced the anomalies to four separate issues. Three of the anomalies were subtle, rarely occuring software errors in the Electra transceiver that had not been detected prior to these in-flight occurrences. The fourth anomaly was related to a

flaw in the Proximity-1 protocol implementations on the CE-505 transceiver, and was only triggered by a specific rapid change in link characteristics. (This fourth anomaly was in fact observed once in ground testing prior to Phoenix landing, but when it was not able to be reproduced it was erroneously attributed to a test configuration problem.)

The flexibility of the Electra software-defined radio architecture allowed a number of operational workarounds to be implemented, which greatly reduced the ongoing anomaly rate. By increasing the horizon mask for relay passes and eliminating unnecessary hailing cycles, only one anomaly was experienced after sol 34. And ultimately, updated software was uploaded to the MRO Electra payload on Oct 6, 2008 to address the four anomaly types. After that upload, no further relay anomalies were observed during the remainder of the Phoenix mission. Nonetheless, in hindsight it is clear that more rigorous and thorough Phoenix-MRO relay testing should have been performed. The diversion of resources to address the MRO EMI issues probably contributed to the insufficient level of compatibility testing. But in the future, more thorough compatibility testing will be conducted, over a wider range of link dynamics and with more flight-like emulation of the full spacecraft avionics environment, in order to identify these types of anomalies prior to flight operations.

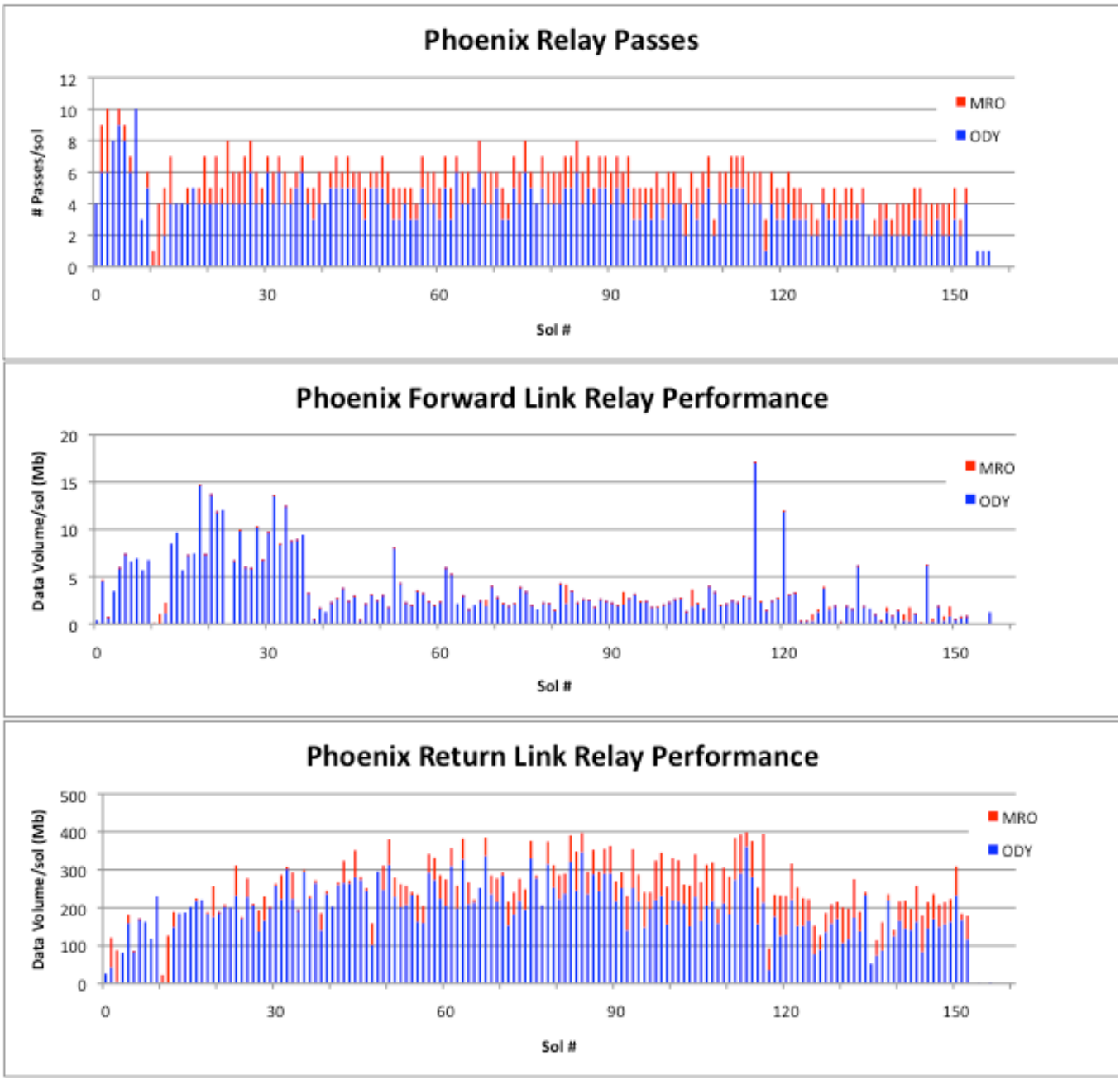

Figure 6: Phoenix Relay Metrics Over the Entire Surface Mission Duration: a) Number of Passes Per Sol; b) Forward Link Performance; c) Return Link Performance.

In spite of these issues, Odyssey and MRO were able to meet Phoenix's relay requirements with considerable margins. Phoenix operations continued well beyond the nominal 90-sol mission before succumbing to the shorter days and reduced power as Martian winter approached. On sol 152, the lander's fault protection software triggered a safe mode, and over the next several sols the lander experienced a number of low-energy faults. The last UHF contact occurred on sol 157.

Over the duration of the Phoenix mission on the Martian surface, Odyssey and MRO supported 860 relay passes for an average of more than 5 passes per sol. Odyssey provided the majority (71%) of the relay contacts, primarily reflecting the fact that, by agreement, after the initial surface characterization phase, Phoenix limited its use of MRO to no more than two passes per sol, given that MRO was still in the midst of its primary science mission at this time.

Based on these contacts, 574 Mb of command data were delivered to Phoenix. The vast majority (97%) of the command traffic was handled by Odyssey, due to the favorable local Mars solar time of its morning contacts. On the return link, Phoenix returned over 38 Gb of data via Odyssey and MRO over the duration of the surface mission. (Roughly one-third of this data volume corresponded to Phoenix fill bits, corresponding to periods when the relay bandwidth exceeded the volume of stored data on the lander.) This corresponds to an average of 242 Mb/sol, more than four times the Phoenix requirement of 60 Mb/sol.

Table 3 summarizes the aggregate Phoenix relay metrics integrated over the entire surface mission, while Figure 6 shows the statistics for number of passes and for forward and return link data volume on a per-sol basis.

Although Mars Express was not used routinely to support Phoenix during the surface mission, its availability as a backup relay asset significantly increased the overall robustness of the Phoenix mission. On the third sol of surface operations, a demonstration pass was successfully conducted, verifying Mars Express's capability to provide relay support to Phoenix. The pass was configured for an 8 kbps forward link rate and a 32 kbps return link rate. A single "NOOP" command was transmitted on the forward link, and approximately 30 Mb of Phoenix telemetry were received on the return link. Several additional demonstration passes were conducted to verify Melacom performance for various data rate combinations.

6. Radio Metric Lander Positioning

In addition to providing forward and return link telecommunication services, the orbiter UHF relay payloads also are capable of acquiring radio metric observations of the phase or frequency of the received UHF carrier signal, which can be used to determine the position of the user spacecraft in the Mars *in situ* reference frame. Both Odyssey and MRO were used to collect radio metric observations during the initial sols of the Phoenix surface mission in order to quickly determine a precise location for the landing site. For these passes, the Phoenix UHF transceiver was configured to operate in a coherent mode, deriving its return link carrier signal from the received orbiter forward link carrier. The resulting 2-way Doppler observable provided an accurate measure of the range rate of the orbiter with respect to the Phoenix Lander. Given that the trajectories of the orbiters were known with high accuracy based on conventional X-band Doppler tracking by the Deep Space Network, the UHF Doppler observations could be processed to extract the Phoenix position on the Martian surface.

Based on all of the X-band tracking of the Phoenix cruise stage on final approach to Mars, the landing site error ellipse initially had an uncertainty (3σ) of roughly 30 km. With the additional knowledge provided by the inertial measurements collected by the Phoenix entry vehicle during EDL, the landing site knowledge was improved to approximately 10 km. However, after just three short, 2-min UHF overflights, the UHF Doppler-based position of the lander was determined with an accuracy of 120 m. After several sols, during which eight Odyssey Doppler passes and three MRO Doppler passes were conducted, the landing site uncertainty was reduced to a formal error of 12 m, Independent solutions based on Odyssey-only and MRO-only showed good agreement, a important conclusion based on the very different implementations of the CE-505 and Electra UHF transceivers. Figure 7 summarizes these Doppler analysis results.

HiRISE imaging of the landing site by MRO offered yet another independent method of validating the accuracy of the UHF Doppler position determination. The image-based position for the lander was consistent, within the 12 m uncertainty, of the UHF-based latitude. The longitude, however, was offset by roughly 50 m, well beyond the UHF-based covariance. This offset is likely due to the inherent uncertainty in the current definition of the Mars

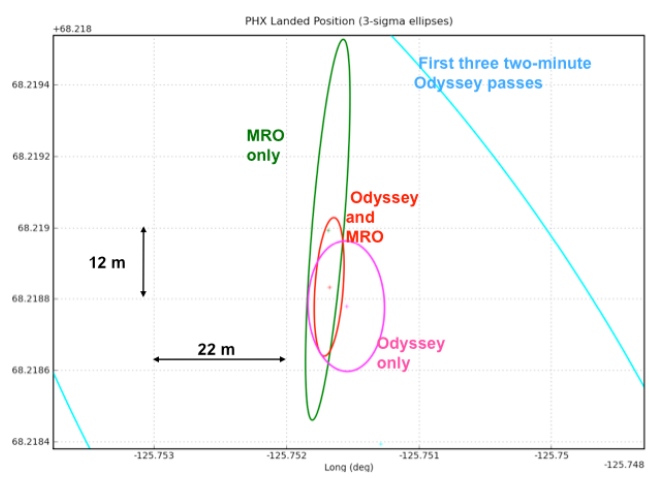

Figure 7: Phoenix Surface Position Covariance Based on Odyssey and MRO UHF Doppler Tracking

prime meridian. Ultimately, these and similar future radio metric measurements will be required to accurately define a Mars-fixed coordinate frame that is properly tied to the inertial radio reference frame.

7. SUMMARY

UHF relay communications played a key role in the success of the Phoenix Lander, NASA's first Mars Scout mission. With no direct-to-Earth communications capability after separating from the cruise stage, all commands and telemetry functions were provided by an international fleet of relay-equipped orbiters at Mars, including NASA's Odyssey and MRO spacecraft and ESA's Mars Express orbiter. During Phoenix EDL, all three orbiters collected information over the UHF link that would have supported fault reconstruction had a mission-ending anomaly occurred during this critical mission event. The unique UHF capabilities of each orbiter were leveraged to provide both real-time visibility of Phoenix performance during EDL as well as robust capture of signal characteristics for post-processing.

On the surface, Odyssey and MRO provided operational command and telemetry services, supporting 860 passes over the full surface mission, for an average of more than five passes per sol. The average data return per sol was more than four times the Phoenix requirement of 60 Mb/sol. In addition, Mars Express orbiter conducted several passes early in surface operations to validate the capability of its Melacom relay payload to provide relay services to Phoenix, and was available as a backup relay asset, significantly increasing the robustness of the telecommunications plan for the UHF-only Phoenix mission.

Observations of the Doppler shift on the UHF relay link also demonstrated the power of this radio metric observable to quickly provide high-accuracy *in situ* positioning for Mars relay users; just a handful of UHF overflights provided nearly three orders of magnitude improvement in the lander position knowledge relative to a solution based on pre-entry DSN tracking and inertial measurements during EDL.

The Phoenix relay support represented the first operational use of the MRO Electra UHF relay payload. Electra's software defined radio architecture allowed post-launch implementation of a filtering strategy that mitigated EMI from several of the MRO science instruments, enabling MRO relay operations to be carried out without having to power off the relevant instruments; this increased science return and reduced risk to the science instruments during the Phoenix relay support period. Several Electra software anomalies were discovered early in flight operations; the flexibility of the Electra payload permitted a quick implementation of operational mitigations and ultimately allowed a new software upload to address all of the anomalies. In light of the Phoenix lessons-learned, however, more extensive link testing is planned in preparation for the future relay support of the 2011 Mars Science Laboratory mission.

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