Managing PV Power on Mars – MER Rovers

Paul M. Stella, Keith Chin, Eric Wood, Jennifer Herman, and Richard Ewell,
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109

ABSTRACT

The MER Rovers have recently completed over 5 years of operation! This is a remarkable demonstration of the capabilities of PV power on the Martian surface. The extended mission required the development of an efficient process to predict the power available to the rovers on a day-to-day basis. The performance of the MER solar arrays is quite unlike that of any other Space array and perhaps more akin to Terrestrial PV operation, although even severe by that comparison. The impact of unpredictable factors, such as atmospheric conditions and dust accumulation (and removal) on the panels limits the accurate prediction of array power to short time spans.

Based on the above, it is clear that long term power predictions are not sufficiently accurate to allow for detailed long term planning. Instead, the power assessment is essentially a daily activity, effectively resetting the boundary points for the overall predictive power model. A typical analysis begins with the importing of the telemetry from each rover's previous day's power subsystem activities. This includes the array power generated, battery state-of-charge, rover power loads, and rover orientation, all as functions of time. The predicted performance for that day is compared to the actual performance to identify the extent of any differences. The model is then corrected for these changes.

Details of JPL's MER power analysis procedure are presented, including the description of steps needed to provide the final prediction for the mission planners. A dust cleaning event of the solar array is also highlighted to illustrate the impact of Martian weather on solar array performance.

INTRODUCTION

For conventional spacecraft the array is usually sized to meet the maximum expected power loads at any time, end-of-life in particular. As a result the array capability generally exceeds the S/C needs throughout the mission. For the MER rovers, the power generation is so minimal and variable that the mission power profile must be adjusted to the expected power generated. It is clear that long term power predictions are not sufficiently accurate to allow for detailed planning of routine Rover operations, mobility and scientific investigations. Instead, the power assessment has become essentially a daily activity, resetting the boundary points for the overall predictive power model that includes not only generated energy, energy storage, and energy consumption from the solar array and battery but overall rover power budgeting due to mobility, science, and general housekeeping activities. At the beginning of the rover surface operations

JPL had developed a Multi-Mission Power Analysis Tool (MMPAT) model to provide near term predictions of power. In its initial version it was comparatively simple, assuming a steady dust caused loss to the array power based on observations from the Mars Pathfinder lander and rover. From those observations[1], "The MAE measurements indicate steady dust accumulation at a rate of about 0.28% per day. This value is consistent with the performance of the lander solar arrays, which decreased in power at an estimated rate of 0.29% per day over the same period."

With increasing operational experience on MER rovers, overall power subsystem modeling was found to be a gross simplification of the actual situation and the MMPAT model was accordingly updated to deal with a much more volatile situation. MMPAT is a general-purpose full power subsystem model that has been interfaced with JPL ground systems to output critical power predictions of available solar array energy and battery state-of-charge (SOC) information for each rover planning cycle. The most recently known power state from actual S/C telemetry (e.g., battery SOC, various temperatures, load states, bus voltages, etc.) must be provided as model inputs. MMPAT relies heavily on daily model adjustments to the estimated dust loading developed from S/C telemetry to ensure maximum model fidelity. Ostensibly, both Opportunity and Spirit have unique power operational idiosyncrasies due to degradation and anomalies that must be accounted for in daily model management activities. To further complicate the rover power management efforts, there are also frequent occasions where this daily update can not be made, usually due to incomplete or missing telemetry data. In some cases the predictions have had to cover multiple days. Obviously, higher uncertainties are assigned to these predictions than those based on actual rover telemetry to avoid the possibility of planning activities that would leave the Rovers unacceptably power negative (low battery capacity). The following basically takes the reader through the process of Rover daily power management.

ROVER POWER ANALYSIS

Before processing of a new sol "Make New Sol" must be run to create a mode in the sol-by-sol file system for the power data to be processed. After creating the new sol directory the current sol number is updated. This is reflected in the status command display and provides an appropriate default argument for most of the commands that follow.

A typical analysis procedure begins with the importing of the telemetry from the previous day's power

subsystem activities recorded on the rover's on-board memory. This will include the array power generated, the battery state-of-charge, the rover power loads, and rover orientation, all as functions of time. The predicted performance for that day is compared to the actual performance to identify the extent of any discrepancies. These discrepancies are typically the result of rapid changes in the dust environment and/or deviations of actual power loads from the predicted loads.

The initial step in the near daily updating of the rover power prediction model is the running of the "status" command. This tool basically summarizes the status of the process of developing the daily power predicts. The first step in what is usually a daily process is to do a status check on the model. This command will verify that the appropriate sol (Martian day) is being processed. As shown in Figure 1 below, there are a number of status lines in the display. The example is for MER A (Spirit) for sol 1893 of the mission. "Predict from sol" is the sol that is being processed, from which the predictions will be made, typically the sol corresponding to the most recent telemetry downlink. The "current LST" (Local Solar Time) is the actual local mission time on Mars, in this case just prior to midnight of sol 1893. (Fortunately, the actual earth time was a more user friendly early morning time.)

```
predict from sol:  1893
current LST: 1893/23:34
update_inprofile: inprofile_hist.sip -> a1893_0935-
1894_1000_ap.sip (history ends at 1894/12:46:18.998)
Sol 1893 Tau: not available
current Tau: 0.855, from sol 1892
Sol 1893 Array Dust: not available
current Array Dust: factor(Fo): 0.4182 adj: 1.1491
get_postDTE_time: not done
run_forward: not done
predict_next_sol:  not done
summarize_sol:  not done
```

Fig. 1. Initial status check

The "update_inprofile" shows that a preliminary rover operating power plan has been placed into the model for the next day (1894). The MMPAT power model invokes this rover activity plan to provide the time phased power loading profile throughout the next day. This activity plan includes power expended in science, mobility, and rover housekeeping activities. Tau is the optical depth parameter for the solar array model of MMPAT. This includes power expended in science, mobility, and rover housekeeping activities. Sol 1893 tau shows as not available, indicating that there is presently no tau value for 1893. The current tau of 0.855 (a moderately clear day) is actually the value from a previous sol, 1892. Sol 1893 array dust is the value for array dust coverage on day 1893. It is not yet available since downloaded Rover data for sol 1893 have not been received at this time or that the data were not sufficient for the calculation. Unlike most of the downloaded data available covering power engineering performance, the dust factor and tau values are intertwined as dictated by the daily Martian weather. In other words, tau and dust factor represent a combined loss to the array power that is not predictable, especially over long durations. Separation of the overall energy loss due to atmospheric and dust loading parameters requires a separate science input to provide a measure of tau [2]. This is important in the modeling since the two factors can change quite independently of each other.

The current array dust line shows that the model dust factor is based on sol 1891 data, and has not been updated. The get_postDTE_time is the last known power state of the rover based on actual telemetry. The run_forward indicates whether or not the model predictions for battery SOC (and other integrated values) have been updated to the time of the last down link, and also projected to the starting time of the next planning cycle. Propagation of estimated battery SOC come from the MMPAT battery model given any power plan shown in update_inprofile. The predict_next_sol identifies if a prediction for the rover power condition for the next sol has been completed or not. Available solar array energy is based on current sol model management activities. The final line, summarize_sol, provides indication of available actual power values for a daily power summary used by the mission operations planning.

Thus, the status command provides a summary of daily power activity. As shown by the status in Fig. 1, the power activity is far from completion.

Update history

The rovers record up to 26 hours of essential power telemetry at 10 minute intervals in the BCB (battery control board) memory PROM, and are downloaded daily as "BCB History" files for state-of-health assessment. This is in contrast with normal telemetry which is recorded at one minute intervals, but only when the rover is "awake". In this step the history files for power are processed to the appropriate power subdirectory files for data querying.. BCB History files are not always received in a timely manner. This results in an inability to estimate the actual solar array energy received during the sol. For the present discussion it will be assumed that appropriate BCB History files are received and processed into the proper data folders.

Update tau

The atmospheric science team provides, from downloaded Pancam data a daily estimate of atmospheric dust also known as optical density or tau. [2] The update_tau program fetches this information and deposits it in its proper place in the power processing files (Fig. 2). It is important to have a daily reading of tau since it and the dust layer on the array are two big factors affecting power product that are to some degree unpredictable. Without knowing tau it is impossible to make an accurate estimate of the dust layer.

```
predict from sol: 1893
current LST: 1893/23:40
update_inprofile:  inprofile_hist.sip -> a1893_0935-
1894_1000_ap.sip (history ends at 1894/12:46:18.998)
Sol 1893 Tau:  0.862
current Tau: 0.862, from sol 1893
Sol 1893 Array Dust:   factor(Fo): 0.4182   adj: 1.1491 factor(Fo):
0.4101   adj: 1.0839
current Array Dust: factor(Fo): 0.4101 adj: 1.0839
get_postDTE_time:  1893/16:13:25.000
run_forward: not done
predict_next_sol: not done
summarize_sol: not done
```

Fig. 2. Update of tau

Update the dust factor

Once the tau value has been updated, the computation of the daily dust factor must be performed to support the MMPAT solar array model.   The main degradation mechanism impacting solar array performance is assumed to be dust accumulation. To ensure optimal model fidelity, a dust factor algorithm was developed to automatically compute a daily dust factor based on rover telemetry.   It has been found that sun angle interacts with the dust layer resulting in the actual dust loss. Therefore the sun angle must be used along with the observed power loss to compute a normalized dust factor. The dust factor represents the fraction of light remaining after the loss due to dust accumulation. (A factor of 1 corresponds to zero dust accumulation)

Finding the dust factor requires that the model be run in a "postdict" mode, where actual rover attitude, and bus voltage are fed to the model to eliminate any confounding effects of misestimated loads or battery SOC. (Fig 3.)

```
predict from sol: 1893
current LST: 1893/23:45
update_inprofile: inprofile_hist.sip -> a1893_0935-
1894_1000_ap.sip (history ends at 1894/12:46:18.998)
Sol 1893 Tau:  0.862
current Tau: 0.862, from sol 1893
Sol 1893 Array Dust:  factor(Fo): 0.4101   adj: 1.0839
current Array Dust:  factor(Fo): 0.4101  adj: 1.0839  from sol: 1893
get_postDTE_time:  1893/16:13:25.000
run_forward: not done
predict_next_sol: not done
summarize_sol: not done
```

Fig. 3. Update of dust factor

Run query

This step converts the data into formats that can be used by the MATLAB tool portion on MMPAT. This provides time phased plots of the downloaded data against the modeled data for the present day. It is at this point that the completeness of the data downloaded can be reviewed. The plots provide a quick glance as to the

overall status of the rover power system, including array output, temperatures, battery condition, voltages, as part of the suite available. A typical systems power graph is shown below in Fig. 4. Other graphs present information ranging from array and battery temperatures to rover orientation. Although the latter is not readily translated into actual power, glitches in array performance can often be related to movement of the rover, changing the sun orientation.
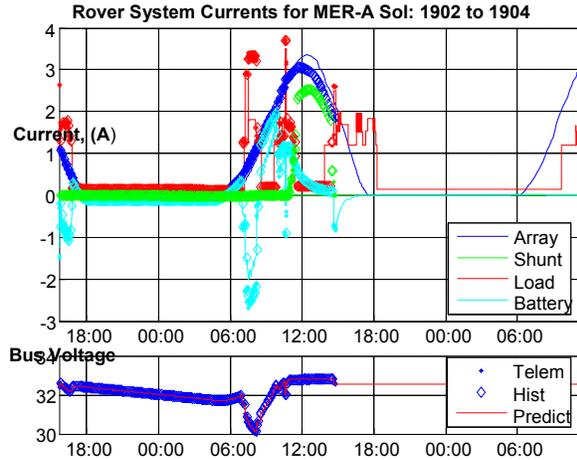

Fig. 4. Sample power system currents summary graphs from MATLAB

Get postDTE_time

This command ascertains the time of the rover's last know power state and creates a file containing important telemetry values such as battery SOC, and certain temperatures, among others.   Propagation of future predictions is based on the power state of this time. If telemetry data has not been received in time, see the next section, "Spoof".

Spoof

As mentioned earlier, it is not always the case that good downlink data is available. Sometimes there is not any downlink, due to other commitments on the Deep Space network for example. Or sometimes only partial data packets are received with missing power systems data. These situations are not frequent nor are they uncommon. The procedure then is to run a Spoof, rather than a get postDTE_time, which basically extends the previously known good data points forward in time. New tau and dust factor values will be missing. Obviously this adds to uncertainty in the predictions and in fact this greater uncertainty is included in the power report to mission planning.

Run forward

Run forward uses the MMPAT tool to now run the power loading, solar array input, and battery state, through the day just completed creating a model configuration file accurate as of the downlink time. It also projects a model configuration file as of the start time of the planning period for the next sol. This projected file is provided to the planning team to use with the model when developing and validating the next day's plan.

For the sol processing used in the example (Fig. 5), it can be seen that the current LST has changed from 1893 to 1894. In other words the date on Mars has changed as the clock moved past midnight. Since the length of a day on Mars is slightly longer than a day on Earth, the relationship between Martian time and earth time continually moves. In the early days of the Rover mission, the desire to provide synchronized commanding and operations of the rovers meant that the operations personnel would start their work day about 40 minutes later each day causing day shifts to gradually turn into night shifts and vice versa.

```
predict from sol: 1893
current LST: 1894/00:39
update_inprofile: inprofile_hist.sip -> a1893_0935-
  1894_1000_ap.sip history ends at 1894/12:46:18.998)
Sol 1893 Tau: 0.862
current Tau: 0.862, from sol 1893
Sol 1893 Array Dust: factor (Fo): 0.4290 adj: 1.1340
current Array Dust: factor (Fo): 0.4290adj: 1.1340
get_postDTE_time: 1893/16:13:25.000
run forward: SOC: 1894/08:00: 9.3 ahrs1894/12:47: 13.4 ahrs
predict_next_sol: not done
summarize_sol: not done
```

Fig. 5. Update of run_forward

Predict next sol and report

Predict next sol predicts the energy expected to be available on the next sol. Report produces a concise report that includes the energy estimate as well as the expected starting battery SOC. This report is provided to planners to be used in the initial stages of the planning process to rough out a plan. (Fig.6)

```
predict from sol: 1893
current LST: 1894/00:42
update_inprofile: inprofile_hist.sip -> a1893_0935-
  1894_1000_ap.sip (history ends at 1894/12:46:18.998)
Sol 1893 Tau: 0.862
current Tau: 0.862, from sol 1893
Sol 1893 Array Dust: factor(Fo): 0.4290 adj: 1.1340
current Array Dust: factor(Fo): 0.4290 adj: 1.1340 from sol: 1893
get_postDTE_time: 1893/16:13:25.000
run forward: SOC: 1894/08:00: 9.3 ahrs 1894/12:47: 13.4 ahrs
predict next sol: Solarray: 385.5 whrs Heaters: 0.0  whrs
94/05:00 shtdn 1894/14:40 sunset: 1894/17:55
sunrise: 1895/05:01 SOCtarg: 12 ahrs shad: on
summarize_sol: completed and available for report!
```

Fig. 6. Update for predict next sol and report

Summarize_sol

This command provides a detailed summary of the critical MMPAT power analysis formatted as a single line destined for a spreadsheet that allows for easy viewing and reporting. It is most useful for reviewing multi-sol trends. (Fig. 7)

```
Model Tau at Noon = 0.862
Predict Solar Energy = 369
Total Solar Energy = 392
Peak Array Current = 1.91
Total Shunt Energy = 96 Max SOC = 13.7
Min SOC = 11.5
Min Usable SOC = 10.1
Min Bus Voltage = 31.14
Max sspa Temp = 20.85
Min sspa Temp = -11.21
Max Batt Temp = 16.46
Min Batt Temp = 0.44
Max Battl cellV spread = 0.060
Max Batt2 cellV spread = 0.077
Min Battl cellV = 3.93
Min Batt2 cellV = 3.92
Predict Next Sol Predict = 373
```

Fig. 7. Summarize_sol results

Summary report

With a convergent summarize_sol and MATLAB plots showing that the downlink data for not only the solar array but also batteries was sufficiently complete, a summary report is printed as shown below in Fig. 8. The first section presents the power data summary for the day completed by the rover. This includes the maximum and minimum battery state-of-charge through the period, the total solar array energy and peak current. In addition, there is an entry for shunt energy, the amount of solar energy that was in excess of operational power needs and battery recharging.

The second part of the summary print out is the prediction for power system performance over the next sol.

```
SPIRIT POWER downlink report for SOL 1893   Fri 2009-05-01 15:19:30 UTC

ACTUAL RESULTS FOR SOL 1893:
    Maximum SOC = 13.7 A-hrs
    Minimum SOC = 11.5 A-hrs
    Total Solar Array Energy = 392 W-hrs
    Total Shunt Energy = 96 W-hrs
    Peak Solar Array Current = 1.91 Amps

Following predicts based on EH&A data as of
1893/16:13:25.000 LSTA

    SOC at 1894/08:00:  9.3 A-hr (1.0 A-hr uncert)
    SOC at 1894/12:47: 13.4 A-hr (1.0 A-hr uncert)
    Solar Energy, sol 1894:  385 W-hr  (20 W-hr uncert)
    tau: 0.862  as of Sol 1893.0
    dust factor: (Fo): 0.4290 (adj): 1.1340 (Sol): 1893.0
```

Fig. 8. Summary report for Sol 1893

A MAJOR DUST CLEANING EVENT

As mentioned previously, the daily power performance modeling for the MER rovers is necessary due to rapid changes that can occur in tau or the array dust coverage. Fig. 9 (actuals) and 10 (predicts and actual tau and dust factors) present results from the Sol 1900 Spirit report, 7 days after the example above. Solar array energy has increased by 67% with a corresponding increase in peak solar array current. This is seen to be the result of a modest decrease in atmospheric dust (tau), and more importantly, a large increase in the dust factor, indicating a major dust cleaning event had occurred prior to Sol 1900. Downlink data on subsequent sols confirmed the dust factor values. The 0.6755 dust factor was the highest seen since 630 sols previously.

```
ACTUAL RESULTS FOR SOL 1900:
    Maximum SOC = 14.1 A-hrs
    Minimum SOC = 11.8 A-hrs
    Total Solar Array Energy = 656 W-hrs
    Total Shunt Energy = 283 W-hrs
    Peak Solar Array Current = 3.15 Amps
```

Fig. 9. Telemetry data results for Sol 1900.

```
predict from sol: 1900
current LST: 1900/20.21
update_inprofile: inprofile_hist.sip -> a1900_0935-
1901_1000_ap.sip (history ends at 1901/10:12:01.001)
Sol 1900 Tau: 0.806
current Tau: 0.806, from sol 1900
Sol 1900 Array Dust: factor(Fo): 0.6755 adj: 1.0936
current Array Dust: factor(Fo): 0.6755 adj: 1.0936 from sol: 1900
get_postDTE_time: 1900/15:36:54.000
run forward: SOC: 1901/08:00: 10.9 ahrs 1901/10:12: 13.1 ahrs
predict next sol: Solarray: 672.7 whrs Heaters: 0.0 whrs sunrise: 1901/05:05 wake: 1901/09:48-09:53 shtdn 1901/15:55 sunset: 1901/18:01 sunrise rise: 1902/5:05 SOCtarg: 12 ahrs shad: on
summarize_sol: completed and available for report!
```

Fig. 10. Prediction for Sol 1901 performance based on 1900 actuals and 1901 operations plan

The MATLAB plot for rover array current for Sol 1899 (May 7, 2009) is quite interesting. From Fig. 11, a dramatic increase in array current over the expected prediction (solid red line) at approximately 11am is quite clear. The BCB history and normal telemetry data are basically the same with history data down linked as a data "dump" from BCB memory storage and the telemetry data from telemetry memory storage. The interval over which the current increases is approximately 2 minutes (the interval between the quickly changing data points in the plot). This is consistent with dust removal through a "dust devil" rather than an overall increase in wind activity. Although speculative, the single telemetry data point at ~11:56 am located well below the adjacent history and telemetry values is possibly at the time when the "dust devil" passed over the array, reducing sunlight with it's churned up dust cloud. During this time the Rover (and array) had a net tilt of ~16°, possibly aiding in the dust removal. The array power estimate for Sol 1901 shows a further increase of 2.5%, which combined with the previous increase totals nearly 70% increase in array power. The majority of this is attributable to reduced dust coverage of the array, with a secondary factor being the reduction in atmospheric dust (tau).
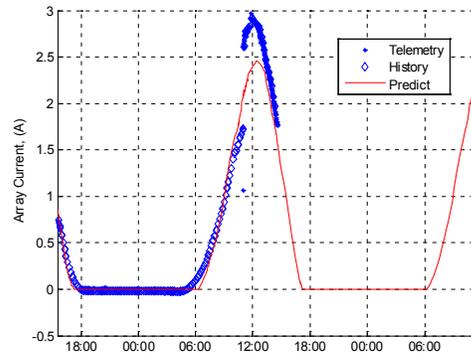

Fig. 11. Rover array current for Spirit on Sol 1899

The result of this cleaning event and subsequent smaller events has been to return Spirit to near pristine cleanliness and a more than 2 fold increase in power. (Fig. 12)
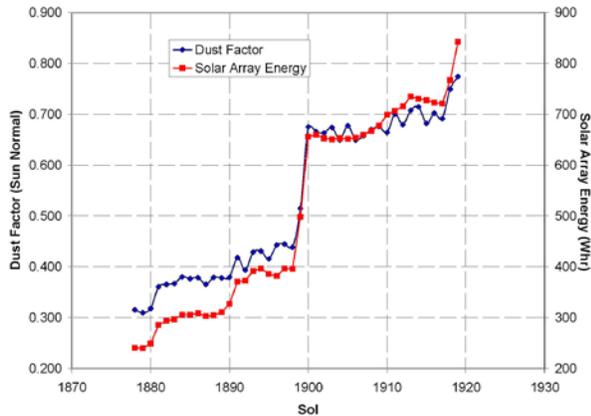

Figure 12. Spirit dust cleaning results

CONCLUSION

The MER rovers have provided an opportunity to develop a model and analysis process for long term Mars surface PV/battery operation. It is interesting to realize that if the MER rovers had not continued much beyond their initial goal of 90 Sols, much of this engineering capability would not have been developed. From a simple model using linear dust degradation assumptions, the added capabilities were augmented to accommodate the needs of a much more ambitious and scientifically rewarding mission. Combined with the development of very low power modes for the Rover, deep sleeping for example, with its minimal overnight power draw, the 90 days have continued to more than a half decade of operation. At this time, it is felt that the power system capabilities remain at a level that would allow operations for many additional years.

The major limitation of array power continues to be the influence of atmospheric or deposited dust. The experience to date has shown that typically changes in atmospheric dust are tolerable with the possible exception of the infrequent major dust storms. At the same time, the winds that drive up the atmospheric dust have also removed dust from the solar arrays. The deposited dust is a greater problem because it persists for very long times with heavy reduction of sunlight onto the solar panels. A major dust removal event, recorded in the Spirit data downlink, has been presented herein. It is notable for the short duration of the dust removal, and the suggestion of the occurrence of a "dust devil".

The MER experience indicates that long term PV/battery systems can be used on Mars through appropriate design. Rovers or planet wide stationary science stations (weather, seismic, etc.) come to mind as realistic applications. Development of a reliable method for array dust removal from solar panels would be a key feature in extending mission life. Combined with low power modes, including temporary cessation or reduction of science data acquisition to accommodate severe dust storms, decade or longer operations should be considered feasible.

REFERENCES

[1]   Geoffrey A. Landis and Phillip P. Jenkins, Ohio Aerospace Institute, NASA John Glenn Research Center, Cleveland, Ohio, Measurement of the settling rate of atmospheric dust on Mars by the MAE instrument on Mars Pathfinder, Journal of Geophysical Research, Vol. 105, No. El, Pages 1855-1857, Jan. 25, 2000

[2]   Jeffrey R. Johnson,[a],* William M. Grundy,[b] and Mark T. Lemmon[c], (a) United States Geological Survey, Flagstaff, AZ, (b) Lowell Observatory, Flagstaff, AZ, (c) Department of Atmospheric Sciences, Texas A&M University, College Station, TX, Dust deposition at the Mars Pathfinder landing site: observations and modeling of visible/near-infrared spectra, Icarus 163 (2004) 330–346