**Measuring the Martian Heat Flow using the Heat Flow and Physical Properties Package (HP$^3$).**
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**Introduction:** The *InSight* Discovery-class mission to study the martian interior will deliver a geophysical package to the surface of Mars in 2016. The primary payload of the *InSight* lander consists of a seismometer and the HP$^3$ heat flow probe [1,2]. *InSight* will thus address fundamental questions of martian geophysics. The main mission goals are the determination of the size, physical state, and composition of the core and mantle, the thickness of the crust, and the thermal state of the martian interior.

HP$^3$ will measure the heat flow at the landing site in Elysium Planitia (139$^o$E 1$^o$N), and thereby provide an important baseline to constrain mantle potential temperatures and the bulk abundance of heat producing elements in the martian interior [3].

**Instrument description:** HP$^3$ will emplace a suite of sensors into the martian subsurface by means of a mechanical hammering mechanism tugging an instrumented tether (Figure 1). Sensors include temperature sensors and heaters to measure the thermal gradient and thermal conductivity of the regolith, tilt sensors to determine the position of the instrument in the ground, and a sensor to measure the deployed length of the tether. The instrument is planned to penetrate at least 3m – sufficiently deep to reduce errors from daily surface temperature forcings - and up to 5 m [4] into the martian regolith and perform depth resolved measurements, from which the surface planetary heat flow can be directly determined. In addition, HP$^3$ has been augmented by a radiometer [5] to determine the surface brightness temperature and aid in the data inversion.

HP$^3$ will be deployed onto the martian surface by the lander's robotic arm, and the deployed instrument configuration is shown in Figure 1. Heaters to determine the thermal conductivity are located on the mole hull, and tilt sensors are mounted in the payload compartment at the back of the mole. Damping springs will protect the electronics from the mole shock environment. 14 temperature sensors are located on the scientific tether, and will measure the thermal gradient after the final depth has been reached and thermal equilibrium has been attained.

**Operations:** After landing, HP$^3$ will be deployed onto the martian surface, and the instrument placement site will be chosen to minimize disturbances from permanent shadows caused by the lander and seismometer [6]. HP$^3$ will then execute hammering cycles, penetrating 50 cm into the subsurface at a time, followed by a cooldown period of 48 h to allow heat built up during hammering to dissipate. After an equilibrated thermal state has been reached, a thermal conductivity measurement is executed for 24 h. This cycle is repeated until the final penetration depth of 5 m is reached or further progress becomes impossible. In this way, a depth resolved profile of thermal conductivity will be obtained. The subsequent monitoring phase consists of tether temperature measurements on the hour and lasts up to the end of the mission.

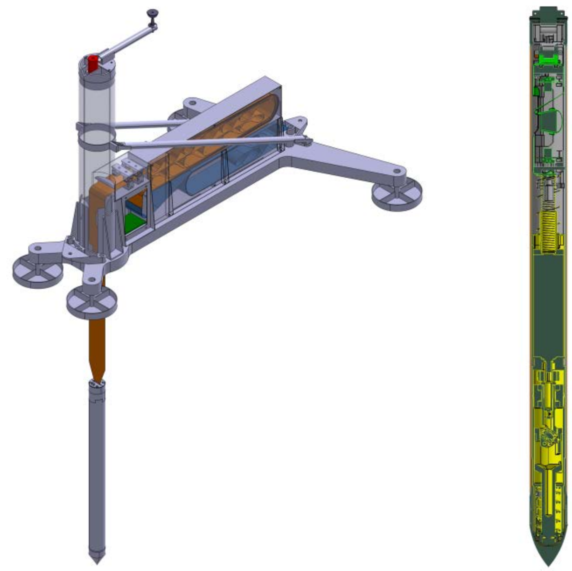

**Figure 1:** Schematics of the deployed elements of the HP$^3$ instrument. Left: Support system after starting initial penetration. The Mole has left the support system, trainling behind the scientific tether (orange). A tether (blue) running to the E-box on the lander is also shown. Right: Profile of the Mole showing the hammering mechanism (yellow), static tiltmeters (green), and TEM-A heating foils wrapped around the mole body (thin orange outline).

**Measurement Approach:** HP$^3$ will measure temperatures using platinum resistance temperature detectors mounted on the tether and will allow a temperature profile with a depth resolution of 35 cm on average to be determined. The thermal gradient in the regolith is then obtained from the combination of temperature and position measurements, i.e., the deviation of the mole path from the vertical, and the amount of paid out tether.

The basic principle applied to determine the thermal conductivity is the controlled injection of a specified amount of heat into the medium and a measurement of the subsequent temperature increase of the heater, the so-called self-heating curve [7]. We will use the Mole as a modified line heat source and determine thermal conductivity from a 2-dimensional numerical thermal model of Mole and regolith accounting for axial heat transport. An additional independent measurement of the regolith's thermophysical properties will be obtained from a measurement of the attenuation of the annual temperature wave amplitude.

**Measurement Requirements:** The primary objective of the HP$^3$ instrument is a determination of the interior heat flow at the landing site with an uncertainty of better than 10%. For the range of expected heat flows and regolith thermal properties, temperature differences between sensors need to be determined with an uncertainty of better than 50 mK. Furthermore, in order to determine the thermal gradient, deviations of the mole path from vertical need to be known to within 3°. Current estimates of HP$^3$ performance indicate temperature and orientation uncertainties of 15 mK and 1°, respectively, giving sufficient margin to guarantee the required accuracy.

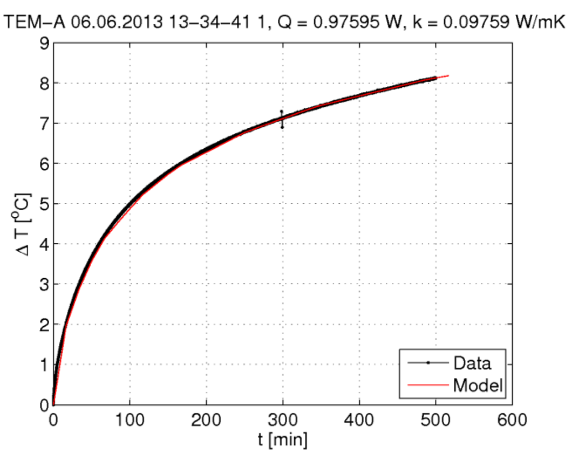


**Figure 2:** Thermal conductivity laboratory measurement in granular material with a reference conductivitiy of 0.100 W/mK.

To fulfil requirements, the thermal conductivity needs to be determined to within 7%. A major source of uncertainty for the conductivity error budget is the availability of low conductivity reference materials that are tracable to NIST standard. For HP$^3$, the certified reference material IRMM440 with a conductivity of 0.032 W/mK has been used to calibrate the reference conductivity measurement. Tests with the HP$^3$ prototype show that conductivity of granular material can be measured to within 3% (Figure 2) of the reference value.

**Operational Requirements**: In order to determine thermal conductivity, measurements need to be started close to an equilibrated thermal state. However, the mole introduces significant heat into the ground during hammering that needs to dissipate prior to starting a measurement. Simulations of regolith heating during hammering suggest that a cooldown period of 48 h is sufficient to reduce the error of the thermal conductivity measurement below 1% (Figure 3).

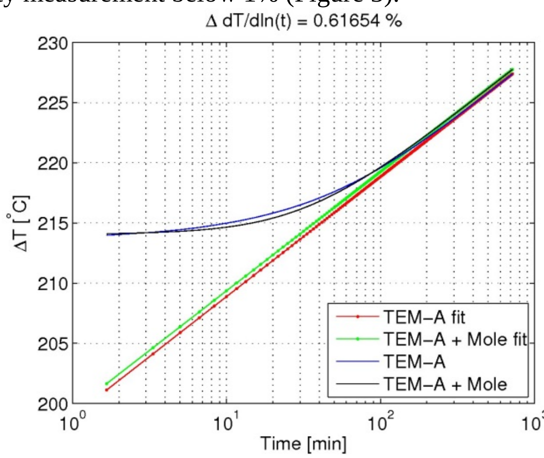


**Figure** 3: Modeled thermal conductivity measurement with and without contributions of heat remaining in the regolith after cooldown of the mole. For a 48 h cooldown period and a regolith conductivity of 0.05 W/mK, the difference is below 1%.

In order to remove perturbations of the temperature profile from annual temperature forcings at the surface, HP$^3$ needs to log the borehole temperatures for at least 400 sols if the final mole depth is 3.5 m. In the best case scenario of a 5 m penetration depth and low regolith conductivity (0.02 W/mK), heat flow can be determined from a single temperature profile.

**Conclusions:** The HP$^3$ instrument currently being developed for an application on the *InSight* mission to Mars will conduct the first planetary heat flow measurement since Apollo. The primary objective is a determination of the local heat flow of Mars to within 10%, and HP$^3$ will provide an important baseline measurement to constrain the thermal state of the planet.

**References:** [1] Spohn et al., *Plan. Space Sci.*, 49, 1571–1577, 2001. [2] Spohn et al., *Ground-Based Geophysics on the Moon*, LPI Contribution No. 1530, p.3016, 2010. [3] Plesa et al., Constraining the Amount of Radiogenic Elements in the Intrior of Mars from the HP$^3$ Heat Flow Measurement, this meeting. [4] Hansen-Goos, Predicted Penetration Performance of the InSight HP$^3$ Mole et al., this meeting. [5] Müller et al., The HP$^3$ Radiometer for the InSight Mission, this meeting. [6] Grott, *PSS*, 57, 1, 7177, 2009. [7] Hammerschmidt and Sabuga, *Intern. J. Thermophys.*, 21, 6, 2000.