Riders on the Storm: NASA InSight Lander and the 2018 Mars Global Dust Storm

Dr. Michael E. Lisano
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-0765
michael.e.lisano@jpl.nasa.gov

Myron R. Grover
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-0765
myron.r.grover@jpl.nasa.gov

Abstract—**On May 5, 2018, NASA's InSight spacecraft, carrying an international scientific payload with which to explore the interior of Mars, launched from Vandenburg AFB, California, and began its six-and-a-half-month voyage to Mars. Four weeks later, on June 3, 2018, a powerful regional Martian dust storm surged through Meridiani Planum and within days had left the 14-year-old Opportunity rover in darkness and generating insufficient solar power to operate. On June 10, Opportunity sent signals including information that the optical depth ("tau") of the thick dust blanketing the atmosphere was an all-time high ever measured from the Martian surface, at a value of 10.8. Then Opportunity soon afterwards experienced a power fault and ceased communicating with her ground controllers. By June 20, the storm had spread across the entire planet Mars, darkening the skies at Gale Crater where the Curiosity Rover had been ascending the foothills of Mount Sharp, on the opposite side of Mars from Opportunity. Record-setting, high atmospheric dust levels continued to be measured and reported by the Curiosity team, as the storm became global. Among those keeping daily tabs on the enormous storm that swiftly enshrouded the Red Planet were the InSight flight team of engineers and scientists, whose recently-launched spacecraft was functioning quite well in flight and now five and a half months away from an unchangeable landing date at Mars – November 26, 2018.**

As our spacecraft hurtled through interplanetary space towards its destination, the InSight team took stock of the situation. Would this enormous dust storm still be raging when InSight arrived? What, if anything, had this storm changed in the assumptions made by InSight's design and test engineers about Martian atmospheric conditions for descending to the surface, or generating power there? Would InSight survive and carry out her mission?

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1. INTRODUCTION

After six years of design, development, testing, a launch delay and a restart, and even more testing, NASA's InSight spacecraft lifted off at the very opening of its launch window on an Atlas V rocket from Vandenburg Air Force Base on May 5, 2018, on its way to land on Mars on November 26, 2018. The InSight spacecraft's design is based on NASA's 2007-2008 Phoenix Mars lander, including its Entry, Descent and Landing (EDL) system (Fig. 1) and its solar-powered lander design (Fig. 2). The InSight mission would mark the first attempt by NASA to land and begin operating on the surface of Mars in the midst of the annual season when global dust storms sometimes occur.

Unlike the Phoenix mission, InSight takes place at a near-equatorial (as opposed to near-polar) region of Mars, Elysium Planitia, at a site about 600 km away from Curiosity's exploration site at Gale Crater, nearly the same distance as from Los Angeles to Phoenix (Arizona, not the spacecraft), and InSight must perform its main science mission – quiescent measurements with a seismometer placed on the Martian soil and internal heat measurements with a 15-meter-deep thermal probe – for a whole Martian year (688 days, plus a few-month instrument deployment period) as opposed to the 90-day Phoenix spacecraft primary mission. These differences meant that InSight's EDL system, and also its lander solar-power system design required some modifications over and above the Phoenix design, to be able to withstand a dust storm, which could take place during landing or indeed at other times during its Mars-year-long science operations after it landed.

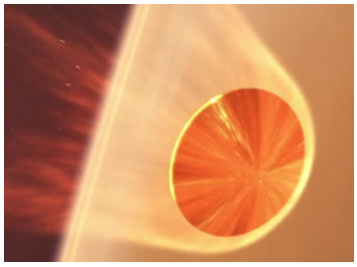

Fig. 1: *The InSight Entry, Descent & Landing system is nearly identical to the system that successfully landed Phoenix in 2008.*

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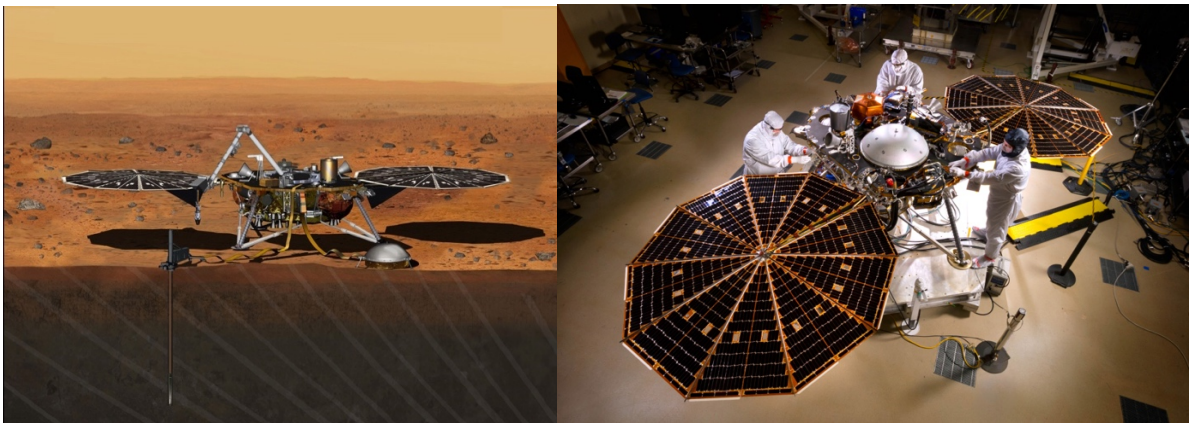

Fig. 2: *At left, the solar-powered InSight Lander with its instruments deployed, as it will appear on the surface of Mars. At right, the InSight Lander during its first landed solar array deployment test at Lockheed Martin in Denver, Colorado. InSight's landed solar arrays are the largest ever to operate on the surface of Mars; under benign tilt and dust conditions they are capable of generating up to about 4 kilowatts of power.*

As discussed in the next section, the Mars global dust storm of June 2018 was a record-breaking event that had implications for the just-launched InSight spacecraft: that is, the storm exceeded the design environments that had been assumed for InSight during its design phase – and for any solar-powered Mars vehicle ever flown to date.

2. The 2018 Mars Global Dust Storm

On June 3, 2018, the opacity of the skies over the Mars Exploration Rover Opportunity, in its 14th year of exploring the Meridiani Planum region of Mars, suddenly increased over the prior sol (a *sol* is a Martian day). Over the course of the next seven sols, the skies became increasingly darker and darker. As seen in a succession of images taken by camera on the Mars Reconnaissance Orbiter (Fig. 3), this darkening of the sky was due to a large, fast-moving dust storm surging down from the north into Meridiani. Optical depth of dust in the Martian atmosphere results in the Beers' Law (exponential) attenuation of light passing through a column, symbolically represented as "tau". Tau at Meridiani is measured frequently, essentially each sol, based on Opportunity camera images of the sky that are processed on Earth.

Figure 4 is an early version of a plot of tau measured by Mars rovers Opportunity (first 6 data points of purple curve) and Curiosity (last two data points of purple curve) in June 2018, during the first weeks of the dust storm, compared with tau measurements and estimates from other historic dust storms. The 2018 dust storm was intense at Meridiani, and Opportunity reported a final measurement of tau of 10.8 before communications were lost with her. In the steadily thicker atmospheric dust conditions, which rendered the surface as dark as night all day long for days on end, Opportunity's solar arrays in had been unable to generate more enough energy to keep her batteries charged; the rover power faulted on about June 10, and its operators would subsequently need to wait until the storm died down to see if the rover's arrays would again charge the batteries and the rover would begin communicating again.

Having now settled into cruise operations, the InSight team was keeping abreast of the situation on Mars, and began to assess the impacts of this sudden and significant storm, particularly focusing on the safety and success of InSight EDL and surface power production.

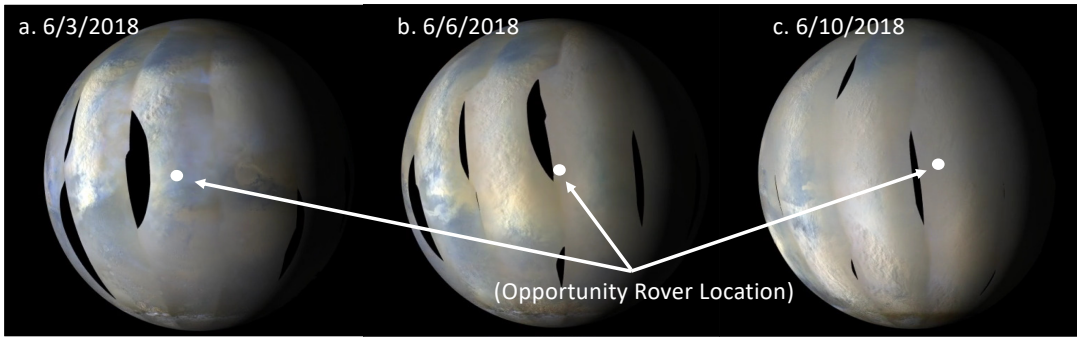

Fig. 3: *Mars on June 3, 6 and 10, 2018 (a., b., and c., respectively), as imaged by camera on NASA's Mars Reconnaissance Orbiter (images courtesy of Malin Space Sciences, www.msss.com); the dust storm swept quickly down on Meridiani, and contact was lost with the Opportunity on June 10, after the atmospheric opacity based the rover's cameras was reported at a record high of 10.8.*

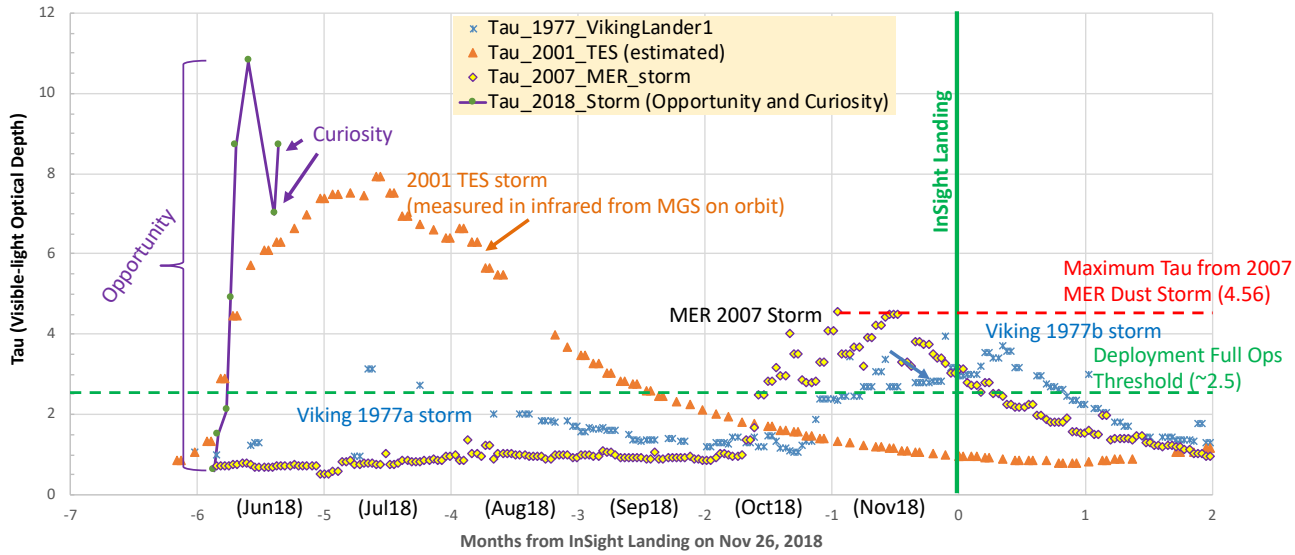

Figure 4: *Early plot of "tau" of the 2018 Dust Storm, by InSight team in mid-June 2018, shown with measured tau of other historic storms. The storm time traces are aligned seasonally, i.e. co-plotted per the Mars solar longitude when they occurred. The storm was clearly a record-setting event, rising up early in the dust storm season compared with the MER 2007 storm or Viking 1977b storm; it rose up in about the same Mars solar longitude as the 2001 storm measured by the TES instrument.*

3. Assessing EDL Impacts

The InSight team had known from the beginning of the InSight project the spacecraft would arrive at Mars during Martian dust storm season. Being the first Mars lander to arrive during dust storm season, this presented a unique challenge for InSight.

To meet the challenge of landing in dust storm season, the EDL team undertook a number of actions, the first of which was working with project scientists to establish the range of atmosphere conditions possible during dust storm season. This led to establishing the following four baseline engineering atmosphere models to be used for EDL performance assessment: Background Atmosphere, (representing a non-storm condition), Regional Dust Storm Atmosphere, Global Dust Storm Atmosphere, and Decaying Dust Storm Atmosphere. During the development phase of InSight, these models ensured the EDL system was being designed to successfully perform in any atmosphere condition reasonably likely during dust storm season.

As can be seen in the EDL simulation results shown in Table 1, there are general trends in EDL performance as dust in the atmosphere increases. Because dust in the atmosphere changes the distribution of density by altitude, as dust increases, peak deceleration reduces, peak heating also reduces, total heating during entry increases, and the parachute deploy altitude lowers with increasing dust. The EDL system was designed to be successful given these trends in performance.

Table 1: *Entry, Descent and Landing performance trends with increasing dust atmosphere.*

EDL Performance Metric	Atmosphere Type			
	Background	Regional	Decay	Global
Peak Deceleration (Earth g)	7.5	7.2	7.0	6.4
Peak Heating (W/cm^2)	45.7	44.5	42.0	42.0
Total Heating (J/cm^2)	2687	2765	2745	2828
Parachute Deploy Altitude (km)	11.5	11.7	11.2	10.7

Another action taken by the EDL team was an assessment of possible abrasion of the landing system heatshield as a result of flying through a dusty atmosphere. This "sandblasting" effect could erode the Super-Lightweight Ablator (SLA)-561V thermal protection system protecting the lander during the intense heating of entry. Assuming a worst-case atmosphere dust loading during a global dust storm, the assessment resulted in the decision to add an extra 0.2 inches of SLA-561V to the InSight heatshield thickness, as sacrificial material in the event dust abrasion occurred during entry. This also provided additional aerothermal performance margin in the event of no dust storm.

In addition to dust storm impact on EDL performance, dust storm activity can affect approach targeting and course correction maneuver design leading up to EDL. As the amount of dust increases in the atmosphere, the same change in density distribution by altitude responsible for trends in EDL performance also cause changes in trajectory, and the landing location on the surface of Mars to move. Increasing dust means the landing trajectory will

fall short of the intended target, causing it to move uptrack. To compensate for this phenomenon, an approach targeting process was developed by InSight to allow for the landing point to move within safe limits. If the safe limits are violated, entry flight path angle is modified to adjust the EDL trajectory to bring the landing point back within safe limits. Fig 5 illustrates how the InSight landing ellipse both changes size and moves uptrack (to the left) as the atmosphere becomes dustier.

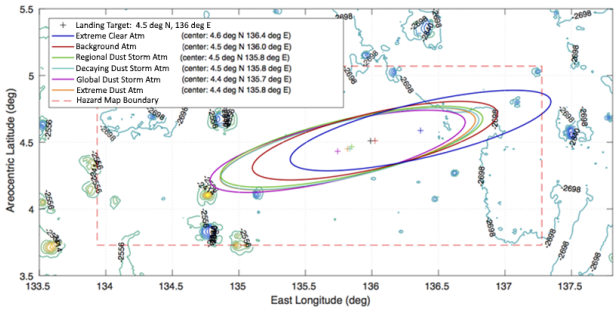

Figure 5: *InSight landing location uptrack trend with increasing dust.*

With significant work done during development to ensure EDL success during a dust storm, the development of the 2018 global dust storm in early June 2018 (with InSight on the way to Mars) elicited two responses from the EDL team. The first response was to monitor the storm development to understand how the atmosphere conditions it generated compared to the atmosphere models used in development. As reported by atmospheric scientists, even at its peak, the models used for InSight EDL development bounded the storm activity on Mars. The second response was, given the storm activity on Mars, request of atmospheric scientists a prediction of landing day dust content, in case early landing site targeting assumptions needed to be modified. The prediction provided assumed the 2018 global storm would decay to background (low dust) conditions by the time of landing, and thus early landing site targeting assumptions did not change.

4. Assessing Surface Energy Impacts

As with EDL, Martian dust storms were given heavy consideration in the design and sizing of InSight's Phoenix-based surface solar power generation and battery subsystems, as well as the fault protection design, e.g. of triggers and responses for its energy-conserving safe mode. Prior to establishing the Environment Requirement Document (ERD) for InSight spacecraft and instrument specifications, first a "Dust Storm Almanac" was developed to include all historic measurements of tau that had been made from the surface of Mars with landers and rovers, combined with estimated tau levels made based on orbital measurements. The contents of the InSight Dust Storm Almanac are described in detail in [1], and its updating to account for the InSight launch slipping from 2016 to 2018 is discussed in [2].

The InSight surface solar power design brought changes to the Phoenix design, to give it higher power generating capability, more capable batteries, and more efficient power-consuming loads. Specifically, modifications have included:

- increasing lander solar array area from 4.2 m^2 to 5.0 m^2, to generate sufficient energy for survival, with sol-by-sol complete battery recharge, in a worst-case dust storm having tau of 4.56;
- updating array photovoltaics to a more recent ZTJ technology to take advantage of their higher current-production capability; and
- updating the chemistry of our Yardney-provided batteries to incorporate a next-generation cathode material as well as a new low-temperature electrolyte, which InSight testing in development showed significantly increased both capacity and expected battery lifetime under our expected load and temperature regime (which is more extreme in both hot and cold than Phoenix).

Once InSight has landed, within 20 minutes its solar arrays deploy automatically based on an onboard sequence. The landing at Elysium Planitia occurs in late afternoon local solar time, at a site in an extended flat, relatively featureless region that is approximately 4.5 degrees north of the equator. Hence, just before nightfall on our landing sol ("Sol 0"), the arrays generate power only for a couple of hours to recharge the batteries which have discharged some during EDL. The first opportunity for the team to give its go-ahead to proceed with deploying InSight's instruments takes place after a full morning and afternoon of solar power generation on Sol 1, and that evening's lander power telemetry are evaluated.

The InSight surface team has procedures for handling a severe dust storm event during landing; this begins with monitoring of the storm's progress in the weeks and days before InSight lands. Tau data from measurements made on the surface by the Curiosity rover, together with imagery and measurements from orbit (especially the MRO surface-imaging cameras and MCS thermal profiling instruments) help to assess and forecast the range of likely tau conditions at Elysium Planitia. If a severe storm had risen up and in progress, and had a tau level higher than our design point (4.56, the highest tau measured by a surface asset prior to the 2018 storm), this would further reduce the power generation during late afternoon on Sol 0, to a level below sustaining our planned initial-landing loads with safe margins. There is a listed combination of activities planned for Sols 0 and subsequent sols that the surface energy team would advise be removed from the post-landing sequence to put the lander in a "hunkered down" survival configuration. This combination of load reductions includes deletion of early imaging of the terrain beside the lander, and cancelling planned gyrocompassing with the IMU, as well as changing from the operational electronics enclosure heaters to survival heaters, which are

at lower thermostat set points and hence consume less energy.

The 2018 dust storm produced peak optical depth levels exceeding what had ever been measured from the surface prior to InSight launch. The storm was, however, in family with reconstructions of a severe 2001 dust storm that appeared in our Dust Storm Almanac [1]. That 2001 storm had been explicitly considered in InSight's surface energy designs as a stressing condition occurring rarely in its specific season, and not expected to be survivable for an extended duration. It was also observed as the InSight environment requirements were established in 2012 that for the 2001 storm, the "visible-light, up-looking" tau had been approximately estimated based on "infrared, downward-looking" measurements made from orbit, as there were no surface assets on Mars at the time of the 2001 storm. For the 2001 storm, it was noted that there was a wide range of uncertainty on what the maximum tau as measured from the surface would have been, so InSight engineers chose the most conservative interpretation (i.e. that the 2001 dust storm had peak tau levels around 8 or 9, as opposed to different calibration methods that produced levels around 4 or 5, see discussions in [1]). The high levels of tau measured by both Opportunity and Curiosity in the 2018 storm bear out the higher-tau-level interpretations of the 2001 storm. A tau history of the 2018 storm in its entirety is co-plotted with the 2001 giant storm versus time for comparison, based on their respective Mars solar longitudes (Ls) of occurrence, in Fig. 6.

As seen in Fig. 6, by September 2018, the 2018 storm's tau had receded below survival and also operational levels safe for InSight surface operations (blue and green hashed vertical lines), as expected, over two months prior to InSight's landing (green vertical line). Later-in-season storms with moderately high (previously record-setting) storms - specifically the MER 2007 storm and Viking 1977b storm, shown on the plot – was reflected in the InSight Dust Storm Almanac, and are handled with positive margin by InSight's power system design and energy management approach [1, 2].

Even after the 2018 storm had receded, in the several weeks prior to landing, the concern remained that a second dust storm could rise up around the time InSight landed. The view taken on InSight was that there was a high probability a second storm would be survivable. Multiple very large (broad-regional-to-global scale) dust storms are not a common occurrence on Mars; indeed only one instance of back-to-back global storms in a single Mars dust storm season has been measured – by the Viking landers in this case. This is also shown in Fig. 6 (light blue symbols). While Viking experienced two dust storms in one season, it is seen that the earlier storm (1977a) was not nearly as severe by far as the 2001 and 2018 storms, which is suggestive that it was not as energetic an event as the 2001 storm or 2018 storm, and perhaps leaving global dust surface distributions in an unstable configuration that permitted a later storm (1977b) to occur that year.

5. Epilogue: InSight at Mars

The prediction that "background" atmospheric conditions would be present held true for InSight's approach to Mars. As part of InSight approach operations, a team of atmospheric scientists, called the InSight Council of Atmospheres (CoA), met regularly to provide predictions of the atmosphere conditions on landing day. Beginning on November 7, 2018, the CoA provided periodic updated predictions of landing day conditions, increasing in frequency to daily updates during the final week prior to landing. The predictions were based primarily on thermal sounding profiles generated by the Mars Reconnaissance Orbiter's (MRO's) Mars Climate Sounder (MCS) instrument. The regular observations showed that background atmosphere conditions persisted for the duration of approach and landing, with some small variations observed likely due to daily atmospheric pressure waves. The small variations seen kept movement of the landing target on the surface well within the predetermined tolerances and thus did not require consideration of changing entry flight path angle for landing safety.

While InSight was designed to land successfully in global dust storm conditions, the landing occurred during a plain day on Mars with no storm activity, and with atmospheric dust levels consistent with background conditions expected for the season.

InSight's solar arrays opened without problem, and were found to produce solar energy at a rate greater than 4000 Watt-hours per sol, every sol, for the first weeks of the mission. This was noted to be a record rate of energy production on Mars' surface for any landed asset – rover or stationary, solar or radioisotope powered. The previous highest energy production in a single sol had been by NASA's radioisotope-powered Curiosity rover, 2806 Watt-hours on Aug 12, 2012 [3].

InSight measured tau using the camera mounted on its robotic arm. This camera is primarily purposed with making images of the landing site, especially the "workspace" of soil on the southern side of the lander, where the two InSight instruments were to be placed. The camera is also used in targeting and confirming grappling of the instruments by the arm, to move them from the upper deck of the lander down onto the soil in the workspace. For this reason, the camera is not generally pointed towards the sky, and so tau measurements happen about once every two weeks, at least until the instruments are deployed. Changes from day to day in solar power telemetry are our most sensitive and timely means of detecting atmospheric change – or dust accumulation on the solar arrays – compared with imaging. The values of tau measured at Elysium after InSight landed (on Sols 14, 26 and 38) are shown in Fig. 6, closely matching historic data from TES.

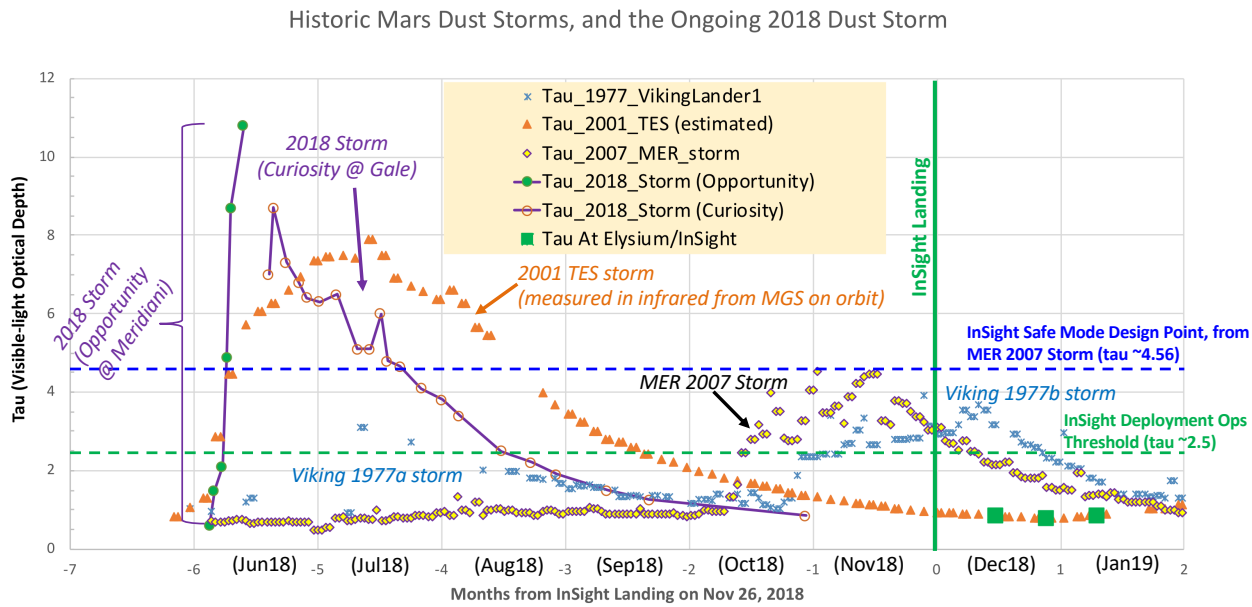

Figure 6: *Plot of the 2018 dust storm tau through its lifecycle, combining measurements from Opportunity at Meridiani until Oppportunity succumbed, and from Curiosity at Gale Crater until Curiosity encountered memory issues in September 2018. The 2018 storm rose up in a seasonal timeframe (Ls ~180°) and at a rate markedly similar the large global dust storm measured in infrared in 2001 with the Mars Global Surveyor orbiter's TES instrument (orange triangles); the two storms also decayed at similar rates. By the time InSight landed (green vertical line) the 2018 storm had fully receded. Post-landing tau measured by InSight (green squares) has been moderate, and corresponded almost exactly with the TES 2001 data from the same season.*

6. SUMMARY

The selection and usage of relevant environmental data for designing new deep space missions is a perennial systems engineering challenge. Our total experience of the environments at Mars – e.g. radiation, temperature, atmospheric density, winds, dust, landing site rock size and distribution - is limited to historic measurements made by relatively few robotic spacecraft at Mars, which makes it hard to set reasonable bounds on what really happens there. On InSight, worst-known dust storm conditions were applied to the designs for both Entry, Descent and Landing (EDL) and surface power generation, with performance margins established over and above these worst case, to contend with unknown, worse-than-worst case conditions.

The 2018 dust storm produced peak optical depth levels exceeding what had ever been measured from the surface prior to InSight launch. The storm was, however, in family with reconstructions of a severe 2001 dust storm that appeared in our Dust Storm Almanac, which had been considered in InSight's design as a stress point not likely to be survivable for an extended duration. For that older storm, visible-light, up-looking tau had been approximately estimated based on infrared, downward-looking measurements made from orbit (there were no surface assets on Mars at the time of the 2001 storm). The lessons for future, extended Mars surface missions are simple, even stark: a long-lived solar-powered asset (Opportunity) was silenced after several sols in the planet-wide, extended, light-extinguishing environment this storm brought on, while a radioisotope-powered one (Curiosity) withstood the months of darkness and is still operating.

The appearance of a storm of this magnitude while InSight was on its cruise to Mars resulted in the InSight team to consider impacts to likely in-flight performance if this new storm should persist for several months, or recede and then repeat itself as we landed and commenced operations on Mars. The data that has been accumulated on historic Martian dust storms since Mariner and Viking – which now includes 2018 storm – is of utmost value in the design of future Mars missions. Given their infrequency of occurrence, we still have little experience with Mars global dust storms. On matters of the storms actual physical triggers and timing relative to seasons, we are largely left to speculate; these are subjects of continued scientific investigation, as we continue to gain experience landing and operating upon Mars with missions like InSight.

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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, its Launch and Cruise Phase Lead, and also the mission's 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 18 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.*

Rob Grover *is the InSight Entry, Descent & Landing Team Lead at the Jet Propulsion Laboratory, California Institute of Technology. He has degrees from Oregon State University and the University of Washington. Previous assignments include the EDL Phase Lead for NASA's Constellation Program. Previous missions include Mars Odyssey, Mars Exploration Rovers, and the Mars Scout lander Phoenix.*