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HP^3 – Experiment on InSight Mission – 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).

The InSight Mission investigates the interior structure of Mars using seismological and geodetical measurements and quantifies the planetary heat budget by measuring the surface planetary heat flow. InSight was launched on the 5th May 2018 and landed successfully on Mars on the 26th November 2018 and is now operating on Mars successfully for more than one Martian year. The main payloads of the InSight lander are a seismometer (SEIS), the HP^3 heat flow probe and radiometer (for surface brightness temperature), as well as the radio science Rotation and Interior Structure Experiment (RISE). An ancillary sensor package consisting of atmospheric pressure and temperature sensors (APSS) as well as a magnetometer complement the payload. After landing on Mars the seismometer and HP^3 were deployed onto the Martian surface by the robotic arm of the lander.

HP^3 is the contribution of DLR (Deutsches Zentrum für Luft- und Raumfahrt e.V., Germany) to the InSight mission. It is designed to determine the geothermal heat flux by measuring the thermal conductivity and the rate of temperature increase with depth.

HP^3 is composed of a set of thermal sensors to determine thermal conductivity and subsurface temperature (TEM), a self-penetrating probe (termed the mole) to emplace sensors in the subsurface, two measurement suites to determine the depth of the thermal sensors (TLM & STATIL), a radiometer to determine the surface temperature forcing (RAD). The instrument is controlled by (backend) electronics (BEE) within the InSight lander's thermal enclosure. The HP^3 deployable elements are housed inside a support structure, and electrical connections to the lander and BEE are provided by the HP^3 supply tethers [1].

The InSight mission has now been operating on Mars for more than one martian year. The radiometer has been monitoring the surface brightness temperature for a full martian year and has measured thermal effects during Phobos eclipses.

The heat flow aspect of the HP^3 investigation has unfortunately been less successful. The mole penetration initially proceeded no deeper than ~37 cm (tip depth below surface). During the past 2 Earth years, extensive recovery activities for the mole were performed on Mars to get the mole penetrated deeper into the surface. These activities were supported by the overall InSight team. The mole is now in its final position intruded into the upper surface layer (mole tilt ~30°) and covered with soil. No further penetration attempts will be performed.

Keywords: Mars, InSight, HP^3, heat flow, temperature, mole

Nomenclature

HP^3	=	Heat Flow and Physical Properties Package
DLR	=	Deutsches Zentrum für Luft- und Raumfahrt e.V.
RISE	=	Rotation and Interior Structure Experiment
APSS	=	Auxiliary Payload Sensor Suite
SEIS	=	Seismometer
TEM	=	Thermal Excitation and Measurement

STATIL = Static Tiltmeter
TCM = Trajectory Correction Manoeuvre
TLM = Tether Length Monitor
SSA = Support System Assembly
BEE = Backend Electronics
RAD = Radiometer
InSight = Interior Exploration Using Seismic Investigation, Geodesy, and Heat Transport
ICC = Instrument Context Camera
IDA = Instrument Deployment Arm
IDC = Instrument Deployment Camera
IDS = Instrument Deployment System
LTST = Mars local true solar time

1. Introduction

HP^3 – 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 [2]).The InSight Mission investigates the interior structure of Mars using seismic and geodetic measurements and quantify 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 November 26th, 2018. The main payloads of the InSight lander are a seismometer (SEIS), the HP^3 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. After landing on Mars, the seismometer and HP^3 were deployed onto the Martian surface by the robotic arm of the lander. Two cameras maped 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 Deplyoment Camera). By moving the arm, the IDC provides stereo images and thus topography of the landing site.

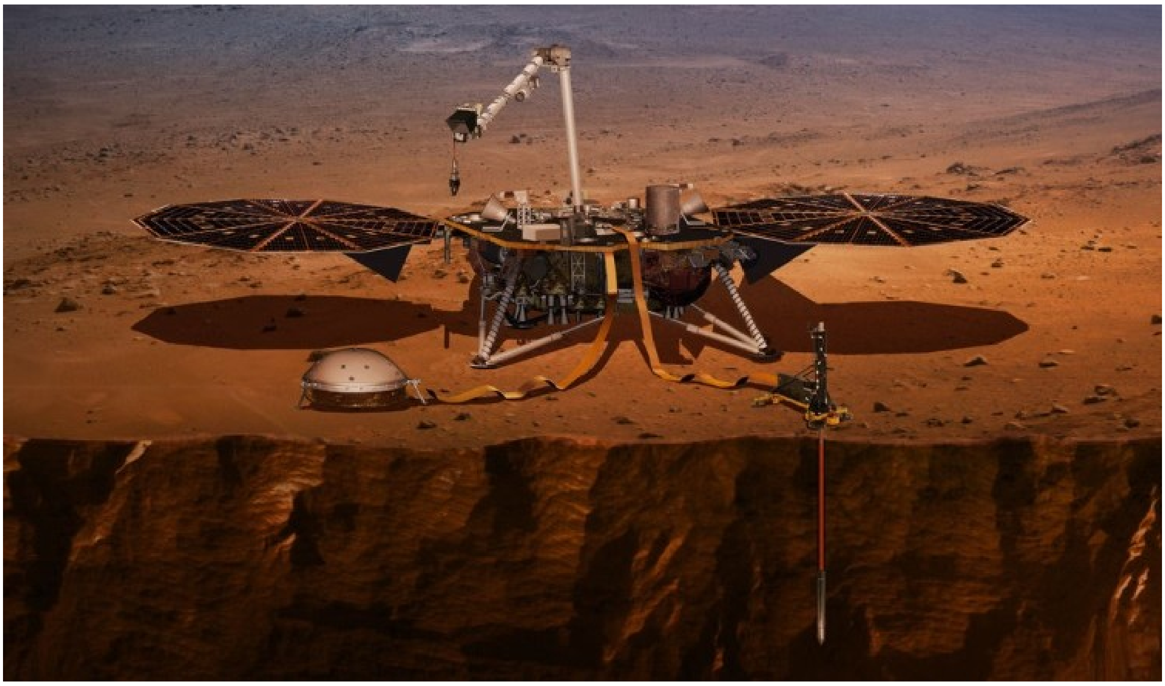

Figure 1: Artist impression of the InSight lander on the Martian surface with HP^3 deployed and the mole located in the subsurface. The radiometer is mounted underneath the deck of the lander, facing away from the instruments (not shown). Image Credit: NASA/JPL-Caltech

HP^3 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 [3]. HP3 is designed to determine the geothermal heat flux by emplacing a suit of temperature sensors to a maximum depth of 5m, by means of a meachnical hammering mechanism (mole). HP^3 is designed to measure the thermal conductivity as function of depth during the hammering phase, and to monitore 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 HP^3) deployed onto the martian surface.

The HP^3 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 the upper soil layers can be derived.

The operations of the radiometer, the thermal conductivity measurements, and the mole are described below in more detail. The radiometer opened its dust cover and started its scientific measurement campaign shortly after the landing on Mars.

After landing, the deployable units of HP3 conducted checkouts and preparations for the instrument deployment to the martian surface which took place on sol 76.

2. Description of the HP^3 Experiment

HP^3 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 [1,4]. 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 HP^3 mole heaters to measure the thermal conductivity of the surrounding regolith. HP^3 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.

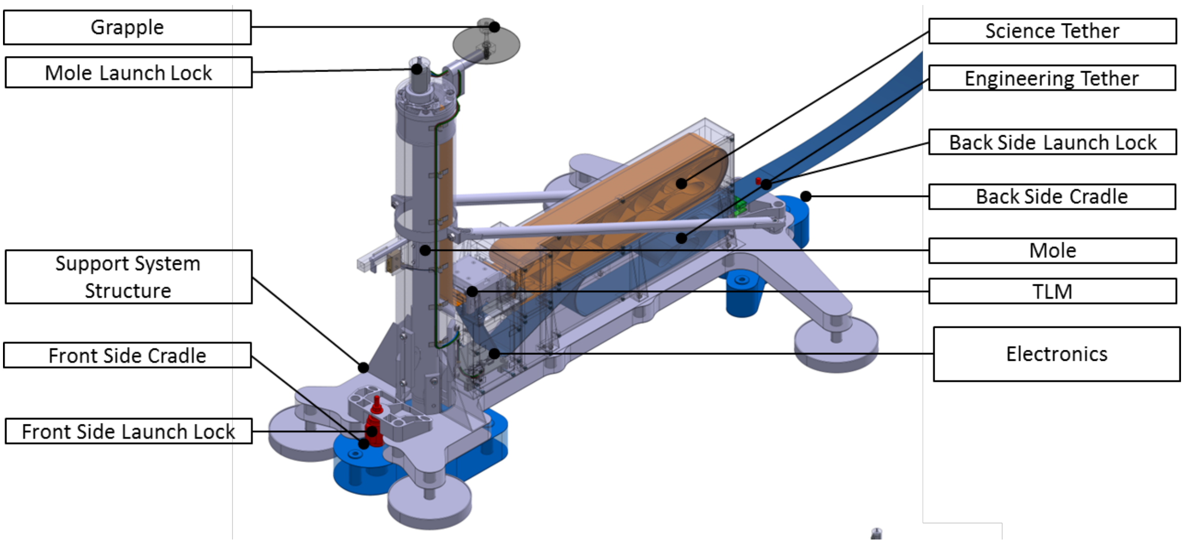

Figure 2: Schematic of the HP^3 Support Structure Assembly (SSA) indicating functional subunits. The grappling hook serves as the interface to the lander's robotic arm, while the cradles are the interface to the lander. The mole launch lock is released after deployment of the SSA onto the Martian surface. The SSA houses the engineering tether, science tether, TLM, mole, as well as an electronics interface board.

HP^3 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 heaters 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 HP^3 deployable elements are housed inside a support structure, and electrical connections to the lander and BEE are provided by the HP^3 engineering tethers. The support structure also securely stored the mole and tethers during cruise and guides the mole during its initial hammeing into the surface after deployment. The support structure assembly is shown in Figure 2 which indicates the major subsystems. The three engineering tethers (blue) connect the deployed SSA to the lander and backend electronics inside the lander's warm electronics box. The engineering tethers interface 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.

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 reacting the small but non-zero recoil of the hammering mechanism that is transmitted to the hull.

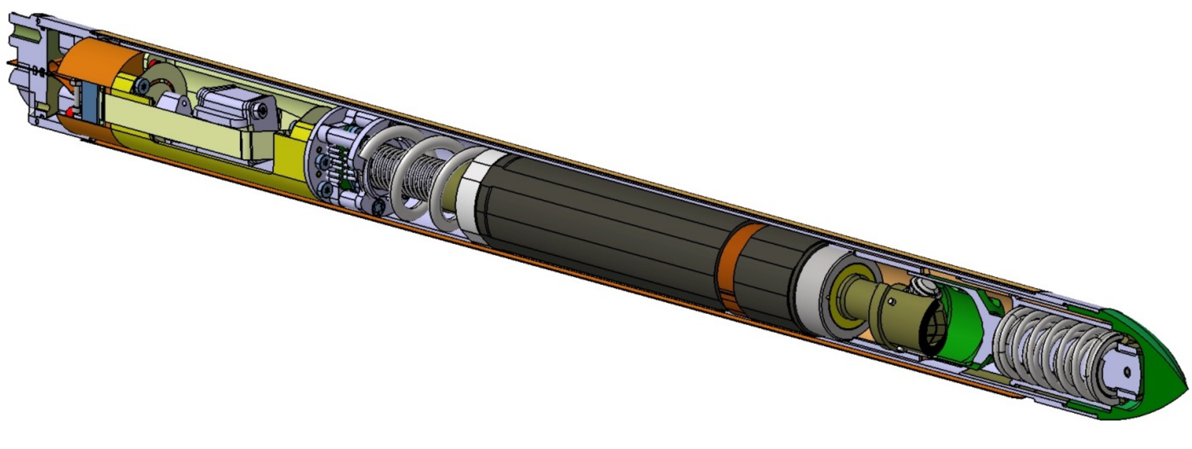

Figure 3: Schematic diagram of the HP^3 mole. The mole interfaces with the science tether on the left hand side. The STATIL assembly (yellow / light gray) as well as the hammering mechanism (dark gray) are also indicated. The ogive shaped mole tip (green) is designed to minimize the soil resistance during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

During hammering and mole advancement into the soil, the STATIL tiltmeter is designed determine the mole angles in the ground, while the Tether Length Monitor (TLM) determines the length of tether extracted from the storage box (see Figure 4). Taken together, these measurements allow for a reconstruction of absolute depth of the mole as well as the depth of the temperature sensors embedded on the tether (see below). The TLM uses infrared LEDs and phototransistors to locate markings on the science tether as it is pulled through the device. Two strings of markers on the left and right edges of the tether encode absolute and relative length, respectively. STATIL is composed of 2 static 2-axis tiltmeters, measuring the inclination of the mole with respect to the local gravity vector. To protect the STATIL from the high shock environment within the mole during hammering, the sensors are mounted on a sled suspended by shock mitigation springs. These produce a transient oscillatory motion of STATIL after each hammer stroke lasting less than 1 second. STATIL measurements on only acquired at times >1 sec after a hammer stroke.

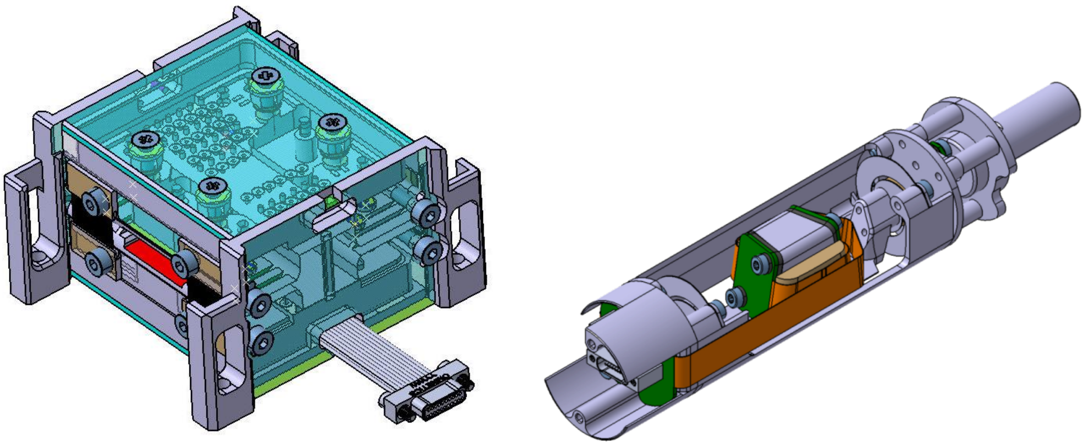

Figure 4: Left: Rendering of the Tether Length Monitor through which the science tether passes. Right: Rendering of the STATIL Measurement suite including the sensor circuit boards (green rectangles) mounted on the canted sides of the sled's plinth and spiral springs for shock mitigation.

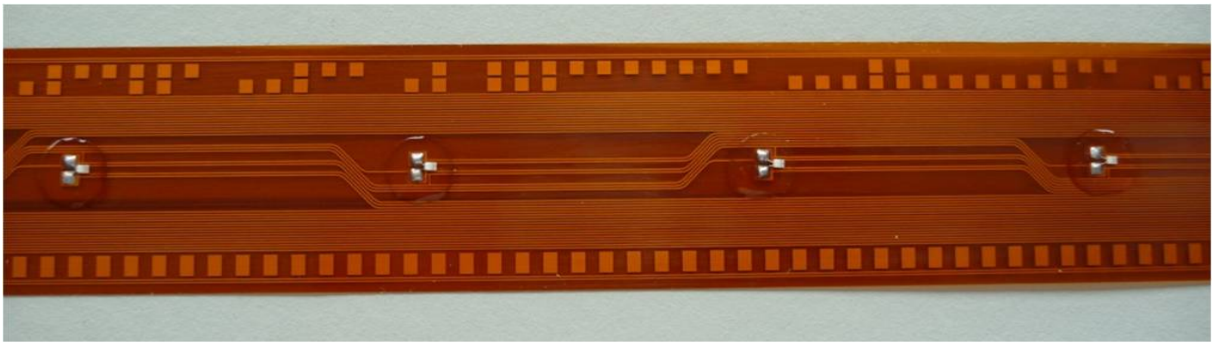

Figure 5: Prototype TEM-P tether showing four PT100 sensors coated by silicon adhesive. Markings for the TLM are also shown. Absolute depth encoding is given on the top, while clock markings are given at the bottom. The flight science tether has sensors at a much larger non-uniform spacing.

The Thermal Excitation and Measurement suite (TEM) is divided into two functional sub-units:

- TEM-A (Active), which measures the soil thermal conductivity
- TEM-P (Passive), which measures the soil temperature gradient

TEM-A is located in the outer shell of the Mole and consists of heating foils acting simultaneously as heaters and resistance temperature detectors. TEM-A measures the thermal conductivity by applying a known amount of heat to the outer body of the mole and measuring the mole self-heating. The amount of self-heating is a measure of the ambient regolith's thermal conductivity, which can be retrieved using a thermal model of mole-regolith interaction.

TEM-P consists of 14 PT100 temperature sensors, which are read out using a 4 wire (Kelvin) configuration. Temperature sensors are soldered onto a 5 m long Kapton tether and protected from abrasion by Nusil silicone adhesive capsule. The Science Tether also contains the electrical lines connecting the Mole (STATIL, TEM-A, and hammering mechanism) to the SSA. TEM-P is designed to measure the temperature gradient as a function of depth in the regolith. The tether is 36 mm wide, slightly larger than the diameter of the borehole to ensure sufficient thermal contact with the borehole wall.

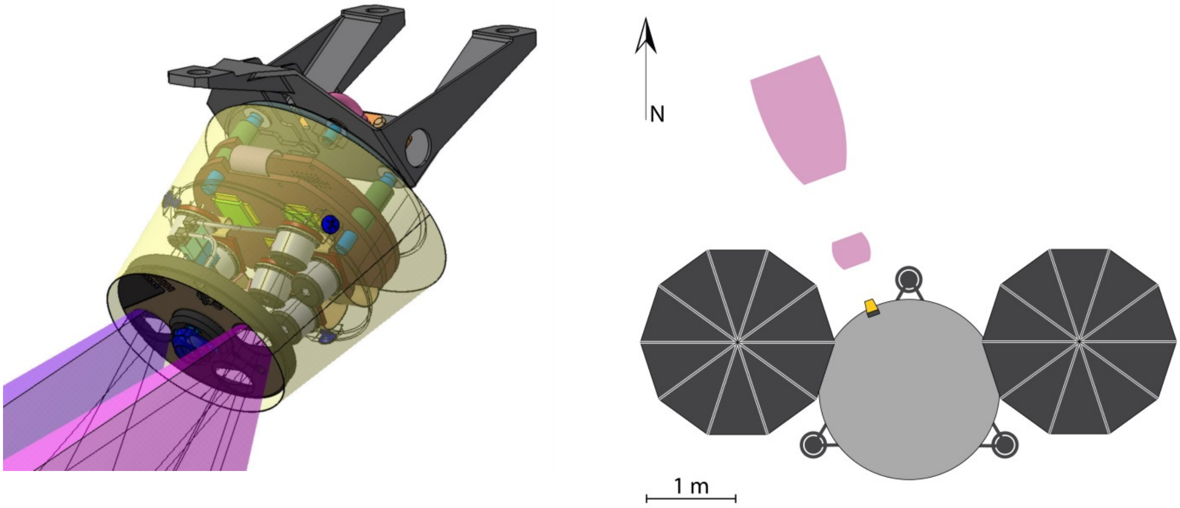

Figure 6: Left: Rendering of the HP^3 radiometer (RAD) which is mounted on the bottom of the lander deck. RAD contains two triplets of thermopile sensors (each triplet consists of three different wavelength windows) which are targeted to two fields of view. Right: The radiometer points away from the 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).

The HP^3 radiometer (RAD, Figure 6) is mounted underneath the InSight lander deck and determines the surface brightness temperature of the martian regolith, from which thermal inertia of the the upper soil layers can be derived. Through repeated observations, the RAD can observe changes in brightness temperature that could be due to (among other causes) the gradual resettling of dust removed during landing. In this way, the RAD helps determine the surface energy balance to quantif the forcing function for the subsurface temperatures to have been measured by TEM-P. The radiometer is operated on Mars in an hourly mode, taking 24 measurements during one martian day to characterize near-surface thermal inertia. For phases of low available energy, the operational concept was reduced to two measurements of the maximum and minimum daily temperture.

All instrument functions are operated and controlled by the HP^3 Backend Electronics (BEE), which also provides the telemetry and commanding interface to the InSight lander. The HP^3 BEE is located inside the lander's thermal enclosure. The InSight lander frequently enters a low-power sleep mode while still providing power to the instruments. The BEE receives command sequences during lander wakes and is designed to store them for time-tagged execution during lander sleep. Two finite state machines for the RAD and SSA run in parellel on the BEE and have been implemented to autonomously execute RAD and TEM measurements, do instrument checkouts, and control the HP3 hammering and temperature measurement activity (see below). To protect HP^3 from bitflip errors, the commanding queue of the BEE is only used occasinally.

3. 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 Manoeuvre) 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 [5].

4. Operations on Mars

All HP^3 subsystems started soon after the landing with checkouts and even science measurements and could continue these throughout the first Martian year. As the radiometer is mounted below the lander deck its measurements are independent of the deployment of the HP^3 support structure and penetration of the mole. The tiltmeter STATIL started its measurement on the lander deck and was cross-calibrated with the landed deck tilt on Mars as measured by InSight lander avionics. TEM measurements were used to monitor the surrounding temperatures before the HP^3 deployment.

The planning of the all HP^3 operations on Mars is performed within the InSight team. Especially resources like power, data budget and link availability need to be planned carefully and in close cooperation in-between system and instrument requirements and constraints. Intensive and detailed planning iterations of the operation teams are performed to maximise the scintific outcome of the InSight mission.

During the deployment phase and the first hammering attempts the instrument teams were colocated at JPL (Pasadena, US) for this intense operation phase. For the surface operation phase which followed, the European teams returned back to their control centers in Germany and France. HP^3 is operated from DLR Cologne – the Microgravity User Support Center (MUSC).

4.1 Instrument Deployment Phase

The operations on Mars started shortly after landing. First checkouts and first scientific measurements were performed during the early phases of the InSight surface mission. The first part 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 deployment site 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 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, HP^3 was successfully deployed to the Martian surface on the 12th February 2019 (sol 76). Figure 7 shows HP^3 in its final position after deployment including the wide-field view from the fixed-view Instrument Context Camera (ICC) with both instruments deployed on Martian surface.

HP^3 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 HP^3 safely onto the surface. In the following sols the position of HP^3 was evaluated including a checkout and tilt measurements of HP^3 and its stability. The HP^3 subsystem STATIL monitored the inclination of HP^3 vs the gravity vector. After the position and status of HP^3 was approved, the arm grapple was adjusted and finally on sol 83 the grapple was released allowing HP^3 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

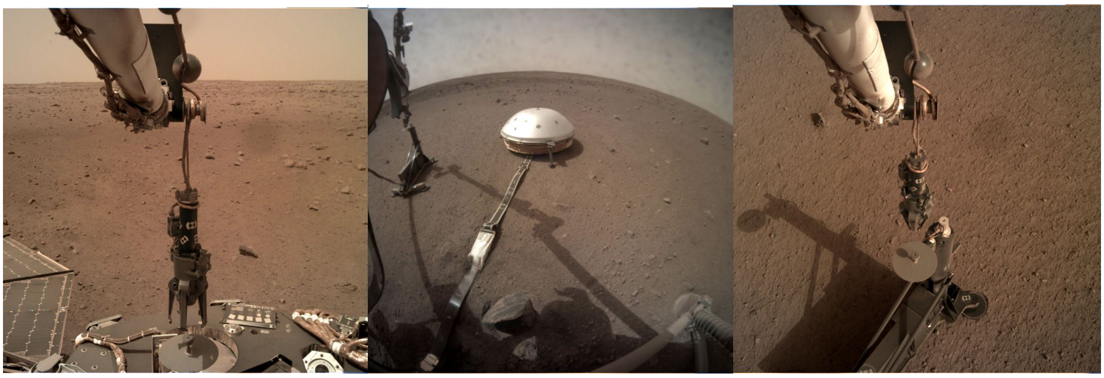

Figure 7: HP^3 deployment onto the Martian surface by the robotic arm of the lander. Left: Sol 74 – HP^3 capture by the robotic arm; middle: sol 76 – HP^3 placement on the surface; sol 83 – Grapple release of HP^3 [credit NASA/JPL-Caltech]

4.2 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.

The hammer cycle operations to the target depth of 3 – 5 m was 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 at a high time resolution during any stage of mole operation. One exception to the planned intervals described above was the first such penetration interval. The TLM is located at about the 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 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 failed to register any movement of the tether, indicating that the target depth of 70 cm had not been 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 surface.

A second hammering session was executed of about 4700 strokes 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.

In sols 118 – 158 two sessions of diagnostic hammering were performed. In each session about 200 hammer strokes were executed while the InSight cameras took pictures during the hammering. No final analysis about the reason for the failed mole progress was derived, although some further shuffling of the support structure due to hammering was visible. At this time there were no indications of failures inside the mole. Different root causes for the issue were under consideration. Amongst those considered to have high likelihood were (1) mole/SSA interaction like snagging of the tether inside the SSA and external factors like (2) a large stone in front of the mole or (3) reduced friction at the mole hull. Other factors with lower likelihood, such as cohesion of sticky soil, moisture of soil, or subsurface ice were considered but ultimately ruled out.

In June 2020 it was decided to lift the support structure from the mole. It is worth mentioning that this and the following manoeuvres of the robotic arm/HP^3 interaction had not been discussed, planned, or tested prior to the occurrence of the anomaly. The InSight Instrument Deployment Arm (IDA) team (i.e., the robotic arm team) performed intense planning and ground tests to make the following activities possible and the overall InSight team agreed that the risks to the arm in these mole recovery actions were acceptable.

The lift of the support structure was performed in three steps (sols 203 – 209). In the first step the HP^3 Support Structure was pulled upwards. One risk in this manoeuvre was that the mole would get additionally pulled up if the mole or tether were snagged inside the tube. In the second part of the lift, the SSA was raised until the science tether became taut and extracted ~55 cm from the TLM. This intermediate step allowed the InSight and HP^3 operations teams to assess whether the tether was extracting smoothly and with little resistance, in addition to ruling out a fault with the TLM as a contributor to the anomaly. The third part of the lift saw the extraction of a further 28.4 cm of science tether through the TLM (as *measured* by the TLM), providing slack for the placement of the SSA back on Mars' surface some distance from the mole (Figure 8).

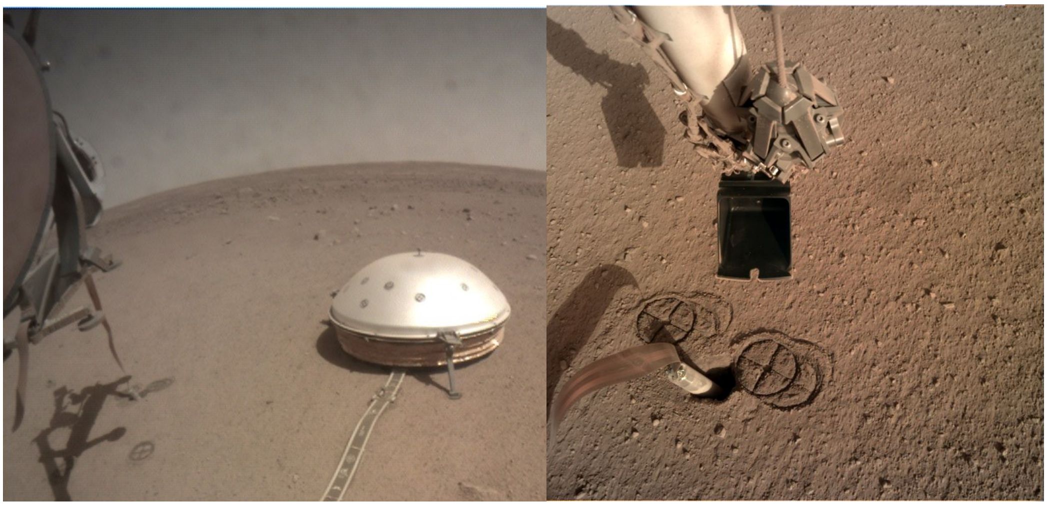

Figure 8: Left picture: Sol 209 – the third part of the SSA lift by the robotic arm (at left) showing science tether extraction for slack at the SSA's highest point, SEIS's Wind and Thermal Shield is visible at right; Right picture: Sol 234 – Mole inside its pit, flanked by the SSA forward footprints [credit NASA/JPL-Caltech]

The repositioning of the SSA provided a clear view of the inclined, partially penetrated mole, the SSA feet imprints, and what came to be known as 'the pit' around the mole. From sol 220 – 257, the pit was photographically characterized at different times of day, and the first arm/regolith interactions were performed. These first interactions were limited to flat pushes with the back side of the scoop and vertical chopping motions with the tip of the scoop.

In the next steps the InSight lander robotic arm pinned the mole from the side and pressed it against the pit wall to increase the friction on the mole's hull. A first hammering test of 20 strokes in this pinned configuration was performed successfully on sol 308. From sol 311 to 318 three hammering sessions in the pinned configuration were performed or 354 strokes in total. The arm renewed the pinning force in-between the hammering sessions via both horizontal and vertical motions. The mole progressed into the surface in each attempt, clearly indicating that there was no obstructing stone preventing progress. This allowed the root cause of the penetration anomaly to be confidently attributed to lack of sufficient friction on the external hull of the mole.

On sol 322, a new configuration was attempted. The preload of the arm against the mole meant that once the mole went deep enough, the arm would 'swipe' to the left, potentially damaging the science tether interface to the back cap. To prevent this, the application of direct pinning force was removed and the scoop flat was pushed into the regolith adjacent to the mole. This, it was hoped, would transfer compressional forces through the regolith into the mole hull. This was the first so-called 'Free Mole Test', where it was attempted to allow the mole to penetrate without direct contact to the IDA scoop. On sol 322, 50 strokes were performed, resulting in some ambiguous motion. On sol 325 two hammering sessions were performed (152 strokes each), with the second being proceeded by a re-application of vertical load to the regolith. While the previous direct pinning attempts had provided the necessary resistance to the mole's natural rebound (estimated to be 5–7 N of force) any friction provided via the regolith push was insufficient to damp the recoiling of the hammer mechanism of the mole. The mole backed out (Figure 9) by about 18 cm and the mole tilt vs gravity increased from ~19° to ~24°.

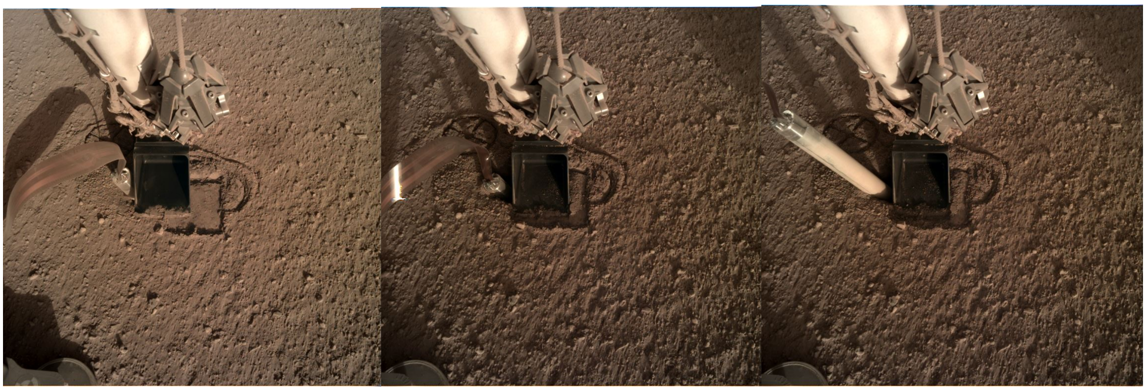

Figure 9: left: Sol 305 – Mole pinned by the arm from the side and pressed against the pit wall. Middle: Sol 322 – Mole almost intruded into the surface; Right: Sol 325 – With no direct contact to the mole from the scoop, insufficient friction existed between the mole and its environment resulting in a mole reversal [credit NASA/JPL-Caltech]

From sols 329 – 380, the mole was again pinned using repeated horizontal and vertical motions of the IDA scoop. The 362 strokes executed allowed the mole to proceed rapidly back into the regolith. The mole angle increased to more than 27° during this second pinning phase. By sol 400, the mole back cap was again nearly level with the regolith surface, resulting in the same problem of potential science tether damage. Instead of preloading the mole both horizontally and vertically, a vertical-only re-pin was performed on sol 400. On sol 407, 150 strokes were commanded. The vertical pinning force thus applied was again insufficient and the mole suffered another reversal event. The back cap popped up to a height of about 7 cm (measured along the mole, not vertically) to the regolith surface.

From sols 414-420, some regolith interaction tests (chopping and scraping) were performed. Chopping was targeted at collapsing the pit walls to increase mole/regolith contact. Scraping was tested in anticipation of future plans to fill the pit (recall that the ability of the IDA to scrape regolith had never been part of the InSight mission plan).

From sols 427 – 557, nine two-step campaigns were undertaken to push against the mole's back cap with a horizontal scoop, thus providing direct resistance to the mole's rebound and a small amount of 'following' motion by the pre-loaded arm. In these nine sessions of direct IDA assistance, totalling about 830 strokes, the mole penetrated into the ground even ~ 1cm below the original Martian surface level. In the last phase (sols 604-645) the arm guided the mole below the Martian surface level using an inclined scoop. During the hammering session on sol 645 the mole executed 252 strokes. The scoop followed the mole until it was stopped by the surrounding regolith. There are indications that the mole penetrated freely, without direct contact to the arm (i.e., a 'Free Mole') for about 90 strokes. Due to obscuration of the mole by the scoop, definite forward motion could not be determined. It was observed that particles in the scoop appeared to move more strongly toward the latter stages of the hammering interval. This could indicate that the initially 'free' mole began to reverse part way through the hammering session, but was blocked by the position of the scoop.

The mole was now outside the arm's reachability for direct contact and guidance. From sol 659-734 the pit was filled by scraping loose surface material to fill it above surface level. Each fresh scrape of material into the pit was followed by a 'tamping' action of the flat scoop. The scoop could now press on the fresh compacted soil material aiming to provide force to the mole via the unconsolidated soil. In the final Free Mole Test on sol 756 the mole performed 506 strokes but no forward motion could be detected.

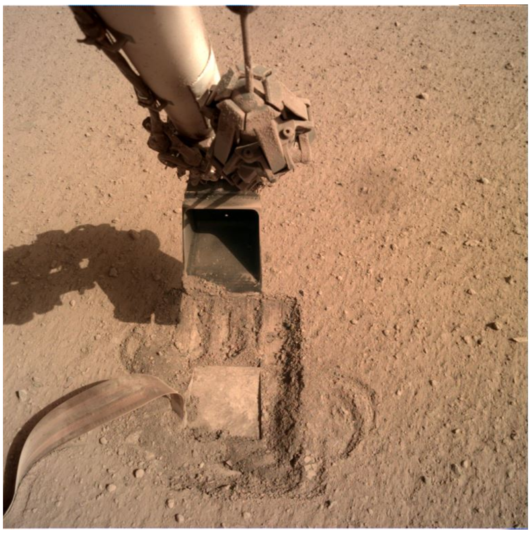

Figure 10: Mole in its final position. Picture of sol 775 [credit NASA/JPL-Caltech]

The mole is now in the surface of Mars in its final position and performs further thermal conductivity measurements in this upper surface layer.

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 camera pictures, tilt and TEM-A measurement 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

4.3 HP3 Continuous Operations on Mars

The main scientific measurement units of HP^3 are the radiometer and TEM (section 2). Shortly after landing the scientific program started with measurements of the radiometer. These operations continued with different configurations of the radiometer measurements during the previous martian year. 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.

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 HP^3 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 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 the flight software included two operation modes, the 'hourly' mode, and the 'standard' mode, to run continuously and take measurements according to schedule, independent of 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 operation 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). When energy became scarce, there was sufficient hourly data to demonstrate that the required record of daily average surface temperature could be achieved with just two measurements per day, observing the minimum and maximum temperature at dawn and shortly after noon. From about sol 550, individual measurements were scheduled at these times, typically at least once per week, which provides a sufficient constraint on the seasonal variation of the surface temperature.

Aside from these main radiometer operations, there were several additional activities. First, self-calibration measurements were performed regularly [6]. 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 [7], and continuous measurements over one or more sols for correlation with the continuous meteorology data [8]. 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 is 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. 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 or the constraints on the profile of subsurface thermophysical properties [9].

The TEM measurement suite (section 2) performed various measurements throughout the first Martian year. Highlights are the TEM-P/A measurements (Table 3). TEM-P/A measurements are composed of several sols of TEM-P monitoring measurements, typically two sols, followed by one sol of TEM-A measurements. The TEM-P measurements monitor the background temperature variations before the active measurement part (TEM-A) starts. The foils inside the mole are used in this case as the relevant temperature sensors. HP^3 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 moles response to heating, regolith properties can then be determined [10].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.

The main scientific goal of the TEM-P/A during these measurements is to determine the thermal conductivity of the soil.

Table 3: List of TEM-P/A measurements performed during first 830 sols on Mars.

Sol	Date (UTC)	Purpose
94 - 98	03 - 07 Mar 2019	Thermal conductivity measurement
114 - 117	24 - 27 Mar 2019	Engineering purpose – Estimations on mole contact to soil inside the pit
118 - 121	28. - 31. Mar 2019	Engineering purpose after diagnostic hammering – Estimations on mole contact to soil inside the pit
146 - 149	26. - 29. Apr 2019	Engineering purpose – Estimations on mole contact to soil inside the pit
158 - 161	08. – 11. May 2019	Engineering purpose after diagnostic hammering – Estimations on mole contact to soil inside the pit
209 – 211	29. Jun – 01. Jul 2019	Thermal conductivity measurement – Estimations on mole contact to soil inside the pit
388 - 393	30. Dec '19 – 05. Jan '20	Thermal conductivity measurement – Long term assessment
536 - 540	30. May – 03. Jun 2020	Thermal conductivity measurement – Estimations on mole contact to soil inside the pit
680 - 683	25 – 28 Oct 2020	Thermal conductivity measurement
795 - 798	20 – 24 Feb 2021	Measurement pressure dependency of thermal conductivity
824 - 827	22 – 25 Mar 2021	Measurement pressure dependency of thermal conductivity

After inserting the mole into the surface to its final position, a first thermal conductivity measurement was performed, and average soil conductivity in the 0.03 to and 0.37 m depth range was found to be 0.039±0.002 W m−1 K−1. Upper limits on soil grain size can be derived from thermal conductivity by a comparison with laboratory measurements under martian atmospheric conditions, and the determined conductivity values indicate that the majority of particles must be smaller than 104-173µm [11].

The present main focus of the TEM-P/A measurements is the atmospheric pressure dependency of the thermal conductivity. The atmospheric pressure on Mars is significantly changing with the season of Mars. Figure 11 shows the already executed measurements and the desired measurements.

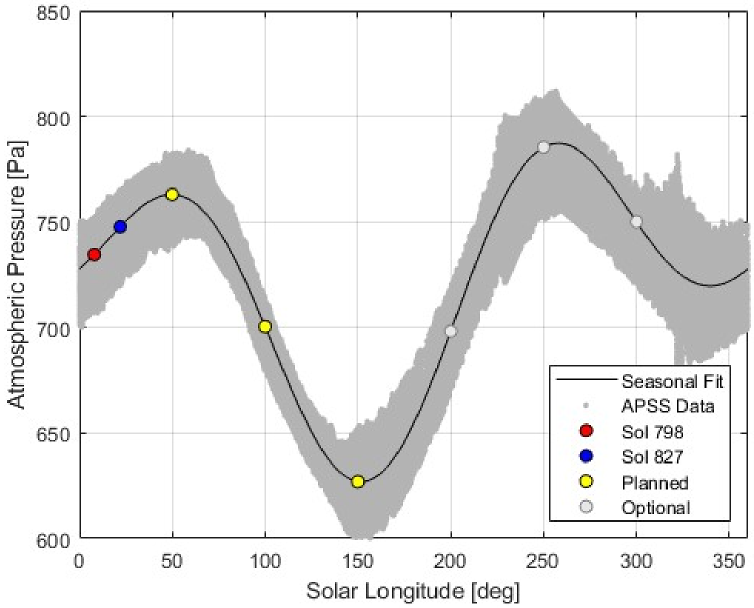

Figure 11: Executed and planned TEM-P/A measurements to monitor the pressure dependency of the thermal conductivity.

5. Summary and Outlook

InSight lander and the HP3 experiment are now operating more than a Martian year on the planet and have begun extended mission operations. The team successfully operated the lander and experiments under numerous adverse conditions on Mars (low power) and Earth (COVID-19). HP3 system and subsystems are healthy after the end of the nominal mission and continue their work during the extended mission phase of InSight.

The radiometer has monitored the surface brightness temperature over a full Martian year. Additional investigations such as high rate sampling and monitoring thermal effects of Phobos eclipse were performed.

The mole was not able to reach its target depth to perform the heat flux measurements, despite almost 2 years of extensive recovery activities performed by the InSight team. The robotic arm of InSight performed 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. The full summary of lessons learned and the analysis on the scientific conclusions are on-going.

The mole is now in its final position and operates as thermal heat probe measuring the thermal conductivity of the upper surface layer.

The HP3 thermal investigations of Mars with the radiometer and TEM will continue throughout the extended mission of InSight.

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