Energy Management Operations for the InSight Solar-powered Mission at Mars

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Abstract—**NASA's InSight Discovery mission to Mars will land its Phoenix-heritage spacecraft to the near-equatorial Elysium Planitia region of Mars in November 2018 - instead of its original planned landing in September 2016 - to collect science measurements over a period longer than one Mars year. Thus, instead of arriving in mid-Mars-global-dust-storm season in 2016 as originally planned, InSight now will arrive in 2018 during the Martian season when dust storms are typically waning. However, it must be able to withstand a global dust storm near the mission's end a Mars year later, by which point dust on the solar arrays is likely to have accumulated significantly more. This paper discusses how the change in launch date has changed the energy management challenges for InSight, and how the energy management approach for surface operations has been adapted to address those challenges. It also describes how energy balance and battery life are protected over the course of the InSight landed mission, in terms of a deliberate balance between autonomous on-board fault protection and ground commanding into reduced-load configurations that still make progress versus specific, prioritized mission success criteria. It describes the project's unique statistical analysis and usage of Mars Exploration Rovers (MER) archived data on solar energy collection to develop and validate an explicit pre-launch margin policy versus energy reductions due to environment variability over multiple-sol sequences. And finally, the paper explains how this archived energy data has influenced the modification of the Phoenix-heritage autonomous fault protection, to guard against quickly-arising inclement power-generation conditions, such as rapid onset of a local dust storm or water ice cloud front.**

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1. INTRODUCTION

In December 2015, NASA announced the delay of the InSight (for "Interior Exploration using Seismic Investigations, Geodesy and Heat Transport") Discovery mission to Mars from its original planned launch in March 2016 until the next possible launch period, in May 2018. InSight now lands a solar-powered Phoenix-heritage lander spacecraft (Fig. 1) to the near-equatorial Elysium Planitia region of Mars in November 2018, to collect science measurements over a period longer than one Mars year.

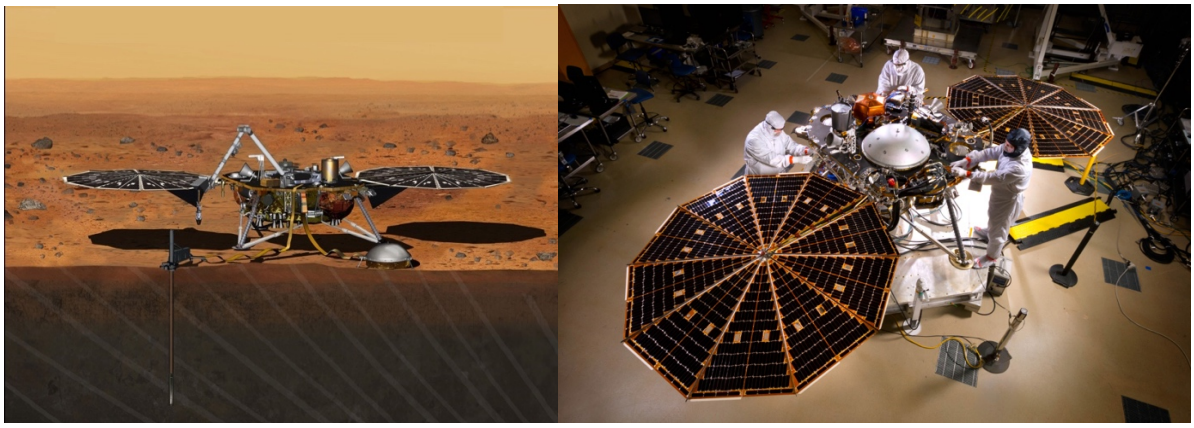

Fig. 1: *At left, the solar-powered InSight Lander with its instruments deployed, as it will appear on the surface of Mars. At right, the InSight Lander during its first landed solar array deployment test at Lockheed Martin in Denver, Colorado, in 2015. InSight's landed solar arrays are the largest ever to operate on the surface of Mars; under benign tilt and dust conditions they are capable of generating up to about 4 kilowatts of power.*

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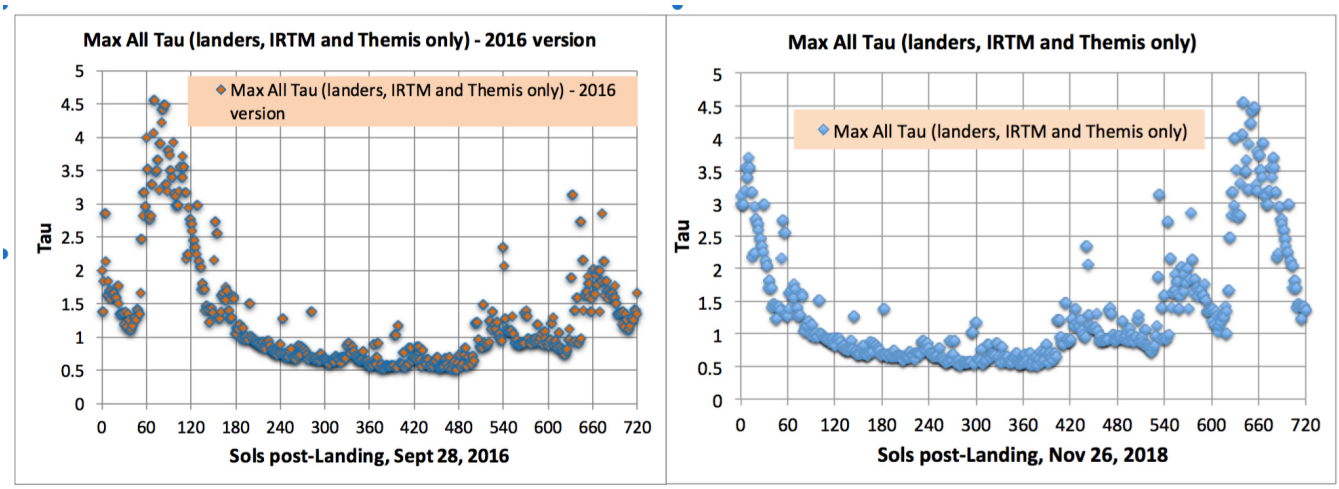

Fig. 2: *Comparison of maximum atmospheric dust opacity (tau) for InSight launch opportunities in 2016 (left, orange symbols) and 2018 (right, bright blue symbols). Note that the peak historic dust storm season now occurs near the end of the mission, whereas it had previously been occurring near the beginning of the mission.*

A key implication of the slipped launch and arrival period is that instead of arriving in mid-global-dust-storm season in September 2016, as originally planned, c.f. Lisano and Bernard, 2013 [1], InSight will now land in a season when the latest-observed global dust storms were waning. While battery discharge levels and energy margins will be prudently monitored regardless, landing after the historical peak of global dust storm season alleviates concerns over solar energy sufficiency while deploying instruments during the start of the surface mission.

However, InSight also must be able to withstand a global dust storm[1] near the mission's end a Mars year after landing, by which point dust on the solar arrays may have accumulated significantly. This is the reverse of the global dust storm scenario that had been originally assumed in developing InSight's surface energy strategy for in the 2016 opportunity, i.e. landing and deploying instruments just before the peak of the global dust storm season, but finishing the primary mission before the peak of the next dust storm season (Fig. 2).

The lander and its unique suite of instruments - a 3-axis precision seismometer and a self-drilling heat probe both deployed with a robotic arm onto the Martian soil - have been designed to operate and/or survive while maintaining a margined battery-charging energy balance every sol, even under the combined effect of worst-observed atmospheric dust opacity ("tau"), worst-case tilt of the solar arrays and a conservative dust accumulation rate on the solar panels that assumes no wind cleanings during the entire mission. The combined ground-based and autonomous on-board monitoring and control of power margins, i.e. power generated and stored vs power consumed, is referred to as InSight's "energy management".

InSight is a lander system with strong spacecraft design heritage rooted in the Phoenix mission. However, Phoenix, unlike InSight, was designed to last for just 90 sols, and landed near the Martian north pole, far from our near-equatorial landing site at Elysium, and this was during the low-atmospheric-dust season (a regional dust storm did contribute to the eventual loss of contact with Phoenix, as polar winter was closing in and sunlight was less available, weeks after successful completion of its primary mission). To establish requirements, designs and operating principals for InSight's Mars-year-long near-equatorial mission, extensive usage was made of archived data for daily atmospheric dust optical depth, solar energy collection, and battery performance from the Mars Exploration Rovers (MER).

In this paper we describe the energy management approach for the InSight mission, and how it was developed using the data in the Dust Storm Almanac described in Lisano and Bernard. We summarize key data and analyses that gave rise to its set of energy-constrained operating profiles and also its manner of autonomously protecting energy balance, in particular during dust storms. We also discuss how the change in launch date has changed the energy management challenges for InSight, and how we adapted the energy management approach for surface operations to address those challenges.

2. InSight Energy Management Overview

During design, integration and testing of flight system, the InSight project has devised a set of energy management policies that are focused on limiting loads and protecting battery life over InSight's Mars-year-long surface operations.

[1] The likelihood for any given Mars year to experience a global dust storm is about 1 in 3, based on the observation by Zurek et al, 1993 [2] that global dust storms typically occur in one out of three Mars years based on astronomical records and Mars spacecraft data. As of writing this paper in 2016, no global dust storm has been observed on Mars for nearly *five* Martian years, since the storm that hampered the Spirit and Opportunity Rovers in July 2007. Prior to the launch slip, it had been a common sentiment among the InSight team that we were likely going to experience a long-overdue global dust storm upon landing in September 2016.

Chief among these project policies are:

1. In-situ measurements of atmospheric optical depth (tau)[2] are made each sol during deployment, with a goal of continuing tau measurement trending on a weekly basis post-deployment.
2. All commanded and autonomous loads executed on the lander will result in energy balance each sol, i.e. recharging the battery each day for net zero daily draw-down.
3. Battery state of charge (based on two healthy batteries with normal levels of capacity fading with time) is to be above 40%.
4. Along with maintaining energy balance, size all loads to have 15% margin[3] versus collected solar energy, to accommodate load modeling errors such as underestimated heater loads, plus an additional margin for environment uncertainty over execution duration of a command sequence.

InSight energy management implements these policies throughout the landed mission, primarily by constraining commanded daily spacecraft and instrument loads to be safely margined beneath conservative predictions of generated energy.

The InSight development team defined a set of reference, driving power load profiles that are designed by superposing instrument and other loads upon the Phoenix lander's safe mode daily activity profiles versus time. These reference profiles (c.f. Fig. 3) correspond to the main scenarios planned for surface operations, and are used for sizing power loads over a sol. The profiles treat the following operating scenarios:

- Deployment survival
- Post-deployment survival
- Penetration
- Full, Conserve, and Minimum Science collection

All of the above profiles are modeled by starting with the post-deployment survival profile shown in Fig. 3, and adding loads, e.g. constant added power draw for instruments - which are left on and collecting data even while the spacecraft command and data handling subsystem (C&DH) is configured for low-power "sleep" mode - but with no change to the load "chimneys" corresponding to C&DH wake-ups for fault protection diagnostics and telecom/science data relay to Earth. The Landing Sol power profile is a special case which has also been assessed but is not discussed in this paper. Details of each profile are not given in this paper but are described in an InSight project memorandum [3].

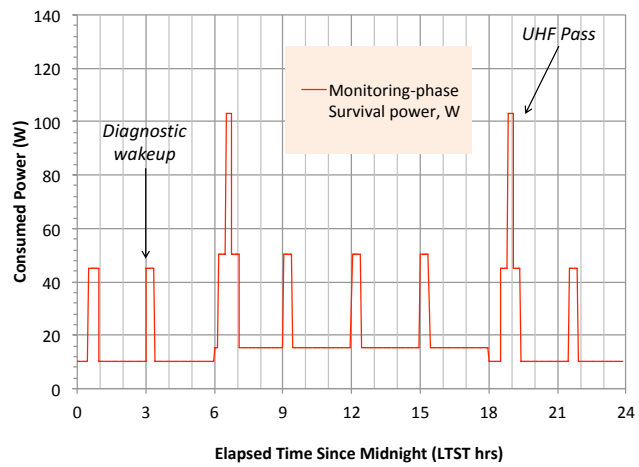

Fig. 3: *Daily Load Profiles on InSight (such as the Survival Power Profile shown here) consist of ~20 hours per sol of C&DH inactivity ("sleep", low flat portions of the red curve) and ~4 hours per sol of C&DH activity (chimney-like features in the red curve), including retrieval of instrument stored data onto spacecraft memory for routing via UHF uplink to Earth, and several-minute-long fault protection diagnostic wake-ups every few hours.*

Power-attenuating events ranging from local ice cloud coverage or regional dust storms that might only last a small number of sols, to planet-encircling global dust storms that would last for weeks, are monitored for and responded to with a combination of autonomous on-board fault protection and ground-based trending of atmospheric dust optical depth ("tau") and also daily solar power generation.

Survival Profiles - The response to ground-based detection of dust storm onset is to command the spacecraft into a survival power profile that consumes minimal energy while protecting spacecraft hardware and maintaining communications for health and safety. A survival profile is commanded either directly via configuring flight software parameters (e.g. enabling survival instead of operational heaters), de-activating payloads, and sequencing minimal C&DH and telecom activities, or via spacecraft safe mode (which always places spacecraft on a pre-loaded, minimum-energy activity profile).

Deployment Survival - The survival profile consumes higher power during the instrument deployment period (the first several weeks after landing), due to the need to maintain certain mission-critical heaters on, that are nominally turned off after instruments have been deployed to the surface. Specifically, during the instrument deployment period and until there is no further need to operate the arm, the joint motors of the Instrument Deployment Arm (IDA) are heated to maintain them at safe temperature levels that avoid

[2] The mission will also trend dust accumulated on the solar arrays based on tau measurements and solar array power telemetry.

[2] The modeling error margin is 25% during the first two weeks of surface operations, as actual thermal and power performance of the landed vehicle is characterized with telemetry.

potential breakage of motor windings due to extreme cold. These heaters consume approximately 300 Wh per sol on a moderate-to-high tau sol.

In atmospheric dust levels that result in moderately reduced energy the lander is commanded into a "conserve" or "minimum science" configuration, with only a subset of instruments activated, so prioritized science measurements can continue. Both the power load and power generation/storage model are strongly influenced by the temperature environment acting on the Lander. External temperature is modeled as a function of time of day and also season, using a reduced-node approximation derived from the InSight high-fidelity system thermal model. During surface operations, this thermal model is correlated with spacecraft thermal telemetry and used to predict heater activation and power usage; predicted heater loads are factored into the daily load planning, to ensure the combination of avionics and heater energy usage per sol remains margined beneath predicted daily solar energy generation.

3. Environment Uncertainty Margin

A key constraint impacting InSight surface operations is that given its flight operations (Phase E) staffing levels, which are streamlined to maintain an "economical" Discovery mission cost profile, new sequences – including commanding of all planned activities for instrument on-time, and avionics wake periods, communication passes, and heaters - will be developed and uplinked to the Lander on a weekly basis, after the instruments have been deployed and commissioned on the surface of Martian. Given that new command sequence development, verification and uplink are expected to take 3 – 5 days to turn around, the total energy consumption per sol must be constrained to provide margin for possible energy supply shortfalls due having uncertainty in tau and dust accumulation levels over 12 sols between data cut-off for power generation telemetry and uplink of a new science sequence. Thus, an energy margin policy for solar-power-generation environment variability was developed based on a conservative analysis of archived, collected MER solar energy data, during those rovers' stationary periods lasting 30 sols or longer.

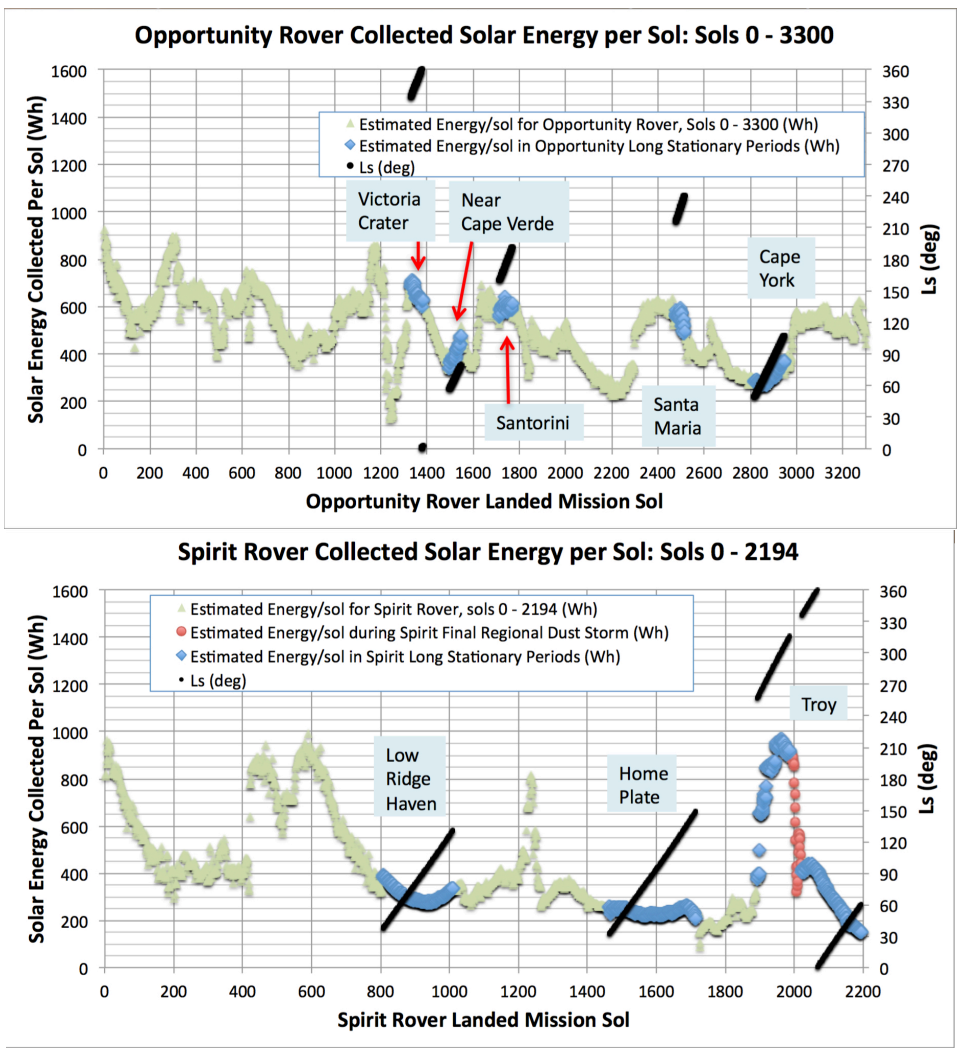

Fig. 4. *The estimated daily energy of the MER rovers (Spirit and Opportunity) are unique and valuable observations of the transient effects on solar energy generation by Mars surface environments, and require no in-situ measurement of tau.*

Stationary periods are used to limit the causes of variability in collected energy chiefly to daily environment variability, and eliminate day-to-day changes in rover solar array orientation associated with rover movement. Reconstructed solar energy collected per sol, based on daily power telemetry received on the ground, are shown in Fig. 4 for both Opportunity and Spirit rover extended stationary periods (blue and red symbols) in dusty and clear seasons.

The top energy plot in Fig. 4 shows that the Opportunity rover, located in Meridiani (which is the opposite side of Mars from InSight's landing site) generally experienced shorter extended non-mobile periods (blue symbols) than Spirit. Approximately 328 sols' worth of extended-stationary energy data were found for Opportunity. The bottom energy plot shows that the Spirit rover, in Gusev crater (the closer of the two MER sites to InSight's landing site) experienced three lengthy, non-mobile periods (blue symbols), at Low Ridge Haven, Home Plate and Troy (where Spirit became stuck, and contact was eventually lost with Spirit). Spirit's final period included a dust storm (red symbols). 726 sols' worth of extended-stationary energy data were identified for Spirit.

The variability in rover energy is calculated as the maximum reduction over N sols after a "zeroth" sol on which energy collection is estimated/measured based on telemetry. Fig. 5 shows, for both Opportunity and Spirit rovers during the "long" stationary periods, the average, 95% and 99%-ile maximum reduction in collected energy, over N elapsed sols. That is, the variability is given as a function of both (1) sequence duration and (2) a desired uncertainty / risk level, as statistical percentile. As these data are being used to evaluate margins for nominal operations, the 2007 global dust storm is not included in the stationary periods; nor is the regional dust storm experienced by Spirit. Opportunity energy was reduced ~10% over 12 sols, 99%-ile, based on 328 stationary sols (Fig. 5, top). However, Spirit energy was reduced ~17% over the same period, based on 726 stationary sols and not including the regional dust storm (Fig. 5, bottom).

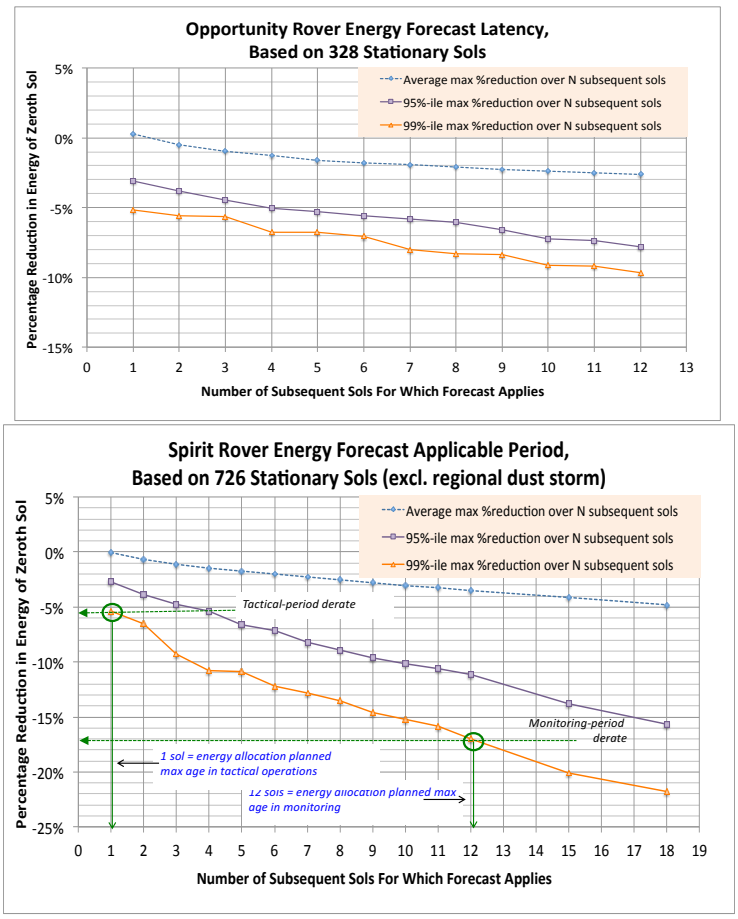

Fig. 5. *The stationary-rover energy data (blue symbols in Figure 4) were used to derive statistics on the variability of solar energy over periods of several sols. At top, statistical curves for Opportunity rover's energy variability based on energy data plotted, for immobile periods for ~30 sols or more. At bottom, corresponding energy variability curve for Spirit rover. These plots indicate that Opportunity, at Meridiani, was less subject to energy loss from atmospheric and accumulated dust over several-day periods than Spirit, at Gusev. Based on this, and noting that Spirit's location is much closer to InSight's landing site than Opportunity's, the orange curve in Figure 5.b for Spirit is used to establish the InSight environment variability margin.*

Table 1. *Energy Management margin policies and key operation cadences change as InSight surface operations progress from landing through deployment, HP3 mole penetration, and science monitoring. Dust storm survival operations have been a driving design case as well.*

Surface Operations Scenario:	***Post-landing Commissioning Period***	***Deployment Period***	***Penetration/ Monitoring Period***	***Dust Storm Survival***
Nominal Number of Sols	*0 - ~4 (incl. 1st tau observation)*	*~5-52*	*53 – 709*	*~3 per regional storm, ~45 for global storm*
Sequence Support Interval	*Daily/Tactical*	*Daily/Tactical (with strategic forecast ~weekly)*	*Weekly (with strategic forecast ~ monthly)*	*Daily/Tactical (with forecasts after storm peaks)*
Tau Observation Frequency	*None or Few*	*Daily*	*Weekly*	*Goal: Daily/as possible*
Key Load Profiles to be evaluated	*Spacecraft and payload check-out, commissioning activities*	*Max Deployment, Conserve, Minimum*	*Max Penetration, Full, Conserve, Minimum + Cold Season heaters*	*Survival Profile*
Margin Policy: Energy Margin held for load allocations	*25% for model predict uncertainty + 5% for environment variability*	*15% for model predict uncertainty + 5% for environment variability*	*15% for model predict uncertainty + 17% for environment variability*	*15% + all remaining available (Survival is Minimum-energy profile)*

InSight project energy margin policy for environment variability is based on the 99%-ile Spirit curves, to de-rate allocated energy, over and above the 15% energy margin policy vs model uncertainty (consistent with institutional best practices and prior Mars lander missions).

While expectations are that during flight operations, the InSight surface operations team will actively trend the power-generating environment and adjust load-planning margins accordingly as activities are planned, this pre-launch analytical sizing of environment variability margin has enabled us to validate that InSight science operations will be compatible with solar power variability levels seen before at Mars, and hence are expected to be manageable over multiple-sol sequences. Table 1 details the resulting total energy margin policy, as it is applied to four key operating scenarios in surface operations.

4. DUST STORM ONSET DETECTION WITH ENERGY TRENDING

Measurements of tau are planned daily using the camera mounted on the IDA during deployment, and while they are not required after deployment, they are planned nominally twice per week during science data collection for the rest of the mission. Hence, if the IDA is decommissioned after instrument deployment due to either arm motor degradation or to avoid its large heater power loads, the IDA will be placed in a static pose[4] that enables continued sky imaging for optical depth.

Given that the IDA and its camera could be non-operational during the later seasons of the InSight surface mission, when atmospheric dust activity as well as rapid-onset ice cloud formations could hamper power collection, both on-board and ground-based methods for detecting quickly-arising threats to energy margins – without resorting to daily measurement of tau - were in order. This need led to updates to the Phoenix onboard flight software autonomy, discussed further down, as well as ground-based criterion based on trending of estimated onboard daily energy collection that incorporates spacecraft solar array power telemetry.

Again, the source for the criterion are solar energy collection data from the MER rovers. Fig. 6 is a plot of Spirit rover energy as it experienced a dust storm near the end of its' life, at the Troy site. Red triangle symbols in Figure 6 indicate sols when the criterion would indicate an impending or in-progress dust storm. The criterion was tripped twice based on this Spirit late storm energy data, corresponding well with sol-by-sol variations in optical depth measurements made independently using Spirit's Pancam camera. The same test criterion also successfully predicted the rise-up of the Meridiani regional dust storm of October 2014, in testing with Opportunity rover data collected during that storm (not shown here).

The storm arrival criterion was also evaluated using data from 8 Spirit and Opportunity "long" stationary periods without local dust storms or significant short-term variability in daily energy. The criterion did not give any false positive indications over hundreds of sols of stationary-rover energy data, and thus is assessed to be appropriately sensitive to a power-reducing event without being overly hair-trigger. The "15% drop in 3 sols" rule trips only during periods when tau is increasing in a dust storm or ice cloud front.

[4] Tau imaging analysis by M. Lemmon calls for maintaining the InSight camera pointing at 15°-25° elevation above the southern horizon [4] for sky imaging ~90° in azimuth from the sun direction, in the mid-to-late afternoon.

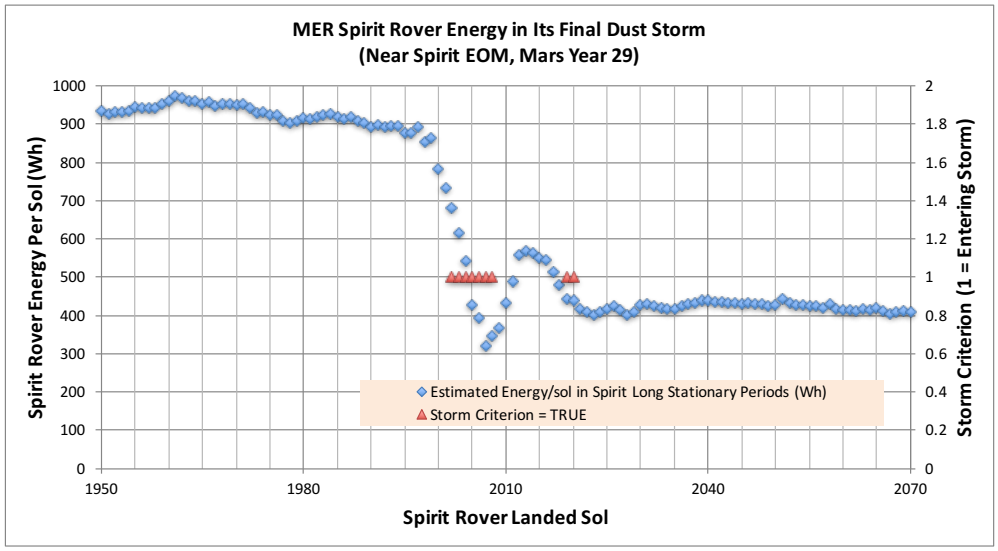

Fig. 6: *Test of a test criterion for detecting onset of a local or regional dust storm based on energy trending, using MER Spirit rover solar energy collection data from near the end of its life (corresponding to red symbols in plot of Fig. 4). Mars Year 29 refers to the 687-Earth-day Martian year that occurred from Dec 9, 2007 – May 3, 2009.*

5. On-board Energy Balance Protection

To guard against unforeseen changes in the dust environment or other events that would adversely affect InSight's power situation, autonomous checking of the health of the power subsystem is incorporated into the onboard fault protection flight software. The design of these fault detection algorithms and their corresponding responses are based on those used on Phoenix, and augmented to better accommodate the operational scenarios and longer surface mission of InSight. These checks include the following:

1) Measuring the power used by each component and comparing it against a worse case power value. A violation of this check, called the "Modeled Power monitor", would indicate that the component has failed in such a way as to draw more power than allowed, so the response in this case is to turn off the component, and flag its condition as "failed" so that other elements of the fault protection system can take appropriate action.

2) Calculating the state of charge (SOC) of the battery based on temperature, voltage and current measurements, and comparing this result with a threshold value that reflects the 40% minimum SOC policy. This check, called the "SOC monitor" also ensures enough energy is stored in the afternoon to allow nominal nighttime operations. A violation of this check results in aborting the nominal sequence of activity and entering safe mode to power off all payloads and assert survival profile operations. See top plot in Fig. 7.

3) Measuring the solar array power and comparing against a configurable lower threshold. A fault detected by this check, called the "Modeled Energy monitor", means the solar array is not producing enough power at that time of sol, which could be caused by a sudden dust storm. The response to this fault is similar to the Low SOC response, where the nominal activity is cancelled and survival profile operations are invoked. See bottom plot in Fig. 7.

In the case of (2) and (3) above, the nominal value of Battery SOC and solar array power varies as a function of the time of sol, therefore the fault threshold for each is represented as a time-varying function rather than a flat line. Fig. 7 illustrate how nominal measurements of these two metrics would compare against notional threshold values.

An analysis of energy levels in median and worst-case tau levels, with a conservative model assuming no wind cleanings of dust accumulated on the solar arrays, was used to establish the limit that the Modeled Energy monitor in spacecraft's onboard fault protection compares measured power production against. See Fig. 8. The black curve is a model of energy collected vs mission sol, in median tau conditions; the power level declines with an exponential accumulation of dust on the solar panels, and varies with changing season as well as moderate atmospheric dust fluctuations. The blue curve is the energy that would be (hypothetically) allocated by the ground team for loads per energy management policies, based on having received spacecraft power telemetry indicating power generation at the median level (black curve), and derating that measured power for power modeling uncertainty and environment variability (per margin policies in Table 1). The gold curve is the power that would be collected in the worst-measured dust levels (Fig. 2).

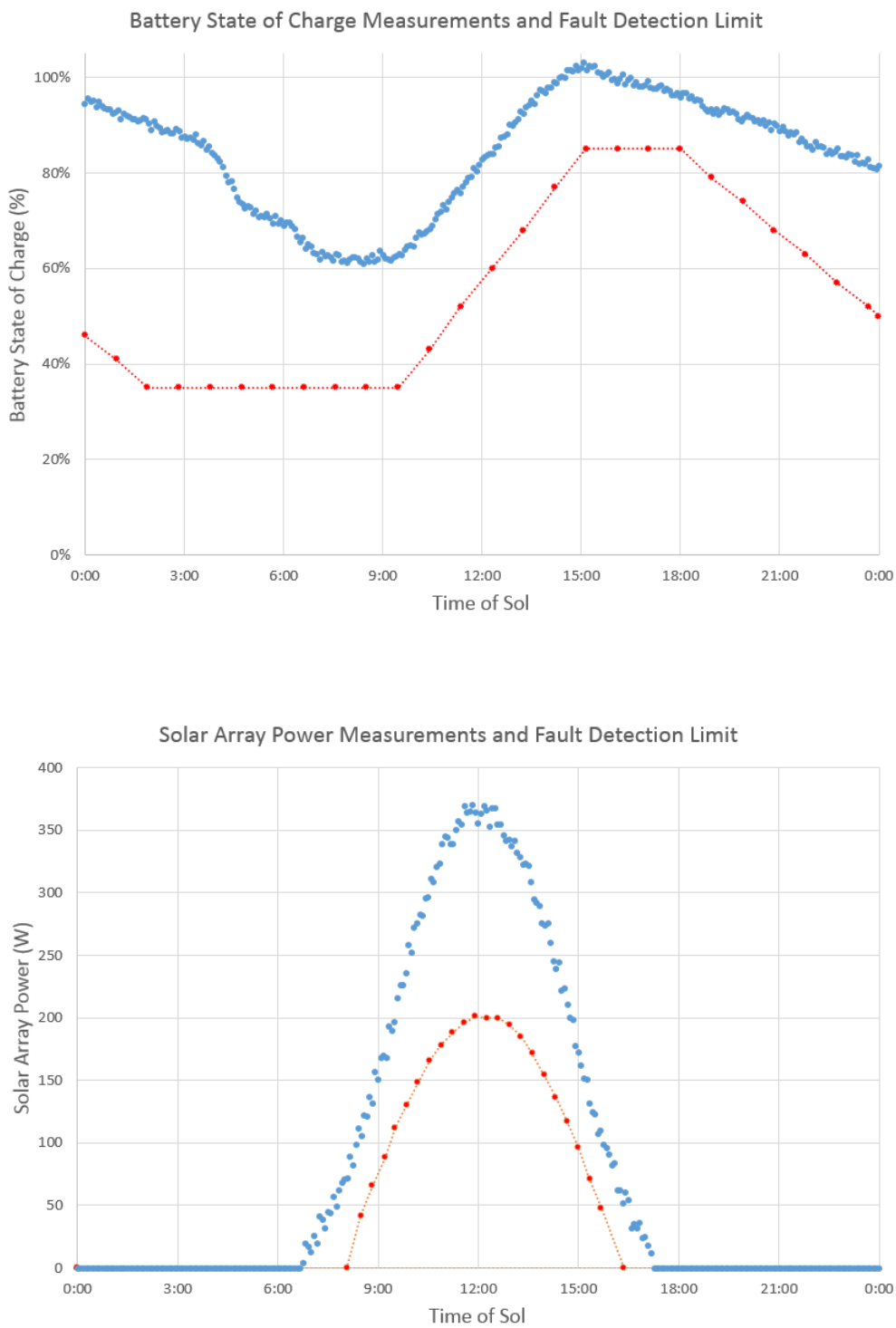

Fig. 7: *Examples of how a typical battery SOC and solar array power measurements (in blue) compare against onboard fault protection limits (in red). When the measured value dips below the red threshold line for either check, the nominal sequence is aborted and safe mode is invoked. This allows the lander to preserve energy, and the ground would command the lander back into nominal operations when conditions improve.*

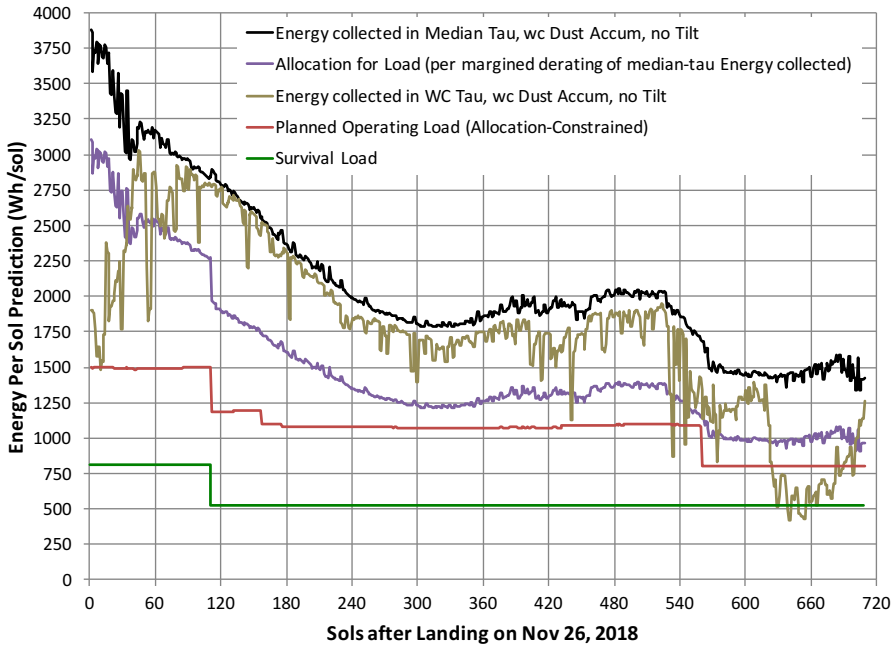

Fig. 8: *Onboard Modeled Energy monitor is based on solar array current, and is triggered when indicated power collection levels fall below the expected daily load level, to protect energy balance versus sudden reductions in available energy.*

The spacecraft is placed in safe mode – and hence on a survival power profile – by the Modeled Energy monitor when onboard power estimates based on solar array current and voltage fall below the expected daily load level (e.g. when the gold curve falls beneath the red curve in Fig. 8), in order to protect energy balance versus sudden reductions in available energy e.g. due to rapid onset of a local dust storm or an ice cloud front. Sols on which worst-case energy collection falls beneath the green survival load curve (an unlikely but not impossible occurrence) would require un-replenished usage of energy stored in the battery on that sol.

6. Energy Management Workflow

The above margin requirements and policies have been synthesized into a daily surface energy management workflow in operations that proceeds as follows:

A. If energy-trending data - and tau/environment observations as available - indicate presence of a dust storm, then the ground commands entry into a survival power profile.

B. Otherwise, a planned deployment or science sequence is deemed "Go" for energy by the energy management lead if all of the following are satisfied in the energy model:
   1) Energy Allocation Sufficiency: The margined and derated Energy Allocation for the upcoming sequence is above the FP modeled energy monitor threshold (unless we are planning to be in Survival and/or spacecraft safe mode)
   2) Energy Load Compliance: Predicted per-sol loads for each sol of the sequence period (including all heaters) consume less energy than the per-sol Energy Allocation for that sequence
   3) Battery State of Charge Sufficiency: Minimum battery state of charge predicted each sol, based on 99%-low collected energy occurring each sol, is above the FP SOC monitor threshold
   4) Predicted battery temperature does not exceed hot AFT's during the sequence interval.

C. If any of (1) – (4) is not true, energy management lead will report on the specific risks of sending up the sequence with the violation(s) un-remedied, and suggest one or more load reductions to remedy the violation(s).

7. Impacts of the Launch Delay on Surface Energy

To understand the changes to InSight surface energy management due to the launch date slip, we consider (1) the effect of delaying launch and arrival by an additional 26 months on the atmospheric dust environment we have qualified the lander to tolerate, and (2) the effect of the later arrival Ls on preparations for the surface campaign.

(1) Changes to Atmospheric Opacity statistics

The InSight Dust Storm Almanac features statistical information for the minimum, maximum, and median observed value of tau on Mars's surface for every sol of the mission. The conservativeness of the maximum and minimum tau levels in the project's Dust Storm Almanac (Feb 2013) was checked using more recent tau measurement data from the Opportunity and Curiosity rovers in August 2016, during the InSight stand-down. Since these newer data had been accumulated after creation of the Dust Storm

Almanac for two Earth years, this provided an opportunity to assess the variability of the maximum and minimum statistics for Mars' atmospheric dust environment over approximately one Mars year.

(2) Over this span of new tau data, there were 18 sols (2.7% of a Mars year) for which new maximum tau values were measured by either Opportunity or Curiosity; and there were 8 sols (1.2% of a Mars year) for which new minimum values were measured. The plot in Fig. 9 shows that these new maximum values only barely and briefly rise above the far more conservative InSight Dust Storm Almanac worst-measured tau (orange curve). For example, around InSight landed sol 550, the October 2014 Opportunity dust storm (blue curve) rises to tau of 2.0, slightly exceeding the Dust Storm Almanac worst-case (orange curve); however, that storm is bounded by higher maximum tau both immediately earlier and later in the Dust Storm Almanac. Thus, the Dust Storm Almanac, discussed in [1], remains conservative as basis for InSight's power system design requirements.

Changes to Energy Management Stance for Deployment and Late Mission

As noted above, because the historic dust storm data are waning during the initial weeks of the landed mission, and the solar arrays should be relatively clean of dust at that time, energy management will be in a guarded stance but primarily focused on establishing prudent load levels that do not over-exercise the battery. (This is a significant shift from the 2016 landing scenario which had been during the season when global dust storm onset has historically occurred, and energy management for surface operations was on a higher state of alert.)

By the time the end-of-mission peak dust storm season arrives, around 600 sols into the 2018 mission, all seismometry and radiometric data required for mission success shall have been collected and returned to Earth. So in a nominal sense, for the new 2018 arrival, end-of-mission energy management will be focused on surviving the dust storm season for purposes of enabling extended-mission operations.

8. Conclusions

For InSight's solar-powered surface operations at Mars, ultimately, a disciplined self-limiting of power loads is the sole tool available to the team to actively preserve prudent margin versus both uncertainty in energy consumption by heaters and variability of atmospheric opacity over the duration of a command sequence. Prior work done to develop the Dust Storm Almanac, then adapt the power and thermal system designs of the Phoenix lander to handle the InSight-relevant thermal and dust environments at Mars' equator, are described in [1].

Subsequent to the Dust Storm Almanac, further analysis of MER historic data for atmospheric dust optical depth, solar array dust accumulation, and solar energy variability has been been key in establishing InSight's energy margin policies, planned energy management and power fault protection approach for surface operations. And while monitoring of atmospheric optical depth is planned, a dust-storm-condition detection method has also been established for InSight that makes use of variations in energy telemetry, again based on data from MER.

During the hiatus before resuming integration and testing for 2018, the lander has been partially disassembled and stored. The flight Li-ion battery has been placed in cold storage at 0°C (+/- 5°C) at 50% state-of-charge, in order minimize fading of charge capacity; quarterly monitoring to evaluate cell voltage has shown the stored battery to be in nominal condition.

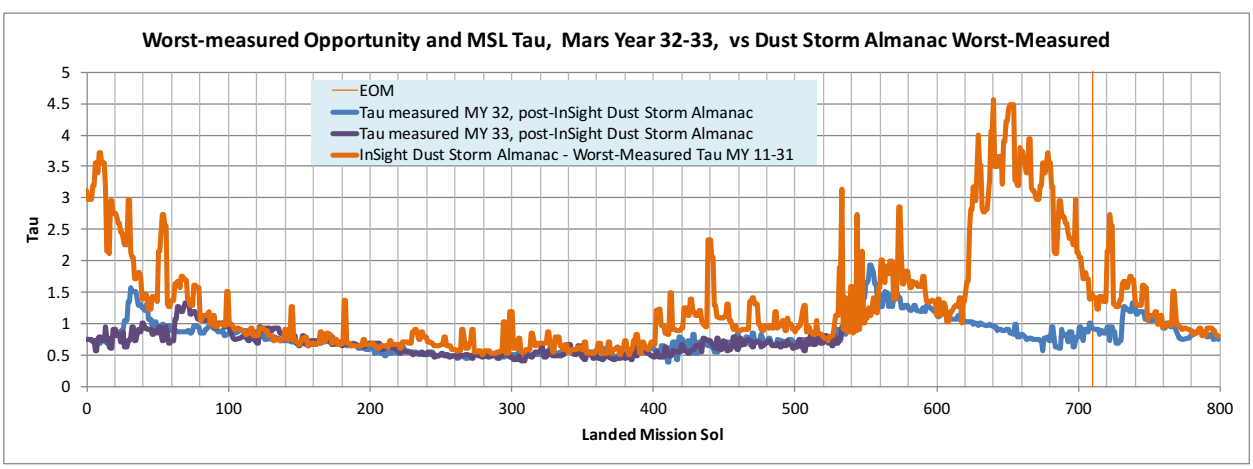

Fig. 9: *Maximum-per-sol tau data collected by Opportunity and Curiosity after creation of the InSight Dust Storm Almanac, compared with worst-observed optical depth data from Viking, MER rovers, IRTM and Themis. These data confirm that the worst-measured tau data in the Dust Storm Almanac remain conservative (thus far) after cutoff of data (in mid-2013) and subsequent passage of about a Mars year.*

The InSight mission exits its hiatus status during the summer of 2017, starting with delivery of the seismometer instrument by CNES, and re-integration and re-test of the flight system at Lockheed Martin in Denver. Solar array deployment testing will be performed, as was done during pre-hiatus spacecraft testing; power and thermal systems will undergo a repeat of system-level verification tests and environment qualifications including surface thermal vacuum testing, using qualification and development unit batteries during these tests. Operational Readiness Tests (ORT's) will be performed to simulate surface operations that will include checkout of Surface Energy Management procedures and tools. The flight battery will be taken from its cold storage and re-integrated with the spacecraft in the final stages of preparing to launch. Subsequently, the InSight launch will take place at Vandenberg Air Force Base during a 3-week period starting on May 5, 2018. InSight arrives at Mars on November 26, 2018 to begin its historic science campaign to measure the Martian interior.

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BIOGRAPHY

Mike Lisano *received his PhD in Aerospace Engineering from the University of Texas at Austin, along with BS and MS from Auburn University, also in Aerospace Engineering. He is the InSight project's Deputy Project Systems Engineer, and also lead Systems Engineer for Surface Energy. Prior to his role on InSight, Mike was a member of the Phoenix mission's EDL team, the lead Radiation Systems Engineer for the Jupiter Europa Orbiter pre-project, and has also served in various line management, mission proposal management, and technology development positions at the Jet Propulsion Laboratory, for the past 16 years. Previous to 2001, he worked for McDonnell Douglas and Lincom Corp at the NASA Johnson Space Center, as a GN&C engineer for Space Shuttle missions and development of ISS visiting vehicle autonomous rendezvous capabilities.*

Pieter Kallemeyn *has been involved in the design, development and operation of many deep space missions for the last 27 years. He is currently the InSight System Design Lead and Surface Phase Lead at Lockheed Martin Space Systems. Prior to his role on InSight, Pieter was the lead Fault Protection Engineer for the 2011 GRAIL lunar orbiter mission, Systems Engineer for the 2007 Mars Pathfinder operations team, and served key roles on the 2001 Mars Odyssey and Spitzer Space Telescope missions. Prior his time at Lockheed Martin, Pieter was a member of the Navigation System Section at the Jet Propulsion Laboratory, where he was the Navigation Team Leader for the 1997 Mars Pathfinder mission. He received his B.S and M.S. degrees in Aerospace Engineering from the University of Colorado at Boulder.*