Tracking Capability for Entry, Descent and Landing and its support to NASA Mars Exploration Rovers

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1. INTRODUCTION

In January 2004, the two NASA Mars Exploration Rovers (MER) – also known as Spirit and Opportunity - arrived at Mars. Before they could start their scientific investigation looking for traces of water and evidence of possible life in the past, the two rovers had to pass through a dangerous stage of entry, descent and landing (EDL). Each rover had to safely enter and descend through the atmosphere, and land onto the Martian surface. This stage took only 6 minutes, relatively brief compared to the 7-month journey to Mars and its minimum 3-month operation. Yet, it was the six minutes of terror, as often referred to by the mission operation team. During this phase, many complex procedures – parachute and bridle deployment, radar signal acquisition, airbag inflation, and retrorocket ignition – had to work perfectly and autonomously in a tightly synchronized manner to ensure a successful landing. No ground intervention was possible due to the speed at which decisions needed to be made and to the 10-minute one-way light time delay.

Due to the difficulty of landing on Mars and the real possibility of an unsuccessful landing, the Mars Exploration Rovers Project had a requirement to receive status information from the spacecraft during EDL. This was accomplished through two different communication paths – an X band direct-to-Earth signal and a ultra high frequency (UHF) signal sent 2-minutes prior to landing to the Mars Global Surveyor. Reception of the direct-to-Earth signal was quite challenging because of the extreme dynamics that the spacecraft underwent and the uncertainty in predicting the spacecraft motion in the Martian atmosphere. As the spacecraft streaked through the Martian atmosphere, the Doppler frequency, and the associated prediction uncertainty, changed quickly and significantly. The frequency error, due to imperfect timing of entry, flight path angle, off nominal atmospheric conditions, and on-board oscillator drift, could be as large as +/- 20 kHz. The corresponding maximum rate of change could reach +/- 750 Hz/s. In addition, the signal level could be both very low due to non-optimal antenna pointing, and oscillatory due to the swinging motion of the lander on the parachute and the backshell bridle. Given these constraints, the mission telecom design team opted for the use of multiple frequency shifted key (MFSK) modulation to enable fast and low-threshold detection. Notification of events during the EDL sequence was transmitted using one out of an alphabet of 256 possible tones.

To support EDL communications, a special set of equipment – namely, the EDL Data Analysis (EDA) - was developed and deployed for operation in the NASA Deep Space Network (DSN). In this paper, we describe the design of EDA equipment. Also discussed is the signal processing strategy for the two landings. Tracking results from both landings are presented. The paper also addresses the lessons learned from operational experience.

2. EDL SEQUENCE OF EVENTS

Figure 1 shows the nominal EDL timeline events. The spacecraft made a turn ready for entry about 70 minutes beforehand. At that time, it switched from the medium gain antenna (MGA) to a low gain antenna (LGA). The broader beamwidth of the LGA made it easier to maintain communications in later descent. Coincided with this MGA/LGA switch was a change in the reception polarization on the ground antenna, from left circular to right circular polarization. At fifteen minutes before entry, cruise stage separation occurred. The protective aeroshell that encased the lander and rover left the cruise vehicle that had carried it to Mars and started its own journey onto the surface of the Red Planet. The communications switched from the standard biphase-shift-keyed (BPSK) to a special multiple-frequency-shift-key (MFSK) modulation. The MFSK offered the advantage of fast signal detection at lower threshold because all signal energy concentrated at one frequency that can be detected with a fast Fourier transform (FFT).

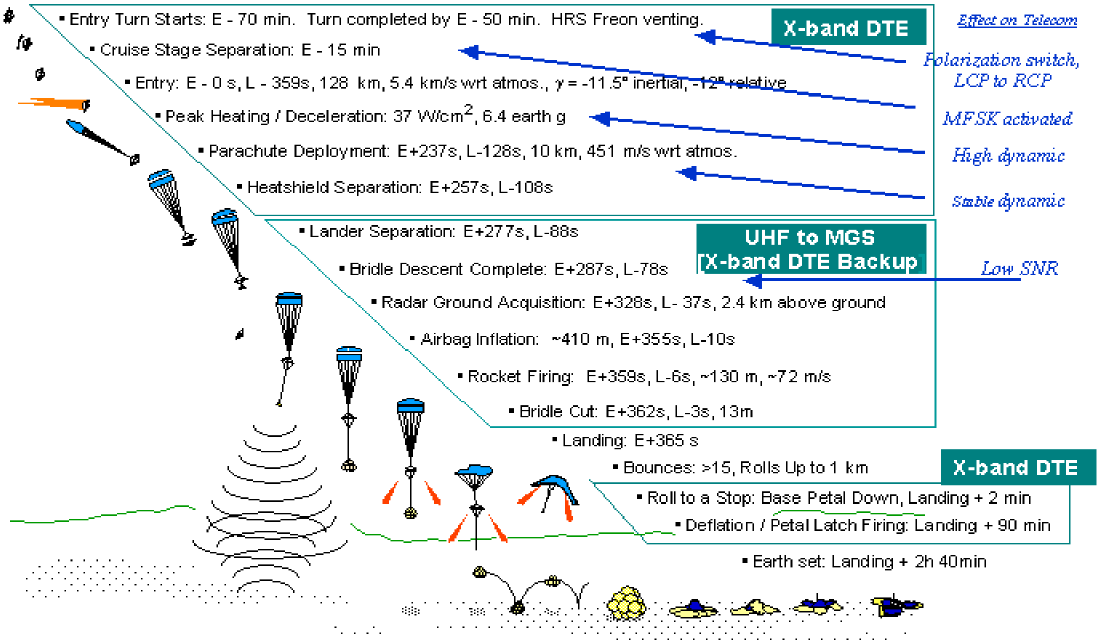


Figure 1. EDL nominal timeline events

At 124 km above the surface, the spacecraft entered the Martian atmosphere. It quickly decelerated from atmospheric friction. The raising temperature, estimated to be about 1500 ^{0}C, affected the spacecraft frequency oscillator; resulted in a quick change in the carrier frequency. This segment also corresponded to high dynamic uncertainty due to imprecise knowledge of the atmospheric density and flight entry angle. Roughly four minutes after entry, the parachute deployed. The spacecraft no longer moved as fast and the Doppler became more stable. Over the next 50 seconds, the spacecraft went through heat shield separation, lander separation and bridle descent. Because of the swinging bridle, the received signal was expected to be oscillatory in both frequency and power. About half a minute before landing, the radar ground acquisition was activated; airbag quickly inflated; retrorocket firing occurred; and the bridle was cut. The lander bounced several times (28 bounces for Spirit [1]and 26 for Opportunity [2]) and rolled to a stop. The signal at this point could be quite weak, depending on the orientation of the lander, but was no longer subjected to any change in frequency. The spacecraft terminated MFSK transmission with the petal low gain antenna tones at about 22 minutes after landing. A more complete description of EDL sequence could be found in Reference [3].

For the most part, communications link was achieved directly to Earth at X-band. A small portion of the descent - 1.5 minutes between the lander separation and bridle cut events - involved a lot of complex maneuvers that affected optimal signal reception on Earth. During this segment, the spacecraft relied on the UHF relay via the Mars Global Surveyor (MGS) satellite as the prime channel, with direct-to-Earth communications as backup. Upon landing, where trajectory dynamic was no longer a concern and also because of the setting of MGS, the spacecraft resumed its direct-to-Earth communications as the prime channel. EDL-related communications completed about 28 minutes post entry. The mission then officially entered the next phase of surface operations.

3. DSN TRACKING CONFIGURATION

Figure 2 shows the tracking configuration for Spirit and Opportunity landings. The tracking took place simultaneously at two DSN complexes at Canberra and Goldstone. Within each complex, the 70-m antenna served as the prime tracking station. For the contingency purpose, two additional 34-m antennas were also used. Their signals could be arrayed with the 70-m antenna at some later time to aid signal recovery should there be a need for it.

The X-band signal received at each antenna was amplified and down-converted to an intermediate frequency of 300 MHz. The signal was distributed to a set of receivers. For EDL processing, the signal was further digitized, bandpass filtered and recorded by the Radio Science Receiver (RSR). A variety of RSR bandwidth setting was shown in Table 1, ranging from 100 kHz (nominal) to 1 MHz (just in case). The 100-kHz bandwidth was considered optimum for real time operation, wide enough to accommodate the Doppler uncertainty and narrow enough to minimize the latency of data processing. The EDA used RSR samples to detect the carrier and MFSK tones. Based on the detected frequency of the tones, relative to the carrier frequency, the EDA identified occurrence of certain associated EDL events. The EDA server physically resided at Canberra and Goldstone tracking complexes. The detection results were sent back to mission control center at the Jet Propulsion Laboratory (JPL).

Table 1 indicates that one RSR channel was dedicated to capture the left-circular polarization signal. This setting was meant for contingency purpose; however, after lesson learned from Spirit, the RCP channel became important and got processed in real time in parallel with the RCP channel in subsequent Opportunity's landing.

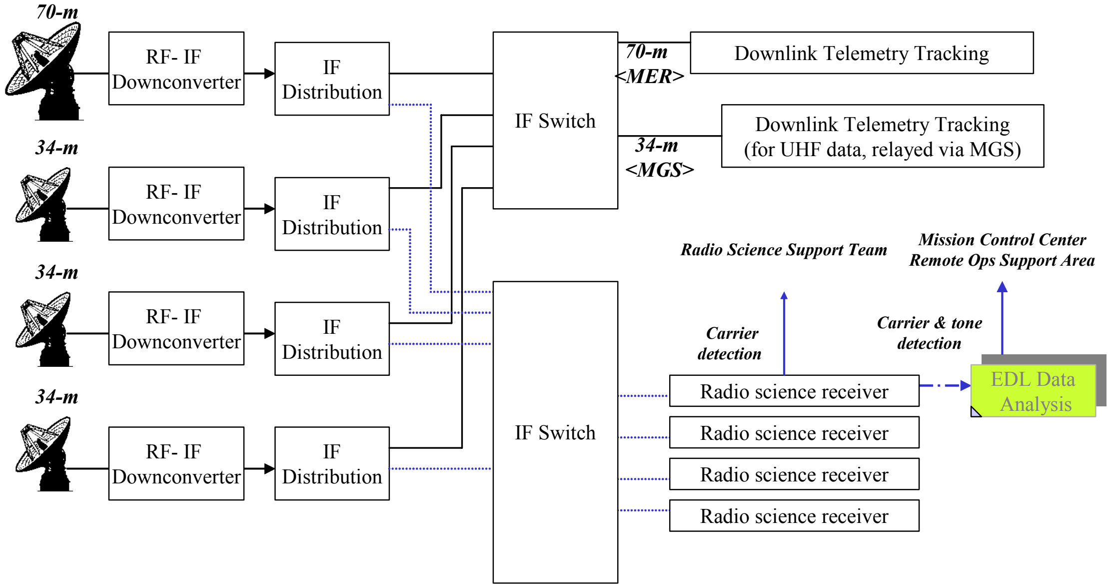


Figure 2. Tracking configuration in support of MER EDL

RSR	Antenna	Bandwidth	Polarization	EDA connection
		Goldstone Complex		
1A	70m (DSS14)	100kHz, 250kHz	RCP	=> EDA1
1B	70m (DSS14)	100kHz, 1MHz	LCP	=> EDA2 (added for Opportunity)
2A	34-m (DSS15)	100kHz, 1MHz	RCP	
2B	34m (DSS25)	100kHz, 1MHz	RCP	
3A	34m (DSS26)	100kHz, 1MHz	RCP	
3B	70m (DSS14)	1MHz	RCP	
		Canberra Complex		
1A	70m (DSS43)	100kHz, 250kHz	RCP	=> EDA1
1B	34m (DSS34)	100kHz, 1MHz	RCP	
2A	34m (DSS45)	100kHz, 1MHz	RCP	
2B	70m (DSS43)	1MHz	RCP	

Table 1. Configuration setting of the RSR and EDA

Also shown for completeness is the equipment that processed the standard BPSK telemetry signal. The Downlink Telemetry & Tracking channel supported operations before activation of the MFSK modulation. The other channel tuned to the UHF data relayed by the MGS spacecraft.

4. EDA DESIGN ARCHITECTURE

The EDA hardware was commercial-off-the-shelf equipment, chosen with sufficient computing power for real-time operation. A UNIX workstation (Sun Blade 100/150) handled the external interfaces and high-level coordination. A cluster of 8 dual-processor LINUX personal computers (PC) supported the computing-intensive tasks. The parallel processing design allowed for more PC nodes to be added to enhance the computational power as needed. The cluster processor operated with a 1600 MHz clock, compared to 650 MHz in the Sun Blade 150. This difference translated to 2.6 folds of improvement. There were sixteen processors in the cluster - two on each PC. Altogether, the cluster increased the computing power by 41 times, relative to the Sun workstation itself.

Figure 3(a) shows the EDA equipment rack. Figure 3(b) illustrates the internal EDA hardware and its connectivity. The EDA Sun workstation served as the main interface to external connection. It was connected to the operational LAN network at the tracking complex for external connectivity with RSR and mission control center. Internal communications between the Sun workstation and PC cluster were established through the 1 Gbps Ethernet switch. Local Sun workstation monitor and keyboard provided on-site monitor & control. The PC cluster also had a local terminal that could be used for diagnostic purpose. It connected to any of the eight PC nodes via a switch.

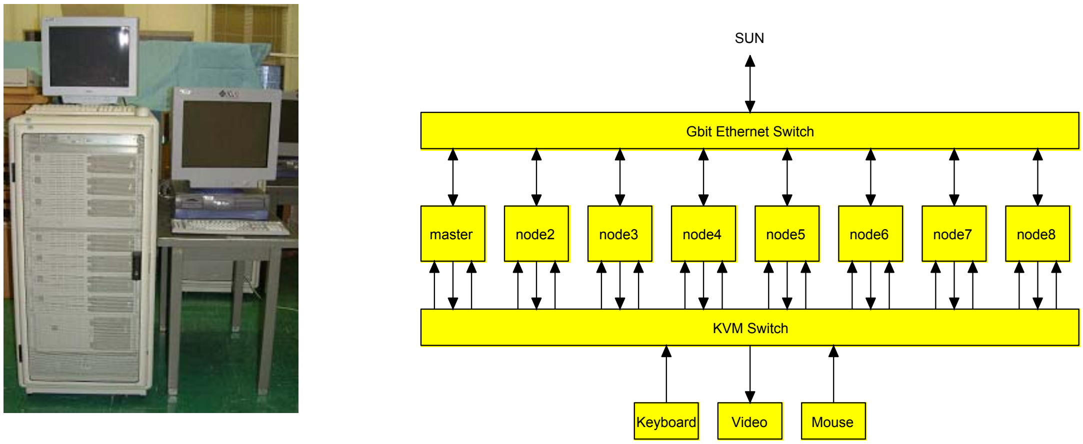


Figure 3. EDA hardware configuration: (a) Actual hardware; (b) Block diagram

The EDA software was built based on a server-client model. It allowed multiple connections between remote monitor centers and the server at each tracking complex. Each data stream took up about 5 kbps bandwidth. To ensure sufficient responsiveness required for real time operations, the EDA data streams were configured with bandwidth guarantee by the routers within the wide area network (WAN) that connected the tracking stations and the mission control center at JPL located thousands of kilometers apart.

Figure 4 shows the structure of EDA software. The four main components are:

Database server (DDS) module - This module fetched and transferred RSR samples onto EDA internal storage. Each data record held 1-second worth of samples. The data were indexed so that only data within the time window of interest got transferred.

Processor (PRC) module - This was the EDA main processing program. The PRC was designed as multi-threaded to take advantage of multiple processing capabilities. Each thread managed the processing of a segment of data, involving the functions of input/output, tracking, backtracking, and refinement. The input/output process managed dispatch of data to the cluster and receiving results. The tracking function set up all processing data forward in time. The backtracking processed data backward, trying to fill the detected gap by using the later acquired state information. The refinement attempted further enhancement on data previously processed by tracking and backtracking.

Operator interface (OPR) module - This program provided the interface to the EDA. The operator controlled the EDA configuration via both the PRC and OPR software components. The OPR also had a command window for diagnostic purposes.

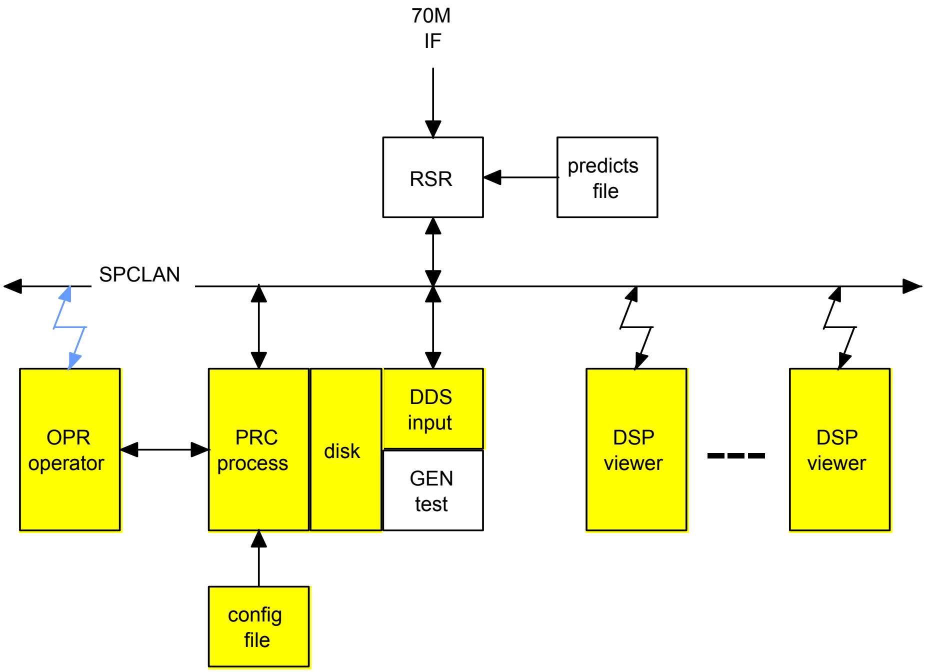


Figure 4. Software components of EDA

Display (DSP) module - This module was installed at the client sites to enable the display of EDA results. The EDA server supported a number of viewers. Operationally, four connection points were designated - one locally at the tracking complex, two at the mission control center at JPL and one at the DSN remote operation area. Through this module, one could observe the time profiles of signal-to-noise ratio for carrier and tones, detected versus predicted frequency, frequency rate and acceleration, tone frequencies, tone event summary, etc.

5. SIGNAL PROCESSING ASPECTS

Figure 5 shows the tracking algorithm used in the EDA. A more complete description of the algorithm and its performance can be found in Reference [4]. The processing employed an FFT-based frequency (and frequency rate) loop. First, to counteract for the moving Doppler during FFT sampling, the samples were compensated with the expected frequency rate change determined from previous measurement. An FFT was then applied. The process was repeated for subsequent segments of data. Each post-FFT segment output could be adjusted with another frequency and frequency rate compensation. The signal from consecutive FFT's was then added to improve the detection probability. The potential signal lied with the frequency component of highest power. To ascertain the signal validity, the observed frequency and power were compared against predicted values and previous measurements. When a match occurred that was within the specified uncertainty, the signal was declared as detected. The frequency of detected tone, relative to the carrier, was mapped to a data dictionary to identify the tone number and associated EDL event.

The EDA software was implemented to allow for maximum flexibility in signal processing. This flexibility was essential because of the uncertain nature of EDL operation. For Spirit and Opportunity support, the EDL sequence was divided into five segments - cruise, entry, parachute deployment, bridle deployment and landing. Each segment was processed with a parameter configuration best suited for its signal conditions. For example, the configuration used for stronger, high dynamic signal in the entry segment would be quite different to that needed for the much weaker, low dynamic conditions after the spacecraft landed on the planet surface. A segment configuration contained several parameters such as the length of the coherent FFTs and the number of FFTs to average incoherently. Within a segment, the processing would normally progress from an acquisition state to a locked state (and back if the signal was lost). The first state was normally a search over a large range of frequencies and frequency rates by using relatively short FFTs and accumulating them incoherently for a second or longer. If signal detection were achieved, the state would advance to the one that narrowed the range of frequencies and rates around the value just detected. The narrowing of the range helped to lower the chance of a false detection. One could specify a number of non-detection occurrences in the upper state before the program reverted to the next lowest state in order to keep the loop locked for low signal level.

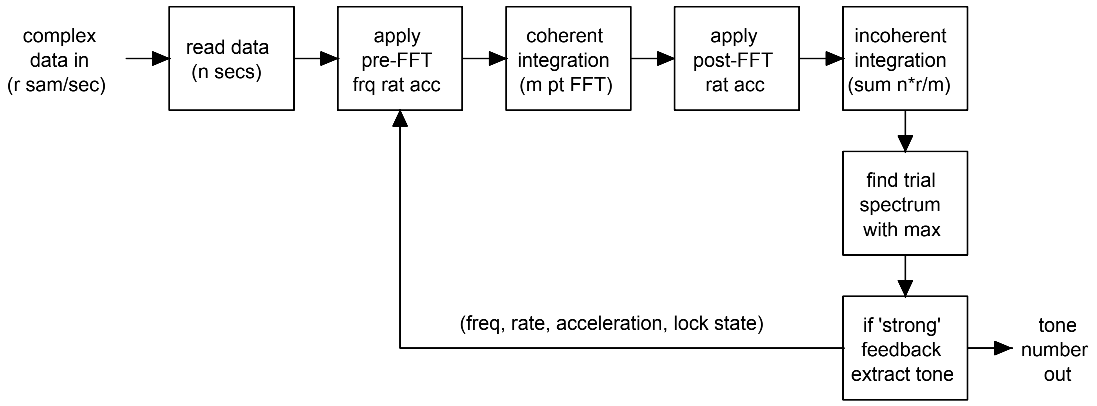


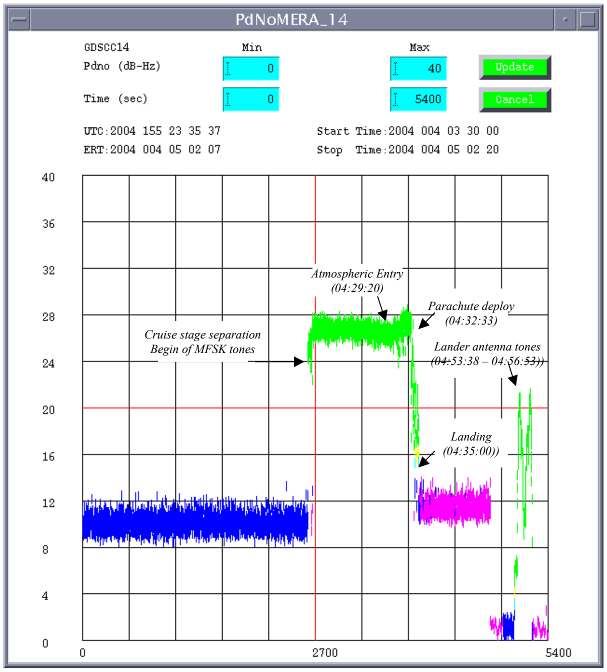
Figure 5. EDA tracking algorithm

Besides narrowing the range of frequency and rate search, it was also possible to increase the length of the FFTs for better signal-to-noise ratio. Option to use frequency acceleration, in addition to frequency and frequency rate, in signal detection was also available. To keep up with the latency requirement for real time operation, the software allowed jump-ahead option when the processing fell behind a specified limit.

Since the EDA operated on pre-recorded RSR samples, its processing could be re-run in post pass to improve detection. One could employ a more extensive configuration to search for signal in the gaps seen in real-time data. The latency in data processing would be greater, but that flexibility was affordable at post pass.

6. RESULTS

This section presents the tracking result from Spirit (MER-A) and Opportunity (MER-B). For Spirit, EDL tracking took place on January 4, 2004. Figure 6 shows the carrier and tone signal-to-noise ratios through various EDL stages. Overall, the field results were better than originally anticipated. All tones signifying critical events such as cruise stage separation, parachute deployment, landing petal antenna deployment, etc., were detected during real time operation. Earlier in mission operation planning, there was a concern on the ability to maintain contact with spacecraft during


PdNoMERA_14

GDSCC14

Pdno (dB-Hz) Min 0 Max 40

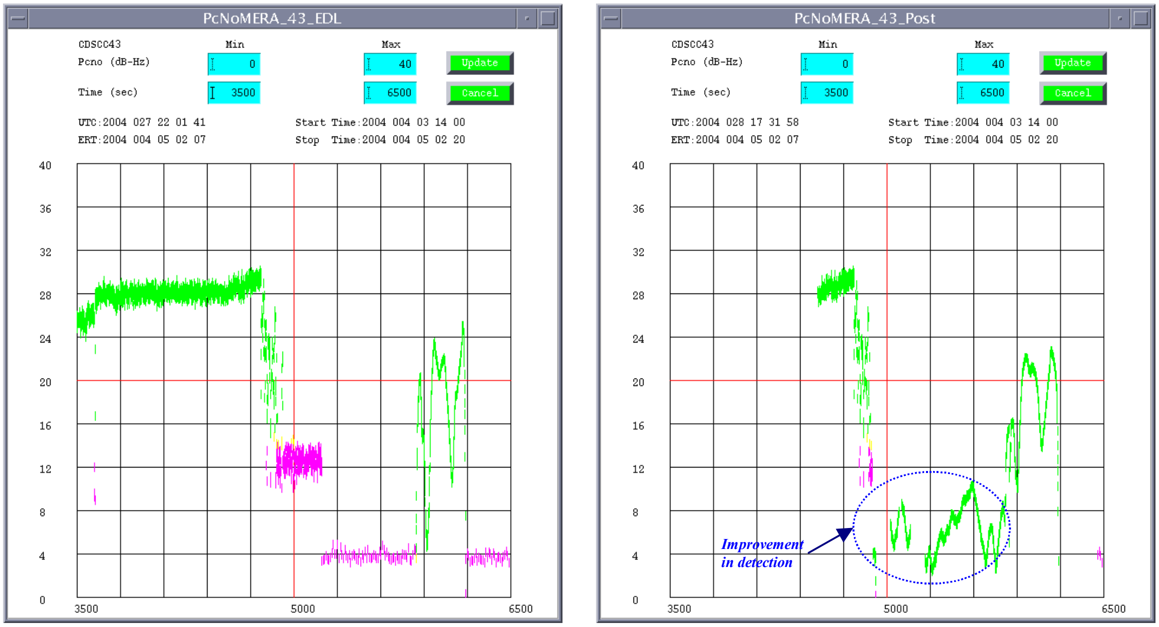
Time (sec) Min 0 Max 5400

UTC:2004 155 23 35 37
ERT:2004 004 05 02 07

Start Time:2004 004 03 30 00
Stop Time:2004 004 05 02 20

Figure 6. MFSK tone power from Spirit EDL

parachute and bridle descent segment. This was prompted by potential antenna mis-pointing from swinging motion. Also of concern was the potential communications blackout upon entry due to the induced plasma caused by the hyper-deceleration. In the 1997 landing of Mars Pathfinder, a 30-second outage was attributed to this cause. In the case of Spirit tracking, constant contact was established during this whole period, all the way until touchdown. The suspense came in between the times of touchdown and first received post-landing signal. There was an expectation of a few minutes of communications outage during this period. In actual track, the outage lasted more than 15 minutes. Later reprocessing with longer integration time and wider frequency rate search recovered 11 minutes of this gap. Figure 7 shows the comparative results of real time and post pass processing. The segment over the time 5000s - 5800s after start in Figure 7(b) is the recovered data, relative to the corresponding undetected segment in Figure 7(a).



CDSCC43
Pcno (dB-Hz) Min 0 Max 40
Time (sec) Min 3500 Max 6500
UTC:2004 027 22 01 41
ERT:2004 004 05 02 07
Start Time:2004 004 03 14 00
Stop Time:2004 004 05 02 20

CDSCC43
Pcno (dB-Hz) Min 0 Max 40
Time (sec) Min 3500 Max 6500
UTC:2004 028 17 31 58
ERT:2004 004 05 02 07
Start Time:2004 004 03 14 00
Stop Time:2004 004 05 02 20

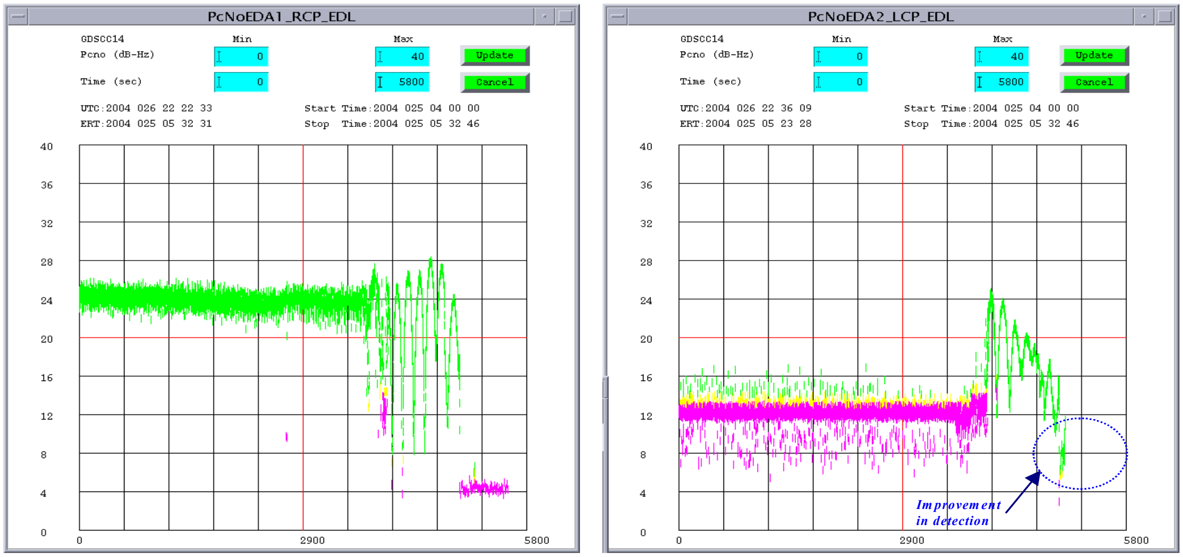
(a) Real time detection **(b) Post pass detection**

Figure 7. Comparison between real time and post pass carrier detection for Spirit EDL

One interesting observation was about reception of LCP signal. During the previously mentioned 15-minute outage during Spirit EDL, there was unexpected report on detection of LCP signal by the Radio Science team. Post landing analysis by the MER project confirmed the possibility of LCP reception. It was attributed to the particular orientation the lander came to a full stop, and the antenna polarization ellipticity in the direction away from the main beam axis. From this experience, additional EDA equipment was deployed to process LCP signal in subsequent landing of Opportunity. Figure 8 shows the carrier detection in the RCP and LCP channels. The LCP signal power was 4 - 8 dB lower than its RCP counterpart, as expected; however, at 4930s after start, the LCP channel remained detected for an additional 1.5 minutes while the RCP experienced outage.

The detection of Opportunity landing was even better than that of Spirit. Again, all critical tones were detected. The post-touchdown outage was only about 1 minute, compared to 15 minutes for Spirit. That particular outage occurred at time of 3950s after start in Figure 8(a).

Samples of other EDA displays from Opportunity landing are shown in Figure 9. They include (a) detected carrier frequency, (b) detected tone ID, and (c) tone summary table. The tone ID refers to the tone number; in the case of Spirit and Opportunity, there were 256 tones. The tone summary table is meant to aid with quick information extraction. This table compressed similar results from consecutive 1-second detection into a single event.



```
GDSCC14                 Min              Max
Pcno (dB-Hz)              0               40
Time (sec)                0             5800

UTC:2004 026 22 22 33            Start Time:2004 025 04 00 00
ERT:2004 025 05 32 31            Stop  Time:2004 025 05 32 46
```

```
GDSCC14                 Min              Max
Pcno (dB-Hz)              0               40
Time (sec)                0             5800

UTC:2004 026 22 36 09            Start Time:2004 025 04 00 00
ERT:2004 025 05 23 28            Stop  Time:2004 025 05 32 46
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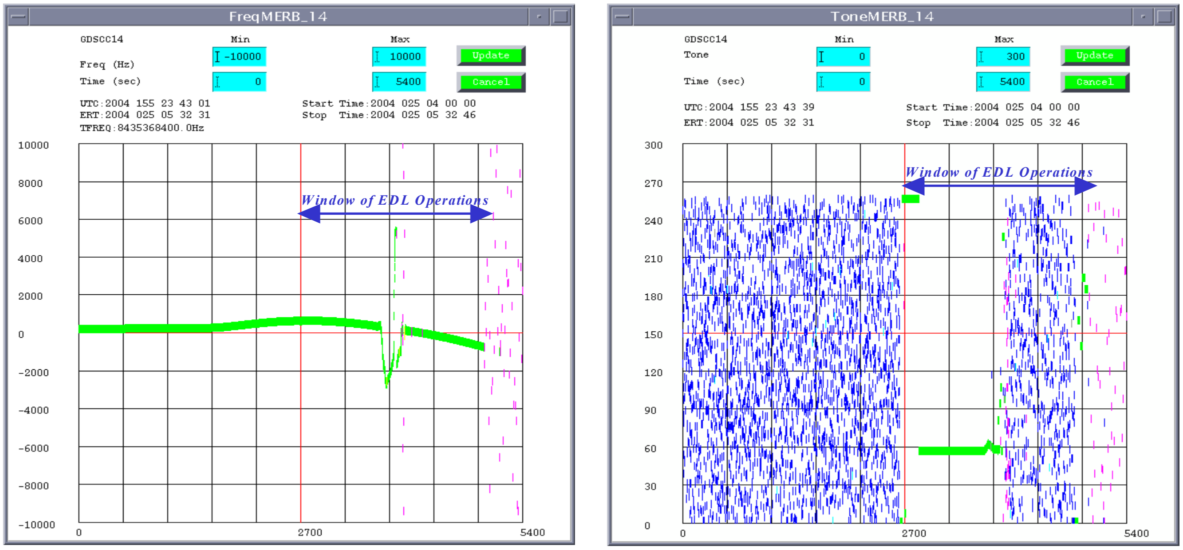
(a) RCP channel (b) LCP channel

Figure 8. Comparison of RCP and LCP carrier detection during Opportunity EDL



```
GDSCC14                 Min              Max
                     -10000            10000
Freq (Hz)
Time (sec)                0             5400

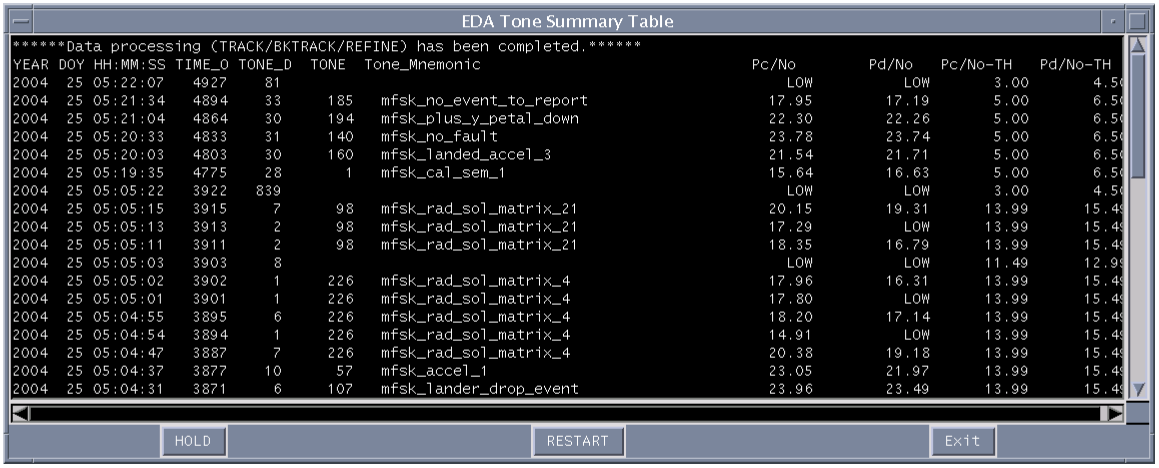
UTC:2004 155 23 43 01            Start Time:2004 025 04 00 00
ERT:2004 025 05 32 31            Stop  Time:2004 025 05 32 46
TFREQ:8435368400.0Hz
```

```
GDSCC14                 Min              Max
Tone                      0              300

Time (sec)                0             5400

UTC:2004 155 23 43 39            Start Time:2004 025 04 00 00
ERT:2004 025 05 32 31            Stop  Time:2004 025 05 32 46
```

(a) Carrier frequency (b) Tone ID



```
******Data processing (TRACK/BKTRACK/REFINE) has been completed.******
YEAR DOY HH:MM:SS TIME_O TONE_D  TONE  Tone_Mnemonic                          Pc/No      Pd/No   Pc/No-TH   Pd/No-TH
2004  25 05:22:07   4927    81                                                   LOW        LOW      3.00        4.5
2004  25 05:21:34   4894    33    185   mfsk_no_event_to_report                 17.95      17.19      5.00        6.5
2004  25 05:21:04   4864    30    194   mfsk_plus_y_petal_down                  22.30      22.26      5.00        6.5
2004  25 05:20:33   4833    31    140   mfsk_no_fault                           23.78      23.74      5.00        6.5
2004  25 05:20:03   4803    30    160   mfsk_landed_accel_3                     21.54      21.71      5.00        6.5
2004  25 05:19:35   4775    28      1   mfsk_cal_sem_1                          15.64      16.63      5.00        6.5
2004  25 05:05:22   3922   839                                                   LOW        LOW      3.00        4.5
2004  25 05:05:15   3915     7     98   mfsk_rad_sol_matrix_21                  20.15      19.31     13.99       15.4
2004  25 05:05:13   3913     2     98   mfsk_rad_sol_matrix_21                  17.29        LOW     13.99       15.4
2004  25 05:05:11   3911     2     98   mfsk_rad_sol_matrix_21                  18.35      16.79     13.99       15.4
2004  25 05:05:03   3903     8                                                   LOW        LOW     11.49       12.9
2004  25 05:05:02   3902     1    226   mfsk_rad_sol_matrix_4                   17.96      16.31     13.99       15.4
2004  25 05:05:01   3901     1    226   mfsk_rad_sol_matrix_4                   17.80        LOW     13.99       15.4
2004  25 05:04:55   3895     6    226   mfsk_rad_sol_matrix_4                   18.20      17.14     13.99       15.4
2004  25 05:04:54   3894     1    226   mfsk_rad_sol_matrix_4                   14.91        LOW     13.99       15.4
2004  25 05:04:47   3887     7    226   mfsk_rad_sol_matrix_4                   20.38      19.18     13.99       15.4
2004  25 05:04:37   3877    10     57   mfsk_accel_1                            23.05      21.97     13.99       15.4
2004  25 05:04:31   3871     6    107   mfsk_lander_drop_event                  23.96      23.49     13.99       15.4
```

(c) Tone detection summary

Figure 9. Samples EDA display from Opportunity EDL

7. SUMMARY

This paper described a new capability recently deployed in the NASA Deep Space Network to support the entry, descent and landing of the two Mars Exploration Rovers - Spirit and Opportunity. This final segment of a 7-month journey was critical step in enabling successful mission operation. The EDL Data Analysis (EDA) equipment processed the open loop recording samples from the existing radio science receivers, extracted the MFSK-modulated tones, and provided information on the occurrence of associated events happened onboard spacecraft. The EDA software supported real-time as well as post pass processing. The design flexibility allowed the track to be divided into different segments, each could be processed with a configuration optimized for its signal conditions and uncertainties. The use of dynamic lock state concept enabled signal detection be done with minimum required computing power - less was spent when signal was steadily detected and more when signal fluctuated. With the server-client design, the EDA supported connections to different remote operation centers for monitor purpose.

The paper also presented the field results from both Spirit and Opportunity landings. The detection were much better than anticipated. All critical event tones were seen in real time. Surprising detection of LCP signal was found with Spirit landing, resulted in a reconfiguration for Opportunity landing to maximize signal detection.

The EDA was originally developed as a mission-specific capability, in this case for Spirit and Opportunity. The success, however, has resulted in the interest to use it for other missions. Upcoming supports include the Saturn Orbit Insertion for Cassini mission in July 2004 and the landing for the Phoenix mission in 2007.

8. ACKNOWLEDGMENT

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