

THERMAL MOONQUAKE LOCATION ALGORITHM AND ANALYSIS. D. Phillips¹ and R. C. Weber²,
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Introduction: Thermal moonquakes are small amplitude events that are produced by diurnal temperature changes near times of sunrise and sunset on the Moon, likely representing a physical process in the shallow regolith. Finding the physical locations of thermal moonquakes will lead to more information about lunar surface processes. For example, if thermal moonquakes are co-located with rocks, this could be an example of thermal stresses causing physical breakdown in rocks, forming lunar regolith over millions of years.

Thermal moonquakes have been observed at Apollo 12-17, but have not been studied intensively due to difficulty in locating the events. To locate an event, at least three data points are needed to perform a triangulation search. Apollo 12, 14, 15 and 16 only had one seismic instrument at each site located ~1,000 km away from each other. A thermal moonquake seen at one station could not be seen at another station due to the large distance and small amplitude of the event. The Lunar Seismic Profiling Experiment (LSPE) on Apollo 17 was different as it had a local network of four different geophones located ~100 meters apart (Figure 1).

LSPE consisted of both an active source and passive source experiment. The primary goal of the experiment was to use eight explosive packages (EPs) deployed by the astronauts to characterize the upper structure of the Moon's crust. After the astronauts left the Moon, the

charges were detonated, providing an active source seismic experiment. Four of the eight EPs, the four geophones, and the lunar module are shown in Figure 1. The secondary goal of the experiment was to provide passive measurements from the four geophones. Duennebier studied the origin of thermal moonquakes using a partial LSPE dataset and concluded they originated from the lunar module, geophone rock, and nearby craters [2]. However, lack of modern technology limited his analysis to inferring event location only using waveform amplitudes.

Most of the passive data were lost in storage until a few years ago [3]. With updated technology, we can apply modern location techniques using waveform arrivals. In initial analysis of this recovered dataset, we discovered that each geophone recorded thousands of thermal moonquakes that appear on all four geophones within several seconds of each other [4]. In addition, we can identify event arrivals to locate the events and better understand the origin of thermal moonquakes.

Location Algorithm: We locate events by minimizing the misfit between the known travel time of the event and a theoretical travel time calculated in a known velocity model using ray tracing. We identify the range of acceptable locations by calculating the 95% chi-squared confidence level. The shallow surface velocity model (shown in Table 1) is based on updated geophone coordinates using LROC imagery [1], new analysis of EP travel times [5], and a regolith layer [6]. We also calculate the best-fitting origin time of each event. Once the location of an event is found, we can plot the position on the Apollo 17 LROC landing site image to determine whether surface features correspond to the recovered location.

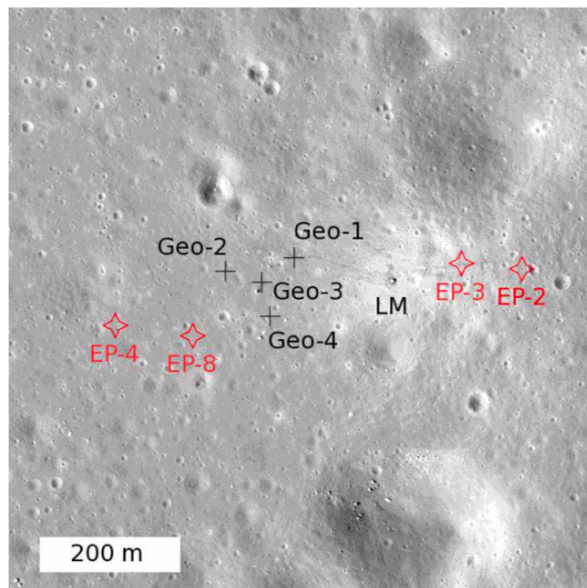


Figure 1: Apollo 17 EP 2, 3, 4, and 8 (red diamonds) locations with the LSPE geophones (black plus) and the lunar module [1].

Table 1: Near-Surface Surface Velocity Model

Depth	P-Wave Velocity (m/s)
0-4 m	100 m/s
4-96 m	285 m/s
96-773 m	580 m/s
773 m-2 km	1825 m/s

To verify the location model, we needed a known event location from Apollo 17. If the location model can accurately predict the actual location of different EPs from the LSPE active data, then it can be used to find the location of thermal moonquakes. We implemented a

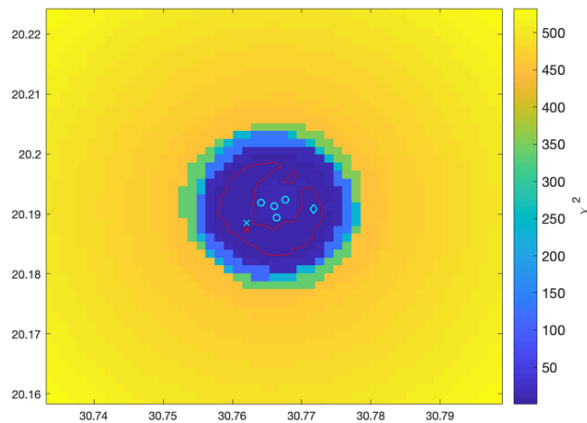


Figure 2: EP 8 location. Light blue circles are the geophone locations, light blue diamond is the lunar module, light blue x is the known location of the EP, and red x is the modeled location. The red contour represents the 95% chi-squared confidence level.

similar approach as the passive data from Apollo 12-16 to better identify arrival times of the EPs using the raw data, a bandpass filter, and a polarization filter [7]. The location of EP 8 is shown in Figure 2. The actual location and the model location are within the same 40 meter grid cell verifying our location algorithm.

Location Analysis: Using a full lunation, or month of data, a complete picture of locations as a function of time, and velocities as a function of location, will help us better understand the origins of thermal moonquakes. A preliminary event recognition algorithm performed on the continuous data suggests three different types of events: impulsive, intermediate, and emergent, each having a distinct waveform occurring at different times within the lunar diurnal cycle [4]. Impulsive events occur almost exclusively at sunrise when the temperature is beginning to rise, while emergent events occur more broadly around lunar sunset. We are interested in determining whether event type depends on the distance from the array. One working hypothesis is that impulsive events are closer to the array while emergent events are further away. Additionally, we are interested in determining spatial patterns in sunrise and sunset event locations.

Preliminary analysis of the LSPE data not only led to the discovery of three different types of events, but also two enhancements of events after sunrise separated by 10 hours. One proposed hypothesis is the first enhancement is a result of thermal “pinging” in the metal of the lunar module (which has a lower thermal inertia and thus heats up faster), while the second enhancement is pinging in the rocks and regolith surrounding the landing site. The cyclic thermal stresses induced in the rocks as they endure repeated diurnal temperature

swings may be causing small cracking events that manifest themselves as thermal moonquakes [8]. This hypothesis can be tested by associating the locations of the events with actual features on the Moon. A proof-of-concept study was performed on 30 sample events with the locations shown in Figure 3. The sample events were constrained to the surface with a standard 1 second misfit shown. Using our verified location algorithm, we want to find the locations of a full lunation of thermal moonquakes with better approximations. This will lead to a more complete picture and understanding of what is happening at the Moon’s surface.

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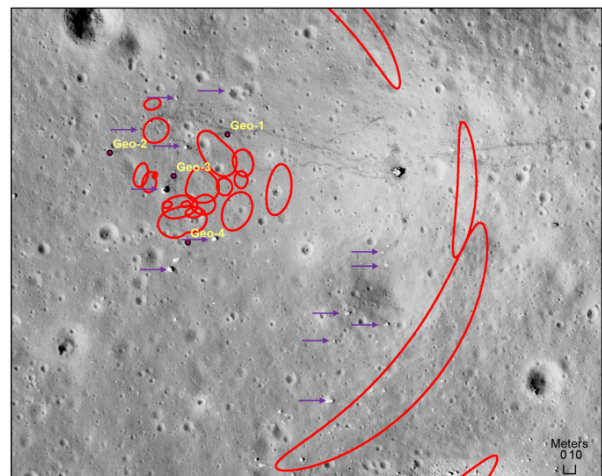


Figure 3: Sample locations with confidence contours overlaid on LROC image of thermal moonquakes with rocks indicated by purple arrows [9].