Earth Rotation from Lunar Laser Ranging

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ABSTRACT. Results from Lunar Laser Ranging data analysis are presented: (a) the values and statistics of UT1 determined by three stations are given; (b) the lunar tidal acceleration $\dot{n}$ is found to be -24.9 ± 1.0 arc sec/century^2; (c) the tidal-effect coefficient k/C for UT1 is shown to be in strong agreement with the theoretical value; and (d) corrections to the IAU values of precession and nutation are estimated.

1. INTRODUCTION

For seventeen years data have been acquired using lunar laser ranging (LLR). Throughout that period there have been continuing enhancements in all areas of the system: improved instrumentation, multiple observing stations, modeling, and refined data processing techniques. This paper presents the results derived from the JPL analysis of the current set of LLR data (August 1969 – July 1986). Included here are Earth rotation comparisons, geophysical parameters, and new estimates for precession and nutation corrections.

2. THE LLR DATA SET

The full span of LLR data comprises 5655 points taken from various combinations of five stations and four reflectors. The point counts by station are given in the following table:

Station	No. Pts
McDonald 2.7 m	3434
MLRS	664
Haleakala	289
Orroral	96
CERGA	1172

3. UT1−UTC

LLR data have provided determinations of UT0 at each of the stations on various days throughout the data span. The method used is that of daily decomposition, whereby post-fit residuals are examined for UT0 signatures for each station-reflector pair on a

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given day. [For details, see Dickey *et al.* (1985). These values are published periodically and appear in each issue of the Bureau International de l'Heure (BIH) Annual Report (Newhall *et al.*, 1986).]

The LLR-determined UT0 is then transformed to UT1−UTC using polar motion derived from the Kalman smoothing process of Morabito *et al.* (1988). Since February, 1985, 154 values of UT1−UTC have been obtained. A comparison of these values with Kalman-smoothed results is graphed in Figures 1–3. The stations used are MLRS, Haleakala, and CERGA. The graphs show the differences and standard deviations between LLR values and those obtained from interpolating a Kalman-smoothed time series whose values are given at the 5-day intervals of the BIH *Circular D*. There is large variation in the scatter exhibited in each of the three figures, but in all cases the scatter is consistent with the standard deviations. (The behavior of the CERGA data in Figure 3 is due to the use of a wide-pulse laser. A narrow-pulse instrument has recently been purchased and is being installed.)

A summary appears below, showing the station, the number of UT1−UTC values, the weighted mean of the differences of the UT1−UTC values, the standard deviation of each weighted mean, and the weighted rms scatter about the mean (all values are in milliseconds):

Station	No. Pts	Wtd Mean	Std Dev	Wtd RMS
MLRS	18	.005	.022	.179
< 12/85	6	.021	.039	.318
≥ 12/85	12	.003	.014	.161
Haleakala	29	.125	.039	.244
CERGA	107	.009	.044	.354

The entry for MLRS is further subdivided into two spans, reflecting station improvements made in December, 1985.

The Kalman-smoothed Earth-rotation and polar-motion series used in this analysis was constructed from observations supplied by a variety of sources: IRIS, LLR, Satellite laser ranging (SLR), and DSN VLBI. UT1 and polar motion values are produced at the same 5-day mesh points as the BIH *Circular-D* values. It is of interest to compare Kalman UT1−UTC values with those from the BIH. Figure 4 is a graph of the difference between 1-day Kalman-smoothed UT1−UTC and correspondingly interpolated *Circular-D* values.

4. GEOPHYSICAL PARAMETERS

4.1 Lunar Tidal Acceleration

The lunar tidal acceleration $\dot{n}$ is the derivative of the mean motion in longitude, induced by tidal coupling with the Earth. The value determined from LLR data is:

$$\boxed{\dot{n} = -24.9 \pm 1.0 \text{ arc sec/century}^2}$$

in precise agreement with the most recent SLR-determined value (Christodoulidis, private communication, 1986). The above figure is equivalent to an increase of 3.7 ± 0.2 cm/yr in the lunar mean distance.

FIGURE 1. MLRS MINUS KALMAN

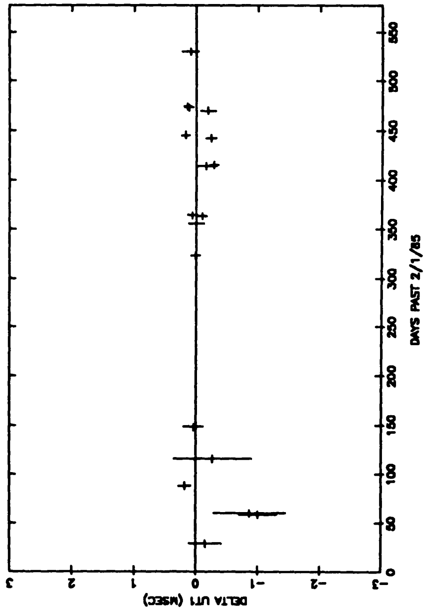


FIGURE 2. HALEAKALA MINUS KALMAN

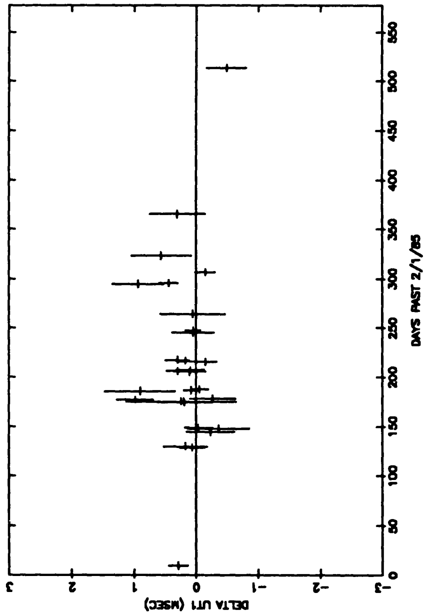


FIGURE 3. CERGA MINUS KALMAN

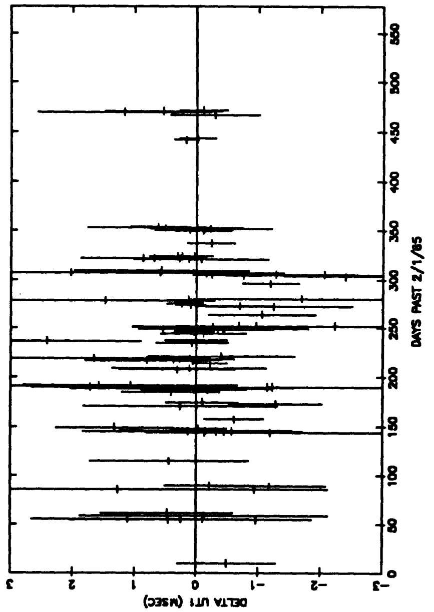
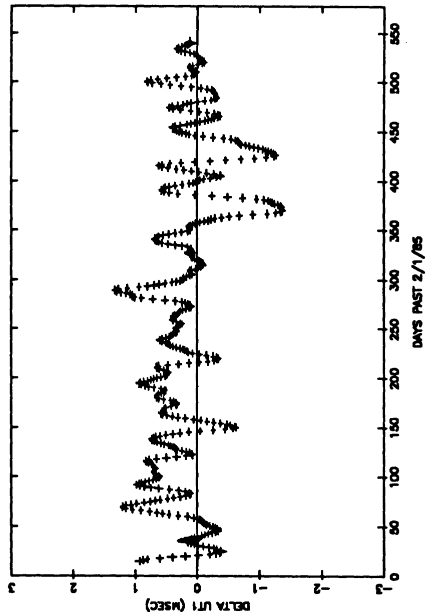


FIGURE 4. KALMAN MINUS BIH



4.2 Short-period UT1 Variations.

A theoretical investigation by Yoder *et al.* (1981) characterized the tidally induced variations in UT1 by the dimensionless quotient k/C, where k is that fraction of the Love number which causes the tidal variation in the moment of inertia of the coupled mantle, crust, and oceans, and C is the polar moment of inertia of the coupled units. (k/C includes the effects of the oceans, a decoupled fluid core, and rotational deformation.) The dominant periods in k/C are 1 month and 2 weeks. The change ΔUT1 to UT1 from this theory can be expressed as separate coefficients multiplying series of fortnightly and monthly terms:

$$\Delta\text{UT1} = -(k/C)_f \times \{\text{fortnightly terms}\} - (k/C)_m \times \{\text{monthly terms}\}$$

The theoretical values and the corresponding LLR results are:

Term	Theoretical Value	LLR Value
$(k/C)_f$	0.94 ± 0.04	0.93 ± 0.08
$(k/C)_m$	0.94 ± 0.04	0.94 ± 0.08

The LLR results and the theoretical values are seen to be in agreement.

5. PRECESSION AND NUTATION

Precession and nutation corrections have been estimated from LLR data. The set includes the luni-solar precession rate, the rate of change of the obliquity ($\Delta\dot{\epsilon}$), and both the 18.6-year and 1-year contributions to the nutations in longitude ($\Delta\psi \sin\epsilon$) and obliquity ($\Delta\epsilon$). The numbers given denote changes to the standard IAU value for each quantity. The LLR data span 17 years, permitting the linear rates and 18.6-year nutation to be separately estimated. Herring *et al.* (1986) used approximately five years of VLBI data to estimate the precession, obliquity rate, and several of the nutation periods (including the 1-year terms, though there were insufficient data to estimate directly the 18.6-year terms.) Then, using the corrections to the ellipticity of the Earth's core implied by the correction observed for the annual term, modifications to the 18.6-year term were calculated and the ocean corrections of Wahr and Sasao (1981) were added. The LLR results and the corresponding values from the Herring paper are compared in Table 1. The largest difference is 1.5σ.

$\Delta\dot{\epsilon}$ is expected to be zero. A correction of −1.3 mas/yr to the precession constant has been derived from a separate 7-year set of VLBI data by O. J. Sovers (private communication, 1986). The three corrections to the new IAU precession constant are modest compared to the 11.0 ± 1.5 mas/yr difference between the old and new IAU values (Fricke, 1981; Lieske *et al.*, 1977), indicating agreement between the value from space techniques and that from optical astrometry.

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Table 1. Comparison of precession and nutation results.

	LLR	Herring *et al.*
Δprecession	-0.5 ± 1.8 mas/yr	-2.4
$\Delta\dot{\epsilon}$	0.4 ± 0.7	0.0
18.6-year		(predicted)
$\Delta\epsilon$ *in-phase*	4.5 ± 3.3 mas	2.5
$\Delta\epsilon$ *out-of-phase*	-1.0 ± 5.2	1.6
$\Delta\psi \sin\epsilon$ *in-phase*	-11.8 ± 5.8	-3.2
$\Delta\psi \sin\epsilon$ *out-of-phase*	-0.1 ± 2.8	1.3
1-year		(observed)
$\Delta\epsilon$ *in-phase*	2.2 ± 2.4 mas	1.8
$\Delta\epsilon$ *out-of-phase*	1.7 ± 1.6	-0.2
$\Delta\psi \sin\epsilon$ *in-phase*	1.6 ± 1.9	1.8
$\Delta\psi \sin\epsilon$ *out-of-phase*	0.5 ± 1.3	0.6

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DISCUSSION

Kaplan: Could you comment on the confidence you have in your lunar ephemeris, in particular, how many parameters of the orbit you solve for? Are thse highly correlated with the precession/nutation parameters?

Reply by Newhall: We solve for 6 basic osculating orbit elements at the initial epoch, GM of the Earth, and the secular acceleration of the Moon's longitude. We also solve for the orientation of the ecliptic with respect to the equator. There is high correlation between these orientation angles and the precession; the correlation between the 18.6–year nutation terms and the lunar orbit is about .5 or less.

W. Kaula: Is there an ongoing effort to determine lunar gravity and tidal parameters, the physical librations, and particularly the k/Q, which, last I hear, was surprisingly high?

Reply by C. Yoder: Skip Newhall has examined differenced data from same station to different reflectors, obtained during the same day. This data set is directly sensible to lunar librations and tends to minimize the effects of timing errors, orbit, etc. This data set has been used to solve for low-order lunar gravity field coefficients, reflector coordinates, lunar Love number k and lunar dissipation or k/Q. The solution for k/Q is of order 1×10^{-3} and agrees with previous global solutions to better than 10%. This solution indicates that orbit errors, etc. have not contaminated the lunar k/Q values previously reported. I might add that the measured k/Q results from a shift in the forced precession of the lunar figure from that of the orbit. Furthermore, frictional couple of a small lunar core produces a similar offset and is a more likely explanation for the effect.