Reports

Earth Rotation Measured by Lunar Laser Ranging

Abstract. *The estimated median accuracy of 194 single-day determinations of the earth's angular position in space is 0.7 millisecond (0.01 arc second). Comparison with classical astronomical results gives agreement to about the expected 2-millisecond uncertainty of the 5-day averages obtained by the Bureau International de l'Heure. Little evidence for very rapid variations in the earth's rotation is present in the data.*

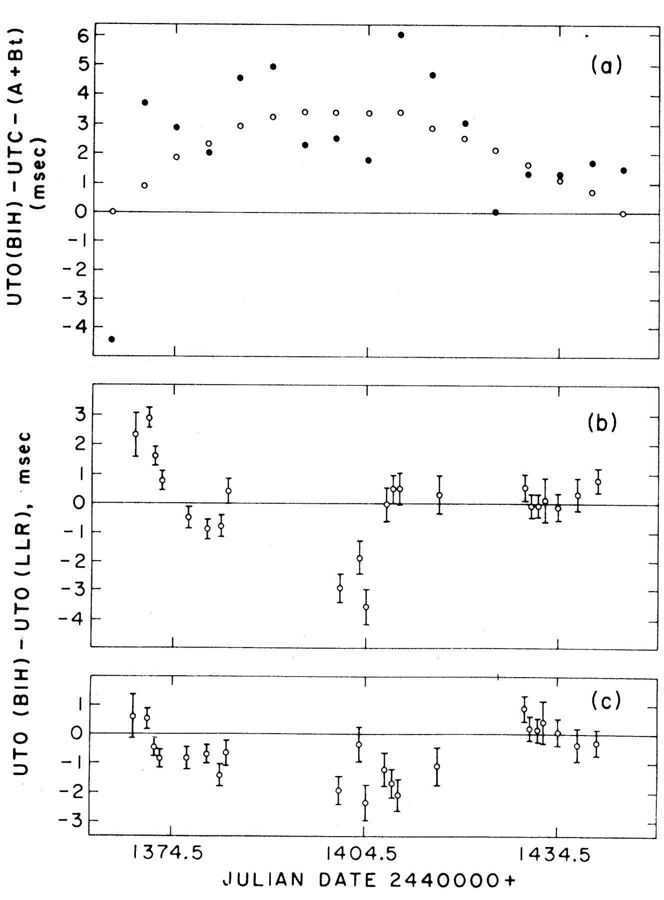
A regular program of pulsed laser measurements of the distance to retroreflectors on the moon has been carried out at the McDonald Observatory in Texas since 1969 (*1–3*). The total number of successful runs obtained is about 1800. The averaged results from each run through 1973 have been published (*4*). The accuracy was usually 30 to 45 cm before the installation of a new calibration system late in 1971. Since then, the typical accuracy for a run has been between 10 and 20 cm.

The lunar laser range data give information on the rotations of the earth and moon about their centers of mass, as well as about the lunar orbit. Progress on analyzing the data through early 1973 is described in (*1*). Further major improvements have enabled us to fit the data at present within 41 cm root-mean-square (r.m.s.) (*5*). In the previous work we used the classical astronomical results of the Bureau International de l'Heure (BIH) for universal time (UT1), the earth's angular position in space, and polar motion. Since the uncertainties in the BIH values are expected to contribute at least 30 cm r.m.s. to the residuals, and the weighted r.m.s. range measurement errors are 12 cm, the errors in the present lunar orbit, librations, reflector coordinates, and so on, are estimated to contribute 25 cm r.m.s. or less.

For data from a single station, we cannot separate errors in UT1 from errors in the component of polar motion perpendicular to the meridian through the station. The combined effect of UT1 and this component of polar motion can be measured, and this combination is designated UT0 (local apparent universal time). An error ΔUT0 gives a range error $\Delta\rho$ which is approximately

$$\Delta\rho \simeq (R_e \cos\phi \cos\delta \sin H)\Delta \mathrm{UT0} \quad (1)$$

Here R_e is the earth's radius, ϕ the geocentric latitude, δ the lunar declination, and H the lunar hour angle. Since errors in the lunar part of the problem give no significant range errors with periods of less than 13 days, one can use the diurnal variation in the range residuals to determine ΔUT0. This sharp spectral separation should make the effective range error for rotation determination much smaller than the overall 41 cm r.m.s.,



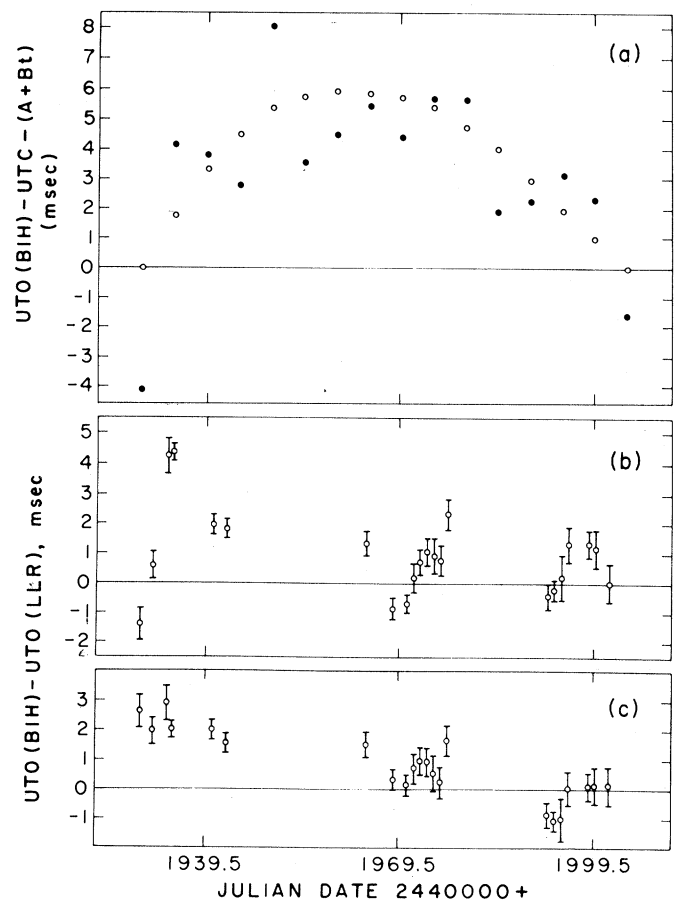


Fig. 1 (left). (a) (•) BIH raw 5-day average values of UT0 − UTC (coordinated universal time), with a linear term subtracted. (○) Vondrak-smoothed BIH values. (b) Differences between linearly interpolated BIH raw values and individual day LLR values. (c) Same, except using Vondrak-smoothed BIH values. Fig. 2 (right). Same as Fig. 1, except for a different time period.

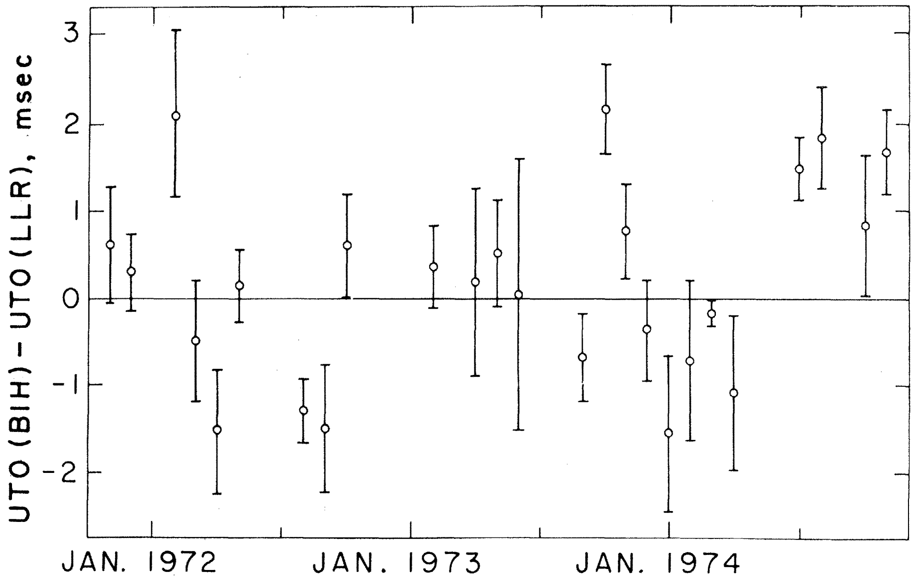


Fig. 3. Lunation means of the differences between the Vondrak-smoothed BIH values and the LLR values. The bars represent r.m.s. departures from the means.

and close to the measurement error estimate of 12 cm r.m.s.

We have analyzed the data acquired between 20 August 1969 and 30 November 1974 to obtain 194 single-day values of ΔUT0. Only days on which measurements were made at times differing by at least 3 hours were included. Corrections to UT0 and the earth-reflector distance were solved for on each day, the latter strongly reducing the effect of uncertainty in the geocentric range to the retroreflectors. A correction to the meridian component of polar motion was not solved for (*6*).

The best, worst, and median accuracies for the lunar laser ranging (LLR) values of UT0 are 0.21, 1.53, and 0.50 msec. This includes the effect of the range measurement uncertainties plus an allowance for the uncertainty in the BIH value for the meridian component of the pole position. When an allowance is also made for the uncertainty in orientation of our present lunar ephemeris with respect to the earth's equatorial plane, we estimate that the median uncertainty in the LLR values of UT0 is increased to about 0.7 msec. The 5-day mean values published by the BIH are currently believed to be accurate to ±40 cm (±0.013 arc second) for each component of polar motion and ±2 msec (±0.030 arc second) in UT1 (*7*), which gives an expected uncertainty in the BIH value of UT0 at McDonald of about 2 msec.

In the work described above, we took as a starting point a 44-parameter Jet Propulsion Laboratory (JPL) fit to the data through November 1974. In this fit, linearly interpolated values of UT1 and polar motion based on the BIH Circular D smoothed values were used (*8*), and corrections were made for: short-period variations in UT1, assuming the Love number k_2 for the earth is 0.29 [(*9*); see also (*10, 11*)]; the effects of the deformable earth and the fluid core on the nutation series (*12*); diurnal polar motion (*13, 14*); atmospheric refraction (*1*); and the vertical component of the solid earth tides. We do not yet correct for the effects of ocean loading or the horizontal component of the tides.

Three of the parameters solved for were the two components of an annual term in UT0 − UT0(BIH) and a linear drift term intended to represent possible long-period model deficiencies. The corrections found were

$$\mathrm{UT0} - \mathrm{UT0(BIH)} = -0.007 \sin L' - 0.023 \cos L' + 0.011(t - t_0) \quad (2)$$

where L' is the solar mean longitude, t is time (years), and UT0 is given in arc seconds. It should be noted that the least-squares solution procedure led to the McDonald longitude being chosen to give zero weighted average offset with respect to UT0(BIH) over the period covered by our data, so that the value of t_0 is roughly 1973. A subsequent analysis for differences between BIH and LLR values of UT0 was done at the Joint Institute for Laboratory Astrophysics with residuals from the JPL solution. Thus the BIH values referred to in the remainder of this report actually are modified by the addition of the terms from Eq. 2 and the short-period variations.

In comparing our results with those of the BIH, we started by using the BIH Circular D smoothed values, but we have also employed (i) the 5-day raw values based on astrometric data only and (ii) additional smoothed values provided by B. Guinot, director of the BIH. In the smoothing done by the BIH, Vondrak's method (*15*) was used, with the smoothing parameter $\epsilon = 10^{-10}$ for the two components of polar motion x and y and 10^{-11} for UT1. We found that the Vondrak-smoothed data agreed best with our determinations. We obtained r.m.s. differences between the BIH and LLR values of 1.77, 1.52, and 1.37 msec, respectively, for the BIH raw data, the Circular D smoothed values, and the Vondrak-smoothed values. We did not remove the corrections for the short-period variations in UT1 (*9*) when using the 5-day raw values, which should have been done. Correcting for this would reduce the r.m.s. difference for the 5-day raw values to 1.63 msec.

An important question concerning the classical astronomical results is whether a substantial part of the short-period fluctuations in the 5-day average values is due to real variations in the earth's rotation. In Figs. 1a and 2a we have plotted the BIH raw values and Vondrak-smoothed values for two periods when the differences were large and we had good LLR data. In Figs. 1b and 2b we show the differences between the linearly interpolated BIH raw values and the LLR values, while in Figs. 1c and 2c we show the differences from the LLR values if the Vondrak-smoothed BIH values are used. The latter differences are smaller than those obtained for the BIH raw values, and the changes in the differences over a few days are considerably smaller. We thus conclude that the Vondrak-smoothed BIH values fit the real rotation of the earth better than the raw values do.

We have also considered the fluctuations during each lunation in the differences between the LLR results and the Vondrak-smoothed BIH results. Only the lunations for which we had determined four or more values of UT0 were used. We do not find any systematic variations. The weighted r.m.s. difference from the lunation mean for all our data is 0.70 msec. Since the median accuracy of our results is 0.50 msec if the ephemeris orientation question is ignored, we conclude that there is only a small amount of power at periods shorter than 1 month in the differences between the true values of UT0 and those deduced from the smoothed BIH data. Moreover, the quoted error budget of the lunar range measurements is probably realistic. The lunation mean values are shown in Fig. 3, along with the r.m.s. departures from the means.

A second U.S. lunar ranging station at

the Haleakala Observatory on Maui has begun operation. It has an accuracy goal of 2 to 3 cm for each normal point. The Australian station at Orroral Valley near Canberra and the Japanese station at the Dodaira Observatory are nearing completion. A new French station is being established at the Calern Observatory near Grasse, and the West German satellite ranging station at Wettzell will be capable of ranging to the moon also. Measurements in the Soviet Union are expected to continue. A 1974 COSPAR resolution (*16*) referring to LLR recommended "the establishment of a coordinated international program to determine variations in the Earth's rotation. . . ." An initial observing campaign called EROLD (Earth Rotation by Lunar Distance) is scheduled to start in 1977 and to continue for 1 year.

We have demonstrated that lunar laser ranging is capable of accurately determining the earth's rotation. The coverage will be substantially improved when the data obtained during the EROLD campaign are available. Values for both UT1 and polar motion should be obtained. In the future, if one or two Southern Hemisphere sites are added and if all of the observing stations achieve a normal point accuracy of 2 to 3 cm, we expect UT1 and polar motion to be determined with similar accuracy (*17*). Data obtained from lunar ranging and from other new techniques (*18*) thus should give valuable new information on short-period changes in the earth's rotation and on the excitation and damping of the Chandler wobble.

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Cloud Condensation Nuclei on the Atlantic Seaboard of the United States

Abstract. *Concentrations of cloud condensation nuclei measured along the East Coast from Virginia to Long Island ranged from 1000 to 3500 per cubic centimeter as compared to 100 per cubic centimeter in clean maritime air and 300 per cubic centimeter in continental air. The global anthropogenic production rate of cloud condensation nuclei may be comparable to the natural production rate; in some industrial areas cloud condensation nuclei are dominated by anthropogenic sources.*

Cloud condensation nuclei (CCN) are those aerosols in the air which serve as nuclei upon which cloud and fog droplets form. Although CCN form only a small fraction of the total atmospheric aerosol, they are important in determining the stability of clouds and the formation of precipitation (*1*). Some anthropogenic sources of CCN have been identified, for example, paper mills and oil refineries, although not all sources of air pollution are sources of CCN (*2*). However, urban areas in general appear to be CCN sources (*3, 4*). The relative importance of natural and anthropogenic sources of CCN on regional and global scales is still a matter for debate.

We present here the results of measurements of the concentrations of CCN and the optical extinction coefficient b obtained from an aircraft flying just off the Atlantic Coast from Cape Charles, Virginia, to Long Island, New York, on 19 November 1973. During the period of the measurements there was a stable northwesterly airstream over the region; therefore, the sampled air was continental in character and had passed over the heavily industrialized and urban areas of the northeastern states. For most of the time the aircraft flew within a surface haze layer at an altitude of 600 m and at a distance of 10 to 15 km east of the Atlantic Coast. Periodically, however, vertical profile measurements were obtained to the top of the haze layer. At 11:45 E.S.T. the top of the haze layer of Delaware Bay was at an altitude of 1000 m. At 12:45 E.S.T. off Sandy Hook (south of New York City) there were two distinct haze layers with tops at 1000 and 1500 m.

The CCN concentrations were measured with an automatic thermal gradient diffusion chamber (*5*). The value of b, due to both aerosol and gas molecules, was measured with an integrating nephelometer over a broad band of wavelengths centered on 500 nm (*6*). The air intake to the nephelometer was heated in order to evaporate any water on the aerosol; therefore, the measured b value should be that due to the dry aerosol. The visibility range L_v is related to b by $L_v = 3.9/b$ (*7*).

The main results of the measurements are shown in Fig. 1, where the magnitudes of the CCN concentrations and b are indicated by the lengths of lines drawn perpendicular to the direction of the flight path. At 0.2 percent supersaturation (*8*), the CCN concentrations ranged from 1000 to 3500 cm^{-3} and