APOLLO LUNAR HEAT FLOW EXPERIMENT: AN EVALUATION OF POTENTIAL CAUSES OF SUBSURFACE TEMPERATURE DRIFT.

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Introduction: In situ measurements of lunar heat flow provide valuable information for our understanding of the Moon's internal structure, composition, and evolution. Existing analysis and interpretations of the Apollo Heat Flow Experiment (HFE) data from Apollo 15 and 17 missions present an opportunity for reinvestigation as newly recovered and restored data have become available [1]. An evaluation of potential causes of observed long-term subsurface temperature drift and decreasing thermal gradient in HFE data will contribute significantly to the study of lunar heat flow and future in situ measurements.

Background and Data: Data from heat flow probes deployed at the Hadley Rille and Taurus-Littrow sites during Apollo 15 and 17 provide temperature measurements at depths below the lunar surface down to 1.7 m and 2.5 m, respectively [2]. Heat flow measurements of 21 ± 3 mWm^{-2} and 15 ± 2 mWm^{-2} from these sites [2] have played a major role in evaluations of the thermal state of the Moon. However, an uncertainty associated with these values due to subsurface temperature drift could significantly alter present heat flow measurements. This investigation therefore maintains important consequences for our understanding of the lunar thermal environment and composition. Recent efforts to process sets of unarchived HFE data from January 1975 through September 1977 yield a more complete data set for reanalysis [1] (Figure 1). Subsurface temperatures notably increase over the experiment timeline with those closest to the surface experiencing the largest degrees of warming.

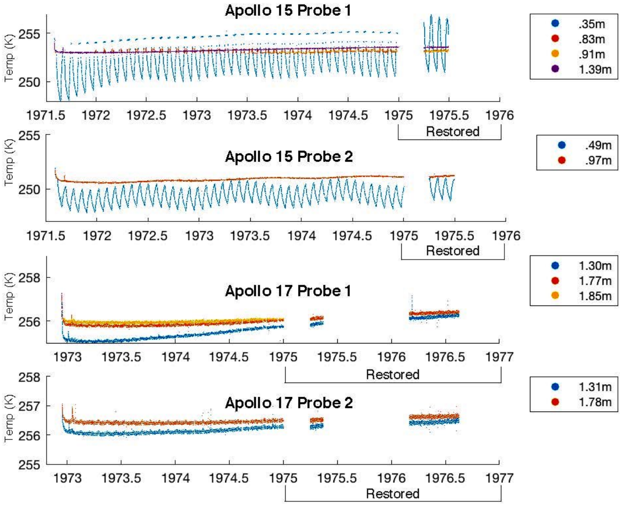

Figure 1: Temperatures recorded by Apollo 15 and 17 heat flow probes including records from original investigators [2] and newly restored data for years 1975 through 1977 [1].

Model: We use a one-dimensional numerical thermal model to consider likely causes for warming. While previous investigations using the restored data employ a basic analytical heat conduction model [1], our method, while still simplified, accounts for spacial and temporal parameter variations not previously considered. This approach has been shown to successfully model thermophysical properties of the moon [3] and proves useful in efforts to explain HFE temperature drift. Variation of temperature (T) with time (t) and depth (z) is described as

$$\rho c_p \frac{\delta T}{\delta t} = \frac{\delta}{\delta z}(K \frac{\delta T}{\delta z})$$

where ρ is density, c_p is specific heat, and K is thermal conductivity. The model assumes increasing regolith density and conductivity with depth, matching Apollo core sample observations [4]. The relationship between density and depth is modeled by

$$\rho(z) = \rho_d - (\rho_d - \rho_s)e^{-z/H}$$

where ρ_s (~1100 kg m^{-3}) is surface density, ρ_d (~1800 kg m^{-3}) is density at depths $z \gg H$-parameter [3]. Additional modeling will be performed in COMSOL Multiphysics to verify and expand upon one-dimensional model investigations.

Approach: We consider three primary potential causes for the multiyear subsurface warming:

(1) *The Moon's 18.6 year orbital precession period* causing increased average day lengths (potentially amplified by surrounding topography) [5].

(2) *Astronaut-induced changes of thermophyscial regolith properties* including decreased albedo and regolith compaction [2]. Figure 2 shows example density profiles for initial surface densities of 1100 kg m^{-3} and 1300 kg m^{-3}.

(3) *Solar radiation down the borestems* warming the probe. Varying relevant input parameters, we evaluate which changes may have caused sufficient subsurface temperature rise [5].

Preliminary Results : Here, we briefly summarize work for new and ongoing efforts to reanalyze Apollo HFE temperature drift. Model results are checked against in situ temperature measurements. Figure 3 shows an example of a test for decreased albedo — the parameter concluded by previous investigators as the most probable cause for subsurface warming [1]. While a .05 decrease in surface albedo is shown to cause temperature drift, present investigations have not concluded if astronaut disturbances were sufficient to cause this change in albedo. An increase in conductivity due to regolith compaction (Figure 4) is also shown to cause warming.

Future Work: Preliminary results suggest this model is an effective approach to understanding Apollo HFE temperature drift. The present work will be extended to combine parameter variations and test additional potential causes of temperature drift and decreasing thermal gradient. Further considerations will include updates to current Apollo heat flow measurements and applications for minimizing perturbations to the measured thermal environment. These results may prove useful for the evaluation of other in situ heat flow measurements, including the Mars InSight mission.

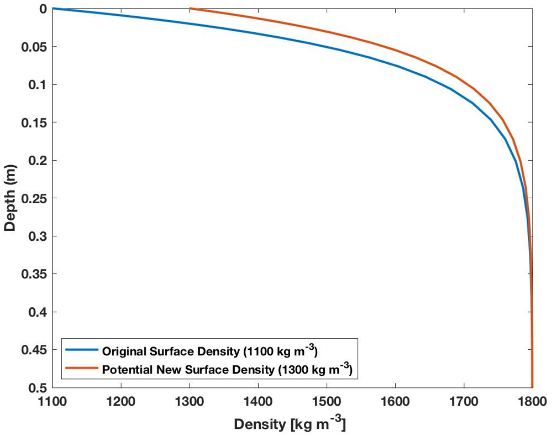

Figure 2: Model density profiles for an original surface density and potential new surface density post-compaction.

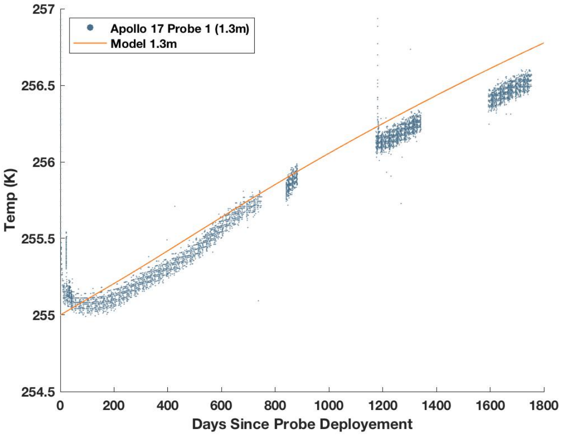

Figure 3: Apollo 17 probe 1 temperatures at a 1.3m depth and model temperature results at 1.3m depth with a .05 decrease in albedo at time of probe deployment.

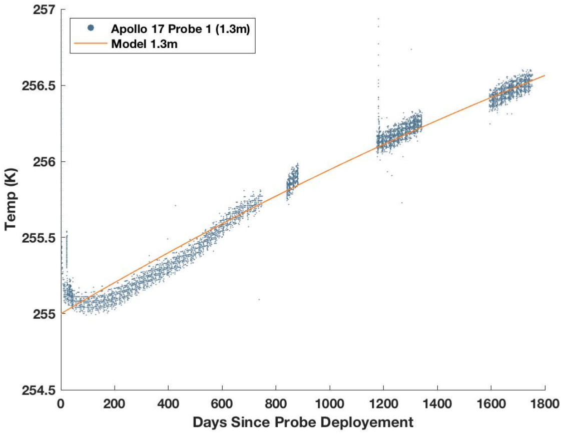

Figure 4: Apollo 17 probe 1 temperatures at a 1.3m depth and model temperature results at 1.3m depth with a 8% increase in surface conductivity at time of probe deployment.

References: [1] Nagihara et al. (2018) JGR Planets, 123 (5): 1125–39. [2] Lengseth et al. (1976) LPSC (Vol. 7, pp. 3143-3171). [3] Hayne et al. (2017) JGR Planets, 122 (12): 2371–2400. [4] Keihm & Langseth (1973) LPSC (Vol. 4, pp. 2503). [5] Siegler et al. (2010) LPSC (Vol. 41, pp. 2650).