The Earth's Rotation

M. G. Rochester

The most ancient and fundamental concern of astronomy is the orientation and motion of a terrestrial observer relative to the stars. Its geophysical aspects date from the time of Newton and Halley, and its mathematical foundations were laid by Euler 200 years ago. Despite this honorable antiquity, the subject is far from moribund and today presents a rich and fascinating array of challenges to observation, experiment, data analysis, and theory. The many-faceted problems of the three-dimensional rotation of the earth about its center of mass now attract astronomers and paleontologists, solid earth geophysicists and electrical engineers, general relativists and oceanographers, and applied mathematicians and scholars of classical texts.

In this review I attempt to summarize, as briefly as possible, the current state of knowledge in a field that is complex, extensive, and resurgent under the impact of late 20th century technology. I shall begin with a survey of the appropriate reference frames and problems involved in defining them and then outline the accuracy with which the earth's rotation can be measured relative to these frames by techniques already in use or on the threshold of realization. Following that, I shall discuss in turn the various spectral features of changes in the axis orientation and spin rate of the so-called 'solid' earth (Table 1) and the physical mechanisms known or likely to effect and affect them (Table 2). Copious references are given for deeper study. I shall concentrate almost exclusively on developments in the past decade or so since the appearance of the now-classic monograph by *Munk and MacDonald* [1960], the standard reference for most aspects of the subject.

Reference Frames

The earth is not a rigid body, and so the selection of a reference frame suitable for describing its rotation is not a completely straightforward matter. Strictly speaking, the phrase 'rotation of the earth' is shorthand for the rotation in space of a certain reference frame fixed in some prescribed way to a set of astronomical observatories distributed over the earth's crust. The difficulty of defining a reference frame is increased by the fact that the observatories are located on different crustal 'plates' that are in relative motion [*Vicente*, 1968; *Markowitz*, 1970; *Arur and Mueller*, 1971; *Tanner*, 1972]. The current choice of astronomers and geodesists is a 'geographic' frame whose origin lies at the earth's center of mass, whose z axis points to the Conventional International Origin (CIO)—corresponding very nearly to the mean position of the rotation pole from 1900 to 1905 determined by the International Latitude Service (ILS)—and whose x axis points at right angles to this in the plane of the Greenwich meridian as determined by the Bureau Internationale de l'Heure (BIH) in Paris. At the y axis the astronomers and geophysicists part company, the former choosing a left-handed set and heading 90°W of Greenwich and the latter going 90°E (Figure 1).

Polar motion, which may be either irregular or periodic (in which case it is called 'wobble'), is the displacement of the instantaneous rotation axis relative to this frame, on a small scale ($a \leqslant 0''.3$, $|x|$, $|y| \leqslant 10$ meters). The term 'polar wander' is reserved for the large departure of the rotation pole from its mean position at any one epoch, achieved only on the geologic time scale. Polar motion has been measured for over 70 years by the ILS and its successor, the International Polar Motion Ser-

---

This article was taken from the keynote address presented at the second GEOP Research Conference on The Rotation of the Earth and Polar Motion, which was held at The Ohio State University, Columbus, February 8–9, 1973.

TABLE 1. Spectrum of Changes in Earth's Rotation

A. Inertial Orientation of Spin Axis	B. Terrestrial Orientation of Spin Axis (Polar Motion)	C. Instantaneous Spin Rate ω about Axis
1. Steady precession: amplitude 23°.5; period $\simeq$25,700 years.	1. Secular motion of pole: irregular, $\simeq$0″.2 in 70 years.	1. Secular acceleration: $\dot{\omega}/\omega \simeq -5 \times 10^{-10}$/yr.
2. Principal nutation: amplitude 9″.20 (obliquity); period 18.6 years.	2. 'Markowitz' wobble: amplitude $\simeq$0″.02(?); period 24–40 years(?).	2. Irregular changes: (*a*) over centuries, $\dot{\omega}/\omega \leqslant \pm 5 \times 10^{-10}$/yr; (*b*) over 1–10 years, $\dot{\omega}/\omega \leqslant \pm 80 \times 10^{-10}$/yr; (*c*) over a few weeks or months ('abrupt'), $\dot{\omega}/\omega \leqslant \pm 500 \times 10^{-10}$/yr.
3. Other periodic contributions to nutation in obliquity and longitude: amplitudes <1″; periods 9.3 years, annual, semiannual, and fortnightly.	3. Chandler wobble: amplitude (variable) $\simeq$0″.15; period 425–440 days; damping time 10–70 years(?).	3. Short-period variations: (*a*) biennial, amplitude $\simeq$9 msec; (*b*) annual, amplitude $\simeq$20–25 msec; (*c*) semiannual, amplitude $\simeq$9 msec; (*d*) monthly and fortnightly, amplitudes $\simeq$1 msec.
4. Discrepancy in secular decrease in obliquity: 0″.1/century(?).	4. Seasonal wobbles: annual, amplitude $\simeq$0″.09; semiannual, amplitude $\simeq$0″.01.	
	5. Monthly and fortnightly wobbles: (theoretical) amplitudes $\simeq$0″.001.	
	6. Nearly diurnal free wobble: amplitude $\leqslant$0″.02(?); period(s) within a few minutes of a sidereal day.	
	7. Oppolzer terms: amplitudes $\simeq$0″.02; periods as for nutations.	

TABLE 2. Mechanisms with Effects Now Distinguishable on the Earth's Rotation

Mechanism	Effect*
Sun	
Gravitational torque	A, B7, C1, C3*c*
Solar wind torque	C2*c* (?)
Moon	
Gravitational torque	A, B7, C1, C3*d*
Mantle	
Elasticity	B1, B3–4, C1–2*a*, C3*c*–*d*
Earthquakes	B1, B3
Solid friction	B3(?), C1
Viscosity	C2*a*
Liquid core	
Inertial coupling	A2–3, B2, B6
Topographic coupling	C2*b*–*c* (?)
Electromagnetic coupling	A4(?), B3, C2
Solid inner core	
Inertial coupling	B2(?)
Oceans	
Loading and inertia	B1, B3, B5, C2*a*
Friction	B3(?), C1
Groundwater	
Loading and inertia	B4
Atmosphere	
Loading and inertia	B4
Wind stress	C2*c*, C3*a*–*c*
Atmospheric tide	C1

*Numbers refer to Table 1.

vice (IPMS). The five ILS observatories are spaced out along the same parallel of latitude (39°8′N), and thus the effects of any systematic errors in star catalogs are eliminated. Both the IPMS and the BIH publish determinations of the pole path about the CIO (Figure 2). The IPMS pole path is based on observations at the five ILS stations, whereas the BIH pole path currently incorporates data on latitude variation from some 50 stations, and thus the effects of star catalog errors are statistically reduced. The difference between the two pole paths, which can amount to $\simeq$0″.1, is a measure of the effects of errors due to local motions of the vertical, plate motions, refraction, instrumental peculiarities, and systematic differences in data reduction techniques. It is worth noting that the individual observations scatter much more widely than the published curves suggest. The IPMS and BIH both claim errors of only ±0″.01 in their published 0.5-year and 5-day means. Certainly, this sets a limit to the precision of which the basic instruments of optical astronomy, the photographic zenith tube (PZT) and the astrolabe, are presently capable.

New techniques, such as Doppler tracking of artificial earth satellites [*Anderle*, 1972], which provides pole positions at 2-day intervals, have already achieved an accuracy comparable to that of the BIH [*Feissel et al.*, 1972]. In fact, the BIH recently began to include in its data set the observations made by the Dahlgren Polar Monitoring Service (DPMS). Laser ranging to artificial satellites offers even greater accuracy together with pole positions determined at more frequent time intervals. *Smith et al.* [1972] report a sequence of

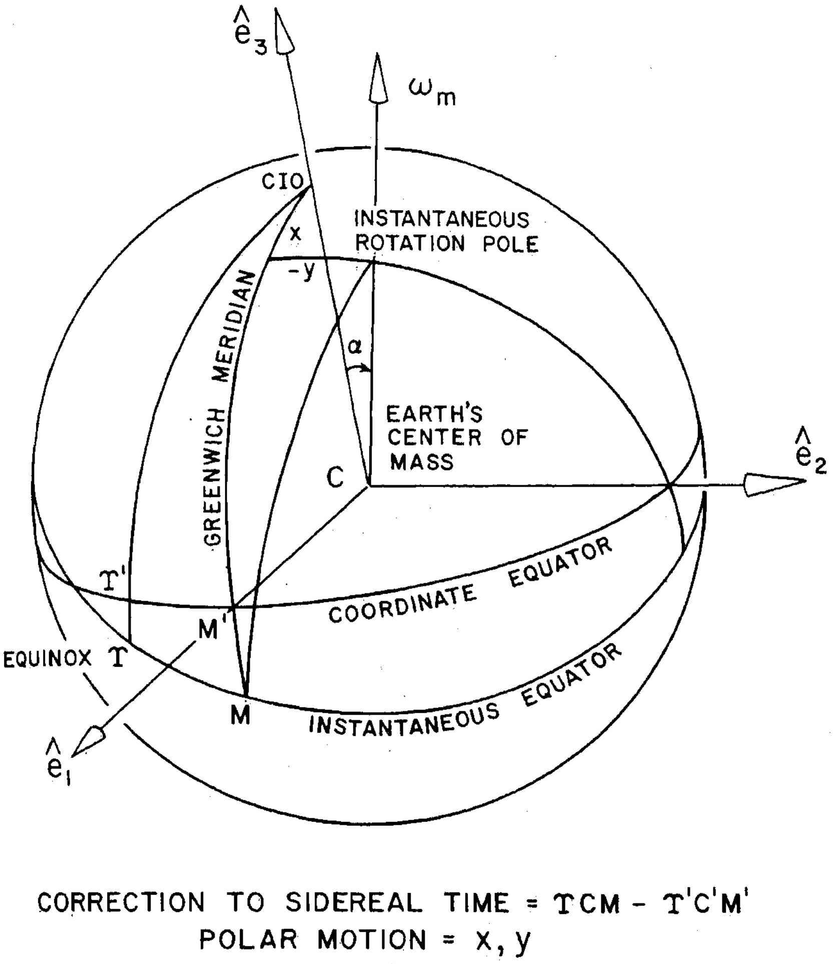


Fig. 1. Time and polar motion.

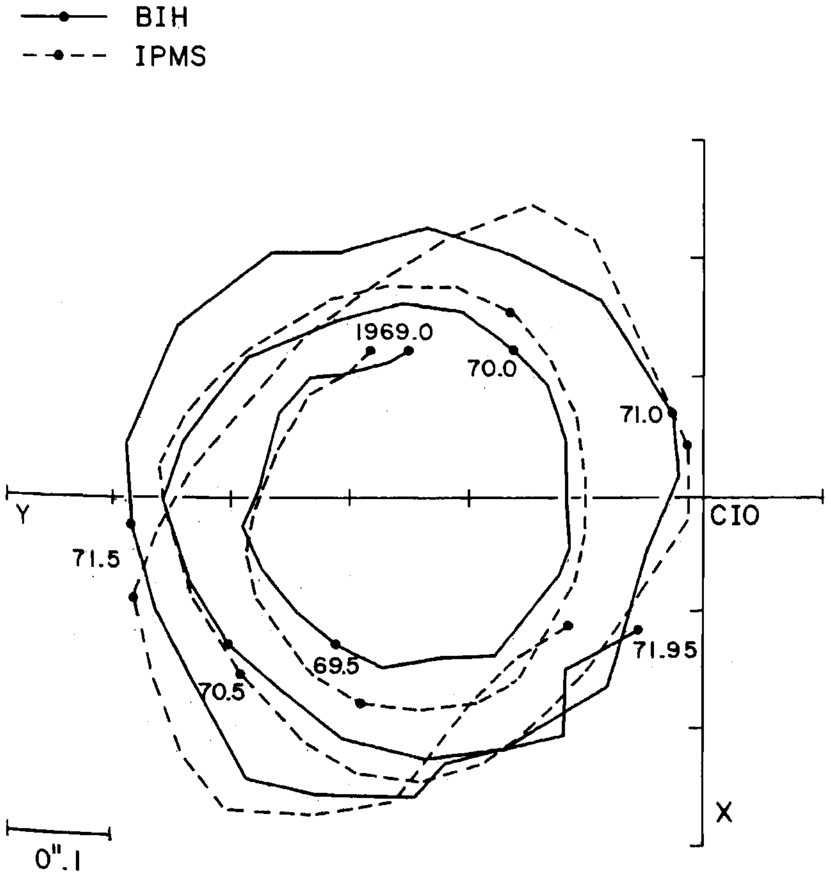


Fig. 2. Pole paths 1969.0–1971.95.

6-hour mean pole positions within ±0".03 of the BIH path from a single laser tracking system operated over 5 months. Accurate tracking of artificial satellites should also permit checking that the geographic axes of reference do pass through the earth's center of mass [*Lambeck,* 1971; *Melchior,* 1972]. *Gold* [1967] and *MacDonald* [1967] first pointed out that very long base line interferometry (VLBI) would make possible very precise measurement of changes in the earth's rotation (see also *Burke* [1969]). Laser ranging to corner cube reflectors on the moon should enable polar motion and spin rate to be measured with an accuracy nearly comparable to that expected from VLBI [*Alley and Bender,* 1968; *Faller and Wampler,* 1970; *Chollet,* 1970; *Rösch,* 1972]. Although the newer techniques will eventually largely replace optical astronomy, it will be important to continue the PZT observations for years to come to provide consistency and a standard of comparison during the transition period.

Orientation of the instantaneous rotation axis in space requires the selection of an inertial frame based on a catalog of fundamental stars, with due allowance for such things as proper motions and galactic rotation [*Woolard and Clemence,* 1966]. The best catalog in current use is FK4, based on over 1500 well-studied stars, but it contains systematic errors of the order of 0".1. Although these could be detected and corrected by a sustained program of laser tracking and photographic observation of artificial satellites [*Williams,* 1972], the development of VLBI seems to promise a better solution in the long run. The ultimate resolution of the order of 0".001 expected to be obtained with VLBI raises the possibility of using radio sources at enormous distances (with negligible proper motions) as a fundamental catalog, if a sufficiently dense distribution of quasars can be found over the celestial sphere.

The orbital motion of the moon and changes in the obliquity of the earth's equator to the ecliptic are connected to problems of the earth's rotation, and so it is useful to define an intermediate reference system tied to the ecliptic and vernal equinox at some epoch. Lunar laser ranging (LLR) will in the course of time greatly improve the determination of the moon's orbit, the lunar ephemeris [*Faller and Wampler*, 1970; *Rösch*, 1972]. The VLBI tracking of spacecraft or artificial satellites placed in orbit around other planets could at some future date tie the ecliptic frame to an inertial frame constructed from the quasar sources [*Preston et al.*, 1972].

Time

Essentially three different kinds of time are required to discuss the earth's rotation. Sidereal and universal time (UT) are both based on the earth's diurnal rotation. Sidereal time is defined by the angle through which the Greenwich meridian has turned past the vernal equinox (Figure 1). Universal time is related to sidereal time by an adopted formula (whose origins are now of purely historical interest) and is therefore an equivalent direct measure of the earth's axial spin. In practice, UT is determined by meridian transits of stars, and so the PZT provides simultaneous determinations of time and latitude. Universal time corrected for polar motion (Figure 1) is called UT1. Since the earth's axial spin shows periodic, irregular, and secular changes, UT1 does not provide a uniform measure of time. Such a uniform reproducible time scale, called atomic time (AT), has been made available since 1955 by atomic frequency standards accurate to 1 part in 10^{13}. These atomic 'clocks,' now widely distributed at astronomical observatories, are presently synchronized by transport and side-by-side comparison, or less accurately by radio signals from quartz crystal oscillators carried in artificial satellites, but remote synchronization using VLBI techniques should soon be feasible. The PZT observations, coupled with atomic timekeeping, from the participating stations are processed and disseminated by the BIH as UT1-AT. Changes in the earth's axial spin rate are therefore obtained by differentiating UT1-AT with respect to (atomic) time.

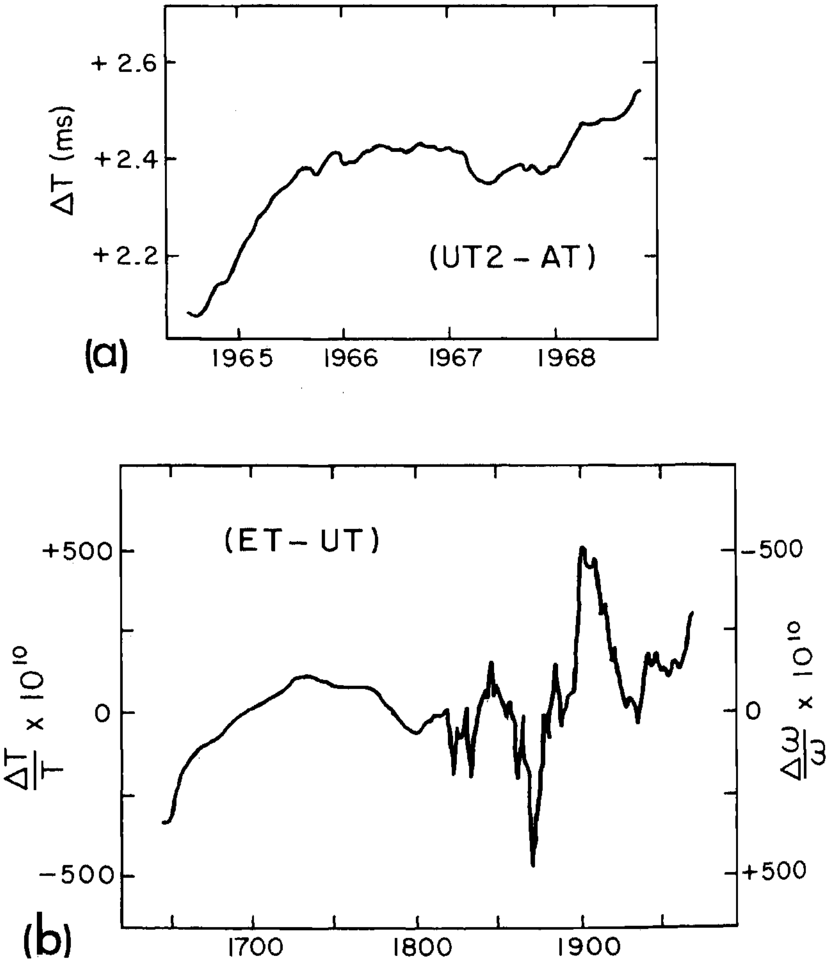
The third kind of time with which we have to deal is ephemeris time (ET), the basis of dynamical astronomy. Ephemeris time is the (presumed uniform) measure of time that appears as the independent variable in Newton's laws of motion and is effectively defined by the motions of the sun, moon, and planets over the past few centuries. Ephemeris time is independent of the earth's rotation but rests implicitly on Newtonian theory. Until the advent of AT, the irregularities in the earth's spin rate were measured by ET-UT (Figure 3). Any divergences between ET and AT will indicate hitherto unsuspected shortcomings in the theory of the moon's motion and/or possible non-Newtonian effects [*Sadler*, 1968; *Shapiro et al.*, 1971; *Oesterwinter and Cohen*, 1972].

The most recent comprehensive treatment of the measurement of time and polar motion is by *Mueller* [1969]. The methods used by the IPMS and BIH in processing their data are described by *Yumi* [1972] and *Guinot et al.* [1972]. The possibilities of the newer observational techniques now coming into use have been explored in the study edited by *Kaula* [1970].

Dynamics of Changes in Earth's Rotation

A change in the earth's rotation can be brought about (1) by a change in its angular momentum due to the application of external torques (lunar and solar gravitational torques on the equatorial bulge, the bodily and ocean tides, the solar wind) or (2) while its angular momentum remains constant, by a change in its inertia tensor (earthquakes, sea level fluctuations, rearrangement of the geographic distribution of air mass) or by internal redistribution of its angular

Fig. 3. Changes in length of day. (a) After Guinot *[1970]. (b) After* Stoyko *[1970].*



momentum (winds, core-mantle coupling).

The role of the core, almost completely enigmatic at the time when Munk and MacDonald wrote their book, has since become much more prominent. During the past decade a number of features of the earth's rotation spectrum, directly affected by the existence of the liquid core, have been identified with varying degrees of certainty [*Rochester,* 1970]. The principal effective mechanisms by which angular momentum can be transferred between the core and mantle are:

(1) inertial coupling due to the hydrodynamic pressure forces that act over the ellipsoidal core-mantle boundary when internal flow is induced in the liquid core by any shift in the earth's rotation axis [*Toomre,* 1966];

(2) electromagnetic coupling due to the operation of Lenz's law consequent upon leakage of geomagnetic secular variation (GSV) into the electrically conducting lower mantle [*Rochester,* 1960, 1968]. The GSV in turn is associated with internal motions of the highly conducting core, driven by mechanisms appropriately examined in the context of geomagnetic dynamo theory but closely connected with the earth's rotation.

Although there is as yet no seismic evidence for (or against) small-scale (not more than a few kilometers high) topography on the core-mantle interface, *Hide* [1969] has for other reasons proposed a coupling mechanism that may be comparable to or even stronger than the electromagnetic:

(3) topographic coupling, in which a stress on the mantle is produced by the flow of the rotating core over any 'bumps' or depressions on the core-mantle boundary.

Significant viscous friction at the core-mantle interface now seems most unlikely because of the very low molecular viscosity of the core estimated by *Gans* [1972] and the apparent ineffectiveness of turbulent (eddy) friction [*Toomre,* 1966; *Rochester,* 1970].

Precession

The combination of dynamical ellipticity (the equatorial bulge), obliquity, and spin causes the earth to respond to the gravitational attraction of the moon and sun by a steady precession of its rotation axis in space at a rate of $5037''$/century (Figure 4). The earth is treated as a rigid body to deduce from this rate the value of one of the fundamental geophysical constants, its dynamical ellipticity $H = (C - A)/C$, where C and A are its axial and equatorial moments of inertia, respectively. The effect of a liquid core, first treated imperfectly by Hopkins in 1839 and then elegantly by Poincaré in 1910, has been discussed most recently by *Stewartson and Roberts* [1963], *Busse* [1968], *Gans* [1969], and *Suess* [1970]. Even if VLBI can reduce the error in the measured lunisolar precession rate to $\pm0''.1$/century in the next decade [*Shapiro and Knight,* 1970], the effect of the liquid core (4 parts in 10^6) would remain undetectable. However, Shapiro and Knight point out that a more immediate result of this refinement will be the observational isolation of the general relativistic contribution to precession ($\simeq 1''.9$/century).

Nutation

The orbital motions of the earth and moon give rise to ripples on the precessional cone (Figure 4), the

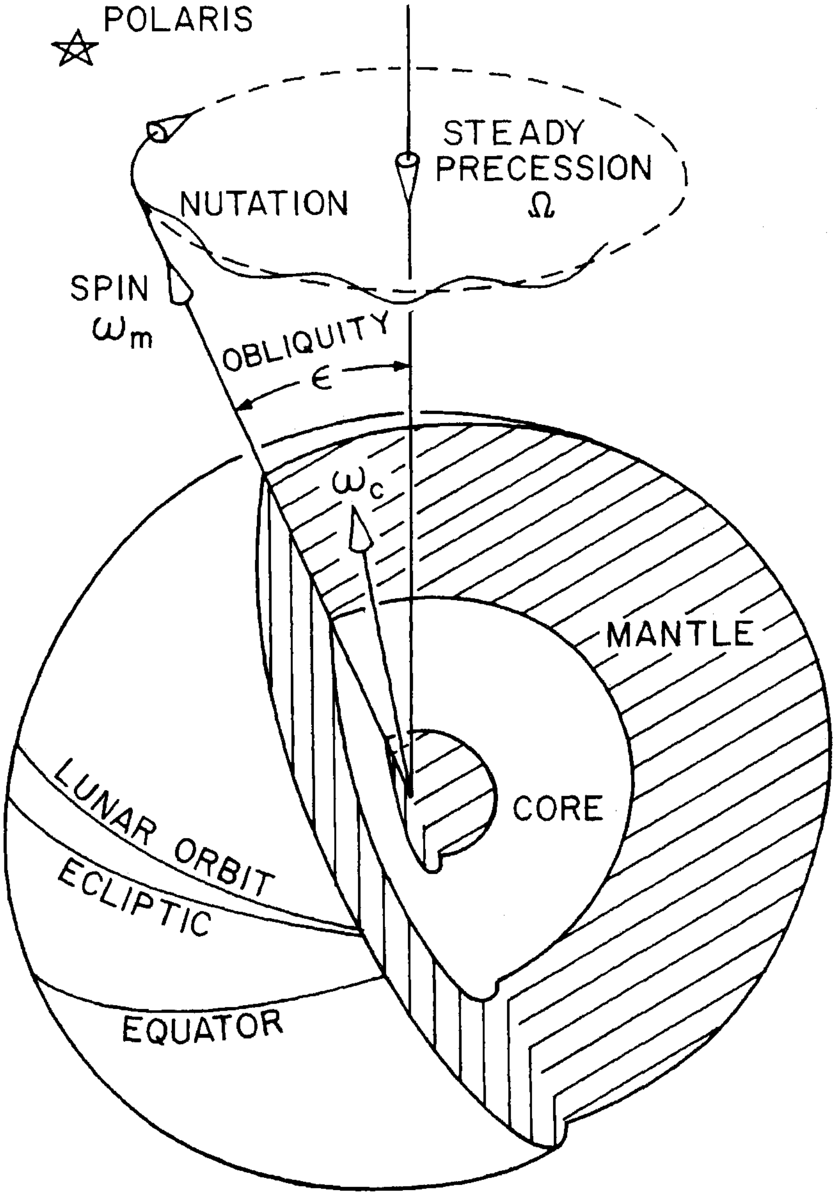


Fig. 4. Precession and nutation.

largest of which, the principal nutation, is associated with the regression of the lunar orbit's line of nodes with a period of 18.6 years. It is an elliptical motion of the rotation axis, the semimajor axis (nutation in obliquity) having an amplitude of $9''.20$. Independently, *Jeffreys and Vicente* [1957] and *Molodenskii* [1961] showed that allowing for mantle elasticity and the liquid core (inertially coupled to the mantle) removed the discrepancy of $0''.02$ between the observed amplitude and that derived from theory assuming the earth to be rigid.

Melchior [1971] has recently reviewed the dynamical effects of the liquid core on the long-period (18.6 and 9.3 years) and short-period (annual, semiannual, and fortnightly) nutations. Annual nutation in obliquity is due entirely to the presence of the core but is of small amplitude ($\simeq 0''.006$). Satisfactory observational confirmation of the corrections required by a deformable earth model has already been obtained by conventional astronomical techniques, according to Melchior (see also *Wako* [1970]). Clearly, the new methods of VLBI and laser ranging to the moon promise more discriminating tests of the earth models adopted by theoreticians.

'Secular' Decrease in Obliquity

The observed 'secular' ($\simeq$40,000-year period) decrease in the obliquity (Figure 4), at a rate $\simeq 47''$/century, can be almost, if not entirely, accounted for by the gravitational perturbations of the ecliptic by the other planets. Earlier analyses indicating a difference of $\simeq 0''.3$/century between calculated and observed rates have been questioned [*Lieske*, 1970; *Fricke*, 1971], and it now appears unlikely that any real discrepancy can exceed $\simeq 0''.1$/century [*Fricke*, 1972]. *Shapiro and Knight* [1970] suggest that a decade of VLBI and timing pulsar signals might suffice to determine whether such a discrepancy is real.

Aoki [1969] has proposed that frictional coupling of the core to the precessing mantle can cause a rotation of the equator in space, in the sense of reducing the obliquity, at approximately the rate indicated by the above possible discrepancy. *Kakuta and Aoki* [1972] claim to have removed certain objectionable features of Aoki's earlier model by taking into account electromagnetic coupling of the mantle to a liquid core, but the problem is complex and far from being satisfactorily solved. It is, in fact, part of a much larger problem of absorbing interest in connection with the possible operation of the geomagnetic dynamo by stirring up the core by the differential precessional torque arising from the 25% difference between the ellipticities of the earth's outer surface and the core-mantle boundary [*Malkus*, 1963; *Gans*, 1969; *Busse*, 1971; *Stacey*, 1973].

Chandler Wobble

The 70 years of systematic latitude observations using optical astronomy have not yet proved adequate to resolve unambiguously the spectrum of polar motion. The principal features are the 14-month (Chandler) and annual wobbles. The Chandler wobble is the torque-free Eulerian wobble for a uniaxial rigid earth with the period lengthened to $\simeq$435 days by allowing for the liquid core, elastic mantle, and the mobility and loading of the oceans. The spectral peak at the Chandler frequency is broad and conventionally interpreted as indicating a more or less randomly excited oscillation damped with a relaxation time of the order of 10–25 years [*Jeffreys*, 1968; *Mandelbrot and McCamy*, 1970]. The value of Q ($\simeq$30–60) thus indicated has seemed anomalously low if the damping is to be attributed entirely to anelasticity of the mantle and if Q is rather independent of frequency [*Stacey*, 1967]. *Rochester and Smylie* [1965] showed that electromagnetic core-mantle coupling failed by a factor of at least 10^4 to provide the necessary damping.

Colombo and Shapiro [1968] have argued that the variable amplitude of the Chandler wobble is strikingly suggestive of a beat between two resonant periods within the Chandler band separated by roughly 10 days and having much sharper peaks, so as to remove the apparent problem with Q. It is difficult to see how two such close frequencies could exist near the Chandler peak for any reasonable model of the earth's interior. The ILS data are sufficiently inhomogeneous and the record length short enough that ordinary spectral analysis cannot with confidence resolve the question of whether they exist [*Pedersen and Rochester*, 1972]. When they are analyzed by Burg's maximum entropy method, neither the ILS data [*Claerbout*, 1969] nor the BIH data [*Smylie et al.*, 1973] yield any evidence for splitting of the Chandler peak. The trouble with Q may not be real, anyway, since the oceans have not been eliminated as a possible sink for wobble energy [*Munk and MacDonald*, 1960; *Lagus and Anderson*, 1968; *Miller*, 1973]. It may be worth noting that *Hendershott* [1972] gets $Q \simeq 35$ for the oceans at the semidiurnal period.

Continued observation of the Chandler wobble, even at increasing amplitude from time to time, in the presence of such strong damping, points to an efficient excitation mechanism. Amplification of the Chandler resonance by sidebands of the annual variation in atmospheric mass distribution is far too small [*Munk and Hassan*, 1961]. Earthquakes, dismissed by Munk and MacDonald, have been revived in a series of papers beginning with the one by *Mansinha and Smylie* [1967]. The far-field displacements accompanying a major earthquake, calculated by the elasticity theory of dislocations in a spherical earth, change the off-diagonal components of the inertia tensor and thus shift the earth's pole of figure (mean pole of epoch). Independent formulations of the theory for a self-gravitating earth model with liquid core and realistic distributions of density and elastic properties in the mantle have been given by *Smylie and Mansinha* [1971], *Dahlen* [1971, 1973], and *Israel et al.* [1973]. Their theoretical treatments differ in detail and have given rise to a small controversy over the physical principles governing static deformation of the liquid core (see also *Jeffreys and Vicente* [1966] and *Pekeris and Accad* [1972]). However, the effect of differing prescriptions of boundary conditions at the core-mantle interface is likely to be small, and the authors generally agree in concluding that a major earthquake can produce a polar shift of the order of 0″.1. However, *Mansinha and Smylie* [1970] and *Dahlen* [1971] disagree on whether the cumulative effect of all earthquakes is enough to sustain the Chandler wobble. The sources of disagreement have not yet been conclusively identified but probably lie primarily in the different ways in which the authors relate the excitation due to a particular earthquake to its seismic character.

Ideally, one would like to test the hypothesis by matching a change in the pole path with the occurrence of a major earthquake and the shift in the pole of figure predicted by elastic dislocation theory from the earthquake's location and associated fault geometry [*Smylie and Mansinha,* 1968]. However, the data are so noisy that such attempts have so far been inconclusive [*Haubrich,* 1970; *Dahlen,* 1971], and we must await a great improvement in the accuracy with which wobble is monitored.

Modeling of seismic effects on the inertia tensor by sudden dislocations leaves so far unexamined the possible effects of creep on polar motion [*Chinnery,* 1970].

During the past decade, excitation of mantle wobble by electromagnetic coupling to the core has been shown to be utterly inadequate by *Rochester and Smylie* [1965], who took step function torques to be sufficiently optimistic, and has been resuscitated, on quite different grounds, by Runcorn and Stacey. *Runcorn* [1970*a*] contends that high-frequency GSV creates the core equivalent of sunspots at the core-mantle boundary and thus supplies an impulsive torque to the mantle that can transfer angular momentum rapidly enough to sustain the Chandler wobble. Earthquakes leave the instantaneous rotation pole unchanged but shift the axis of figure, so that the pole path experiences a discontinuous change in direction. Impulsive torques, on the other hand, leave the axis of figure unchanged and shift the rotation pole, so that the radius of the pole path is changed discontinuously. There is some support for the latter phenomenon in the observations: a change of the order of 0″.1 in arc radius taking place in a year or two [*Guinot,* 1972]. The details of electromagnetic coupling on such a short time scale have not been fully worked out, partly because the high-frequency GSV is screened from our observation by the electrical conductivity in the lower mantle that provides the coupling. But *Kakuta* [1965] concluded that magnetohydrodynamic oscillations in the core could not excite detectable wobble. *Stacey* [1970] uses a quasi-dynamical argument to estimate how much energy could be fed into the mantle wobble from the differential precession torque on the core through a nonlinear electromagnetic coupling mechanism. The proposal is intriguing but needs to be given a more rigorous formulation.

In an interesting translation of geophysics into an astronomical context, starquakes have been offered as an explanation of pulsar wobble [*Pines and Shaham,* 1973], and its damping has been discussed in terms of various mechanisms in the core and mantle of a neutron star [*Chau and Henriksen,* 1971].

Seasonal Wobbles

The amplitude of the annual (and much smaller semiannual) wobble can be sufficiently well explained by the seasonal variation in the geographic distribution of the mass of the atmosphere [*Munk and Hassan,* 1961], although the observed phase requires some additional excitation (snowfall, groundwater), according to *Jeffreys* [1972].

It has been customary to separate the Chandler wobble from the latitude data by removing an annual wobble that is constant in amplitude and phase from year to year, determined by a least squares fit. The suspicion that changing weather patterns from year to year would differentially drive the annual wobble is confirmed by the analysis of *Chollet and Débarbat* [1972], who find its amplitude to vary between 0″.04 and 0″.10 over a 14-year series of observations at Paris. The point is reinforced by *Wells and Chinnery* [1972], who find the annual wobble to be but poorly determined from the IPMS latitude data and conclude that it cannot be well separated from the Chandler wobble by the customary method. *Guinot* [1972], however, finds 'quiet' intervals of a few years over which the annual wobble is nearly constant.

Other short-period terms in the ILS data with very small amplitudes are probably forced wobbles of meteorological origin [*Sugawa et al.,* 1972].

Secular Motion of the Pole

The ILS data also reveal an irregular drift of the pole from its mean position 70 years ago in a rather sluggish sort of 'Brownian' motion that has carried it altogether $\simeq$0″.2 towards Newfoundland in that time [*Yumi and Wako,* 1970; *Mandelbrot and McCamy,* 1970; *Mikhailov,* 1972]. The observed secular motion of the pole may be contaminated by as yet unresolved nonpolar latitude variations due to continental drift [*Arur and Mueller,* 1971]. There seems little reason to doubt that this secular motion is the cumulative result of changes in the inertia tensor due to sea level fluctuations [*Munk and MacDonald,* 1960] and tectonic processes [*Mansinha and Smylie,* 1970]. *Batrakov* [1972] estimates that a gigantic engineering project proposed to turn the flow of Siberian rivers southward will, through a redistribution of groundwater, shift the pole by no more than 0″.014.

Long-Period Wobbles

Markowitz [1970] adduces empirical evidence from the ILS data for a 24-year period wobble, which *Busse* [1970] has suggested may represent the response of the mantle to wobble of the solid inner core inertially coupled to the mantle via the liquid core. *Rykhlova* [1969], using a longer but less homogeneous record, finds evidence for a 40-year period instead. This may be the 'Markowitz wobble' with the period poorly determined because of contamination from the secular motion. But *McCarthy* [1972] also finds from latitude observations at Washington a 'period' somewhat longer than Markowitz's. If it is real, the phenomenon may well be the only observable manifestation of the presence of the solid inner core in the entire spectrum of changes in the earth's rotation.

Nearly Diurnal Free Wobble

Perhaps the most intriguing wobble mode is the torque-free nearly diurnal polar motion made possible in principle by the presence of the liquid core inertially coupled to the mantle, first predicted in 1896 independently by both Hough and Sludskii. The predicted motion is retrograde about the axis of figure with a period about 3 min short of a sidereal day, according to the (slightly different) earth models of *Jeffreys and Vicente* [1957] and *Molodenskii* [1961]. Besides giving a resonance amplification to the nearly diurnal tides, this wobble mode will appear in observations of latitude and time (UT) as a period (relative to the stars) of 464 sidereal days or 204 mean solar days, according to Molodenskii's models. The most recent discussions of the observational evidence are those by *Sugawa and Ooe* [1970], *Popov and Yatskiv* [1971], and *Débarbat* [1971]. If this wobble could be unambiguously identified, its period would serve as a fairly stringent filter for earth models. However, its amplitude ($\simeq 0''.02$, according to Popov) is at noise level, and there is reason to be suspicious of this value, since it must be accompanied by a nutation hundreds of times larger (A. Toomre, private communication, 1973).

Other small ($\simeq 0''.02$) wobbles are forced by the sun and moon. These are the Oppolzer terms due to departure of the axis of rotation from the figure axis during nutation (discussed by *Takagi and Murakami* [1968]).

Short-Period Changes in Length of Day

Although the seasonal variations in the length of day were detected by Stoyko during the 1930's by pendulum clocks, the short-period changes naturally show up much better in UT1-AT, available since 1955. The annual variation (amplitude $\simeq$20–25 msec) is primarily explained by winds and the semiannual variation (amplitude $\simeq$9 msec) by the solar bodily tide, small additions to changes in the axial moment of inertia being contributed by the seasonal redistribution of air mass, ocean load, groundwater, snow, and vegetation [*Munk and MacDonald,* 1960]. The discrepancies in amplitude and phase between the seasonal fluctuations deduced by different workers [*Fliegel and Hawkins,* 1967; *Challinor,* 1971] reflect the year-to-year variability in the excitation mechanisms. *Frostman et al.* [1967] concluded that there are still large unexplained differences in phase between theoretical and observed seasonal variations. This objection appears to have been entirely removed by *Lambeck and Cazenave* [1973], who use much better meteorological data to calculate the seasonal fluctuations in atmospheric angular momentum.

Nordtvedt and Will [1972] point out that theories of gravitation involving a preferred reference frame predict anisotropies in the gravitational constant that change the earth's moment of inertia during its orbital motion and give rise to small annual and semiannual changes in the length of day. These effects are likely to be indistinguishable from the meteorological effects at the level of accuracy with which the latter are known. At present, all one can do is use the uncertainty in the extent to which the known meteorological and hydrological excitations can account for the observed seasonal variations in the length of day to set upper limits on the relevant parameters in nongeneral relativistic theories.

A 9-msec amplitude biennial term in the length of day was first reported by Iijima and Okazaki in 1966 and is presumably related to the 26-month atmospheric oscillation. For reports of other short-period variations (of possibly meteorological origin) see the papers by *Korsun' and Sidorenkov* [1971] and *Iijima and Okazaki* [1972].

Atomic timekeeping now permits unequivocal observation of the small ($<$1-msec amplitude) fortnightly and monthly lunar tidal variations in the length of day [*Guinot,* 1970].

Irregular Fluctuations in Axial Spin Rate

Subtracting from UT1 an adopted value for the seasonal variation in the length of day gives UT2. It is important to note that UT2 will still contain some small meteorological effects, since the seasonal fluctuations change in amplitude and phase from year to year. Irregular changes in the length of day show up in UT2-AT since 1955 and in ET-UT over the last three centuries (Figure 3). The corresponding rotational accelerations have been reviewed by *Markowitz* [1970, 1972]. A change of 1 msec in the length of day is about 1 part in 10^8, so that the data from Figure 3 divide roughly into three categories: (1) changes of a few milliseconds over several decades or longer (accelerations in the spin rate of $\leqslant 5 \times 10^{-10}$/yr), (2) changes of a few milliseconds over a few years to a decade (accelerations $\leqslant 80 \times 10^{-10}$/yr), the so-called 'decade fluctuations,' and (3) changes of a substantial fraction of a millisecond over a few weeks or months (accelerations $\leqslant 500 \times 10^{-10}$/yr), the most rapid of these being the 'abrupt' changes [*Guinot,* 1970].

Changes in this last category were not registered in UT until the atomic clocks came into use. Presumably, VLBI and laser ranging to the moon will enable the time intervals over which such changes can be detected to be whittled down to a fraction of a day, and improved global meteorological data will be used to test whether any appeal to the core must be made to explain such short-term irregularities.

Electromagnetic torques have been shown to be just barely adequate to transfer angular momentum between the core and the mantle at the rate necessary to account for the accelerations characteristic of the decade fluctuations [*Rochester,* 1960; *Roden,* 1963; *Kakuta,* 1965; *Roberts,* 1972]. *Vestine and Kahle* [1968] cite evidence for this mechanism in the correlation of changes in the length of day with changes in the westward drift of a prominent geomagnetic field constituent during the last 80 years.

The more rapid and abrupt changes in the length of day are much more likely to be explained by winds. They cannot be explained by electromagnetic coupling unless the electrical conductivity approaches 10^3 mhos/m at the very bottom of the mantle and there is sufficient power in the GSV at high frequencies, say, $\geqslant 1$ cycle/yr. Topographic coupling may play some role. After a checkered history of claims for detectable effects from the solar wind torque, it appears that this source can be neglected [*Coleman,* 1971; *Hirshberg,* 1972].

The slower changes, of type 1, are readily accounted for by electromagnetic coupling to the long-period GSV in the core [*Rochester,* 1970]. *Braginskii* [1970] and *Wilhelm* [1970] have calculated the long-term changes in the length of day associated with particular features of the GSV. *Munk and MacDonald* [1960] argue that changes in sea level do not contribute significantly to fluctuations in the spin rate on this time scale because there is no indication of the concomitant polar motion over the last 70 years. The same will not be true of sea level changes on a time scale of many centuries or millenia.

Secular Acceleration of Earth's Rotation

The major contributor to secular change in the length of day is tidal friction, which transfers earth's spin angular momentum to the lunar orbit and thus gives the moon an angular acceleration $\dot{n}$ in space. Until recently, the accepted value for the present era was $\dot{n} \simeq -22''/\text{century}^2$, determined over 30 years ago by Spencer Jones from telescopic observations of the sun, moon, and planets over the previous 2½ centuries (ET-UT). It now appears that errors in the poorly determined early observations could change his value by ±100%. More recent values were determined by (1) *Newton* [1968], who found $\dot{n} \simeq -20 \pm 3''/\text{century}^2$ from a few years' tidal perturbations of artificial earth satellite orbits (according to *Newton* [1972*a*], the systematic errors here may be much larger than indicated), (2) *Van Flandern* [1970], who obtained $\dot{n} \simeq -52 \pm 16''/\text{century}^2$ from 15 years of lunar occultations timed against AT and made unusually generous allowances for systematic error, and (3) *Oesterwinter and Cohen* [1972], who arrived at $\dot{n} \simeq -38 \pm 8''/\text{century}^2$ by fitting the last 60 years of lunar and planetary observations against UT and AT.

If the sun's tide on the earth is taken into account, the total gravitational tidal acceleration of the earth's spin is given by $\dot{\omega}/\omega \simeq 1.16\dot{n} \times 10^{-9}$/century, where the coefficient is uncertain to within a few percent owing to uncertainty in the knowledge of the ratio of the lunar to the solar tidal torque (various models range from 3.5 to 4.7). Thus the 'modern' rate of secular deceleration due to tidal friction is probably close to twice the value used by *Munk and MacDonald* [1960]. This in turn nearly doubles the problem of accounting for the accompanying energy dissipation ($\simeq 3.5 \times 10^{12}$ watts, according to Munk and MacDonald).

The shallow seas have long been regarded as the chief sink for tidal energy. *Miller* [1966] found that they could dissipate 1.7×10^{12} watts (±50%). Degradation by scattering into internal modes in the ocean is probably $\leqslant 0.5 \times 10^{12}$ watts [*Cox and Sandstrom,* 1962; *Munk,* 1966]. The contribution by bodily tides in the solid earth is probably not more than a few percent of the whole [*Munk,* 1968]. More recently, *Hendershott* [1972] and *Pariiskii et al.* [1972] have used cotidal charts and, taking ocean loading into account, estimated dissipation in the world ocean and thus obtained values roughly double Miller's (see also *Brosche and Sündermann* [1972]). An overall dissipation rate of $\simeq 3-5 \times 10^{12}$ watts can be inferred from the rough estimate of average (oceanic and bodily) tidal phase lag from gravimetry [*Smith and Jungels,* 1970]. The position appears to be that there are large uncertainties, but ocean tidal friction appears likely to meet the bulk of the dissipation requirements posed by the lunar acceleration.

Records of positions and times of ancient eclipses and of other events involving celestial bodies provide information on the average values of $\dot{\omega}$ and $\dot{n}$ over large segments of historical time. The best determined quantity is an epochal average of $\dot{\omega} - 0.622\dot{n}$, obtained from discrepancies between recorded locations of solar eclipses and those predicted by assuming zero accelerations between then and now. Other kinds of data, even less trustworthy, are used to separate $\dot{n}$ and $\dot{\omega}$. The necessary interpretation of sources, almost always at second- or third-hand, has given rise to energetic controversy. Until recently, a rather limited body of data, much of it of dubious reliability, was worked over by different investigators in as many different ways with varying weightings according to their individual assessments, so that even essentially the same data could be used to give widely divergent results. *Curott* [1966] and *Dicke* [1966] both assumed Spencer Jones's value for $\dot{n}$ to be valid over the last 3000 years in order to deduce values for $\dot{\omega}$ from eclipse data. A major contribution to the subject has been made by *Newton* [1970, 1972*b*], who amassed and extensively discussed the reliability of a much larger body of data and found $\dot{n} \simeq -42 \pm 6''/\text{century}^2$ over the last 2000 years, in agreement with the more recent 'modern' observations cited above.

Newton's analysis gives a nontidal acceleration of the earth's spin $\dot{\omega}/\omega \simeq 20 \times 10^{-9}$/century over the last 2000 years or so. *Dicke* [1966] investigated most of the presently conceivable mechanisms for explaining the acceleration of about half this amount given by his analysis and found that the largest contribution was from the postglacial rise in sea level and the accompanying isostatic adjustment. After other geophysical mechanisms were examined and dismissed as much smaller, the bulk of the remaining acceleration was attributed to the effect (on ET and on the earth's axial moment of inertia) of a decrease in the gravitational constant G with time predicted by certain theories of gravitation. The upper limit to $|\dot{G}|$ set by this reasoning is an order of magnitude smaller than that obtained by *Shapiro et al.* [1971] from radar and optical observations of planets since the advent of AT. Later, *Dicke* [1969] reversed his argument, assumed a contribution due to G and inferred the average viscosity in the deep mantle by attributing the rest of the nontidal $\dot{\omega}$ to the rise in sea level and isostatic recovery following deglaciation. *O'Connell* [1971] has estimated the viscosity profile in the mantle by regarding the entire nontidal acceleration as due to the latter processes.

The rise in sea level assumed by these authors is within the limits set by *Walcott*'s [1972] recent study of postglacial eustatic changes. But their interpretations neglect the possibility of substantial contributions from other geophysical effects. The long-period GSV indicates that the core should be able to store or provide angular momentum on a millenial time scale [*Sekiguchi,* 1956; *Rochester,* 1970]. Electromagnetic core-mantle coupling, limited by *Dicke* [1966] to much smaller effects by inadequate arguments and rather cavalierly dismissed by *Newton* [1970, 1972*a*], was studied in detail by *Yukutake* [1972]. He found that the 8000-year period change in the geomagnetic dipole moment (revealed by archeomagnetism) would give rise to an average $\dot{\omega}/\omega \simeq 5 \times 10^{-9}$/century over the past 2000 years. Also, *Gjevik* [1972] has argued that surface readjustments due to subcrustal phase transitions may mimic postglacial rebound in amplitude and relaxation time.

During the past decade, beginning with the work of *Wells* [1963], efforts have been made to extend estimates of $\dot{\omega}$ and $\dot{n}$ back over geologic time by using the fossil clocks provided by marine organisms whose shell structures show daily, monthly, and annual ridge patterns. The data tend to support an increase in the length of day since the Precambrian at an average rate more compatible with Spencer Jones's value for $\dot{n}$ than with more recent astronomical determinations of the 'modern' value [*Runcorn,* 1970*b*]. There is some evidence for changes in the tidal deceleration rate [*Pannella et al.,* 1968; *Pannella,* 1972]. In view of the possibility that the distribution of shallow seas was very different in the past, such changes would hardly be surprising. However, the uncertainties in the determinants of ridge growth are so great that it seems premature to draw any detailed conclusions from paleontological data regarding the history of the length of day. The most recent review is by *Scrutton and Hipkin* [1973].

Conclusion

This survey of current knowledge and problems of the earth's rotation is necessarily rough and superficial, and I can only hope that it conveys something of the compelling attraction that this global subject exerts on its devotees. There seems little doubt that the coming decade will eclipse even the enormous strides that were taken during the 1960's in the acquisition, accuracy, and analysis of data and bring much closer to resolution several of the tantalizing questions still presented by the rotation of the earth.

Acknowledgment

Financial support of this work from a National Research Council of Canada operating grant is gratefully acknowledged.

References

Alley, C.O., and P.L. Bender, Information obtainable from laser range measurements to a lunar corner reflector, in *Continental Drift, Secular Motion of the Pole, and Rotation of the Earth,* edited by W. Markowitz and B. Guinot, pp. 86–90, D. Reidel, Dordrecht, Netherlands, 1968.

Anderle, R.J., Pole position for 1971 based on Doppler satellite observations, *Rep. TR-2734,* 97 pp., U.S. Naval Weapons Lab., Dahlgren, Va., 1972.

Aoki, S., Friction between mantle and core of the earth as a cause of the secular change in obliquity, *Astron. J., 74,* 284–291, 1969.

Arur, M.G., and I.I. Mueller, Latitude observations and the detection of continental drift, *J. Geophys. Res., 76,* 2071–2076, 1971.

Batrakov, Yu.V., Effect of diverting the flow of Siberian rivers upon the rotation of the earth, *Sov. Astron. AJ, 15,* 853–857, 1972.

Braginskii, S.I., Torsional magnetohydrodynamic vibrations in the earth's core and variations in day length, *Geomagn. Aeron., 10,* 1–8, 1970.

Brosche, P., and J. Sündermann, On the torques due to tidal friction of the oceans and adjacent seas, in *Rotation of the Earth,* edited by P. Melchior and S. Yumi, pp. 235–239, D. Reidel, Dordrecht, Netherlands, 1972.

Burke, B.F., Long-baseline interferometry, *Phys. Today, 22*(7), 54–63, 1969.

Busse, F.H., Steady fluid flow in a precessing spheroidal shell, *J. Fluid Mech., 33,* 739-751, 1968.

Busse, F.H., The dynamical coupling between inner core and mantle of the earth and the 24-year libration of the pole, in *Earthquake Displacement Fields and the Rotation of the Earth,* edited by L. Mansinha, D.E. Smylie, and A.E. Beck, pp. 88–98, D. Reidel, Dordrecht, Netherlands, 1970.

Busse, F.H., Bewegungen im Kern der Erde, *Z. Geophys., 37,* 153–177, 1971.

Challinor, R.A., Variations in the rate of rotation of the earth, *Science, 172,* 1022–1025, 1971.

Chau, W.Y., and R.N. Henriksen, Pulsar wobble, *Astrophys. Lett., 8,* 49–52, 1971.

Chinnery, M.A., Earthquake displacement fields, in *Earthquake Displacement Fields and the Rotation of the Earth,* edited by L. Mansinha, D.E. Smylie, and A.E. Beck, pp. 17–38, D. Reidel, Dordrecht, Netherlands, 1970.

Chollet, F.C., Mouvements de l'axe instantané de rotation de la terre déduits des mesures laser de distance terre–lune, *Astron. Astrophys., 9,* 110–124, 1970.

Chollet, F.C., and S. Débarbat, Analyse des observations de latitude effectuées à l'astrolabe Danjon de l'Observatoire de Paris de 1956.5 à 1970.8, *Astron. Astrophys., 18,* 133–142, 1972.

Claerbout, J., Frequency mixing in Chandler wobble data (abstract), *Eos Trans. AGU, 50,* 119, 1969.

Coleman, P.J., Solar wind torque on the geomagnetic cavity, *J. Geophys. Res., 76,* 3800–3805, 1971.

Colombo, G., and I.I. Shapiro, Theoretical model for the Chandler wobble, *Nature, 217,* 156–157, 1968.

Cox, C.S., and H. Sandstrom, Coupling of internal and surface waves in water of variable depth, *J. Oceanogr. Soc. Jap., 20,* 499–513, 1962.

Curott, D.R., Earth deceleration from ancient solar eclipses, *Astron. J., 71,* 264–269, 1966.

Dahlen, F.A., The excitation of the Chandler wobble by earthquake, *Geophys. J., 25,* 157–206, 1971.

Dahlen, F.A., A correction to the excitation of the Chandler wobble by earthquakes, *Geophys. J., 32,* 203–217, 1973.

Débarbat, S., Nearly diurnal nutation from time measurements, *Astron. Astrophys., 14,* 306–310, 1971.

Dicke, R.H., The secular acceleration of the earth's rotation and cosmology, in *The Earth–Moon System,* edited by B.G. Marsden and A.G.W. Cameron, pp.

98–164, Plenum, New York, 1966.

Dicke, R.H., Average acceleration of the earth's rotation and the viscosity of the deep mantle, *J. Geophys. Res., 74,* 5895–5902, 1969.

Faller, J.E., and E.J. Wampler, The lunar laser reflector, *Sci. Amer., 222*(3), 38–49, 1970.

Feissel, M., B. Guinot, and N. Taton, Comparison of the coordinates of the pole as obtained by classical astrometry (IPMS, BIH) and as obtained by Doppler measurements on artificial satellites (Dahlgren Polar Monitoring Service), in *Rotation of the Earth,* edited by P. Melchior and S. Yumi, pp. 104–111, D. Reidel, Dordrecht, Netherlands, 1972.

Fliegel, H.F., and T.P. Hawkins, Analysis of variations in the rotation of the Earth, *Astron. J., 72,* 544–550, 1967.

Fricke, W., Determinations of precession, *Celestial Mech., 4,* 150–162, 1971.

Fricke, W., On the motion of the equator and the ecliptic, in *Rotation of the Earth,* edited by P. Melchior and S. Yumi, p. 196, D. Reidel, Dordrecht, Netherlands, 1972.

Frostman, T.O., D.W. Martin, and W. Schwerdtfeger, Annual and semiannual variations in the length of day, related to geophysical effects, *J. Geophys. Res., 72,* 5065–5073, 1967.

Gans, R.F., The steady-state response of a contained, rotating, electrically conducting, viscous fluid subject to precessional and Lorentz forces, and its implications regarding geomagnetism, Ph.D. thesis, 94 pp., Univ. of Calif., Los Angeles, 1969.

Gans, R.F., Viscosity of the earth's core, *J. Geophys. Res., 77,* 360–366, 1972.

Gjevik, B., Surface readjustment owing to a subcrustal phase transition, *Phys. Earth Planet. Interiors, 5,* 403–408, 1972.

Gold, T., Radio method for the precise measurement of the rotation period of the earth, *Science, 157,* 302–304, 1967.

Guinot, B., Short-period terms in universal time, *Astron. Astrophys., 8,* 26–28, 1970.

Guinot, B., The Chandlerian wobble from 1900 to 1970, *Astron. Astrophys., 19,* 207–214, 1972.

Guinot, B., M. Feissel, and M. Granveaud, *Rapport Annuel pour 1971,* 183 pp., Bureau International de l'Heure, Paris, 1972.

Haubrich, R.A., An examination of the data relating pole motion to earthquakes, in *Earthquake Displacement Fields and the Rotation of the Earth,* edited by L. Mansinha, D.E. Smylie, and A.E. Beck, pp. 149–158, D. Reidel, Dordrecht, Netherlands, 1970.

Hendershott, M.C., The effects of solid earth deformation on global ocean tides, *Geophys. J., 29,* 389–402, 1972.

Hide, R., Interaction between the earth's liquid core and solid mantle, *Nature, 222,* 1055–1056, 1969.

Hirshberg, J., Upper limit of the torque of the solar wind on the earth, *J. Geophys. Res., 77,* 4855–4857, 1972.

Iijima, S., and S. Okazaki, Short period terms in the rate of rotation and in the polar motion of the earth, *Publ. Astron. Soc. Jap., 24,* 109–125, 1972.

Israel, M., A. Ben-Menahem, and S.J. Singh, Residual deformation of real earth models with application to the Chandler wobble, *Geophys. J., 32,* 219–247, 1973.

Jeffreys, H., The variation of latitude, *Mon. Notic. Roy. Astron. Soc., 141,* 255–268, 1968.

Jeffreys, H., The variation of latitude, in *Rotation of the Earth,* edited by P. Melchior and S. Yumi, pp. 39–42, D. Reidel, Dordrecht, Netherlands, 1972.

Jeffreys, H., and R.O. Vicente, The theory of nutation and the variation of latitude, *Mon. Notic. Roy. Astron. Soc., 117,* 142–161, 162–173, 1957.

Jeffreys, H., and R.O. Vicente, Comparison of forms of the elastic equations for the earth, *Mem. Acad. Roy. Belg., 37*(3), 1–31, 1966.

Kakuta, C., Magnetohydrodynamic oscillation within the fluid core and irregularities in the rotational motion of the earth, *Publ. Int. Latitude Observ. Mizusawa, 5,* 17–42, 1965.

Kakuta, C., and S. Aoki, The excess secular change in the obliquity of the ecliptic and its relation to the internal motion of the earth, in *Rotation of the Earth,* edited by P. Melchior and S. Yumi, pp. 192–195, D. Reidel, Dordrecht, Netherlands, 1972.

Kaula, W. (Ed.), *The Terrestrial Environment: Solid-Earth and Ocean Physics, NASA Contract. Rep. 1579,* chaps. 2 and 4, 1970.

Korsun', A.A., and N.S. Sidorenkov, A spectral analysis of the pulsations in the earth's rotational velocity, *Sov. Astron. AJ, 14,* 896–900, 1971.

Lagus, P.L., and D.L. Anderson, Tidal dissipation in the earth and planets, *Phys. Earth Planet. Interiors, 1,* 505–510, 1968.

Lambeck, K., Determination of the earth's pole of rotation from laser range observations to satellites, *Bull. Geod., 101,* 263–281, 1971.

Lambeck, K., and A. Cazenave, The earth's rotation and atmospheric circulation, 1, Seasonal variations, *Geophys. J., 32,* 79–93, 1973.

Lieske, J.H., On the secular change of the obliquity of the ecliptic, *Astron. Astrophys., 5,* 90–101, 1970.

MacDonald, G.J.F., Implications for geophysics of the precise measurement of the earth's rotation, *Science, 157,* 304–305, 1967.

Malkus, W.V.R., Precessional torques as the cause of geomagnetism, *J. Geophys. Res., 68,* 2871–2886, 1963.

Mandelbrot, B.B., and K. McCamy, On the secular pole motion and the Chandler wobble, *Geophys. J., 21,* 217–232, 1970.

Mansinha, L., and D.E. Smylie, Effect of earthquakes on the Chandler wobble and the secular polar shift, *J. Geophys. Res., 72,* 4731–4743, 1967.

Mansinha, L., and D.E. Smylie, Seismic excitation of the Chandler wobble, in *Earthquake Displacement Fields and the Rotation of the Earth,* edited by L. Mansinha, D.E. Smylie, and A.E. Beck, pp. 122–135, D. Reidel, Dordrecht, Netherlands, 1970.

Markowitz, W., Sudden changes in rotational acceleration of the earth and secular motion of the pole, in *Earthquake Displacement Fields and the Rotation of the Earth,* edited by L. Mansinha, D.E. Smylie, and A.E. Beck, pp. 69–81, D. Reidel, Dordrecht, Netherlands, 1970.

Markowitz, W., Rotational accelerations, in *Rotation of the Earth,* edited by P. Melchior and S. Yumi, pp. 162–164, D. Reidel, Dordrecht, Netherlands, 1972.

McCarthy, D.D., Secular and nonpolar variation of Washington latitude, in *Rotation of the Earth,* edited by P. Melchior and S. Yumi, pp. 86–96, D. Reidel, Dordrecht, Netherlands, 1972.

Melchior, P., Precession-nutations and tidal potential, *Celestial Mech., 4,* 190–212, 1971.

Melchior, P., Earth tides and polar motions, *Tectonophysics, 13,* 361–372, 1972.

Mikhailov, A.A., The polar motion of the earth, *Sov. Astron. AJ, 15,* 1035–1038, 1972.

Miller, G.R., The flux of tidal energy out of the deep oceans, *J. Geophys. Res., 71,* 2485–2489, 1966.

Miller, S.P., Observations and interpretation of the pole tide, M.S. thesis, 97 pp., Mass. Inst. of Technol., Cambridge, 1973.

Molodenskii, M.S., The theory of nutation and diurnal earth tides, *Commun. Observ. Roy. Belg., 188,* 25–56, 1961.

Mueller, I.I., *Spherical and Practical Astronomy with Application to Geodesy,* Frederick Ungar, New York, 1969.

Munk, W.H., Abyssal recipes, *Deep Sea Res., 13,* 707–730, 1966.

Munk, W.H., Once again–tidal friction, *Quart. J. Roy. Astron. Soc., 9,* 352–375, 1968.

Munk, W.H., and E.S.M. Hassan, Atmospheric excitation of the earth's wobble, *Geophys. J., 4,* 339–358, 1961.

Munk, W.H., and G.J.F. MacDonald, *The Rotation of the Earth,* Cambridge University Press, London, 1960.

Newton, R.R., A satellite determination of tidal parameters and earth deceleration, *Geophys. J., 14,* 505–539, 1968.

Newton, R.R., *Ancient Astronomical Observations and the Accelerations of the Earth and Moon,* Johns Hopkins Press, Baltimore, Md., 1970.

Newton, R.R., Astronomical evidence concerning non-gravitational forces in the earth-moon system, *Astrophys. Space Sci., 16,* 179–200, 1972*a*.

Newton, R.R., *Medieval Chronicles and the Rotation of the Earth,* Johns Hopkins Press, Baltimore, Md., 1972*b*.

Nordtvedt, K., and C.M. Will, Conservation laws and preferred frames in relativistic gravity, 2, *Astrophys. J., 177,* 775–792, 1972.

O'Connell, R.J., Pleistocene glaciation and the viscosity of the lower mantle, *Geophys. J., 23,* 299–327, 1971.

Oesterwinter, C., and C.J. Cohen, New orbital elements for moon and planets, *Celestial Mech., 5,* 317–395, 1972.

Pannella, G., Paleontological evidence on the earth's rotational history since early Precambrian, *Astrophys. Space Sci., 16,* 212–237, 1972.

Pannella, G., C. MacClintock, and M.N. Thompson, Paleontological evidence of variations in length of synodic month since Late Cambrian, *Science, 162,* 792–796, 1968.

Pariiskii, N.N., M.V. Kuznetsov, and L.V. Kuznetsova, The effect of oceanic tides on the secular deceleration of the earth's rotation, *Izv. Acad. Sci. USSR Phys. Solid Earth, 10,* 65–70, 1972.

Pedersen, G.P.H., and M.G. Rochester, Spectral analyses of the Chandler wobble, in *Rotation of the Earth,* edited by P. Melchior and S. Yumi, pp. 33–38, D. Reidel, Dordrecht, Netherlands, 1972.

Pekeris, C.L., and Y. Accad, Dynamics of the liquid core of the earth, *Phil. Trans. Roy. Soc. London, Ser. A, 273,* 237–260, 1972.

Pines, D., and J. Shaham, The elastic energy and character of quakes in solid stars and planets, *Phys. Earth Planet. Interiors, 6,* in press, 1973.

Popov, N.A., and Ya.S. Yatskiv, Amplitude variations in the free diurnal nutation of the earth, *Sov. Astron. AJ, 14,* 1057–1059, 1971.

Preston, R.A., R. Ergas, H.F. Hinteregger, C.A. Knight, D.S. Robertson, I.I. Shapiro, A.R. Whitney, A.E.E. Rogers, and T.A. Clark, Interferometric observations of an artificial satellite, *Science, 178,* 407–409, 1972.

Roberts, P.H., Electromagnetic core-mantle coupling, *J. Geomagn. Geoelec., 24,* 231–259, 1972.

Rochester, M.G., Geomagnetic westward drift and irregularities in the earth's rotation, *Phil. Trans. Roy. Soc. London, Ser. A, 252,* 531–555, 1960.

Rochester, M.G., Perturbations in the earth's rotation and geomagnetic core-mantle coupling, *J. Geomagn. Geoelec., 20,* 387–402, 1968.

Rochester, M.G., Core-mantle interactions: Geophysical and astronomical consequences, in *Earthquake Displacement Fields and the Rotation of the Earth,* edited by L. Mansinha, D.E. Smylie, and A.E. Beck, pp. 136–148, D. Reidel, Dordrecht, Netherlands, 1970.

Rochester, M.G., and D.E. Smylie, Geomagnetic core-mantle coupling and the Chandler wobble, *Geophys. J., 10,* 289–315, 1965.

Roden, R.B., Electromagnetic core-mantle coupling, *Geophys. J., 7,* 361–374, 1963.

Rösch, J., Laser measurements of earth-moon distances, *Moon, 3,* 448–455, 1972.

Runcorn, S.K., A possible cause of the correlation between earthquakes and polar motions, in *Earthquake Displacement Fields and the Rotation of the Earth,* edited by L. Mansinha, D.E. Smylie, and A.E. Beck, pp. 181-187, D. Reidel, Dordrecht, Netherlands, 1970*a*.

Runcorn, S.K., Palaeontological measurements of the changes in the rotation rates of earth and moon and of the rate of retreat of the moon from the earth, in *Palaeogeophysics,* edited by S.K. Runcorn, pp. 17–23, Academic, New York, 1970*b*.

Rykhlova, L.V., Evaluation of the earth's free nutation parameters from 119 years of observations, *Sov. Astron. AJ, 13,* 544–545, 1969.

Sadler, D.H., Astronomical measures of time, *Quart. J. Roy. Astron. Soc., 9,* 281–293, 1968.

Scrutton, C.T., and R.G. Hipkin, Changes in the rotation of the earth, *Earth Sci. Rev., 9,* in press, 1973.

Sekiguchi, N., On the secular accelerations in the mean longitudes of the moon and the sun, *Publ. Astron. Soc. Jap., 8,* 163–172, 1956.

Shapiro, I.I., and C.A. Knight, Geophysical applications of long-baseline radio interferometry, in *Earthquake Displacement Fields and the Rotation of the Earth,* edited by L. Mansinha, D.E. Smylie, and A.E. Beck, pp. 284–301, D. Reidel, Dordrecht, Netherlands, 1970.

Shapiro, I.I., W.B. Smith, M.E. Ash, R.P. Ingalls, and G.H. Pettengill, Gravitational constant: Experimental bound on its time variation, *Phys. Rev. Lett., 26,* 27–30, 1971.

Smith, D.E., R. Kolenkiewicz, P.J. Dunn, H.H. Plotkin, and T.S. Johnson, Polar motion from laser tracking of artificial satellites, *Science, 178,* 405–406, 1972.

Smith, S.W., and P. Jungels, Phase delay of the solid earth tide, *Phys. Earth Planet. Interiors, 2,* 233–238, 1970.

Smylie, D.E., and L. Mansinha, Earthquakes and the observed motion of the rotation pole, *J. Geophys. Res., 73,* 7661–7673, 1968.

Smylie, D.E., and L. Mansinha, The elasticity theory of dislocations in real earth models and changes in the rotation of the earth, *Geophys. J., 23,* 329–354, 1971.

Smylie, D.E., G.K.C. Clarke, and T.J. Ulrych, Analysis of irregularities in the earth's rotation, *Methods Comput. Phys., 13,* in press, 1973.

Stacey, F.D., Consequences of energy dissipation by creep in the mantle, *Geophys. J., 14,* 433–438, 1967.

Stacey, F.D., A re-examination of core-mantle coupling as the cause of the wobble, in *Earthquake Displacement Fields and the Rotation of the Earth,* edited by L. Mansinha, D.E. Smylie, and A.E. Beck, pp. 176–180, D. Reidel, Dordrecht, Netherlands, 1970.

Stacey, F.D., The coupling of the core to the precession of the earth, *Geophys. J.,* in press, 1973.

Stewartson, K., and P.H. Roberts, On the motion of a liquid in a spheroidal cavity of a precessing rigid body, *J. Fluid Mech., 17,* 1–20, 1963.

Stoyko, A., La variation séculaire de la rotation de la terre et des problèmes connexes, *Ann. Guebhard, 46,* 293–316, 1970.

Suess, S.T., Some effects of gravitational tides on a model earth's core, *J. Geophys. Res., 75,* 6650–6661, 1970.

Sugawa, C., and M. Ooe, On the nearly diurnal nutation term derived from the ILS *z* term, *Publ. Int. Latitude Observ. Mizusawa, 7,* 123–147, 1970.

Sugawa, C., H. Ishii, and G. Teleki, On the relation between the ILS mean closing error and the ILS *z* term, *Proc. Int. Latitude Observ. Mizusawa, 12,* 176–199, 1972.

Takagi, S., and G. Murakami, Numerical analysis of the Oppolzer terms, *Publ. Int. Latitude Observ. Mizusawa, 6,* 225–229, 1968.

Tanner, R.W., The estimation of plate motions by astronomical methods, *Can. J. Earth Sci., 9,* 1052–1054, 1972.

Toomre, A., On the coupling of the earth's core and mantle during the 26,000-year precession, in *The Earth-Moon System,* edited by B.G. Marsden and A.G.W. Cameron, pp. 33–45, Plenum, New York, 1966.

Van Flandern, T.C., The secular acceleration of the moon, *Astron. J., 75,* 657–658, 1970.

Vestine, E.H., and A. Kahle, The westward drift and geomagnetic secular change, *Geophys. J., 15,* 29–37, 1968.

Vicente, R.O., The possibilities of detecting motions of the crust, *Geophys. J., 14,* 475–478, 1968.

Wako, Y., Interpretation of Kimura's annual *z*-term, *Publ. Astron. Soc. Jap., 22,* 525–544, 1970.

Walcott, R.I., Late Quaternary vertical movements in eastern North America: Quantitative evidence of glacio-isostatic rebound, *Rev. Geophys. Space Phys., 10,* 849–884, 1972.

Wells, F.J., and M.A. Chinnery, Variations in the annual component of polar motion at individual observatories (abstract), *Eos Trans. AGU, 53,* 345, 1972.

Wells, J.W., Coral growth and geochronometry, *Nature, 197,* 948–950, 1963.

Wilhelm, H., Eine säkulare Schwingung des erdmagnetischen Quadrupolfelds als Ursache einer Änderung der Erdrotation, *Z. Geophys., 36,* 697–723, 1970.

Williams, C.A., Corrections to star catalogues from satellite observations *Mon. Notic. Roy. Astron. Soc., 158,* 125–149, 1972.

Woolard, E.W., and G.M. Clemence, *Spherical Astronomy,* pp. 418–440, Academic, New York, 1966.

Yukutake, T., The effect of change in the geomagnetic dipole moment on the rate of the earth's rotation, *J. Geomagn. Geoelec., 24,* 19–47, 1972.

Yumi, S., *Annual Report of the IPMS for the Year 1970,* International Polar Motion Service, Mizusawa, 1972.

Yumi, S., and Y. Wako, Secular motion of the pole, in *Earthquake Displacement Fields and the Rotation of the Earth,* edited by L. Mansinha, D.E. Smylie, and A.E. Beck, pp. 82–87, D. Reidel, Dordrecht, Netherlands, 1970.

Michael G. Rochester is Professor of Physics at the Memorial University of Newfoundland, St. John's, Newfoundland, Canada. He received his B.A. in applied mathematics from the University of Toronto in 1954, his M.A. in physics from Toronto in 1956, and his Ph.D. in physics from the University of Utah in 1959. He has held faculty appointments at the University of Toronto and the University of Waterloo, and has been at Memorial since 1967. He is a member of Canada's National Research Council Associate Committee on Geodesy and Geophysics, and of the International Geodynamics Project's Working Group on Physical Processes in the Earth's Interior.

Supporting Members

Contributing Members

Chevron Oil Field Company
Grumman Aircraft Engineering Corporation
International Business Machines Corporation
Shell Oil Company

Lunar Science Institute
3M Company
Marathon Oil Company
McDonnell-Douglas Corporation
  Douglas Aircraft Company

Corporation Members

Aerospace Corporation
Amoco Production Company
Ball Brothers Research Corporation
Brown & Root, Inc.
Esso Production Research Company
Exxon Corporation
GCA Corporation
General Electric Company
  Missiles and Space Division
Griffin Wellpoint Corporation
Gulf Research & Development Company
Honeywell, Inc.
Lightning & Transients Research Institute
Arthur D. Little, Inc.
Lockheed Aircraft Corporation,
  Missiles and Space Division

National Center for Atmospheric Research
Northrop Corporation
Petty Geophysical Engineering Company
Phillips Petroleum Company
RCA, Astro-Electronics Division
Sandia Laboratories
Schonstedt Instrument Company
W.F. Spregnether Instrument Company, Inc.

Systems, Science and Software
Teledyne/Geotech Division
Tipton and Kalmbach, Inc.
TRW, Inc./TRW Systems Group
United Geophysical Corporation
Universities Space Research Association
Western Geophysical Company

CLASSIFIED

E⊕S offers classified space for Positions Available, Positions Wanted, and Services and Supplies. There are no discounts or commissions on classified ads. Any type that is not publisher's choice is charged for at display rates. Column width is 2-1/16 inches. Replies to ads with box numbers should be addressed to: Box ______, American Geophysical Union, 1707 L Street, N.W., Washington, D.C. 20036.

POSITIONS WANTED
Rates per line
1 time - $1.00, 3 times - $0.85, 6 times - $0.75, 9 times - $0.65, 12 times - $0.55

POSITIONS AVAILABLE
Rates per line
1 time - $2.00, 3 times - $1.75, 6 times - $1.60, 9 times - $1.50, 12 times - $1.40

SERVICES AND SUPPLIES
Rates per line
1 time - $2.50, 3 times - $2.10, 6 times - $1.95, 9 times - $1.90, 12 times - $1.75

Position Available

MRF'S REPS WANTED. We are looking for manufacturer's representatives to sell our new line of seismographs, earth resistivity and soil mechanics instrumentation. Market should include construction contractors, geophysicists, universities, state and federal highway dept., sand and gravel quarries, etc. If you are interested, please send information including background, area covered, lines presently handled, types of markets now serving and financial references to Box M.