PART VI : LUNAR LASER RANGING

ON THE EFFECTIVE USE OF LUNAR RANGING FOR THE DETERMINATION OF THE EARTH'S ORIENTATION

Eric C. Silverberg
Department of Astronomy
University of Texas
Austin, Texas

ABSTRACT

Lunar ranging data have been routinely available since September of 1970, but many problems of a varying nature have delayed the establishment of a world-wide lunar ranging network. As a result, we must re-examine the role which this program can play in the determination of the Earth's rotation and polar motion. Although there are many technical difficulties now inhibiting the widespread use of this technique there seems little doubt but that we can overcome these problems and achieve routine, accurate orientation determinations. The more difficult questions concern how an Earth rotation campaign should now be configured to use the equipment and resources in the best way.

Despite considerable progress by other techniques, the failure to develop a lunar capability for Earth orientation determinations would result in a serious loss of information. Lunar monitoring of long-term effects in the Earth's rotation rate and the relationship of the lunar orbital parameters to a stellar reference frame are two tasks for which there is little redundancy. However, the most cost-effective usage of station resources may not require daily measures, but only periodic, accurate snapshots of the Earth's rotational position relative to the Moon. If some satellite laser ranging facilities could treat the Moon as an object of opportunity, but were able to elevate the program to priority status when global conditions were favorable, the incremental cost of gathering the required lunar data might be drastically reduced. Even though these cost savings could not be achieved without daily communication between cooperating stations, such a detailed interaction is not unreasonable to consider.

1. INTRODUCTION

At this writing, no less than nine laser ranging stations in five different countries have announced returns from retroreflectors deposited on the lunar surface by the U.S. and Soviet space programs (Bender, et

D. D. McCarthy and J. D. Pilkington (eds.), Time and the Earth's Rotation, 247–255.

al., 1973). The typical lunar laser ranging system fires a short pulse of visible light containing approximately 10^{18} photons. If the beam is highly collimated, such that it only illuminates a few square kilometers of the lunar surface, the many-cornered retroreflectors will return sufficient energy to cause a detectable signal at an Earth-based receiver. The basic data recorded by the lunar ranging system consists of the epoch at which the laser shot was fired, the round-trip travel time to the lunar surface, the environmental parameters, and the system calibration corrections.

What is, in principle, a very simple process and merely an extension of artificial satellite ranging technology has proven sufficiently difficult that only McDonald Observatory, of the original nine stations, has maintained consistent data over the last eight years. Many of the problems which have prevented regular observations on a more widespread basis are related to financial constraints and the normal delays to be expected in activating any new technology. Another set of problems, however, is more serious and relates to physical constraints or inherent weaknesses which will remain indefinitely. The purpose of this document is to review our history with the lunar ranging technique, explore some of the reasons which have limited the acquisition of the basic data, and to propose a set of goals based on this nine-year experience which addresses the role which this type of data will play in conjunction with other available techniques.

2. THE LIMITATIONS

Lunar ranging, by its very nature, works close to the threshold of detection for current laser radar technology. If, for instance, the Moon were 30 percent further away, no lunar ranging system currently in existence would be likely to attain routine operations. This peculiar circumstance can be attributed to the state of development in the laser itself. Key parameters which govern the design of the laser radar system are laser pulse width, average power, and the laser divergence. Early lasers required large aperture instruments, such as the 2.7-meter McDonald reflector, due to their large intrinsic divergence. Great strides in the improvement of this area have made practical the use of smaller telescopes, a fortunate occurrence since few of these larger instruments would be available for such an experiment. Shorter pulse width coupled with higher efficiency optics and better detectors have been able to continually improve accuracy despite the lack of collecting power in the smaller apertures. However, there have been no average power gains commensurate with the improvement in the other parameters. The 1.5 watt capability of the McDonald laser is still well within an order of magnitude of the state of the art nine years later. Thus, unless there is a major breakthrough in the availability of high average powered lasers, the experiment will forever require highly collimated output beams and be at the mercy of atmospheric turbulence as well as clouds. Moreover, the high beam collimation required for the lunar work dictates a demanding pointing technology in comparison with other techniques (Silverberg, 1974).

Any operation which operates close to the threshold of detection presents a practical problem for the development of new facilities. The accompanying financial threshold is a very real problem, in that stepwise turn-on is not possible like in many other experiments. A considerable capital commitment is necessary before demonstrable results can be obtained. The same is true in a technical sense. A lunar ranging system is a relatively complex assembly of components, any one of which can prevent the acquisition of data -- not only prevent the acquisition of merely good data, but prevent the acquisition of any data. Once quasi-regular data is acquired from a lunar ranging station, it should be relatively easy to iterate the system to a routine astrometric operation. Unfortunately, that first step is more difficult than we hoped.

3. THE ADVANTAGES

There are, of course, also advantages to lunar ranging which have led many investigators to put a great deal of effort into developing ranging facilities throughout the world. The first and foremost reason for pursuing lunar ranging, as opposed to some other method, is the unique access to the Moon's dynamics. The twofold improvement in monitoring the Moon's motion allows the study of general relativistic terms, the various harmonics of the Moon's rotation, the mass of the Earth/Moon system, and many other aspects which are not studied elsewhere (Williams, 1977). In the sense that the Moon's orbit is very important to Earth rotation, these studies alone are of interest to a symposium of this nature. However, the main reason for discussing this technique in the context of Earth rotation is the sensitivity of any lunar laser station to the time of lunar meridian passage. Each lunar ranging system can, given a successful set of three observations in a single day. determine the time of meridian passage and the geocentric axial distance to approximately the same accuracy as the measurements. A large number of determinations of UT0 have been possible for the McDonald station over the last several years with a formal accuracy of about 0.7 milliseconds, although differences between various analyses indicate that the actual error must be somewhat greater (Stolz, et al., 1976; King, et al., 1978; Harris and Williams, 1977; and Shelus, et al., 1977). Several stations can cooperate to use either the axial distance determinations to orient the Earth's pole, or can directly infer the orientation geometrically once the lunar declination is well known. This monitoring of geocentric station position relative to an inertial reference frame provided by the solar system is a unique contribution in this area, important to tracking the long-term variations in Earth dynamics. Moreover, the analysis of lunar data for rotation variations appears to be much simpler than demonstrated for other techniques, so simple in fact that the on-site ranging crew has a real sense of the status of UT0. Thus, while lunar ranging appears to have the most difficult data gathering problem, this drawback is offset by the simplicity and economics of the data analysis. The fundamental reference provided by the lunar orbit and the simplicity of the data analysis led to strong hopes that an operational system for Earth rotation would be highly competitive with other techniques, even for short-period studies.

4. CURRENT STATUS

The McDonald Observatory station has continued to operate regularly since September of 1970. The normal operating schedule, weather permitting, is three trials per day, approximately 300 days per year. The precision of the measurements is normally about 10 cm, however 5-cm ranges are possible under excellent conditions. Although the development of the station was recently slowed somewhat by financial constraints, the installation has now returned to its regular operating schedule. McDonald has collected over 2300 range measurements to four of the lunar corner reflectors during the last seven years. To this author's knowledge, only the 2.6-meter installation at the Crimean Astrophysical Observatory has also been in regular operation during this period, conducting a limited set of observations which averages a few days per lunation.

Two other lunar laser ranging stations have all of the equipment presently in place and have made some preliminary observations of range. Unfortunately, neither has reached operational status at this writing. The Maui station was an ambitious attempt by the U.S. lunar ranging team to achieve a second generation system which would have not only 2-cm accuracy and 3 times the McDonald signal level, but have the ability to perform blind tracking during day and night-time conditions. Unlike most other experience, the major problem at the Maui station is not one of signal strength, which has been excellent when obtained, but the high complexity of the system which requires extreme reliability in all components and a high degree of crew training.

The Australian station near Canberra is designed around a 1.5-meter telescope formerly used by the AFCRL organization near Tucson, Arizona. This station has been conducting preliminary ranging operations for approximately a year. While there are some difficulties with reliability of components, particularly the laser, the major problem for this station has been the poor signal-to-noise ratio caused by the wide laser pulse and the necessity for large spatial filters.

These four installations can be joined by as many as three others in the near future. A second generation CERGA installation at Grasse is now nearing completion with a 1.5-meter telescope. Modifications are underway to upgrade the artificial satellite station at Wettzell, and it is known that the Tokyo Astronomical Observatory intends to begin a program of lunar range observations.

If any substantial subset of the possible lunar stations can begin coordinated operations, it seems likely that high quality Earth rotation and orientation data will be attained, as envisioned by the COSPAR sponsored EROLD campaign. Modelling by Stolz and Larden (1977) indicate that a regular lunar ranging capability can effectively track the expected variations in pole position with normal weather constraints. Data handling and analysis methods for an Earth rotation service have been demonstrated in coordiantion with the BIH. There is no doubt that an ambitious program of state-of-the-art Earth rotation measurements is possible if the current station problems can be overcome. The question which should be asked, however, is whether the ambitiousness of these goals is, in fact, the reason why progress has been slow. This question is especially relevant when it is possible to foresee a much less ambitious observation program which still contributes substantially to the scientific needs in these areas and provides the necessary information from which further plans could be drawn.

5. COMMENTS ON THE GOALS

The difficulty of designing and operating a lunar laser ranging station is highly related to the percentage of the lunation which the station intends to cover. The necessity for full month operation requires not only a variety in guiding techniques, but the ability to operate day and night during substandard seeing and marginal contrast conditions. Table 1 attempts to characterize the varying degrees of difficulty in relation to the operating time in each lunation, related to items such as the initial complexity of the equipment, the technical operating expertise, and the cost of the operation. With an operating time of five or six days per lunation, the equipment requirements mimic a slightly modified artificial satellite station. On the other hand, twenty-eight day coverage of the orbit requires a level of expertise which has still not, to this investigator's knowledge, been demonstrated. The expense in operating the station must also rise with the ambitiousness of the program, with the first break in cost coming approximately at 12 days per lunation when one crew can no longer be expected to perform all of the functions associated with operating and maintaining such a facility. It is evident that all aspects are highly correlated with the percentage of operating time which is envisioned for each lunation. Good system design will recognize this fact by coordinating the initial investment in equipment with the long-term operating plans for the station. It is also important, however, that the worldwide ranging community recognize this fact with goals which are commensurate with the status of the facilities as they now exist.

Table 2 lists potential goals for the lunar laser ranging technique and the observational requirements, both in order of increasing capability of the stations to cover the entire lunation. Goals which are unique to lunar laser ranging have been indicated with an asterisk. Most require relatively small numbers of observations from a limited number of lunar laser ranging stations. Very important worthwhile projects can be accomplished if a few laser ranging stations have occasional lunar capability. On the other hand, the most ambitious goal for lunar laser ranging, that is, the development of an independent capa-

Table 1. Characteristics related to the percentage coverage of the lunation.

Days Per Lunation	Initial Investment	Operating Technology	Operating Costs	
			Devoted Lunar	Combined with Satellite
28	impractical	---	---	---
25	very high	very high		
20			2 crews	moderate
15	moderately high	routine	1.5 crews	
10			1 crew	low
5	moderate	low		
0				

bility for daily Earth orientation determinations (a need not demonstrated), can also be made by at least two other methods. While lunar ranging can be an effective and unique contributor in the area of Earth rotation and polar motion, it does not appear that the pursuit of daily independent determinations of the latter are justified at this time.

6. RECOMMENDATIONS

In the area of Earth rotation, the most cost-effective goals are the maintenance of the secular variations. Accurate snapshots of the Earth's orientation can be economically achieved by a few laser stations conducting quasi-simultaneous observations for a few days per month. With daily polar tracking by other techniques, any single station's observations of the Moon during the month will also track the Earth's short period rotation variations. Thus, occasional lunar tracking by several stations and frequent lunar tracking by one or two stations will deliver the greatest percentage of the scientific gains, lacking only a daily independent Earth orientation solution. All of the unique lunar scientific goals would be attainable with such data. These suggestions are attainable, cost-effective programs which do not require full lunation capability by a large number of lunar tracking facilities.

Without the motivation associated with the daily independent service for the determination of Earth orientation, it is likely that some of the support for lunar ranging that might otherwise be available will be lost. There is a definite risk that so much support could be lost that even the unique goals available to the data type would be jeopardized. Hopefully, this problem can be successfully addressed by realizing that limited observational goals for a lunar ranging station make it more compatible with other systems. Lunar ranging systems which are designed for a relatively small portion of the lunation need not grossly differ from a satellite ranging configuration. Moreover, the observations can be intermixed with little additional personnel cost

Table 2. Observing requirements.

GOAL	REQUIRED CHARACTERISTIC FREQUENCY OF OBSERVATIONS	REQUIRES MULTIPLE RETROREFLECTORS	REQUIRES MULTIPLE STATIONS WITH EARTH ROTATION/POLE SERVICE	REQUIRES MULTIPLE STATIONS WITHOUT EARTH ROTATION/POLE SERVICE
* Lunar Orbital Studies: gravitation, tidal, fundamental const., relativity	weekly	some	no	probably
* Lunar Libration Studies: selenodesy, c/mr^2, free librations, Q	weekly	definitely	no	probably
Establish Geodetic Benchmarks: continental drift, fault monitoring	monthly	no	yes	yes
Monitor Secular Variations In Earth Orientation: rotation vs. solar system*, pole wander	monthly	no	yes	yes
Provide "Daily" Earth Rotation Service	daily	no	no	yes
Provide "Daily" Pole Motion Service	daily	no	yes	yes

* Unique to Lunar Ranging Techniques

at the same site whether or not the actual hardware is shared between the two systems. It can only be advantageous to have multiple data from the same location when pursuing difficult comparisons of geodynamic solutions at the centimeter level. It seems evident that a very cost-effective package could be addressed to funding agencies in terms of multiple purpose laser facilities, capable of ranging to the Moon as well as a wide variety of lower objects. These stations could track artificial satellites for much of the month, but would be available periodically to make high accuracy snapshots of the Earth's orientation relative to the Moon, hence the solar system, at favorable times. The observations by the multiple stations could easily be coordinated such that they occurred on or near the same day, once the capabilities of all the stations were determined.

7. SUMMARY

Surveying the situation for lunar ranging in the context of this symposium, we have, on one hand, the observational difficulties associated with obtaining data, the gap at new Moon, and the lack of many observatories. On the other side are the unique contributions in the field of lunar science, the geocentric measurements in an inertial frame and the very simple and economical data handling and analysis. The establishment of an effective daily independent determination of Earth orientation does not seem cost-effective at this time, due to the requirements for coverage of the entire lunar cycle implied by this activity. On the other hand, the foreseeable laser network can expect to track longer term (monthly) variations in Earth rotation and polar motion in a cost-effective manner, particularly if further consolidation with satellite tracking problems is achieved. Lastly, the availability of polar motion data from another technique would permit the very economical, real time determination of Earth rotation from any individual lunar station which happened to operate over a high percentage of the lunation.

These discussions have been limited to questions relating to the basic data gathering activities of lunar ranging. It must be emphasized that this alone is not the total picture. The final measure of the success of any technique must be based on many factors including proven accuracy and relative costs. It has been proposed that, in view of the difficulties which have occurred in the development of lunar laser ranging stations, less ambitious immediate goals should be considered for lunar laser ranging than those envisioned by the international EROLD campaign -- lesser goals which can be chosen without drastically altering our access to unique scientific data. The final decisions between what should or should not be considered long-term goals for this technique are still open questions and will be for some time. However, it seems likely that by combining the lunar laser ranging equipment, to as large an extent as possible, with the need for tracking artificial satellites, an extremely cost-effective package can be developed. The use of further coordination with the pole solutions from other areas such as VLBI can further increase availability of scientifically meaningful data from individual lunar stations. It is evident that while lunar ranging has much to offer, it's most cost-effective scenario includes detailed coordination with complementary methods. It is of interest to consider whether the same is true of the other proposed techniques.

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DISCUSSION

W. E. Carter: Lunar ranging near new Moon is difficult, and measurements of Earth rotation could only be obtained on about 20 days per month unless sophisticated systems were used. This means that lunar laser ranging is not, by itself, a suitable technique for an Earth rotation monitoring system.

E. C. Silverberg: That is true.