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ANALYSIS OF LUNAR LASER RANGING DATA FOR EARTH DYNAMICS APPLICATIONS

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I. Introduction

Under this grant we have analyzed data from laser ranging observations of the moon, obtained by the McDonald Observatory of the University of Texas between October 1970 and October 1979. The chief goal of our analysis was the determination of the axial rotation of the Earth, as measured by Universal Time.

The data analyzed were 2,651 "normal points," representing ranges measured to the Apollo 11, 14, and 15, and the Lunokhod 2 retroreflectors. The method of analysis was similar to that described by R. W. King, C. C. Counselman III, and I. I. Shapiro in "Universal Time: Results From Lunar Laser Ranging," J. Geophys. Res., 83, 3377-3381 (1978), but incorporated several improvements. Due largely to these improvements, the r.m.s. of the postfit residuals from the fit of our computer model to the range data was reduced about 33% from 28 centimeters for the analysis of 1,668 normal points presented in our 1978 paper, to 19 centimeters for the analysis described here.

II. Data Analysis Methods

The first of the improvements to our laser ranging data analysis involved our numerical model of the moon's rotation. In the equations of motion for the rotation, we incorporated the effects of elasticity and of tidal friction within the moon. The details of our numerical model are given by R. J. Cappallo in his 1980 M.I.T. Ph.D. thesis, entitled "The Rotation of the Moon." By virtue of the inclusion of these lunar-tidal effects in our dynamical model, the r.m.s. of the residuals from the fit to the lunar range data was reduced by about 15%.

Addition of the kinematic effects of solid-body tides on the positions of the observing site and the retroreflectors reduced the post-fit r.m.s. by about 2%.

A further 7% reduction in the r.m.s. of the residuals was achieved by reweighting and editing the data. We felt that in some cases the original uncertainty estimates, by E. C. Silverberg and co-workers at the University of Texas, were too small. This was especially true for observations from the period February 1973 to May 1976. Silverberg has confirmed that for this period the uncertainties are probably larger than originally thought. Increasing the uncertainty assigned to an observation causes it to carry less weight in our least-squares data analysis, in which an observation has a weight inversely proportional to the square of the assigned (one-sigma) uncertainty.

We deleted any observation whose residual was larger in absolute value than four times the r.m.s. of its immediate neighbors. In addition, some isolated points were deleted. An "isolated point" was an observation too far separated in time from other observations to be free from suspicion. Of the original 2,816 normal points obtained between October 1970 and October 1979, 35% were reweighted and 7.2%, including 1.2% isolated points, were deleted.

Using feedback from our analyses and from those of other groups, Silverberg also determined that the instrumental delay calibrations in 1972 and in September and October of 1974 were probably biased. Thus, for each of these periods, a constant

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The remaining 9% reduction in the postfit residuals is attributable to improvement of our model for the rotation of the earth. Lunar laser ranging observations are sensitive to variations of the latitude of the observing site as well as to Universal Time. In the analysis of King et al. (1978), the variation of the latitude of McDonald Observatory was computed from the polar motion data published by the Bureau International de l'Heure (BIH). We have found, however, that the BIH polar motion data, even in the "corrected" 1979 system, have significant errors. A test in which we analyzed a subset of the lunar laser ranging data that, by virtue of observing geometry, had minimal sensitivity to variations in latitude, yielded postfit residuals some 30% smaller in r.m.s. value than we had obtained with the complete data set. Now, we model the variation in the McDonald Observatory latitude, in addition to UT0, with unknown parameters that we estimate simultaneously with the various other parameters that affect the theoretical values of the range observable. (UT0 is the apparent Universal Time at the observing site, not corrected for the effect of polar motion.)

The variation of latitude and UT0 are modelled as continuous, piece-wise linear functions of atomic time, with roughly one-month spacing between the tabular points that mark the "joints" of the functions. Ninety-six tabular values for each, the variation of latitude and UT0, are used to span the nine-year period of the observations.

Approximately monthly spacing of the tabular points appears so far to be sufficient to model the variation of latitude. However, more frequent estimation of the variations in UT0 appears necessary. Since it is not practical to increase the number of tabular points in our program very much beyond 96, we have resorted to a two-step procedure for the estimation of the UT0 variations. In the first step of the procedure, we estimate all parameters simultaneously, including the 96 latitude and the 96 UT0 parameters. Then the postfit range residuals from this step are analyzed separately for one observing day at a time, to obtain an incremental correction to the estimate of UT0 for each day. We estimated two parameters, 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. Thus, we obtained 636 daily estimates of UT0. The formal standard deviation of a single-day estimate of UT0 was typically about 0.5 ms.

The daily estimates were then smoothed and a continuously defined estimate obtained by convolution with a Gaussian function of time. Functions with full widths at half maximum of about 4, 8 and 16 days were tried. We do not yet know which of these smoothing times produces the most realistic determination of UT0.

III. Discussion of Results

We compared the smoothed estimates of Universal Time that we had derived from lunar laser ranging, with the smoothed values published by the BIH, in the Bureau's 1968 and 1979 systems. For these comparisons we converted our values of UT0 to corresponding values of UT1 using the BIH data for polar motion. (UT1 measures the rotation of the earth about an axis that passes through the Conventional International Origin, the origin of coordinates adopted for the description of polar motion.) The comparisons would not have been affected significantly, had we used our own estimates of polar motion. (Note that we were able to estimate only one of the two coordinates of the pole, the coordinate along the meridian of McDonald Observatory, because we had lunar ranging data from only that one observing site.)

Figure 1 shows an example of a comparison with 1979 BIH data. The width of the smoothing function in this example was 8 days. The r.m.s. difference, for the entire nine-year time span and again with 8-day smoothing, between the lunar laser ranging and the BIH determinations in the 1979 system is 1.97 ms. The r.m.s. difference between the lunar laser ranging and the BIH determinations in the 1968 system is 2.13 ms. The results of our comparisons will be presented at the 1980 spring meeting of the American Geophysical Union. An abstract is in EOS [R. B. Langley, R. J. Cappallo, C. C. Counselman III, R. W. King, and I. I. Shapiro, "Lunar Laser Ranging Determinations of Universal Time," EOS Trans. A.G.U., 61, page 212 (1980)], and a full-length paper is being prepared for publication.

IV. Future Work

This work is continuing under another NASA contract, number NAS5-25833. Under that contract, further comparisons of the lunar laser ranging determinations of UT0 with those derived from other techniques, especially very-long-baseline interferometry (VLBI), will be undertaken. Our determinations of the variation of latitude will also be refined, and these results will be compared with results from analyses of satellite Doppler, satellite laser ranging, and VLBI observations.

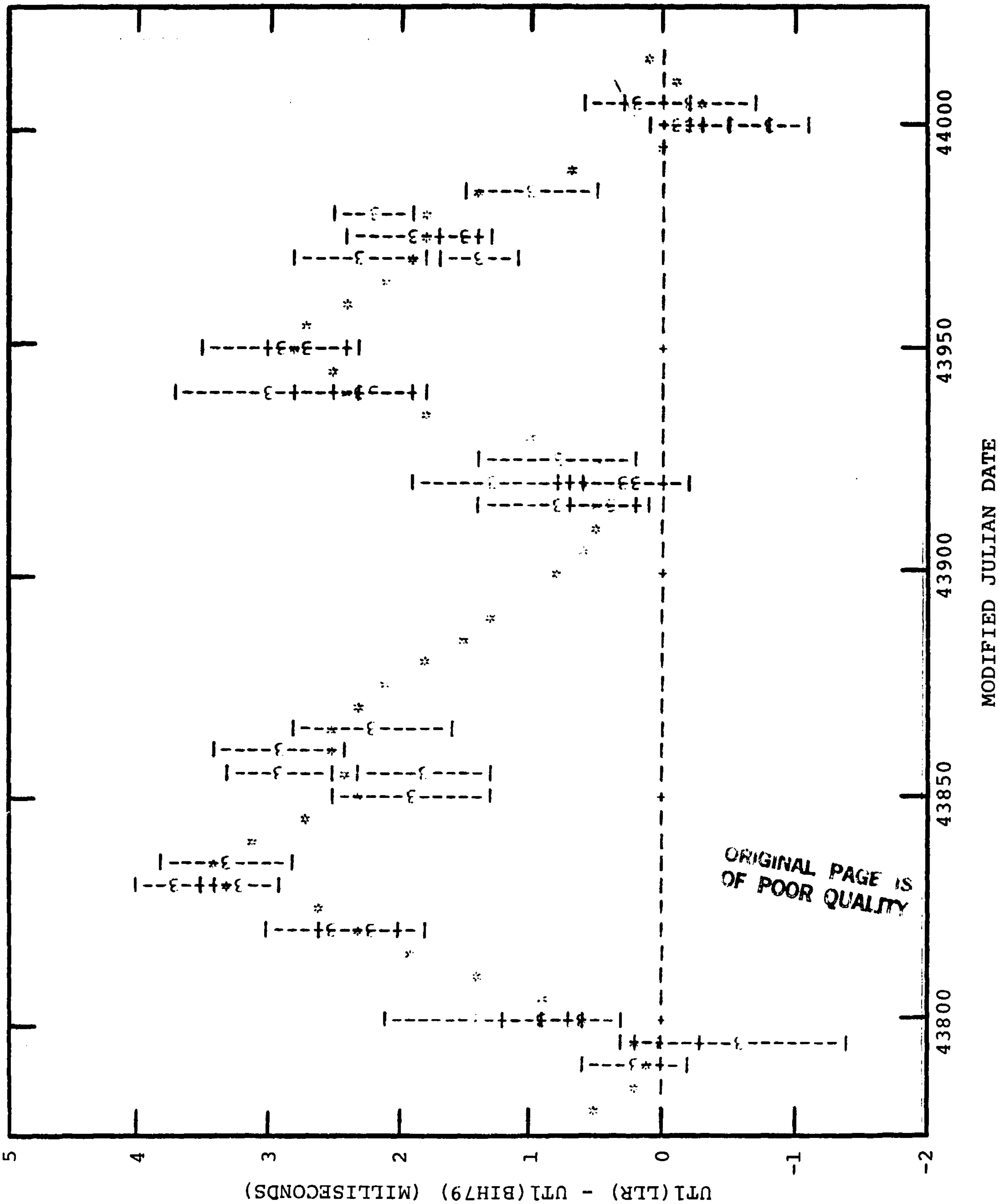

FIGURE 1. DIFFERENCE BETWEEN DETERMINATIONS OF UNIVERSAL TIME BY LUNAR LASER RANGING AND BY B.I.H.