Operations Strategies for the Mars Exploration Rovers During the 2007 Martian Global Dust Storm[1,2]

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Abstract—In June and July 2007 Mars experienced a dust storm that grew to envelop all but the polar latitudes of the planet. This dust storm was the first global dust storm to occur while the twin Mars Exploration Rovers (MER) began surface operations. It is estimated that the dust in the atmosphere prevented over 99.6% of direct sunlight from reaching the surface at the peak of the storm. Data collected indicated that solar array energy output was reduced to approximately 15% of maximum. The reduction in insolation and energy output posed the greatest risk of ending the mission for both rovers at that time.

To maintain the health of the rovers, the sequencing team modified the nominal planning strategy to reduce power consumption to levels matching solar array energy generation. Existing planning and sequencing tools were used in new ways to increase confidence in the modeled state of the rover, including the power state. This paper will discuss the process used to predict the state of the rover during the storm.

As the storm began to subside, the dust began to fall out of the atmosphere. Opportunity's arrays were cleaned by the wind blowing dust off of its solar arrays. Spirit's solar arrays accumulated a significant amount of dust as no cleaning events were experienced. Spirit was parked on a north-facing slope in January 2008 as preparation for the southern Martian winter. There was concern that Spirit's power levels during winter would be reduced to below those experienced during the dust storm. Strategies developed during the dust storm served as a foundation for low power winter operations. Operating both vehicles during the dust storm gave the team high confidence in their ability to guide Spirit through its third Martian winter.

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1. INTRODUCTION

Martian dust storms have been observed by telescope since 1877 [1]. Each Martian spring through fall, there are numerous local dust storms [2]. Frequently, although not every Martian year, a local storm will expand to a cover a very large area of the planet, even encircling it. The Martian dust storm cycle and the mechanism that creates these large storms are not completely understood, but modern spacecraft observations have helped with our understanding of this phenomenon [3].

Mars Global Surveyor (MGS) was orbiting Mars during the 1999 and 2001 dust storms. MGS was able to estimate the atmospheric opacity with the Thermal Emission Spectrometer (TES) and Mars Orbiter Camera (MOC). The fraction of the direct beam sunlight that reaches the planet's surface from the top of the atmosphere is defined as e□, which means □ (i.e. tau) can be used as a value of atmospheric opacity. The maximum Tau measured by MGS was 2.13 (12% transmission) in 1999 and ~2.0 in 2001 [4, 5]. The Viking Lander 1 (at 22.3 N Latitude) and Viking Lander 2 (at 47.7 N Latitude) operated on the Martian surface for 3.3 and 1.9 Mars years, respectively. There were two global dust storms during the Viking mission, but the Tau was never measured to exceed 4.0 (2% transmission) in value [6], although recent analysis of the data has implied that atmospheric opacity could have actually peaked as high as 8 (0.03% transmission) [7]. Note: the Viking landers were not solar powered, the dust storm did not interfere with their operation.

Sojourner, the Mars Pathfinder rover, operated on the Martian surface at 19.2 N Latitude from Ls 145 to Ls 185. Ls is the angle of the Mars-Sun line from the Mars-Sun line at the northern hemisphere vernal equinox. During that time, it observed Tau values in only the 0.4 to 0.6 range [8].

The MER-A Spirit (14.6 S Latitude) and MER-B

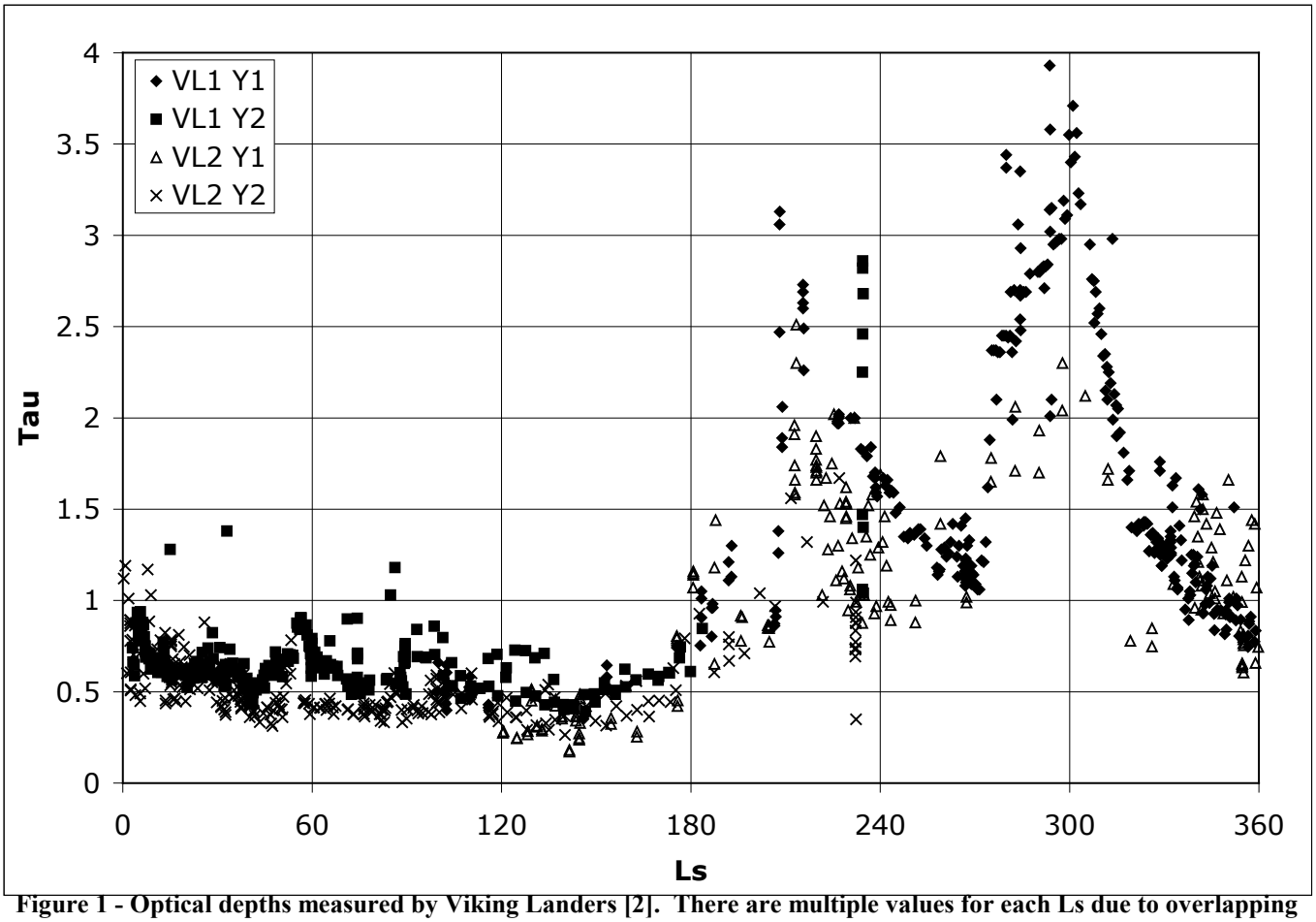

Figure 1 - Optical depths measured by Viking Landers [2]. There are multiple values for each Ls due to overlapping Mars years. VL1 and VL2 are the Viking 1 and 2 landers. Y1 and Y2 refer to the Martian years of each mission.

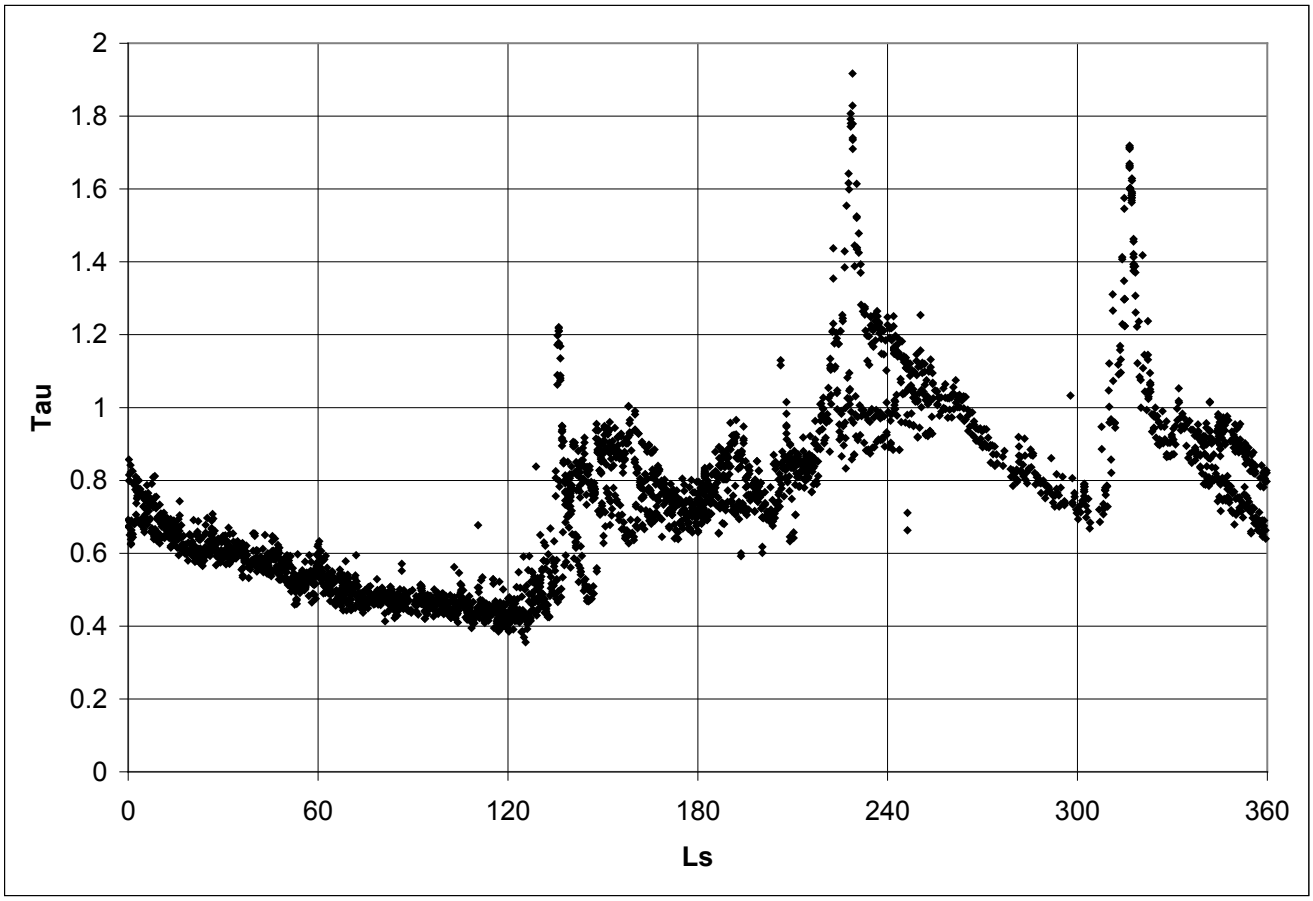

Figure 2 - Optical depths measured by the MER Opportunity rover through sol B/1200, a period prior to the 2007 dust storm. There are multiple values for each Ls due to overlapping Mars years.

Opportunity (1.9 S Latitude) rovers landed on the Martian surface during January of 2004. Because of atmospheric opacity measurements from other spacecraft, the MER mission's expectation was that the Tau could easily exceed 3.5 – and possibly rise as high as 8 - during any given Martian summer. Neither rover was designed to survive a sustained dust storm with a Tau above 5.0. This design trade was based on the prime mission duration for each vehicle of 90 sols. Based on observations from prior missions, the most likely time for Martian dust storms is from Ls 145 to Ls 225 [9]. For the MER team during the summer of 2007, it was known that the atmospheric opacity could increase, but there was also an awareness that 1) the rovers had already experienced two Martian summers without a Tau higher than 2.0 (see Figure 2) and 2) all of the prior missions were in the opposite hemisphere.

Starting on MER-B sol 1213 (B/1213), the Tau rapidly rose above the 2.0 level (on sol B/1218), and stayed above that level for over 60 sols (see Figure 3). The peak Tau value was not measured because there was not enough energy that sol to take a measurement; however, the peak Tau value was estimated to be 5.6 on sol B/1237. In just one month the array energy dropped over 80%, from 726 W-hrs on sol B/1207 to 128 W-hrs on sol B/1237.

One complication of such a great and sudden rise in atmospheric opacity is the difficulty in estimating how much energy to allocate in the next set of activity plans. During the 2007 Martian dust storm, the weather updates from the Mars Odyssey Orbiter (especially the THEMIS instrument) and Mars Reconnaissance Orbiter (especially the MARCI instrument) teams were a significant and critical part of the MER team's ability to plan.

A solar-powered vehicle is not expected to survive a planet-encircling dust storm of long duration. The dust storm simultaneously reduces the available array energy while increasing the load energy required to support survival heaters. The purpose of this paper is to describe the impact the 2007 planet-encircling dust storm had on MER Opportunity, and on the several modifications to spacecraft operations that allowed it to survive.

2. RISKS POSED TO THE MISSION

The dust storm posed three distinct risks: reduced power generation, reduced ambient temperatures, and instrument contamination. The reduction in power and temperature are coupled as both are driven by the solar radiation reaching the surface at each rover's location. Instrument contamination is a function of the density of dust suspended in the local atmosphere.

Reduction of power generation directly affects the number and duration of science activities that can be conducted. It also requires any drive activities to be shortened in both duration and subsequently in distance traveled.

The reduction in solar array output below the minimum consumption levels of the rover will lead to depletion of the batteries. Below a bus voltage of 24V the rover will automatically enter a low power fault mode. This low bus voltage (down from a nominal bus voltage of 32V), indicates that a significant number of activities are being supported by battery power and that the solar arrays are not producing enough power to charge the battery in addition to supporting activities. The Low power fault mode attempts to charge the battery until the bus voltage is increased to 27V.

Nominally the batteries would recharge prior to the wake-up timer set by the flight software when low power fault mode is initiated. During the dust storm it was likely that any low power mode recharging would complete well after the last wake-up timer. In this event the rover would not reawake until a solar array wake up occurred by having more than 2.0A being generated by the solar arrays. In a prolonged dust storm the batteries would continue to deplete until they cannot provide sufficient power to operate the rover.

The reduction in solar flux reaching the surface also caused ambient daytime temperatures to drop to the level where heaters are required to maintain the temperature of the vehicle. Conversely the dust in the atmosphere acted as an insulator allowing overnight low temperatures to be higher than expected. The latter effect was not expected to be as pronounced as it turned out to be. Without the trapping of surface heat the thermal risk to the rovers would have been much greater.

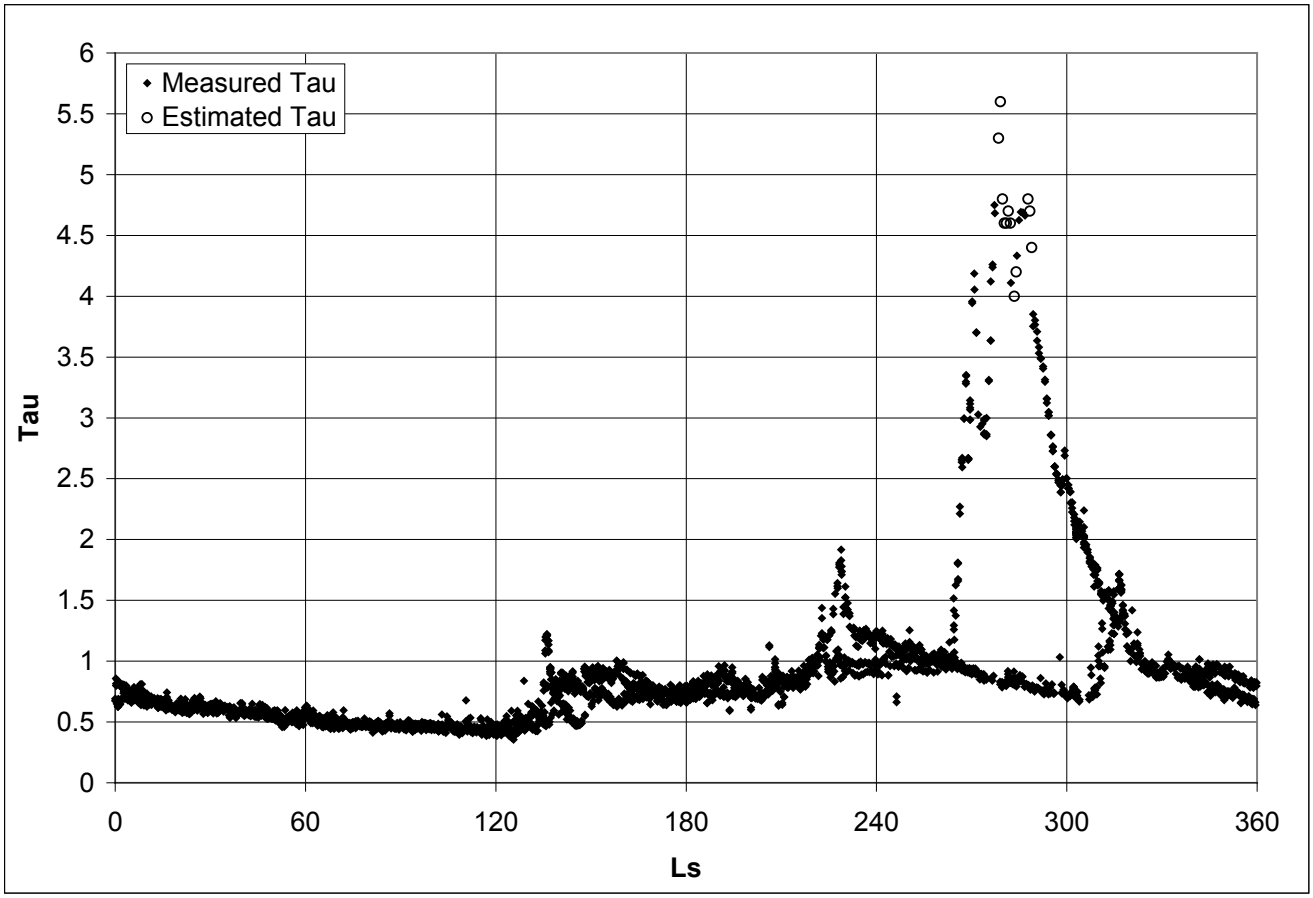

Figure 3 - Optical depths measured by the MER Opportunity rover through sol B/1300, a period that includes the 2007 dust storm. Chart includes Tau values that were estimated from the array energy output. There are multiple values for each Ls due to overlapping Mars years.

The decrease in average ambient temperature compounds the power risk, as heaters will be needed initially to heat individual components, and later all of the rover's electronics. The Mini-Thermal Emission Spectrometer (MiniTES) automatically begins heating at an instrument temperature below –38.2°C. The MiniTES heaters use 16W and have approximately a 50% duty cycle. The batteries begin heating when their temperature is below –19.2°C on Opportunity and –19.0°C on Spirit. The battery heaters require 15.3W while in use. Finally the rover electronics module (REM) will begin heating at an internal temperature of -37.7°C. The REM heaters use 90W.

Instrument contamination, while not a risk to the health and safety of the vehicle, is a major risk to the mission. Only MiniTES, Alpha Particle X-Ray Spectrometer (APXS), and Microscopic Imager (MI) on each rover were designed with coverings to prevent or minimize dust contamination. The doors covering the APXS have been left open since early in the mission to prevent having them seize shut. They were not closed on either vehicle during the dust storm.

3. RISK MINIMIZATION STRATEGIES AND ACTIONS

Addressing Risks to the Mission

Instrument contamination was the first to be addressed during the dust storm. Dust contamination would occur before power or thermal risks would be experienced.

To minimize the dust contamination risk to the science payload steps were taken to minimize each instrument's exposure to the atmosphere. Of the 12 individual sensors on the vehicle only eight were designed to be continuously exposed to the environment. These eight sensors are the two panoramic cameras (Pancams), the two navigation cameras (Navcams), and the four hazard avoidance cameras (Hazcams). The remaining instruments were each designed with coverings or doors to prevent dust contamination.

The Hazcams were considered a low contamination risk. The four Hazcams are located on the body of the rover below the rover solar arrays. This resulted in the Hazcams only being exposed to blowing dust. Dust accumulation was not considered to be a serious risk to the Hazcams. The Hazcams are angled 45° and 35° below the horizon for the front and rear pairs respectively. These elevation angles cause dust that impacts the lens to fall away from the lens.

The contamination risk to the Pancams and Navcams was considered somewhat high. Both pairs of cameras are located on a single camera bar at the top of the mast. The pitch of the camera bar is adjusted to provide variable elevation pointing. The camera bar is currently stowed 17° below the horizon instead of the original 90° below the horizon. This preserves the ability to gather terrain images if the elevation actuator fails. The -17° stow angle was not enough to ensure all dust that impacted the Navcams and Pancams would immediately fall away. Contamination of the optics was not significant enough to risk stowing the camera bar at a lower elevation angle.

The turret containing the instruments and rock abrasion tool (RAT) on the IDD was rotated such that the APXS was facing the body of the rover. This action minimized the amount of dust that could be directly blown into the cavity on the instrument.

The Mini-TES cover was in the closed position for the duration of the storm when no science was being conducted. On Sol 1217, 27 June 2008, Opportunity's Mini-TES began to show anomalous spectra when looking at the atmosphere and surface. Later investigations have determined that a layer of dust coated the elevation mirror. As of this writing efforts are underway to remove the dust from the mirror.

After the storm subsided, there were varying degrees of dust contamination on all exposed cameras. The Navcams and Pancams saw the most dust deposition. In the months following the dust storm, wind erosion has reduced dust deposits on the camera lenses.

Addressing Risks to the Vehicle

The first technique used during the dust storm was to model power resources assuming rapidly increasing tau values. The power initial conditions (incons) used by the team during normal planning contain the previous sols tau value. Due to uncertainty of what the next sol's tau value, it became necessary to evaluate the power model for various tau values.

The power engineer initially delivered the likely tau for the sol being planed. The likely tau was the previous sol's tau plus the increase seen between two sols ago and the previous sol. This likely tau would be used to model power production. The power engineer would then model other values of tau and determin the predicted solar array energy output in each case. This allowed worst-case scenarios to be modeled and evaluated. The Tactical Activity Planner (TAP) would initially model the delivered "likely" tau input. If upon evaluation the tactical team decides to review one of the alternate tau values, the power engineer would deliver the new tau to the TAP for modeling. Using the likely and worst-case scenarios it was possible to adjust the rovers activity load to ensure a power positive plan. Final reports were generated using the most likely tau value.

The tau during the dust storm continued to rise. It was found that the power modeling tool could not accept a tau value greater than 5.00. This limitation was built into the tool as at the time of development it was thought that the rovers could not survive a tau value higher than 5.0. This was problematic for the team as power modeling for taus

above five would not be possible. As such the engineering team would have to make informed assumptions as to the actual solar array output and to keep load energies as low as possible.

During the peak of the storm, power output from the solar arrays was reduced over 80%. The minimum one-sol array energy for Opportunity dropped to 128Whrs. The energy needed to conduct one sol of operations was approximately 180Whrs. Each sol with a load energy in excess of the array energy drew power from the batteries and reduced the battery state of charge. An operations strategy that minimized power consumption, to prevent irrecoverable discharge of the batteries, while maintaining commandability of the vehicle was needed. The plan that was settled upon was three sols in duration. The sequence bundles would be uplinked and activated on the first sol. The second sol contained no activities other than a commanded wakeup for 15 minutes. The third sol would have telemetry relayed to the Odyssey orbiter for relay to Earth. This strategy reduced the rover's single sol energy consumption to approximately 150Whrs per sol. Fortunately the solar array energy output was not below 150Whrs/sol for more than a few sols. The battery energy was not depleted. Table 1 provides a comparison of a pre-dust storm three sol plan with a three sol plan at the height of the storm.

The REM temperatures on both rovers were significantly reduced as a byproduct of the reduced activity level. The power and thermal engineers estimated that the REM heaters would use a minimum of 200Whrs before the REM reached an acceptable temperature. To reduce unexpected power consumption, the REM heaters on both vehicles were disabled. To prevent the REM from reaching too low of a temperature, the internal temperature was maintained by increasing the awake duration each sol. The initial awake duration of 45 minutes was not able to reverse the cooling of the REM. An awake duration of 1 hour did stabilize the REM temperature and required approximately 40Whrs.

The low power fault mode was also modified to minimize power consumption. The awake time for the low power fault mode was reduced to 30 minutes. The low power fault communication windows were shortened to 20 minutes in duration and set to receive only. This change eliminates the use of power for transmission. The transmission of telemetry direct to Earth can be initiated by a real time command.

As the storm began to weaken, activity levels on both vehicles were increased while maintaining a positive power profile. The REM heaters and low power fault states were reverted to their original settings after the storm had mostly dissipated.

4. LESSONS LEARNED FOR SPIRIT'S THIRD MARTIAN WINTER

Multi-sol limited activity planning developed during the dust storm formed the basis of the strategy to allow Spirit to survive its third Martian winter. Power levels were expected to drop to approximately 150Whr per sol and temperatures were expected to cause all survival heaters to be activated.

A strategy was developed where Spirit would only support UHF relay downlinks every fourth sol. To further conserve power, the UHF communication sessions were shortened from 15 minutes to 6 minutes.

Table 1 - Opportunity Pre-Dust Stom (Sols 1152-1154) and Dust Storm (Sols 1237-1239) Three Sol Plans

Sol 1152 • X-Band Uplink • Pancam Tau • MiniTES Sky & Ground • Pancam 3x1 mosaic • Pancam of target Jaen • MiniTES stares at targets Badajos, Castellon, Coruna, Rioja, & Jaen • Nap • Pancam Tau • MiniTES sky & ground • UHF Downlink • APXS Argon measurement • Nap • Mini-Deep Sleep • Nap • Pancam sky survey • Nap • Navcam bitty cloud • MiniTES sky and ground	**Sol 1237** • X-Band Uplink • Nap • Deep Sleep
Sol 1153 • Pancam Tau • MiniTES sky & ground • Drive • Post drive imaging • Navcam 5x1 • Post-drive Pancam • Nap • UHF Downlink • Nap • Deep Sleep • Nap • Pancam Tau • MiniTES sky & gound	**Sol 1238** • Nap • Deep Sleep • Nap
Sol 1154	**Sol 1239**

• Pancam Tau • MiniTES sky & ground • MiniTES ground stares • Pancam Tau • Nap • Pancam Tau • MiniTES sky & ground • UHF Downlink • Nap • Deep Sleep • Nap • Pancam Tau • Pancam sky spot • Navcam bitty cloud • MiniTES sky & ground • Nap • MiniTES sky and ground	• Nap • UHF Downlink • Nap • Deep Sleep

Each plan would last three, four, or seven sols. The sequences for each plan would be uplinked via the high-gain antenna (HGA) two sols prior to the start of the plan. Uplinking on the sol before plan kickoff was provided as a backup. This planning strategy was only possible due to the confidence in the modeling tools acquired during the dust storms.

5. CONCLUSION

A combination of historical data on tau values during planet encircling dust storms, combined with realtime observations from spacecraft orbiting Mars and the resourcefulness of the science and engineering teams led to the survival of both of the Mars Exploration Rovers. The techniques and strategies developed have influenced operations of both vehicles as the mission continues. The strategies developed during the dust storm were highly influential in the survival of the Spirit rover during its third Martian winter.

Both rovers continue to operate on the Martian surface. Spirit is resuming more normal operations as spring approaches. Opportunity is departing Victoria crater, which it entered immediately after the 2007 dust storm, to begin a trek towards Endeavor Crater 12km to the Southeast.

It is hoped that the lessons learned from the continued operation of these two rovers will provide valuable lessons that can be applied to future surface explorations of Mars and other planets and moons.

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BIOGRAPHY

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