SEISMIC STUDIES FROM THE LUNAR SOUTH POLE WITH RUGGED, LOW-COST MET SEISMOMETERS. T.A. Hurford[1], L. Dai[2], M.J. Fouch[3], E.J. Garnero[2], V. Lekić[4], W. Lin[2], R. Maguire[4,5], K.G. Olsen[4], N. Schmerr[4], J.D. West[2] and Y. Xu[2], [1]Goddard Space Flight Center, Greenbelt, MD, USA (terry.a.hurford@nasa.gov), [2]Arizona State University, Tempe, AZ, USA, [3]Samara Data, Washington, DC, USA, [4]University of Maryland, College Park, MD, USA, [5]University of New Mexico, Albuquerque, NM, USA.

Introduction: Constraining the details of the Moon's internal structure and seismic activity is required to understand its origin, history, and internal dynamics. Further, characterization of moonquake magnitudes and distribution is an essential element of providing safety to human-driven exploration of the lunar surface. These observations and constraints are primarily enabled via monitoring of seismic and bolide activity on the Moon. Data from seismometers therefore provide a critical approach to enable a detailed mapping of the interior of the Moon from regolith to core, to constrain physics of internal lunar dynamics, and to catalog and characterize moonquakes and bolide impacts. The key technological challenge is to produce a modern, rugged, high-performance seismometer that can provide the range of seismic data necessary to achieve these objectives.

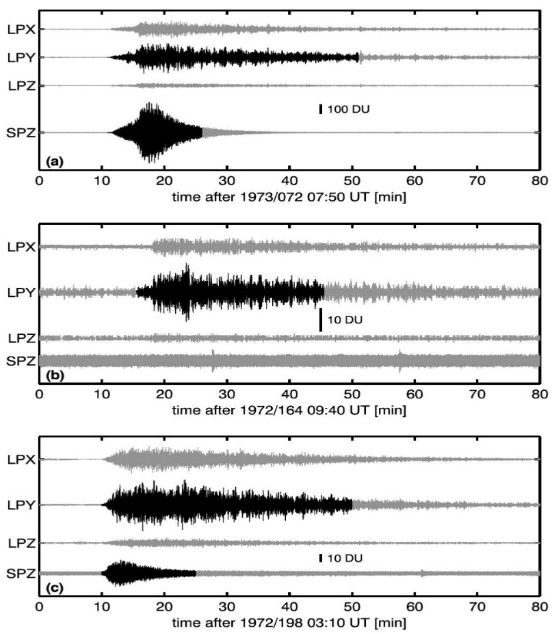

Figure 1 Characteristic seismograms [1] for a shallow moonquake (top), a deep moonquake (middle) and an impact event (bottom).

Moonquakes*:* Moonquakes are prolific and widespread in time and space. From 1969 to 1977, some 12,000 seismic events were recorded by the Apollo Lunar Surface Experiments Package (ALSEP) array including meteor and artificial impacts as well as deep and shallow moonquakes. Moonquakes typically release energies equivalent to terrestrial magnitude 3 events (stress drop typically 10 kPa), although the largest are equivalent to terrestrial magnitude 4 events (stress drop typically <5 MPa) [2]. Lunar seismic signals (Fig. 1) differ considerably from terrestrial signals, and are characterized by a long duration and high frequency content. Resolving the arrival of the P and S body waves within lunar seismic signals remains a substantial challenge, and surface-wave arrivals are generally obscured by the long train of scattered waves (coda).

Lunar seismic events were initially categorized on the basis of their character and later in terms of their source and origin. Deep moonquakes have focal depths of 700-1,200 km and are the most common events observed; more than 7,000 were recorded [3,4,5,6,7,8,9,10,11]. Deep moonquakes have energies corresponding to a Richter magnitude <3. They occur in some 106 spatially well-defined "nests" or clusters (Nakamura, 2005) and they do not occur randomly in time. The signal character of each "nest" is unique and repeatable and there is a high correlation between the timing of such events and the tidal cycle [4].

Shallow moonquakes, also known as high-frequency events, are the most infrequent events but are also the highest magnitude; seven of the 28 recorded events have a Richter magnitude >5 [7,12,13,14,15,16]. Focal depths are estimated to be between 50 and 200 km, within the mantle. Most of the energy released is at frequencies of 1-5 Hz and falls off above 5 Hz; P- and S-wave arrivals are relatively distinct. Recently, Watters et al. [17] have shown that many shallow moonquakes lie near young thrust faults, and it has been suggested that these tectonic events release stress resulting from the cooling Moon. However, other studies suggest that they too may be tidally driven, releasing stress built up from tidal deformation of the Moon [18].

Seismology near the pole: The active and passive seismic experiments of the Apollo Lunar Surface Experiments Package (ALSEP) provided a bounty of information regarding the seismic state of the Moon and its interior structure. Given that no seismometers have been deployed on the lunar surface for over 4 decades and the ALSEP array was powered off in 1977, those data are still being mined as new data analysis techniques are developed. Insights into the structure of the lunar interior come from analysis of ALSEP seismic data, but these results are limited by instrument capabilities (bandwidth) and distribution of seismic stations. The deployment of modern seismic equipment is ultimately necessary to provide fundamentally improved data and constraints on myriad aspects of lunar structure and dynamics, as well as to assess surface characteristics prior to more advanced missions. A seismic station near the south pole can reveal new information about the Lunar interior structure. In particular, if sites of seismic activity active during the Apollo timeframe are still active, then subsurface properties between the south pole and those sites can be determined, and crustal-thickness models calibrated. Furthermore, recordings at the south pole can detect farside moonquakes, if present.

Rugged, cost effective seismic systems: A seismometer based on Molecular Electronic Transducers (MET), which is a robust technology used in terrestrial seismology, uses a fluid within the sensor that responds to seismic accelerations, and measures the seismic accelerations. Because the MET seismometer has been developed specifically for lunar and other planetary applications, it possesses many characteristics that make it ideal for a broad range of lunar seismic studies on higher-risk lander missions or multiple lander missions. The MET sensor has distinct advantages over other seismometer designs, including high shock tolerance, arbitrary installation angle, and excellent ability to survive in challenging environmental conditions, while maintaining high sensitivity and wide dynamic range. Moreover, the instrument has no mechanical moving parts and is easy to fabricate, making it an ideal seismic system for use in any range of lunar missions.

Cost-effective for multi-station deployment: The long-term goal is to have a network of seismic stations monitoring the seismic activity of the Moon. Over time, additions of seismic stations, particularly on the far-side, will improve our ability to locate moonquakes, bolide impacts, and to characterize heterogeneities in the Lunar interior. Therefore, it is advantageous to have a cost-effective instrument so that a large number of seismic stations is feasible and affordable. Current ultra-sensitive planetary seismometers, such as the SEIS-VBB instrument on the InSight mission, require expensive landers for deployment with highly specialized equipment, and deploying even a small network of four stations would require the budget of a Flagship class planetary mission (a few billion dollars). In contrast, the MET seismometer has been designed for simple and flexible deployment, enabling it to be incorporated into a broad range of low-cost Lunar missions with varying deployment strategies or in simple packages that can be deployed by human explorers.

In fact, cost-effective, rugged MET seismometers make deployments of small aperture lunar seismic arrays possible [19]. On Earth, small aperture arrays (~1-5 km station spacing) have been used to study Earth's interior from the uppermost crust to the inner core (e.g., [20]), and are also used frequently for detecting and locating weak seismic sources (magnitudes ≤2.0) over a larger range of distances. The MET seismometer technology allows arrays of 10-20 seismometers to be affordably deployed via both lander and robotic missions. Further, they are simple to deploy, making it possible for human crews to place the array within a short landed mission time frame.

Flexible deployment: With the new focus on the Moon, there will be different types of opportunities for instrument deployments. The MET seismometer is a rugged seismometer that enables flexible deployments with simple requirements, allowing it to be incorporated in multiple types of mission opportunities. For example, as discussed above, it is ideally suited for inclusion into low-cost commercial lander systems. Moreover, its unique feature combination of low power and mass, ruggedized form factor, and its ability to be deployed at any angle make it ideal for future surface packages that can be deployed remotely or by human missions to monitor the Lunar environment.

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