ROTATION OF THE EARTH FROM LUNAR LASER RANGING

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ABSTRACT. We have extended our estimates of variation of latitude and UT0 from the McDonald Observatory lunar laser ranging (LLR) observations to span the period October 1970 to November 1980. The typical formal uncertainties of our values are about 6 milliarcseconds (mas) and 0.5 milliseconds (ms) of time, respectively. We have compared our values of variation of latitude with those derived from the smoothed Circular D pole positions published by the Bureau International de l'Heure. The root-mean-square (rms) difference about the mean difference is 14 mas. A comparison of our smoothed UT0 estimates with those calculated from the smoothed Circular D values of UT1 and pole position gives a corresponding rms difference of 1.5 ms. For the period covered by the MERIT Short Campaign, we have also compared our smoothed UT0 values with (unsmoothed) ones derived from daily UT1 and pole-position values obtained by the Goddard Space Flight Center / Massachusetts Institute of Technology / Haystack Observatory group from very-long-baseline interferometric observations spanning two one-week periods. The rms difference about the mean difference is 0.3 ms.

We have analyzed the McDonald Observatory LLR data acquired between 1971 and 1980 to determine variation of latitude, $\Delta\phi$, and UT0. This analysis is an extension of our earlier work which was described by Langley et al. (1981a). Since the same technique has been used, only a shortened account will be presented here.

The data set we analyzed contained 3121 "normal points" (Shelus 1976-1981). These normal points were constructed by the University of Texas from the individual photon returns obtained between October 1970 and November 1980 from the Apollo 11, 14 and 15 and Lunakhod 2 retro-

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reflectors. We edited and reweighted these data to improve their consistency, in the same manner as described by Langley et al. (1981a).

Our method of analysis is similar to that of King et al. (1978), but incorporates several improvements. First, solid-body elasticity and dissipation in the moon are included in our model of the rotation of the moon (Cappallo 1980), and solid-body tides have been added to the model for the positions of the observatory and the reflectors. Second, the motion of the earth's rotation axis in space is calculated using expressions for precession based upon the International Astronomical Union's 1976 System of Astronomical Constants (Müller and Jappel 1977, Lieske et al. 1977) and Wahr's theory of nutation (Wahr 1981). Third, instead of using values for $\Delta\phi$ computed from pole-position data published by the Bureau International de l'Heure (BIH), we incorporate in our analysis a continuous piece-wise-linear model for this variation, similar to the one used for UT0 (King et al. 1978).

Our models of $\Delta\phi$ and UT0 have the form:

$$f(t) = g_i + \frac{g_{i+1} - g_i}{t_{i+1} - t_i}(t - t_i);$$

$$t_i \leq t \leq t_{i+1};\ i = 1,2,3,\ \ldots,\ n-1,$$

where the $g_i \equiv f(t_i)$ are the $\underline{n}$ parameters ("tabular points") estimated in the analysis. The time intervals between successive tabular points need not be uniform; they are chosen at nearly monthly intervals to coincide approximately with the center of the usable LLR data for each lunation. For the period ending November 1980, 112 tabular points were used in the model for the variation of latitude and an equal number, at the same epochs, in the model for UT0. Since LLR observations are sensitive only to changes in the earth rotation parameters, one tabular point for each model was held fixed.

Approximately monthly spacing of the tabular points appears so far to be sufficient to model the variation of latitude: after estimation of these parameters, the LLR residuals show little evidence of signatures characteristic of variation of latitude with periods less than a month. On the other hand, there remain in the residuals significant signatures indicative of short-period fluctuations in UT0. In order to avoid increasing the number of tabular points by the several hundred necessary to model these fluctuations, we used a two-step procedure to estimate UT0. In the first step, we estimated simultaneously all parameters, including 111 parameters each for latitude and UT0. In the second step, we analyzed the postfit residuals from each day of observations separately (see, e.g., Stolz et al. 1976) to obtain a range bias and a correction to UT0 for each day on which there were two or more observations of a single reflector spanning a period of 1.5 hours or more. The 1.5 hour criterion is a compromise: requiring the observations to span a longer period results

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in fewer daily values and increases the number of gaps in the estimates; using a shorter period results in far "noisier" estimates. These daily estimates from the residuals were combined with those of the piece-wise-linear model to produce 706 values of UT0 for the period between October 1970 and November 1980. We have explicitly removed from these values Woolard's (1959) fortnightly and monthly tidal terms in UT1 with amplitudes of 0.17 ms and larger.

The typical formal uncertainties of our $\Delta\phi$ and UT0 values are about 6 milliarcseconds (mas) and 0.5 milliseconds (ms) of time, respectively.

We iterated our solution once and found that each of the changes in $\Delta\phi$ and UT0 was less than its standard error, indicating satisfactory convergence. The postfit root-mean-square (rms) of the range residuals was 18 cm.

Our new values of $\Delta\phi$ and UT0 for the period October 1970 to October 1979 do not differ significantly from our values in the BIH Annual Report for 1980 (Langley et al. 1981b). For the period November 1979 to November 1980, the values are available from the authors. We have smoothed our daily estimates of UT0 using a Gaussian smoothing window with a full-width-at-half-maximum of about 8 days and interpolated among the smoothed values to obtain a set of values at 5-day intervals. These values are also available from the authors.

For the approximately 10-year span from October 1970 to November 1980, comparisons of our $\Delta\phi$ and UT0 estimates with those calculated from the smoothed Circular D pole-position and UT1 values published by the BIH (Vondrák smoothing parameter $\varepsilon = 10^{-7}$) give rms differences about the mean differences of 14 mas and 1.5 ms, respectively.

For the period covered by the MERIT Short Campaign (Wilkins 1980), we have compared our values of UT0 at McDonald Observatory with values derived from daily UT1 and pole-position values obtained by the Goddard Space Flight Center / Massachusetts Institute of Technology / Haystack Observatory group from very-long-baseline interferometric (VLBI) observations of extragalactic radio sources (Ryan et al., personal communication 1981; see also, Ma 1981). Figure 1 shows (i) the LLR daily estimates, (ii) the curve resulting from a smoothing of these values and (iii) the VLBI daily estimates. An irrelevant offset has been applied to the VLBI values so that the mean difference with respect to the LLR curve is zero. The average formal uncertainty of the LLR daily values is 0.5 ms with a median value of 0.4 ms. Their weighted rms about the smooth curve is 0.3 ms. The average and median formal uncertainties of the VLBI values are both 0.2 ms and the weighted rms scatter of the VLBI values about the LLR curve is 0.3 ms. Figure 1 indicates good agreement between the LLR and VLBI values of UT0 on a weekly basis. However, there are fluctuations of the VLBI values with respect to the LLR curve which may be significant. Further observations, analyses and comparisons are required to

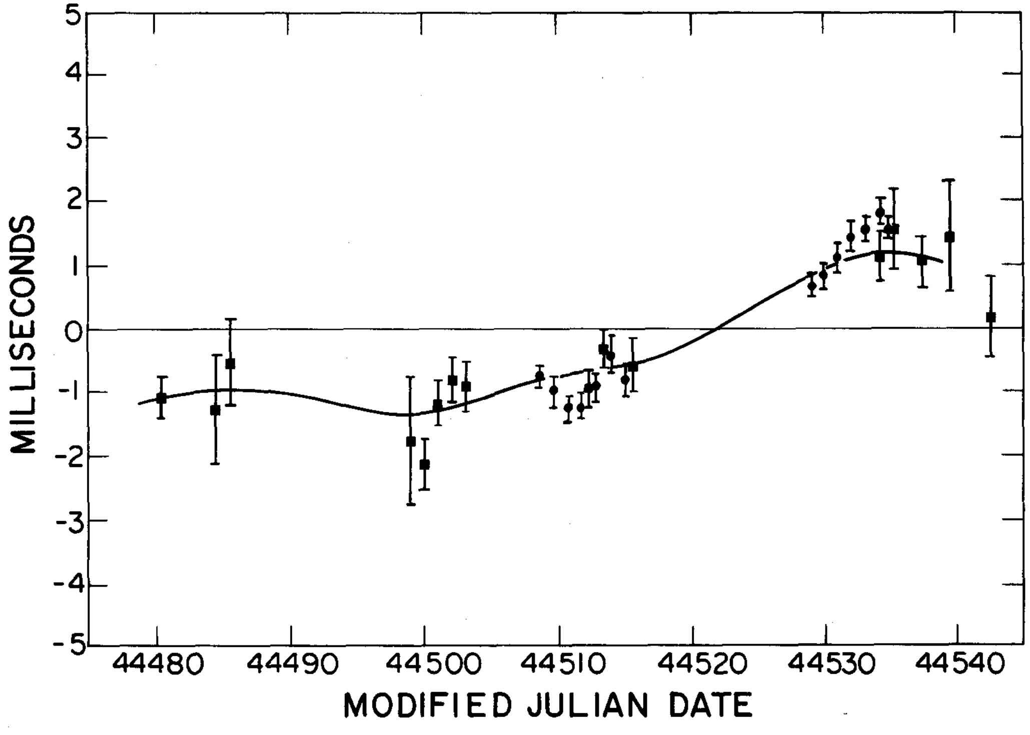

Figure 1. UT0 at McDonald Observatory from LLR and VLBI observations minus UT0 derived from the smoothed Circular D pole-position and UT1 values published by the BIH (Vondrák smoothing parameter $\varepsilon = 10^{-7}$) for the period covered by the MERIT Short Campaign. Fortnightly and monthly tidal terms have been removed from both the LLR and VLBI values (see text). LLR daily values: ⫫, VLBI daily values: ⫫. The curve was obtained from a smoothing of the LLR daily values. Modified Julian Date 44480 corresponds to 29 August 1980.

determine whether such short-period fluctuations are real or whether they are artifacts of the analysis of either (or both) sets of data.

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DISCUSSION

Klepczynski : What lunar ephemeris do you compare against ?

Langley : We have developed our own numerically-integrated model of the lunar orbit and we estimate the initial conditions and other parameters of this model simultaneously with the near-monthly tabular points in our models of UT0 and $\Delta\phi$.

Feissel : The long term and medium term structure of the differences of UT results with BIH Circular D differs somewhat from the structure of the residuals obtained by Fliegel during the same period of McDonald observation (1971-1980). Can you comment on this fact ?

Langley : We have not seen the most recent JPL results. However, any differences between the MIT and JPL results are probably due to the different models used to reduce the LLR data. In an effort to reduce the coupling between the Earth rotation parameters and those describing the orbit and rotation of the Moon, we estimated monthly variations in UT0 (and latitude) simultaneously with all other parameters affecting the observations. From the residuals of that analysis we then estimated higher frequency variations in UT0 This is a different approach from that adopted by JPL. In addition, there may be other specific differences in the models used which could account for the differences in UT0 results. We intend to investigate these differences in our future work.