JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 45, No. 3, May–June 2008

Entry, Descent, and Landing Communications for the 2007 Phoenix Mars Lander

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DOI: 10.2514/1.33789

This paper addresses NASA's requirement on the 2007 Phoenix Mars Lander to provide spacecraft communications during entry, descent, and landing on Mars to allow the identification of probable root cause should any mission failure occur. The Phoenix mission launched on 4 August 2007 and will land on 25 May 2008 on the northern plains of Mars to conduct a three-month study of the Martian environment. The paper discusses the architectural trades in designing a communications link and surveys the entry, descent, and landing communications approaches taken by previous missions. It then discusses the Phoenix-specific constraints and degrees of freedoms and presents a novel and robust implementation approach to entry, descent, and landing communications. The overall methodology and conclusions described herein can serve as a pathfinder for the entry, descent, and landing communications architecture and implementation of future Mars landed missions.

Nomenclature

c	=	speed of light, m/s
f	=	transmission frequency, Hz
G_R	=	orbiter receive antenna gain, dBic
G_T	=	wraparound antenna or helix gain, dBic
L_S	=	space loss, dB
L_P	=	polarization loss, dB
L_R	=	receive path losses on the orbiter, dB
L_T	=	Phoenix transmit circuit losses, dB
P_R	=	power received at the orbiter transceiver, dBm
P_T	=	transmitted power, dBm
R	=	distance between Phoenix and the orbiter, m
$\boldsymbol{v}_{\mathrm{PHX}}$	=	velocity of Phoenix, m/s
$\boldsymbol{v}_{\mathrm{orb}}$	=	velocity of the orbiter, m/s
Δf_D	=	Doppler shift, Hz
λ	=	signal wavelength, m
$\mathbf{1}_{\mathrm{orb-to-PHX}}$	=	line-of-sight vector from the orbiter to Phoenix

I. Introduction

ENTRY, descent, and landing (EDL) on Mars constitutes the most technically complex and feared aspect of every landed Mars mission. In the course of just a few minutes, the arriving spacecraft is decelerated from entry speeds exceeding 5 km/s to a standstill, thereby experiencing temperatures of more than 1400°C. Moreover, it is performing multiple separations, deployments, and other configuration changes, most of which are exercised for the first time during the mission. Because the Mars–Earth distance is several light minutes at landing day, the spacecraft executes the EDL sequence autonomously using onboard sequences and event-based triggers. The ground control teams are left with monitoring the progress of EDL using any signals and/or telemetry sent by the spacecraft.

However, establishing a communications link during EDL is a formidable task. Fast approach speeds and attitude changes cause rapidly changing geometries, and the high dynamic forces that the spacecraft is subjected to during entry result in large Doppler shifts in the transmitted signal. Moreover, during the fiery entry, a plasma will surround the spacecraft, potentially leading to a signal blackout [1]. Also, once on the parachute and during the subsequent terminal descent phase, large attitude excursions of the lander spacecraft may lead to signal dropouts due to antenna offpointing.

Designing a viable communications strategy during EDL thus requires addressing a multitude of aspects, including approach and entry trajectory design, telecom subsystem design, command and data handling, ground data systems, and a significant level of overall systems engineering. The collaboration of a multidisciplinary team and an iterative design process are required to converge on a feasible design. This paper will address these challenges and discuss the overall approach to EDL communications, also referred to as *EDL comm*, for the 2007 Phoenix Mars Lander (PHX).

Generally, communications links during EDL can be established directly to Earth or via a spacecraft orbiting Mars that serves as a relay for the arriving lander. Each of the approaches has its distinct advantages and disadvantages. A direct-to-Earth (DTE) link relies on terrestrial assets only, which are easier to maintain and more readily available than orbital assets. On the downside, the distance to Earth is vastly larger than to a relay orbiter, resulting in larger signal space loss and, ultimately, a distinctively reduced data rate. A relay link via an orbiting asset allows for a significant increase in data rate due to its relatively close proximity to the landing spacecraft. On the other hand, using relay links requires close coordination with the orbiting assets to ensure their readiness and availability as well as some orbital choreography to ensure that they are in the right place at the right time and pointed in the right direction. In the past, Mars missions have adopted a variety of architectures that provided different levels of communications during EDL.

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The 1976 Viking 1 and 2 missions each consisted of an orbiter and lander spacecraft that arrived at Mars attached to each other. After the spacecraft was inserted into an $1500 \times 33,000$ km elliptical Mars orbit, the lander separated from the orbiter and began its entry, descent, and landing to Mars. During EDL, it communicated via the orbiter, which served as a relay. The lander used a UHF link to the orbiter to transmit spacecraft state information such as altitude and velocity-profile information. It used a simple one-way link with about 4-kbps throughput [2]. During the entry phase, a short blackout of a few seconds was believed to have occurred, though it was not conclusively observed. The orbiter received the incoming UHF stream and retransmitted it as a "bent pipe" via its S-band link back to Earth. In addition, orbiter UHF engineering data, such as the received signal level, was downlinked.[**] This arrangement allowed the ground teams to witness the landing, delayed only by the one-way light time.

The 1997 Mars Pathfinder (MPF) mission [3] landed on the surface of Mars after performing a direct entry into the Martian atmosphere without first going into orbit around Mars. During EDL, the spacecraft continuously transmitted an X-band-carrier wave signal directly to Earth. Superimposed on the carrier were semaphores confirming the execution of events at key times as the sequence progressed. The semaphores were implemented using two different schemes. Before landing, semaphores were constructed by switching between two selectable subcarrier frequencies on the spacecraft. Once on the surface, the semaphores were produced simply by turning on and off an unmodulated X-band carrier. The carrier signal was detected at ground stations, delayed just by the one-way light time, allowing the mission control team to monitor the EDL progress. Although the semaphores were not detected in real time during the actual EDL event, some of them were recovered using postflight processing. Finally, there was a 30-s communications blackout observed during the peak deceleration portion of the trajectory that could have been caused by a number of factors, including excessive vibrations, plasma blackout, or coronal discharge.

The 1999 Mars Polar Lander (MPL) communicated via X-band throughout its cruise phase from Earth to Mars. The X-band system was part of the cruise stage, and with the separation of the latter from the entry vehicle a few minutes before the onset of EDL, X-band communications were disabled. Because of cost constraints, there were no communications planned throughout EDL until after the lander successfully landed on the surface of Mars, after which the lander would have communicated DTE using its X-band radio and to the Mars Global Surveyor (MGS) spacecraft via its UHF transceiver [4]. However, the MPL spacecraft failed in the course of EDL, leaving the ground teams with little direct insight into the nature of the failure. Not surprisingly, after the MPL failure, NASA imposed a requirement on all future NASA missions to provide spacecraft communications during all critical events (in particular, during EDL) to allow the identification of probable root cause should any mission failure occur.

The 2003 Mars Explorations Rovers (MER) were the first landers subject to the new EDL communications requirement. The project addressed it by using a communications approach derived from the original MPF mission, but augmented with additional UHF communications for the latter part of EDL [5]. Specifically, MER transmitted an X-band carrier and semaphores directly to Earth, but, unlike MPF, which used only a handful of semaphores, MER had 256 different semaphores available. These semaphores signaled specific EDL events as they were unfolding and provided general spacecraft state and health. Each semaphore was transmitted for 10 s, allowing the ground stations to perform detection and monitoring of EDL events as they unfolded, delayed only by the one-way signal light time. No signal blackout was observed and this was believed to be mostly due to MER's lower entry velocity when compared with MPF [1]. Once the lander separated from the backshell assembly (though still on the parachute), it initiated an additional UHF link to the MGS spacecraft flying overhead. Once established, the latter was the prime link for the remainder of EDL due to its higher data rate of 8 kbps and better link margin. The data transmitted to MGS were relayed to ground stations in bent-pipe mode with little delay beyond the one-way light time.

Finally, the 2003 European Beagle 2 lander, by design, had no communications capability during EDL. After it separated from ESA's arriving Mars Express (MEX) orbiter, there were no communications planned throughout EDL until after the lander successfully landed on the surface of Mars. After landing and successful deployments, the lander would have contacted MEX using its UHF transceiver. Unfortunately, the spacecraft failed in the course of EDL, leaving the ground teams with little direct insight into the nature of the failure. A subsequent accident investigation report recommended the addition of telecom capabilities for critical events such as EDL [6].

The Phoenix mission is the first mission in NASA's Scout Program [7] and will deliver the first lander onto the Martian surface since the two Rovers landed in 2004. Scouts are designed to be highly innovative and relatively low-cost complements to major missions being planned as part of the agency's Mars Exploration Program. The Phoenix lander launched on 4 August 2007 and will land on the northern plains of Mars on 25 May 2008, before the start of the northern Martian summer. For the next three months, the mission will analyze the environment (both surface and subsurface) and the expected water ice for its chemical composition and will search for evidence of a habitable zone. Unlike the mobile Mars Exploration Rovers Spirit and Opportunity, Phoenix is a fixed lander. It will use a robotic arm to dig to the ice layer and analyze samples with a suite of sophisticated on-deck scientific instruments. Phoenix is specifically designed to measure volatiles (especially water) and complex organic molecules in the arctic plains of Mars, in which the Mars Odyssey orbiter has discovered evidence of ice-rich soil very near the surface. Similar to its namesake, Phoenix resurrects the spacecraft and a number of instruments from the 2001 lander project, administratively mothballed in 2000 after the MPL mission failure. The Phoenix mission is managed by NASA's Jet Propulsion Laboratory and is conducted in collaboration with the University of Arizona, Lockheed Martin Astronautics, and a number of international partners.

Just as for the preceding MER mission, NASA levied a requirement on the Phoenix mission to provide telecommunications coverage during all critical events, especially EDL, sufficient to diagnose faults and/or failures, should they occur. To meet this requirement, two basic questions have to be addressed: namely,

1) What communications link (and thus what data throughput) can the mission support?

2) What type of information is downlinked to support the identification of failures?

Accordingly, this paper is organized as follows: Section II discusses the constraints and the degrees of freedom in the design of the Phoenix EDL communications architecture. Section III presents the orbital geometry and resulting link budget. Section IV discusses the overall Phoenix EDL comm implementation strategy and associated challenges, and Sec. V discusses the strategy for data selection to help identify faults. Finally, Sec. VI provides a summary and conclusions.

II. Phoenix Design Constraints and Degrees of Freedom

There are numerous factors that have to be considered when designing a communications link for Phoenix EDL. They include the Phoenix arrival geometry, the EDL trajectory and timeline, and the specific capabilities of Phoenix and the relay orbiters. In theory, all these factors are interrelated and need to be addressed in an iterative fashion. However, in reality, some of these factors are driven by other considerations and higher-priority needs. In particular, the EDL trajectory and timeline are driven by a large number of

[**]In the case of Viking 2, the received signal level was the sole indicator of the lander's progress toward the surface, because the real-time bent-pipe capability containing the lander engineering data was interrupted shortly after separation from the orbiter.

considerations, most of which are related to vehicle health and safety during EDL and are beyond the scope of this paper. Thus, in the context of designing an EDL communications link, the approach and EDL trajectory and the EDL timeline are treated as an input to the communications link design process. The relay communications architecture, on the other hand, provides some degrees of freedom to optimize the communications link design. The constraints and degrees of freedom are discussed next in more detail.

A. Phoenix Launch-Arrival Geometry

Phoenix launched on a Delta II 7925 rocket from Space Launch Complex 17A at the Cape Canaveral Air Force Station on 4 August 2007. After a 10-month journey from Earth to Mars on a Type-II trajectory, Phoenix will arrive at Mars on 25 May 2008 [8]. It will then enter and descend through the atmosphere and land on the northern plains of Mars.

The atmospheric flight-path angle (i.e., the angle with which Phoenix will enter the Martian atmosphere) is one of the key parameters that need to be carefully set, because it is crucial for both mission success and spacecraft design. Too steep of a flight-path angle will result in too large of a peak deceleration during atmospheric entry, potentially exceeding the spacecraft's design limits. Too shallow of a flight path will cause Phoenix to skip out of the atmosphere after an initial entry, thus missing Mars altogether. The flight-path angle is currently set for −13 deg and the approach trajectory is designed accordingly.

At the time of writing this paper, various landing sites within a narrow region around 68.18°N latitude and 233.36°E longitude are being evaluated. At the time of arrival, Mars is just emerging from northern Martian spring and the nominal mission duration of 90 Martian days (also referred to as sols) coincides with northern summer. During this time period, the polar CO_2 ice has receded and the solar power generated by Phoenix is sufficient to achieve all the scientific objectives. A landing at a later date would jeopardize Phoenix meeting its full mission success criteria. Another important factor affecting the trajectory is the Mars local time at landing. A daytime landing is desired to ensure that there is enough time after landing and solar array deployment to recharge the batteries to power all the activities and heaters needed during the first night on the Martian surface.

All these constraints drive the approach trajectory design and are captured in the launch-arrival trade space, also known as the "porkchop plot," shown in Fig. 1. The plot shows the combinations of launch dates (on the x axis) and arrival dates (on the y axis) for an atmospheric flight-path angle of −13 deg. The C3 curve shown in the picture represents the energy imparted on the Phoenix spacecraft by the Delta II and upper stage (i.e., the injection energy per unit mass). The maximum C3 of 29.2 km^2/s^2 is contoured in black. This contour splits the launch-arrival space into two regions: the region above the C3 curve represents the set of feasible launch-arrival combinations (from an energy perspective), and the region below the C3 curve shows the launch-arrival combinations that are not achievable. The feasible region is further reduced by limitations on how late Phoenix can arrive at Mars and still maintain positive energy margin throughout the 90-sol mission. This further reduction is shown by the shaded region that extends from an arrival date of 10 June or later. Within the remaining feasible region, the two bars indicate the launch-arrival combinations adopted by Phoenix for all their mission design work. A launch between 3 August and 17 August 2007, also referred to as the opening leg of the launch window, would thus result in a landing on 25/26 May 2008, whereas a launch between 18 August and 24 August 2007, also called the closing leg of the launch window, would yield a landing on 5 June 2008. For the remainder of this paper, these two possible landing dates are thus referred to as *open* and *close*. With an actual launch date of 4 August 2007, the landing is now set for 25 May 2008, as shown in Fig. 1, and the open case applies in reality. However, during the project implementation, an EDL communications strategy had to be developed that was capable of supporting the entire launch/arrival design space. As such, analyses for both the open and close cases are presented herein. Figure 1 also indicates the Mars local time of day at landing. At the beginning of the launch window, the local time is close to 1600 hrs Mars local time

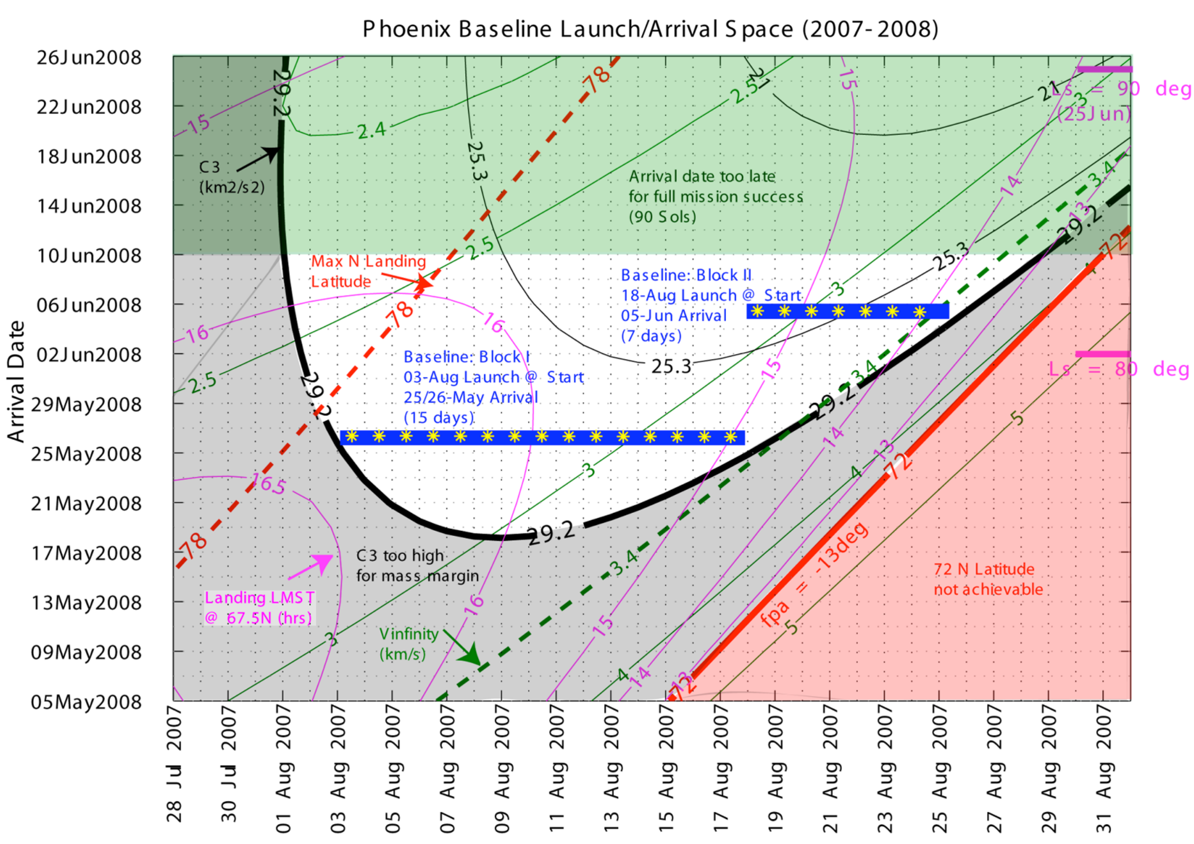


Fig. 1 Launch-arrival design space.

(midafternoon), whereas toward the end of the launch window, the landing time moves to earlier in the afternoon, thus meeting the need for daylight at landing.

There are a number of other requirements levied on the Phoenix project in direct support of EDL communications that the trajectory designer has to accommodate. First, given the absence of an X-band DTE capability after cruise stage separation (CSS), subsequently explained in more detail, the Phoenix spacecraft needs to relay its EDL telemetry via its UHF radio to spacecraft in Mars orbit at the time of EDL. In particular, it is envisioned that both NASA's Mars Odyssey (ODY) spacecraft and Mars Reconnaissance Orbiter (MRO) will be operational during EDL and thus support EDL comm concurrently, for redundancy purposes. ODY and MRO arrived at Mars in October 2001 and March 2006, respectively. Both orbiters are in a circular sun-synchronous orbit, with an orbit period of approximately 2 h. ODY is in a 350×420 km orbit with a 5-pm descending node, and MRO is in a 250×300 km orbit with a 3-pm ascending node. ESA's MEX orbiter is available as an additional relay path. Unlike ODY and MRO that are in circular low Mars orbits, MEX is in a $350 \times 10,050$ km elliptical orbit with an orbit period of 6.7 h. It thereby provides a very different vantage point and thus complements the communications coverage by ODY and MRO. In addition to flying a trajectory that allows for direct line-of-sight communications to the orbiters, the relative dynamics between Phoenix and the orbiters (that is, range rate and the resulting signal Doppler shift) has to meet certain limitations, as subsequently explained in more detail. Furthermore, Phoenix is required to design a trajectory that has the EDL event occurring while the spacecraft is in the line of sight of Earth. The intent of the latter is to not preclude any attempts by terrestrial ground stations to observe the EDL events, should they have the capability to do so.

Figure 2a gives an overview of the resulting arrival geometry as seen from the Mars North Pole for the open case. It shows the Phoenix arrival and entry trajectory, the vectors to Earth and the sun, and the orbits of the resident orbiters. The Phoenix entry vehicle and the orbiters, depicted as small circles, are shown in their respective position at entry time. The arrival geometry for the close case, shown in Fig. 2b, differs visibly from the open case [8]. For the open case, the Phoenix trajectory crosses MRO's orbital plane, whereas for the close case, Phoenix lands before crossing either orbiter's plane. The changes in Phoenix's trajectory results in different relative geometries to the orbiters, affecting the line of sight and range rate between the spacecraft. This is subsequently explained in more detail. Also, as can be seen in Fig. 2, the Phoenix approach and entry trajectory are in direct view of Earth.

Finally, the geometry shown in Fig. 2 is invariant (to first order) to the longitude of the landing site, because both the Phoenix arrival trajectory and MRO's and ODY's orbital planes are fixed with respect to the sun–Mars line. With Mars rotating underneath the fixed relay orbiter orbital planes and the sun terminator, the Mars local time of landing stays approximately the same, with only the Universal Time Coordinated (UTC) time of landing changing as a function of longitude. This invariance is significant because, at the time of writing this paper, final landing site selections are still underway. However, this invariance does not apply to MEX because it is not in a sun-synchronous orbit.

B. EDL Timeline

Figure 3 gives an overview of the Phoenix EDL sequence of events. (Some of the event times indicated in Fig. 3 may differ from the actual event times, due to dispersions in entry and atmospheric

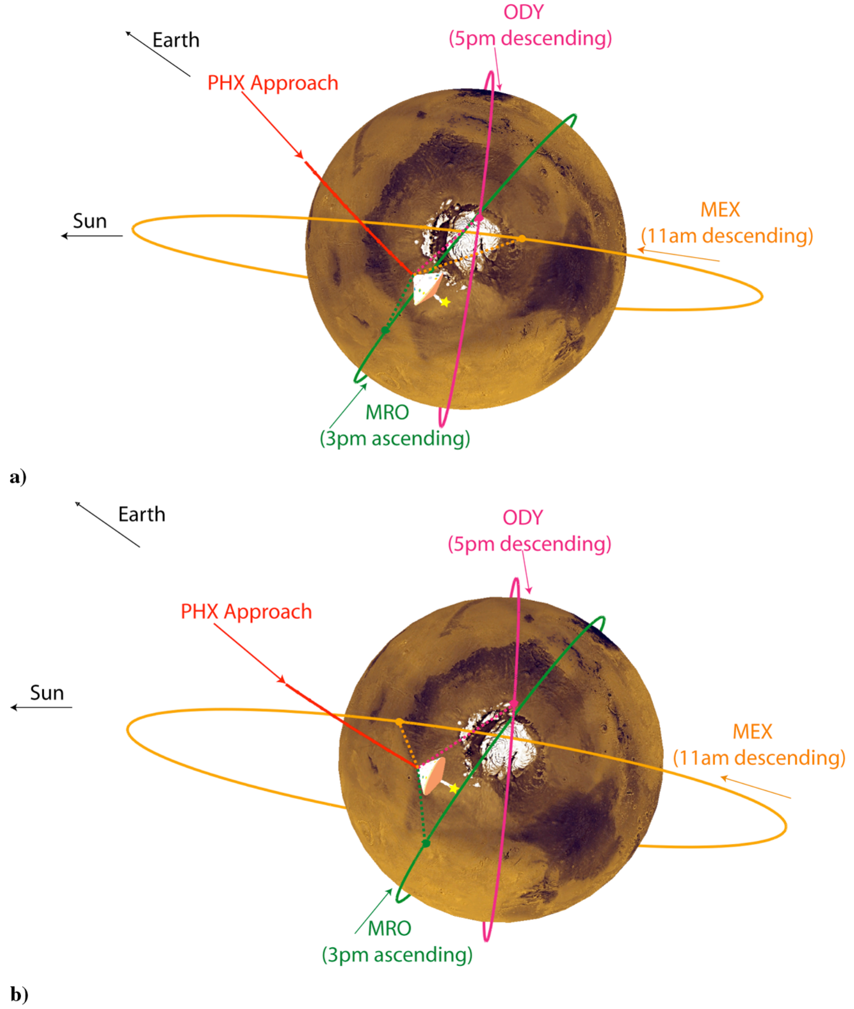


Fig. 2 EDL communications geometry for a) open case and b) close case.

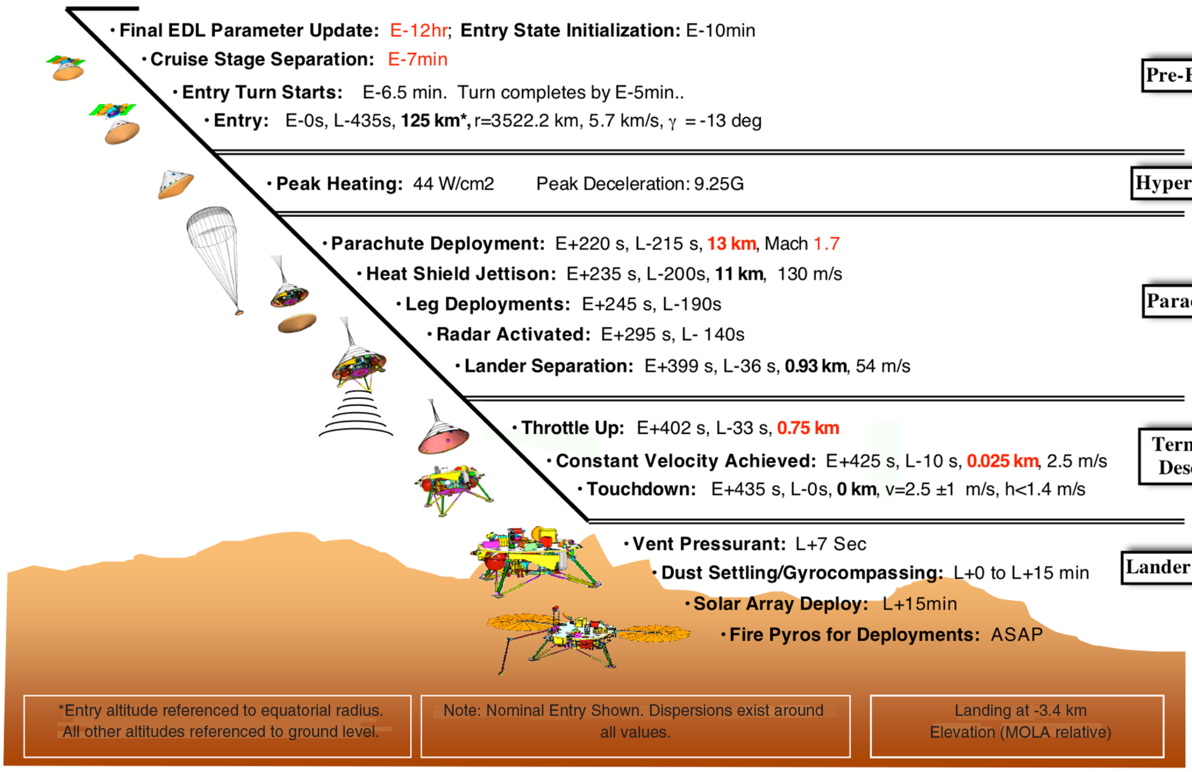


Fig. 3 Notional EDL timeline.

conditions encountered during EDL.) Seven minutes before the spacecraft arrives at the atmospheric entry point, defined to be at a distance of 3522.2 km from the center of Mars, or at roughly 125 km above the surface, it will separate from its cruise stage and turn to its entry attitude. Up to this point, Phoenix will have communicated via an X-band system directly to Earth. After the separation, Phoenix will start transmitting via its UHF transceiver to the relay orbiters to meet the communications requirement for coverage during critical events.

Shortly after passing the entry point, the spacecraft will enter the Martian atmosphere with an entry velocity of approximately 5.7 km/s relative to the Mars atmosphere and a flight-path angle of -13 deg. Approximately 2 min after entry, Phoenix will experience its peak deceleration of approximately 9 g and peak heating of 44 W/cm^2. A potential plasma blackout lasting between 1 and 2 min and centered around the peak heating event may disrupt the communications link to the orbiters.

At entry plus 220 s ($E + 220$ s), the spacecraft will have slowed down sufficiently to deploy the parachute. Fifteen seconds later, the heat shield will separate. At $E + 245$ s, the landing legs will deploy, and 50 s later, the landing radar will activate. When reaching terminal velocity on the parachute at around $E + 399$ s at an altitude of approximately 1 km, the lander will separate from the backshell/parachute assembly, perform a Gravity turn, and ignite its descent engines. In the course of the next 30 s, the lander will slow its descent to a constant velocity of 2.5 m/s before touching down at 435 s after passing the entry point. The specific EDL communications requirement levied on Phoenix calls for the spacecraft to continue transmitting to the orbiters until 60 s after touchdown to provide the ground teams with information on the postlanded spacecraft state. Figure 4 shows Phoenix's various spacecraft configurations throughout launch, cruise, EDL, and landing.

C. Relay Communications Architecture

As noted in the preceding sections, the EDL communications architecture needs to rely on a UHF relay link to existing assets in Mars orbit (in particular, the ODY and MRO orbiters), because there is no X-band DTE system once the spacecraft separates from the cruise stage. In addition, the Phoenix spacecraft is required to communicate with both orbiters at the same time to provide redundancy in the link.

Whereas the Phoenix approach and EDL trajectory are treated as an input to the EDL communications design process, some aspects of the orbiter trajectories are considered adjustable elements of the EDL comm link design. In particular, the orbiter's mean anomaly (i.e., the location as a function of time within the orbit plane) can be adjusted with little extra fuel consumption. However, any change in the relay orbiter orbit plane itself would involve a prohibitive fuel expense. The mean anomaly adjustment is henceforth referred to as in-plane *phasing*. Phasing can be achieved by either a dedicated phasing-maneuver pair or by using regularly occurring momentum-desaturation firings to bias the orbiters into a specific direction within its orbit. However the orbiters are maneuvered to observe EDL, both orbiters are expected to be able to phase their orbital position to within ± 30 s of the requested phasing.

When phasing the MRO and ODY orbiters, the goal is to achieve relay-link coverage starting at Phoenix CSS until after landing $+60$ s. Moreover, because of the requirement for redundant orbiter coverage, the phasings of MRO and ODY are to be done independently of each other. In case the orbiter coverage for the entire duration of EDL to landing $+60$ s cannot be achieved, the Phoenix design team established a prioritized list for EDL event coverage: 1) terminal descent (through touchdown), 2) parachute phase (entirety of time on chute), 3) hypersonic phase, and 4) preentry (from cruise stage separation)

The list is prioritized according to the perceived risk of a given event or phase during EDL and thus to the criticality of providing communications coverage during this event. In particular, terminal descent is considered to be the most dynamically complex part of the EDL sequence, due to closed-loop powered descent, and thus maximum coverage has to be provided during this phase of EDL. Next, the parachute and hypersonic phases warrant coverage because of a number of spacecraft deployments and the high dynamic forces that the spacecraft is subjected to during parachute deployment and peak deceleration events. The least emphasis (relatively speaking) is given to the period around atmospheric entry in which the atmosphere is still tenuous and the forces that the spacecraft is subjected to are still small. In addition, there is little-to-no spacecraft activity to monitor during this period.

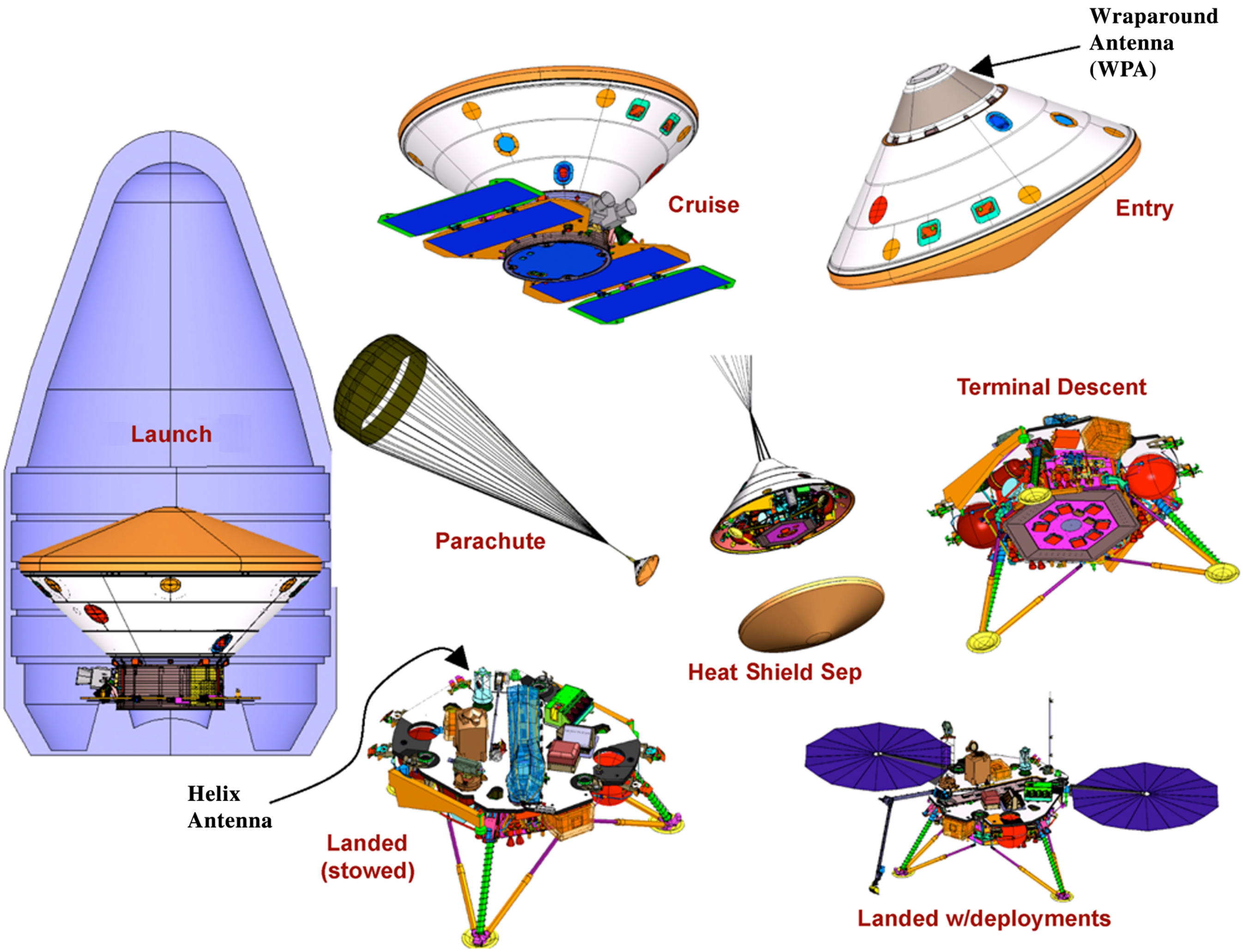


Fig. 4 Phoenix spacecraft configurations.

With the periapse of its elliptical orbit over the North Pole region, MEX traverses this region significantly faster than the other orbiters, resulting in a more dynamic line of sight relative to Phoenix. To this end, analysis has shown that only parts of the Phoenix EDL trajectory will be visible to MEX. The orbiter could therefore be phased to augment ODY's and MRO's coverage either for the early phases of EDL (including CSS) or for the latter phases (including terminal descent). Following the preceding EDL coverage prioritization, a MEX phasing that provides coverage for the later parts of EDL is preferred.

An additional degree of freedom in designing the links to the orbiters is their respective attitude. Both MRO and ODY use a helix UHF antenna. To take advantage of maximum antenna gain, the Phoenix spacecraft has to stay within 30 deg of the respective orbiter helix antenna boresight. To accommodate this, the orbiters will slew to an attitude different from their nominal attitude for the duration of Phoenix EDL. In particular, MRO is typically pointing its UHF antenna toward the planet (i.e., nadir), because it is coaligned with most of the scientific payloads. For the purposes of EDL coverage, however, MRO will perform a single constant-rate slew to minimize the angle between the antenna boresight and Phoenix. Similarly, ODY is typically pointing its antenna (also coaligned with the payload) to a 17-deg aft-of-nadir direction with respect to its velocity vector. However, unlike MRO, ODY cannot easily support fast slewing maneuvers, due to its large instrument boom. In support of EDL coverage, ODY is envisioned to assume a fixed inertial direction along the Phoenix EDL trajectory. Finally, similar to MRO, MEX is envisioned to slew to keep Phoenix close to its antenna boresight.

As an additional constraint, the relative dynamics between Phoenix and the ODY orbiter has to result in a Doppler frequency shift of less than 8 kHz at the orbiter, to ensure that the orbiter UHF transceivers can lock onto the signal. The next section discusses the impact of all these constraints and design choices on the line-of-sight range, range rate, and resulting link budget.

III. Geometry, Dynamics, and Link Budget

A. Relative Geometry, Range, and Doppler

Figure 5 shows the relative geometry between Phoenix and the orbiters for both the open and close cases. The geometry is the result of an ODY and MRO phasing according to the guidelines outlined in the previous section. For this analysis, MEX is phased to emphasize terminal descent for the open case and mid-EDL for the close case. The plots show the range between Phoenix and the orbiters, the angle between the Phoenix antenna boresight and the orbiters, and the Doppler shift observed at the orbiters for the duration of EDL. The plots are for nominal entry trajectories. The time $t = 0$ s corresponds to the entry time. For the open case (shown in Fig. 5a), the range between Phoenix and the orbiters at CSS ($t = -420$ s) is approximately 3900 km for MRO, 3200 km for ODY, and 5500 km for MEX. The distance is gradually decreasing throughout the hypersonic phase. At the time of parachute deployment ($t = 218$ s), the distances to MRO, ODY, and MEX decreased to 800, 1300, and 1600 km, respectively.

The Doppler shift shown in Fig. 5 is derived from the range rate between Phoenix and the orbiters by

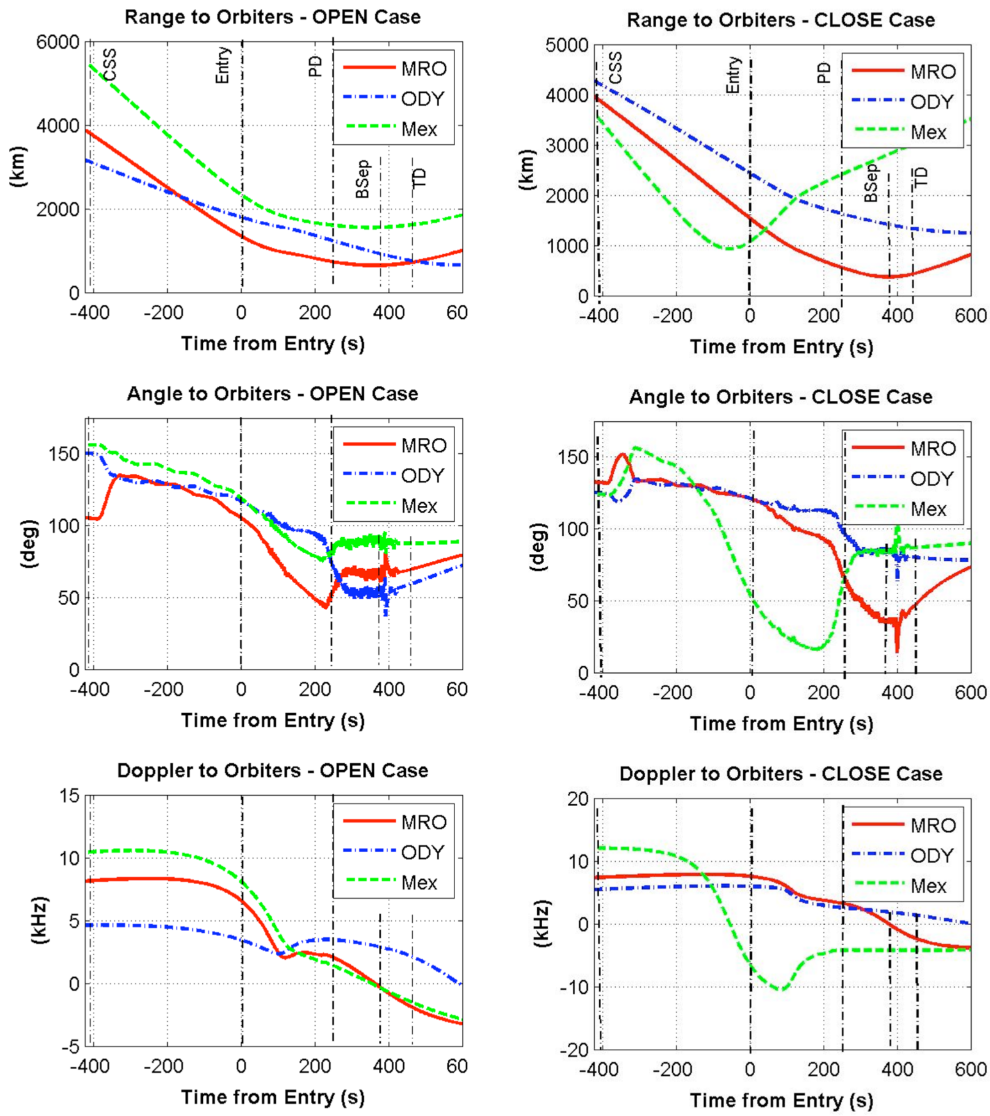


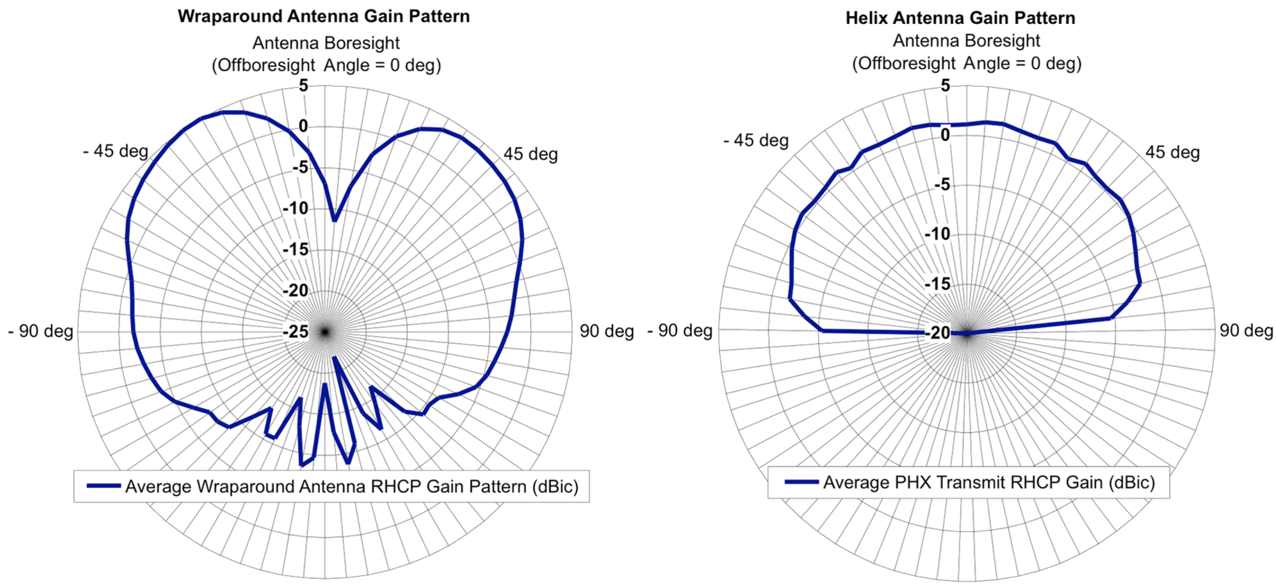
Fig. 5 EDL communications relative geometry: range, angle, and Doppler to the orbiters for a) open case and b) close case.

$$\Delta f_D = -\left(\frac{\boldsymbol{v}_{\mathrm{PHX}} - \boldsymbol{v}_{\mathrm{orb}}}{c} \bullet \mathbf{1}_{\mathrm{orb\text{-}to\text{-}PHX}}\right) \cdot f \tag{1}$$

where f is a transmission frequency of approximately 401 MHz. Because of the minus sign in Eq. (1), approaching spacecraft (i.e., range rate is negative) generate a positive Doppler shift, whereas separating spacecraft (i.e., range rate is positive) generate a negative Doppler shift. As indicated by the zero crossing in Fig. 5, the closest approach between Phoenix and MRO occurs at $t = 360$ s, shortly before terminal descent. At this point, MRO and Phoenix are 640 km apart. For ODY, the closest approach occurs well past touchdown at $t = 590$ s, with a distance of 650 km. Similar to MRO, MEX reaches its closest distance of 1550 km shortly before terminal descent at $t = 352$ s. Also, as can be seen in the figure, the observed Doppler shift on ODY does not exceed the desired limit of 8 kHz. Figure 5b shows the equivalent information for the close case.

For the angles between the Phoenix antenna boresight and the orbiters, there is a noticeable difference between the open and close cases. This is a direct result of Phoenix's arrival and EDL trajectories, as shown in Fig. 2. For both the open and close cases, Phoenix is turning to its entry attitude 30 s after CSS and the effects of this are clearly visible in changing angles to the orbiters. Also, the onset of oscillations at $t = 220$ s reflects the effects of the Phoenix spacecraft swinging beneath the parachute after it is deployed.

The significance of the offboresight angle on the communications link is best understood by examining the corresponding Phoenix antenna gain pattern. During the first part of EDL, Phoenix will employ a wraparound antenna (WPA) that is mounted on the backshell, as shown in Fig. 4. The WPA first emerges once Phoenix is separated from the cruise stage. Its boresight is pointing aft with respect to the entry velocity vector (i.e., opposite to the heat shield) along the spacecraft main axis of symmetry. Figure 6a shows the gain pattern of the WPA as a function of the offboresight angle. The antenna main region of transmission is between an offboresight angle of 10 and 135 deg, with the gain rapidly diminishing outside of this region. As Phoenix is approaching its atmospheric entry point (see Fig. 2), the orbiters are in front of the heat shield. Because this lies in the antenna null region, the link performance is initially diminished. Shortly after entry, the orbiters appear in the main region of radiation. After the backshell/WPA assembly separates, the lander continues to transmit using a helix antenna mounted on the deck of the spacecraft. Figure 4 shows the helix antenna in the landed configuration. The helix gain pattern is shown in Fig. 6b. The antenna main region of transmission is up to an offboresight angle of 87 deg, with the gain rapidly diminishing outside of this region. As can be seen in Fig. 5, the angles to ODY and MRO fall within the useful region of the pattern, whereas the angle to MEX is at the boundary of the useful gain pattern for terminal descent. The effects of the instantaneous antenna gain on the overall link budget are explained next.



a) b)

Fig. 6 Antenna gains: a) wraparound and b) helix.

B. EDL Comm Link Budget

In addition to the Phoenix transmit antenna gain, there are a number of additional factors affecting the overall link performance, as shown by the classic link equations

$$P_R = P_T L_T G_T L_S L_P G_R L_R \tag{2}$$

$$L_S = (\lambda/(4\pi R))^2 \tag{3}$$

As outlined in preceding sections, the actual antenna gains to be used in Eq. (2) are a function of the location of Phoenix and the orbiters in each other's antenna pattern. The other driving factor of the overall link performance is the distance between the spacecraft and the resulting space loss. Figure 7 shows the total power received at the orbiter transceiver as calculated by Eq. (2) for the duration of EDL. As expected, the power received is initially very low (starting at −135 dBm) and then steadily increases as Phoenix is approaching its landing site. This trend is expected, because ODY and MRO are phased to support the terminal descent. The range and the resulting space loss and the offboresight angles are large at the beginning and then steadily improve as Phoenix approaches its landing site. Also shown in Fig. 7 are the main EDL events including CSS, entry, parachute deployment, backshell separation, and touchdown. For ODY in the open case, the total power received decreases initially during the turn to the entry attitude because the orbiter passes temporarily through the WPA antenna null, but then increases to −120 dBm by entry and to −112 dBm by parachute deployment. The oscillations due to parachute swinging previously observed in the angle plot, are also visible in the plots in Fig. 7. Similarly, for MRO in the close case, the turn to entry is visible in the plot because MRO is passing through the WPA antenna null. The received power then steadily increases to −98 dBm in the parachute phase. The sudden drop of 5 dBm at backshell separation reflects the switch to the helix antenna. Finally, for MEX, the effects of the phasing choices are clearly reflected in the received-power curves. For the open case, the phasing is optimized for terminal descent and, consequently, the coverage starts at $E - 200$ s and lasts beyond touchdown. On the other hand, for the close case, the phasing emphasizes mid-EDL, and thus the coverage starts at CSS and shows a maximum received power during entry. In both cases, however, the effects of the orbiter angle straddling the useful region of the helix antenna pattern are clearly visible after backshell separation, after which large oscillations in received power are discernible.

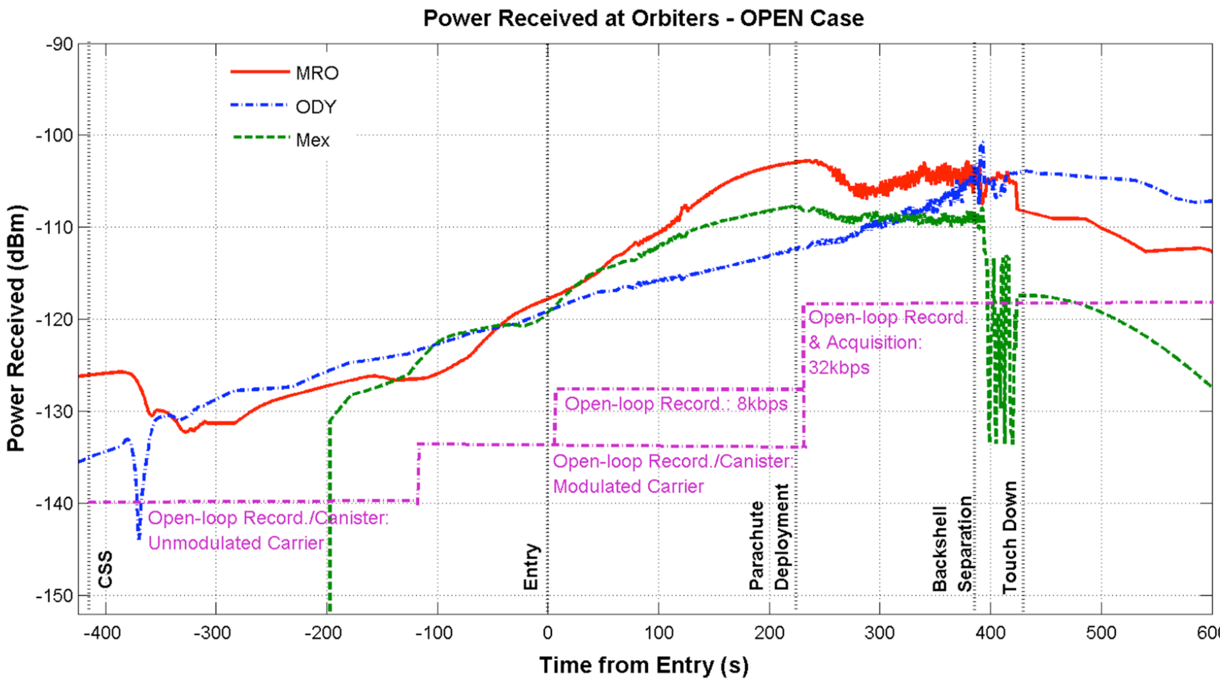
C. Plasma Blackout and Link Outages

There are a number of instances during EDL in which the link may be disrupted for short time intervals. First, there is temporarily no communication during the CSS event, because the X-band system is disabled beforehand and the entry vehicle's UHF system is not powered up and transmitting until the entry vehicle separates and emerges from the cruise stage. Second, during the hypersonic entry into the Martian atmosphere, a plasma sheath is generated around the spacecraft and the WPA. Preliminary analysis indicates that a potential plasma blackout may last between 1 and 2 min and be centered around the peak heating event. Third, with the Phoenix spacecraft swinging beneath the parachute after its deployment, the total power received at the orbiters may temporarily fall below the necessary thresholds, leading to short signal dropouts. Fourth, once the backshell separates and the lander emerges, the lander will use the deck-mounted helix antenna. To avoid switching the antennas while the transceiver is radiating, the UHF transmitter is put into standby and the data transmission is suspended for a few seconds until after the lander clears the backshell completely. In addition, during the actual separation event, the offboresight angles to the orbiters may temporarily exceed 90 deg in some cases (i.e., the orbiters may temporarily be below the lander deck), extending the signal dropout by a few seconds.

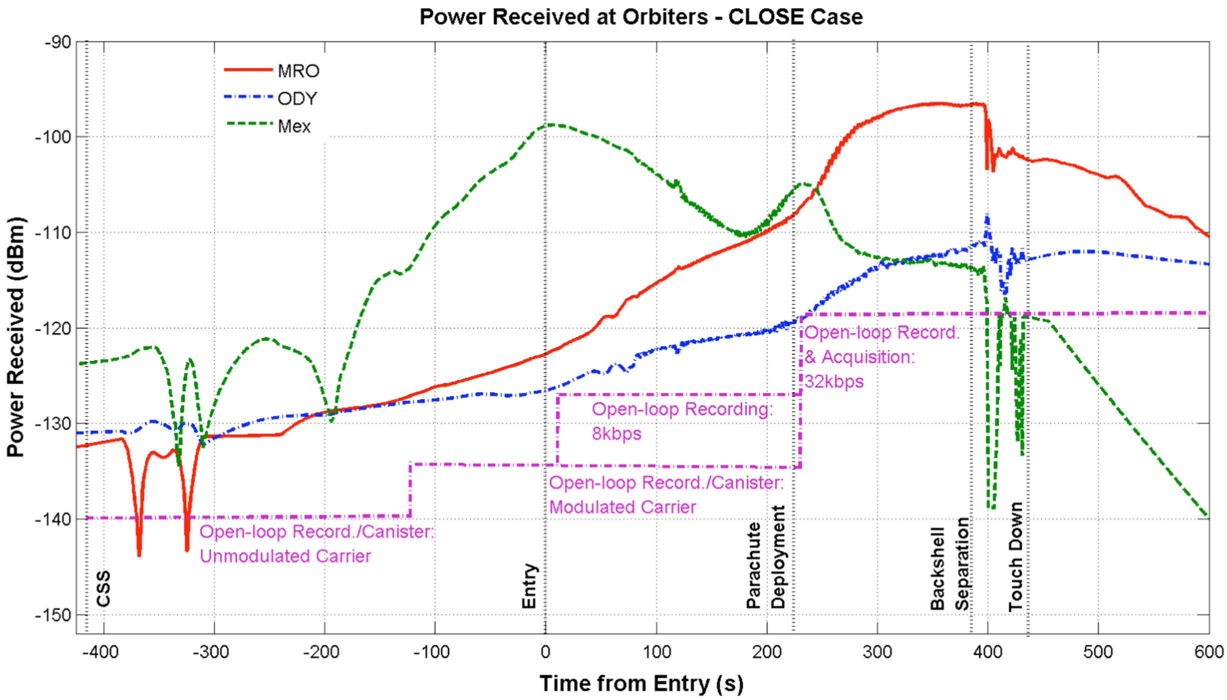
This section covered the overall link geometry, relative dynamics, and resulting link budgets between Phoenix and the orbiters, as well the expected link outages. However, a number of additional factors have to be considered in architecting the EDL comm implementation. These include the UHF transceiver capabilities, the communications protocols employed, the real-time aspect of information, and the quality of information obtained. All these factors will be discussed in following sections.

IV. EDL Comm Implementation and Challenges

Generally, the more critical and complex that a specific EDL event is, the more information that the ground would like to obtain about it to identify any faults, should they occur. In principle, with event criticality increasing as EDL progresses from entry to terminal descent, a respective increase in data rate would be expected. Moreover, based on Phoenix's command and data handling architecture, telemetry latency and downlink data rate are directly coupled, and a faster downlink rate results in smaller data latencies. However, whether a sustainable link can be established and what data rate can be achieved depends not only on the signal power received at the orbiter's transceiver, but also on the latter's capabilities and sensitivities (i.e., thresholds).



a)



b)

Fig. 7 Link performance for a) open case and b) close case.

A. Communication Modes

The relay orbiter and Phoenix UHF transceivers share the same protocols and will therefore interoperate.[††] They can be configured in a number of operational modes and transmission protocols, all of which may affect the achievable data rate.

When configured to acquire the incoming signal, the orbiter's UHF transceiver attempts to lock onto the incoming signal. Once acquired, Phoenix data are demodulated from the incoming signal in the receiver and passed along to the orbiter command and data handling system for further downlink via the X-band link to the ground. Once received on the ground, the Phoenix data are displayed on ground control stations. A number of different protocols can be employed in this configuration, including whether or not to use any kind of handshaking between the orbiter and lander. With handshaking enabled (also referred to as *reliable* mode), data corrupted during the transmission will be re-sent by the lander. However, in the context of EDL, this function is not desired, because a potential link dropout may result in repeated re-sends of the same data at the expense of more recent spacecraft state data. In *one-way unreliable* mode, data are transmitted without the use of a handshaking protocol, thus ensuring a continuous data flow and preventing any data buildup due to interrupted links. However, in

[††]The transceiver protocols comply with the standards established by the Consultative Committee for Space Data Systems (CCSDS); data available online at http://public.ccsds.org [retrieved 4 April 2008].

Table 1 Required total power received

Mode	Power
Open-loop recording/canister mode: carrier (unmodulated)	−140 dBm
Open-loop recording/canister mode: carrier (modulated)	−134 dBm
Open-loop recording: 8 kbits/s	−127.6 dBm
Open-loop recording: 32 kbits/s	−118.1 dBm
Signal acquisition: 32 kbits/s	−119 dBm

case of a momentary link dropout, the missed data are not recoverable, but will instead be superceded by more recent spacecraft state data.

When configured in *sample and recording* mode (also referred to as *canister mode* or *open-loop recording*), the orbiter UHF transceiver will sample and record the incoming signal without attempting to lock onto it. Instead, the transceiver samples and records the incoming signal as it is received, and the recorded data are passed along to the orbiter command and data handling system for downlink. Once the recorded samples are received on the ground, software will regenerate the UHF signal, lock onto it, and demodulate the data from the signal. In the case of MRO, the sampling is done with high enough resolution to capture most of the signal content, allowing the extraction of both the original carrier signal and the telemetry modulated on top of it. In the case of ODY and MEX, the sampling is done with a 1-bit resolution, leading to distortion and signal loss, and all that can be extracted is the original carrier information.

There are a number of advantages and disadvantages to each of the two approaches. Sampling and recording is generally more robust because it shifts the data processing entirely to the ground system, which has a more powerful set of signal processing algorithms available than does the onboard UHF transceiver. In the case of carrier signal and Doppler-shift extraction, ground-based algorithms can process weaker carrier signals than the onboard transceiver (configured in signal-acquisition mode) can acquire. Another advantage is that the sample and recording configuration is independent of the incoming signal's data rate, and thus no configuration change is required when Phoenix is changing its data rate during EDL. Finally, sample and recording is more robust to signal dropouts and reacquisition. Drawbacks of sample and recording are the loss of data information for ODY and MEX, due to their 1-bit quantizer and the significant postprocessing time required on the ground for MRO.

Because of its advantages, sample and recording (open-loop recording) is baselined for MRO during the entire Phoenix EDL. In addition, this mode is baselined for ODY (canister mode) for entry and the hypersonic phase of EDL. The loss of telemetry during this mode is offset by the increased robustness during the dynamic entry phase. However, for the latter part of EDL (that is, during parachute phase and terminal descent), ODY will be configured to acquire the incoming signal to obtain telemetry during the critical phases of EDL. Similar to ODY, MEX will be configured to sample and record the incoming signal (canister mode). However, unlike ODY, MEX remains in this mode for the entire duration of EDL and serves as a robust augmentation to ODY and MRO.

B. Link Margins and Data Rate

To understand the achievable link performance and ultimately achievable data rate during EDL, the total power received at the orbiter needs to be compared with the required orbiter UHF transceiver thresholds. The relevant thresholds are indicated in Fig. 7 and in Table 1. The thresholds of interest are 8 kbits/s, 32 kbits/s, and carrier-only, because these are the only modes supported by the lander's transceiver in this data-rate range. The total power received that is necessary for detecting a carrier and Doppler signal depends on whether the signal has data modulated on top of it. If it has, then the carrier signal is suppressed (i.e., has less energy) and the total power received must be 6 dB higher (shown as an adjusted threshold in Fig. 7 and Table 1). For clarity, the thresholds for 32-kbits/s telemetry acquisition and open-loop recording are shown as one line in the figure.

To ensure a robust link for a selected data rate, the power received must be above the indicated threshold for this data rate by a certain margin. The latter is referred to as the *link margin*. Because the power received curves shown in Fig. 7 merely represent a nominal case of the EDL comm link, the link margin must be large enough to account for dispersions in both the EDL geometry and the UFH system performance. The former may include effects such as dispersions in the arrival time and flight-path angle and variations in the Martian atmosphere. UHF system performance variations may include tolerances in line loss, transmitted power, or antenna gain. Based on a Monte Carlo analysis, an average link margin of 8–9 dB was deemed to be sufficient for Phoenix EDL.

Figure 8 shows the resulting overall EDL comm implementation. Phoenix (PHX) starts transmitting carrier-only immediately after CSS until approximately 2 min before entry. All three orbiters are configured in sample and recording mode at this point in time (MRO in open-loop recording and ODY and MEX in canister mode). As shown in Fig. 7, the received signal power is above the threshold for extracting the carrier and Doppler information by the desired margin, but would not suffice to extract 8-kbits/s data. Two minutes before entry, Phoenix starts transmitting 8-kbits/s telemetry data modulated onto the signal carrier. All orbiters remain in their current sample and recording configuration. However, the signal power received at MRO is now sufficient to demodulate the 8-kbits/s telemetry stream on the ground. For ODY and MEX, on the other hand, the 8-kbits/s data are now lost during the sample and recording. Although ODY could lock up onto the 8 kbps, the current design is more robust to the expected signal dropouts. After parachute deployment, Phoenix is increasing its telemetry downlink data rate to 32 kbits/s, providing more bandwidth and less overall latency with the onset of the more critical parachute and terminal descent phases. MRO remains in open-loop recording mode, and at this point in time, the received signal strength is sufficient to demodulate the 32-kbits/s data once the recorded signal is received on the ground. ODY, on the other hand, is switching to a configuration that allows it to acquire and track the incoming signal as well as to demodulate the 32-kbits/s telemetry stream. With the nominal received power in the close case just above the threshold (as shown in Fig. 7b), ODY's lockup onto the 32-kbits/s telemetry may, under offnominal conditions, be somewhat delayed until the link margin has sufficiently grown. MEX continues to record the incoming signal in canister mode for later Doppler signal extraction. The latter Phoenix and orbiter configurations stay in effect until the EDL communications coverage is completed at 1 min after landing.

C. End-to-End Information Flow

Another factor that needs to be considered is the real-time aspect of information. Here, too, the orbiter's capabilities differ between MRO, ODY, and MEX. ODY can receive a UHF signal from Phoenix via its UHF antenna and, at the same time, downlink the collected signal information and/or telemetry via its X-band high-gain antenna to NASA's Deep Space Network (DSN), essentially operating in a bent-pipe mode for as long as the DSN is in view of the orbiter. This is significant because it allows the ground teams to monitor the progress of EDL as it unfolds (only delayed by the one-way light time). MRO and MEX, on the other hand, do not have the capability to perform the relay function and communicate with the DSN at the same time. Instead, they will downlink the data collected after the relay pass is over at the next opportunity in which there is DSN coverage.

Figure 9 shows the overall end-to-end information system architecture for EDL comm. Once the data are downlinked to the DSN via the orbiter's X-band link, the data are first processed by the respective orbiter's ground data system (MRO GDS and ODY GDS). Next, the raw data are passed on to the Phoenix ground data system (PHX GDS). In the case of ODY, the carrier and Doppler data are extracted from the recorded signal and displayed for the ground

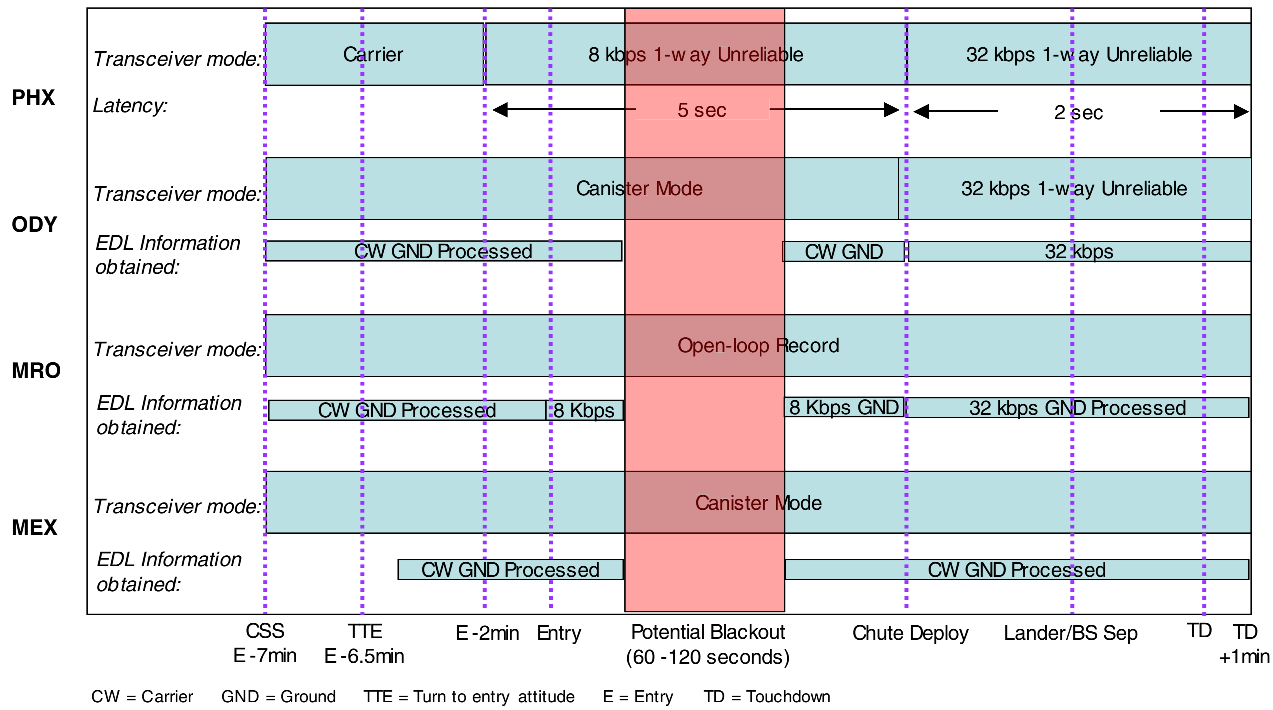


Fig. 8 EDL comm implementation overview.

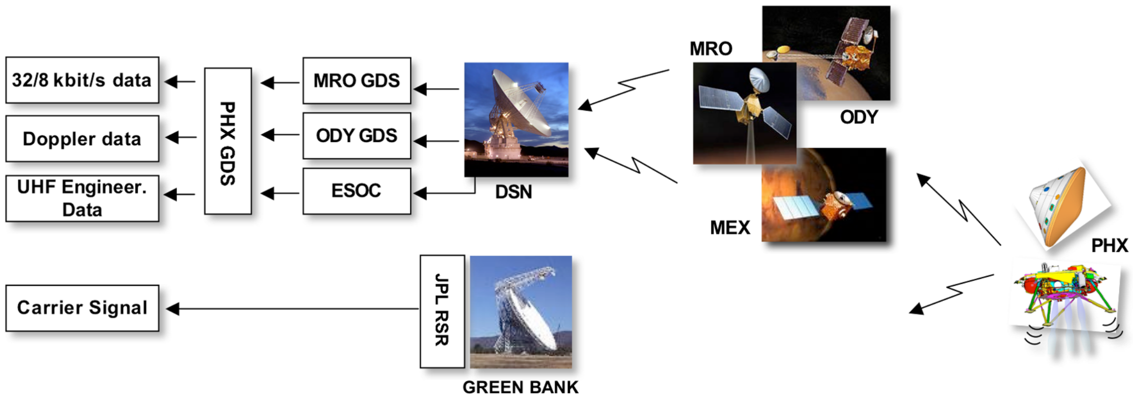


Fig. 9 End-to-end information system.

control teams in near-real time. This is supplemented by the 32-kbits/s data after parachute deployment. In addition, ODY provides real-time UHF engineering data that provide insight into the quality of the link (signal strength), as well as Doppler information once it tracks the signal. In the case of MRO, the recorded signal is received on the ground after the EDL coverage completes. It is then postprocessed to extract the carrier/Doppler information and the actual 8- and 32-kbits/s Phoenix telemetry. Finally, for MEX, the recorded signal is received after the completion of the EDL coverage at ESA's operations center (ESOC), from where it is transmitted to the Phoenix ground teams. Once received, carrier and Doppler information is extracted.

D. Coordination Across Multiple Spacecraft

The preceding EDL comm architecture relies on the orbiters and the Phoenix lander to be in the right location, right attitude, and right transceiver configuration at the right time. To accommodate this, all four spacecraft are synchronized to UTC time. Moreover, both Phoenix's trajectory and arrival time at the atmospheric entry point, as well as the orbiter's position in their orbit, can be predicted and controlled to within a few seconds. Subsequently, the orbiter's pointing and slewing maneuvers are initiated based on Phoenix's predicted entry time. Similarly, the time of CSS and start of the UHF links from Phoenix to the orbiters is known, and the orbiter's transceivers can thus be configured based on an expected UTC start time. Whereas MRO and MEX remain in sample and recording mode for the entire duration of EDL, ODY will switch from an initial sample and recording mode to a 32-kbits/s one-way unreliable mode once Phoenix deploys the parachute. However, the latter time is not known a priori, because the parachute deployment is triggered by onboard sensors and is therefore dependent on a number of atmospheric (and other) conditions present at landing day. Based on numerous Monte Carlo analyses, it was determined that parachute deployment time can be dispersed by up to ± 20 s. To accommodate this uncertainty, ODY is switched at a UTC time that corresponds to the earliest expected parachute deployment time. Consequently, ODY most likely will switch to the 32-kbits/s one-way unreliable mode before Phoenix does.[‡‡] Finally, Phoenix continues to transmit until 1 min after its landing. Similar to parachute deployment,

[‡‡]In this case, with Phoenix still transmitting 8 kbits/s, ODY may lock up onto the carrier and continue to provide carrier information until acquiring the 32-kbits/s data after Phoenix switches to 32 kbits/s. This is preferred over the alternative in which ODY switches to 32 kbits/s *after* Phoenix. In such a case, ODY would continue to collect canister data with the carrier extracted on the ground. However, once ODY switches to 32 kbits/s, signal lockup may be delayed because ODY cannot take advantage of Phoenix's carrier-only acquisition signal that is sent out at the beginning of the 32-kbits/s transmission.

Phoenix's landing time is not known a priori; rather, it is dependent on a large number of factors present at landing day. Analysis has shown that the landing time can vary by as much as ±55 s. Consequently, the orbiters are configured to continue the UHF link to accommodate the latest landing time.

E. Additional Assets

Analysis has shown that parts of EDL are also observable via a DTE UHF link. This venue has thus been baselined as an augmentation to covering EDL using a relay architecture. There are a number of UHF ground stations distributed across the planet including stations in Stanford, California; Green Bank, West Virginia; and Parkes, Australia. Depending on the UTC time of EDL, which in turn is a function of the launch date, only a subset of these stations will be in view of Mars. For a launch at the opening of the launch period, including the actual 4 August 2007 launch date, Green Bank and Stanford are in view during EDL, whereas Parkes and Stanford would have been in view for a launch at the close of the period. Because Green Bank has up to 10-dB higher sensitivity compared with other ground stations, it will be used to support the DTE UHF link. Still, due to the significant distance to Mars and the associated space loss, only a carrier signal and its Doppler (but no telemetry) can be detected during EDL. Figure 9 shows the DTE UHF link architecture. A radio science receiver (RSR) provided by the Jet Propulsion Laboratory is used to record and display the incoming UHF signal at Green Bank. Similar to ODY, this venue allows the ground teams to monitor the presence of the Phoenix signal during the actual EDL (delayed only by the one-way light time).

V. Identification of Probable Fault and Data Selection Strategy

A. Types of Information

NASA's requirement calls for the Phoenix mission to provide communications coverage during all critical events, especially EDL, sufficient to diagnose faults and/or failures, should they occur. The requirement does not specify what kind of communications link or data rates have to be used or what kind of data need to be transmitted. The paramount requirement is that the ground can determine the nature of mission failures, should they occur. To this end, there are a number of information sources that the ground can draw on to diagnose what happened:

Signal presence: The detection of a signal at the relay orbiter's UHF transceiver (or via DTE UHF) provides a positive indication that the spacecraft is still powered and functional enough to transmit signals. Conversely, the point in time at which an abrupt and unexpected loss of signal occurs may provide an important clue to the nature of the failure. In particular, it allows the failure investigation team to focus their investigation on the time frame leading up to the time of signal loss. For example, signal loss around the time the parachute is supposed to deploy may point in the direction of a structural failure associated with this event.

Signal strength: Typically, the orbiter's UHF transceiver measures not only the presence of an incoming signal, but also the actual power received at the transceiver using their automatic gain control (AGC) loop. AGC information is useful when compared with a predicted profile of the power received at the orbiters to determine whether EDL is progressing in a nominal way. For example, a lower-than-expected power level may be an indication of an offnominal entry vehicle attitude, with the orbiters now appearing in an area of lower antenna gain.

Doppler shift: A significant increase in visibility is gained when information about the dynamics of the entry vehicle is available. Measuring the Doppler shift of the incoming carrier signal is a direct indication of the line of sight or relative dynamics between the entry vehicle and the orbiter (Fig. 5 shows a typical Doppler profile). Because the orbiter trajectory is well known, its effects can be subtracted, giving the ground teams insight into the dynamic environment that the vehicle is experiencing during EDL. Events such as the deceleration during hypersonic entry and parachute deployment result in distinct Doppler signatures that can be detected in the Doppler measurement (although peak deceleration most likely falls during the plasma blackout). When configured in signal-acquisition mode, the orbiter's UHF transceiver is using its carrier phase-locked-loop to measure the Doppler shift. When configured in sample and recording, the Doppler information is processed on the ground from the recorded signal. Using only Doppler information to monitor the health and state of the vehicle is appropriate in cases in which the entry vehicle is quiescent and the link margin is insufficient to support a data link.

The previous three types of information provide *inferential* insight into the vehicle health and state; they do not, however, provide a definitive assessment of the latter. To achieve this, the ground needs to obtain actual vehicle health and state data. Again, a number of different methods exist:

Semaphores: As in the case for MER, a transceiver may have the capability to transmit a multitude of different carrier and/or subcarrier frequencies (i.e., tones). These tones can then be used to indicate specific spacecraft states, events (e.g., deployments), and/or faults that may have occurred. In the case of MER, there were 256 semaphores available and each one was 10 s in duration.

Spacecraft telemetry: Telemetry transmitted by the spacecraft provides the most insight into the vehicle health and safety. It provides a detailed account of all critical spacecraft functions, including the environment that the spacecraft senses (e.g., decelerations and attitudes), the control corrections that the spacecraft applies to counteract any disturbances it perceives (e.g., thruster firings), the various trigger logic calculations (e.g., the parachute deployment time), overall spacecraft state (e.g., critical voltages and temperatures), and spacecraft health and fault-protection data (e.g., tripped monitors and executed responses).

What information is available at any point in time is not only a function of the signal strength and resulting link margin (as shown in Fig. 7), but also of the level of spacecraft activity that needs to be observed. For Phoenix, between CSS and entry, the link margin supports a carrier/Doppler-based link only. At the same time, little spacecraft activity is planned during this time interval and the environment is still benign. At the onset of the hypersonic entry, the effects of the atmosphere start being noticeable and spacecraft activity starts increasing. At this point Phoenix will switch to a 8-kbits/s data rate. Finally, with the parachute deployed, the spacecraft prepares for terminal descent (the most challenging part of EDL) and switches to a data rate of 32 kbits/s.

Table 2 lists the type of information that previous missions transmitted and puts Phoenix's capability into perspective. As can be seen, Phoenix provides a wealth of bandwidth, compared with the other missions. The next section will outline what information is transmitted.

B. Telemetry and Data Selection Strategy

The capability to transmit at 8 or 32 kbits/s provides an opportunity to gather an unprecedented amount of spacecraft *data* during EDL. But what is the *information* that is most valuable in case a failure occurs and how much information is necessary? The answer to this question is not always straightforward, because the number of potential failures is infinite and many of them may manifest themselves in ways the designer cannot anticipate when selecting the telemetry. Thus, a more methodical approach needs to be employed to come up with the right information to be transmitted. In particular, should a failure occur, the obvious questions to ask are as follows:

1) What event just happened that may have contributed to the failure?

2) What was the spacecraft state just before the failure occurred?

3) Did the spacecraft itself detect any anomalies leading up to the failure?

Consequently, the telemetry can be grouped into the following three categories, each addressing one of those questions: 1) event-data telemetry confirming that a specific event has occurred, 2) state-

Table 2 EDL comm capabilities

Missions	CSS to entry	Hypersonic phase	Parachute phase	Terminal descent
Viking	UHF 4 kbits/s	UHF 4 kbits/s	UHF 4 kbits/s	UHF 4 kbits/s
MPF	X-band carrier/semaphores	X-band carrier/semaphores	X-band carrier/semaphores	X-band carrier/semaphores
MER	X-band carrier/semaphores	X-band carrier/semaphores	X-band carrier/semaphores	X-band carrier/semaphores/ UHF 8 kbits/s
Phoenix	UHF carrier	UHF 8 kbits/s	UHF 32 kbits/s	UHF 32 kbits/s

Table 3 Spacecraft event telemetry

#	Events	Physical manifestation	Telemetry	Identifiable
1	Cruise stage separation	Impulse in acceleration Onset of UHF signal on WPA	x-axis acceleration UHF signal presence	Yes (probably)
2	Peak deceleration (during plasma blackout)	Peak deceleration	x-axis acceleration	No (during blackout)
3	Deceleration profile (outside plasma blackout)	Increasing/decreasing deceleration	x-axis acceleration	Yes
4	Parachute deployment (mortar and chute)	Step change in deceleration	x-axis acceleration	Yes
5	Heat-shield deployment	Change in deceleration	x-axis acceleration	Possibly (10% change in mass)
6	Radar lock-on	Radar declares lock-on	Radar health status	Yes
7	Lander backshell separation	Free fall Onset of UHF signal on helix	x-axis acceleration UHF signal presence	Yes
8	Transition to tip-up maneuver and descent engine start	Attitude excursion Change in deceleration	Attitude x-axis acceleration	Yes
9	Transition to gravity turn	Constant deceleration Aligning of velocity vector with Martian gravity	x-axis acceleration Attitude	Yes
10	Rolling to landed attitude	Rolling motion	Attitude Attitude rates	Yes
11	Transition to constant velocity phase	Vertical velocity 2.4 m/s $\pm$ 1.0 m/s	Navigated velocity x-axis acceleration	Yes
12	Touchdown and engine shutdown	Settling on the ground, deceleration to zero	x-axis acceleration	Yes

data telemetry describing the general state of the spacecraft, and 3) fault-protection data telemetry indicating whether the spacecraft detected any anomalies. Each of the three categories is discussed next.

Table 3 shows the significant spacecraft events and the necessary spacecraft telemetry to observe these events. As shown, acceleration sensed along the spacecraft longitudinal axis (defined as the main axis of symmetry, or x axis) is the primary observable for most of these events. This is not surprising, because many of the events are tied to a change in velocity of the entry vehicle. In addition, spacecraft attitude and rates provide insight into the rolling motion of the spacecraft, and a number of discrete telemetry channels indicate various events along the EDL timeline, such as pyro firings for separations and staging events (although these are only indirect indications). Still, if nothing but spacecraft acceleration was transmitted, significant insight into the progress of EDL could be obtained.

Spacecraft state data typically encompasses telemetry from all subsystems and provides context information, should there be a need to diagnose a failure. Table 4 shows a high-level list of spacecraft states. As before, spacecraft acceleration (in all axes) and attitude are again paramount to understand the dynamic state of the spacecraft. In addition, there are a number of navigational states, sensor outputs, and discrete status words that allow insight into the guidance, navigation, and control loops. Finally, a number of critical voltages, temperatures, and pressures allow insight into power, thermal, and propulsion systems.

The spacecraft health and safety status is best captured with fault-protection-driven telemetry. During spacecraft operations, the spacecraft fault protection monitors all essential functions and flags any anomalies it finds. By transmitting various fault counters and quick-look fault-protection status words (as shown in Table 4), ground teams can observe the faults detected onboard the spacecraft.

By following the aforementioned approach, a set of telemetry is obtained that provides insight into the unfolding EDL events, as well as general context and health and safety information. One way of *validating* this set of telemetry is by analyzing its efficacy in diagnosing failures. To this end, an EDL *fault tree* can be constructed that outlines all conceivable spacecraft failures. Next, the selected set of telemetry can be used to identify which of the faults in the fault tree can indeed be diagnosed with the available information. Naturally, this process also helps identify if additional telemetry is necessary to diagnose a particular fault and, if available, this telemetry can be added. At the same time, the process can pinpoint failures that are not identifiable due to inherent limitations in observability. Finally, the ground team can exercise the failure identification process by analyzing the telemetry of simulated spacecraft failures.

VI. Conclusions

This paper discussed how NASA's requirement for communications coverage during entry, descent, and landing of the 2007 Phoenix Mars Lander is met. The architectural trades in designing the communications link and the implementation of previous Mars missions were explained first. Next, the numerous design limitations and challenges that drive the link implementation and the degrees of freedom were outlined. The actual orbital geometry and the resulting power received at the orbiters were then presented. Next, the actual UHF transceiver operating modes and the achievable data rates were discussed, and the resulting end-to-end EDL comm architecture was

Table 4 Typical spacecraft state and health telemetry

GNC	Housekeeping	Fault protection
Body accelerations: x–y–z axis	Propulsion subsystem pressures	High-level fault-protection status words
Body rates: x–y–z axis	Critical bus voltages	Component-level fault-protection status words
Attitude: yaw, pitch, and roll	Battery state of charge	Radar-health status words
Navigated altitude	Propulsion subsystem temperatures	
Navigated velocity: x–y–z axis	UFH system temperatures	
Thruster status words	GNC component temperatures	
EDL separation and deployment times	Event records	
Touchdown sensor	Telemetry statistics command dispatch history	

explained. Finally, the different types of information that can be transmitted were surveyed, and an overall methodology for selecting and validating the right telemetry set was discussed.

The EDL communications design for the 2007 Phoenix Mars Lander distinguishes itself in a number of ways from implementations of previous missions. It employs, for the first time, a sample and recording scheme onboard the orbiters instead of acquiring the signal directly. In the case of MRO, all the data are demodulated on the ground. For ODY, only Doppler data are extracted initially, but during the latter parts of EDL, the orbiter locks onto the 32-kbits/s signal. For MEX, which serves as an augmentation to the other orbiters, Doppler data are extracted for the entire duration of EDL. Moreover, because of the unprecedented high data rate, the amount of data collected in the later, more critical, parts of EDL allows for detailed insight into the events unfolding during terminal descent.

Designing a communications link during EDL is a complex endeavor involving a large and interdisciplinary team. A number of design trades are highly coupled and need to be addressed in the context of a number of design constraints levied by other aspects of the mission. Moreover, close coordination across multiple spacecraft teams is necessary to accurately choreograph the position, attitude, and timing of the supporting relay orbiters. As future Mars landed missions emerge, similar challenges and constraints may apply. The overall methodologies outlined in this paper, as well as the actual flight experience of the 2007 Phoenix Mars Lander, will greatly benefit the EDL comm architecture and implementation of these missions.

Acknowledgments

This development work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology. The authors would like to thank Peter Ilott, Kris Bruvold, Ed Satorius, Bradford Arnold, Sami Asmar, Roberto Aguilar, and David Bell (Jet Propulsion Laboratory Communications, Tracking and Radar Division), Rob Grover (Jet Propulsion Laboratory Systems and Software Division), Tim Priser and Scott Toro-Allen (Lockheed Martin Astronautics Denver), Christopher Grasso (Blue Sun Enterprises, Inc.), and Jill Prince (NASA Langley Research Center) for their contributions in developing the entry, descent, and landing communications architecture.

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