COMPACT, MODULAR HEAT FLOW PROBE FOR THE LUNAR GEOPHYSICAL NETWORK MISSION.
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Introduction: The latest Decadal Survey by the National Research Council [1] recommends a *New Frontiers*-class, *Lunar Geophysical Network* (LGN) mission. This mission would deploy a 'global, long-lived network of geophysical instruments on the surface of the Moon'. Heat flow measurement is considered a top priority for the LGN mission. Heat flow is obtained as a product of two separate measurements: the thermal gradient and the thermal conductivity of the depth interval of the regolith penetrated by a probe. In anticipation of a future LGN mission, a panel of scientists [2] recommended that a heat flow probe on a future lunar mission should penetrate to a minimum of 3 m into the lunar regolith, ~0.7 m deeper than the depth reached by the Apollo 17 heat flow experiments [3]. Here we report our progress in designing and testing prototypes of low-mass, low-power lunar heat flow probes for possible use in future lunar robotic missions like the LGN.

System Description: A heat flow probe on the LGN mission must be a light-weight, compact system, because the spacecraft would likely to deploy multiple landers at different locations on the Moon, and each lander will be limited in size and its payload capacity. This low-mass requirement precludes use of the coventional drilling techniques for reaching the target 3-m depth, such as a rotary-percussive drill with a carousel for feeding drill extensions.

Our heat flow probe utilizes a pneumatic excavation system in deploying thermal sensors into the subsurface. The deployment mechanism (~28-cm tall, Fig. 1) of the probe spools out a glass fiber composite stem downward. The stem then forms a hollow cylinder of ~1.5-cm diameter (Fig. 2). It pushes the penetrating cone into the regolith, while gas jets, emitted from the cone tip, blow away loosened material. Removing material from the bottom of the excavated hole allows the stem to advance deeper with minimal thrust. A short (~1.5 cm), thin (~2-mm diameter) thermal probe attached to the cone tip (Fig. 3) measures temperatures and thermal conductivities of the regolith by stopping for 30 minutes at different depths on the way down. During each stop, to measure the thermal conductivity of undisturbed regolith, the probe shuts off the gas jet and pushes the needle probe into the bottom-hole regolith. After the stem reaches the targeted, 3-m depth, the temperature sensors embedded on the fully extended stem monitor long-term stability of the thermal gradient.

In its current design, the probe weighs 1.2 kg and can operate with a minimal power (< 10 W). The compressed gas required for excavation can be provided from a dedicated gas tank or from a pressurant tank which is part of the propulsion system (and in turn comes "free"). The gas excavation efficiency can reach 1:6000 (1 g of gas can loft 6000 grams of soil) in vacuum [4].

Figure 1. The latest prototype of the lunar heat flow probe with the stem stowed.

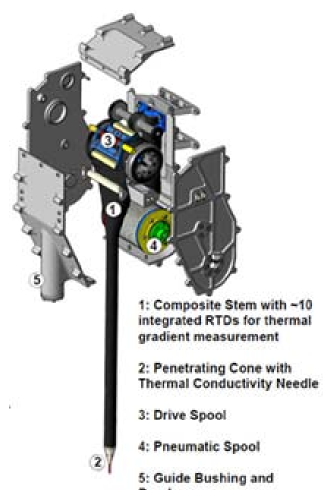

Figure 2. Schematics of the major components of the heat flow probe.

Figure 3. The cone-tip thermal conductivity probe.

The *in-situ* thermal conductivity probe (Fig. 3) utilizes a variant of the so-called needle probe method, widely used for *in-situ* measurements on terrestrial soil [e.g., 5]. The electric heater, which runs along the length of the probe, emits heat at a constant rate, and the temperature sensor of the probe monitors the warming of the surrounding regolith material. The thermal conductivity is inversely proportional to the rate of temperature increase in the natural-log time scale [6].

Our heat flow probe is a modular system, and it can be accommodated into a variety of lander configurations (Fig. 4). It only requires a stable platform for deployment on the lunar surface. It is also an ideal science payload for a human lunar-landing mission, because it is a set-it-and-forget-it system from the astronaut's point of view. All the astronauts need to do is to find a suitable location and set up the probe. Then, it can be remotely deployed from the earth [7].

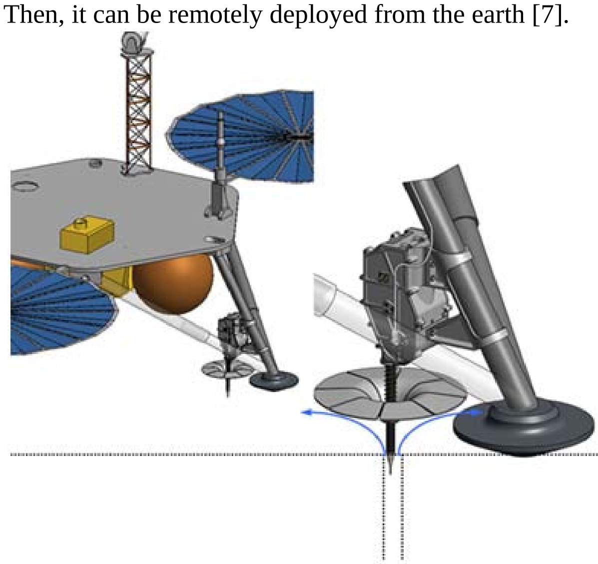

Figure 4. Left: a conceptual diagram showing the heat flow probe attached to a leg of a lunar lander. Right: an enlarged view of the probe with dust deflector deployed during an excavation.

Lab Tests: At the previous instrument workshop, we presented the results from our thermal conductivity probe measurements on JSC-1A lunar regolith simulant in a vacuum chamber [6]. Here, we focus on our recent excavation tests using the latest prototype of the heat flow system (Fig. 1).

In our first test, the probe was deployed into well compacted JSC-1A lunar simulant filling a 1-m deep bin placed in a vacuum chamber set at 4 Torr (Fig. 5). The penetrating cone reached the bottom of the bin in less than one minute, using 5 grams of nitrogen gas pressurized at 400 kPa, while weight on bit (WOB) was kept under 30 N most of the time (Fig. 6).

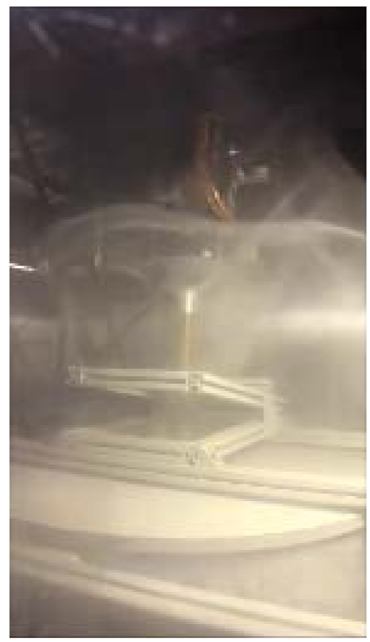

Figure 5. A snapshot taken during the excavation into JSC-1A lunar regolith simulant. The probe was place on the lid of the soil bin. A plume of the simulant blown out of the hole in the middle of the lid is seen.

Next, we deployed the probe into NU-LHT-2M lunar highlands simulant filling a 3-m tall bin placed in a vacuum chamber. Using gas pressures and thrusting forces similar to our earlier penetration tests, we were able to advance the probe down 1.9-m depth into the simulant in ~2 minutes. The penetration stopped at that depth even at increased gas flow rates. Inspection after the test revealed that simulant particles were blown inside the hollow cylinder of the stem instead of being lofted between the stem and the borehole.

Finally, we carried out a stop-and-go operation test into NU-LHT-2M simulant in a vacuum chamber. The probe excavated down to 0.5-m depth, stopped for 30 minutes for a heating experiment for thermal conductivity measurement, resumed excavation down to 1-m depth, and carried out another heating experiment successfully. This demonstrated that it is possible to stop and re-start penetration, and in turn conduct thermal conductivity tests at various depths.

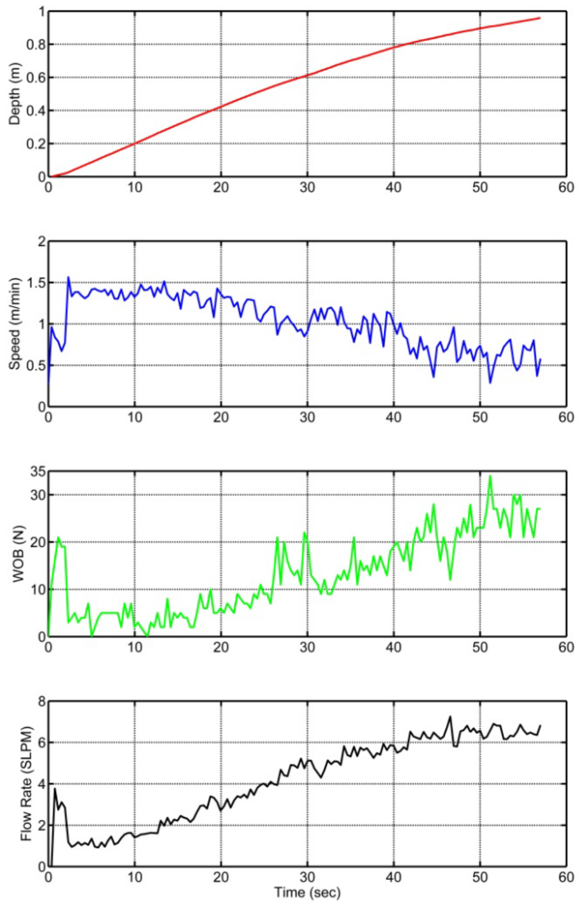

Figure 6. Instrument readouts from the 1-m excavation test on JSC-1A lunar regolith simulant in vacuum chamber.

Discussion and Future Work: The reason why our excavation test fell short of reaching the 3-m target depth was that some regolith particles found their way into the inside of the cylindrical glass-fiber stem. When the stem forms a hollow cylinder as it spools out, it has a 165-degree overlap in order to gain more strength to prevent buckling. At an early stage of the excavation operation, some of the dust particles, lofted up from the bottom of the hole, become wedged between the overlapping stem. Once the overlap opens a gap, larger particles make their way inside the hollow cylinder of the stem, because the inner stem now becomes the primary escape route for the gas. As more regolith/simulant particles build up inside the stem, the friction between the stem and the borehole increases and eventually becomes high enough to halt the advance of the stem. The regolith particles inside the stem also make their way into the deployment mechanism and cause it to jam.

Therefore, we are now designing a new stem that can be sealed along the overlap or have a sealable membrane inside. Both options have been prototyped and demonstrated for other applications by the Composite Technology Development Co., the manufacturer of the composite stem for the heat flow probe. Solving this problem should enable us to reach the targeted 3-m depth. On a seprate test, we have already confirmd that a 3.5-m long, hollow aluminum tube can penetrate to 3-m depth into NU-LHT-2M just by blowing gas down the tube and its nose cone. The 3-m depth was reached in 3 minutes.

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References: [1] National Research Council (2011) pub# 13117. [2] Cohen, B. A. et al. (2009) *ILN Final Report*. [3] Langseth et al. (1976) *LPSC VII* 3143-3171. [4] Zacny, K. et al. (2011) *LEAG* 2028. [5] Von Herzen , R. P., and Maxwell, A. E., (1959) *J. Geophys. Res.*, 64, 1557-1563. [6] Nagihara, S. et al., (2012) *International Workshop on Instrumentation for Planetary Missions*, 1014. [7] Nagihara, S. et al. (2013) *Workshop on Golden Spike Human Lunar Expedition*, 6003.