Communicating by Doppler: Detecting Spacecraft Dynamics During Critical Maneuvers

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Communicating information from spacecraft in deep space utilizes sophisticated techniques of modulations onto a microwave signal carrier. Under most conditions, there is a high success rate of sending commands to the spacecraft and receiving science data acquired by on-board instruments along with health and status information. There are conditions, however, where the signal dynamics are too high and/or the received signal-to-noise ratio is below the receiver threshold. Under these conditions, often by design and sometimes as a result of planned or unplanned critical maneuvers, events (e.g., orbit insertion or descent and landing), safe mode, etc., it becomes highly critical but exceedingly challenging to receive information about the health and dynamical behavior of the spacecraft. The Deep Space Network, being a world-class instrument for Radio Science research, developed open-loop receivers, called the Radio Science Receiver, designed to capture the raw incoming electromagnetic signals and associated noise for Radio Science experiments; post data capture digital signal processing extracts the signal carrier for scientific analysis. This receiver provides a high level of configuration flexibility and can be optimized for the various types of experiments. In addition to its scientific utility, it proved to be useful, and in some cases critical, for the support of missions during specific scenarios were the link budget is below the threshold of the tracking receiver to maintain lock or the frequency dynamics are faster than the limits of the tracking receiver. In these cases, the signal carrier is often detected only in the open-loop receiver to provide information on the specific behavior of the spacecraft from the carrier dynamics. This paper describes the utility of the system to support mission-critical events for the three cases of Cassini's Saturn orbit insertion, Huygens Titan landing, and Mars rovers landing.

I. Introduction

Communications with spacecraft in deep space utilize data modulations onto a microwave signal carrier. These radio links have been successful in providing data rates that meet mission requirements under most conditions of mission operations. There are conditions, however, where the signal dynamics are too high and/or the received signal-to-noise ratio is below the receiver threshold to acquire and lock onto the signal. Under these conditions of planned critical maneuvers, unplanned events, or emergency safe mode, it becomes highly critical to be able to receive information about the health and dynamical behavior of the spacecraft.

NASA's Deep Space Network (DSN) supports the communications and navigation functions of flight projects. The DSN is also a world-class instrument for scientific research in the areas of Radio Science, Radio Astronomy, and Planetary Radar. The DSN's open-loop receiver, called the Radio Science Receiver (RSR), captures the raw incoming electromagnetic signals and associated noise for Radio Science experiments. Post-pass digital signal processing by users extracts the signal carrier for scientific analysis. The receiver provides a high level of configuration flexibility and operability that can be optimized for the particular experiment or mission support event.

The RSR proved to be useful, and in some cases critical, for the support of missions during cases were the signal level is below the threshold of the tracking receiver to maintain lock or the frequency dynamics are faster than the limits of the tracking receiver. In these cases, the signal carrier can be detected in the RSR to provide the project information on the state of the spacecraft from the carrier dynamics. We discuss the historic cases of the Cassini Saturn Orbit Insertion (SOI) maneuver, the Huygens Titan probe landing, and the Entry, Descent and Landing (EDL) of the Mars Exploration Rovers.

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II. The Cassini Saturn Orbit Insertion

The Cassini spacecraft was launched in 1997 for a long mission to explore Saturn, its moons, rings and environment. It has been very successful with numerous discoveries and was granted mission extensions. Upon arrival at Saturn in 2004, after a 7-year cruise period, a maneuver dubbed Saturn Orbit Insertion (SOI) was required such that the spacecraft's main engine is fired for precise time duration. This was optimized for the spacecraft to be captured in orbit around Saturn with a minimum amount of fuel consumption since fuel was required for the remainder of a long mission; one third of all the was used for SOI engine burn. A slight error in the engine firing would lead to escaping the orbit or crashing into the planet. Adding to possible risk of the maneuver, the spacecraft trajectory took it through a gap in the rings of Saturn, where small particles posed a potential risk of impacting the spacecraft. In order to mitigate this risk, the spacecraft's large high gain antenna (HGA) was pointed in the direction of travel to act as a shield, which was not in direction to Earth for communications with ground station. This created a five-hour gap in communications during a critical maneuver, which was against requirements, especially for such an advanced and expensive interplanetary mission.

A Low Gain Antenna (LGA) was utilized instead. However, the link budget for this scenario was deemed insufficient for the ground receiver to lock-up onto the carrier or demodulate telemetry. The Cassini Program called upon the Radio Science Systems Group (RSSG) to device a communications solution utilizing the RSR. The orbit insertion required a critical navigational maneuver that involves firing the orbiter's thrusters leading to the capture of the spacecraft in the gravity well of the planet. During this maneuver, the spacecraft turned away for Earth pointing to fire its thrusters. In this orientation, the LGA was used to receive the one-way signal, referenced to the on-board Ultra Stable Oscillator (USO). Four factors made the signal acquisition difficult: the physical orientation of the spacecraft, the ring system of Saturn, the main engine propellant burn, and the gravity well of Saturn itself.

The SOI maneuver required that the spacecraft turn such that the HGA is between 40 and 28 degrees off earth boresight over the course of the burn. Because the half-power beam width of the X-band signal on the HGA is only about half a degree, the LGA #1, which is mounted along the same boresight as the HGA (see Figure 1), provided sufficient power margin to acquire the signal carrier on earth even when the spacecraft is off-point by 40 degrees. The received signal strength was estimated to be ~10 dB/Hz. Cassini's engines were fired for about one hour and thirty-six minutes in order to slow down the spacecraft enough to be captured by Saturn's gravitational pull. The burn induced a rate of change of the received signal frequency of between 1 and 3 Hz per second (see Figure 2).

During the maneuver, the spacecraft was occulted as seen from Earth by the rings of Saturn. Because the rings are typically not transparent at X-band (3.6 cm wavelength), the ring crossing caused additional drops in received signal strength. Saturn itself had the greatest effect on the frequency of the received radio signal due to the large gravitational force and corresponding Doppler shift. Although this dominated the other effects, Saturn's gravity was modeled accurately. When the spacecraft approached the planet, it was pulled away from Earth and a negative Doppler shift was observed. Once the spacecraft turned and the engine fired, the motion of the spacecraft slowed down in preparation for orbit insertion. On the other side of the planet, the spacecraft continued to be pulled towards the planet but that motion relative to Earth yielded a positive Doppler shift. Figure 3 shows a predicted time-history of the frequency with and without an engine burn. The correct modeling of Saturn's gravitational field will be critical to the acquisition of the radio signal. The Doppler data revealed subtle motion of the spacecraft due to the pull of Saturn. Errors in Cassini's arrival time of as little as two seconds would increase the uncertainty of the received signal frequency by a one order of magnitude.

The combination of the effects of the weak received signal power as well as frequency dynamics made the acquisition of the signal transmitted by the LGA very challenging. The DSN tracking receiver would not be able to maintain lock on the spacecraft signal throughout the event. The monitoring of this critical event relied on the RSR operated remotely from JPL by the RSSG. An open-loop receiver driven by tuning predictions, it does lock or track a signal, so the signal dynamics are not a big concern given reliable tuning predictions based on very recent navigation solutions. The RSR down-converts and records the digitized signal and noise in a pre-selected bandwidth. Specialized software was developed by the RSSG to aid in the real-time visibility of the data received by the RSR. The accuracy of the displayed data distinguished the effects of a successful engine firing and the expected emersion of the spacecraft on the other side of Saturn. Two sets of frequency predictions were used, the first based on the Cassini nominal trajectory, which model very accurately the expected received signal frequency at the ground station. The second predict set modeled the expected Doppler shift due to the burn of the Cassini main engine causing a deviation of approximately 11,500 Hz (based on simulations) from the actual spacecraft transmit frequency over the course of 95 minutes, with an average drift rate of 2 Hz per second. The real-time displays of the RSR data included power spectra and time history of the power and frequency profile estimated from a Fast Fourier Transform (FFT) algorithm. More accurate processing of the data took place after the completion and of the activity. The Radio Science data were processed and converted into a format that the Cassini Navigation team used to reconstruct the events in order to prepare for any required follow-up cleanup maneuvers. Figure 4 shows the resulting profile that was populated on a display in real-time and used solely to declare the success of the maneuver to the relief of the project.

Figure 1. Cassini Spacecraft with location of communication antennas.

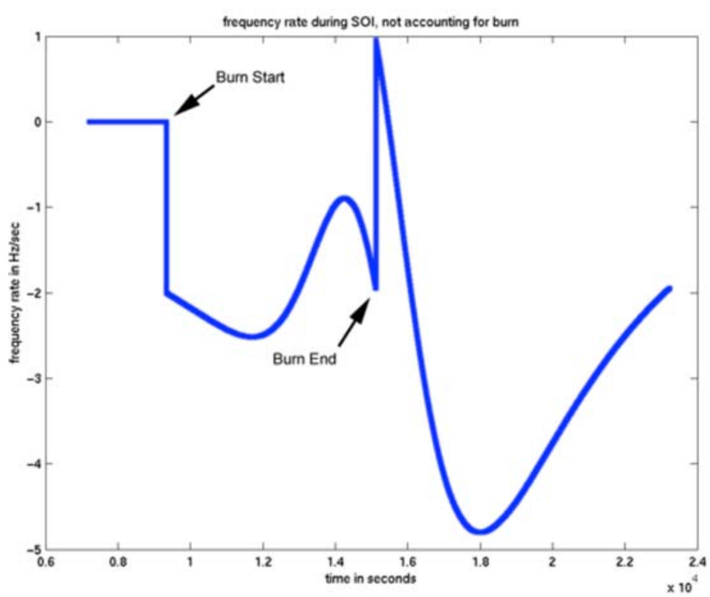

Figure 2: Predicted frequency acceleration.

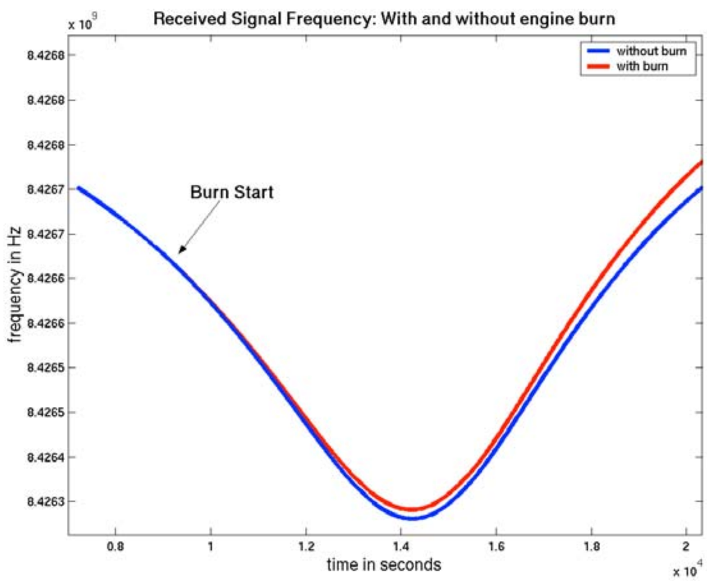

Figure 3: Predicted received frequency for the cases of modeling and not modeling the engine burn.

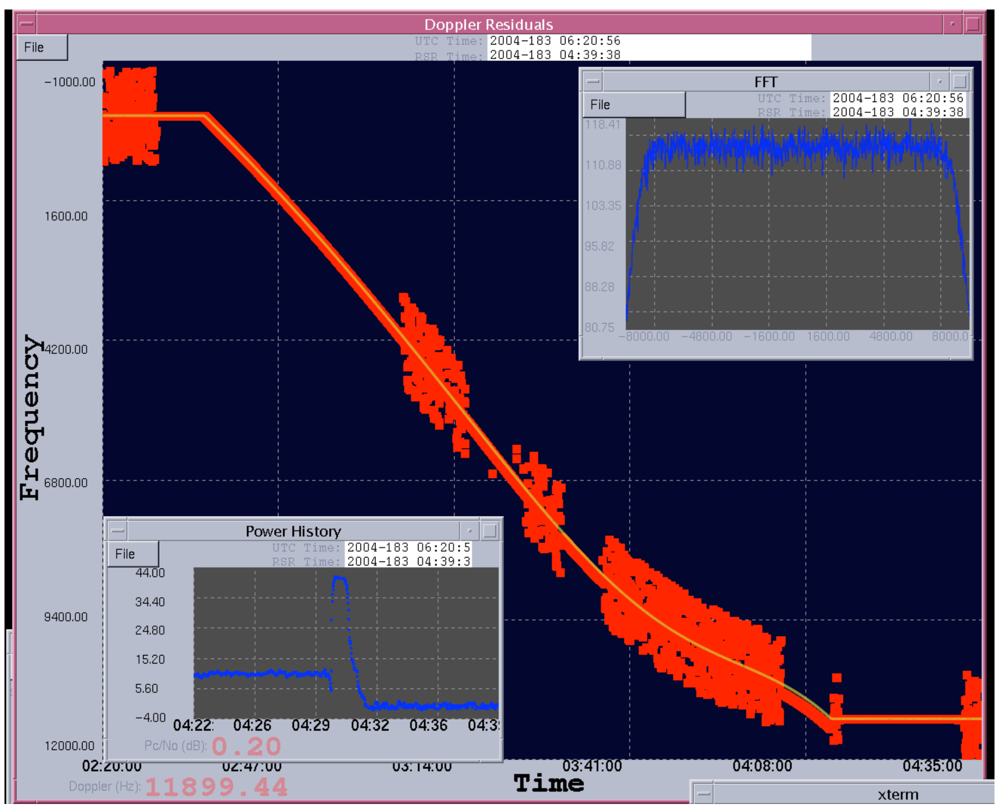

Figure 4: …x
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III. Huygens Landing on Titan

The Huygens probe was released from the Cassini spacecraft on 25 December 2004 and entered the atmosphere of Titan on 14 January 2005. A heat shield used to protect the probe during the initial deceleration was ejected after atmospheric entry and shortly after deployment of the main parachute. One of the investigations of the Huygens probe during its descent onto the surface was an experiment to measure the speed and direction of the wind in Titan's atmosphere. The Doppler Wind Experiment (DWE) instrumentation transmitted a radio signal while in motion during the descent stage to be received by the Cassini orbiter. It relied on accurate reconstruction of the Doppler effect of the received signal to generate a profile of the wind zonal velocity.

Not anticipating anomalies with the mission, a team of radio scientists had scheduled several large radio telescopes worldwide to listen to the weak signal from Huygens (not designed to be received on Earth) for the purpose of enhancing the once in a lifetime DWE. The Cassini orbiter was intended to receive the probe's signal but an operational problem prevented that. As a result of the loss of the DWE nominal data onboard Cassini, the ground-based Doppler observations became the only available Huygens DWE data and formed the basis for the zonal wind profile published by the science teami. Radio transmission was started about 45 seconds after parachute deployment and the signals reached Earth 67 minutes later (one-way light time). Huygens landed on Titan at approximately 2.5 hours after entering the atmosphere. After landing the probe continued to transmit until the last radio telescope. The Huygens downlink is outside the receiving capability of the DSN.

The instrumentation on the Huygens probe included a rubidium-based Ultra-Stable Oscillator (USO) to provide a reference for the transmitted signal. During its decent, the probe transmitted two radio signals on two channels at opposite polarizations, one was referenced to the USO and the second to a less stable oscillator. Channel A transmission at 2.040 GHz was referenced to the USO in order to provide a frequency reference sufficiently stable to achieve the required Doppler measurement accuracy. Channel B, at a frequency of 2.097 GHz and in opposite polarization to channel A, was driven by a crystal oscillator not sufficiently stable for useful precision Doppler measurements. The probe's antenna was fixed to the body of the spinning probe and pointed vertically upward along the nominal spin axis.

Reliable detection of the Huygens signal at Earth, not planned when the mission was developed, required the use of large-diameter antennas (>50 m). With no single radio telescope of this size able to view Titan for the entire probe descent period, a combination of several telescopes was used. The 100-meter diameter Robert C. Byrd Green Bank Telescope (GBT) in West Virginia was used to observe the initial part of the descent. The 64-meter Parkes Telescope in Australia was used to observe the final part as well as a period of time after the probe had landed. An interval of ~24 minutes of the descent was not observable by either large telescope. Four 25-meter telescopes of the Very Long Baseline Array in the USA were enlisted to fill in this period: Pie Town, Owens Valley, Mauna Kea, and Kitt Peak. In principle, the signals from the four small antennas can be combined to an equivalent 50 m diameter antenna, but this has not been carried out.

Due to weak received signal-to-noise ratio and potential errors in the predictions of the signal dynamics, open-loop receivers were required for reception of the Huygens probe carrier signal. The RSRs were borrowed from the DSN and shipped to the GBT and Parkes telescopes. The RSR utilized a frequency prediction file for tuning of its digital local oscillator. Large bandwidths were used for recording at right- and left-hand circular polarizations. Simpler recorders without tuning were also used as back up at the two large telescopes and primary recorders at the smaller telescopes. Using the RSR, the Huygens S-band carrier was detected in real-time using FFT displays of the RSR data samples. The detection was reported in real-time to the Huygens project at Darmstadt, Germany, to the relief of the mission staff. With that, the project knew that the probe was alive and functioning several hours before telemetry was received via the Cassini relay. Post-recording processing of the open-loop data resulted in a construction of the published zonal wind profile. Figure 6 shows the resulting wind profile at Titan generated from the data acquired during this activity.

All the participating telescopes were also a subset of a larger network participating in Very Long Baseline Interferometry observations for the purpose of determining the probe's precise position on the sky which required that the telescopes alternately point at Titan and at an extragalactic radio source over a three-minute cycle, of which about 100 seconds were available for Huygens tracking. The coordination of a large number of radio telescopes worldwide and providing adequate real-time communications between them was very challenging. More time was needed to test the RSR and remove spurious signals generated by other subsystems at the telescopes or by outside sources. One important lesson learned was to schedule the telescopes for longer viewing in case the probe continued to transmit beyond the predicted time limit. One operational lesson that has already been acted upon is the development of a portable RSR that can be carried to a telescope facility. Finally, the most important lesson learned from ground-based tracking of the Huygens probe is that, although the primary configuration of the Doppler Wind

Experiment was via a relay from the Cassini spacecraft, this back-up method proved to be critical to restoring the experiment. Future probes should schedule ground-based observations whenever possible.

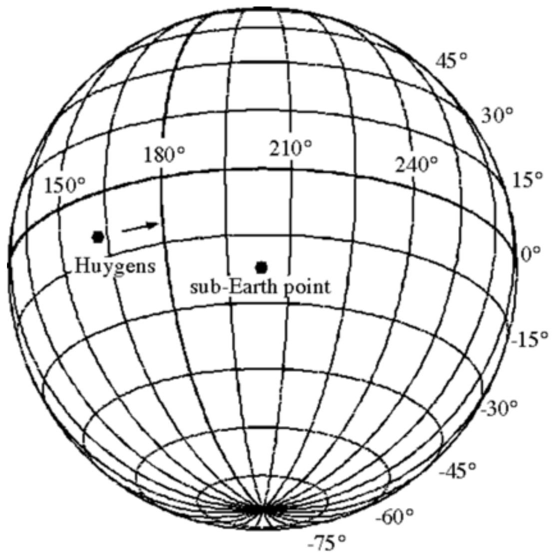

Figure 5: Titan disk as viewed from Earth during the landing of the Huygens probe.

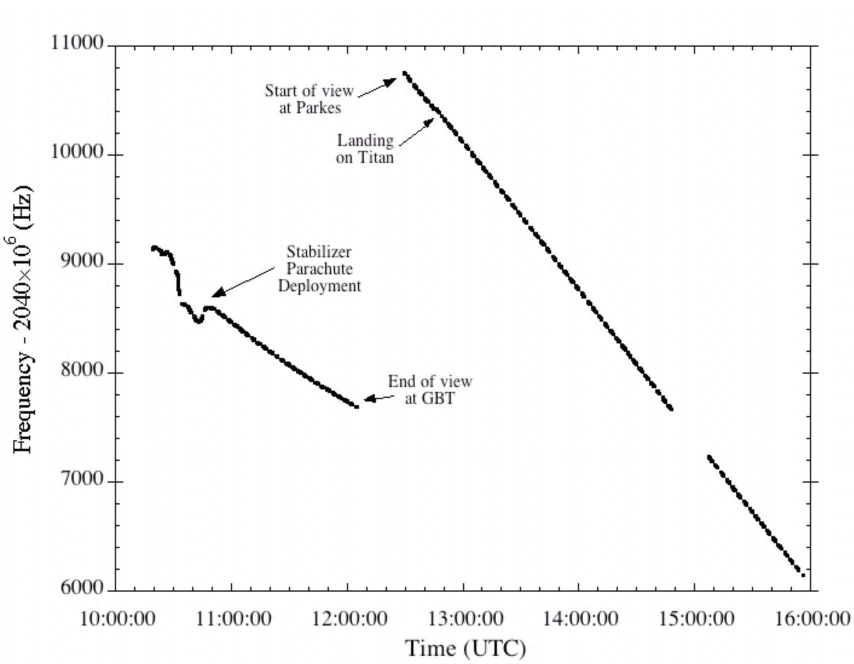

Figure 6: The Huygens Channel A sky frequency received at radio telescopes

IV. Landing on Mars

On 4 July 1997, the Mars Pathfinder spacecraft entered the atmosphere of Mars after a seven-month cruise period. The velocity of the spacecraft, with its progeny of a planetary lander and the Sojourner rover, was approximately 7 kilometers per second relative to the Martian atmosphere at the time of entry. In the ensuing five minutes the spacecraft performed a complex sequence of events to safely decelerate and land at a predetermined destination in the Ares Vallis region of Mars' Northern Hemisphere. After landing, the sequence continued for nearly four hours as the lander employed an automated strategy to right itself, retract the air bags that cushioned its impact, and open its solar-cell-covered petals. It then waited silently for the sun to rise and the Earth to reach a sufficient elevation angle to enable digital communications to stations of the DSN. The Pathfinder spacecraft was not specifically designed to support communications with Earth during EDL. Nevertheless, it was possible to configure the spacecraft and DSN such that "primitive" communications could be maintained through at least part of the EDL period. The communications strategy was purposely kept simple: record the X-band carrier frequency along with *semaphore* signals which could corroborate key events in the lander's arrival and deployment on Mars. The recorded signals would enable flight path reconstruction, confirm sequence execution, and provide crucial data for analyses in case a mishap should occur. All communications during EDL were received solely by the Madrid DSN complex with the 70-meter diameter antenna. Since the lander's signal was dynamic in amplitude, frequency and polarization, recordings were made at both right- and left-hand circular polarizations using an RSR. The receivers were aided with carefully constructed predicts that modeled the descent profile and ephemeris of Mars.

Superimposed on the Pathfinder X-band carrier were *semaphores* confirming the execution of events at key times as the EDL sequence progressed that were implemented using two schemes. Prior to landing semaphores were constructed by switching between two selectable subcarrier frequencies in the spacecraft. Once on the surface, the semaphores were produced simply by turning on and off an un-modulated X-band carrier. Pathfinder's descent sequence presented a unique challenge to recovering its carrier frequency on earth. Not only were large Doppler frequency shifts imposed during braking, but after chute deploy the signal amplitude fluctuated considerably as the spacecraft spun and swung at the end of its tether. Of primary interest was peak deceleration, when the spacecraft slowed from 16000 mph to approximately 500 mph. Due to extreme sensitivity to modeling error, the receiver tuning predicts proved inadequate to maintaining a carrier in band. The task was successful, and the real-time report from the RSR reception declared EDL success to the mission. Figure 7 outlines the EDL events of Pathfinder and Figure 8 shows the resulting radio detection data.

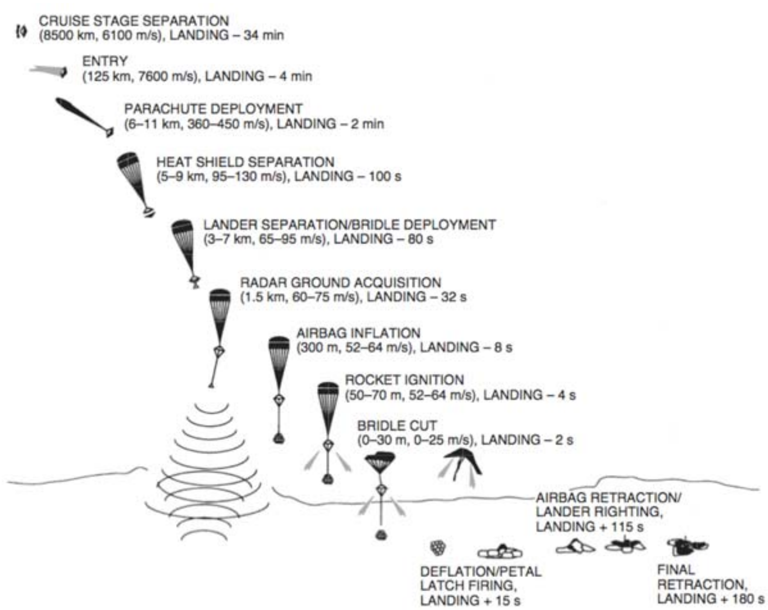

Figure 7: Mars Pathfinder EDL event progression.

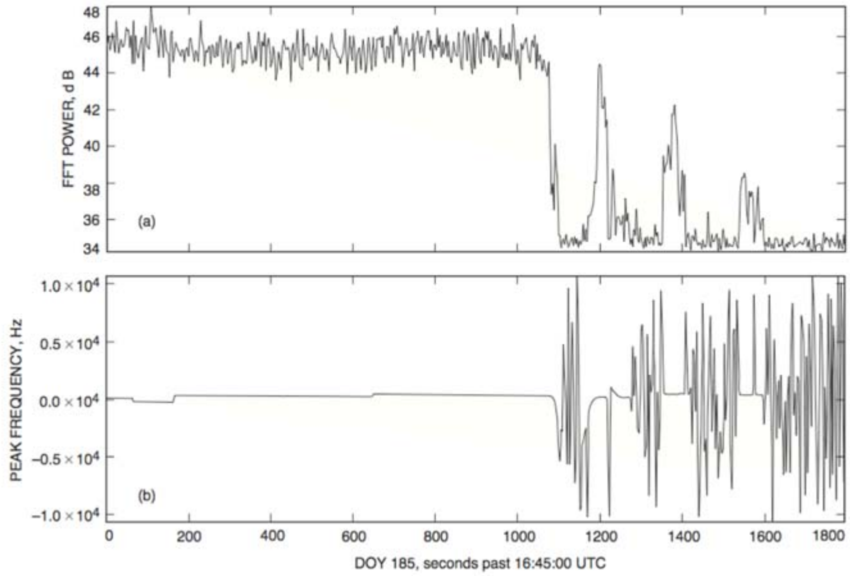

Figure 8: Received Mars Pathfinder EDL static FFT detection results, power and frequency.

The semaphore signaling technique utilized in 1997 was proven to work for both carrier and sideband semaphores. Missions after Mars Pathfinder built on this concept to develop communications tones during EDL. The Mars Exploration Rovers (MER) Spirit and Opportunity, both of which landed in January 2004, benefitted from the experience to date. Again, the low power levels of the communication signals during EDL of the rovers prevented the transmission of telemetry at X-band signal to inform the mission center of the health and progress of the spacecraft. As an alternative, a series of tones were sent to indicate basic spacecraft conditions and execution of critical events. They were acquired by the DSN's RSR assisted by a post-processing real-time computer. Up to 256 different tones were possible. All tones were successfully identified and the carrier was tracked down to the surface for one rover, and through the bouncing on the surface for the second rover.

Four selected RSR recording bandwidths ranged from 4 kHz to 1 MHz in order to account for frequency error tolerances in the predictions and keep sub-carrier tones in the recorded bandwidth. The narrowest band was used to detect the carrier signal up to parachute deploy. At the top of the atmosphere, the friction caused the velocity to drop dramatically and the spacecraft transitioned from speeding up towards Mars to slowing down. The deployment of the parachute caused a 7 kHz fast change in the received signal. Both Spirit and Opportunity rovers behaved well and the signal never went outside a 100 kHz band.

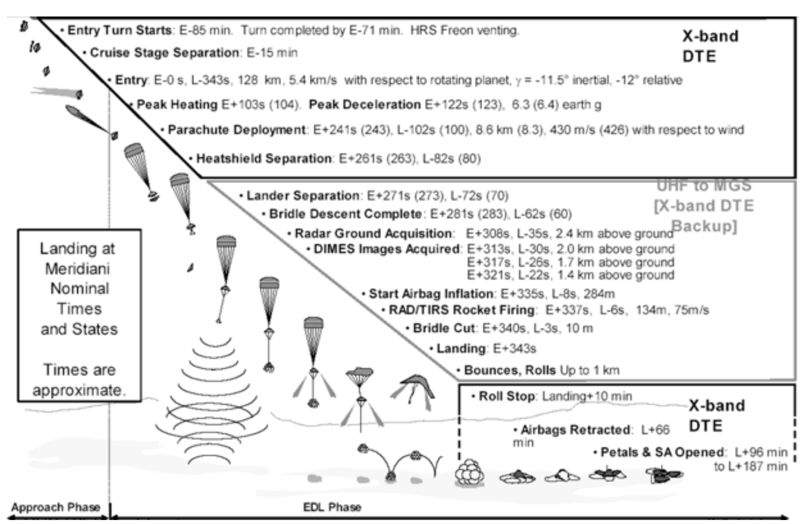

Figure 9: Typical MER EDL sequence of events.

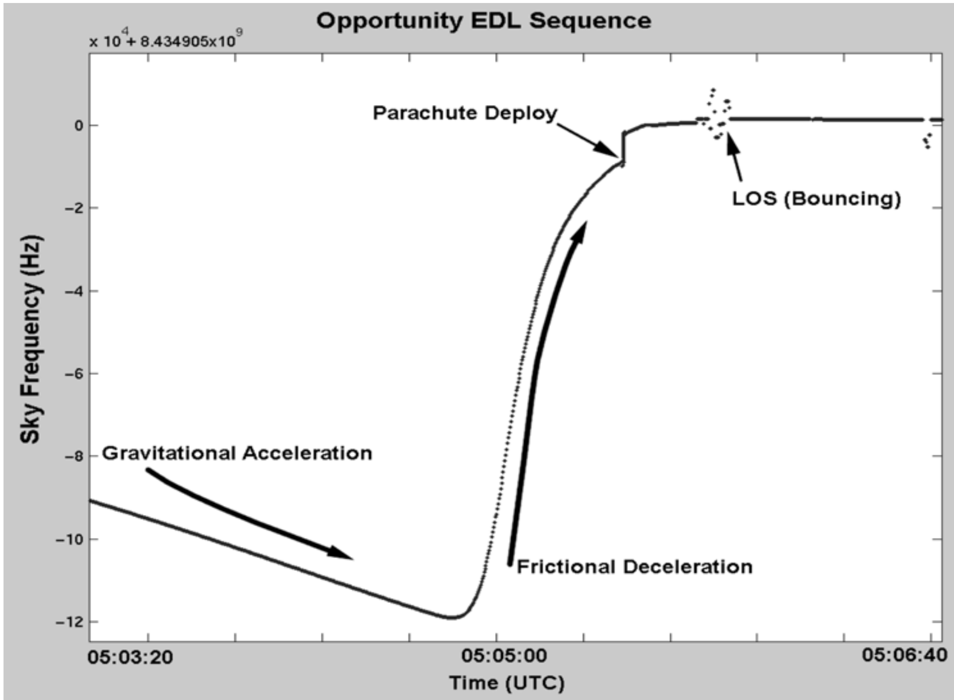

Figure 10: The Opportunity MER EDL sequence resulting signal observations.

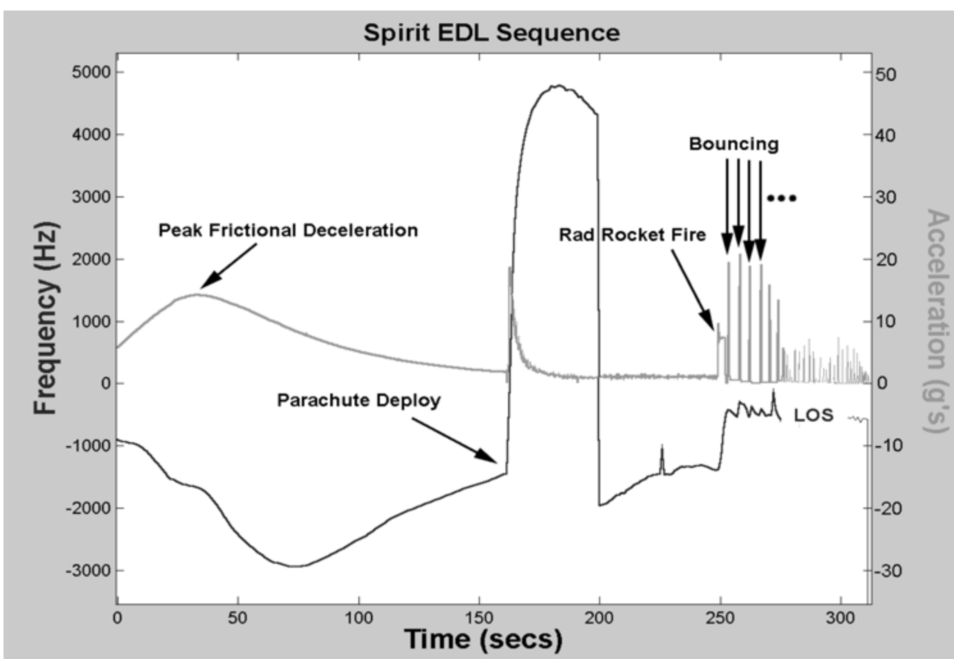

Figure 11: The Spirit MER EDL sequence resulting signal observations.

V. Summary

Mission scenarios where the communication is not favorable during critical maneuvers or emergencies include post launch initial signal acquisition, landing on planetary surfaces, trajectory correction maneuvers, spacecraft safing and other emergencies or serious anomalies. Communication challenges can include suboptimum pointing of the spacecraft antenna, sub-optimum transmission levels, or amplitude/frequency dynamics that prevent the usual receiver lock-up and tracking on the signal and extraction of telemetry. An independent open-loop receiver, designed and optimized for high fidelity Radio Science experiments, is used to support these mission scenarios. In most cases, a reconstructed Doppler profile is sufficient information to be communicated to assess the dynamical behavior and general health and status of the spacecraft. JPL's Radio Science Systems Group developed the tools and operational strategies to conduct this work on behalf of planetary missions. The cases for the Cassini Saturn Orbit Insertion, Huygens and Mars rover landings were described. Other recent examples also included the loss of Mars Observer, the characterization of the early nutation of Ulysses, characterizing the Galileo spacecraft high gain antenna, NEAR asteroid landing, the Phoenix EDL, MESSENGER orbit insertion maneuver, the upcoming Mars Science Laboratory EDL, and virtually all post-launch initial acquisition activities. The power of the described techniques was further expanded with experience from each case. The current Radio Science Receiver and associated tools and experienced science staff provide a critically useful service to space operations.

Appendix A
Acronym List

DSN	Deep Space Network
EDL	Entry Descent and Landing
FFT	Fast Fourier Transform
GBT	Green Bank Telescope
RSR	Radio Science Receiver
RSSG	Radio Science Systems Group
SOI	Saturn Orbit Insertion
USO	Ultra Stable Oscillator

Acknowledgments

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