Radio Science Receiver Support of the Mars Exploration Rover Landings

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ABSTRACT

The low power levels of the communication signals during the Entry Descent and Landing (EDL) sequences of the Mars rovers prevented the transmission of telemetry at X-band signal to inform the mission operations 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. An open-loop receiver designed for Radio Science experiments was used to acquire the signal during this time. The receiver recorded over a 100 Khz bandwidth to identify the presence of the carrier and tones. The data were fed in real-time to a processing unit which detected the carrier and the frequency separation of the tones from the carrier, in order to determine which event has occurred. Up to 256 different tones were possible. During the actual events, all tones were identified, and the carrier was tracked down to the surface, and for the second rover, through the bouncing which followed, and finally, while stopped on the surface, found the carrier and tones which indicated the spacecraft was alive. In order to identify the tones, the ground receivers had to be able to respond to the bevy of events occurring in the relativly short timespan of EDL.

INTRODUCTION

In January 2004, two spacecrafts, the Mars Exploration Rovers (MER), landed on the surface of Mars. As of June 2004, both rovers are functional and have returned a combined amount of data surpassing those returned by any previous Martian lander. Both landers have successfully completed their prime mission and continue collecting data on extended missions. The scientific knowledge gained about the geological history of Mars has been enormous, especially the pursuit of scientific evidence for past presence of water on the Martian surface[1]

The twin Rovers were launched separately in 2003. Spirit took flight on June 10th, and Oppurtunity on July 7th, both from Cape Canaveral, FL to coincide with a time of close relative distance between Mars and Earth. About six months later they arrived at their destination with the second most arduous part of their journey, after launch, being the Entry, Descent and Landing (EDL) process. This phase consists of dropping into the Martian atmosphere, preparing the lander for surface impact, guiding the rover to a few meters above the planetary surface, and finally bouncing prior to resting on the ground. Although the time from atmosphere entry to touchdown lasted only six minutes, this period consisted of the intricate and completely autonomous execution of many one-time-only commands.

Telecom System Overview

The X-band communication system of MER consists of three separate units, seen in Fig. 1. The High Gain Antenna (HGA) is attached to the rover inside of the lander assembly, and is not used until after EDL completes and the rover unfurls itself. The primary communication antenna during cruise and EDL is the three-part waveguide antenna, which transverses from the rover through the lander, through the backshell, and terminates on the cruise stage. During the EDL process, the upper parts of the waveguide, in the cruise stage and backshell, will separate, ultimately leaving a one piece waveguide projecting vertically from the rover. A polarizer present in the cruise stage connects both a low gain antenna (LGA) and a medium gain antenna (MGA). The MGA serves as the primary antenna throughout interplanetary cruise.

A small patch antenna is placed on the bottom of the lander for use in communication shortly after landing, before the airbags are deflated and retracted. This antenna is referred to as the petal low gain antenna (PLGA). The rover is equipped with an auxiliary oscillator (aux osc), for use in generating a 1-way signal. The aux osc is used throughout EDL to provide near real-time communications with Earth.

Radio Science Receiver Overview

NASA's Deep Space Network (DSN) is comprised of three complexes around the globe and each complex contains one 70-meter diameter and at least 2 34-meter stations. Two independent receivers are available at these stations, the tracking receiver and the Radio Science Receiver (RSR). While the tracking receiver locks onto the signal

carrier, the RSR is an open-loop receiver that is tuned via a local oscillator. The latter is driven by a file uploaded to the digital receiver from the Jet Propulsion Laboratory containing the tuning frequencies based on navigation information and prediction of the position and velocity of the spacecraft relative to the specific ground station. Designed for radio science experiments (measurement of typically small changes in the received carrier frequency/phase, amplitude, or polarization due to a propagation medium under study of motion due to planetary gravitational fields) the high stability receiver is typically scheduled to support science experiments and not daily tracking operations. However, the ability to record a frequency spectrum centered around a chosen bandwidth makes the RSR ideal for identification of higly unstable and low power signals, such as the MER signal during EDL. The user-selected bandwidth (choices from 1 kHz to 4 MHz, depending on the mode) determines the sampling rate and, thus, the range of possible error in timing or frequency profile before the signal is not present in the recording bandwidth.

Four bandwidths were recorded for EDL: 4 kHz, 100kHz, 250kHz, and 1MHz. The 100kHz signal is used by a separate piece of hardware developed specifically for MER EDL, the EDL Data Acquisition unit (EDA). The EDA used the information recorded on the RSR in real-time to monitor the carrier and subcarrier signals. The 100kHz bandwidth is the minimum supported bandwidth which could encompass the nominal frequency error tolerances of EDL and still keep the subcarrier tones in the recorded bandwidth, as described later. The larger bandwidths were not monitored in real-time, and would be used if a non-nominal condition (parachute malfunction, etc) occurred during EDL which would cause the downlink signal to drift out of the ± 50 Khz band. The 4kHz band was used only to detect the carrier signal up to parachute deploy. Both Spirit and Opportunity behaved very well, and the signal never went outside of the 100kHz band.

Because of the low signal strength and large frequency accelerations during the EDL procedure, the DSN closed loop receivers, used during all nominal spacecraft operations for collecting telemetry, could not maintain lock. In order to determine basic spacecraft health, safety and state information, a system was devised to send one of 255 sub-carrier tones in addition to the carrier signal [2]. The tones are symmetric about the carrier starting at 5000 Hz and spaced 40 Hz apart. This system is called Multi Frequency Shift Keying (MSFK). The MSFK tones indicated things such as the accelerations the spacecraft is seeing, when the parachute deploys, which petal the lander stopped on, and various fault conditions.

EDL SEQUENCE

Pre-EDL

The telecom system transitions through several stages leading up to the EDL sequence shown in Fig. 2. The spacecraft begins in the nominal cruise configuration, transmitting a 2-way coherent signal from the MGA. The first change to occur takes place one hour and forty-five minutes before Mars atmospheric entry interface (henceforth entry), when the spacecraft transitions from the MGA to the LGA. The ground receivers are reconfigured to look for the one-way signal using right circular polarization (RCP) and the telemetry rate drops to 10 bps. When the aux osc is turned on a warm up transient is observed. Inflight measurements were consistent with preflight testing, observing a frequency increase of approximately 300 Hz over the first fifteen seconds of operation, then a slow decay to steady state. The temperature of the aux osc is stabilized by the Heat Rejection System (HRS). During the interplanetary cruise, the HRS was active to keep the temperature of the spacecraft environment stable. The cyclic behavior of the HRS caused an oscillatory behavior of the aux osc frequency. The period of the HRS cycles tended to be approximately six minutes in duration.

The next effect seen is caused by an attitude turn of the spacecraft. The cruise stage LGA of the spin-stabilized craft resides off of the center of rotation, and therefore the 2 RPM spin signature is easily seen in the downlink signal. Several effects can be seen in Fig 2. The first order effect is the drift of the aux osc, causing the mean frequency to move from 170 Hz at 03:20, to a peak of 185 Hz at 03:36, then back down to 180 Hz by 03:45. The second order effect is the cycling of the HRS, evidenced by the 6 minute, 12 Hz peak-to-peak oscillations. The third order effect is the spacecraft spin Doppler. The period captured in Fig. 2 is during the turn to entry, and the increase in Doppler due the the off axis turn can be seen. After turn to entry, the peak-to-peak variation is 3.3 Hz, at two RPMs.

Before entering the Martian atmosphere, the HRS is disabled. Without the temperature control provided by the HRS, the temperature of the aux osc rises from the inflight temperature of approximately 0° C. Fig. 5 shows the expected frequency behavior of the aux osc when warmed. A 2 kHz rise was expected from 0° C up to 8° C, followed by a 7 kHz drop before landing as the temperature reaches 25° C.

Fifteen minutes before entry the cruise stage is jettisoned from the landing package. The firing of the pyros imparted a force on the lander. Seen in Fig. 3, a 10 Hz Doppler shift was seen in the received signal. The two second signal outage is caused by the discarded cruise stage blocking the downlink signal path, on its way to burning up in the Mars atmosphere.

Entry and Descent

The spacecraft is now prepared to undertake EDL. The beginning of the sequence is rather benign, hitting the top of the Martian atmosphere. Soon however, the friction causes the velocity to drop dramatically, and the spacecraft transitions from speeding up towards Mars to slowing down, as seen in Fig. 6. The deployment of the parachute causes an almost instantaneous 7 kHz jump in the received signal. Fig 6, from MER-B, shows parachute deploy at 05:04:08 followed by ignition of the rad rockets at 05:05:31. Seven seconds later the signal is temporarily lost as the craft begins bouncing on the surface. The MER-B craft came to rest by 05:06:09.Fig 7 shows the relative frequency shifts as compared to acceleration data recorded on board the craft and transmitted via UHF to MGS.

Telecom Parameters

A 100kHz bandwidth used to monitor the MER signal during EDL. This bandwidth encapsulates the magnitudes of all the expected frequency error sources. The first source of error is the instability of the aux osc. The drift of the aux osc was given a 1kHz error allotment. The next source of error again deals with the aux osc, is the temperature dependent frequency, and was given a 10kHz error allotment. Next is the trajectory uncertainty. Even small differences in the flight path angle (FPA) or atmospheric densities could cause considerable deviations in the received frequency.

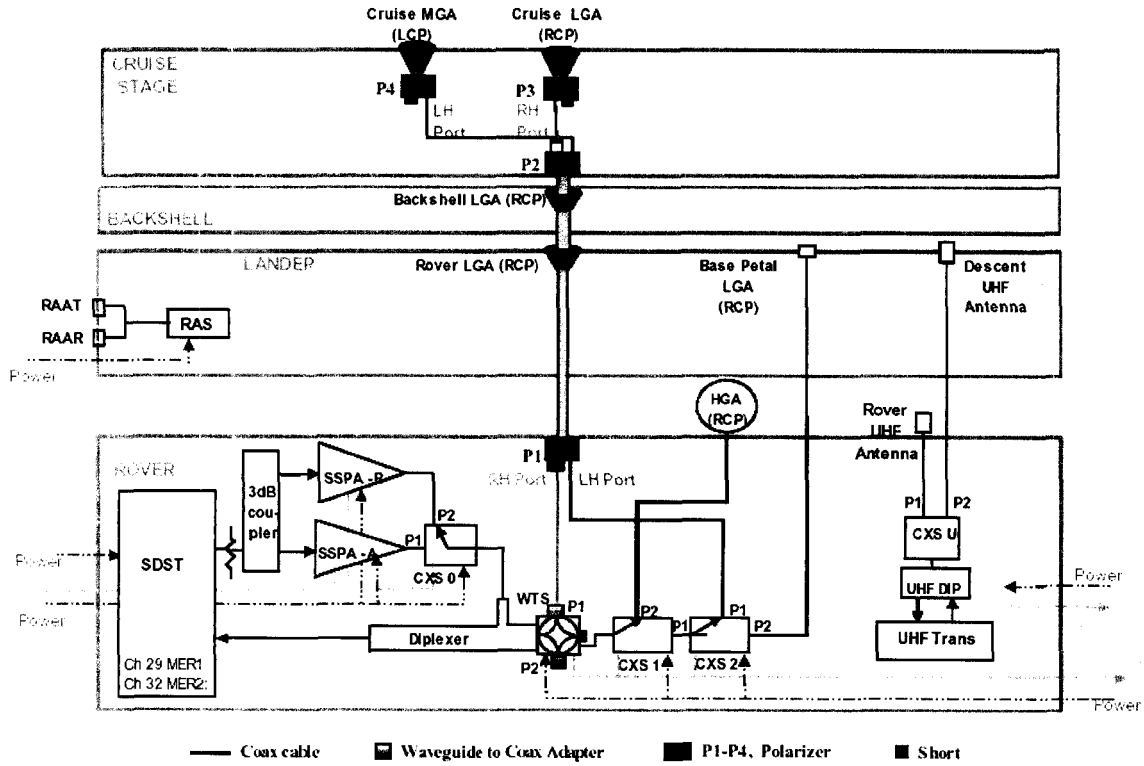

Figure 1: MER telecom system block diagram.

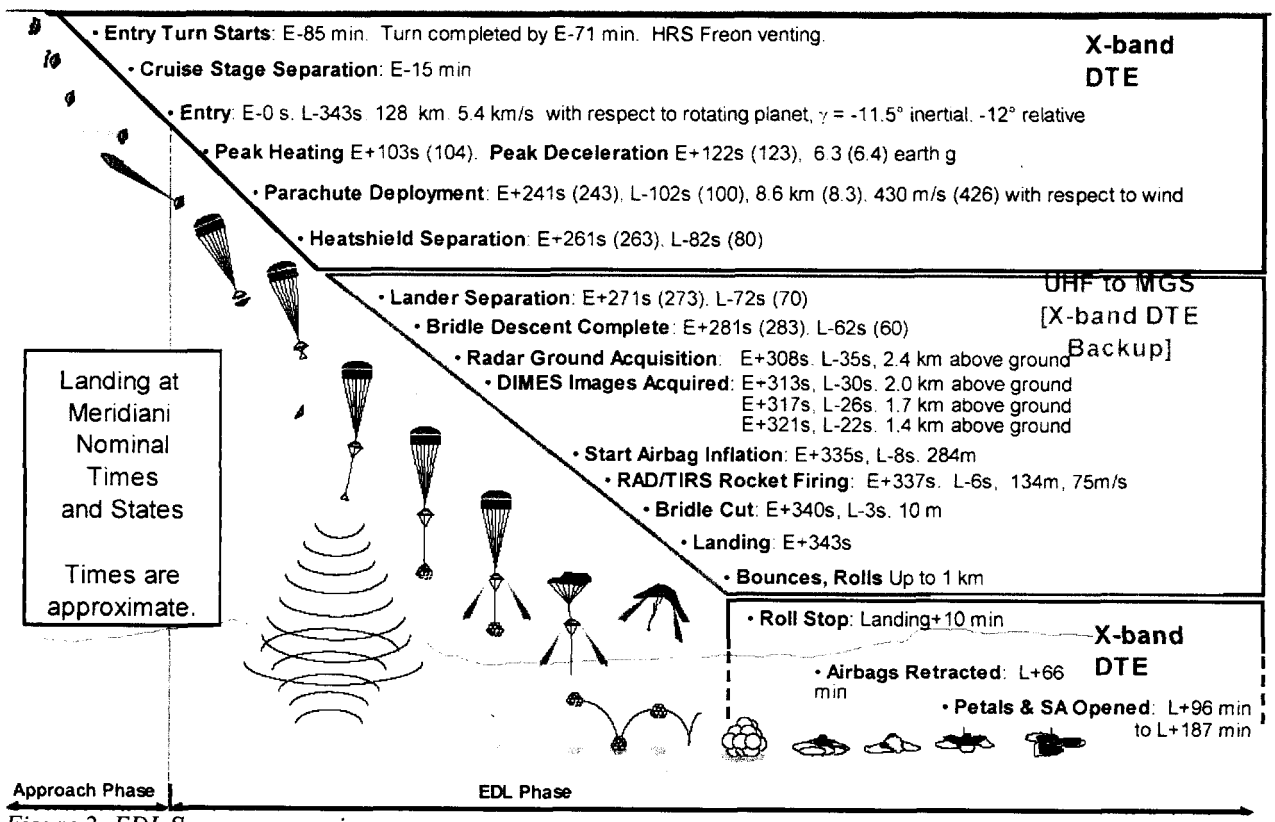

Figure 2: EDL Sequence overview

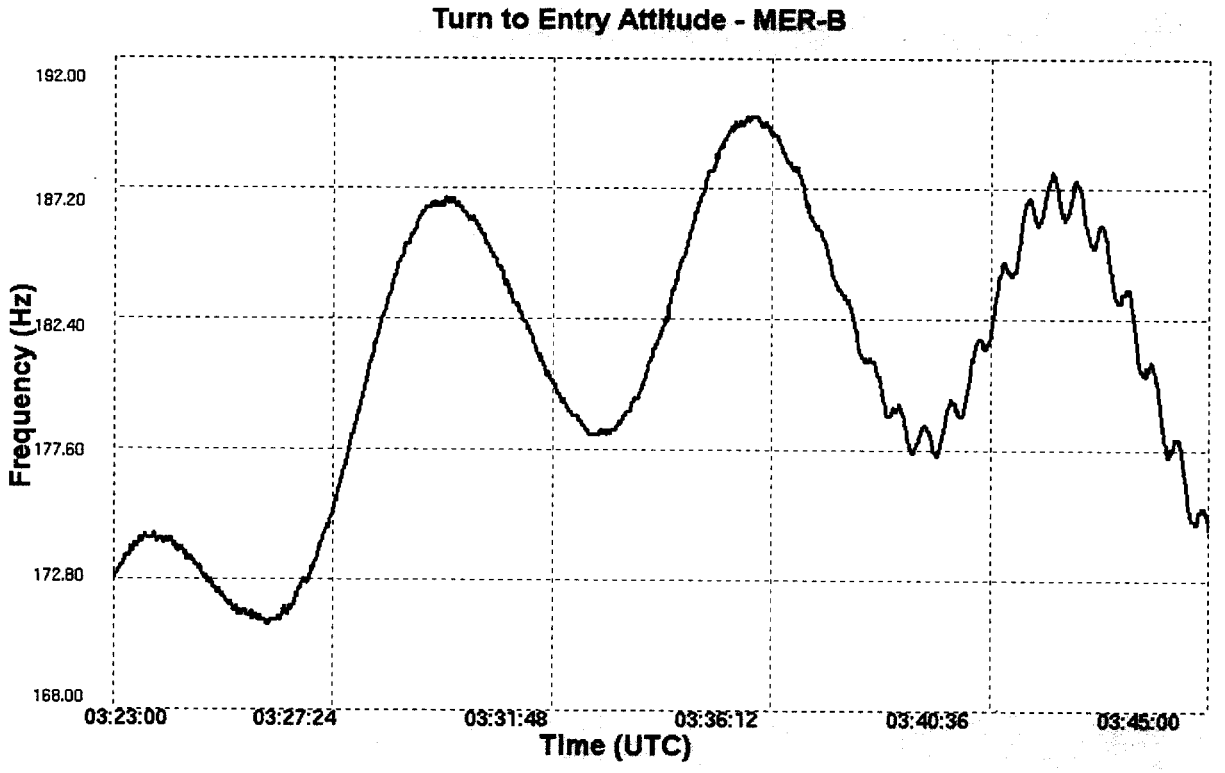

Figure 3: As the MER spacecraft turns to face the entry attitude, the Doppler shift caused by the rotating antenna becomes more apparent.

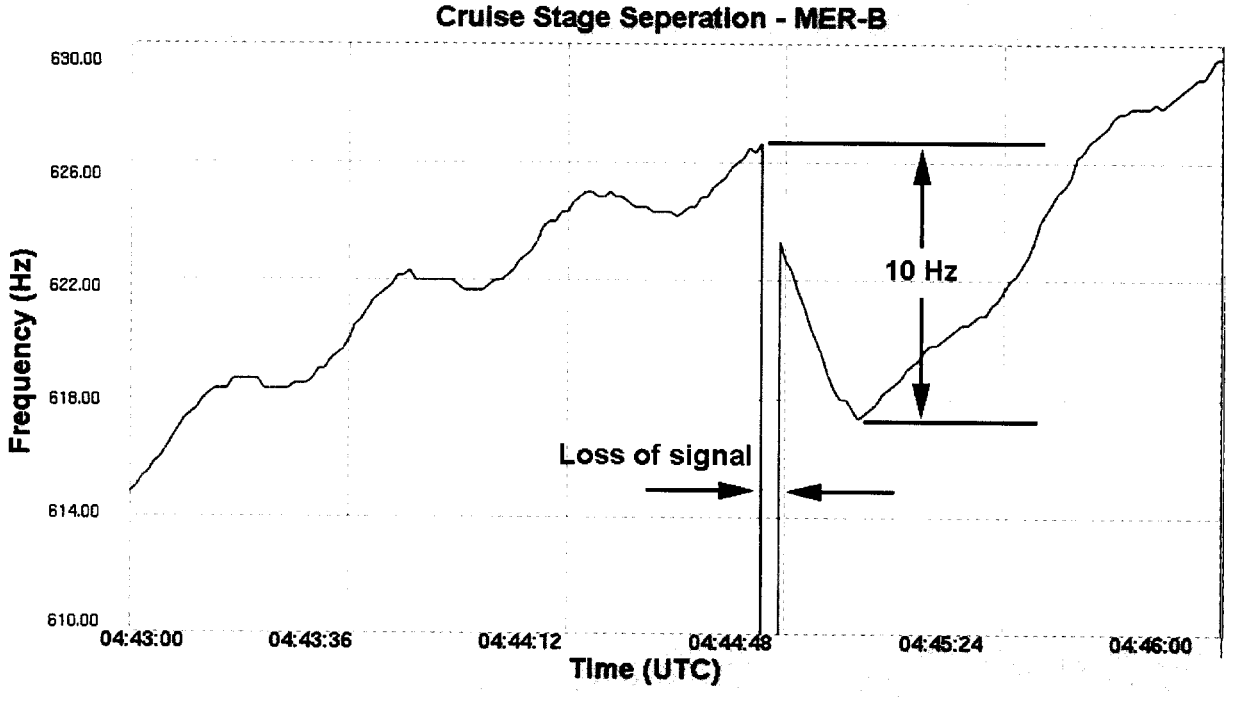

Figure 4: When the Cruise Stage separates from the Landing Package a small force is imparted on the Lander, and the ejected shell briefly blocks the signal path.

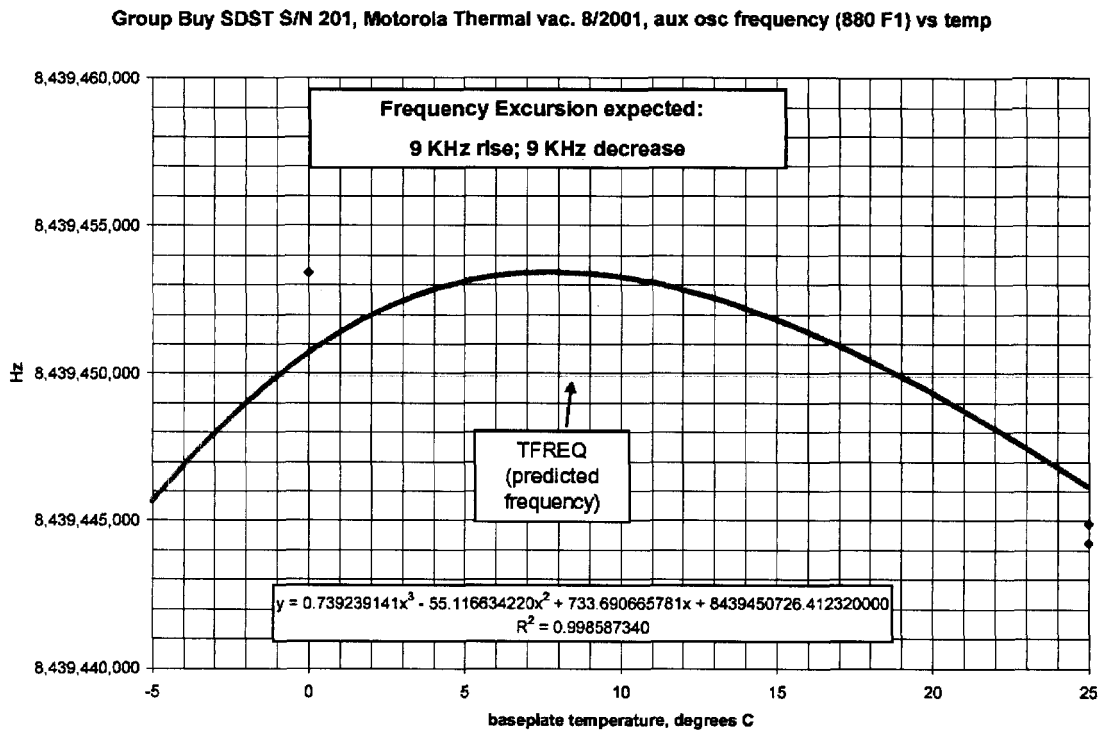

Figure 5: Behavior of Aux Osc Frequency vs. Temperature

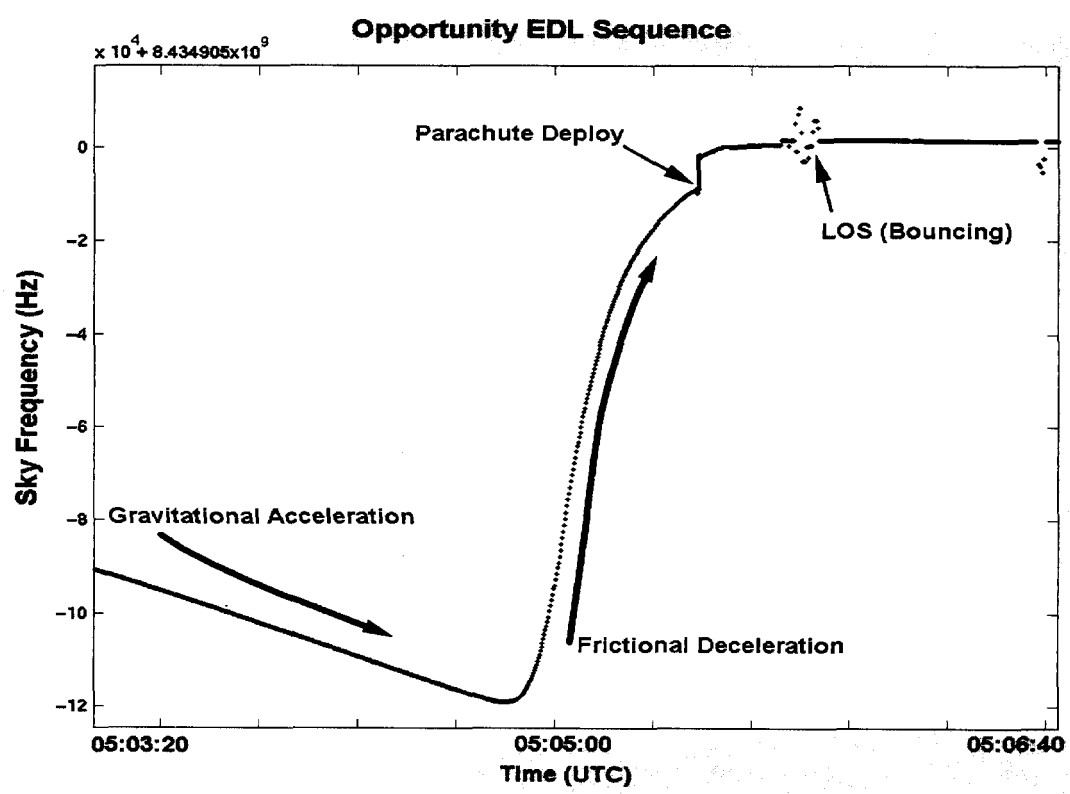

Figure 6: After entering the Martian atmosphere, the frictional drag begins to overtake the gravitational pull. Once slowed sufficiently, the parachute is opened, rad rockets fired, and landing takes place.

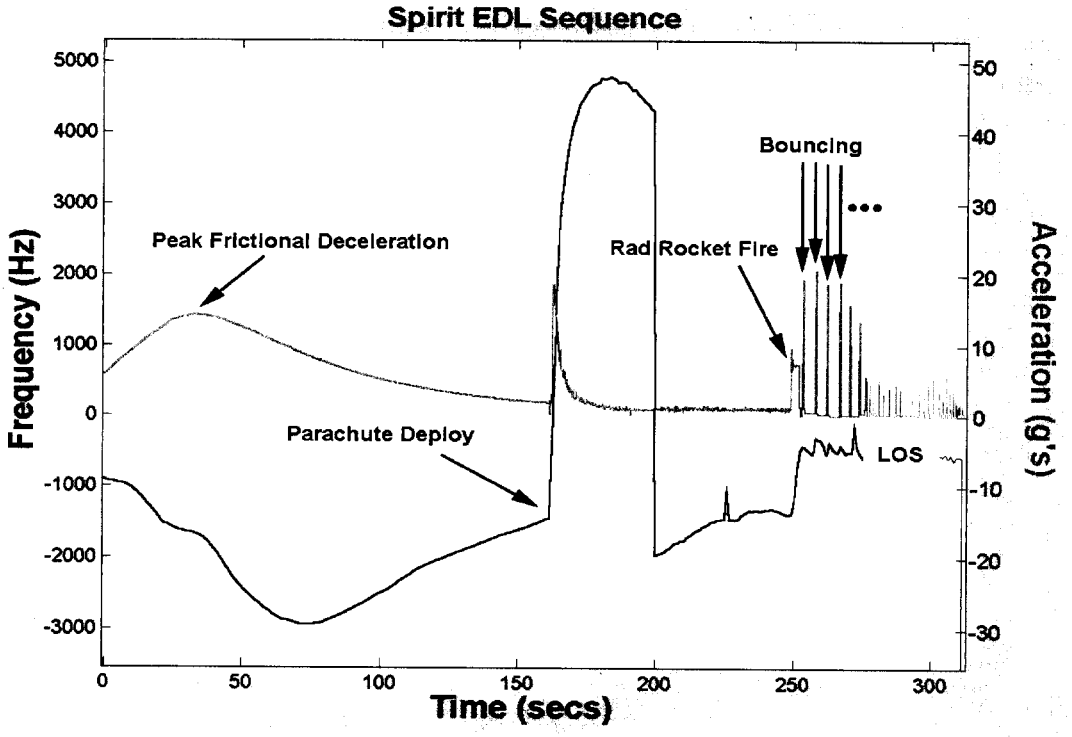

Figure 7: The large accelerations occurring during the EDL sequence causes rapid frequency changes. These quick changes in frequency combined with low power levels makes signal tracking difficult.

References:
[1] http://mars.jpl.nasa.gov/mer
[2] E. Satorius, P. Estabrook, J. Wilson, D. Fort, IPN Progress Report 42-153

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