Sleuthing the MSL EDL Performance from an X band Carrier Perspective

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Abstract – **During the Entry, Descent, and Landing (EDL) of NASA's Mars Science Laboratory (MSL), or Curiosity, rover to Gale Crater on Mars on August 6, 2012 UTC, the rover transmitted an X-band signal composed of carrier and tone frequencies and a UHF signal modulated with an 8kbps data stream. During EDL, the spacecraft's orientation is determined by its guidance and mechanical subsystems to ensure that the vehicle land safely at its destination. Although orientation to maximize telecom performance is not possible, antennas are especially designed and mounted to provide the best possible line of sight to Earth and to the Mars orbiters supporting MSL's landing. The tones and data transmitted over these links are selected carefully to reflect the most essential parameters of the vehicle's state and the performance of the EDL subsystems for post-EDL reconstruction should no further data transmission from the vehicle be possible. This paper addresses the configuration of the X band receive system used at NASA / JPL's Deep Space Network (DSN) to capture the signal spectrum of MSL's X band carrier and tone signal, examines the MSL vehicle state information obtained from the X band carrier signal only and contrasts the Doppler-derived information against the post-EDL known vehicle state.**

The paper begins with a description of the MSL EDL sequence of events and discusses the impact of the EDL maneuvers such as guided entry, parachute deploy, and powered descent on the frequency observables expected at the DSN. The range of Doppler dynamics possible is derived from extensive 6 Degrees-Of-Freedom (6 DOF) vehicle state calculations performed by MSL's EDL simulation team. The configuration of the DSN's receive system, using the Radio Science Receivers (RSR) to perform open-loop recording for both for nominal and off-nominal EDL scenarios, is detailed. Expected signal carrier power-to-noise levels during EDL are shown and their impact on signal detection is considered. Particular attention is given to the selection of the appropriate RSR processing bandwidths and to its configuration for real-time signal detection. The X-band carrier frequency obtained through post-processing of the open-loop recorded spectrum is given. Detection of spacecraft status and completion of key vehicle events through their Doppler signature is discussed and illustrated. This Doppler-derived information is compared against the very accurate vehicle data obtained post-EDL via MSL's UHF radio subsystem. The paper concludes with a discussion on the advantages and disadvantages of transmitting the X-band carrier and tone signal in the general context of EDL communications and lessons learned for future missions with EDL sequences are given.

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1. INTRODUCTION

Spacecraft designers and mission operators often cite the Entry, Descent and Landing phase of each Mars mission as the most challenging and tense mission phase. During these few minutes, the vehicle autonomously executes hundreds of events, shedding its cruise stage, deploying its parachute, ejecting its heat shield, computing the distance to the surface and lowering the lander/ rover for final landing on the planet. Depending on the mission design and distance between Earth and Mars, the one-way signal

latency can vary from 4 to 20 minutes, thus ensuring that all events must be carried out without intervention from the flight operations team. Only essential subsystems related to vehicle survival during EDL are operated so that the avionics can be focused on rapidly acquiring sensor data and performing the required computations to trigger each event precisely. Ensuring data flow to Earth or adjusting the vehicle's attitude to maximize data return may only decrease mission success. Yet acquiring vehicle status information is critical to understanding the performance of the complex EDL system, and in the advent of a failure, this data may only be obtained during EDL.

The Mars Pathfinder (MPF) Mission was the first NASA mission to attempt to use the X-band communication subsystem to reconstruct the performance of the spacecraft during EDL [1]. The concept was simple. On July 4th, 1997, during EDL, no attempt to control the spacecraft attitude to Earth for the benefit of the communication signal was undertaken. Instead an unmodulated carrier signal was transmitted from the ~15W Solid State amplifier; this was recorded and processed in near-real time at the only Deep Space Network Complex in the line-of-sight to MPF to determine its Doppler. From the Doppler signature, the spacecraft motion and status in the EDL sequence was determined. In addition, at three critical moments, a second signal at a subcarrier frequency of 22.5 KHz or 375 KHz was transmitted in order to signal heat shield release, full extension of the bridle separating the lander from the parachute, and when the lander was determined by the vehicle's radar to be 600 meters above the surface. Once on the surface, the carrier was turned on and off to indicate progress in the lander's deployment. At the DSN, a Full Spectrum Recorder (FSR) was used to record the received signal and simple FFTs were used to detect the carrier signal and the semaphores in real time. For MPF, the carrier was able to be detected at times during EDL but no semaphores were able to be detected in real time. This innovative scheme, designed by Gordon Wood et al., allowed mission operators to determine that the spacecraft was still functioning during key moments as it descended onto the Martian surface. Post EDL data processing permitted tracking of the carrier throughout much of EDL and recovery of one of the three semaphores, thus confirming the power of this technique.

The Mars Exploration Rovers Spirit and Opportunity, landing on 1/4/2004 and 1/26/2004, respectively, build upon the MPF signaling scheme. Using a newer version of the FSR called the Radio Science Receivers [2] and dedicated real-time data processing hardware, the EDL Data Analysis equipment [3], the mission operations team was able to receive in real-time the carrier signal and semaphores transmitted every 10 sec representing the specific spacecraft state. In addition, the MERs successfully transmitted 8 Kbps digital data to the Mars Global Surveyor and Mars Odyssey orbiters. [4]

This paper describes the Mars Science Laboratory X-band signaling scheme, built upon the successful MPF and MER schemes, and focuses on how detection of this signal allowed the mission operators to confirm MSL's status in real-time and via post processing.

2. MSL System Overview

Although orientation to maximize telecom performance is not possible, antennas are especially designed and mounted to provide the best possible line of sight to Earth and to the Mars orbiters supporting MSL's landing. The tones and data transmitted over these links are selected carefully to reflect the most essential parameters of the vehicle's state and the performance of the EDL subsystems for post-EDL reconstruction should no further data transmission from the vehicle be possible.

X-Band Telecom Subsystem Overview

This article deals only with the reception of X-Band signals via the RSR. Although UHF played a critical role in EDL and permitted reception of signals from the rover through successful touchdown, the role of the UHF subsystem in EDL is outside the scope of this article.

Much of the Telecom subsystem description provided here is taken directly from [6] and readers are referred to that article for details. Only EDL-revelant X-Band subsystem information is presented here. Figure 1 is a block diagram of the X-Band Telecom subsystem, and Table 1 describes some of the terms used in Figure 1.

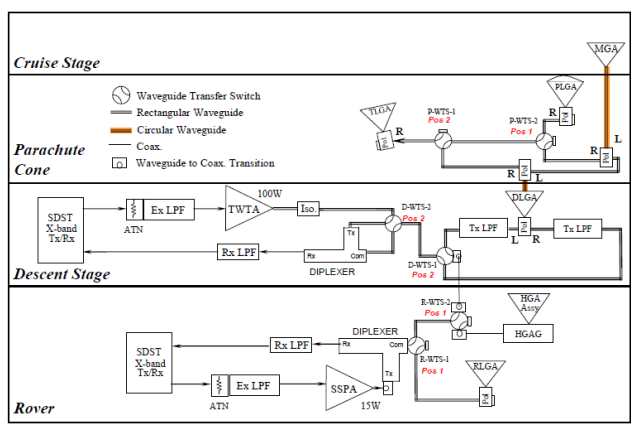

Figure 1 – The MSL X-Band Telecom Subsystem

Table 1. Terms used in Figure 1: the X-Band Block Diagram

Term	Definition	Term	Definition	Term	Definition
Assy	Assembly	L	Left circular polarization	RLGA	Rover low gain antenna
ATN	Attenuator	LPF	Low pass filter	SDST	Small deep space transponder
Com	Common	MGA	Medium gain antenna	SSPA	Solid state power amplifier
D-	Descent	Pol	Polarizer	TLGA	Tilted low gain antenna
Ex	Exciter	P-	Parachute	TWTA	Traveling wave tube amplifier
HGA	High gain antenna	R-	Rover	Tx	Transmit
HGA G	High gain antenna gimbal	R	Right circular polarization	W	Watt
Iso	Isolator	Rx	Receive	WTS	Waveguide transfer switch

During EDL:

(1) Three antennas were used: the PLGA, the TLGA, and the DLGA.

(2) Link margins were not sufficient to support even 10 bps telemetry, and tones were chosen for this reason.

(3) Descent stage X-Band components were used for X-Band tones during EDL. In particular, the descent stage SDST was the X-Band transponder and the TWTA in the descent stage was the power amplifier.

(4) The key stages of EDL are shown in Figures 2 through 4 inclusive. These provide a pictorial narrative of EDL

(5) Complementing Figures 2 through 4 is Figure 5. This shows key Telecom events during EDL, including the key X-Band events that are the focus of this document

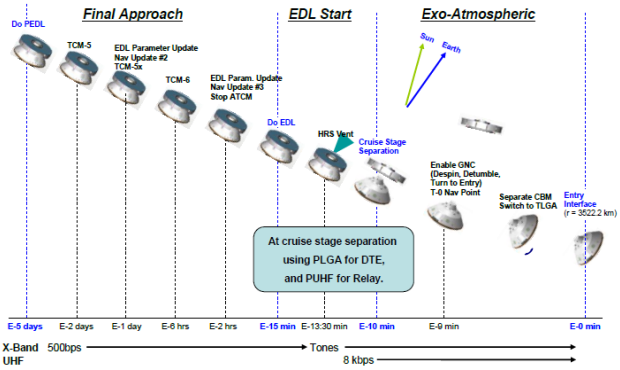

Figure 2 – Timeline: Cruise stage separation to entry interface

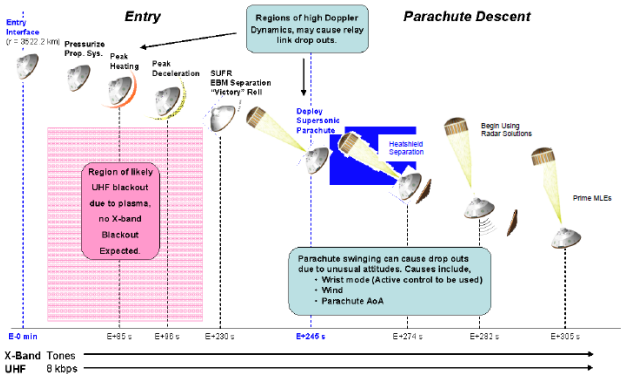

Figure 3 – EDL timeline: entry interface to backshell

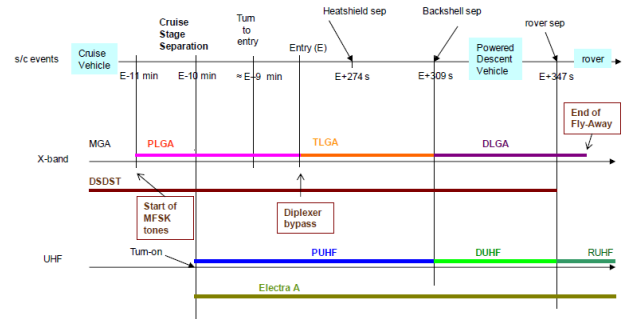

Figure 4 – Telecom events and antenna usage during EDL. The letter "E" denotes atmospheric entry

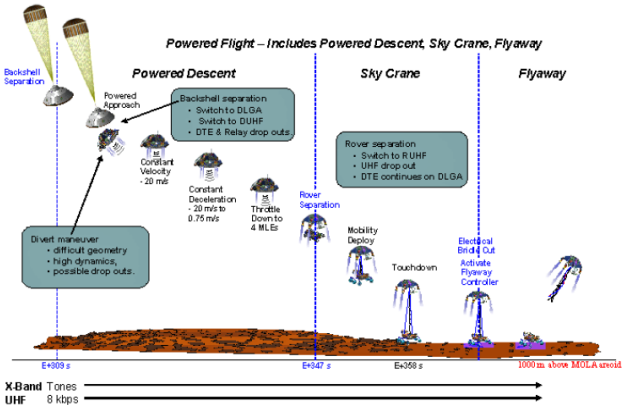

Figure 5 – EDL timeline: backshell separation to fly-away

Due to occultation during EDL, X-Band communications were expected to be lost with Earth setting below the horizon as seen from the spacecraft during EDL. Indeed, as anticipated, communications were lost due to Earth set at E+299 seconds where E denotes atmospheric entry.

Since two-way coherent communications, in which the spacecraft transponder (SDST) uses an uplink signal from

Earth as a frequency reference and in which the downlink signal is fully coherent with the uplink, could not be maintained reliably under EDL conditions, X-Band signals during EDL were transmitted with the SDST set to 1-way mode using its internal auxiliary crystal oscillator (AUX OSC) as the downlink frequency reference. The implications of AUX OSC usage are discussed in Section 4.

During EDL, cruise stage separation occurred as planned, resulting in the loss of the MGA used through much of the later part of cruise. The PLGA was thus used during the earlier portions of EDL to send tones. However, during the banking maneuvers, the TLGA provided a better angle to Earth than the PLGA could have, and the TLGA was thus selected 20 seconds prior to atmospheric entry. Finally, once the backshell separated, the TLGA and the PLGA were both lost, resulting in the use of the descent stage LGA (DLGA). However, backshell separation occurred after Earth occultation, as expected, which means that none of the tones radiated via the DLGA could be received on Earth.

Since components in the parachute cone and descent stage were chiefly used during EDL, the rover stage X-Band components were not used. Moreover, since the descent stage SDST and TWTA were both used, radiated power (via the 100 watt TWTA) was far greater than what could have been achieved using the 15-watt SSPA. Moreover, the TLGA provided a better Earth view angle during tones radiation (the portions viewable prior to Earth occultation) than could have been achieved using the PLGA. These are just some of the improvements over MER EDL.

MER EDL X-Band Comparison

The MER X-Band subsystem and EDL information, based on [7], are presented for comparison purposes. The Telecom subsystem diagram for MER is shown in Figure 6, and a pictorial representation of MER EDL events is shown in Figure 7.

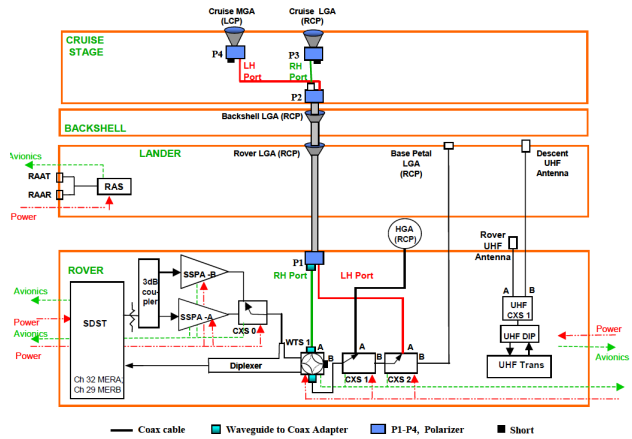

Figure 6 – MER Telecom Subsystem

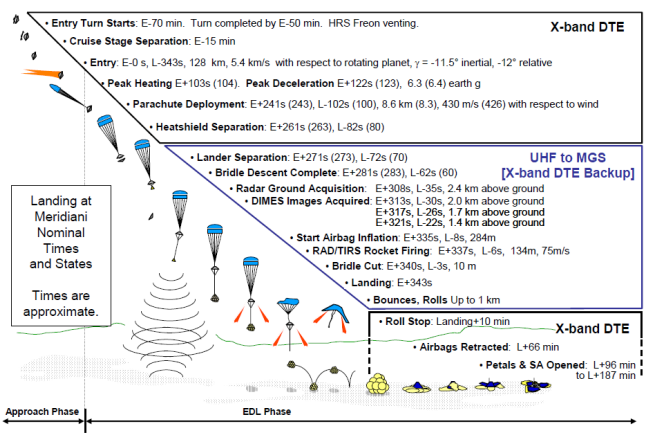

Figure 7 – Pictorial representation of MER EDL events

There are several differences between MSL and MER EDL. Note that UHF usage is outside the scope of this paper.

(1) MER relied entirely on the SDST and the SSPA (prime SSPA) in the rover.

   a. Hence, only the rover's SDST was used, as no descent stage SDST existed.

   b. The SSPA was limited to 15 watts. There was no 100 watt TWTA as with MSL's descent stage Telecom subsystem.

(2) MER had a different set of antennas.

a. Cruise LGA (CLGA).

b. Backshell LGA (BLGA).

c. Petal LGA (PLGA).

d. Rover LGA (RLGA).

(3) MER also used its antennas differently

a. The CLGA, BLGA, and RLGA were all mounted on the same circular waveguide "stack". During the course of EDL, as stages separated, portions of the stack "broke off" as planned. For example, the CLGA was lost with cruise stage separation, leaving the BLGA behind. Separation of the rover on the bridle during EDL and bridle cut left the rover with only the RLGA and the PLGA.

b. In MSL, the descent stage X-Band components were used for tone, and the descent stage flew away and crashed as planned. The descent stage would have taken the DLGA with it. Rover stage components were not used for tones. In MER X-Band signals continued to be sent from the rover and from the RLGA and the PLGA post-landing [7], and since there was no separate X-Band transponder or power amplifier outside of the rover itself, rover stage components were the only ones available!

(4) The operations scenarios differed:

a. In MSL's case, Earth occultation occurred prior to going to the DLGA so no tones sent via the DLGA could be received.

b. In MER's case, X-Band signals continued to be seen on Earth well after safe, successful landing for both rovers.

3. DSN System Overview

The Deep Space Network of NASA is comprised of three antenna complexes around the world. Each complex contains one antenna that is 70 meters in diameter and at least two antennas that are 34 meters in diameter. The stations have two types of tracking receivers, one of which locks onto the carrier signal in a "closed-loop" fashion and is known as the Block-V receiver. The second type of receiver, known as "open-loop," does not lock onto a signal but rather is tuned by pre-determined frequency predictions and records a certain segment of the electromagnetic spectrum which is then down-converted to an intermediate frequency centered about that prediction. These open-loop receivers, also known as radio science receivers (RSRs), are typically used for radio science experiments, but their ability to record a frequency spectrum without needing to lock onto a signal makes them ideal for activities involving signals that are weak or which may have sudden, unpredictable Doppler shifts. The entry and descent of the Curiosity rover is one example of such a case. The RSRs are controlled remotely from the Radio Science Operations computers (RSOPS) at JPL.

The Canberra Deep Space Communications Complex tracked Curiosity during its final approach and descent. In particular, the 70-meter station, DSS 43, tracked Curiosity, and the RSR was configured to record the signal acquired at this station. A spacecraft trajectory was generated by the Curiosity navigation team to account for the Doppler shift between Curiosity and DSS 43. Slowing of the spacecraft due to the Martian atmosphere was included in this trajectory, but the deployment of Curiosity's parachute was deliberately excluded since the timing of that event could not be reliably predicted. This trajectory was used by the DSN to calculate a frequency prediction for the event. With parachute deployment left out from the frequency prediction, this event would stand out in the Doppler profile in real time during the event.

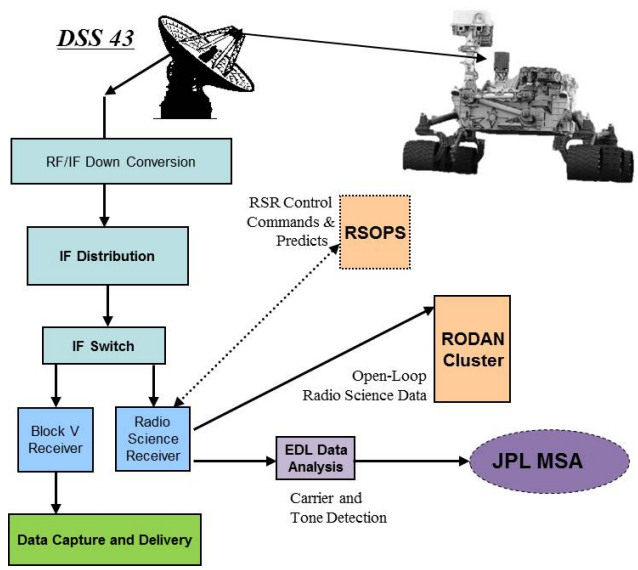

Figure 8 – MSL Radio Science Receiver Data Flow

Several different bandwidths were configured on the RSR for recording of the signal. The primary channel was configured with a 100-KHz bandwidth, and the data were passed in real time to a separate piece of hardware known as the Entry Descent Assembly (EDA). As was done for the twin MER rovers in 2004, the EDA detected a number of tones within the bandwidth that were used to identify various events occurring on the spacecraft, and the

succession of these events was displayed in real time in the JPL Mission Support Area (MSA). While the primary method of communication from Curiosity to Earth was via UHF link to the Mars 2001 Odyssey orbiter, the EDA would provide another source of information until the point at which the spacecraft was geometrically occulted by Mars. The tones were to occur within a 20 KHz range, but another 20 KHz on either side were added to account for uncertainty regarding the frequency drift of the spacecraft's Auxiliary Oscillator caused by temperature variation. The closest available setting on the RSR to account for this range was 100 KHz.

Several other bandwidths were configured, including a 1-MHz setting as a "fallback" in case of any unforeseen Doppler shifts. Narrower channels were recorded as well, including 8, 16, 25, and 50 KHz. When possible, narrower bandwidths are used because weaker signals tend to be easier to detect due to less noise. Also, a smaller data volume facilitates post-processing. The sum of the Doppler shift induced by temperature variation and successful parachute deployment ultimately totaled around 12 KHz, too close to the edge of the 25-KHz bandwidth, and outside that tracked by the 8- or 16-KHz bandwidths. Therefore, the 50-KHz data are primarily shown in this paper. All data were transferred from the RSR to the Radio Occultation Data Analysis Network (RODAN) at JPL for archival..

Ground System Support

Due to differences in Earth-Mars geometry during MSL EDL and during MER EDL, MSL had only single DSN complex support via the Canberra complex. This was the only DSN station in view during MSL EDL. By contrast, MER had dual complex support. A failure of one 70-meter antenna could have been compensated by the 70-meter antenna at the other complex. Also, MSL EDL suffered from a partial Earth occultation (Earth setting in the Martian sky as seen by the MSL spacecraft during EDL) that MER did not encountered, so X-Band tones could not be used to verify a successful landing. Rather, successful landing was verified by means of UHF relay via the Odyssey orbiter and by the camera images sent back from the surface as a part of this UHF relay, which is out of the scope of this paper.

4. EXPECTED EDL PERFORMANCE

Use of One-Way Downlink Mode

As stated previously, the free-running AUX OSC crystal oscillator was used for MSL as well as for MER EDL. This, combined with high Doppler dynamics during EDL, presented a number of challenges. Cuise temperatures remained quasi-steady, with changes occurring very slowly. This made AUX OSC frequency quite predictable. For this reason, MSL Telecom had taken a time series of AUX OSC frequencies versus temperature during the course of cruise in order to derive AUX OSC frequency as a function of temperature.

Since the Radio Science Receiver (RSR) has a bandwidth of +/- 50 kHz (100 kHz in all), there was a challenge during EDL. High Doppler dynamics caused large frequency variations, and temperature changes to the non-temperature-compensated AUX OSC crystal oscillator would both result in significant variations in downlink frequency. Hence, RSR bandwidth had to be wide enough to accommodate:

(1) Large and rapid frequency changes due to Doppler dynamics.

(2) The tones bandwidth of +/- 20 kHz, since subcarrier tones ranged in frequency up to 20 kHz.

(3) Changes in AUX OSC output frequency due to temperature changes during EDL.

MSL Telecom had determined, on the basis of AUX OSC output frequency during cruise that the AUX OSC would likely undergo an increase in output frequency of as much as 9 kHz if temperatures were to rise from approximately -2.5 deg C (cruise nominal value close to EDL) up to about +15 deg C. This was based upon data taken in cruise shown in Figure 8.

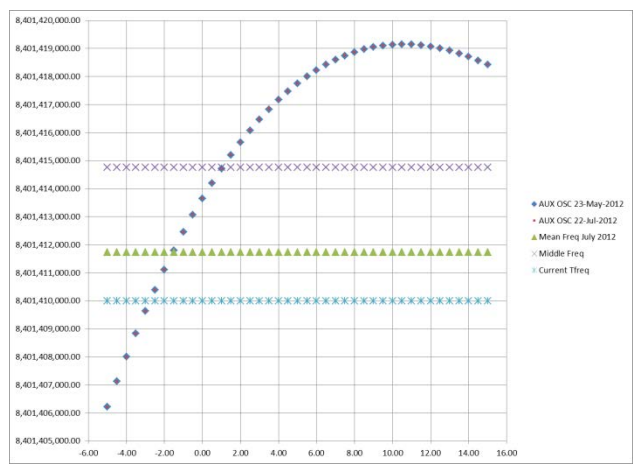

Figure 9 – Polynomial best fit to cruise AUX OSC data from descent stage SDST

Actual temperature versus time data are shown in Figure 9 below. Here, we note that the baseplate temperature used in Figure 8 rose quite sharply compared to AUX OSC and VCO temperature measurements, which indicates the SDST itself was not in thermal equilibrium during EDL. As a consequence, the actual frequency variation appeared to be

less than what we anticipated based on baseplate temperature predictions

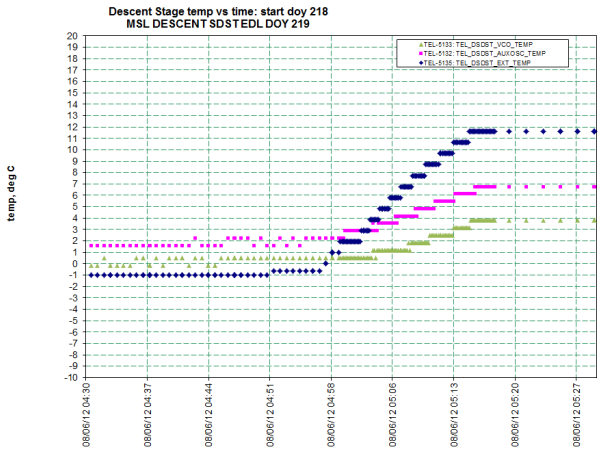

Figure 10 – SDST temperatures during EDL.

Note that baseplate temperature rises much more rapidly than internal AUX OSC and VCO temperatures, indicating no thermal equilibrium during EDL

Since the actual EDL temperature variation was from -1.0 deg C to almost +12 deg C measured at the SDST mounting plate, one would expect a nearly +7 kHz increase in output frequency. However, the actual frequency rise was significantly lower, only about +3.5 kHz. It is believed that the SDST was likely not in thermal equilibrium during the course of EDL, and Figure 9 above shows that baseplate temperature rose much faster than actual oscillator temperature. *However, predictions of downlink frequency variation had to be based on baseplate temperature because internal oscillator temperature predicts were unavailable: only baseplate temperature predicts were available.*

The "actual" variation of +3.5 kHz is based on the assumption that EDL frequency predicts made prior to EDL faithfully model the Doppler dynamics, leaving remaining frequency variation only to AUX OSC temperature variation. Readers are cautioned that this is an imperfect assumption that would reduce the accuracy of the statement that AUX OSC frequency output variation due to temperature was approximately +3.5 kHz. Barring the availability of improved a posteriori EDL frequency predicts, it is impossible to determine the actual AUX OSC temperature-based frequency variation with greater accuracy. However, we are able to state that the variation beyond Doppler predicts due to dynamics was smaller-than-expected. Hence, although the analysis proved to be conservative, it was still adequate for the purposes of assessing RSR bandwidth.

5. EDL PERFORMANCE

Figures 11 and 12 illustrate the real time performance of the RSR. Figure 11 shows the spectrum of the carrier signal recorded in a 25 KHz channel prior to cruise stage separation. The signal is transmitted from the spacecraft's MGA, its power to noise level is measured at 35 dB-Hz.

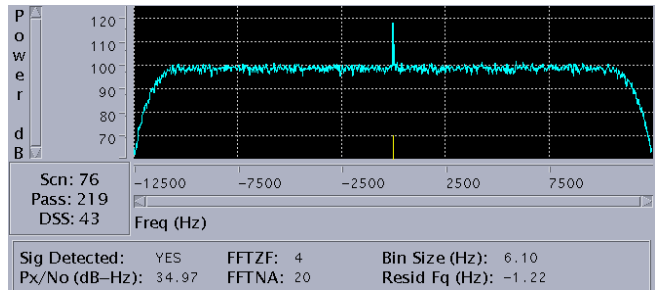

Figure 11 – Example of Real-time RSR FFT SNR

Figure 12 gives the frequency residual of the carrier during the vehicle banking after Entry. The frequency excursion at 5:23:26 UTC is an erroneous data point resulting from the power loss caused by the switch from the PLGA to the TLGA.

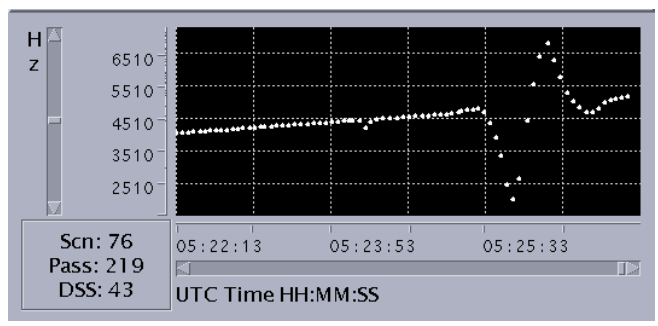

Figure 12 – Example of Real-time RSR Frequency Residual

Figures 13 – 15 are the result of post-processing of the RSR data. Figure 13 shows the frequency signature of 2 rpm caused by the MSL spin-stabilized cruise stage. Figure 14 gives the carrier signal-to-noise and residual frequency during the Approach, Entry, Descent, and Landing Phase. Key events are inscribed in the figure. Finally Figure 15 lists the carrier signal-to-noise and residual frequency at the time of parachute deploy. The parachute deploy event is

clearly seen to occur at 5:28:54 UTC.

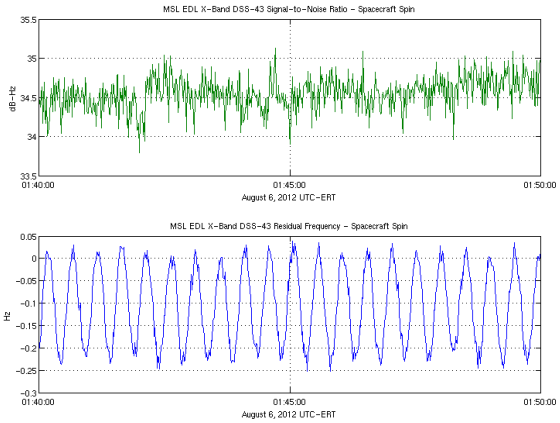

Figure 13 – MSL EDL X-Band DSS-43 Signal-to-Noise Ratio and Residual Frequency – Spacecraft Spin

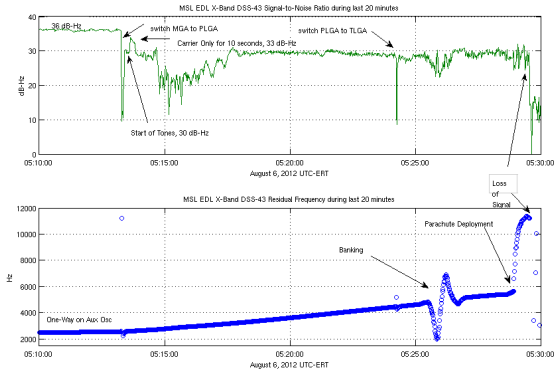

Figure 14 – MSL EDL X-Band DSS-43 Signal-to-Noise Ratio and Residual Frequency during the last 20 minutes

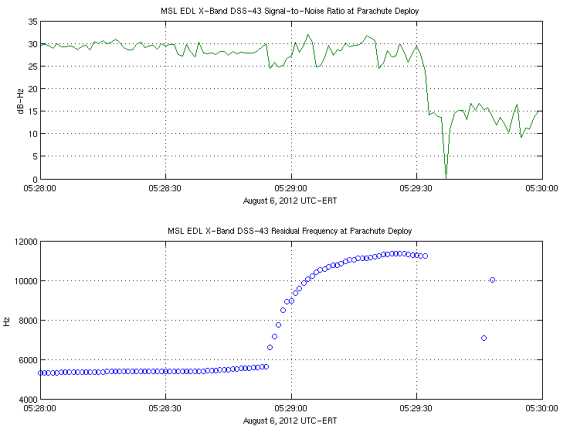

Figure 15 – MSL EDL X-Band DSS-43 Signal-to-Noise Ratio and Residual Frequency at Parachute Deploy

6. ACKNOWLEDGMENTS

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REFERENCES

[1] Wood, G.E., Asmar, S.W., Rebold, T.A., Lee, R.A., *Mars Pathfinder Entry, Descent, and Landing Communications*, JPL TDA Progress Report 42-131, November 15, 1997.

[2] Johnston, D., Asmar, S., Chang, C., Estabrook, P., Finley, S., Pham, T., Satorius, E., *Radio Science Receiver Support of the Mars Exploration Rover Landings,* ESA 3rd workshop on Tracking, Telemetry and Command Systems for Space Applications, TTC 2004, Darmstadt, Germany.

[3] Pham, T., Chang C., Fort D., Satorius E., Finley, S., White L., and Estabrook, P., *Tracking Capability for Entry, Descent, and Landing and its support to NASA Mars Exploration Rovers,* ESA 3rd workshop on Tracking, Telemetry and Command Systems for Space Applications, TTC 2004, Darmstadt, Germany.

[4] Edwards, C. D. Jr, Barbieri, A. J., Theisinger, P., Ludwinski, J., Estabrook, P., Gibbs, R., Mase, R., Thorpe, T., Brower, E., Schmidt, R., Horttor, R., *A Martian Telecommunications Network: UHF Relay Support of the 2003 Mars Exploration Rovers by the Mars Global Surveyor, 2001 Mars Odyssey, and Mars Express Orbiters,*IAF, Vancouver, Canada, Fall, 2004.

[5] Asmar, S. and Renzetti, N.A., *Deep Space Network as an Instrument for Radio Science Research*, Jet Propulsion Laboratory, Pasadena, California April 1993

[6] Makovsky, A., Ilott, P., and Taylor, J., *Mars Science Laboratory Telecommunications System Design,* Design and Performance Summary Series, Article 14, DESCANSO, Jet Propulsion Laboratory, Pasadena, California, November 2009.

[7] Taylor, J., Makovsky, A., Barbieri, A., Tung, R., Estabrook, P., and Thomas, A. G., *Mars Exploration Rover Telecommunications,* Design and Performance Summary Series, Article 10, DESCANSO, Jet Propulsion Laboratory, Pasadena, California, October 2005.