Echoes from the Moon

Luca Girlanda

INFN, Sez. di Pisa, Largo Filippo Buonarroti, I-56127 Pisa, Italy

and Liceo Scientifico "E. Fermi", Via Enrico Fermi 2, I-54100 Massa, Italy *

(Dated: March 19, 2009)

We report on a determination of the Earth-Moon distance performed by students of an Italian high school, based on measurements of the time delay of the "echo" in the radio communications between Nasa mission control in Houston and the Apollo astronauts on the lunar surface. By using an open-source audio-editing software, the distance can be determined with three digits accuracy, allowing to detect the effect due to the eccentricity of the orbit of the Moon.

I.   INTRODUCTION

How far is the Moon? A possible answer to this question can be given knowing the Moon diameter, which may be found to be about 2/7 of the Earth diameter from the duration of a lunar eclipse, cfr. Refs.[1,2,3]. Dividing by the angular width, about half a degree, one finds about 60 times the Earth radius, a result which is considered to lie at the foundation of the Newtonian inverse-square law of gravitation, since the lunar centripetal acceleration is found to be 3600 times smaller than g.

Nowadays the Earth-Moon distance d_{EM} is constantly monitored, since the first experiment on August 1st 1969[4], by measuring the time of flight (about 2.5 s) of a laser pulse which is directed from Earth towards an optical retroreflector array placed on the lunar surface during the Apollo 11 mission. In this note we report on a measurement based on the same principle, using instead the delay in the communications between NASA mission control in Houston and the Apollo astronauts on the lunar surface. This activity was carried out by students of an Italian high-school (age range 14-19), by analyzing conversations between the astronauts and mission control. These conversations were recorded by NASA and are available from NASA's web site[5].

Students were divided in 10 groups of two or three. A first round of measurements was performed with chronometers, by listening to the conversation with Neil Armstrong during

the Apollo 11 mission, during which the famous sentence "one small step for man, one giant leap for mankind" can be heard. The 10 groups were provided with the tapescripts and they measured the delays in Houston's and Armstrong's replies, as shown in Table I. Only the delays in Armstrong's replies are affected by the time of flight of the radio signal, since the tape was recorded at Houston. From the minimum delay in Armstrong's replies (last column of the 2nd row) an upper bound for the Earth-Moon distance was found, $d_{\mathrm{EM}} < (4.5 \pm 0.7) \cdot 10^8$ m.

Replies from	Time delays (s)						
Houston	1.55 ± 0.15	0.35 ± 0.15		1.35 ± 0.25	1.7 ± 0.2	0.85 ± 0.15	
Armstrong			4.05 ± 0.25				3.0 ± 0.2

TABLE I: Time delays of the replies in the 3-minutes conversation between Houston and Armstrong during which the famous sentence "one small step for man, one giant leap for Mankind" can be heard. The errors represent the ranges of values measured by the 10 groups of students with chronometers. The very short delay in the 2nd column corresponds to a radio check requested by Armstrong and promptly replied by Houston. The mp3 file of this famous conversation is available at the NASA web site[7].

It came as a surprise that sometimes a clear echo of the sentences from the Earth was audible, due to the retransmission of the signal from the speaker through Armstrong's microphone. In such cases a much more accurate measurement of the time of flight of the radio signals is possible with the help of audio-editing software.[14] This allows for a very precise determination of d_{EM}.

II.   DATA ANALYSIS

We have used Audacity[6], a freely available open-source program, running under Windows, Mac OS X and GNU/Linux operating systems. This software allows to visualize the level of audio output as function of time, with the time scale arbitrarily adjustable. In this way the time windows of single syllables and of their echoes can be clearly identified and isolated. We have singled out the word "over" in the sentence "Columbia, Columbia, this is Houston, AOS [acquisition of signal], over", at 110h:07m:58s from ignition time, for which a clear echo was audible, cfr. Fig. 1.
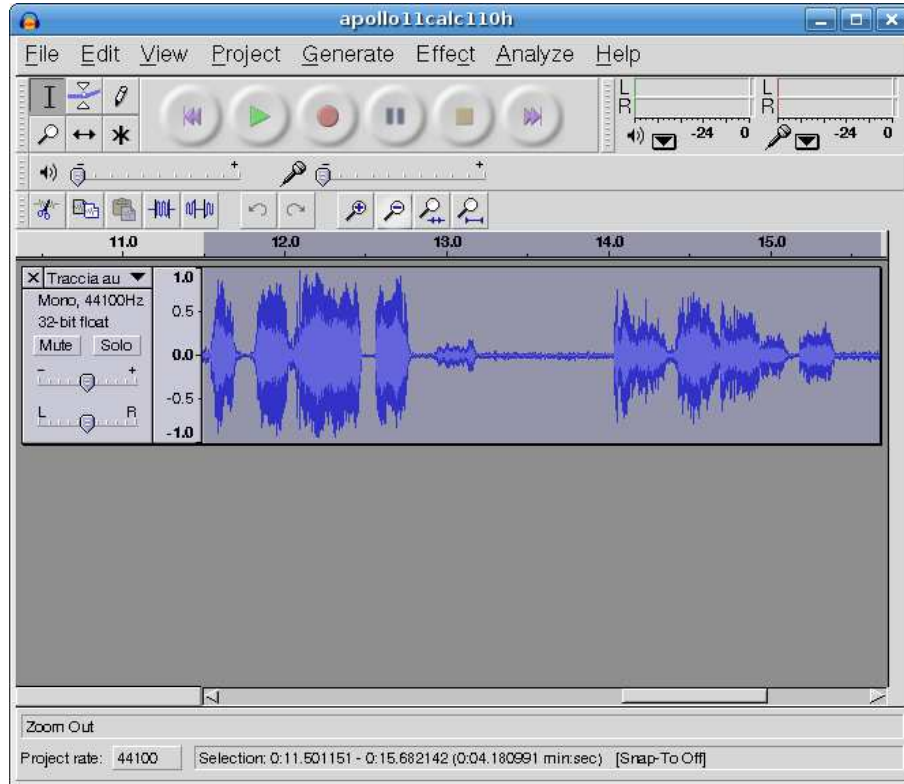
FIG. 1: Audio output of the words "... Houston, AOS, over", as displayed using the opensource software Audacity[6]; the pattern clearly reveals the echo effect. The small signal at about 13 s is a beep ("Quindar tone") used to trigger ground station transmitters. The time scale can be arbitrarily expanded allowing an accurate determination of the echo delay.

Several methods of measurement of the time delay of the echo can be adopted and the students were given freedom to devise the more appropriate one: some chose to mark the times at the beginning or at the end of the syllables, others at the maximum of the signal within a syllable. Each measurement has an associated uncertainty, that the students were asked to estimate as well. For instance, the duration of a syllable and of its echo can be measured, and the difference be taken as an estimate of the uncertainty. Specifically, four groups chose to use the beginning of the word "over", three the end of the same word, and three the maximum of the audio signal within the word, the uncertainties associated to the latter method being however substantially larger. As a final result, without affording a thorough statistical analysis, students agreed to take the average of the 10 measurements with the maximum shift from average as uncertainty, $\Delta t = (2.620 \pm 0.007)$ s. This translates into $d_{\mathrm{EM}} = (3.93 \pm 0.01) \cdot 10^8$ m, quite an accurate measurement. The above error estimate is

clearly larger than what would be obtained by a correct statistical treatment of the data: the standard deviation of the 10 measurements is ~ 0.005 s, and therefore the predicted standard deviation of the mean is ~ 0.002 s. A maximum likelihood fit to the 10 measurements would yield instead $\Delta t = (2.616 \pm 0.001)$ s, where the central value is the weighted average and the error corresponds to an increase of the χ^2 by 1; correspondingly, $d_{\rm EM} = (3.921 \pm 0.002) \cdot 10^8$ m.

Which number one has to compare to? At this level of accuracy one should be able to detect several effects, such as the variation of $d_{\rm EM}$ due to the ellipticity of the orbit (up to $5 \cdot 10^6$ m per day). This has been the second task of our activity. To this aim we have chosen to analyze the Apollo 17 mission, which lasted longer than all the others, about 300 hours. Special attention had to be payed to the fact that even the Earth rotation would affect the measurements. One way to isolate the effect due to the eccentricity of the orbit is to take measurements at 24h-separated times (or rather at 24h50'-separated times): at intermediate times radio signals were probably following different paths.

III. RESULTS

We have identified three sentences with a clear enough echo, which at the same time almost satisfied the 24h separation constraint. Our measurements of the minimum time delay of the echoes are reported in Table II. The corresponding values of $d_{\rm EM}$ are plotted in

word	time (hh:mm:ss)	delay (s)		time shift (s)
"Houston"	117:03:11	2.62 ± 0.02	2.617 ± 0.006	0.043 ± 0.006
"Geno"	141:24:11	2.565 ± 0.006	2.568 ± 0.002	0.034 ± 0.002
"three"	166:06:22	2.53 ± 0.03	2.526 ± 0.006	0.030 ± 0.006

TABLE II: Time delays of the echoes during the radio communications of the Houston mission control with the Apollo 17 astronauts on the Moon. The delays were measured by 10 groups of students. In the 3rd column the average of the 10 measurements is shown, with the error representing the maximum deviation from the average. A more proper statistical treatment of the data (maximum likelihood fit, as explained in the text) would yield the results in the 4th column. The times in the 2nd column are counted from "ignition time". In the 5th column we show the differences of the times in the 4th column with the Moon ephemerides[10]. The mp3 files of the registration are available at the NASA web site[7].
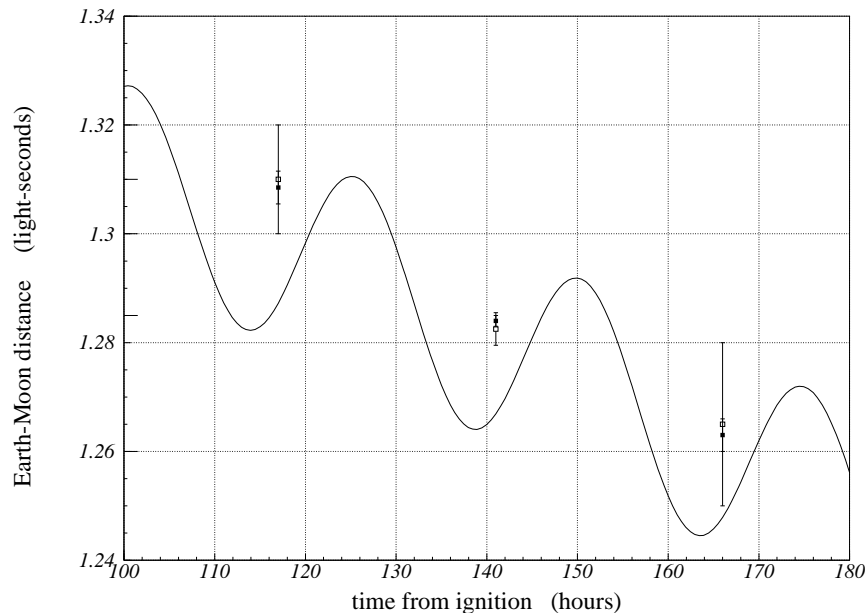
FIG. 2: Distance between Houston and the astronauts on the Moon in light-seconds. Data points correspond to our measurements, i.e. the values in Table II divided by 2. Empty squares are the students' results (3rd column of the Table), filled squares (with much smaller error bars) are from the 4th columns. The curve is obtained by using the Moon ephemerides[10] and refers to the distance between Houston and the Moon center.

Fig. 2.

Also shown for comparison are the lines from the Moon ephemerides, calculated with the JPL HORIZONS system[10], setting as location the geographical coordinates of Houston, latitude $29°45'26''$ N, longitude $95°21'37''$ W; to this aim one can also profitably use the opensource program Stellarium[11], which yields the same results and is much more fun for students. The zero of the time axis is the "ignition time" for the Apollo 17 mission, 5:33:00 a.m. (GWT) on December 7th 1972.

It can clearly be seen that our measurements follow the decrease of the Earth-Moon distance, with a shift of about 0.017 ± 0.001 s (half of the values in the 5th column of Table II), to be ascribed to the delay in electronics and other systematic effects. One such effect is the fact that the radio signal did not follow a straight line from Houston to the Moon surface. Indeed, according to the report on the Apollo radio communication system[12], three main ground antenna were used during the lunar phases of the missions, which were

situated in Goldstone (California), Canberra (Australia) and Madrid (Spain), the closest one to Houston being 2100 Km far. This produces a delay of at least 0.007 s. An additional delay, possibly of the same order of magnitude, could be due to the fact that the radio signal was probably transmitted from the receiving antenna to Houston through a satellite. It should also be noted that the Moon ephemerides give the distance of the center of the Moon from Houston, while the astronauts were on the lunar surface (at about $\sim 20°$ North latitude, $\sim 30°$ East longitude[13]), which is ~ 1500 Km closer to Houston than the center of the Moon. All these effects, which in some case, however, tend to compensate one-another, are of the same order of magnitude as the observed shift.

IV. DISCUSSION

The experiment that we have reported represents an exemple of "open" research-oriented activity, in which no "correct answer" can be anticipated *a priori*. This aspect should be emphasized whenever possible in the teaching of physics, since it gives students the flavor of what physicists do in their experimental or theoretical work. Another aspect of our experiment - common to most of present-day experimental research in physics - is the analysis of raw data (in our case the audio registrations) by means of sophisticated software, which gives the opportunity to extend the discussion on the "error sources".

The students have very much appreciated the use of open-source software that they could easily install in their computers at home, especially the program "Stellarium", which simulates the appearance of the sky at all times and from every location.

In summary, the reported activity has constituted an important cultural achievement for the students: for interdisciplinary reasons -the study of the Apollo missions, one of the most fascinating accomplishements of mankind, the use of English as a foreign language - but also for reasons more proper to physics - the ellipticity of Kepler's orbits, the invariance of the speed-of-light as foundation of the experiment, the propagation of sound and of electromagnetic waves. Not to mention the thrill for measuring a shorter time delay than allowed, which would constitute a planetary scoop as evidence in favor of much popular "conspiracy theories" about Apollo missions.

Acknowledgments

It is a pleasure to thank Prof. L. Bracci for a careful reading of the manuscript, Prof. M. Coluccini and Dr. U. Penco for inspiring discussions, the students of 1SD and 1SE (year 2005/2006) of Liceo Scientifico "A. Vallisneri" (Lucca, Italy) for their involvement and enthousiasm, and an anonymous Referee for helpful suggestions. This activity was performed within the "Progetto Lauree Scientifiche", of the Italian Ministry of Education.

---

* Electronic address: girlanda@pi.infn.it

[1] E. M. Rogers, "Physics for the inquiring mind; the methods, nature, and phylosophy of physical science", Princeton University Press, 1960, chapter 14.

[2] E. Roger Cowley, Am. J. Phys. **57** (1989) 351.

[3] David H. Bruning Am. J. Phys. **59**, (1991) 850.

[4] J. Faller *et al.*, "Laser Beam Directed at the Lunar Retro-Reflector Array: Observations of the First Returns", Science **166** (1969) 99.

[5] http://www.hq.nasa.gov/alsj/frame.html

[6] http://audacity.sourceforge.net

[7] http://history.nasa.gov/alsj/a17/a17.html

[8] D. Keeports, Phys. Teach. **44** (2006) 414.

[9] F. Glick, Am. J. Phys. **40** (1972) 1867.

[10] J.D. Giorgini *at al.*, "JPL's On-Line Solar System Data Service", Bulletin of the American Astronomical Society **28** (1996) 1158; http://ssd.jpl.nasa.gov/?horizons

[11] Stellarium 0.8.2, http://www.stellarium.org

[12] K.E. Peltzer, "Apollo Unified S-Band System", Goddard Space Flight Center, 1966, available at http://history.nasa.gov/alsj/TM-X55492.pdf

[13] Apollo 17 Mission Report, available at http://history.nasa.gov/alsj/a17/A17_MissionReport.pdf

[14] The same observation was made in Ref.[8] and used to estimate the speed of light, see also Ref.[9].