McDONALD OBSERVATORY LUNAR LASER RANGING:

BEGINNING THE SECOND 25 YEARS

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1. Introduction

Lunar laser ranging (LLR) (Dickey *et al.*, 1994) consists of measuring changes in the round-trip travel time for a laser pulse traveling between a transmitter on the Earth and a reflector on the Moon. The lunar surface reflectors are still operating normally after almost three decades of use. The ranging data exhibit a rich spectrum of change due to many effects.

During the early days of the experiment, McDonald Observatory was the only facility that could routinely range to the Moon (Abbot *et al.*, 1973, Mulholland *et al.*, 1975, Shelus *et al.*, 1975). It used as its fundamental component the 2.7-m telescope (Silverberg, 1974). This system was decommissioned in 1985 to be superseded by a dedicated system, the McDonald Laser Ranging Station (MLRS) (Shelus, 1985, Shelus, *et al.*, 1993b), that can range to both artificial satellites as well as the Moon. Due primarily to distance, it is more than a trillion times more difficult to range to the Moon than it is to range to an artificial satellite.

The new station, initially placed in the saddle between Mt. Locke and Mt. Fowlkes at McDonald Observatory, became operational in 1983. Wind tunneling effects at the saddle site produced serious problems with seeing and the MLRS was moved to the top of Mt. Fowlkes in early 1988. Although the MLRS observing emphasis has always been placed upon ranging to artificial satellites (see Figure 1), the Moon continues to be a vital part of the operation (Shelus, 1987). At this point in time, it is the only station in the US that is capable of ranging to the Moon.

S. Ferraz-Mello et al. (eds.), Dynamics, Ephemerides and Astrometry of the Solar System, 409–414.

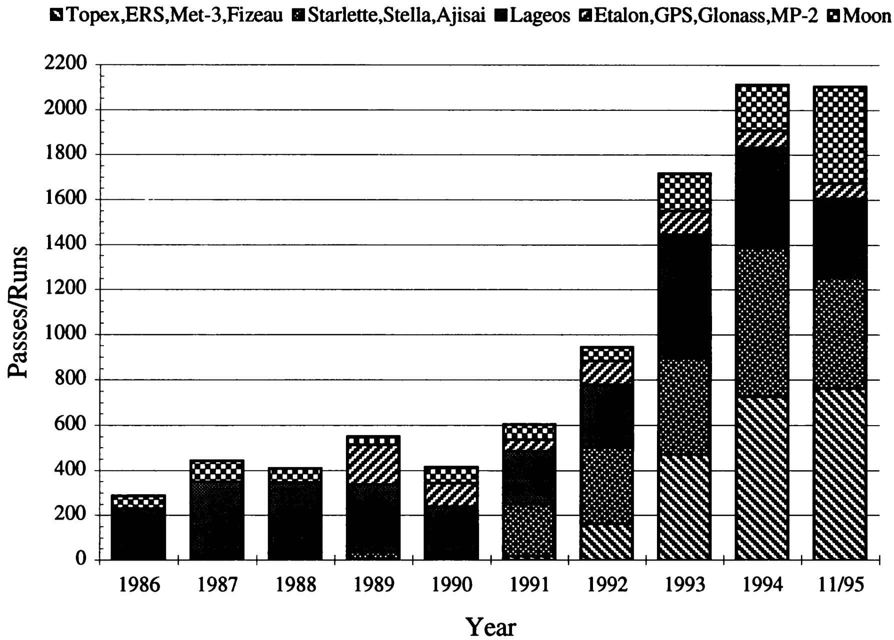

Figure 1. MLRS Laser Ranging Activity.

2. MLRS LLR Upgrade History

The transition of LLR operations at McDonald Observatory from the original 2.7-m system to the 0.76-m MLRS caused a marked decrease in the volume of data, mainly because of the reduction in aperture. The number of normal points obtained annually with the MLRS in the late 1980's was well under 100, while those obtained with the 2.7-m system had been close to 400. Data accuracy and precision were improved, however, due to a decrease in laser pulse length. In the early 1990's a program to improve MLRS LLR data volume, and improve precision and accuracy, was begun.

The first upgrade was an x-y offset guiding stage (Shelus *et al.*, 1993a). Such a device allows an observer to guide on a sun-lit, off-axis feature, or a star, while the reflector is on the shadow side of the lunar terminator. Not only does this provide for a greater number of observing opportunities during a lunation, ranging to a reflector in the dark produces virtually noise free data. Installation was completed and operation began in the spring 1993 with a dramatic increase in the amount of LLR data obtained.

An MLRS laser pulse contains 3 x 10^{17} photons. In lunar mode, only a very few photons per minute make it back through the receive path. This mandates single photon detection and as large a system efficiency as possible. The spectral filter must eliminate as many noise photons as possible, but must transmit as many signal photons as possible. Also, spectral filter requirements change with lunar phase and sky conditions. A third spectral filter, of intermediate specification between those already in hand, was purchased in spring 1993 and immediately placed into service. Further, in August 1994, because of aging and laser induced damage, the telescope's # 3 dichroic mirror was replaced. The additional scheduling flexibility and extra energy throughput that these two changes provided resulted in a significant increase in the amount of LLR data.

With the MLRS, intensive manual guiding is required to keep the telescope on target. In spring 1993 we specified the MLRS Auto-Guiding and Imaging System (AGIS), an integrated hardware/software system that accepts real-time video signals, i. e., a highly magnified image of the lunar surface or a stellar or artificial satellite image. It performs real-time image processing and allows the user to select among various levels and types of image enhancement. It provides tracking error signals to the control computer for guiding control. The AGIS was received and installed in February 1995. Integration of the error signals into the pointing control loop is in progress. A correlation tracking board for the AGIS is under development.

The German laser ranging group at Wettzell designs and builds avalanche photo-diode (APD) devices. An APD detector in use at the French LLR site exhibits a significant increase in sensitivity and an improved accuracy and precision. Other APD's are used for artificial satellite laser ranging elsewhere. In spring 1993 the Wettzell group built an APD for use at the MLRS for LLR operations. Although this APD was received at the MLRS in early 1994, early difficulties were encountered. A new device was received in mid-summer 1995. Improvements in sensitivity and jitter were immediately noted. Normal APD use at the MLRS will begin shortly.

The MLRS station clock is a cesium-beam device. These are expensive and must undergo considerable preventive maintenance on a time-critical basis. A cheaper, easier to maintain steered oscillator can provide short-term stability and a GPS receiver, used as a fly-wheel, can provide long-term stability. With such a combination of devices, a significant cost and time savings in operation and maintenance could result, with an improvement in timing accuracy and precision. We have taken delivery of a Totally Accurate Clock (TAC), designed by Dr. Thomas A. Clark. This may form the basis for a new timing system to replace the current Cesium device.

We have just completed the replacement of the 15 year old Data General NOVA control computer with a LynxOS based, X-windows, real-time UNIX system running on PC hardware. This was coordinated with upgrades at other NASA laser ranging stations. It has created a system with compatible hardware and software architecture in an open-systems environment. It allows a maximum amount of software portability and sharing.

3. The LLR Data Set

Some parameters in LLR analysis separate on relatively short time scales. Others separate on the 18.6 year period of the lunar nodal regression, or longer. When analyzing any data set, it is important to consider the distribution of observations over the relevant parameter space. The histograms in Figure 2 show the distribution of LLR data with respect to the fundamental arguments of the lunar theory. After more than 25 years of observations, the data distribution with respect to the lunar mean anomaly, l, the solar mean anomaly, l', and the argument of the lunar latitude, F, is reasonably flat. The fact that Ω, the mean longitude of the ascending node of the lunar orbit, covers significantly more than a full period is extremely important. New and full moon effects are seen in the distribution of observations with respect to the mean elongation of the Moon from the Sun, D. This is a consequence of scheduling lunar operations at 1st and 3rd quarter phases, when data is easiest to obtain.

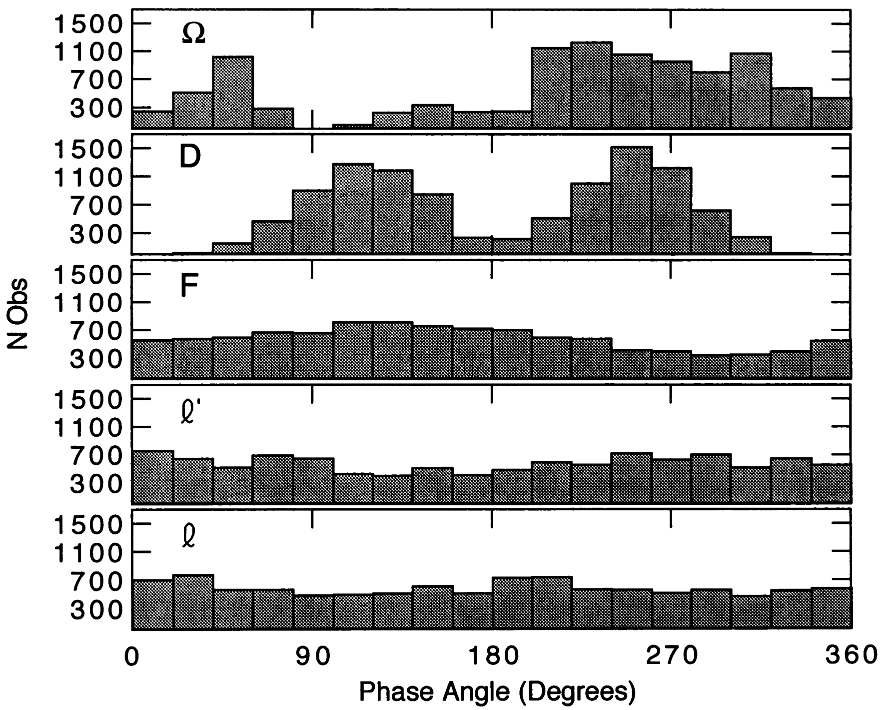

Figure 2. Distribution of LLR observations with respect to the fundamental arguments of the lunar orbital motion. The sampling interval is 20°.

Illustrating the long span of McDonald LLR data, data volume, and formal uncertainty is Figure 3. We show yearly totals of normal points and

https://doi.org/10.1017/S0074180900127755 Published online by Cambridge University Press

the weighted root-mean-square of post-fit residuals. As a result of the recent MLRS up-grades, not only are the accuracy and precision of its LLR data significantly better than that of the 2.7-m system, the MLRS data volume matches it as well. There is also a significant drop in the rms of MLRS LLR data during 1995. Although not shown here, the number of photons per normal point is now double what it had been prior to the beginning of the MLRS upgrade. Table 1 details this increased MLRS data volume from 1992 to the present and compares it to the French LLR effort.

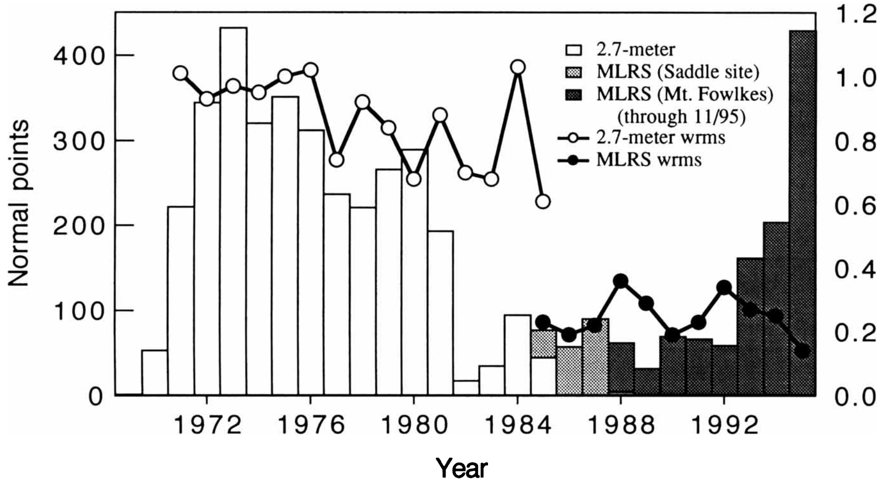

Figure 3. The number of normal points and the weighted RMS of the post-fit residuals from our analysis of the McDonald LLR observations. To insure large enough samples to be statistically significant, the RMS values were calculated from ranges to the Apollo 15 retroreflector only.

Table 1. MLRS/CERGA Comparison (1992-11/95)

		MLRS				CERGA			MLRS/CERGA		
		1992	1993	1994	11/95	1993	1994	11/95	1993	1994	11/95
LLR	Ap 11	-	3	25	34	53	55	56	6%	45%	61%
Normal	Ap 14	-	8	17	49	53	44	46	15%	39%	107%
Points	Ap 15	58	151	160	341	433	499	446	35%	32%	76%
	Lnk 2	-	1	3	6	12	17	10	8%	18%	60%
	Total	58	163	205	440	551	615	558	30%	33%	77%
Nights	Ap 11	-	2	16	21	27	23	23	7%	70%	91%
LLR Data	Ap 14	-	5	12	27	26	17	23	19%	71%	117%
Taken	Ap 15	23	56	61	95	75	71	63	75%	86%	151%
	Lnk 2	-	1	3	4	11	9	7	9%	33%	57%
UT0 pts.		5	26	33	54	49	44	60	53%	70%	90%

4. Conclusions

McDonald Observatory laser ranging operations has pursued a significant and substantial LLR up-grade at the MLRS. That effort has been a remarkable success. We have just a short time ago celebrated the 25th anniversary of the first Apollo manned placement of a retroreflector package on the lunar surface. The lunar laser ranging experiment remains the only active Apollo experiment and it is still marching at the forefront of science. Concerning the availability of the LLR data type, the Crustal Dynamics Data Information System (CDDIS), maintained at Goddard Space Flight Center, archives all lunar laser ranging data. Normal points are available through an on-line data base; filtered photon returns are archived on magnetic tape. Further information about the LLR data set and the CDDIS may be obtained via the Internet from pjs@astro.as.utexas.edu or from noll@cddis.gsfc.nasa.gov.

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