COST-EFFECTIVE GEOPHYSICAL EXPLORATION OF THE MOON USING INSTRUMENTED MICO-LANDERS.

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Introduction: Since the Clementine mission in 1994, a number of lunar missions using small spacecrft have flown, including Lunar Prospector, SMART-1, Selene-A, Chang'e-1, and Chandrayan-1. Despite the increase in knowledge of lunar science provided by all of these missions and the original lunar missions of the 1960s and 1970s, there remain fundamental questions regarding the structure and composition of the lunar interior. High priority goals identified by a recent National Research Council report on The Scientific Context for Exploration of the Moon [1] and in the LEAG Lunar exploration Roadmap [2] include a determination of the thickness of the lunar crust and its lateral variability, the characterizing of the chemical/physical stratification in the mantle, determine the size, composition, and state of the core of the Moon, and characterizing the workings of the planetary heat engine. Much of our current seismological understanding of the Moon comes from analyses of the past Apollo lunar seismic data [c.f. 3], which provided important information regarding the distribution and magnitude of lunar sources and the 1-dimensional seismic velocity structure. However, the Apollo scientific capabilities are limited by the fact that instruments were clustered in the equatorial near side of the Moon and by the narrow bandwith and low dynamic range of the seismometer package. Thus many have recognized that a future, geographically distributed geophysical network is needed to answer the fundemental questions regarding the inner workings [4] and bulk composition [5] of the Moon and a design incorporating high sensitivity broadband seismometers would improve the recording of waveforms and the ability to detect secondary phases [6]. We suggest that small spacecraft missions including microlanders may provide a relatively cost-effective approach for such a mission.

Micro-technology Delivery: A critical factor in using seismology to probe the lunar interior is the cost of installation of a global network. Possible mission scenarios include deployment of penetrators from one or more orbiting spacecraft [7] or a series of soft landers as discussed for the International Lunar Network [8]. All have suffered from the perceived high cost, in spite of the valuable scientific results to be returned. We clearly need a low-cost alternative of delivering a geophysical network.

The Hawaii Space Flight Laboratory at the University of Hawaii at Manoa is developing a program to become a low-cost gateway to space and to place the the University of Hawaii as the only university in the world to have both satellite fabrication capabilities and unique, direct access to orbital space. Faculty and students from the UH School of Ocean and Earth Science and Technology and the College of Engineering are developing the capabilities to design, build, launch, and operate microsatellites in the 1-150 kg range that can be configured for a variety of science and education tasks. Using vehicles derived from proven technology, the system will be capable of delivering 300 kg to low Earth orbit. The first launch to LEO is scheduled for mid-2011.

Using the latest in micro-technology for spacecraft, we estimate that it is possible to do a mission to the Moon for under $300 million (for just the installation component) including launch costs, the deployment of four instrumented micro-landers to install four geophysical stations at widely spaced geographic locations, and an orbitor to allow communication with instruments on the farside. The mission would soft-land a ~40-kg lunar lander onto the surface, with about 20 kg devoted to science payload, and take measurements. The duration of the experiment will be limited by power capabilities, but even a limited duration experiment is likely to provide answers to outstanding scientific questions. Thus, a sound lunar seismic network can be emplaced within the cost cap of the Discovery program. .

Scientific Analyses: The prior Apollo LP seismometers provided low resolution data in a narrow high frequency band around 0.5 Hz, where waveforms show intense scattering, making identification of secondary arrivals diffcult and precluding deterministic waveform modeling. Data from a future multicomponent, sensitive, broadband seismometer network [6], should allow low frequency analyses, such as study of direct, reflected, refracted, and converted body wave phases using many modern techniques in global and regional seismology as well as allow possible identification of surface waves and normal modes. Equally important, a network of widely-spaced stations is crucial in improving the ray path sampling of the deep mantle and core, which was not well sampled by Apollo data [4].

Assuming the existence of such a functional network, the dominant limitation on the scientific analyses will be the locations and signal-to-noise of the seismic sources and their frequency of occurence. Apollo studies have characterized the frequency-magnitude relationship of lunar sources. Approximately one magnitude 5 or greater shallow moonquake occurs per year [8]. Small (magnitude < 3), deep clusters of repeating moonquakes occur with tidal periodicities [c.f. 9] and the regularity of Apollo deep moonquakes lends credence to the suggestion that these source regions are likely to remain active and be observable by future missions [7, 8]. However, because deep moonquakes are small in magnitude and background noise levels on the Moon are low, the seismometer will require high sensitivity and 24 bit dynamic range. It has been recommended that in the frequency band of 0.001-1.0 Hz that instrument sensitivity be at least an order of magitude better than the Apollo long-period instruments [8].

Implementation Issues: We have made a reasaonable first estimate of the cost of spacecraft design, construction, and launch, and others [6, 10] have reported advanced designs for seismometers. The central issues we have identified at present are outlined here.

Power. It appears that at least a one-year mission is possible. For example, the Lunar-A mission would have utilized Li-SOCL2 batteriess with quoted power density of 430W/kg [7]. The power requirements for a seismometer may be on the order of 0.5-1W/day; see details at [9]. Power is a crucial issue because it constrains station lifetime. While we are optimistic about achieving a one- or two-year lifetime, the final report of the scientific definition team for the ILN anchor nodes recommends operations of at least six years and the development of long-lived power sources [8].

Instrument deployment. High sensitivity seismometers demand thermal and mechanical stability. Burying a seismometer improves thermal control and coupling, but requires additional instrumentation, such as a mole [6], hence adding more mass.

Targeting. A preliminary mission design study suggests a landing ellipse of about 200 km, without the need to go into lunar orbit first. If more precise targeting is needed for a small (four-sites) network, we will need detailed trade studies.

Other measurements. Additional instruments may be needed or desired, such as a camera for documenting the site, a heat-flow probe, or chemical analyzers. These have to be balanced with the goal of making the mission cost effective and with the payload and power capabilities of the system. A priority list of geophysical instruments is recommended by [8].

Reliability: It has been four decades since a geophysical experiment was conducted on the Moon. Thus no modern instrumentation exists that is field tested in the lunar environment. While selection of mission instrumentation would likely undergo extensive competitive review, comparative analysis of proposed instrumentation at a common test facility such as the Albuquerque Seismological Laboratory may prove useful. It may also be possible, depending on power and weight considerations, to build a level of redundancy in the deployment by operating multiple sensors.

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