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HP³ – Experiment on InSight Mission Wrap-up Operations on Mars

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Abstract

HP³ – the Heat Flow and Physical Properties Package – is an experiment package on-board the NASA Mars Mission InSight (Interior Exploration Using Seismic Investigation, Geodesy, and Heat Transport) to investigate the interior structure of Mars. InSight was launched on 5th May 2018 and landed successfully on Mars on 26th November 2018. The lander operated successfully for about 2 Martian years till the end-of-mission on 20th December 2022. The main science experiments of the InSight mission are a seismometer (SEIS), the HP³ heat flow probe and the Rotation and Interior Structure Experiment (RISE). An Auxiliary Payload Sensor Suite (APSS) consisting of atmospheric pressure, wind and temperature sensors as well as a magnetometer complement the payload. After landing on Mars the seismometer and HP³ were deployed to the Martian surface by the robotic arm of the lander.

HP³ is the contribution of DLR (Deutsches Zentrum für Luft- und Raumfahrt e.V., Germany) to the InSight mission [1]. It is designed to determine the geothermal heat flux by emplacing a suit of temperature sensors to a maximum depth of 5 m, by means of a mechanical hammering mechanism. HP³ is designed to measure the thermal conductivity as function of depth during the hammering phase, and to monitor the thermal profile of the subsurface for a full martian year.

During the past 4 Earth years, the InSight lander and its payloads operated successfully under the harsh environmental conditions on Mars. The HP³ experiment performed various different kinds of operations during this period. Operational highlights of the HP³ instrument include the mole hammering and recovery activities as well as thermal conductivity and Radiometer measurements. This paper summarizes new results with content already presented at the SpaceOps2021 contribution [2]. Main parts like the instrument description and already performed activities (e.g., the mole recovery) are published in this paper [2] but are also repeated here for completeness.

Keywords: Mars, InSight, HP³, heat flow, temperature, mole

Acronyms/Abbreviations

APSS = Auxiliary Payload Sensor Suite
BEE = Backend Electronics
DLR = Deutsches Zentrum für Luft- und Raumfahrt e.V.
HP³ = Heat Flow and Physical Properties Package
ICC = Instrument Context Camera
IDA = Instrument Deployment Arm
IDC = Instrument Deployment Camera
IDS = Instrument Deployment System
InSight = Interior Exploration Using Seismic Investigation, Geodesy, and Heat Transport
JPL = Jet Propulsion Laboratory
LTST = Mars local true solar time
NASA = National Aeronautics and Space Administration
RAD = Radiometer
RISE = Rotation and Interior Structure Experiment
SEIS = Seismometer
SSA = Support System Assembly

STATIL = Static Tiltmeter
TCM = Trajectory Correction Maneuver
TEM = Thermal Excitation and Measurement
TLM = Tether Length Monitor
WTS = Wind Thermal Shield

1. Introduction

HP³ – the Heat Flow and Physical Properties Package – is an experiment package on-board the NASA Mars Mission InSight (Interior Exploration Using Seismic Investigation, Geodesy, and Heat Transport [3]). The InSight Mission investigated the interior structure of Mars using seismic and geodetic measurements and quantified the planetary heat budget by measuring the surface planetary heat flow at the landing site. InSight was launched in May 2018 and landed on Mars on 26th November 2018. The main payloads of the InSight lander are a seismometer (SEIS), the HP³ heat flow probe and radiometer, as well as the radio science Rotation and Interior Structure Experiment (RISE). An Auxiliary Payload Sensor Suite (APSS) consisting of atmospheric pressure and temperature sensors and a magnetometer. The main InSight mission was planned for 1 martian year (2 Earth years). In the end, the mission lasted with its extended mission phase for about 2 Martian years (4 Earth years).

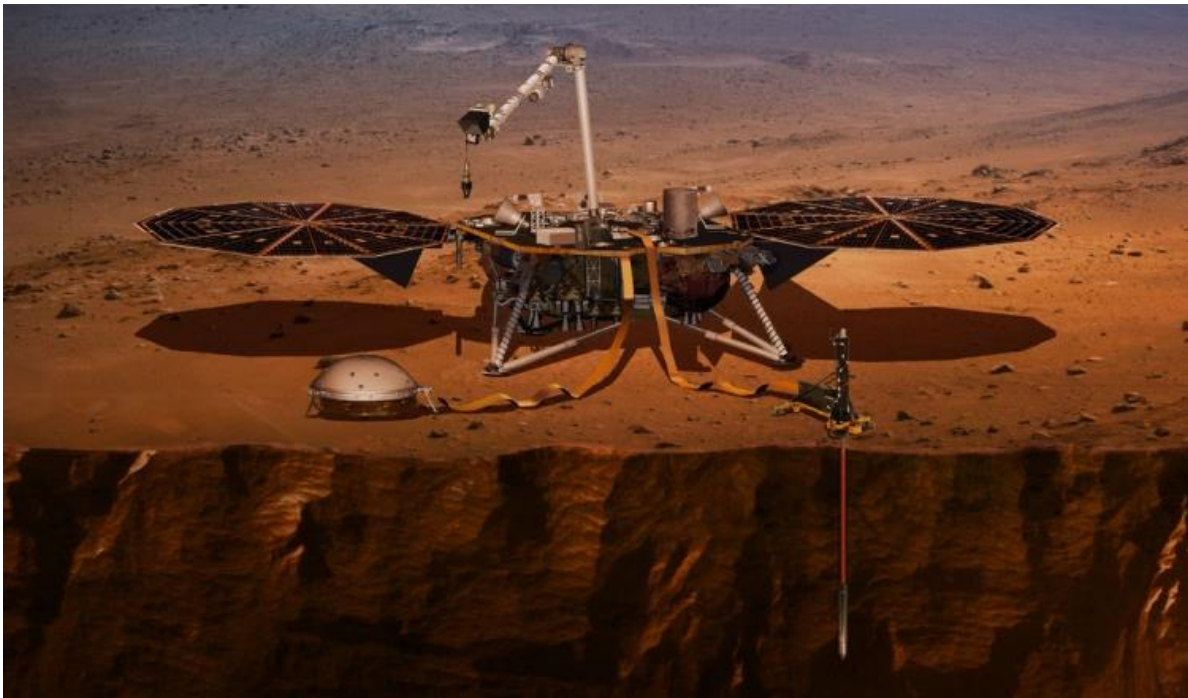


Figure 1: Artist impression of the InSight lander on the Martian surface with HP³ deployed and the mole located in the subsurface. The radiometer is mounted underneath the deck of the lander, facing away from the instruments (not shown). Image Credit: NASA/JPL-Caltech

HP³ is the contribution of DLR (Deutsches Zentrum für Luft und Raumfahrt, Germany) to the InSight mission. Heat flow is a major constraint on models of the current state of Mars' interior and is key to understanding the evolution of terrestrial planets in general [1,4]. HP³ is designed to determine the geothermal heat flux by emplacing a suit of temperature sensors to a maximum depth of 5 m, by means of a mechanical hammering mechanism (mole). HP³ is designed to measure the thermal conductivity as function of depth during the hammering phase, and to monitor the thermal profile of the subsurface for a full martian year. An overview of the InSight lander is shown in Figure 1 with both main instruments (SEIS and HP³) deployed onto the martian surface. The HP³ radiometer (RAD) is mounted underneath the InSight lander deck and determines the surface brightness temperature of the martian regolith, from which regolith thermal inertia of the upper soil layers can be derived.

The InSight mission operated about 4 Earth years (2 Mars years) on the martian surface. HP³ operated until about summer 2022 when the available energy on the lander dropped too low for operating the instrument. During this long

timespan the lander and HP³ went through different operational phases starting with the instrument deployment phase right after landing on Mars. After landing on Mars, the seismometer and HP³ were deployed onto the martian surface by the robotic arm of the lander. Two cameras mapped out the instrument deployment space, one of which is mounted on the lander (ICC, Instrument Context Camera) and one on the robotic arm (IDC, Instrument Deployment Camera). By moving the arm, the IDC provides stereo images and thus topography of the landing site. The mole hammering started after the deployment phase had finished and the instruments were placed on the martian surface. As the mole ran into issues during the hammering phases, the InSight team and internally within the HP³ team, performed intense tests and recovery activities for the mole. In parallel the radiometer performed intense measurement campaigns. At the end of the mission, the operational activity and execution was dominated by the effects of the reduced available energy on the lander.

2. Description of the HP³ experiment

HP³ is composed of a self-contained hammering probe (termed the mole) to emplace sensors to a depth of up to 5 meters into the martian subsurface [1,5]. As the mole moves forward, it pulls a tether behind it that both provides the power and data link from the lander to/from the mole, but is also instrumented with temperature sensors. During hammering, the instrument was planned to stop at 50 cm depth intervals to use the HP³ mole heaters to measure the thermal conductivity of the surrounding regolith. HP³ is equipped with a tether length monitor (TLM) within the support structure assembly, and a tilt measurement suite (STATIL) within the mole itself. Together these were to have been used for the determination of the mole depth and path in the subsurface.

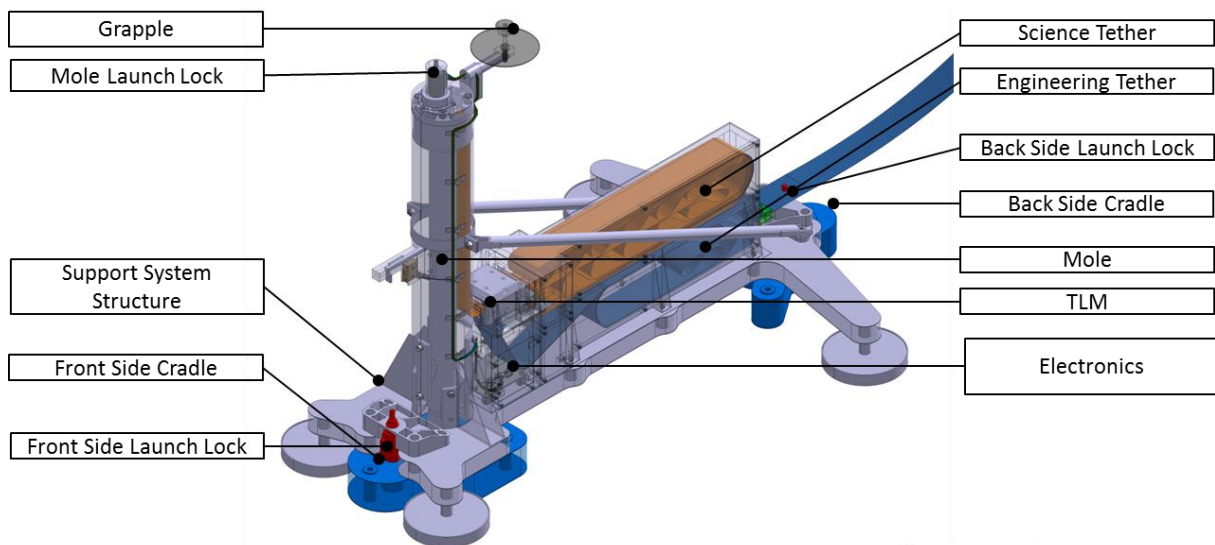


Figure 2: Schematic of the HP³ Support Structure Assembly (SSA) indicating functional subunits. The grappling hook serves as the interface to the lander’s robotic arm, while the cradles are the interface to the lander. The mole launch lock is released after deployment of the SSA onto the Martian surface. The SSA houses the engineering tether, science tether, TLM, mole, as well as an electronics interface board.

HP³ is composed of the following subsystems:

- A set of thermal sensors (collectively called the Thermal Excitation and Measurement or TEM) to determine thermal conductivity (active: TEM-A) and subsurface temperature (passive: TEM-P)
- A self-hammering probe (the mole) to emplace TEM-P sensors in the subsurface. The mole contains within its hull the sensors for the TEM-A experiment and its whole body serves as the source of a transient heat pulse.
- Two measurements suites (TLM & STATIL) to determine the depth of the mole and TEM-P thermal sensors
- A radiometer to determine the surface temperature forcing (RAD)
- The instrument’s main (backend) electronics (BEE)

The HP³ deployable elements are housed inside a support structure, and electrical connections to the lander and BEE are provided by the HP³ engineering tethers. The support structure also securely stored the mole and tethers during cruise and guides the mole during its initial hammering into the surface after deployment. The support structure assembly is shown in Figure 2 which indicates the major subsystems. The engineering tether (blue) connect the deployed SSA to the lander and backend electronics inside the lander’s warm electronics box. The engineering tether interfaces with the science tether and the other SSA systems in the SSA electronics board. The science tether is then fed through the tether length monitor (TLM) before it connects to the mole’s backend. During flight, the tethers are stored inside the Tether Storage Box of the SSA.

The HP³ mole is a mechanically actuated mechanism which operates by compressing a spring using an eccentrically shaped cylindrical cam, which upon release accelerates a mass towards the front tip of the mole propelling it forward through the soil. Recoil is taken up by a suppressor mass and a break-spring, and finally transmitted to the mole hull where it is dissipated by wall friction with the soil. By design, the mole takes advantage of the difference between static and kinetic friction to achieve optimal hammering performance. The interior elements of the mole are shown in Figure 3. It is worth mentioning at this point that the external friction is a key requirement to achieve forward motion with the mole by balancing the small but non-zero recoil force from the hammering mechanism that is transmitted to the hull.

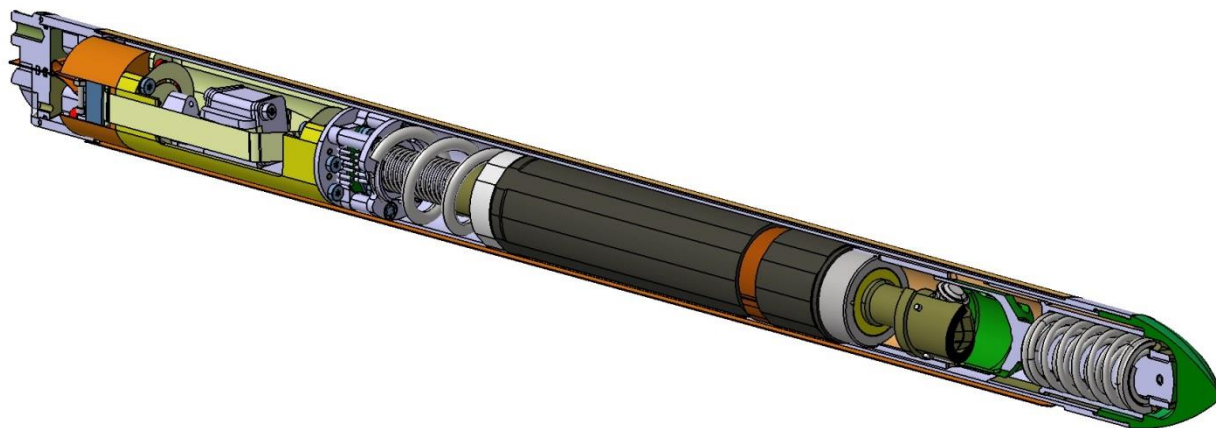


Figure 3: Schematic diagram of the HP³ mole. The mole interfaces with the science tether on the left hand side. The STATIL assembly (yellow / light gray) as well as the hammering mechanism (dark gray) are also indicated. The ogive shaped mole tip (green) is designed to minimize the soil resistance during mole operation.

The STATIL tiltmeter is designed to determine the change of the mole attitude in the ground during hammering and mole advancement, while the Tether Length Monitor (TLM) is used to determine the length of tether extracted from the storage box (see Figure 2). Taken together, these measurements allow for a reconstruction of the absolute depth of the mole as well as the depth of the temperature sensors embedded on the tether (see below).

2. Launch, Cruise & Landing

The launch of InSight took place on the 5th May 2018 from Vandenberg Air Force Base with a Atlas.-V-401 rocket. In July 2018 a checkout of HP³ was performed during cruise.

After 6 TCMs (Trajectory Correction Maneuver) the lander unit entered the Martian atmosphere on 26th November 2018.

The InSight landing took place in Elysium Planitia at 19:52:59 UTC on the 26th November 2018, early afternoon on Mars. The landing site is in the western part of Elysium Planitia (4.5° north, 135.6° east). The landing site was selected for safety purposes during landing and from science perspectives for the research of Martian interior [6].

3. Operations on Mars

All HP³ subsystems were started soon after the landing with checkouts and even science measurements. As the radiometer is mounted below the lander deck its measurements are independent of the deployment of the HP³ support structure and penetration of the mole. The tiltmeter STATIL started its measurement on the lander deck and was cross-calibrated with the deck tilt on Mars as measured by InSight lander avionics. TEM measurements were used to monitor the surrounding temperatures before the HP³ deployment.

The planning of the HP³ operations on Mars was performed within the InSight team. Especially resources like power, data budget and link availability needed to be planned carefully and in close cooperation in-between system and instrument requirements and constraints. Intensive and detailed planning iterations of the operations teams were performed to maximise the scientific outcome of the InSight mission.

At the beginning of the on-Mars surface mission the available energy of the lander was nearly 5000 Wh per sol (a martian day). Operational drivers at this early time of the mission were the lander internal temperatures, the external subsystem temperatures and the data budget. During this timeframe, even the extensive subsystem operational requests could be fulfilled. All high energy consuming activities, especially the complex instrument deployment onto the martian surface were performed and the mole penetration to depth was planned to occur in this timeframe.

During the deployment phase and the first hammering attempts the instrument teams were co-located at JPL (Pasadena, US) for this intense operation phase. For the surface operations phase which followed, the European teams returned back to their control centers in Germany and France, respectively. HP³ was operated from the DLR Microgravity User Support Center (MUSC) located in Cologne.

3.1 Instrument Deployment Phase

InSight operations on Mars started shortly after landing. First checkouts and first scientific measurements were performed during the early phases of the InSight surface mission. This early phase of the mission was further dominated by the selection of the instrument deployment sites. Shortly after the landing, the robotic arm of the lander was released and imaged the potential deployment sites in detail. These pictures and resulting analysis were a basic input for the site selection for the instruments' deployment.

During and after the instrument deployment site selection process, the IDA Team (Instrument Deployment Arm) performed intense deployment tests of the instruments to the modelled Mars terrain on Earth. After the instrument deployment site selection had finished, the different instruments were deployed starting with SEIS and the WTS (wind & thermal shield). After SEIS and WTS deployment activities were finished, HP³ was successfully deployed to the martian surface on the 12th February 2019 (sol 76). Figure 4 shows HP³ in its final position after deployment including the wide-field view from the fixed-view Instrument Context Camera (ICC) with both instruments deployed on the martian surface.

HP³ was deployed in the late afternoon of sol 76 on Mars. One consideration for this time of day was the expected ambient wind speed, as had been measured by the APSS since shortly after landing. Before the deployment, tether heaters within the SSA were activated to increase their temperature and thus their flexibility. After firing of the frangibolts that affixed the SSA to the deck, the InSight robotic arm placed HP³ safely onto the surface. In the following sols the position of HP³ was evaluated including a checkout and tilt measurements of HP³ and its stability. The HP³ subsystem STATIL monitored the inclination of HP³ vs the gravity vector. After the position and status of

HP³ was approved, the arm grapple was adjusted and finally on sol 83 the grapple was released allowing HP³ to stand free on the martian surface.

Table 1: Main instrument deployment steps

Sol	Earth date [UTC]	Activity
Sol 22	19. December 2018	SEIS deployment
Sol 66	02. February 2019	WTS deployment
Sol 74	10. February 2019	Robotic arm grapples HP ³ on the lander deck - HP ³ gets ready for deployment
Sol 76	12. February 2019	HP ³ deployment - Activation of tether heaters - Firing frangibolts - HP ³ placed on martian surface
Sol 83	20 February 2019	HP ³ Grapple release - HP ³ standing free on Mars



Figure 4: HP³ deployment onto the martian surface by the robotic arm of the lander. Left: Sol 74 – HP³ capture by the robotic arm; middle: sol 76 – HP³ placement on the surface; sol 83 – Grapple release of HP³ [credit NASA/JPL-Caltech]

3.2 Mole Recovery Activities

The nominal mole penetration activities started with firing of the mole frangibolt inside the support structure. Upon firing, the mole was free for hammering activities.

Hammer cycle operations to the target depth of 3 – 5 m were planned in 50 cm steps. After each hammering step a TEM-P/A measurement was planned to determine the thermal conductivity of the soil. In the mole housing tube, a contact switch at the vertical midpoint was used to indicate that half of the mole (20 cm) had left the support structure. The STATIL sensor within the mole provided tilt data with respect to local gravity. One exception to the planned intervals described above was the first such penetration interval. The TLM is located at about 150 mm above surface level (Figure 2). At the moment of mole release, approximately 25 cm of tether extends from the TLM to the back of the mole at the top of the tube. The TLM device would only provide data once this loop was exhausted and the tether began to move past the LEDs and photo sensors within the TLM. Determination of the depth of the mole, as reported by the TLM, was thus limited to depths greater than ~0.6 m. So, the first target point for mole penetration was chosen to be 70 cm, allowing the TLM to fully engage and read multiple relative depth markers printed on the tether in addition to reading one complete marker for absolute depth.

The mole hammering cycles could be stopped either by reaching the target depth or by hammering timeout which limits the number of strokes.

The first hammering cycle was performed on sol 92. About 3900 strokes were performed. The hammering itself was executed nominally by the BEE and the mole. However, the TLM did not register any movement of the tether, indicating that the target depth of 70 cm was not reached. A strong inclination change of the mole could be detected by STATIL at the beginning of the hammering session. As the TLM had no measurement at this point in time we had no indication about the real depth of the mole in the regolith.

A second hammering session of about 4700 strokes was executed on sol 94 attempting to bring the mole to a depth of 70 cm. The activity executed nominally, but again there was no indication of tether movement through the TLM. After both initial hammering attempts, it was observed that the support structure had moved slightly on the surface, as shown by impressions left by the SSA feet.

An almost 2 years mole recovery activity was launched after this event to evaluate the situation and to continue the mole operation. Details to this activity were reported in [2] and a detailed description of the various activities and strategies considered can be found in [7,8].

The view of the mole and the tether was blocked by the support structure. After sessions of diagnostic hammering, it was decided to remove the support structure to get a view of the mole and of the pit that the mole had excavated during the first hammering rounds. In this configuration with the surrounding pit the mole had no friction at its outer hull which is mandatory for forward motion; it had encountered a difficult environment, a deep cohesive duricrust, which was not expected beforehand [8].

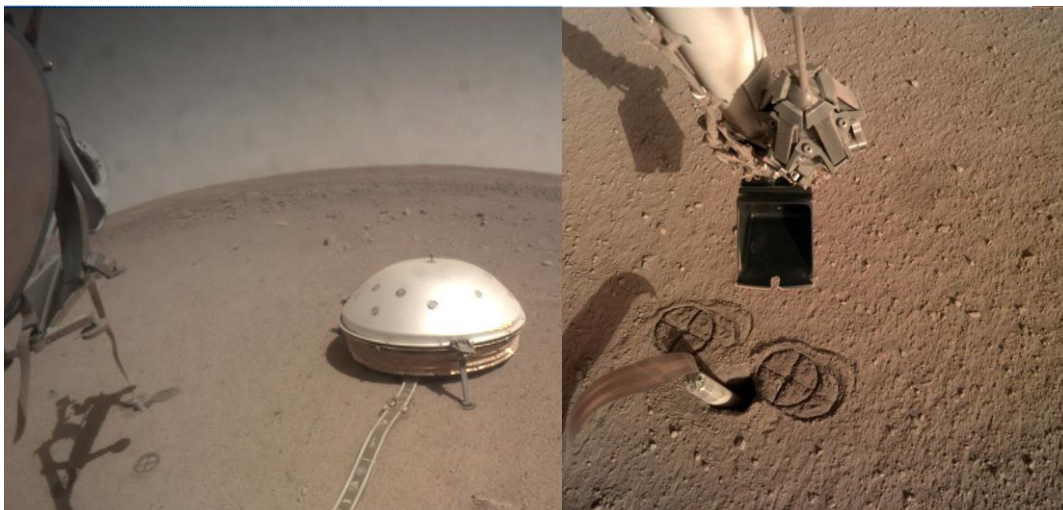


Figure 5: Left picture: Sol 209 – the third part of the SSA lift by the robotic arm (at left) showing science tether extraction for slack at the SSA’s highest point, SEIS’s Wind and Thermal Shield is visible at right; Right picture: Sol 234 – mole inside its pit, flanked by the SSA forward footprints [credit NASA/JPL-Caltech]

In various sessions during about 1,5 years the team worked on burying the mole with challenging operations which originally had never been planned to be executed on Mars [9]. The IDA team was able to pin the mole from the side with the robotic arm of the lander providing the necessary friction for a forward penetration. In this way the mole penetrated into the surface but recoiled again when the additional friction provided by the force of the arm could not be applied anymore.

The IDA team filled dust in the pit by chopping and scrapping. In the end the scoop could even be placed on the back cap of the mole right beside the tether with the supporting lines of the mole. With this difficult and risky maneuver and an inclined scoop, the mole could penetrate again into the surface and even below surface level with the back cap.

A final free mole hammering test was performed with the mole buried with soil which was preloaded by the scoop at the top surface level. But no forward motion could be detected and the recovery activities were stopped. The mole is now in its final position underneath the martian surface. All further scientific measurements were performed in this final position (see below).

Table 2: Summary of the main mole recovery steps. Listed are the different hammering sessions and corresponding arm activities. The activities went along with numerous photographic images, tilt and TEM-A measurements which are not all noted down in the list. The distance of the back cap above the surface is determined along the mole axis.

Sol	Day [UTC]	Activity	#Strokes	Back cap distance to surface [cm]
92	01-Mar 2019	First Hammering ~3600 strokes, target depth 70 cm	3881	7±1
94	03-Mar 2019	Second Hammering ~5000 strokes, target depth 70 cm	4720	7±1
97 - 117	06-Mar 2019 27-Mar 2019	Tilt & TEM-A Measurements for further assessments of mole situation		7±1
118 - 158	28-Mar 2019 08-May 2019	2 Diagnostic hammering sessions for the investigation of the mole situation. TEM-A measurement additionally performed	395	7±1
203 - 209	23-Jun 2019 29-Jun 2019	Lift of support structure (SSA) in three steps followed by detailed mosaic pictures of the pit		7±0.5
237 - 257	28-Jul 2019 18-Aug 2019	Arm soil interactions to fill the pit. Flat scoop pushes and chop tests attempt to collapse the pit		7±0.5
308	09-Oct 2019	First hammering with the mole pinned by the scoop against the pit wall	20	6±0.5
311 - 322	12-Oct 2019 23-Oct 2019	4 Hammering sessions in pinned configuration. The back cap of the mole is almost on surface level on sol 322	404	1.5±0.5
325	26-Oct 2019	2 Hammering sessions with the arm mainly pushing on the surface aiming to transfer force to the mole in the pit. The transferred force is not sufficient to damp the recoiling of the hammering mechanism. The mole reversed.	254	18±0.5
346 - 380	17-Nov 2019 22-Dec 2019	The mole is pinned by the arm again, 5 Hammering sessions performed. Starting with small number of hammer strokes. Successful penetration permits recovery from the reversal event	362	3±0.5
407	19-Jan 2020	Re-pinning and hammering session, mole reverses	151	7±0.5
420	01-Feb 2020	Arm chops the pit and filled part of the pit		7±0.5
427 - 454	08-Feb 2020 07-Mar 2020	Arm back cap pinning of the mole with a horizontal scoop and preloading		7±1
458 - 557	11-Mar 2020 21-Jun 2020	9 hammering sessions renewing of preload to the back cap before each hammering with a horizontal scoop; starting with small number of hammer strokes. The mole descends into the surface.	826	0±1
604 - 632	08-Aug 2020 06-Sep 2020	Back cap pinning with inclined scoop and 5 hammering sessions. The mole back cap is below surface level at the end of this phase.	202	-1.7±1
645	19-Sep 2020	A long hammering session of 252 strokes. The mole back cap is below surface level. The scoop of the robotic arm is already inclined. For the last 90 hammer strokes the mole has no guidance by the arm.	252	-2±1
659 – 734	03-Oct 2020 20-Dec 2020	Imaging of the pit; regolith is scraped into the pit; each scrape is followed by a flat-scoop tamping action.		-2±1
754	09-Jan 2021	Free Mole Hammering Test. The arm pushes on the filled pit and prevents the mole against reversal. No forward motion detected	506	-2±1

3.3 HP³ continuous Operations on Mars

The main scientific measurement units of HP³ are the radiometer and TEM. Shortly after landing the scientific program started with measurements of the radiometer. These operations continued with different configurations of the radiometer measurements during the two martian years. The operations plan of the radiometer also includes measurements in parallel with other InSight instruments for investigation of the atmospheric boundary layer, and the observation of the temperature effect of eclipses on Mars.

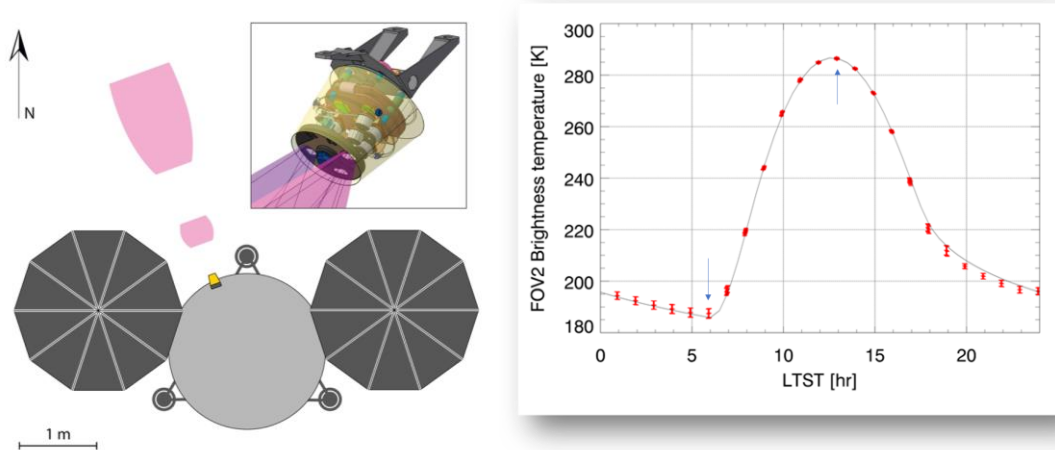


Figure 6: Left: Rendering of the HP³ radiometer (RAD) which is mounted on the bottom of the lander deck. RAD contains two triplets of thermopile sensors (each triplet consists of three different wavelength windows) which are targeted to two fields of view. The radiometer points away from the instrument deployment area producing two fields of view (near and far) shown in violet. Instruments are deployed to the south of the lander (not shown). Right: Timing of the Rad hourly measurements during a sol, arrows are indicating the timing of Rad single measurements during the energy reduced measurement scenario with Rad Single mode usage.

The main task of the radiometer is to generate a long-term record of the daily average surface brightness temperature next to the lander. This measurement was intended to support the HP³ TEM-P heat flow measurement by constraining the seasonal heat wave in the underground and how this is influenced by the presence of the lander. To achieve this, it was planned to observe the shape of the diurnal temperature profile with measurements taking place hourly at least bi-monthly (Mars calendar), and otherwise take measurements 4 times a day to save energy. For this the instrument flight software included two operation modes, the ‘hourly’ mode, and the ‘standard’ mode, to run continuously and take measurements according to schedule, independent of the lander wake status. In the early phase of the mission a design flaw was discovered that resulted in a small overrating of an electrical part during the standard mode, when the instrument was heated up autonomously for operations at night. Since energy was not scarce in the beginning of the mission, the ‘hourly’ mode could be used almost continuously, and the ‘standard’ mode was not used anymore. One main operations task was to keep the measurements approximately synchronized with Mars local true solar time (LTST). For certain science measurement tasks, the configuration of the Rad measurement modes was changed to enable the radiometer to record measurements quasi continuously for a dedicated period of time or an entire sol. This kind of measurement was used for example for lander shadow or Phobos eclipse observations (see below).

The radiometer observed the surface temperature of two spots next to the lander for about 1.8 Mars years. During the first year, RAD data coverage provides the essential information about seasonal and diurnal temperature variations, with additionally about 14 sols of continuous observations for correlation with other sensors on even higher frequencies. In the second year, the energy shortage meant reduced observations that nevertheless provided sufficient information on seasonal and interannual temperature variations (Figure 7).

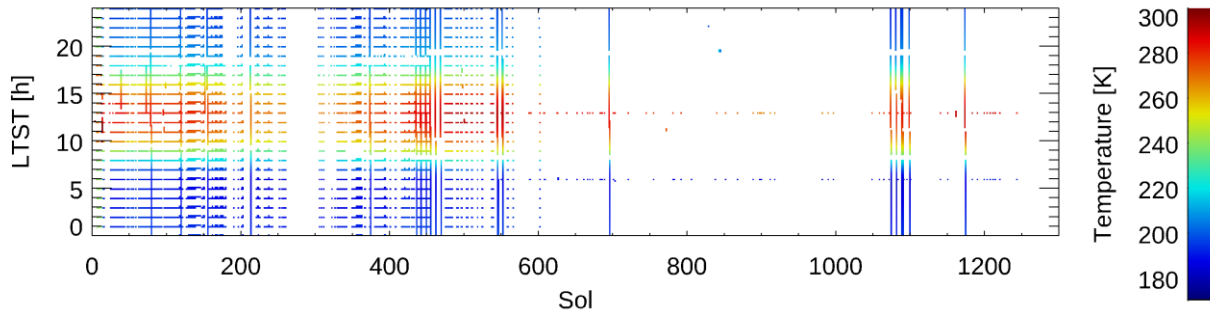


Figure 7: Sketch of Rad measurement distribution along the on-surface operations of InSight mission. At the beginning of the mission Rad hourly measurements were mainly performed, which include measurement during the entire sol whereas in the second half of the mission just Rad Single measurements at the sol min/max temperatures could be performed.

Aside from these main radiometer operations, there were several additional activities. First, self-calibration measurements were performed regularly [10]. The cadence of these measurements was increased between sol 325 and 400, when one of the sensors experienced an unexpectedly rapid drift. Since the surface of Mars contributes a background signal to these calibration measurements, the self-calibration had to be synchronized with the normal measurements to be able to subtract this contribution. Other observations for opportunistic science include high sampling rate observations (0.5 Hz) at times when the sunlight incident on the observed spots was reduced temporarily by either the solar arrays or the Mars moon Phobos [11,12], and continuous measurements over one or more sols for correlation with the continuous meteorology data [13]. Of these, the transits of Phobos were most challenging to observe since they last typically only 30 seconds and occur only rarely, so that accurate timing was of high importance. The effect of these transits is similar to that of a solar eclipse on Earth, in that the temperature drops by a few K [11,12]. Other opportunistic science was already enabled by the hourly mode measurements in the early mission, such as the effect of a dust storm on the shape of the diurnal curve [14], constraints on the profile of subsurface temperatures [15] and thermophysical properties [16], and thus contributing to local geological studies [17].

The TEM measurement suite (section 2) performed various measurements, highlighted by the TEM-P/A measurements. TEM-P/A measurements are composed of several sols of TEM-P monitoring measurements, typically two sols, followed by one sol of TEM-A active heating and measurements. The TEM-P measurements monitor the background temperature variations before the active measurement part (TEM-A) starts [18,19]. HP³ measures thermal conductivity in the TEM-A mode using the mole as a modified line heat source. In this approach, the probe is heated using known power while simultaneously measuring the resulting temperature rise. Using laboratory-verified numerical models of the mole response to heating, regolith properties can then be determined [19]. The TEM-A measurements are typically started at the same time of day (21 LTST).

Most of the TEM-P/A measurements at the beginning of the mission were used for engineering purposes for the mole recovery. These TEM-P/A measurements were used to estimate the contact of the soil to the mole inside the pit. After the mole recovery activities ended and the mole was placed in its final position, main scientific TEM measurements started for the investigation of thermal conductivity dependencies in the martian surface. Different TEM-A measurements were performed at different martian seasons (solar longitudes) and thus different atmospheric pressures to determine the seasonal dependency of the thermal conductivity in the upper martian surface layers (see Figure 8).

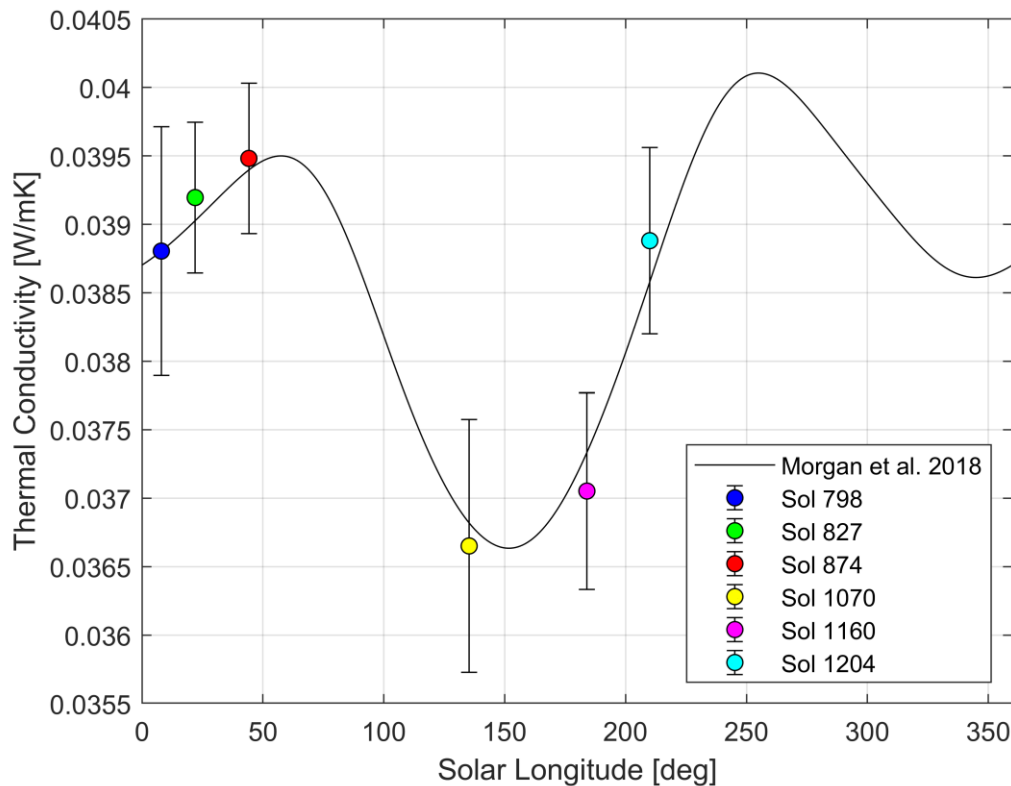


Figure 8: Thermal conductivity as a function of martian season. Six active heating experiments were conducted over the period of $L_s = 8.0^\circ$ to $L_s = 210^\circ$ before the reduction of solar power on the InSight lander prevented further measurements to be made towards the end of the mission. A model of thermal conductivity as a function of atmospheric pressure is shown for reference [20].

As is evident from Figure 8, soil thermal conductivity at the landing site strongly correlates with atmospheric pressure. The retrieved thermal conductivities vary within the range predicted by models for unconsolidated soils under martian atmospheric conditions [18,20]. Furthermore, results are consistent with laboratory experiments [21,22]. The observed strong correlation between thermal conductivity and atmospheric pressure indicates that heat transport through the pore-filling CO_2 gas is a major contributor to the total heat transport in the soil. The thermal conductivity data retrieved by HP^3 active heating experiments are the first direct evidence that the martian atmosphere interacts with the martian soil on decimeter scales.

3.4 Final activities of HP^3 Operations

During the first months of the on-surface mission the regular sandstorm season on Mars started to cover the solar cells with dust. The raised dust during the landing also settled back on the martian surface and the solar cells after landing. Also, outside the duststorm season the dust coverage of the solar cells continued, slowly, but continuously. The JPL tools forecasting the available energy throughout the martian year worked extremely well and were one of the corner stones during operational planning activities. During the regular InSight mission duration, the lander provided enough energy to fulfil all operational science goals. With the start of the extended mission phase after 1 martian year (2 Earth years) the available energy of the lander started reduce to a significant lower level after the second duststorm season (see Figure 9). The lander system and the instrument teams started to operate the instruments in reduced energy consumption modes. The lander system team succeeded even in performing cleaning events on the dusty solar cells which resulted in an increased energy budget for the instruments. These solar cell cleaning events were limited to dedicated solar cell areas by geometrical aspects of the lander.

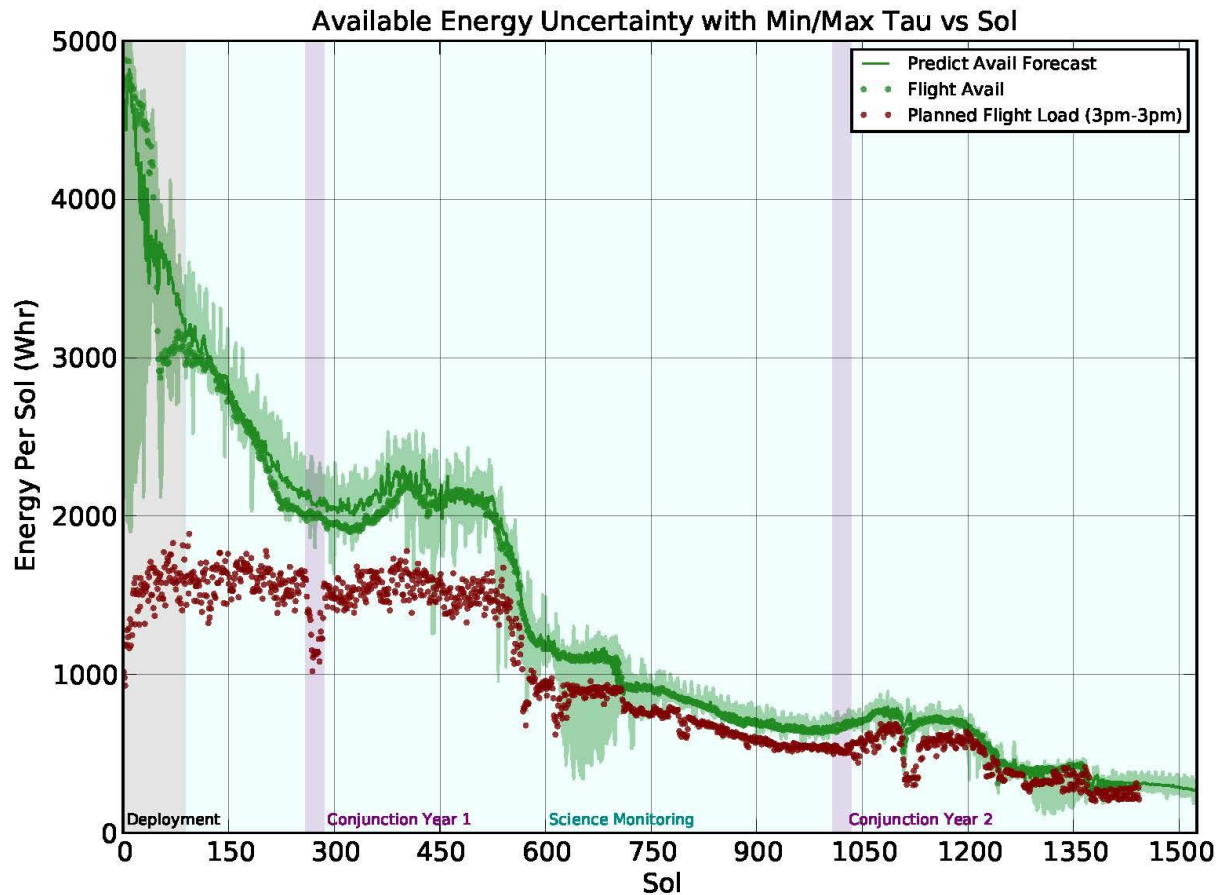


Figure 9: InSight lander predicted available energy for life of mission
[credit NASA/JPL-Caltech & Lockheed Martin Space Systems]

HP³ followed different approaches to reduce the energy consumption and increase efficiency. HP³ and especially the radiometer could already look back to the first martian year of almost a complete radiometer measurement coverage of the martian brightness temperature coverage throughout the seasons (Figure 7). The full martian day measurements (hourly mode) could be replaced by measuring just the minimum and maximum temperatures of a daily temperature cycle (Figure 6). This reduced the energy consumption by about 100 Wh per sol. Full Rad hourly measurements were scheduled occasionally (target every month) in the plan. Furthermore, the instrument calibration activities were reduced to the necessary minimum. The final HP³ command sequences were optimized for power consumption and prepared in a way to be robust to be used after anomaly situations without additional ground loops.

The last HP³ and RAD operations, a pair of RAD measurements, was successfully executed on sol 1245 (28. May 2022). Thereafter, the energy available to the lander decreased so much that even SEIS, the prime instrument, could not be operated continuously anymore. The instrument needed to be power cycled. In the end, the available energy of the lander decreased such that on 15th December 2022 the last data of the InSight lander from Mars were received on Earth. End of mission was declared on the 20th December 2022 after two communication attempts from the lander had failed.

4. HP³ Ground Segment Design

4.1 Overview

The overall operations of InSight were distributed among multiple control centers in multiple countries with different control centers being responsible for different systems and instruments. The whole telemetry of the InSight Lander was received and processed by the operations team of Lockheed Martin and JPL, who then distributed the telemetry of the different instruments to the respective teams.

The operations of the instruments HP³ and RAD were performed for the first months after landing by the DLR operations team being co-located at JPL in Pasadena, afterwards at the HP³ Control Center at DLR in Cologne and finally during the Covid19 pandemic via multiple mobile control centers.

The three different operation scenarios required different approaches of processing and exchanging data products.

4.2 Colocation at JPL Pasadena

One goal of this co-located operations phase was to be fully functional and yet independent of any technical infrastructure of the HP³ control center in Cologne. To achieve this goal, a mobile ground segment was created which was based on several different laptops which served either as server systems to host all needed services like the mission control system and any other needed tools, or as client systems to access these services. The required network infrastructure to allow access between the mobile ground segment systems and the JPL data distribution systems was provided by JPL in coordination with the DLR operations team.

Since the HP³ science and system teams were also co-located in Pasadena, the data distribution could be managed directly by the mobile control center.

To be able to quickly recover from outages, some redundancy was included into the mobile ground segment. For example, all were processed on two servers in parallel to be quickly able to switch the connection to the backup server laptop in case the primary server laptop would break down. Regarding the recovery from permanent hardware issues, some spare devices and measures to regularly backup data were foreseen. In addition, all received and processed data were transferred to the data management system at the HP³ control center in Cologne for archiving purposes and off-site backup.

4.3 HP³ Control Center at DLR Cologne

Back in the HP³ control center in Cologne, the existing server-, client- and network infrastructure could be utilized to conduct the HP³ operations. While being able to connect directly to the JPL data distribution systems while being co-located, this connection was replaced by a secure site to site VPN connection between the control centers at JPL and at DLR.

The distribution of data to the science and system teams was changed to a web-based telemetry distribution system to allow access regardless of the location. This system allowed to export pre-defined sets of telemetry within a timeframe that can be freely chosen at the time of export. Another feature of the web-based data distribution system was to directly plot configurable graphs to gain a quick overview of the instrument or any subunit before transferring the exported data to own tools.

4.4 Mobile Control Centers

During the Covid19 pandemic, the access to the HP³ control center in Cologne was possible but very restricted. To cope with this situation, the concept of the mobile control center was reapplied with some changes. Instead of having separate laptops to act as server or client systems, both roles were combined into single laptops. This also included hosting some services as separate virtual machines on the laptop. With this configuration, all needed services could be hosted and used autonomously on a single device which allowed the HP³ operations team to take a full ground segment home and perform the needed tasks from there.

To access the JPL data distribution systems and other needed services, JPL provided a secured connection solution to safely transfer the telemetry and other needed products to the mobile ground segment systems.

The distribution of data to the science and system teams was continued via the web-based data distribution system since this allowed also those teams to work from home. The system was controlled by the HP³ ground segment team via another dedicated VPN connection.

To be able to continue operations in case of an outage of a mobile ground segment system, all HP³ operators were supplied with an own system to be able to take over. Again, all received and processed data have been transferred to the data management system at the HP³ control center in Cologne for archiving purposes and off-site backup. In this way the HP³ was able to continuously operate the experiment on Mars together with the partners.

5. Conclusions

The InSight mission performed 4 years of operation on Mars. The HP³ experiment performed successful operations and scientific measurements during 3.5 years of this timeframe.

The mole was not able to reach its target depth to perform the heat flux measurements, despite almost 2 Earth years of extensive recovery activities performed by the InSight team. Instead, the mole provided penetrometry and thermal data for the top about 40 cm of the regolith [7,18,19]. The robotic arm of InSight was used for a number of impressive first-of-a-kind activities on Mars to support the mole recovery. The SEIS instrument was able to monitor the hammering and arm activities and derive seismic velocities [23].

The scientific measurements were reduced in the final mole position, but significant and unique measurements could be performed also in cooperation with the other InSight instruments. The radiometer has monitored the surface brightness temperature for almost 2 martian years. Measurements during Phobos eclipses were performed and opportunistic science measurements with high sampling rates.

The operational planning was always a challenging activity for the various teams involved but perfectly handled by the experienced JPL and Lockheed Martin Spacecraft Team. At the beginning of the mission plenty of activities had to be scheduled during each sol. The activity schedules were challenging especially due to their complexity. Towards the end of the mission and till its end the team had to deal, handle and plan with every single Watt-hour of the lander. InSight and HP³ were successfully operated under the harsh environmental conditions of Mars but also under adverse conditions on Earth like the restrictions due to the pandemic.

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