A SEISMOMETER AT THE LUNAR SOUTH POLE. R. Bulow[1] and P. Lognonné[1], [1]Institut de Physique du Globe de Paris, 4 Avenue de Neptune, 94107 Saint Maur des Fossés, France (bulow@ipgp.jussieu.fr).

Introduction: The South polar region of the Moon is currently high on the list of future lunar landing sites [1], and it is likely that a seismometer will be emplaced there [2]. Although a network of multiple instruments is desirable to maximize the scientific return of a lunar seismic mission [3], a single seismometer may still be capable of addressing several questions.

Activity of known clusters: A major discovery of the Apollo-era lunar seismic network was the existence of many deep moonquake clusters (Figure 1), each of which produced unique repeatable waveforms [4]. In the likely event that these clusters are still active, a South-pole seismometer may be able to detect moonquakes originating from these locations. Apollo seismograms from the known distribution of deep moonquakes may correlate with those recorded at the polar station, allowing us to pinpoint the origin of a recorded event without the usual minimum of 4 stations needed to constrain location.

Waveform similarity has been exploited in recent studies to recover previously undetected moonquake signals from the continuous Apollo data through the use of cross-correlation [7]. We can test the likelihood that Apollo seismograms will correlate with those from a polar station by performing correlations between deep moonquake waveforms recorded at different pairs of Apollo stations. For example, if A1 waveforms recorded at station 12 correlate with those recorded at station 15 ($\Delta = 57.3°$), they may also correlate with future seismograms recorded at the South pole ($\Delta = 66.4°$). Unfortunately, preliminary results (computed between a representative A1 event recorded at station 12 and all A1 events recorded at the remaining 3 stations) suggest the correlations will be poor, probably due to site effects unique to each station location. Correlations performed for other clusters may confirm this.

Still, it may be possible to constraint the location of events detected at the South pole using the P- and S-wave arrival times. The S-P arrival time differences can be compared to those predicted from ray theory [8] for the known distribution of deep clusters.

Information on the lunar core: Seismic phases from the lunar core were not observed on Apollo seismograms, in part due to a) the strong scattering of seismic energy in the lunar regolith and b) the limited sensitivity of the instruments. Many deep moonquake signals occurred at or just slightly above the Apollo instrument detection threshold, and if any seismic phases were observed at all, these were typically the main P- and S-wave arrivals. Since the predicted amplitudes of the lunar core phases are many times smaller, the Apollo seismometers could not be used to place a seismic constraint on the size of the lunar core.

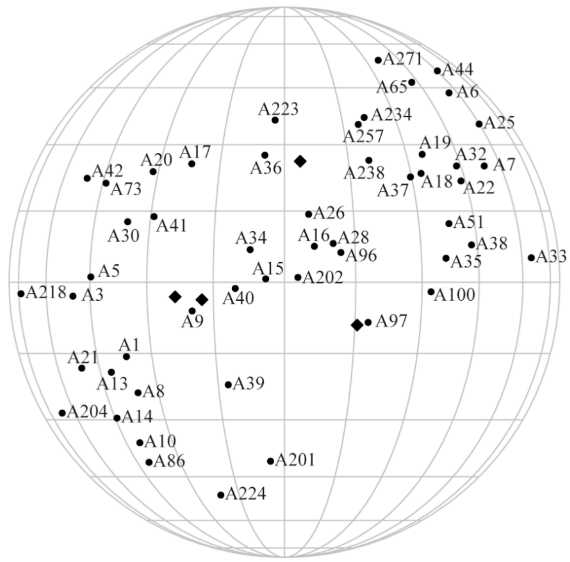

Figure 1: Locations of the 51 deep moonquake clusters [5] consisting of at least 35 events [6], indicated by circles. Diamonds represent, from left to right, the locations of the Apollo 12, 14, 15, and 16 seismometers.

If the effects of scattering can be accounted for, a more sensitive broad-band seismometer such as the SEIS instrument currently in development for the ESA mission ExoMars [9], and easily transferable for use on the Moon, should be able to resolve core phases.

For a known source-receiver geometry, travel times for reflected (e.g. PcP and ScS) and converted (e.g. PKP and SKS, see Figure 2) core phases can be computed using ray theory [8], and their amplitudes can be estimated from synthetic seismograms. We compute synthetics using normal mode seismology. For a given radial model of the Moon's structure [10] we can compute the normal modes of oscillation, assuming a spherical body. The modes are computed using the MINOS code [11], developed for terrestrial seismology and in this case adapted for the Moon. Seismograms for any proposed source-receiver configuration can be computed using normal mode summation, which models the complete seismic wavefield.

We compute all modes in the frequency range 0.2 to 200 mHz. Using the calculated normal mode catalog

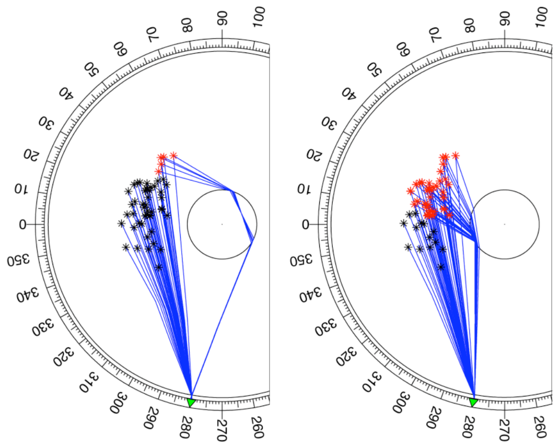

Figure 2: Ray paths for converted core phases from the known distribution of deep moonquakes at a South-polar station. Left: PKP and P. Right: SKS and S.

and a predicted source process, we can compute the synthetic seismograms received at the proposed South-polar station from the known distribution of deep moonquake source regions. The amplitudes of the core phases will depend on the magnitude of the quake and the orientation of the failure plane, defined by the strike, dip, and rake of the fault at depth. Deep moonquake body wave magnitudes have been calculated to fall between 1 and 3 [4,12], with a majority of sources producing quakes falling towards the low end. Fault mechanisms for the deep moonquakes were not obtained from the Apollo seismic network, due both to the low signal level of most deep moonquakes, and the paucity of stations. However, we know from observations of Apollo deep moonquake seismograms that the S-wave amplitude is usually larger than the P wave amplitude. This information may constrain the range of possible focal mechanisms somewhat (Figure 3).

For the deep moonquake cluster A6, using a body wave magnitude equal to 1, strike and dip equal to 45°, and rake equal to 90°, we computed arrival amplitudes for the core phases PcP, ScS, PKP, and SKS by comparing the predicted travel times with the synthetics. We observed that the smallest-amplitude core arrival has an amplitude of 0.02 times that of the S-wave arrival. If we assume that the smallest recordable deep moonquake signal has a maximum S amplitude of 1 DU (digital unit) as measured by the Apollo instruments (correlating deep moonquake signals arriving at the Apollo network have been observed at that level [7]), corresponding to 5.9×10^{-9} cm at a period of 2.2 seconds, then in order to resolve core arrivals at the South pole the SEIS instrument would have to be capable of detecting ground motions

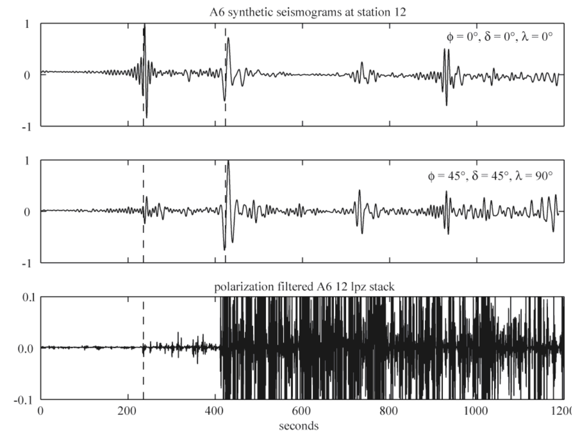

Figure 3: A6 deep moonquake synthetic seismograms for both an unrealistic focal mechanism (top) and one which better reproduces the observed large S- to P-wave arrival amplitude ratio (middle). A filtered stack of actual A6 events is shown for comparison (bottom). The P and S arrivals are indicated by the vertical dashed lines.

of 1.18×10^{-10} cm at 2.2 seconds (approximately 0.5 Hz), which is within design parameters.

By similarly constraining the focal mechanisms of other clusters using the P and S arrival amplitudes observed on the Apollo instruments, we can compute synthetics at the South polar station and examine the likelihood of observing their core phases.

References: [1] Proceedings of the 2007 LEAG workshop. [2] Crawford, I. A., Houdou, B., Kemph, S., Koschny, D., Lognonné, P., Pradier, A., Ricci, C., and Vaujour, P. D. (2008) Abstract *LPSC XXXIX*. [3] Neal, C. R., Salvati. L., Lognonné, P., Banerdt, B., and Nakamura, Y. (2006), *Eos Trans. AGU, 87(52), Fall Meet. Suppl.*, Abstract U44B-06. [4] Lammlein, D. R., Latham, G. V., Dorman, J., Nakamura, Y., and Ewing, M. (1974) *Reviews of Geophysics*, Vol. 12 No. 1 pp. 1-21. [5] Nakamura, Y. (2005) *JGR*, Volume 110 doi:10.1029/2004JE002332. [6] Nakamura, Y., Latham, G. V., Dorman, H. J., and Harris, J. E. (1981) *UTIG Technical Report* 118. [7] Bulow, R. C., Johnson, C. L., and Shearer, P. M. (2005) *JGR*, Vol. 110, doi:10.1029/2005JE002414. [8] Knapmeyer, M. (2004) *SRL* Vol. 75 No. 6. [9] Schibler, P., Mimoun. D., Lognonné, P., Giardini, D., Pike, W. T., and Banerdt, B. (2006), *Eos Trans. AGU, 87(52), Fall Meet. Suppl.*, Abstract P51D-1219. [10] Lognonné, P., Gagnepain-Beyneix, J., and Chenet, H. (2003) EPSL Vol. 211 pp. 27-44. [11] Woodhouse, J. H. (1988) in *Seismological Algorithms*, Elsevier, p. 321-370. [12] Goins, N., Dainty, A., and Toksoz, M. (1981) JGR Vol. 86 pp. 378-388. [13] Lognonné, P., Gagnepain-Beyneix, J., Banerdt, B., Cacho, S., Karczewski, J. and Morand, M. (1996) *Planet. Space Sci.,* Vol. 44 No. 11 pp. 1237-1249.