DETERMINATION OF COORDINATES FOR THE ORRORAL LUNAR RANGING STATION

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ABSTRACT. Using models of the Earth-Moon system developed from analysis of 10 years of laser ranging observations from the McDonald Observatory, we have analyzed observations obtained by the Orroral Lunar Ranging Station since April 1978. Normal point residuals from many of the observations performed before April 1980 using a 20 ns, mu tiple-mode laser pulse are discreetly spaced, as multiples of 6 ns, and may have been corrupted by variations in pulse shape. Further evaluation is required before these observations are used in scientifi analyses. Observations performed during the MERIT Short Campaign (August - October 1980) using a 6 ns, single-mode pulse are apparentl reliable. Using 27 single photoelectron events, obtained on 7 nights during this period, we have estimated the coordinates of Orroral, with respect to McDonald, with uncertainties of 1-2 m in cylindrical radius and longitude and 5-10 m in z-axis distance.

INTRODUCTION

Data from the National Mapping (Natmap) Orroral Lunar Ranging Station, located in Australian Capital Territory, Australia, consist of :

1) 144 normal points formed from observations made between April 1978 and April 1980, using a 20 nanosecond (ns) multiple-mode ruby lase The precision of these normal points varies from 1 to 10 ns in accordance with the Chi-square distribution;

2) 127 individual photoelectron events obtained from observations made using a 6 ns, chopped, single-mode ruby laser on 16 days betw 31 July 1980 and 30 October 1980. The equivalent normal point precision of these data is 1.5 ns.

A previous analysis of the data obtained during 1978 was carried

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O. Calame (ed.), High-Precision Earth Rotation and Earth-Moon Dynamics, 305–311.

out by Calame (1979). More recently, Shelus (1981) analyzed the data through April 1980. Estimates of coordinates obtained from both of these analyses are given in Table 1.

We performed our analysis of the Orroral data with the Massachusetts Institute of Technology Planetary Ephemeris Program (PEP) (Ash 1972), using models of the Moon's orbit and rotation developed through analysis of 10 years of LLR observations from the McDonald Observatory (Langley et al.1981). We first performed analyses using different combinations of Orroral data : 1) 20 ns data; 2) 6 ns data; 3) combined 20 ns and 6 ns data. In each analysis we estimated only the three coordinates of the Orroral telescope, holding all other parameters fixed at the values obtained from analysis of the McDonald data. The estimated values of the telescope coordinates obtained from these analyses were significantly different, both from each other, and from the values previously obtained by Calame and Shelus. The postfit residuals also showed significant inconsistencies, even within the 20 ns and 6 ns observations. We tried various editing schemes, but were unable to obtain a data set which both a) fit our model within twice the estimated uncertainty of the observations, and b) contained at least 75 % of the data.

ANALYSIS OF THE 6 NANOSECOND OBSERVATIONS

The difficulty we encountered in understanding both data sets led us to examine more carefully the 6 ns photoelectron events for systematic signatures that might be predictable from the geometry of the observations. Consider the well-known approximate expression for the range to the Moon

$$\rho = R - r_c \cos \delta \cos H - z \sin \delta \tag{1}$$

and its sensitivity to observing site coordinates

$$\Delta\delta = -r_c \cos \delta \cos H \, \Delta r_c - r_c \cos \delta \sin H \, \Delta\lambda - \sin \delta \, \Delta z \tag{2}$$

ρ is the observed range between the telescope and the retroreflector,

R is the distance between the center of mass of the Earth and the reflector

r_c is the cylindrical radius of the telescope,

λ is the west longitude of the telescope,

z is the distance north of the equator of the telescope,

δ is the declination of the reflector, and

H is the local hour angle of the reflector.

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The geometry of the observations is controlled by the lunar declination, δ, and by the local hour angle, H. For these observations δ varied from $-20°$ to $+20°$ over a month whereas H varied by ± 1-2 hr ($\pm 15°$-$30°$) over each observing session. Thus, there are three distinct signatures one expects to see in the residuals: a bias, proportional to Δr_c; a nearly linear drift with hour angle (the zero-crossing portion of a diurnal sinusoid), proportional to $\Delta\lambda$; and a monthly sinusoid, proportional to Δz.

We used equation (2) to develop a linear regression model consisting of a constant bias, a diurnal term, and a monthly term. Using this model with various subsets of the data, we found a small subset of 27 photoelectron events, spanning 7 days, which we were able to fit within the estimated 6 ns uncertainty. These events covered the full $-20°$ to $+20°$ range of lunar declinations and had a maximum local hour angle spread on any given night of 1.5 hours. Having determined the coefficients of our simple 3 - parameter model from the 6 ns data, we applied it to the larger 20 ns data set. We found that an appreciable portion of the 20 ns normal points could also be fit within their estimated uncertainty.

In order to estimate the coordinates of Orroral, we next used PEP to analyze the selected 6 ns data together with the McDonald data. In this analysis, we estimated simultaneously : three coordinates each for Orroral and McDonald ; 30 parameters in our mathematical models of the orbits of the Moon and Earth-Moon barycenter and the lunar rotation (see, e.g., Cappallo et al. 1981) ; three coordinates each for the four lunar retroreflectors ; and two ranging biases for McDonald.

Our estimated values and their formal (one-sigma) uncertainties for the McDonald and Orroral coordinates are presented in Table 1, together with those previously obtained by Calame and Shelus. For McDonald, the three sets of values differ by ~1 m or less, except for large (10-20 m) differences in longitude. The large longitude differences are expected since our respective reference systems have not been tied to a common origin of longitude. For the Orroral coordinates there are significant differences between the three sets of values, ranging from 3 to 20 m. We attribute these differences to inconsistencies between the subsets of 20 ns data used by Calame and Shelus, and between those data and the 6 ns data set that we used.

In order to obtain an external check on the LLR results we compared our coordinates with those deduced from Doppler observations of U.S. Navy navigation satellites. The McDonald values were determined by the National Geodetic Survey (Hothem 1979) and are based on 367 satellite passes, whereas Orroral values were obtained by Natmap (Roelse 1981) and are based on 22 such passes. The Doppler values are also given in Table 1.

Our LLR estimates for McDonald coordinates differ from those obtained from Doppler observations by 5 m in radius, 35 m in longitude, and 3 m in z. As for the comparison between the various LLR estimates, the large longitude difference here represents simply a rotation between the LLR and the Doppler reference systems. The 5 m and 3 m differences in r_c and z, respectively, are consistent, within a factor of two with known uncertainties in the NWL system. Comparison of the McDonald differences (LLR-Doppler) with those for Orroral provides the best available check of our estimated Orroral coordinates. These differences are 1 m in r, 2 m in λ, and 7 m in z. The large difference in z may be due to the limited Orroral data set, which covers the full declination range of the Moon, but lacks adequate redundancy. From this comparison we conclude that the uncertainty in our estimated values for the Orroral coordinates is 1-2 m in radius and longitude and 5-10 m in z-axis distance.

Finally using these coordinates in conjunction with the results of the filtered photoelectron events of the University of Texas and the station logs from Orroral, we find that there are signal events within the raw returns (signal plus noise) on 6 of the 9 rejected days. A reinterpretation of these returns may produce a data set covering as many as 13 of the days of the MERIT short Campaign.

ANALYSIS OF THE 20 NANOSECOND NORMAL POINTS

Using the coordinates of Orroral derived from the 6 nanosecond photoelectron events, we reanalyzed the 20 ns normal points and examined the residuals. The most striking feature of these residuals is that, of the 23 days when three of more normal points are available, 9 days show residuals spaced by multiples of 6 ns,the roundtrip time of light in the laser cavity. A careful examination of the station logs, especially the oscillograms taken of the outgoing laser pulse, shows that there is a strong tendency for structured residuals to occur on days when the laser pulse exhibited significant mode structure. Figure 1 shows a typical "clean", mode-free, laser pulse associated with ranging on 9 December 1979. The figure also shows a typical "structured", mode-contaminated, laser pulse associated with ranging on May 15 1979. The residuals associated with the events of each of these nights are also tabulated in the figure.

We believe that the pattern in the residuals is due to variations in laser pulse shape. Since timing begins as soon as the outgoing pulse passes a given threshold level, changes in the mode structure of the pulse could introduce errors in the time-of-flight measurement. The oscillograms shown in Figure 1 for 15 May 1979 show an example of a change in pulse shape between the beginning and end of a sequence of shots. The spacing of the sub-peaks in the second oscillogram for this day is 6 ns.

It is possible that more of the inconsistencies between the 20 ns data and the 6 ns data can be explained in terms of mode structure in the former data. A careful review of the station logs,including oscillograms, to determine the prevailing laser mode structure will be necessary before

Table 1 Coordinates for McDonald and Orroral

	Calame (1979)	Shelus (1981)	This paper	Doppler
McDONALD				
r_c(km) cylindrical radius	5492.41465 ($\pm 0.86 \times 10^{-3}$)	5492.41480 ($\pm 0.10 \times 10^{-3}$)	5492.41348 ($\pm 0.03 \times 10^{-3}$)	5492.41846 ($\pm 0.11 \times 10^{-3}$)
λ(°) west longitude	-255.978013 (fixed)	-255.97721 ($\pm 0.5 \times 10^{-5}$)	-255.9781367 ($\pm 0.05 \times 10^{-5}$)	-255.9777879 ($\pm 0.23 \times 10^{-5}$)
z(km) distance north of equator	3235.69604 ($\pm 1.35 \times 10^{-3}$)	3235.69788 ($\pm 0.15 \times 10^{-3}$)	3235.69758 ($\pm 0.05 \times 10^{-3}$)	3235.6945 ($\pm 0.14 \times 10^{-3}$)
ORRORAL				
r_c(km) cylindrical radius	5190.7128 ($\pm 1.6 \times 10^{-3}$)	5190.72068 ($\pm 0.5 \times 10^{-3}$)	5190.71010 ($\pm 0.16 \times 10^{-3}$)	5190.71406 ($\pm 1.3 \times 10^{-3}$)
λ(°) west longitude	-148.939402 ($\pm 2.1 \times 10^{-5}$)	-148.939945 ($\pm 2.8 \times 10^{-5}$)	-148.9394709 ($\pm 0.58 \times 10^{-5}$)	-148.9390997 ($\pm 1.4 \times 10^{-5}$)
z(km) distance north of equator	-3696.2623 ($\pm 2.0 \times 10^{-3}$)	-3696.2661 ($\pm 2.5 \times 10^{-3}$)	-3696.25005 ($\pm 0.62 \times 10^{-3}$)	-3696.26024 ($\pm 1.5 \times 10^{-3}$)

Error estimates are formal (one-sigma) values.
Note that 1×10^{-5} ° is approximately 1×10^{-3} km.

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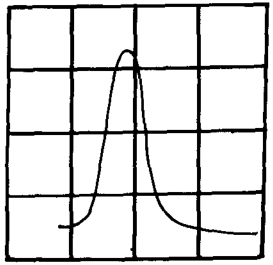
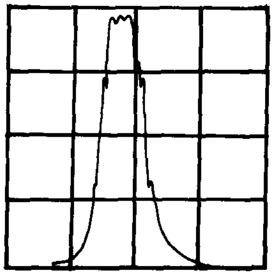
Example of constant, mode free pulse



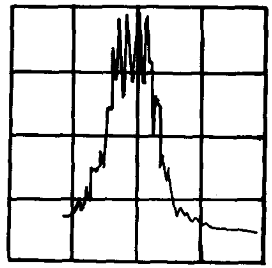
9 December 1979

Time	Residual (ns)
18:44:22	2.6
19:32:05	-4.3
19:48:11	-5.0
19:56:05	0.4
20:03:49	-8.7
20:38:15	-2.1
20:49:48	-3.1

Example of variable, mode-contaminated pulse.



Pulse after adjustment of the laser cavity and before the start of sequence of shots.



Pulse at the end of the sequence.

15 May 1979

Time	Residual(ns)
17:23:28	31.7
17:48:39	26.1
18:52:47	19.8
19:50:59	-2.7

Figure 1. Typical oscillograms from observing sessions using a 20 ns multiple-mode laser pulse, and associated normal point residuals. The horizontal time base of the oscillograms is 40 ns/division.

any of the 20 ns data can be used reliably to estimate the station coordinates.

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DISCUSSION

Shelus : Were the solutions for Orroral station location parameters made simultaneously with the McDonald data set ?

Morgan : Yes. Orroral was adjusted simultaneously with McDonald. However, the adjustment of McDonald's coordinates relative to a McDonald only solution was less than 10 cm in each of three coordinates. The data set used for McDonald ran from 1971 through 1980.