MEASURING HEAT FLOW ON THE MOON – THE HEAT FLOW AND PHYSICAL PROPERTIES PACKAGE HP³.

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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]. Measurements at the two sites differed by 25% and different theories concerning this large spread have been proposed: (1) Being close to the Procellarum KREEP terrain, 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 (HP³), a robotic heat flow probe which we propose as an instrument to address these questions.

Instrument description: The Heat Flow and Physical Properties Package (HP³) [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, HP³ is a relatively lightweight heat flow probe, weighting less than 1800 g.

![Figure 1: Schematics of the HP³ 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.](image-url)
thermal gradient in the regolith is then obtained from
the combination of temperature and position measure-
ments, 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 ther-
mal conductivity is the controlled injection of a speci-
fied amount of heat into the medium and a measure-
ment 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 HP3 geometry, and the
lesser dependence on contact resistance of these meth-
ods compared to steady state methods. In case of HP3,
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 neg-
ligible heat capacity. We use the payload compart-
ment as a modified LHS, e.g., a LHS with finite
length/diameter ratio and heat capacity. We will mea-
sure the temperature increase in the center of the pay-
load compartment to account for the deviation from
ideal LHS geometry. Due to the relatively complex
internal structure of the payload compartment a de-
tailed numerical thermal model for the determination
of the thermal properties will be implemented [6].

An independent measure of the regolith’s thermo-
physical properties will be obtained by a measurement
of the attenuation of the amplitude of the diurnal tem-
perature wave.

Measurement uncertainties: For the measurement
approach pursued here, the attainable accuracy for the
thermal conductivity determination is 5.8 % if the ideal
LHS geometry is applied in the asymptotic tempera-
ture domain [5]. However, it has been shown that fi-
nite 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 com-
pensated 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 con-
tributions from positioning uncertainties (here assumed
to be 2 cm), which result in the observed offset. Over-
all accuracy is expected to be 4%, but certainly better
than 10%, even if the Mole gets stuck at shallow depth.

Together with an assumed uncertainty of 5 % for
the thermal conductivity measurement, an attainable
uncertainty of 7 % is expected for the heat flow deter-
mination, which compares favourably to the uncer-
tainty of 15 % [1] given for the Apollo heat flow ex-
periments.

Payload compartment sensor options: The pay-
load compartment houses heaters, tilt sensors and elec-
tronics, but could be augmented with further instrumen-
tation. Other options include a densitometer, as de-
volved in the frame of the ESA precursor studies, or a
permittivity probe, as developed for a Martian applica-
tion in the frame of the ExoMars mission.

Conclusions: The HP3 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 pre-
developed 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 densitometer to constrain the re-
golith density and stratification.

References: [1] M.G. Langseth et al. (1976), Lu-
Wieczorek and R.J. Phillips, JGR., 105, E8, 20417-