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LUNAR LASER RANGING EXPERIMENT - A JOURNEY TO THE MOON AND BACK

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Abstract

The Moon has played an important role throughout the development of human civilization. It is the only permanent natural satellite of Earth and the closest astronomical object in the universe. Between the years of 1969 and 1971 the American and Soviet space programs left a total of five retroreflectors on the lunar surface. Astronomers have been able to use powerful lasers and telescopes to perform highly accurate measurements of the distance to these artifacts. The data that have been collected have led to significant improvements in the understanding of some aspects regarding the Earth-Moon system. Lunar Laser Ranging (LLR) has influenced astronomy, lunar science, gravitational physics, geodesy, geodynamics and numerous other fields. The purpose of this research is to state the historical development of Lunar Laser Ranging, what is involved in this process, the scientific accomplishments and the importance of this experiment for future explorations.

Key words: *Apollo missions, Earth-Moon distance,Lunar Laser Ranging, retroreflector.*

INTRODUCTION

The Moon has always been fundamental to the understanding of the universe.The first attempt to determine the distance to the Moon was made over 2000 years ago by the ancient Greeks.In order to do that, they had to measure the Earth.

Eratosthenes, the Greek philosopher,discovered that during the summer solstice the Sun shone directly down a well in the city of Syene at noon and, at the same time, it was not shining straight down in Alexandria. He was able to measure that angle.

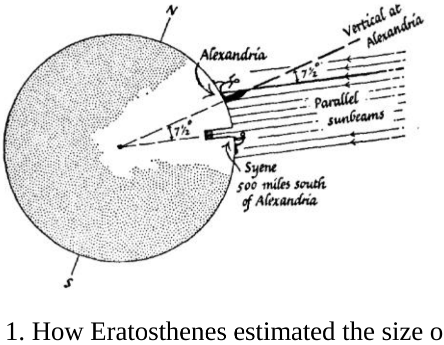

Figure 1. How Eratosthenes estimated the size of the Earth

The legend says that he paid someone to walk the distance between the two cities in order to find the distance between them. But probably he just used the numbers found by earlier surveying missions.

Once he knew the distance and the angle, he calculated the Earth's circumference with the use of geometry. His result was very close to the actual dimension. It was the first time humans had determined a scale to the Universe.

Once the dimension of Earth was known, other distances could be found. For example, during a lunar eclipse, the shadow of the Earth is cast on the Moon. The curve of the Earth's edge can be seen as the shadow moves across the Moon. Simply by knowing the Earth's size, and with the use of geometry, we can determine the distance to the Moon. Also, the phases of the Moon depend on the angles and distances between the Earth, Moon, and Sun.

Using the size of the Earth as a stepping stone, Aristarchus of Samos was able to calculate the distances to the Moon and the Sun as well as their sizes. The accuracy of his measurements was not the best, but his methods were important, and they were used later by great thinkers like Ptolemy and Hipparchus to increase the accuracy of size and distance measurements.

Aristarchus developed an ingenious method to calculate the Earth-Moon distance by using the principle of parallax. The term comes from Ancient Greek παράλλαξις (parallaxis), which means ‘alteration’. It is defined as the effect whereby an object seems to have different positions or directions when viewed from different agles.

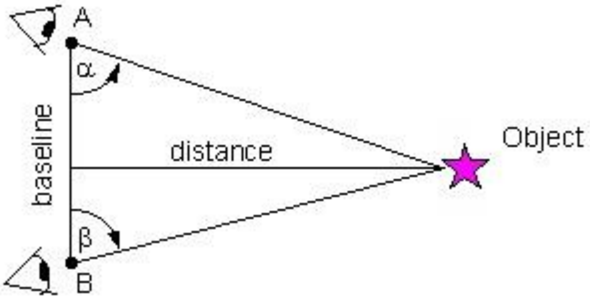

Figure 2. A representation of the principle of parallax

For example, because humans have binocular vision, when we look at a nearby object, the left eye sees it at a slightly different angle than the right eye. The brain overlays the images and gives us the sense of distance to that object. This is called depth perception. The focused object seems to alter its position relative to more distant objects. That shift is called parallax. The amound of shift is given by the distance between your eyes and the distance to the object.You can determine the distance to the object if you know the distance between your eyes. If the object is closer, it shifts more; if it is farther, it shifts less.

The Moon is beyond the limit of our eyes. If we want to measure the distance to the Moon using parallax, we need a bigger baseline than the few centimeters between our eyes.

MATERIALS AND METHODS

R. H. Dicke, professor at Princeton University, and a few of his colleagues, started in the late 1950’s the lunar laser ranging experiment in the gravitational research program. They had in mind to use a very dense artificial satellite orbiting in high altitude, to search for possible slow changes in the gravitational constant G by precision tracking. Another method they thought of was to place retroreflectors on the satellite and pulsed searchlight illumination from the Earth. This method would determine the angular motion with reference to the stars. With the creating of the first ruby laser in the 1960, it became more and more clear that the accuracy of laser range measurements to retroreflectors placed on satellites would be greatly improved.

Within the Apollo project and the Ranger missions in 1962, there was a proposal to place a retroreflector on the moon’s surface, to allow the Earth-Moon distance to be measured using laser ranging. In May of the same year, Louis Dijour Smullin and atmospheric physicist Giorgio Fiocco announced that they managed to reflect ruby laser pulses from the moon.This type of measurements was also declared by the Russians who later reported successful results using a Q-swithced ruby laser.Although the experiment was a success, because of the irregular surface and the curvature of the Moon, the accuracy of the measurements was limited to 200 meters.

By retrieving light from these retroreflectors on the Moon, there is the benefit that the signal would be retuned much more intensive than it would from the natural surface of the Moon. The bigger advantage would be that, being a well defined point on the surface of the Moon, there would be a short return pulse and allow point-to-point ranging accuracy at the level of centimeters.

A corner-reflector is an ultra-precision version of the reflector-type optical mirror used on bicycles and traffic stop-signs. It would send any beam of light directed toward it directly back to the source. Each corner-cube or retroreflector does for the three-dimensional world of light what the corner of a billiard table does for the two-dimensional world of billiards. The advantage of this type of mirror is that it only needs to be placed, but not precisely oriented, on the lunar surface in order for it to reflect pulses of laser light directly back to Earth.

So you could just drop one on the surface of the moon. And that is what they did. They encapsulated in silicone a retroreflector, offcentered it so when thrown from a spacecraft it would set itself facing upward and remain a mark on the Moon for laser ranging. This allowed the distance and the variations of the distance to be accurately calculated by measuring the 2.5 seconds light traveled to the Moon and back.

During the Apollo 11 mission, astronauts Aldrin and Armstrong set up an array of retroreflectors on the lunar surface. Just a little over a week after the Apollo 11 array had been deployed on the lunar surface, acquisition took place and the first precision Earth-Moon distance measurement using a short-pulsed ruby laser was made by a group of workers at the Lick Observatory in California.

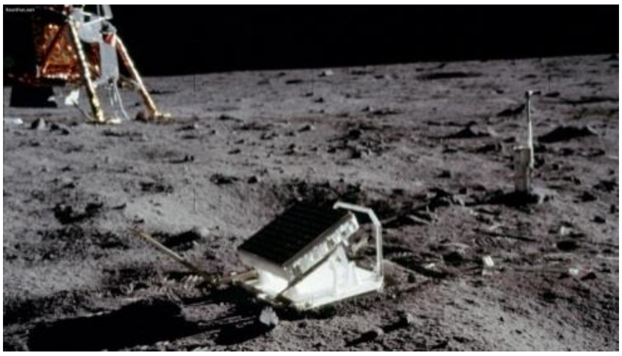

Figure 3. Photography of the reflector array placed by Apollo 11

This success, which included the first ten-meter Earth-Moon distance measurement, showed that all parts of the experiment were operating well.

Four additional reflector panels have been placed at other locations on the lunar surface since 1969. The first was a French-built package of 14 glass corner reflectors, each 11 cm on an edge, carried to the moon by the Soviet spacecraft Luna 17 in November 1970. The package was mounted on the eight wheeled lunar exploration vehicle Lunokhod 1.

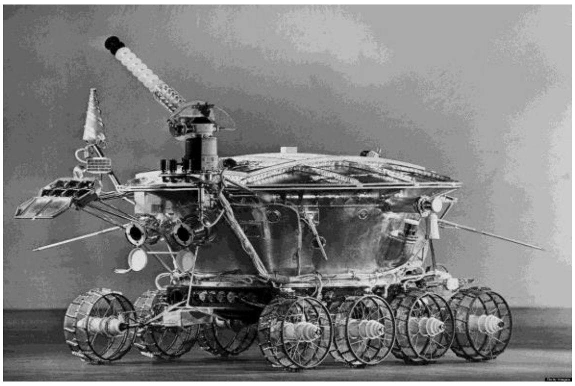

Figure 4. Photography of Lunokhod 1

The next two lunar reflector arrays were carried on the Apollo 14 and Apollo 15 missions. The retroreflectors used in both arrays were similar to those employed for Apollo 11. The overall design of the Apollo 14 array is similar to that for Apollo 11, except for some modifications of the supporting pallet to minimize weight, and the number of corner reflectors is the same.

The Apollo 15 array contains 300 corner reflectors mounted in a hexagonal close packed arrangement in order to minimize the size and the weight. The overall dimensions are 104 cm by 61 cm. A major purpose in making the array larger was to permit regular observations with simple ground equipment for groups of investigators who are interested mainly in obtaining geophysical information, and who therefore do not have to observe more than one reflector. An additional advantage in using the Apollo 15 array is that observable lunar surface features located nearby simplify the guiding of the telescope.

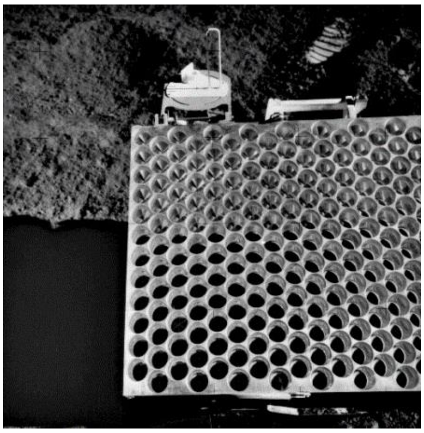

Figure 5. Photography of the reflector array placed by Apollo 15

The fifth reflector package was carried to the Moon by Luna 21. It is a French-built package similar to that carried by Luna 17, and it is mounted on Lunokhod 2.

The three Apollo reflectors form a large triangle on the lunar surface with sides of 1250, 1100, and 970 km. The complex angular motions of the moon about its center of mass can be separated with high accuracy from the range changes due to center of mass motion by differential range measurements to the different reflectors.

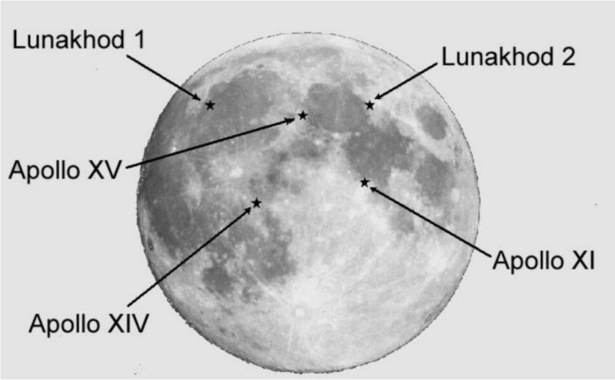

Figure 6. Distribution of the reflectors on the lunar surface

Three reflectors are needed to triangulate the Moon’s position, four are needed to understand its tidal distortions, but a fifth would reveal insights about the Moon’s more subtile movements.

Since 1970 there were few LLR observing stations. The first one was McDonald Observatory (2.7-m telescope) near Fort Davis, Texas (USA). It was fully dedicated to lunar ranging and ceased operation in 1985 after maintaining routine activities for more than 15 years. The transition was made in the mid-1980s to the McDonald Laser Ranging Station (0.76-m telescope) on two sites (Saddle and Mt. Fowlkes): MLRS1 (1983-1988) and MLRS2 (since 1988) which share lunar and artificial satellite ranging facilities.

Figure 7. McDonald Laser ranging station (Fort Davis, Texas)

In the 1980s, two other stations have carried out Lunar Laser Ranging. The Haleakala Observatory on Maui, Hawaii (USA) produced high quality data over a few years around 1990. Since 1982, the CERGA station (Centre d’Etudes et de Recherche en Geodynamique et Astronomie) has been operating at the ’Observatoire de Cˆote d’Azur’ (OCA) on the ’Plateau de Calern’ near Grasse (France), with a 1.54-m Cassegrain telescope which replaced its Rubis laser by a YAG in 1987.

Figure 8. CERGA Laser ranging station (Plateau de Calern, Caussols, France)

Occasionally some other artificial-satellite stations have performed successfully LLR observations such as in Australia and in Germany.

One of the lasers used in measuring the distance to the Moon is located in Southern New Mexico, called APOLLO (Apache Point Observatory Lunar Laser-ranging Operation). This laser is mounted on a telescope wich has amirror of 3.5 m, with a diameter of 3.5 m and a weight of more than 2000 kg. Using the wide aperture of the telescope, there was a big increase of returned photons per pulse unlike previous Lunar Laser Ranging facilities wich recorded an average of 0.01 photon return per pulse. This greatly increased the accuracy of the measurements to 1 mm.

RESULTS AND DISCUSSIONS

The Moon is thought to have formed about 4.51 billion years ago, not long after the Earth. There are four major scientific theories regarding the origin of the Moon: fission – the Moon is a piece detached from the rapidly moving Earth; co-formation (also known as the “Sister Planet” theory) – the Moon was formed of a cloud of particles from around the Earth; capture – the Moon was initially formed as an independent planet, then it was captured by the gravity of Earth; collision - the Earth-Moon system was formed of the blasted material resulted from a planetary collision with the Earth.

The data gathered from measuring the distance between the Earth and the Moon reveals that the maximum distance to the Moon reached until now is 406,720 km, and the minimum distance is 336,375 km. The average distance to the Moon is 384,400 km. This distance varies because the Moon revolves around the Earth, and it has an elliptic orbit.

The Moon orbits the Earth at a speed of approximately 3,683 km/h, and travels a distance of 2.290.000 km around the Earth. Its average diameter is of 3,476 km, roughly the size of Africa. The mass of the Moon is $7{,}342\times10^{22}$ kg and the mean density 3,344 g/cm^3. The surface temperature of the Moon varies from 117°C (during the day) to -173°C (during the night).

The results of the lunar laser ranging experiments have been plentiful and impressive. Firstly, these rangers have defined the Moon's orbit orders of magnitude better than before. Also, careful observations of the Moon's movement have shown that its center has a different axis of rotationthan of the outer layers. This subtlety reveals that the Moon's core must be liquid.

The lunar laser ranging experiments have also confirmed Einstein's theory of relativity. Measurements of the Moon's orbit match relativistic predictions exactly. The results have not been limited to the Moon either. Through the tracking of reflector arrays on the Moon, the exact locations of the telescope stations are also determined. These data have revealed details of the Earth's rotation, precession, tides, as well as movement of tectonic plates.

A method of improving the Lunar Laser Ranging Experiment could be the one of determining the lunar surface temperature simoultaneously. This measurement could be accomplished by using a powerful Infrared Radiometer at the same time with the process of measuring the distance to the Moon.

The Infrared Radiometers measure the temperature of an object or an environment without touching the surface. Their function is based on the thermal radiation of objects, a universal property that is missing only in the case of inert gases or close to the absolute zero value of the temperature.

At lower temperatures, the object radiates in a natural, but invisible way, in infrared. When the temperature rises, the object becomes red, then yellow, and, at a very high temperature, bright white.

All the objects emit and absorb electromagnetic radiations. The emitted radiation has a continuous spectrum and a specific distribution of energy depending on the temperature. The receivers used in measuring those frequencies are called radiometers.

An important parameter is the brightness of the electromagnetic radiation. In infrared, the brightness increases at the same time with the temperature. After reaching the maximum level, it suddenly decreases leaving a glow in the visible area which can be seen in the case of high temperature objects.

A radiometer is a sensitive receptor that measures the radiation of an object in a certain frequency band.

Infrared radiometers are often called infrared thermometers due to the fact that the temperature is the desired parameter to be measured, even though the sensors detect radiation.

If it would be included into the distance measurement process used in Lunar Laser Ranging Experiment, it would help keeping a better track of the temperature of the Moon, which would lead to better Moon observations.

CONCLUSIONS

Lunar Laser Ranging data analysis provides an excellent method for determining parameters of the Earth-Moon system, including the Earth orientation parameters. The expected increased data density and improved accuracy in the future will permit higher understanding of the Earth, the Moon and the Earth-Moon system, answering old questions and revealing new phenomena to be explored. The diversity of problems to which information from this experiment is applicable staggers the imagination. All five reflectors placed on the Moon are still operational and will allow further scientific exploration in the future.

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