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Steady State Planetary Heat Flow from a Shallow Transient Measurement

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Abstract

Planetary heat flow is defined by the product of the thermal conductivity and thermal gradient [1]. HP^3 is an experiment package deployed by a mole which will return heat flow data of the upper 5m of a planetary subsurface. Most planetary heat flow experiments take advantage of ocean bed measurements, large measurement depth and/or multiple measurements and locations over long periods of time to access steady state conditions. Due to mission constraints HP^3 may not have these benefits. This project aims to develop a method of recovering the steady state (long period) heat flow from a short term HP^3 measurement which will contain a damped and lagged record of the unsteady (short periodic) surface thermal perturbation. A promising method is functional least squares inversion [2]. Results of the application of this method to HP^3 data will be presented here.

1. Introduction

One dimensional heat flow is governed by the heat conduction equation:

$$\rho(z)c\frac{\partial T(z,t)}{\partial t} = \frac{\partial}{\partial z}\left(k(z)\frac{\partial T(z,t)}{\partial z}\right) + S \qquad (1)$$

where $\rho(z)$ is density, c is specific heat capacity, $T(z,t)$ the temperature at depth (z) and time (t), $k(z)$ represents the thermal conductivity and S regolith heat sources or sinks. Setting the LHS of equation 1 to zero, subtracting S and integrating over z gives steady state heat flow (F):

$$k(z)\frac{\partial T(z)}{\partial z} = -F \qquad (2)$$

where the negative sign indicates that heat flows down the temperature gradient.

The certainty to which planetary heat flow can be determined is therefore dependent on the accuracy of thermal conductivity and temperature profile measurements.

1.1 Measuring Heat Flow

Terrestrial heat flow measurements take place over depth scales of m (gravity driven probe ocean sediment measurements) to 100s of m (boreholes). These conveniently allow the steady state thermal gradient to be accessed below the penetration depth of any unsteady surface thermal perturbation and small scale inconsistencies in thermal conductivity to be ignored. The steady state measurements have provided supporting evidence for the theory of plate tectonics and the concentration of radioisotopes within the continental crust [1] while unsteady state measurements have aided in palaeoclimatic studies [3]. Heat flow measurements were performed on the Moon in the Apollo missions over a period of 3yr allowing observation of the evolution of surface temperature over time and to a depth where the steady state heat flow was accessed (1.3-2.5m). Depending on the mission scenario, HP^3 will burrow to a maximum depth of 5m and might measure for a period of less than 24hr, therefore, as explained in Section 2 the measurement may record the steady state thermal gradient at the lower depths or may be dominated by an unsteady thermal component of unknown phase. This project anticipates the latter scenario.

1.2 Modelling Heat Flow

The extraction of boundary or initial conditions from transient thermal profile measurements is known as inversion. The functional least squares inversion method [2] uses a priori knowledge of the boundary conditions and regolith properties to generate a thermal profile (the forward modeling component).

The measurement and model are then compared where residuals are used to update the a priori information until the model and measurement data arrive at a best fit solution (inverse modeling component). This method is computationally efficient and lends itself to straightforward modification to include additional parameters and spatial dimensions.

2. Results and Future Work

Current forward modeling results have shown that a depth of 5m will be enough to access the steady state thermal profile on bodies with low thermal inertia and/or dominantly short period heating (e.g. diurnal) cycles where for the Moon (Figure 1) the steady state can be accessed below 1.5m.

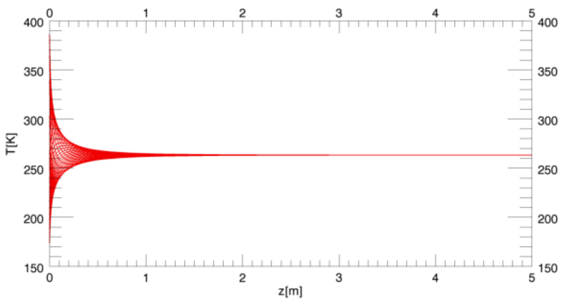

Figure 1: Forward model results of thermal profile of lunar subsurface over 1 lunation. T is the temperature in K and z the depth in m. The curve parameter is time.

The thermal profile on planetary bodies with relatively high thermal inertia and/or dominantly long period (e.g. annual) heating and cooling cycles – such as Mars (Figure 2) – will be dominated by the unsteady thermal profile.

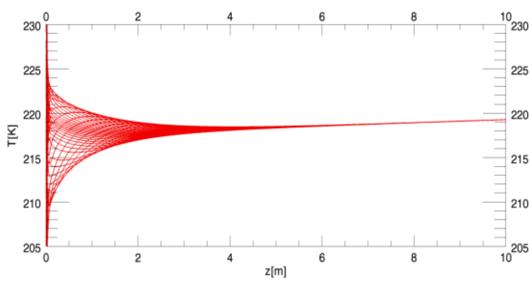

Figure 2: Forward modeling results of the Martian subsurface over 1 Martian yr. Diurnal (sol) variations are attenuated within the first 10cm. Parameters as in Figure 1.

Figures 1 and 2 illustrate the lagging and damping of the surface thermal perturbation as it propagates into the regolith. This coupled with HP^3 instrument noise means that there will be a limit to which the temperature gradient can be determined where greater accuracy will be achieved in situations represented by Figure 1. Additionally, unknown regolith response to temperature changes and unknown subsurface features may contribute to non-ideal thermal profiles. These challenges can be addressed by prudent choice of measurement locations and accurate determination of initial conditions. Increasing the dimensionality of the problem has potential to increase the accuracy of the inversion [3], however the computing and time resources required for this are currently a drawback. Testing of the 1 dimensional inverse model with both error free and inaccurate synthetic HP^3 data will establish performance parameters of this method.

3. Summary and Conclusions

The HP^3 is a subsurface mole deployed experiment which will measure the transient thermal profile of the upper 5m of a planetary subsurface. The aim of this project is to recover the steady state heat flow from this transient measurement. The functional least squares inversion method – used with accurate a priori data – is currently the most promising method of recovering the steady state heat flow from a short term HP^3 measurement.

Acknowledgements

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