HP³ – A HEAT FLOW PROBE PROPOSED FOR THE INTERNATIONAL LUNAR NETWORK.
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Introduction: NASA has initiated multiple new robotic lunar science missions, one of which will be a lunar lander network, the ILN. The main objective of the U.S. nodes of the ILN is to understand the interior structure and composition of the Moon, including a characterizing the thermal state of the lunar interior. Here we will present the Heat Flow and Physical Properties Package (HP³), which we propose as a heat flow probe to directly address this question.

Instrument description: The Heat Flow and Physical Properties Package (HP³) [1] consists of a suite of sensors that will be emplaced into the lunar subsurface by means of an electro-mechanical hammering mechanism. Sensors include temperature sensors and heaters to measure the thermal gradient and thermal conductivity of the regolith as well as motion and tilt sensors 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. Furthermore, the instrument can be augmented with either a permittivity probe to measure the electrical conductivity and relative permittivity of the regolith or a densitometer to directly measure the regolith bulk density.

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. It can also house either a permittivity probe or densitometer. 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 and soil thermal conductivity experiments. 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 is currently developed further for a Martian application in the framework of ESA's ExoMars mission. The current readiness level of the instrument is TRL 4.6 (ESA pre PDR Sep. 2008). As no drilling is required to achieve soil penetration, HP³ is a relatively lightweight heat flow probe, weighting less than 1800 g.

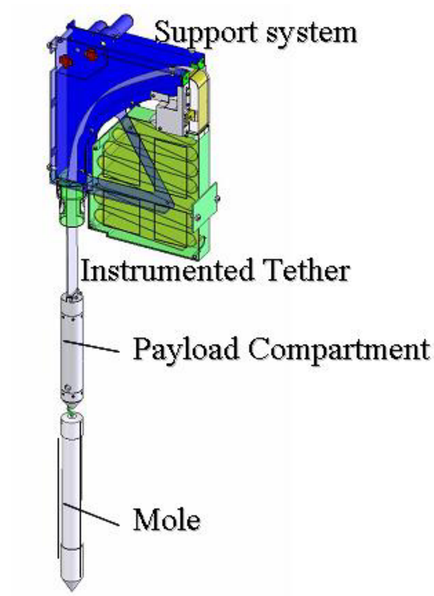

Figure 1: Schematics of the HP3 instrument showing the functional subsystems.

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 and/or electrical/density 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: HP³ 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 and will allow for a determination of the column temperature profile with a depth resolution of at least 50 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 [2].

The LHS method requires cylindrical symmetry and ideally an infinitely long and thin heater with negligible heat capacity. We intend to 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 [3].

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 THS geometry is applied in the asymptotic temperature domain [2]. However, it has been shown that finite element models taking the deviation from the ideal geometry into account can reach accuracies of 4.6 % [3], which is the approach adopted here.

Absolute temperature measurements will be calibrated against secondary standard reference thermometers, which are accurate to within 20 mK. However, the precision of the sensors can be even better depending on the homogeneity and stability of the calibration bath. The calibraton procedure adopted here will result in an initial sensor precision of 10 mK. However, it is expected that the sensors will drift due to thermal cycling and mechanical stresses, such that the overall precision of the temperature measurements is expected to be no better than 100 mK. Given a thermal gradient of 1.75 K m^{-1} [4] and an absolute uncertainty of 0.1 m for the position measurement, the accuracy of the thermal gradien determination is expected to be 8 %.

Together with an uncertainty of 5 % for the thermal conductivity measurement, an uncertainty of 10 % is expected for the heat flow determination, which compares favourably to the uncertainty of 15 % [4][5] given for the Apollo heat flow experiments.

Permittivity Probe: A Permittivity Probe can be included in the payload compartment of the HP^3 instrument and would permit measurements of relative permittivity and electric conductivity as a function of depth and frequency. These quantities are determined by impedance spectroscopy measuring the sample impedance and phase angle. Impedance spectra can be used to deduce soil porosity and composition and help to constrain the density. Furthermore, thermal conductivity measurements would be put into context as we would learn about a possible stratification at the landing site and the presence of rock bodies below the surface. A permittivity probe has been developed and built for the Martian application in the framework of ESA's ExoMars mission. The overall, the uncertainty of the heat flow values obtained by the Apollo experiments is given to be 15 %[2].

Densitometer: A gamma-ray backscatter densitometer can be included in the payload compartment and has been developed and built during the HP^3 precursor studies. The densitometer comprises a radioisotope source (^{137}Cs), a high density shielding, two semiconductor gamma ray detectors and associated electronics. A direct density measurement using the densitometer would reveal regolith stratification in terms of the bulk density variation and allow for a more reliable determination of the thermal conductivity from the thermal diffusivity.

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 4.6. We expect to be able to measure the lunar heat flow with an uncertainty of 10%. Furthermore, the instrument can be augmented with a permittivity probe or densitomer to constrain the regolith density and stratification.

References: [1] T. Spohn et al. (2001), Plan. Space Sci., 49, 1571–1577. [2] U. Hammerschmidt and W. Sabuga, Intern. J. Thermophys., 21, 6, 2000. [3] B.W. Jones, J. Phys. E.: Sci. Instrum., 21, 832-839, 1988. [4] M.G. Langseth et al. (1972), The Moon, 4, 3-4, 390-410. [5] M.G. Langseth et al. (1976), Lunar Science Conference, 7^{th}, 3143-3171.