Retrieving the Martian Planetary Heat Flow from Measurements at Shallow Depth. M. Grott¹, A.C. Plesa¹, I. Daubar², M. Siegler², T. Spohn¹, S. Smrekar², and the HP³ instrument team, ¹Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany, ²Jet Propulsion Laboratory, California Institute of Technology, Pasadena

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 Heat Flow and Physical Properties Package (HP³) [¹,²], which will measure heat flow at the landing site in Elysium Planitia (139°E 1°N). HP³ will emplace a suite of temperature sensors to a depth of up to 5 m into the martian regolith and monitor subsurface temperatures for a full martian year.

After deployment onto the surface, HP³ will execute thermal conductivity measurements at 50 cm depth intervals until the final penetration depth of 5 m is reached or further progress becomes impossible. The subsequent monitoring phase consists of periodic temperature measurements and lasts up to the end of the mission.

Subsurface temperature structure: The aim of the HP³ investigation is the determination of the martian planetary heat flow, and this information needs to be extracted from the temperature and thermal conductivity measurements. The subsurface temperature structure of the martian regolith is determined by insolation, heat flow coming from the planetary interior, and regolith thermophysical properties (density $\rho(z)$, heat capacity $c_p$, and thermal conductivity $k(z)$), with $k$ being the most important. In order to test the proposed data inversion algorithm we simulate HP³ measurements by first calculating subsurface temperatures.

Temperatures are determined by solving the heat diffusion equation subject to a constant heat flux boundary condition at depth, while the radiation balance

$$k(z_0) \frac{\partial T}{\partial z}(z=0) = \Omega e \sigma T^4 - \Omega e R_0 - (1 - A(t))S'(t)$$

is solved at the surface. Here, $A(t)$ is the surface albedo, $S'(t)$ is the total solar radiation, $R_0$ is the downwelling thermal radiation (assumed isotropic), $T$ is the kinetic temperature of the surface, $k(z_0)$ is the thermal conductivity of the top regolith layer, $\Omega$ is the visible fraction of the sky, $e$ is surface emissivity and $\sigma$ the Stefan-Boltzmann constant. We use the KRC thermal model [³] to parameterize $S'(t)$ and $R_0$.

Density is assumed to vary between 1600 and 1800 kg/m$^3$, $c_p$ is constant at 670 J/kgK, $\Omega$ is 1, $e$ is 1, and the undisturbed surface albedo $A$ is 0.25 [⁴]. Thermal conductivity is assumed to be a function of density and

$$k = k_0 + \rho \frac{dk}{dp}$$

where $k_0 = 0.025$ W/mK and $dk/dp = 14 \cdot 10^{-6}$ Wm/kgK [⁵], resulting in a thermal conductivity of about 0.05 W/mK. This represents a conservative worst case scenario, and expected conductivities at the landing site range from 0.02 to 0.05 W/mK.

![Figure 1](image)

Figure 1: Depth at which the difference between the background thermal gradient and the disturbed gradient results in a heat flow perturbation of 3 mW/m² for a high conductivity case. Albedo is assumed to return to pre-landing values within 1 martian year [⁴].

During landing, dust will be removed by the InSight landing system, and as a result surface albedo will be reduced. This needs to be taken into account in the data inversion, which therefore needs to be capable of extracting the background heat flow from the superposition of the signals caused by insolation (diurnal and annual temperature waves) as well as perturbations caused by landing (surface albedo changes). While the former can be modeled by averaging data for a sufficiently long period of time [⁶], the latter needs to be explicitly taken into account, and the depth to which albedo induced perturbations travel as a function of time is shown in Figure 1 for three different initial albedo changes. As is evident from the figure, significant perturbations reach depths of 3 to 5 m within 0.2 martian years after landing.

Data Inversion Approach: HP³ will measure a depth profile of thermal conductivity as well as the temperature time-series at depths $z_j$ for the duration of the mission. Temperature data will be modeled by assuming temperatures to vary according to
\[ T(z_j, t) = T_0 + (z_j - z_0) \text{grad}_T + \text{erfc} \left( \frac{z_j}{2\sqrt{\kappa t}} \right) + \sum_{i=1}^{2} A_i \exp \left( -\epsilon_i z_j \right) \sin \left( \frac{2\pi}{P_i} t + \Phi_i - \epsilon_i z_j \right) \]

where \( T_0 \) is the average temperature at the surface, \( \text{grad}_T \) is the underlying thermal gradient, \( \text{erfc} \) is the complementary error function, \( D \) is the amplitude of the albedo perturbation, \( \kappa \) is thermal diffusivity, \( A_i \) and \( \Phi_i \) are the amplitudes and phases of the annual \((i = 1)\) and half annual \((i = 2)\) temperature waves, \( P_i \) are the corresponding periods, and \( \epsilon_i = \sqrt{\pi/P_i \kappa} \) the resulting skin-depths. Using this approach, albedo changes are treated as step-changes of surface temperature, which is a good approximation as long as the decay time of the perturbation is long compared to the measurement period.

The problem of fitting the data is thus reduced to determining the 6 unknown parameters \( T_0, \text{grad}_T, A_i, \) and \( \Phi_i \) given the temperatures \( T(z_j, t) \) as well as \( \kappa \) and \( \epsilon_i \), which are derived from the measurements of thermal conductivity and estimates of \( \rho \) and \( c_p \). Given an initial guess for the unknown model parameters \( m_0 = (T_0, \text{grad}_T, A_1, A_2, \Phi_1, \Phi_2)_0 \), the inversion is achieved by linearizing and iteratively solving the matrix equation

\[ d = Gm \]

where \( d \) is a vector containing the temperature data and \( G \) the model matrix.

**Results:** We have simulated HP³ measurements by calculating regolith temperatures and adding the following measurement errors: 1) a temperature uncertainty of 15 mK, 2) a thermal conductivity uncertainty of 5 %, 3) a density uncertainty of 10 %, and 4) a heat capacity uncertainty of 1 %. Zero mean Gaussian distributions were assumed for these uncertainties and we have then run Monte-Carlo simulations inverting 5000 realizations of the measurements for heat flow. We also randomly varied the measurement duration to estimate the time needed to robustly determine heat flow from the data.

Results of these calculations are shown in Figure 2, where 1-sigma contour lines of the obtained inversion results are shown for three different final emplacement depths of the sensors. Results are for a worst case scenario, assuming large initial albedo changes of \( A(t_0) = 0.08 \) [4] and high thermal conductivity [5]. For a shallow emplacement depth of 3 m, heat flow can be inverted with an uncertainty of \( \pm 10 \) mW/m², while larger depths will allow for a determination to within \( \pm 3 \) mW/m². If thermal conductivity is low, heat flow can be inverted with an uncertainty of better than \( \pm 3 \) mW/m² for all penetration depths below 3 m. Further-more inversion results are expected to be improved if surface albedo measurements from the lander cameras as well as radiometer surface temperature measurements are included in the inversion.

**Figure 2:** Results of the Monte-carlo simulations (5000 models) for 3 final penetration depths, showing the range of inverted heat flows as a function of measurement time, indicating the \( \pm 5 \) mW/m² error bounds as a reference. A background heat flow of 18 mW/m² has been prescribed.

**Conclusions:** The HP³ instrument will determine heat flow at the InSight landing site. For a worst case scenario, the proposed data inversion algorithm is capable of extracting the background planetary heat flow from the HP³ data with an uncertainty of 3-10 mW/m², depending on penetration depth. The time needed to perform the measurement is close to 0.25 martian years. For lower thermal conductivities, inversion uncertainty is below \( \pm 3 \) mW/m² for all depths below 3 m.

In the presented analysis we have not considered insolation changes due to lander shadowing [7], which is a topic of ongoing studies [8,9]. However, perturbations caused by shadows are expected to be similar to those induced by albedo changes, and the combined effect can likely be modeled by the already implemented step-function approach.