

Appendix A: The Scientific Rationale for MoonLITE

Context for a Lunar Network Mission using Penetrators

By 2014, remote sensing will provide global maps of unprecedented detail, giving a synoptic view of the lunar surface. Topography and gravity data will reveal the crustal structure of the Moon, albeit in a non-unique fashion, and will provide new constraints on its planetary dynamics. The thermal environment, particularly of polar regions, will be better understood. Mission planning will have multiple datasets available to select targets. What will be lacking are several key measurements of the near-surface, humanly accessible environment that will determine the course of future exploration, along with measurements of the deeper interior that will resolve fundamental scientific questions of lunar origin and evolution. The required seismological, thermodynamic and compositional measurements can only be performed in-situ, and require a widely distributed suite of sensors to obtain the necessary geometry and provide global comparisons.

The MoonLITE mission is uniquely suitable for obtaining near-surface geophysical and compositional measurements. The mission will likely be the first robotically deployed, global network and will include a dedicated communication orbiter. Its duration will necessarily be shorter than that of landed systems being explored internationally but the mission would be expected to overlap and enhance the scientific return of these efforts. The study of the lunar interior will require many years to fully understand its structure, but the MoonLITE concept is a pathfinder for robotic systems, with strong implications for planetary exploration. The inherent network concept and penetrator deployment render MoonLITE a unique and scientifically valuable mission.

The baseline mission of four penetrators deployed from low orbit was evaluated for its ability to address first-order scientific questions. These questions include: What is the size and mass of the core? What is the thickness distribution and stratification of the crust? What is the heat budget of the interior, and are there regional differences? What is the major element composition of the crust, and how does it compare to results inferred from remote sensing? In regions where volatiles may be frozen into the near-surface regolith, what is their composition, concentration and accessibility?

As proposed a four-penetrator MoonLITE mission provides an adequate number of network nodes, while allowing for the case where one probe is compromised. At least 3 stations are required to locate seismic events, and to investigate geographical variations in heat flow.

The technologies proposed have sufficient heritage and maturity (Lunar-A and Deep Space-2) to evaluate their capabilities for answering these questions and to suggest paths for further development. The penetrator device solves several problems at once: sufficient depth of deployment into the regolith is reached to achieve a relatively benign thermal environment; a suitable depth of sampling is obtained (for sub-surface volatiles);

good contact is assured. The manufacture and qualification of four nearly identical units should lead to greater reliability and reproducibility of results.

The U.S. is considering the development of four nodes of an International Lunar Network, two to be launched in 2014, and the remaining two in 2016. The current goal is that there be 6 years of overlapping operations. The inclusion of four working nodes from MoonLITE would provide scientific opportunities not possible with either the U.S. or UK nodes individually. The resulting network would allow much improved epicentre locations and interior structure determination. The deployment of heat flow experiments on both penetrators and soft landers will allow measurement of this quantity using different approaches as well as better assessment of global variations in heat flow.

It will take many more years to fully understand the lunar interior structure, but the MoonLITE concept is a pathfinder for robotic systems, with strong implications for planetary exploration. The inherent network concept and penetrator deployment render MoonLITE a unique and scientifically valuable mission.

Rationale for a Seismic Experiment

Fundamental outstanding scientific issues in understanding Earth's Moon are the interior structure and seismic activity of that body. The Apollo Passive Seismic Experiment (APSE) demonstrated the presence of shallow (< 200 km) and deep (~ 900 km) moonquakes. However our understanding of lunar seismicity is severely limited by the near-side-only, geometry of the four Apollo seismic stations. For example we have little to no information on whether moonquakes occur on the far side, or in the polar regions which are likely locations for future lunar exploration. Of particular interest to future exploration are increased monitoring of shallow moonquakes - these can have body wave magnitudes greater than 5.0 - and improved estimates of the lunar meteoroid flux.

Surface geophysical data, satellite-based remote sensing information and sample data all indicate the presence of distinct lunar crust and mantle compositions. Gravity and topography data indicate large relative variations in the crustal thickness geographically, however it has only been possible to seismically infer the absolute thickness of the crust in the vicinity of Apollo sites 12 and 14. While several indirect geophysical measurements suggest the presence of a lunar core that may be partially molten, this has not been confirmed with direct seismological measurements and there are large uncertainties in possible core size and composition. Improved knowledge of the Moon's interior structure is essential to understanding its present state and its evolution. Measurements of absolute crustal thickness are needed to estimate the volume of the crust, which in turn is related to the early lunar magma ocean and subsequent differentiation. Seismic measurements, when combined with other measurements from missions such as GRAIL, will allow definitive identification of a lunar core, measurement of its size, and information on its state, all of which are critical to bulk composition models (lunar origin), to thermal evolution models, and to the interpretation of the record of crustal magnetic anomalies.

Rationale for a Heat Flow Experiment

Global compositional data for the Moon, namely Lunar Prospector results from 1998, have shown that the Moon's early differentiation is more complex than previously thought. In particular, gamma-ray measurements from orbit appear to show that KREEP-rich materials (a geochemical component that contains a high abundance of heat-producing elements) are concentrated in a single geochemical province – the Procellarum KREEP terrane - on the nearside hemisphere, which is correlated with the locations of extensive mare basalt deposits.

Measurement of the surface heat flow at several localities is key to understanding the interior temperature of the lunar mantle and the distribution, the origin and petrogenesis of mare basalts. In addition, since the average heat flow of the Moon is related to its bulk abundance of heat producing elements, the average heat flow is related to the bulk composition of the Moon, which is currently not well constrained.

Two heat flow measurements were made during the Apollo era at the Apollo 15 and 17 sites, both of which are on the Moon's near side hemisphere. Unfortunately, these measurements suffer from several fundamental problems, such as their non-representative locations at the edge of the two main geochemical provinces. MoonLITE would remedy this problem by measuring the heat flow at four localities far from the Apollo landing sites, including a first far-side heat flow determination. This would place fundamental constraints on the asymmetric differentiation of the Moon, the asymmetric distribution of heat producing elements, and the asymmetric distribution of mare basaltic eruptions.

The heat flow determinations are to be performed by measuring two key quantities: the temperature gradient near the surface, and the *in situ* thermal conductivity of the lunar regolith. Both of these quantities could be determined by either embedding temperature sensors and heaters within the penetrator body, or by extending a short needle probe into the regolith surrounding the penetrator body. The measurements of the temperature gradient and thermal conductivity are both challenging, and it is likely that the needle probe approach has a higher probability of meeting the science requirements. Nevertheless, we recommend that both approaches be investigated in a Phase A study.

Rationale for Polar Volatile Detection

Substantial amounts of water may lie frozen in the permanently shaded regions of craters near both poles on the Moon. As a record of the inventory and flux of volatiles in the inner solar system, and as a potential resource for future lunar bases, the detection and measurement of frozen water in the polar regolith is a high scientific and strategic priority.

The water is believed to originate primarily from the impact of comets with the Moon, producing a temporary atmosphere primarily of water vapour, some of which could be

trapped in the polar shadows, where the temperature is less than 100K. Some of it may have been exhaled, presumably long ago, from the interior of the Moon. Although the exposed upper surface is predicted to be very dry, water-bearing materials may accumulate in the sub-surface. Any ice present is probably mixed with regolith material, as a result of diffusion and/or ‘gardening’ by micrometeorites, to a depth of several metres below the surface. Penetrators are ideal vehicles for accessing the icy layers if they can be targeted into the coldest parts of the deepest polar craters. The strawman payload for MoonLITE includes a suite of five possible instruments to characterize the amount of volatiles in the material near the probe, and their composition and hence origin. Such in-situ measurements are a necessary complement to satellite-based remotely sensed observations.

Rationale for Compositional Measurements

Samples with a known geologic context have been obtained only from 9 locations on the near-side hemisphere of the Moon. A variety of sophisticated remote sensing techniques operating from orbit provide measurement of the surface composition far from these locations, and demonstrate that the Moon is more compositionally diverse than might have been expected from the sample data alone. The geochemical results from remote sensing data alone, however, are not always consistent in detail, and many suffer from calibration issues. For this reason, it is of fundamental importance to compare orbital measurements with known *in situ* compositional data to be assured that lunar compositional terranes are placed in the proper geologic context.

MoonLITE proposes to make geochemical measurements at four additional sites using in-situ experiments such as an X-ray spectrometer. In addition to obtaining major element compositions, this particular instrument can obtain information on some important trace elements as well. These *in situ* measurements would aid in the interpretation of orbital remote sensing data sets. In addition, geochemical measurements of selected high-priority science targets could have a high science return, such as from within the South Pole-Aitken basin.