THE MARS SURFACE ENVIRONMENT AND SOLAR ARRAY PERFORMANCE

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ABSTRACT

January, 2010, marked the 6th anniversary for MER. This also marked the completion of more than three Martian years of solar array operation on Mars. During the spring of 2010, the MER rovers broke the RTG powered Viking Lander record for robotic operations on the Mars surface. Not only has a wealth of scientific information been obtained from MER but also a large quantity of data regarding factors that impact solar array performance. These include measurement of atmospheric dust, i.e., the atmospheric tau value. Additionally, dust buildup and removal from the solar array surfaces has been tracked. It is expected that the data from the rovers will enhance the prediction of future Mars surface solar array performance. Seasonal and annual trends have been identified. The results of these parameter analyses will be presented to assist in the design of future Mars surface solar power systems, both rover and stationary.

INTRODUCTION

Spirit (MER-A) landed at 14.6 degrees south latitude and 175 degrees east longitude. The Opportunity (MER-B) landing site was nearly on the opposite side of Mars at 354 degrees east longitude and slightly south of the equator at -2 degrees latitude. The data provide information reflecting local and global patterns.

A critical part of the array performance is played by the atmospheric dust concentration or tau. Exhibiting both seasonal variations and shorter duration "random" variations these changes can be gradual or abrupt. Although the MER mission was given a life expectancy of only 90 Martian days (sols), this was not due to any particular limitations in the rover hardware. Rather, it was tied to anticipated loss in array power due to dust accumulation on the panels (based on information from the short lived Pathfinder Lander and rover), and additional sunlight loss from the encroaching winter season.

The orbital period of Mars is approximately 687 days, but this measurement is in 24-hour Earth days, not Martian sols, which are almost forty minutes longer. As a result, the Martian year is also 668.59 sols from one vernal equinox to the next. The MER data is presented in terms of sols corresponding to the full day-night cycle on Mars.

MARTIAN SURFACE ENVIRONMENT OBSERVATIONS AND MEASUREMENTS

The Mars dust environment plays a critical part in the performance of solar arrays on the surface. The combination of atmospheric dust and deposited dust serve to reduce the light intensity received by solar cells. These effects combine seasonal and random aspects in a complex manner making long term power prediction difficult. The Mars rovers provide an experienced based data base that can be used to develop a baseline performance prediction for future mars surface photovoltaics use. Typically, data is obtained daily. However, there are a number of situations, such as commitment of the Deep Space Network to other missions that can interfere with this.

Tau (Atmospheric Opacity)

Figures 1 and 2 depict the sol to sol change in tau for Spirit and Opportunity (data provided by Mark Lemmon, of Texas A&M University) throughout the mission. In all tau and dust factor data plots presented here blank spots represent days when data was not available. The data is plotted up to June 2010 for MER-B. MER-A data extends through Mar 2010, the last time telemetry was received from MER-A before the winter "hibernation". A general correlation between the two rovers is evident, even though they are on nearly opposite sides of Mars. A major dust storm, occurring at approximately 2 Mars years into the mission, can be seen through the large increase in tau from the high atmospheric dust content.

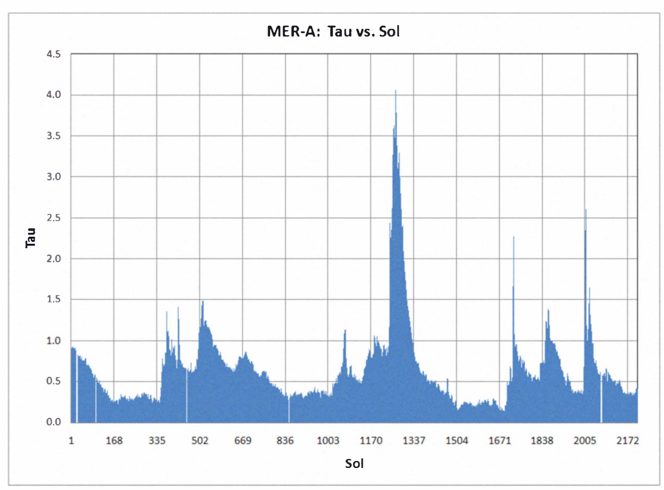

Figure 1. Tau vs. Sol (Mars day) for Spirit

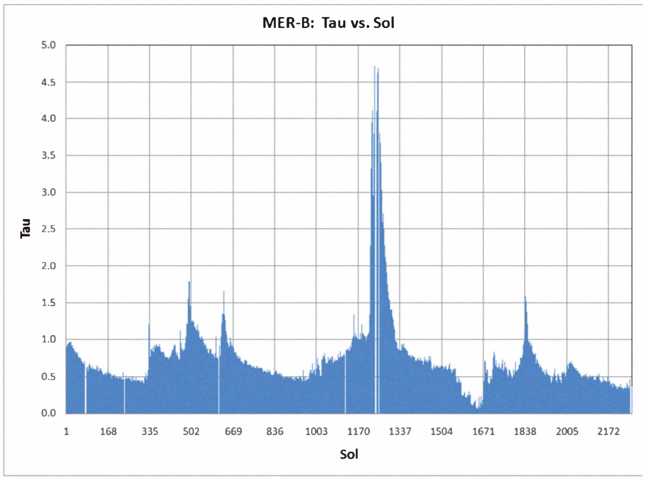

Figure 2. Tau vs. Sol for Opportunity
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The "yearly" cycle for tau can be clearly seen in Figures 3 and 4 where each year's data is plotted separately. The annual pattern is actually quite dramatic. The lowest tau values occur during the winter season, when overall solar intensity and air turbulence is at a minimum. Summer, in comparison, is a period of relatively high tau and atmospheric activity.

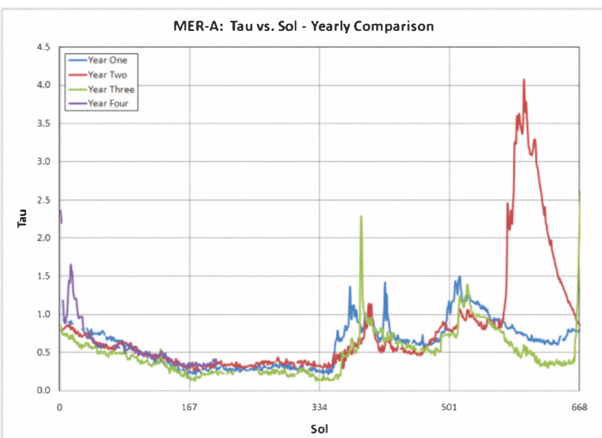

Figure 3. Mer A Tau vs. Sol – Mars year to year comparison

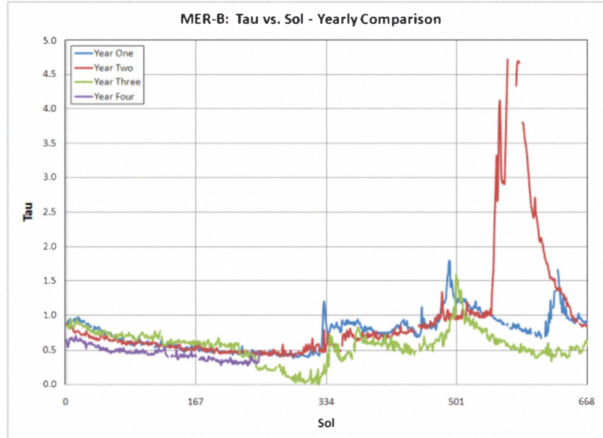

Figure 4. Mer B Tau vs. Sol – Mars year to year comparison

The relatively quiet and low tau periods (left region of Figures 3 and 4 above) correspond to the autumn and winter seasons. Atmospheric dust activity picks up noticeably throughout spring and summer. Table 1 lists the average and mean tau values experienced by Spirit and Opportunity along with highs and lows. Although there is a large range of tau, for the most part values remained around 0.6 to 0.7, which is considered a moderately clear day, for the majority of the mission. Seasonal effects such as solar distance and planetary inclination are major factors in the array performance. Figure 5 and Table 2 show tau as a function of season on Mars. Tau impacts the rover array performance, not only directly, but indirectly through the relation to dust buildup on the panel surface. Table 3 summarizes daily energy values through Mar, 2010 for Spirit and June, 2010 for Opportunity. There is more than an order of magnitude difference in the maximum and minimum values.

MER Tau Values		
	MER-A	MER-B
Average	0.64	0.72
Median	0.54	0.62
Variance	0.24	0.22
Highest	4.06	4.72
Lowest	0.13	0.01

Table 1. Tau values measured for Spirit (Gusev Crater location) and Opportunity (Meridiani location)

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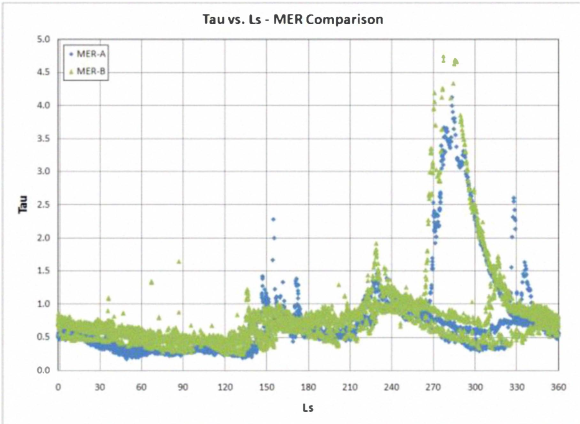

Figure 5: Tau vs. Ls for both Mars Exploration Rovers.

Ls (deg)	Southern Hemisphere
0	Autumnal Equinox
90	Winter Solstice
180	Vernal Equinox
270	Summer Solstice

Table 2. Relationship between Ls and the Martian seasons.

MER Energy Values		
	MER-A	MER-B
Average	433	534
Median	363	553
Highest	994	932
Lowest	90	128

Table 3. Daily Solar Array Energy (W-hrs) for MER.

Array Dust Factor

Figure 6 compares the solar array dust factor with tau for Spirit. As used by the MER operations team, the dust factor represents the fraction of initial light that is incident to the cell through any deposited dust layer. A value of 1 for the dust factor means that there is no loss due to dust. The two curves are seen to differ in that the dust factor has an overall slope corresponding to dust buildup. However, in many instances the array cleanliness (dust factor) is seen to improve with increasing atmosphere dust (Tau), so there is some correlation in the shorter term behaviors. What is happening is that the increase in tau tracks with an increase in winds. These winds not only drive dust into the atmosphere but can also remove dust from the solar panels when the local winds increase. Conversely, tau decreasing corresponds to decreasing winds, and the dust in the atmosphere begins settling, only to deposit on the panels. This process can involve global or local atmospheric conditions, resulting in a wide range of dust removal and collection rates. The very large increase in tau during year 2 not only removed panel dust rapidly but was followed by a rapid re-deposition. The rather modest increase in tau around sol 1800 produced an even greater array cleaning, resulting in generated power approximating the amount initially generated at rover arrival. The residual amount of atmospheric dust quickly dissipated and subsequent array dust buildup has been slow. Throughout the mission a wide range of dust deposition rates can be observed.

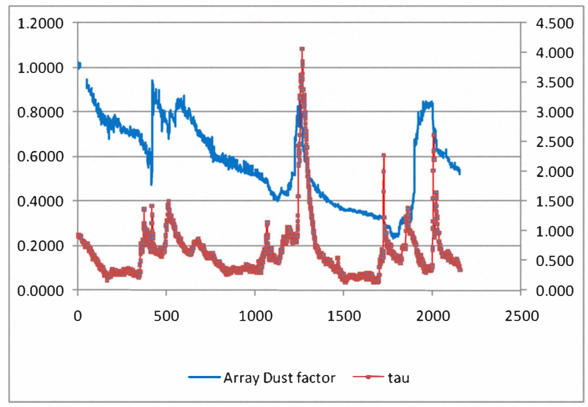

Figure 6. Spirit Array dust factor and tau vs. sol

Array Energy

Although dust build up on the panels leads to reduced array energy generation, the dust storms have often resulted in greater energy generation. Figure 7 compares the solar array dust factor with the daily energy generated for Spirit. The result is surprising at first glance since the power depends on many factors such as sun distance and angle (season), tau, and panel dust coverage among the most important. The apparent result of these factors is that high rover array power tracks somewhat with high tau, not an obvious outcome. This does follow from the observation that a higher tau corresponds to certain seasons and that it also corresponds to higher winds which can, in turn, remove panel dust.

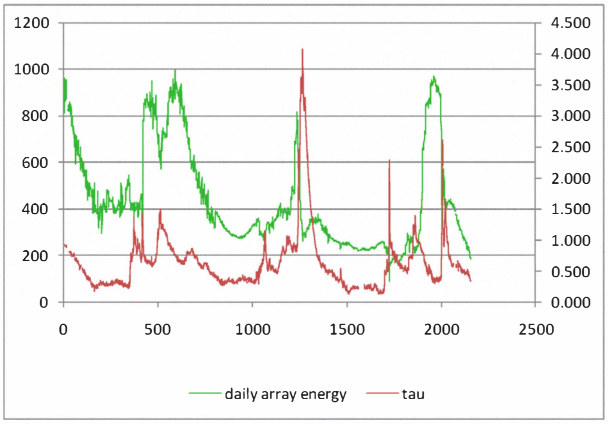

Figure 7. MER-A Tau and solar array daily energy vs. sol

The final figures in this section provide a convenient summary for all factors for each rover. Figure 8 gives the values for Spirit and Figure 9, for Opportunity.

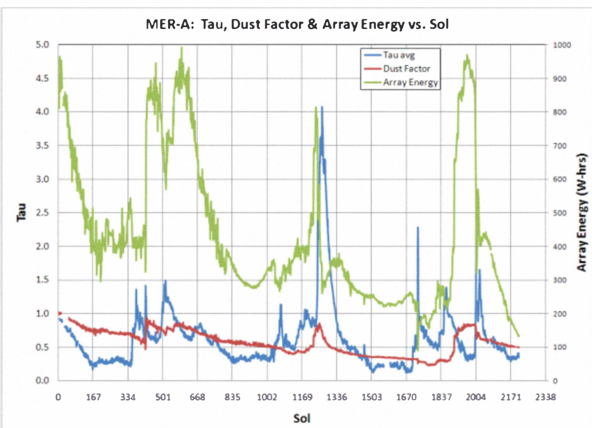

Figure 8: Tau, Array Dust Factor and Solar Array Energy (W-hrs) vs. Sol for Spirit

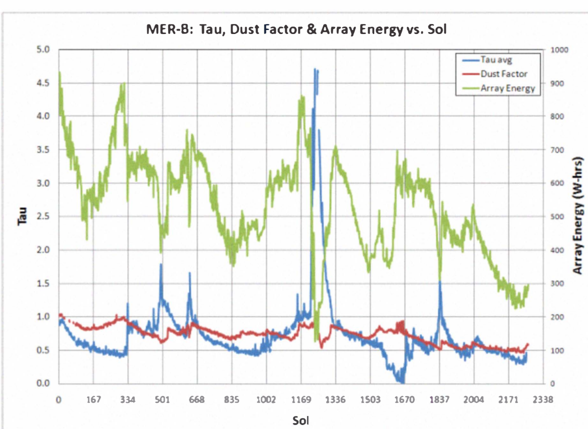

Figure 9: Tau, Array Dust Factor and Solar Array Energy (W-hrs) vs. Sol for Opportunity

Array Temperature

The array temperature presented here is measured on the –X panel (Figure 10). This is the panel located at the rear of the rover. The +/_ Y panels also have thermocouples. These panels consist each of two "sub" panels. The primary of these each have shunt radiators on the rear surfaces that would introduce extraneous heat into the panels, depending on the rover loads. Consequently, it was felt that data from the –X panel would provide the best indication of actual panel temperatures due only to solar illumination and radiation/convection to the Mars environment. Figure 11 plots the measured typical monthly temperatures for MER B. The "daily" high value is obtained around noon. The data for the low temperature, in comparison is obtained over a wider range of times, typically early in the morning, before appreciable solar heating. This is an artifact of the energy conserving "deep sleep" mode for the rovers. During this mode panel temperature data is not measured. The temperature data starts to be measured when the rover "wakes up" shortly after sunrise. The actual "wake up" time can vary depending on the uplinked operations plan.

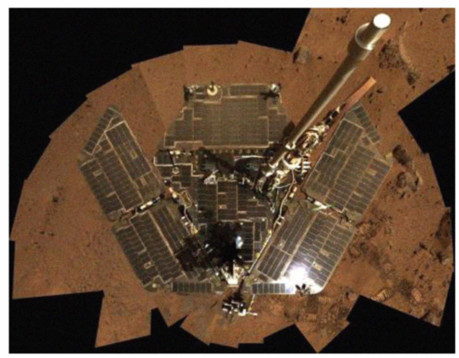

Figure 10. -X panel is shown at top (Spirit "self portrait")

The daily highs are seen to vary as much as ~10C year-to-year, although the annual spring temperatures have been within a degree or two. The lowered daily high and increased daily low during the summer of Martian year two corresponds with a major dust storm. The turbulent and dusty atmospheric conditions reduce the daily fluctuation in temperature, as might be expected from the high dust content in the air. For MER-B, the average array temperature over the mission has been 13.8C and for MER-A, 14.3C. MERB's maximum daily high has been 30C and minimum daily high, -15C. MER-A has been slightly warmer over its mission life (although data has not been available since Spirit began hibernation in April, 2010) with a maximum daily high of 34C and minimum daily high of -6C.

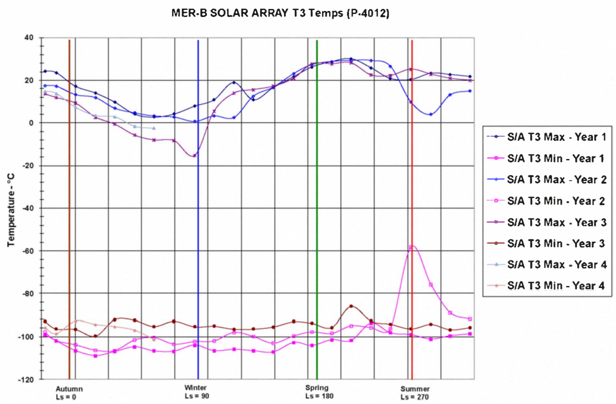

Figure 11. MER B Yearly temperatures (Charles Porter of JPL)

CONCLUSION

The extended MER mission has provided a wealth of scientific data on Mars. At the same time, the continued operation is providing data pertinent to the use of photovoltaics on the Mars surface. The operation of photovoltaics on the Martian surface is certainly less predictable than operation in space. However, MER is providing valuable information for predicting future Mars surface solar power generation. The major limitation of array power continues to be the influence of atmospheric and deposited dust, although it is now evident that these need not lead to continued degradation in array power. After more than three Martian years of operation, recurrent incidences of dust removal and low atmospheric tau have allowed for continued and ambitious rover operations.

The MER experience indicates that long term PV/battery systems can be used on Mars through appropriate design. Rovers or stationary stations (weather, seismic, etc.) come to mind as possible applications. Development of a reliable method for array dust removal from solar panels would be a key feature in extending mission life. Any such process need not provide continuous cleaning, but rather be intermittent, followed by long periods of relative array cleanliness. Combined with low power modes, including temporary cessation or reduction of science data acquisition to accommodate severe dust storms, decade or longer operations can be considered feasible.

ACKNOWLEDGEMENT

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