MEASURING HEAT FLOW ON THE MOON – THE HEAT FLOW AND PHYSICAL PROPERTIES PACKAGE HP^3.

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Introduction: Planetary heat flow is a fundamental parameter characterizing the thermal state of a planet. However, while tens of thousands of terrestrial measurements have been made to constrain the heat flow of the Earth, to date only two independent measurements have been performed to constrain heat flow on the Moon [1]. Mesurements at the two sites differed by 25 % and different theories concerning this large spread have been proposed: (1) Being close to the Procellarum KREEP terraine, heat flux may be strongly influence by the different concentrations of heat producing elements in the subsurface [2]. (2) The thickness of the Th-enriched ejecta blanket from the Imbrium impact differs at the two locales [3]. Irrespective of the cause, these ambiguities make estimates of the global lunar heat loss unreliable and many questions concerning the thermal state of the Moon remain unresolved. Here we will present the Heat Flow and Physical Properties Package (HP^3), a robotic heat flow probe which we propose as an instrument to address these questions.

Instrument description: The Heat Flow and Physical Properties Package (HP^3) [4] consists of temperature sensors and heaters that will be emplaced into the lunar subsurface by means of an electro-mechanical hammering mechanism. Furthermore, motion and tilt sensors are included to determine the position of the instrument in the ground. The instrument is foreseen to penetrate up to 3 m into the lunar regolith and perform depth resolved measurements, from which the surface planetary heat flow can be directly deduced.

The instrument consists of four functional subsystems as shown in Fig. 1. The mole houses the electro-mechanical hammering mechanism to provide capability for penetration into the regolith. The payload compartment incorporates motion and tilt sensor heads, front-end electronics and soil heaters/sensors for the soil thermal conductivity experiment. The instrumented tether provides the power and data link to the surface and acts as a carrier for the temperature sensors for the thermal gradient measurement. The support system stays on the surface after deployment and provides secure storage of Mole, Payload Compartment and Tether during all flight phases. It also serves as the mounting locale for the instrument's back-end electronics.

The instrument has been pre-developed in two ESA funded precursor studies and has been further developed in the framework of ESA's ExoMars mission. The current readiness level of the instrument is TRL 5.62 (ESA PDR Apr. 2009) which has been achieved with several Breadboards developed and tested between 2004 and 2009. As no drilling is required to achieve soil penetration, HP^3 is a relatively lightweight heat flow probe, weighting less than 1800 g.

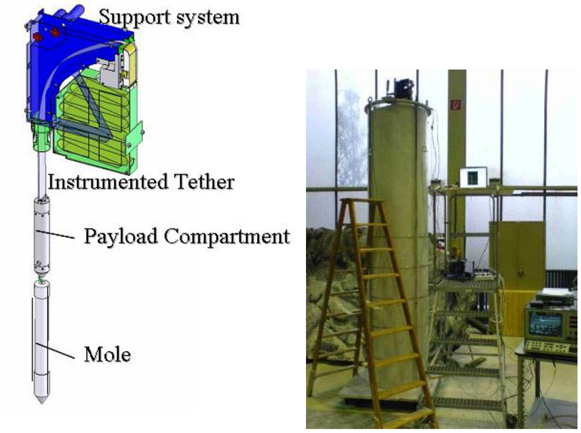

Figure 1: Schematics of the HP^3 instrument showing the functional subsystems (left); HP3 Breadboard during 2.3 m soil intrusion test (right) – Support System is positioned at top of soil cylinder.

Instrument Operations: After deployment of the instrument onto the lunar surface, instrument operations will be split into two phases. During the penetration phase soil intrusion is achieved by means of the electro-mechanical hammering mechanism. The net hammering time is expected to be ~12 h to reach the final depth of 3 m, but hammering will be interrupted at intervals of 0.5 m to conduct thermal conductivity measurements.

After the final penetration depth has been reached, the instrument will switch to the monitoring mode. This mission phase basically consists of column temperature readings initially on the hour, decreasing to several times daily and lasts to the end of the mission.

Measurement principle: HP^3 will measure temperatures using copper based resistance temperature detectors (RTD's), which are mounted on the tether and will allow for a determination of the column temperature profile with a depth resolution of 20 cm. 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 self-heating curve. We focus on transient methods because of the finite time available for the measurements, the specific HP^3 geometry, and the lesser dependence on contact resistance of these methods compared to steady state methods. In case of HP^3, we use a modified version of the line heat source (LHS) method [5].

The LHS method requires cylindrical symmetry and ideally an infinitely long and thin heater with negligible heat capacity. We use the payload compartment as a modified LHS, e.g., a LHS with finite length/diameter ratio and heat capacity. We will measure the temperature increase in the center of the payload compartment to account for the deviation from ideal LHS geometry. Due to the relatively complex internal structure of the payload compartment a detailed numerical thermal model for the determination of the thermal properties will be implemented [6].

An independent measure of the regolith's thermophysical properties will be obtained by a measurement of the attenuation of the amplitude of the diurnal temperature wave.

Measurement uncertainties: For the measurement approach persued here, the attainable accuracy for the thermal conductivity determination is 5.8 % if the ideal LHS geometry is applied in the asymptotic temperature domain [5]. However, it has been shown that finite element models taking the deviation from the ideal geometry into account can reach accuracies of 4.6 % [6], which is the approach adopted here.

Given the requirements for mounting the temperature sensors on the Tether, foil sensors will be employed. These are intrinsically less stable than other sensor designs and can only be calibrated to within 100 mK, as compared to the accuracy of 50 mK reached by the Apollo sensors [1]. However, this drawback is compensated by the larger amount of sensors employed and the longer baseline aimed for by the current setup. The resolution of the temperature measurements is only limited by the employed electronics and will be a few mK. Fig. 2 shows the expected relative error for the thermal gradient determination for a background thermal gradient of 1.75 K m^{-1} [1]. Errors include contributions from positioning uncertainties (here assumed to be 2 cm), which result in the observed offset. Overall accuracy is expected to be 4%, but certainly better than 10%, even if the Mole gets stuck at shallow depth.

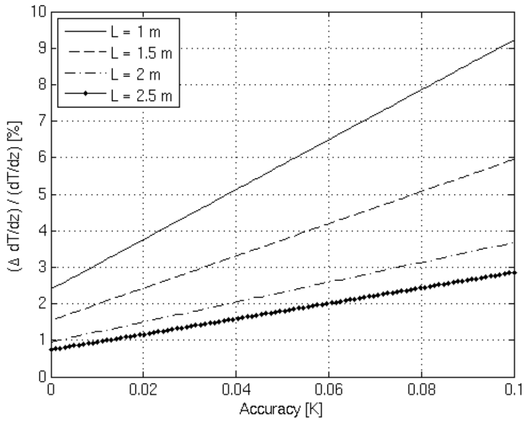

Figure 2: Relative error of the thermal gradient determination as a function of absolute sensor accuracy for 4 different baseline lengths (penetration depths) *L*.

Together with an assumed uncertainty of 5 % for the thermal conductivity measurement, an attainable uncertainty of 7 % is expected for the heat flow determination, which compares favourably to the uncertainty of 15 % [1] given for the Apollo heat flow experiments.

Payload compartment sensor options: The payload compartment houses heaters, tilt sensors and electronics, but could be augmented with futher instrumentation. Other options include a densitometer, as devloped in the frame of the ESA precursor studies, or a permittivity probe, as developed for a Martian application in the frame of the ExoMars mission.

Conclusions: The HP^3 instrument is a light weight (< 1800 g) heat flow probe, that can access the lunar subsurface to a depth of at least 3 m. It has been predeveloped to the breadboard stage and has a current readiness level of TRL 5.62. We expect to be able to measure the lunar heat flow with an uncertainty of 7%. Furthermore, the instrument can be augmented with a permittivity probe or densitomer to constrain the regolith density and stratification.

References: [1] M.G. Langseth et al. (1976), *Lunar Science Conference*, 7th, 3143-3171. [2] M.A. Wieczorek and R.J. Phillips, *JGR.*, 105, E8, 20417-20430, 2000. [3] A. Hagermann and S. Tanaka, *GRL*, 33, 19, L19203, 2006. [4] T. Spohn et al. (2001), *PSS*, 49, 1571–1577. [5] U. Hammerschmidt and W. Sabuga, *Intern. J. Thermophys.*, 21, 6, 2000. [6] B.W. Jones, J. *Phys. E.: Sci. Instrum.*, 21, 832-839, 1988.