SEARCH FOR FAR-SIDE DEEP MOONQUAKES — A PROGRESS REPORT. Y. Nakamura, Institute for Geophysics, University of Texas at Austin, 4412 Spicewood Springs Road, Bldg. 600, Austin, TX 78759-8500; yosio@utig.ig.utexas.edu.

Introduction (Why Search Now?): A truly unexpected finding of the Apollo missions, 1969-1972, was a discovery of deep moonquakes. Analysis of the data from the seismic network, which operated for eight years from 1969 through 1977, identified more than 100 discrete source regions at depths approximately half way to the center of the moon. Their distribution, however, was not uniform, as all but one of the source regions found were on the front hemisphere of the moon [1]. Thus, a question remains whether the observed one-sided distribution of deep moonquake sources represents their true distribution or instead occurs because all seismic stations are on the near side of the moon. If it is the former, it means that the interior of the moon is truly asymmetric, structurally and dynamically; if it is the latter, it means that we simply did not identify most moonquakes on the far side and that their identification will be a great help in investigating the deep interior of the moon, including existence of a possible metallic core.

There is a reason to believe that the latter is the more likely explanation. The deep interior of the moon, below the level of deep moonquake foci, appears to be partially molten, thus preventing transmission of seismic shear waves [2]. Without clear shear-wave arrivals it is extremely difficult to identify deep moonquake signals visually, which was the only practical method available to us in our earlier analysis. This is because most of the deep moonquake signals were identifiable by their clear shear-wave arrivals, distinct from those of surface impacts, and by their nearly identical waveforms as they occur repeatedly at near-monthly intervals. Of 12,558 seismic events detected on the long-period instruments during the eight years of observation, 1359 events were positively identified as deep moonquakes and 9129 events were left unidentified in our original analysis [3]. The remaining 2070 events were identified either as meteoroid impacts (1744), shallow moonquakes (28), artificial impacts (9), or certain others (289). We considered cross-correlating waveforms of all unidentified events to find more deep moonquakes, but this was beyond the capability of the computer facilities available to us at the time.

A recent advancement in computer technology has removed this obstacle. Simultaneously storing a large quantity of data on a hard disk and performing a cross-correlation analysis of them all are now well within the capability of a modern desk-top workstation. Thus, we have started to perform this analysis to complete the identification of previously unidentified events, some of which may well be of deep moonquakes originating from the far side of the moon. Obserst and Mizutani [4] reported an initial result of such an analysis for the Apollo 12 station data last year. We have now completed the cross-correlation of the entire long-period data set, and are in the process of locating the newly identified groups of deep moonquakes to see if any of them are on the far side.

New Computational Approach: The approach we took was a combination of cross-correlation of seismic waveforms and single-link analysis. The data, which were originally on more than 10,000 7-track magnetic tapes, had already been transferred to eighty 8-mm video cassette (Exabyte) tapes with support from the Institute of Space and Aeronautical Science (ISAS) of Japan [5]. This data set is now available from IRIS Data Management Center.

For each of the deep moonquake and previously unidentified events mentioned above, we first selected an 800-sample (~2 min.) time window using an event detection scheme base on long-term/short-term average amplitudes of the long-period wave train. Then, we cross-correlated this waveform with the waveform of every other event with a sliding time window of ±800 samples, searching for the maximum value of cross correlation. This formed the basic set of cross-correlation coefficients involving all possible pairs of events at each of the four stations.

Next we used single-link cluster analysis [6] to classify events into groups. This is based on the premise that the greater the cross correlation coefficient the shorter the distance separating the events. A threshold to separate dissimilar groups was chosen to conform generally with the original deep moonquake classifications when they existed.

The analysis was not devoid of problems. The data set is contaminated with numerous 'glitches,' large transient noises that were likely caused by sudden tilt of the instrument due to temperature changes. These glitches were easy to ignore when we were visually analyzing the data, but the computer is not so forgiving, and an appropriate measure must be devised to deal with such problems. We have tried matching filters to remove them with limited success.

Single-link cluster analysis often links more than one cluster through some weakly linked members that do not really belong to either of the clusters. Often a glitch mentioned above may act as a bridge to connect two dissimilar groups. To avoid this problem, after a group of linked events was found with the cluster analysis, we searched for a subgroup of events that were linked at a high degree of correlation to all others, stacked their waveforms to form a reference waveform, and then computed its cross-correlation with each of the entire set of events to find events belonging to the group. If a significant number of events were left in the originally linked group after going through an initial subgrouping, the process was repeated with the remaining events to find additional subgroups. This was to assure no significant groups were left undetected through the process.

Results to Date: The new computer-based approach has resulted in identification of many more deep moonquake events than previously known. Table 1 below summarizes the number of events thus identified.

Table 1. Number of events identified as deep MQ

Original catalog [3]			
Positively identified as deep MQ	1,359		
Unidentified	9,129		
Suspected of being deep MQ		1,787	
Others		7,342	
New identification			
Identified as deep MQ	7,245		
at multiple stations		5,825	
in previously know source regions			3,956
in new source regions			1,869
at a single station		1,420	
Remain unidentified	3,267		

The number of identified deep moonquakes has increased from 1359 to 7245, a more than five-fold increase. 3956 of the 7245 events are associated with previously identified deep moonquake sources, A1-A114, nearly a three-fold increase for these alone. The remaining 3289 events are from previously unknown sources. Of these, 1869 events are observed at more than one station, and they are now determined to be originating from 88 newly identified source regions. The remaining 1420 events are classified into more than 150 groups, but since each of them was observed at a single station their source locations cannot be determined.

The new cluster analysis shows that several groups originally thought to be of different source regions are identical to each other. This has reduced the number of previously known source regions to 77. Also several cases have been found where two or more groups are partially related. One might say that they are close neighbors.

Another interesting finding is that there is a continuous range of values of cross-correlation coefficients among events of any given group. This was not obvious when we were visually matching the event waveforms, but with the greatly expanded data base for any given group, as inferred above, this is not unexpected, and leads us to question validity of our earlier result that the spatial extent of A1 source region is no more than 1 km in radius [7]. This problem must be studied in more detail in the future.

The updated Passive Seismic Experiment long-period event catalog, levent.1102, is available from our public ftp site: ftp.ig.utexas.edu/pub/PSE/catsrepts.

Current and Future Plans: We are currently working on locating the newly identified source regions. Before proceeding with this, however, we need to stack all matched waveforms to enhance the signal-to-noise ratio so that seismic arrival phases can be picked with increased certainty.

Waveforms of some of the newly identified groups look very similar to those of A33 events, the lone far-side source previously identified, with no clear shear-wave arrivals at some stations. Thus, it is likely that some of the newly identified groups did originate on the far side of the moon. This, however, must be proven with reliable location of these sources.

Once far-side sources are identified, the next step will be to use these signals to infer the deep interior of the moon.

Acknowledgements: I appreciated many stimulating discussions I had with my colleagues, in particular, Cliff Frohlich of UTIG, Jürgen Obserst of DLR and Junji Koyama of Hokkaido University. This material is based upon work supported by the National Aeronautics and Space Administration under Grant No. NAG5-11619 issued through the Office of Space Science.

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