SECOND GENERATION TIMING SYSTEM FOR RANGING EXPERIMENT APOLLO LUNAR LASER *

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The following is a brief description of the current status of the timing electronics for the new Lunar Laser Ranging Station on Mt. Haleakala, on the island of Maui in Hawaii. The general aim of the Lunar Laser Ranging Experiment is to measure, with high accuracy, the distance from a fixed point on the earth, the observatory, to a retroreflector array which was placed on the lunar surface. In practice, we use three such arrays, placed on the surface during the flights of Apollo-11, -14 and -15. Measurements to these fixed fiducial marks permit an accurate analysis to be performed, in which the various parameters which affect the range may be separated.

The present operating procedure is to direct a short laser pulse through a telescope to the retroreflector on the surface of the moon. This retroreflector then returns the light in the direction from which it originated. The signal is received in the telescope, and the round trip travel time is measured. At present, this time interval is measured with an accuracy of the order of one nanosecond. This is achieved by averaging over about 150 laser shots or about ten received photoelectrons. Ranging attempts to the several reflectors are scheduled three times during each lunar day.

The general method of data analysis is to compare the ranges obtained over a long period of time to the predictions derived from integration of the lunar motion and from data on the earth rotation. The initial scientific objective of the experiment is the production of an improved lunar ephemeris. Following this, a study of the rotations of the moon about its center of mass can improve the values for the moments of inertia of the moon. This data addresses the question of a lunar core and the chemical differentiation of the moon. In addition, since the rotation of the earth produces a significant alteration to the range, one may extract information on the motion of the spin axis of the earth, variations in the rate of rotation of the earth, continental drift, and other similar phenomena. I will not go into the details of these questions, since they have been discussed elsewhere. Finally, the gravitation theory which describes how the moon travels about the earth may be tested to the level of being able to distinguish effects due to the Brans-Dicke theory and effects caused by the gravitational effect of gravitational self-energy of the earth.

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At present, measurements with the full accuracy of 15 cm are accomplished on over about 50 percent of the attempts on the above mentioned schedule. The studies of short periods of data give results which are consistent with the 15-cm accuracy. The long-term fitting of the lunar orbit has an rms agreement of better than ten meters. This is believed to be due primarily to the difficulty in the libration theory of the moon. Adjustments are made in this long term fit to the fifteen parameters, which include reflector locations, earth station locations as well as initial conditions of the orbit. The primary effort at present, on the theoretical side, is the process of extracting, from the differences between the measured ranges and the numerically integrated orbit, the more interesting lunar orbit parameters, initial conditons for the integration, and so on. Due to correlations between certain of these parameters, some of these numbers are less accurate than the ten meter residuals of the long term fit.

The currently used timing equipment, developed by the University of Maryland for use at the McDonald Observatory, has a potential accuracy of 1/10 nanosecond. This is significantly better than the limit of about one nanosecond which is imposed by the length of the presently used laser pulse which is three to four nanoseconds. In order to obtain this accuracy, which is of the order of a part in 10^{10}, the determination is split into two separate parts. A start vernier measures the time interval from the time of detection of the outgoing laser pulse to the next pulse in a 20-MHz train of pulses. A digital counter then measures the interval in units of 50 nanoseconds. A stop vernier measures the time interval from the detection of the single photoelectron return, returning from the moon, to the next count of the 20-MHz counter. The return photoelectron also stops the counter, thus yielding the three components required to determine the accurate time interval. There are the attendant requirements in the McDonald System for epoch to an accuracy of about 50 microseconds and a knowledge of the frequency to the order of a part in 10^{10}. Both of these requirements are significantly more stringent than the minimum requirement to produce an uncertainty equal to that which results from averaging over a few returns. At McDonald we are operating once every three seconds so that we have a nice leisurely capability of firing off a pulse to the moon and sitting and waiting for it to come back before sending another. The state of the laser art at the time of station construction dictated a pulse width of three to four nanoseconds, which defined the accuracy of about one nanosecond. This is achieved by averaging over the pulse width since with less than one photoelectron per shot we are sampling the whole pulse width rather than the leading edge.

In the new Haleakala Station which is being coordinated by the Institute for Astronomy of the University of Hawaii, a new type of laser with a pulse width of 1/10 nanosecond will be used. It will have a firing rate of a few shots per second and is currently being developed under the direction of Dr. Plotkin at the Goddard Space Flight Center. Dr. Faller, formerly of Wesleyan University and now with the Joint Institute for Laboratory Astrophysics, is fabricating a specialized multielement telescope to receive the light from the moon. Our group at the University of Maryland is constructing the timing electronics and timekeeping system.

Several new problems are presented by the Haleakala installation. These are both due to new requirements on the equipment and also due to the 10,000 foot altitude of the station. Particular problems are the high repetition rate of the new laser, the large noise background rates, the short laser pulses which permit the use of better timing accuracy, and the need for increased automation due to the effect of altitude on human operators.

Although the new laser for use at the Haleakala Station will operate at a rate of a few pulses per second, similar types of lasers, which are being studied by Dr. C. O. Alley at the University of Maryland, may operate at rates of 30 to 100 pulses per second. The use of a timing system similar to the one which was developed for the McDonald station would then require the use of up to several hundred counters which is obviously ridiculous. To circumvent this we have gone from interval timing to event timing. More explicitly, in the McDonald System, we measured precisely the time interval between two events. In the Haleakala System, we measure the epoch of each event with high accuracy, so the difference of the two epochs yields the event time difference. Our equipment measures the epoch of outgoing and return pulses to a precision of 1/10 nanosecond. With this system, only one event timer is required, rather than many time interval counters.

The event timer consists of a 10-MHz synchronous counter with multiple latches and verniers. Until a triggered event arrives, the "latch" produces a binary output which is identical to the output of the pulse counter. Upon reception of the triggering event it "latches," that is, it holds the values which the pulse counter displayed at the time of the event. At the same time the vernier circuit starts to determine the time interval between the event and the time of which the counter is latched. The verniers are dual slope intergrators based on an EGG design. When an event comes, a capacitor starts charging at a fixed rate. It stops charging, and starts discharging when the counter is latched. An 80 MHz counter is gated on during the time the capacitor discharges back to zero. The rate of discharge is such that there is one count per 1/10 nanosecond.

Since the McDonald system goes dead after the first pulse in a predetermined gate interval is measured, a noise pulse from the sunlit moon can mask a photon returning from the retroarray. For this reason the large background noise rate, which occurs because of the high transmission and collecting area of the receiving optics, makes a multistop system desirable. Our new equipment supplies this by using four verniers and four counter-latches which are combined to permit four successive pulses from a photomultiplier-discriminator to be measured. When a particular vernier-latch unit is activated by an incoming pulse, it enables the next unit in the chain and it ignores all subsequent pulses. With this configuration, the pulses can then be fed in parallel to high impedence inputs on each unit and the incoming pulses do not have to be switched. This eliminates the problem of delays in the routing circuits. This system can measure pulses with separations down to 80 nanoseconds, which is less than the dead time for our photomultiplier discriminator.

The sequencing and activation of the timing electronics is controlled by a mini-computer, it also calculates predicted ranges for use in the temporal gating of the returns. For this task the original McDonald system read precalculated ranges from a magnetic tape supplied by J.D. Mulholland of JPL. But with many laser shots per second, this is not feasible; both in terms of the amount of magnetic tape needed and the computer time necessary to precalculate the ranges for all possible operating times. The computer also reads the outputs of the latches and verniers, stores this data for real time processing, and records the data on magnetic tape. The computer time necessary could be reduced somewhat by an interpolation scheme but it is more efficient to calculate the ranges directly from a Tschebyscheff polynominal fit. This procedure will work to at least ten shots per second, but faster rates will require interpolation.

It is also desirable to have real-time operator feedback yielding the preliminary results of the ranging operation. This allows the crew to move on to the next reflector when sufficient returns have been accumulated and it indicates possible malfunction when no returns are received. In the McDonald System, this is accomplished by printing, for each received photoelectron, the residual (or difference) between the observed round trip travel time and the predicted round-trip travel time. Most of these will be noise. However, the laser returns appear bunched in one close time interval of a few nanoseconds. This may be displaced from the prediction for a variety of reasons. A monitoring program in the computer notes when a residual is within a few nanoseconds of a previous residual and produces an audible indication to permit real-time feedback to the person guiding the telescope. The higher data rate on the new station precludes printing the results for each shot so a histogram will be displayed by the computer on a CRT Monitor. The scale and offset of the histogram can be varied to allow a detailed examination of a small portion of the display. Due to the high background, small bins will be needed to distinguish the buildup due to real returns. Drafts in the prediction could then cause real returns to fall into several adjacent bins. To compensate for this, provision will be made to subtract a linear drift from the residual ranges before they are histogrammed.

The computer will also be used for the collection of data on the general operating parameters of the system (temperature and so on), specific data on the run (seeing, number of shots), and on the operation state of the housekeeping subsystem. The computer has a self-controlled crystal oscillator that is used to create an internal clock time-base which, though not very accurate, can serve to indicate gross malfunctions in the station block. The computer uses its internal clock to provide a digital display of the current time (operator reference) on the CRT monitor.

The main station clock consists of a stable crystal oscillator and a specially built counter to indicate the epoch. The station clock will be compared to Loran-C and perhaps a rubidium atomic standard. In order to match the overall distance measurement accuracy the station frequency must be maintained with a long-term accuracy of four parts in 10^{11}. It seems feasible to increase this to about four parts in 10^{12} and thus remove it as a source of error. This same free-running crystal oscillator is also used to provide the time base for the 2-1/2 second averaging times typical of the lunar range. The frequency changes due to aging are monitored by the Loran-C comparison. The requirement that one be able to make an instantaneous determination of the nominal 2-1/2-second period to a precision of 1/10 nanosecond requires careful control of the ten-MHz signal. Subharmonics have appeared in the clocks we have studied and this must be controlled with careful filtering. Crystal filters were installed on the new station oscillator that lead to a jitter reduction of less than 0.1 nanosecond. The epoch of the measurement must be maintained to 50 μsec in order to match our overall measurement accuracy, since the earth rotates approximately 1.5 cm in this time. The previously mentioned comparison to Loran-C, along with periodical frequency adjustment, maintain the proper epoch. The epoch of the crystal with respect to Loran C, as well as to other standards such as VLF or the rubidium standard, is monitored by the computer and automatically recorded on tape 12 times per hour.

At present, the new equipment is in the final test stages. It will be run in parallel with the previously constructed equipment at McDonald in early February of the coming year. Installation at Haleakala should take place this summer.