Reanalysis of the Active Seismic Experiments performed on the Moon during Apollo 14 and 16 Missions.

Chloe Helene Martella[1*], Sebastian Emanuel Lauro[1], Elisabetta Mattei[1], Barbara Cosciotti[1], and Elena Pettinelli[1]

[1]Mathematics and Physics Department of Roma Tre University, Roma 00146, Italy.

*chloe.martella@uniroma3.it

Introduction: Robotic and human Moon exploration is currently living a new renaissance, as it is considered a benchmark for future human expansion in the Solar System. Many space agencies and private companies are developing strategies to bring the man back on the Moon by the end of this decade. This new international race will be driven by scientific, technological, and economic interests, and will require an in-depth understanding of the Moon subsurface environment. Several new geophysical instruments have been proposed to explore the Moon subsoil at different spatial scales. Amongst these, active seismic methods (reflection and refraction) are two of the most reliable techniques to investigate the lunar shallow stratigraphy. Indeed, refraction seismic technique was already tested during Apollo14, Apollo16 and Apollo 17 missions, providing some information on the thickness and the mechanical properties of the lunar regolith at the three landing sites. In this work we present a reanalysis of the Active Seismic Experiments (ASE) conducted on the Moon during Apollo 14 and 16 missions. We analyzed all data collected along the seismic lines using the thumper source and we applied modern seismic attributes approach [1] to better perform the first arrival picking. Conversely to previous works that used the LM ascent impacts and grenades, we were able to detect for both sites the direct and the head waves only using the thumper shots and compute the compressional wave velocities for the first and second layer. Finally, we compared our results with those published in previous works.

The ASE thumper operation: For each mission, the operation was originally designed with 21 explosive charges, also known as Apollo Standard Initiators (ASI's). The explosive charges were mounted inside a thumper device and detonated by the astronaut into an aluminum plate located on the ground. The thumper device was also provided with a pressure switch, to set the initial time of each detonation [4]. Three geophones were mounted at 45.72 m intervals and the explosive charges were detonated at 4.572 m intervals, parallel to the line of geophones. Due to malfunctioning of the thumper, only 13 shots were actually detonated during Apollo 14 mission and 19 during Apollo 16 mission.

Data and Methods: Unfiltered seismic signals are affected by large noise, especially when the first layer is made of loose material; this condition makes the picking of first arrival times rather difficult. To improve the S/N ratio, we first analyzed the frequency content of the seismic signals using the Fast Fourier Transform (FFT) and the Stockwell Transform, then we applied a Butterworth Bandpass 8-pole filter (7÷40 Hz). Arrival times were selected through two different methodology. In the first method (M1) we picked the arrival time as the first break (i.e., the maximum amplitude of the signal) on the filtered traces. In the second method (M2) we computed the instantaneous amplitude of the filtered seismic trace using the Hilbert transform and we picked the arrival time as the onset on the envelope. For both landing sites we assumed a simple model with flat layers having uniform seismic velocity [2]. This model is considered a good approximation when source and receiver are relatively close to each other (distance lower than a few km) and is valid for the ASE experiments where the distance between the thumper and the geophones was varied between 0 and 91.44 m. The velocity for the direct and head waves were computed applying a linear fit to the arrival times plotted as a function of distance, and the depth of the first layer was determined through seismic refraction theory [2].

Results: Applying both methods (M1 and M2) to the Apollo 14 data, we were able to pick the arrival time of the direct wave, up to 30 m distance between source and receiver, at all three geophones. Conversely, the head waves were only detectable on the traces recorded at geophone 2 for the thumper shots detonated on the left of the geophone (G2L). For the Apollo 16 data, the first method (M1) allowed us to detect the direct arrivals for the first 30m of the seismic line. However, no head waves could be picked with such method. On the contrary, using the second method (M2) we were able to pick the head waves arrival times on all three geophones. Note that for Apollo 16 data, the head wave arrival times were never be detected before on the thumper traces, but only on the Lunar Module (LM) ascent and grenades seismic records [3],[5]. Table 1 summarizes the velocities calculated at the three geophones using method M1 as well as an average value computed for the direct and head waves using M1 and M2 data sets (Table 2). According to M1 data, at the Apollo 14 landing site the depth of the first layer is located at 9.2 ± 0.9

m whereas nothing can be said for the Apollo 16 landing site. Combining both datasets, the depth of the first layer at the Apollo 14 landing site is a bit smaller, 7.5 ± 0.7 m, and quite similar to that of the first layer at the Apollo 16 landing site, 7.8 ± 0.8 m. Previous works [3] estimated for the first and second layers at the Apollo 14 landing site a velocity value of 104 m/s and 299 m/s, respectively. From these data the thickness of the first layer was computed as 8.5 m. For the Apollo 16 landing site, such velocities were estimated as 114 m/s and 250 m/s, with a first layer thickness of about 12.5 m. [5].

M1	*Apollo14*		*M1*	*Apollo16*	
Geophone	v_0 *(m/s)*	v_1 *(m/s)*	*Geophone*	v_0 *(m/s)*	v_1 *(m/s)*
G1	100 ± 5	-	G1	113 ± 5	-
G2L	113 ± 5	241 ± 12	G2L	108 ± 5	-
G2R	91 ± 4	-	G2R	100 ± 5	-
G3	100 ± 5	-	G3	116 ± 5	-

Table 1 Direct and head wave velocity v_0 *and* v_1 *evaluated for ASE data through method 1 (M1). Results for Apollo 14 on the left and for Apollo 16 on the right side.*

	M1+M2	
Mission	v_0 ***(m/s)***	v_1 ***(m/s)***
Apollo 14	100 ± 5	267 ± 13
Apollo 16	110 ± 5	290 ± 14

Table 2 Average value of direct and head wave velocity obtained combining data sets from M1 and M2 at Apollo 14 and 16 landing site.

References: [1] Al-Mashhor et al. (2019) *IEEE Access* 7:128806-128815. [2] Stein et al. (2003) *Blackwell Publishing Ltd*, USA. [3] Cooper et al. (1974) *Rev. Geophys. Space Phys*. 12.3, 291-308. [4] McDowell (1971). *Bendix Tech. J. 4*, 40-51. [5] Kovach et al. (1972) *Nasa Sci. Tech. Inf. Office*: 10, 1-14.