DETERMINATION OF 'DECADE' FLUCTUATIONS
IN THE EARTH'S ROTATION 1620-1978

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ABSTRACT: The 'decade' fluctuations in the Earth's rotation in the period 1620-1978 are derived from astronomical observations. The torques on the mantle which produce these fluctuations attain a magnitude of 10^{18}Nm (10^{25} dyn cm) around 1900.

1. INTRODUCTION

The terrestrial frame of reference fixed in the mantle varies from a uniformly rotating frame because of tidal interactions with the Moon and Sun and changes in the distribution of angular momentum between the core, mantle and atmosphere. From an analysis of the apparent fluctuations in the position of the Moon relative to the stars, Brouwer (1952) found variations in the rate of rotation of the mantle occurring over decades which are two orders of magnitude greater than those due to tidal forces. Munk and MacDonald (1960) argued that the changes are too great to be explained by the re-distribution of angular momentum between the atmosphere and mantle, or by changes in the moment of inertia of the mantle. They, therefore, concluded that the changes were caused by the interchange of angular momentum between the core and mantle.

In this paper we report our results obtained by extending the number and range of observations available to Brouwer, particularly in the 17th century. Our results should provide a tighter constraint on the proposed mechanisms for the interchange of angular momentum between the core and mantle.

2. OBSERVATIONS AND REDUCTION

The main source of observations for this analysis are the timings of occultations of stars by the Moon taken from the catalogues of Morrison and Stephenson (1981) for the years 1623-1860, Morrison and Lukac (1980) for 1861-1942 and Morrison (1978a) for 1943-1971. Timings of contact 4 of solar eclipses were used to supplement the occultation observations before 1670 (Morrison and Stephenson, 1981).

E. M. Gaposchkin and B. Kołaczek (eds.), Reference Coordinate Systems for Earth Dynamics, 181–185.

The reduction of timings of occultations and eclipses leads to the determination of the difference ΔT between the uniform time-scale derived from the time-argument of the lunar ephemeris (dynamical time, TD) and the time-scale derived from the rotational period of the Earth (universal time, UT). Beginning with 1955 the values of ΔT are given by TAI−UT1+$32^{s}.184$, where TAI is the international atomic time-scale TAI+$32^{s}.184$, by adding the following empirical correction to the time-argument and hence the values of ΔT: $-1^{s}.821(-1.54+2.33T-1.78T^2)$, where T is measured in centuries from 1900.0 (see Morrison, 1979a). The greatest uncertainty in this empirical correction is ±1.0 in the coefficient of T^2 which arises from the tidal acceleration. This produces a possible systematic error of $\pm\ 1^{s}.8(T-0.55)^2$ in the values of ΔT before 1955. Each determination of ΔT is also subject to random errors in timing, the catalogue position of the star, the limb-profile heights of the Moon, and the lunar ephemeris. These produce the standard deviations (σ) listed in Table I for the values of ΔT derived from single observations. The errors in ΔT derived from TAI−UT1+$32^{s}.184$ beginning in 1955 are negligible in the present context. The numbers of observations within 3σ of the mean in each period are also listed in Table I.

Table I

Standard deviation of ΔT and number of observations within 3σ

Period	σ	$N<3\sigma$	Period	σ	$N<3\sigma$
1620–1669	1m	94	1820–1860	1.5s	1265
1670–1699	15s	65	1861–1942	1.3s	24800
1700–1759	5s	169	1943–1954	1.0s	~10000
1760–1819	2s	313			

In the period 1620–1860 the individual values of ΔT were smoothed by cubic splines having 13 knots spaced at proportionately smaller intervals of time according to the increase in the number of observations. From 1861 onwards annual means were calculated and smoothed using a 5-point convolute (see Morrison, 1979b). The resultant smoothed curve for ΔT is shown in the upper section of Fig 1. This is an improvement over the curve deduced by Brouwer in that we have extended the range and number of observations and have applied corrections for the limb-profile heights of the Moon in reducing the occultations. The erratic changes in Brouwer's results on a time-scale of less than 5 years do not appear in our results.

3. ANALYSIS

3.1 Difference in time-scales, ΔT, and the rotational displacement angle $\Delta\theta$.

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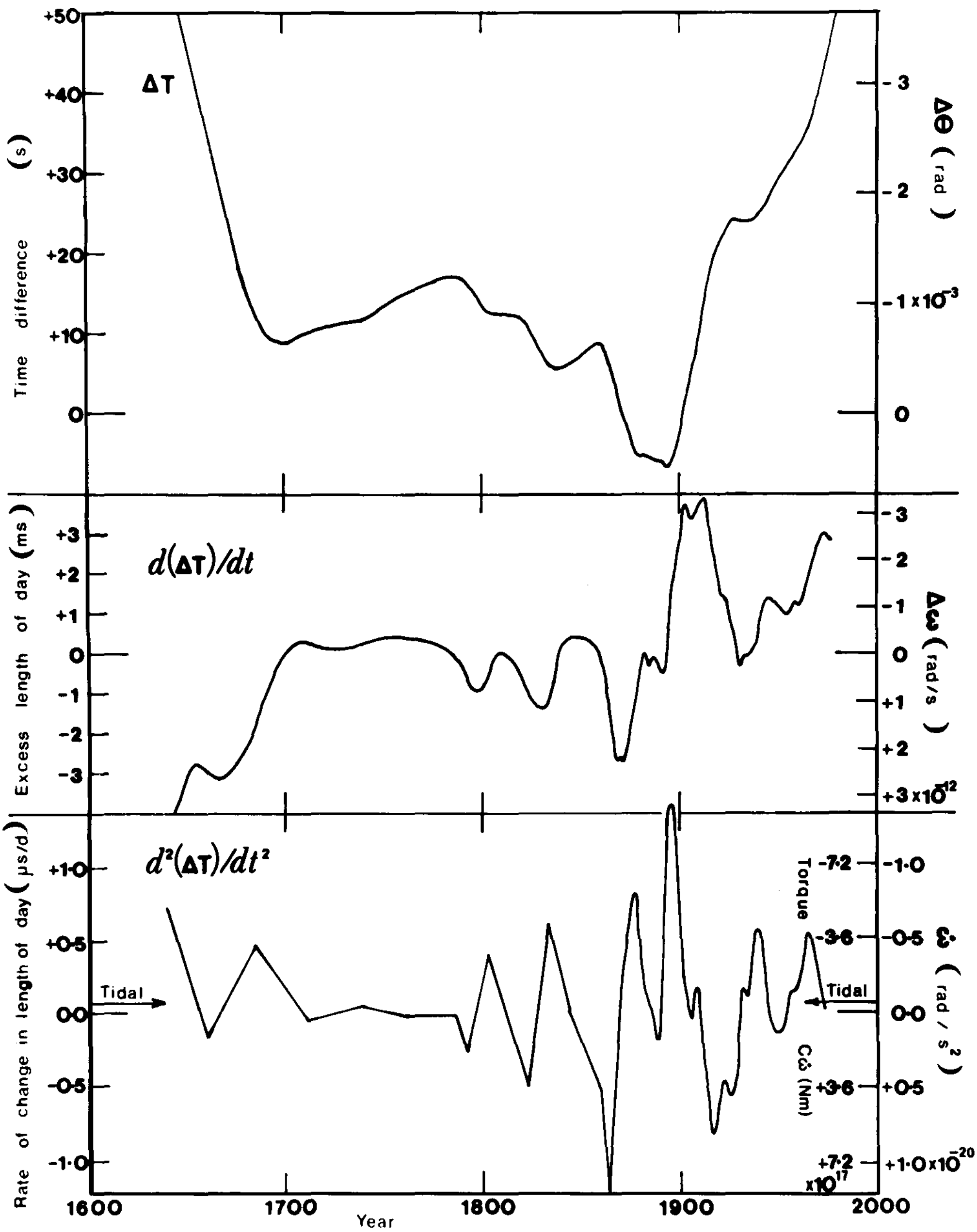

Fig. 1. Smoothed values of ΔT, and its first and second derivative, derived mainly from timings of lunar occultations. The bottom section shows the deduced magnitude and temporal behaviour of the torque operating on the mantle.

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If $\omega = \omega(t)$ is the actual sidereal rate of rotation of the mantle, the sidereal displacement angle of the Greenwich meridian, $\Delta\theta$ (radians), from a co-rotating frame of constant angular velocity ω^1 is given by

$$\Delta\theta = \int_{t_o}^{t}(\omega - \omega^1)dt + \Delta\theta(t_o).$$

The reference angular velocity ω^1 is (see Explanatory Supplement 1961, p.76)

$$\omega^1 = 1.00273\ 78119\ 06(2\pi/86400) \quad \text{rad/s},$$

which is close to the average rate of rotation of the mantle during the 18th and 19th centuries.

The time-difference ΔT, measured in seconds of mean solar time, is related to $\Delta\theta$ by

$$\Delta\theta = -1.002737\ \Delta T(15/206265) \quad \text{rad.}$$

As a consequence of a resolution of the International Astronomical Union in 1976 (IAU 1977), ΔT is defined to have the value given by the following relation at the epoch t_o = 1977 January 1 0^h TAI,

$$\Delta T(t_o) = +47^s.52,$$

and hence $\Delta\theta(t_o) = -0.003465$ rad. Thus,

$$\Delta\theta = -0.003465 \text{ rad} + \int_{t_o}^{t}(\omega-\omega^1)dt.$$

3.2 Angular velocity of rotation.

The first derivative of ΔT with respect to dynamical time (atomic time after 1954) is plotted in the middle section of Fig. 1. It was obtained by taking the derivative of the spline curves up to 1860 and by applying a 5-point convolute to the annual values of ΔT thereafter (see Morrison 1979b). We have

$$\begin{aligned} d(\Delta T)/dt &= d(TD-UT)/dt \\ &= 86400 \text{ SI seconds per SI day} - \text{number of mean solar seconds per SI day.} \end{aligned}$$

Thus, the first derivative of ΔT can be regarded as expressing the excess length of the mean solar day over the SI day of 86400 SI seconds, and is conveniently measured in units of milliseconds. The right ordinate in Fig 1 gives

$$d(\Delta\theta)/dt = \omega-\omega^1 = \Delta\omega \quad \text{rad/s},$$

where the value of the reference velocity ω^1 is given in section 3.1.

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3.3 Angular acceleration of rotation and torque.

The second derivative of ΔT with respect to dynamical (atomic) time is plotted in the lower section of Fig. 1. Before 1861 the second derivative consists of 13 straight lines between the knots of the cubic splines. From 1861 onwards the smoothed curve was derived by applying an 11-point convolute to the annual values of ΔT (see Morrison 1979b). The second derivative measures the rate of change in the length of the mean solar day and is conveniently measured in microseconds per day. Multiplying the angular acceleration by the principal moment of inertia of the mantle, $C = 7.2 \times 10^{37}$ kg m^2, gives the magnitude of the torque acting on the mantle (in units of Newton metres = 10^7 dyne cm). The results before 1800 are unreliable due to the sparsity of observations. From Fig. 1 it is seen that around 1900 the torques reach an amplitude of 10^{18}Nm in about 5 years. The tidal acceleration due to the Moon, Sun and atmosphere is $-(68\pm5) \times 10^{-23}$ rad/s^2 (Morrison, 1978b), which produces a torque of $-(0.49\pm0.04) \times 10^{17}$ Nm. The magnitude and temporal behaviour of the non-tidal torques impose fairly severe constraints on the possible mechanisms for core-mantle coupling (see Lambeck 1980).

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