

## **Appendix B: Recommendations on issues during or after Phase A Study**

### **Programmatic**

- It is important to assure broad peer-reviewed participation of the UK community in instrument selection and all aspects of the MoonLITE mission as it proceeds.
- To maximize the science return from the MoonLITE network, the MoonLITE team is strongly urged to closely coordinate site selection with international participants of the International Lunar Network.
- Similarly, it would be exceptionally valuable to plan and carefully target artificial impacts of the current and future spacecraft that orbit the Moon with the international community. The Apollo experience has shown such well defined and targeted impacts to be the most valuable seismic events for determination of crustal thickness.

### **System-level**

- Investigate coordination with other international agencies, in particular NASA, for potential back-up assets to provide redundancy in communication capabilities
- Further testing of the penetration process and its effect on instrumentation should continue by performing multiple tests
- Investigate the possibility of increasing the mass of the scientific payload and battery longevity

### **Seismic Experiment and Instrumentation**

- Instrument sensitivity: As proposed, the MEMS seismometer has a theoretical noise level close to that measured on the Moon by the Apollo horizontal LP instrument. The actual noise level measured by the microseismometer on the Moon will be larger than the theoretical level shown: how much larger has implications for event detection. Telemetry and power constraints provided to the panel in an email indicate that 3-component 10Hz (possibly 25Hz) data from ~200 events, lasting 1 hour each, will be transmitted over the course of the 1 yr experiment. During Phase-A instrument noise levels likely on the Moon should be verified to be sufficiently low such that the signal-to-noise ratio (SNR) for the P-waves recorded from these events is significantly greater than 1 (see triggering issue below). Even in the Apollo data, secondary phases such as reflected energy from the core have not been identified to date, although recent studies suggested this may be possible in the future using deconvolution techniques. These results strongly suggest that the seismometers that are ultimately selected for the MoonLITE mission should be as sensitive as possible.

- Duration of experiment - Power Trade Studies: Based on instrument noise levels that are comparable to, or slightly worse than the Apollo noise levels, the minimum seismic network duration that can yield scientifically meaningful results is 1 year. All possible trades that can permit a longer (> 1yr) experiment duration should be examined: increased battery capacity, effects of the penetration impact on battery power, trades among different instruments and power required for downlinking data from the penetrator to the orbiter.
- Triggering Algorithm: Many of the scientific results from the Apollo data have resulted from our ability to investigate the full continuous data set on the ground. The proposed MoonLITE investigation following the first month of operation, involves on-board event detection using a triggering algorithm on a single horizontal component to detect P-wave arrivals, followed by power-on of the second horizontal and the vertical components. Thus three-component data will only be recorded at the time of an event. Critical to the success of the seismological investigations then is the triggering algorithm. Phase A studies should demonstrate successful triggering algorithms, in particular ones that can deal with the likely low SNR that will be characteristic of P-wave arrivals. In addition, because a limited number of events can be uplinked to the orbiter from the penetrator (due to power and viewing constraints), it should be verified that the triggering algorithm also minimizes the number of false returns. These studies could be performed using existing Apollo data.
- Sensor Orientations. Internal sensors will provide the tilt, but essential to the scientific return of the seismological data will be the ability to determine azimuth of orientation of the horizontal sensors by using the communication system radiation pattern as seen by the orbiter. This is particularly critical for techniques that might be applied to investigate crustal thickness.
- Telemetry. The importance of returning as much data as possible cannot be overemphasized. Every effort should be made to incorporate low power, high bandwidth telecommunications to allow maximum data downlink from the penetrator to the orbiter, and ultimately to Earth.

## **Heat Flow Experiment and Instrumentation**

The success of the proposed heat flow experiment depends on measuring two quantities, the temperature gradient and the thermal conductivity, both with a precision of about 10%. Both measurements are challenging to perform, and the Phase A study should demonstrate that these measurement goals can indeed be met. One proposed approach (approach 1) to measure these quantities, as investigated in the Japanese Lunar-A program, is to embed sensors within the body of the penetrator. The other approach (approach 2) is to extend a needle probe sensor into the surrounding regolith a few centimeters away from the penetrator body. The benefit of this approach is that needle probe experiments are well studied and are known to have a high accuracy. In addition, it

should be possible to measure the undisturbed temperature gradient directly, without having to wait for the penetrator to come to thermal equilibrium with the surrounding regolith. While both approaches should be investigated in the Phase-A study, it appears likely that the needle probe approach will prove to be more accurate.

Specific recommendations follow:

- Approach 1 - embedded sensors: *Determination of the temperature gradient.* In this approach, the temperature at two ends of the probe are measured after the probe comes into thermal equilibrium with the surrounding regolith. As these temperatures are not equal to the initial undisturbed temperature, it is necessary to develop a complex modeling procedure to invert for the initial temperatures. This modeling will certainly be made more difficult if the probe is constructed out of a high thermal conductivity material (such as aluminum), and it may be desirable to instead use a probe constructed out of a different material (such as a carbon composite as with Lunar-A). In addition to accounting for the thermal short-circuiting effect of the probe, it is also necessary to take into account the disturbance of the surround regolith (i.e., compaction during the impact process), as well as the nature of any disturbed regolith that will likely collapse onto the top of the probe following the impact. Both of these effects are difficult to quantify, and it should be demonstrated that this fundamental uncertainty will not prohibit the determination of the initial undisturbed temperature gradient. A detailed numerical thermal model used for the retrieval of the initial undisturbed temperature gradient should be developed to address the following questions.
  1. Should the penetrator body be made of a carbon composite instead of aluminum in order to increase the precision of the inverted undisturbed temperature gradient?
  2. Does compaction of the regolith surrounding the penetrator during the impact process need to be accounted for in determining the undisturbed temperature gradient? And what is the magnitude of this effect?
  3. Does the disturbed nature of the regolith overlying the probe introduce a fundamental uncertainty in the inversion of the undisturbed temperature gradient? And what is the expected magnitude of this effect?
  4. Does the internal heat dissipation of the probe, and possibly heaters, interfere with the determination of the temperature gradient?
- Approach 1 - embedded sensors: *Determination of thermal conductivity.* The thermal conductivity is to be determined by heating a sensor embedding in the penetrator's body, and it will be necessary to develop a detailed numerical thermal model to extract this important quantity. This model should include the thermal linkages between the regolith, heater, and probe, and a possibly disturbed regolith zone just adjacent to the probe. The phase-A study should demonstrate that the analysis of data from a thermal conductivity experiment can extract the thermal conductivity to an accuracy of about 10%.

- Approach 2: needle probes: *Determination of temperature gradient.* A detailed thermal model that includes the needle probe and penetrator body should be developed to answer the following questions.
  1. How far does the needle probe need to extend into the regolith in order to measure the undisturbed regolith temperature?
  2. How long does one have to make the temperature measurements before the transient thermal wave associated with the penetrator itself affect the temperature of the regolith in contact with the needle probes?
  3. How many needle probes are needed to extract the temperature gradient, assuming that the final penetrator orientation is not vertical?
- Approach 2: needle probes: *Determination of the thermal conductivity.* Needle probes are commonly used on Earth to measure the thermal conductivity of particulate materials, and it is likely that such an approach will also work on the MoonLite mission as well. Nevertheless, several affects need to be investigated in order to determine if these measurements are representative of undisturbed regolith. A detailed numerical thermal model should be developed to answer the following questions.
  1. When can one perform the thermal conductivity experiment? Initially after the impact, or does one need to wait for the probe and surrounding regolith to achieve thermal equilibrium?
  2. Does compaction of the surrounding regolith during the impact of the penetrator significantly modify the thermal conductivity of the regolith?
  3. The high conductivity of the penetrator body invalidates the assumptions used in inverting needle probe data for the thermal conductivity (i.e., an infinite thin needle in a uniform media). Does the high thermal conductivity of the penetrator body affect or bias the thermal conductivity determined by the needle probe technique?

### **Volatile Experiment and Instrumentation**

- Study targeting capabilities to establish the design requirements for the mission that will permit the precise targeting of penetrators so that they impact in the coldest areas (as defined by infrared mapping from LRO, for example) of the near-polar craters. An error ellipse of a few km will be required for this purpose.
- Study the physical properties of potential impact sites, including regolith simulants cemented together by about 5% H<sub>2</sub>O at a temperature of 100K, to ensure the safe deployment of the probe and instruments in a variety of possible surface components.
- Verify the availability of suitable RHU heaters for survival of batteries etc. in the polar night. (The ice detection experiment can be conducted fairly quickly, but the polar penetrator(s) are required to have a long life as part of the seismology experiment).