Earth Rotation

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1. INTRODUCTION

The study of the Earth's rotation in space (encompassing Universal Time (UT1), length of day, polar motion, and the phenomena of precession and nutation) addresses the complex nature of Earth orientation changes, the mechanisms of excitation of these changes and their geophysical implications in a broad variety of areas. In the absence of internal sources of energy or interactions with astronomical objects, the Earth would move as a rigid body with its various parts (the crust, mantle, inner and outer cores, atmosphere and oceans) rotating together at a constant fixed rate. In reality, the world is considerably more complicated, as is schematically illustrated (Figure 1). The rotation rate of the Earth's crust is not constant, but exhibits complicated fluctuations in speed amounting to several parts in 10^8 [corresponding to a variation of several milliseconds (ms) in the length of the day (LOD) (Figure 2a) and about one part in 10^6 in the orientation of the rotation axis relative to the solid Earth's axis of figure (polar motion) (Figure 3). These changes occur over a broad spectrum of time scales, ranging from hours to centuries and longer, reflecting the fact that they are produced by a wide variety of geophysical and astronomical processes. Geodetic observations of Earth rotation changes thus provide insights into the geophysical processes illustrated (Figure 1), which are often difficult to obtain by other means. In addition, these measurements are required for engineering purposes; for example, the tracking and navigation of interplanetary spacecraft place strong constraints on measurement accuracies.

The principle of conservation of angular momentum requires that changes in the Earth's rotation must be manifestations of (a) torques acting on the solid Earth and (b) changes in the mass distribution within the solid Earth, which alters its inertia tensor. Angular momentum transfer occurs between the solid Earth and the fluid regions (the underlying liquid metallic core and the overlying hydrosphere and atmosphere) with which it is in contact; concomitant torques are due to hydrodynamic or magnetohydrodynamic stresses acting at the fluid/solid Earth interfaces. Changes in the inertia tensor of the solid Earth are caused not only by interfacial stresses and the gravitational attraction associated with astronomical objects and mass redistributions in the fluid regions of the Earth but also by processes that redistribute the material of the solid Earth, such as earthquakes, postglacial rebound, mantle convection, and movement of tectonic plates. Earth rotation provides a unique and truly global measure of natural and man-made changes in the atmosphere, oceans, and interior of the Earth.

Theoretical studies of Earth rotation variations are based on the application of Euler's dynamical equations to the problem of finding the response of a slightly deformable solid Earth to a variety of surface and internal stresses [51, 53]. Let **H** be the angular momentum of the Earth and **L** be the external torque exerted on the Earth. The fundamental equations of a rotating body, Euler's dynamical equations, require that

$$\dot{\mathbf{H}} = \mathbf{L}\,. \qquad (1)$$

In an arbitrary rotating terrestrial frame with a rotation vector $\boldsymbol{\omega}$, the appropriate form of Euler's dynamical

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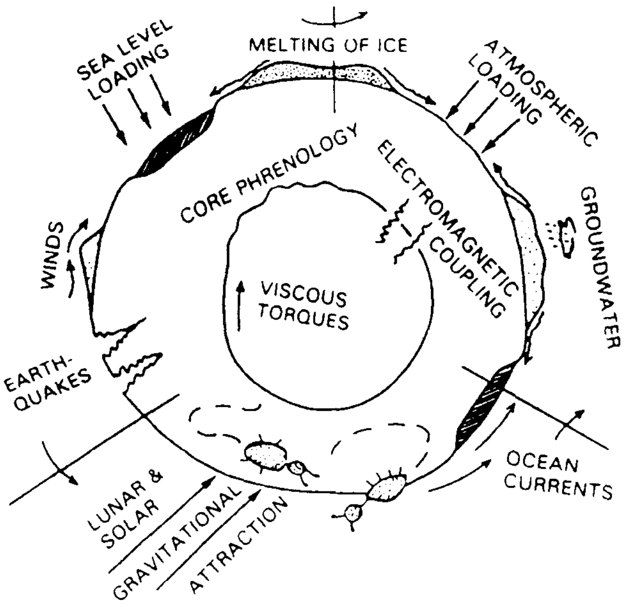

Fig. 1. Schematic illustration of the forces that perturb Earth rotation. Topographic coupling of the mantle to the core has been referred to as "Core Phrenology" by R. Hide, while the beetles, following T. Gold, represent the effect of continental drift. After [52].

equations is given by:

$$\dot{\mathbf{H}} + \boldsymbol{\omega} \times \mathbf{H} = \mathbf{L} \tag{2}$$

which is exact in any rotating reference frame. In both cases, the angular momentum is given by

$$\mathbf{H}(t) = \mathbf{I}(t)\boldsymbol{\omega}(t) + \int \mathbf{x}(t) \times \dot{\mathbf{x}}(t)dm, \tag{3}$$

where I(t) is the inertia tensor of the mass over which (1) or (2) will be applied. The formulation of equation (2) is usually used when the torques change slowly in an Earth-fixed frame; examples include atmospheric excitation and Chandler wobble problems. On the other hand, equation (1) is usually utilized when torques change slowly in inertial space; precession/nutation problems are prime applications. One must be able to transform from an Earth-fixed system (i.e., a Terrestrial Reference System, TRS, where equation (2) applies) to one attached to an inertial system (that is, the Celestial Reference System, CRS, where equation (1) applies). This transformation requires a minimum of three angles; however, the traditional formulation includes the conventional representations of nutations and polar motions and hence five angles are utilized, four of which change slowly with the remaining angle (representing the solid Earth's sidereal rotation) changing at an almost uniform rate. Table 1 provides estimates of the moments of inertia for the Earth's various sub-systems, giving the reader the relative important of each.

Space geodetic techniques, including laser ranging to the moon and artificial satellites (LLR and SLR) and very long baseline interferometry (VLBI) using radio telescopes, have brought about a new age in Earth rotation and related studies. The length of day and polar motion are now routinely measured at the ~0.5 milliarcsecond level (~1.5 cm) [44], while periodic corrections to the standard nutation model have been determined to the 0.1 milliarcsecond level for many terms [38].

This paper provides an overview of Earth rotation, defining terms, describing the measurements and their availability, the models and constants used in their reduction, and the application and analyses of these data. The second section provides definitions and describes the measurement techniques, while the third section highlights applications and advances in the analysis of Earth rotation. Section 4 discusses the constants and models used in the analysis and interpretation of Earth rotation data. The final section addresses the availability of data and outlines the activities of the International Earth Rotation Service (IERS).

The reader is referred to several more detailed accounts of the excitation of Earth orientation changes. References to early work can be found in [64] and recent work is reported in [6, 14, 40-44, 51, 53, 62, 77].

2. DEFINITIONS AND MEASUREMENTS

Earth rotation refers collectively to variations in the orientation of the solid Earth, encompassing Universal Time (UT1), length of day, polar motion, and the phenomena of precession and nutation. Universal time (UT1) is the rotation angle of the Earth: the direction of the Greenwich meridian in an equinox-based inertial frame. The UT1 measurements are usually given in units of time (1 msec is 46 cm at the equator). The actual observable is UT1-T, where T is some independent time series such as ET (ephemeris time) or IAT (international interatomic time). The LOD can be estimated from the time rate of change of UT1-T. The motion of the pole can be divided into two classes, nutational motion (which includes precession) and the polar motion (PM). Nutations are motions of the spin axis of the Earth with respect to an inertial reference frame, while polar motion or wobble is the motion of the solid Earth with respect to the spin axis of the Earth. The precession is the gravest nutation with a period of about 26,000 years, caused by the gravitational

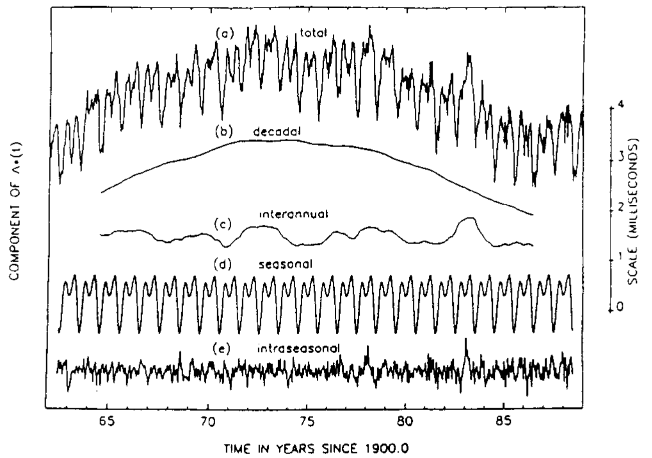

Fig. 2. Time series of irregular fluctuations in the length of the day from 1963 to 1988 (curve a) and its decadal, interannual, seasonal, and intraseasonal components (curves b, c, d and e, respectively). The decadal (curve b) component largely reflects angular momentum exchange between the solid Earth and the underlying liquid metallic outer core produced by torques acting at the core-mantle boundary. The other components (curves c, d and e) largely reflect angular momentum exchange between the atmosphere and the solid Earth, produced by torques acting directly on the solid Earth over continental regions of the Earth's surface and indirectly over oceanic regions. (b) Time series of the equivalent axial torques. Adapted from [44].

torque on the Earth's equatorial bulge from the Sun, Moon and planets.

Earth orientation measurements in current use can be classified as arising from two sources: classical techniques (optical astrometry and lunar occultation) and modern space geodetic techniques. Optical astrometry is based on measurements of the apparent angular positions of selected bright stars [24, 35]. Both the latitude and the longitude of the observatory can be determined from observations of the time and elevation of the star at meridian passage. A network of stations with a proper geometry can be used to determine all components of the Earth's rotation. Polar motion has been routinely observed since 1900; from 1900 through 1980, the International Latitude Service [81] produced measurements based on a network of five stations located at the same latitude. Nutation values have been determined through the analysis of optical data sets beginning in 1955 (see for example, 4); the classical determination of the precession constant is based on the analysis of stellar proper motions [27, 28]. Prior to the advent of modern atomic clocks (1955), records of the solar time of ancient solar and lunar eclipses and of occultation of stars by the Moon form the basis for historical time series of UT1 and LOD [74].

The classical techniques were superseded by the new space geodetic techniques in the 1970s and 1980s. The new techniques are all based on measurements of electromagnetic signal delay or its time derivative. Delay and delay rate measurements are both more precise and somewhat less sensitive to systematic error than angular measurements. These measurement types include Very Long Baseline Interferometry (VLBI), satellite and lunar laser ranging (SLR and LLR), and utilization of the Global Positioning System (GPS) technology. VLBI is based on positional observations of distant quasars using the techniques of radio astronomy; SLR and LLR use range measurements to corner reflectors on artificial satellites and the Moon, respectively. GPS utilizes a large constellation of satellites transmitting at microwave frequencies together with a globally distributed network of receivers to determine universal time and polar motion variations. In each technique, changes in Earth orientation are monitored by observations of extraterrestrial objects from the surface of the Earth. The observed objects or signals are used to approximate a reference frame, either directly, for example, in the case of slow-moving objects such as quasars, or from dynamical theories of their motion in the case of planetary and satellite observations. In each case, Earth orientation is estimated from the apparent motion of the Earth with respect to this frame as defined by each technique. The accuracy of each technique is thus limited by unmodeled reference frame rotations, intrinsic measurement error, and any unmodeled motions of the observatories. In addition, measurements are most often referenced to some standard frame (see later discussion on reference frames); hence, error is also introduced by the frame tie determinations.

Improvements in the observing systems (hardware, software and the development of well-distributed global networks) have lead to dramatic improvements in the determination of Earth orientation parameters. For example, estimates from a combined Kalman-filtered series utilizing the modern space techniques of LLR, SLR and VLBI have uncertainties in polar motion and universal time (UT1) at the ~2 mas (6 cm) and the 0.5 ms (~23 cm) level, respectively, for the late 1970s, whereas current uncertainties have improved to 0.3 mas for polar motion and 0.03 ms for UT1 [32]. There has also been an impressive increase in time resolution. The classical optical technique, utilizing a global network of more than 50 observatories, obtained UT1 at the millisecond level at 5-day intervals [24]; in contrast, the VLBI Extended Research and Development Experiment (ERDE) obtained sub-hourly measurements of both UT1 and polar motion [12, 37].

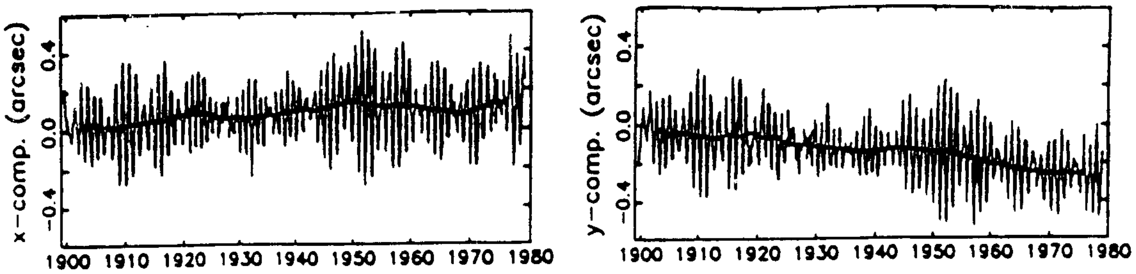

Fig. 3. Polar motion, 1900-1980, after [31].

3. APPLICATION AND ANALYSIS OF EARTH ROTATION

3.1. Universal Time (UT1) and Variations in the Length-of-Day

Observed variations in the Earth's rate of rotation—or changes in the length-of-day (LOD)—are attributed to a variety of sources (Figure 1) and can be roughly divided into three categories: an overall linear increase from tidal dissipation, irregular large variations on a time scale of decades, and the smaller higher frequency changes—interannual, seasonal and intraseasonal. The linear increase in the LOD, determined from ancient eclipse records [e.g., 74] is estimated to be about 1 to 2 msec per century. The LOD has large, irregular variations over time scales of 10 years to centuries (Figures 2a, curve B) with amplitudes of many milliseconds; these changes are too large to be of atmospheric origin and are thought to arise from fluid motions in the liquid outer core [40, 47, 51]. Variations with periods of five years or less are driven primarily by exchanges of angular momentum with the atmosphere (Figures 2a, curves C, D and E). Estimates of the equivalent torques associated with each component, formed by taking centered differences in the time domain, are shown (Figure 2b). Although the amplitude of the decadal LOD time series is larger than that of the faster components (Figure 2a), the corresponding equivalent axial torque time series has the smallest amplitude (Figure 2b—these are a consequence of the time derivatives in equations 1 and 2). At the other extreme, the most rapid intraseasonal contributions have the smallest amplitude, typically less than 0.2 ms, but are associated with the largest torques. The decadal fluctuations integrate coherently over many years resulting in large variations, in contrast, the intraseasonal atmospheric excitations are quite sizable but cancel out to a large extent. The apparent increase in the magnitude of the extraneous torques during the period studied reflects improvements in both quality and quantity of Earth rotation data as well as better sampling methods, leading to a decreasing uncertainty in the LOD estimates with time. The Kalman filter used to produce this LOD series automatically adjusts the effective smoothing to the formal errors in the data, leading to increasing high-frequency variability in the latter part of the series allowing more precise estimation of the magnitude of the shorter-period torques. These pronounced and rapid torque variations probably reflect changes in the orographic contribution to the total torque exerted by the atmosphere on the underlying planet, associated with the passage of synoptic weather systems over mountain ranges. Determinations incorporating space-geodetic data, in fact, show that the intraseasonal torque can change by as much as 50 Hadleys (1 Hadley = 10^{18}Nm) in 10 days. Synoptic variations in the atmosphere occur on these time scales, associated with surface pressure gradients which, if applied across a mountain range with the dimensions of the Rockies or Andes, would produce transient torques of this magnitude. The seasonal torque, which, by definition, fluctuates with constant amplitude over the 30-year span of data used, reflects annual and semi-annual variations of the position and strength of the major atmospheric jet streams.

The exchange of angular momentum between the atmosphere and solid Earth is evident in fluctuations in the length-of-day at periods of a year and less (Figure 4). Recent improvements in Earth rotation measurements have been accompanied by improvements in numerical models and measurements of Earth's global atmosphere which can be used to calculate the atmospheric angular momentum (AAM) [for a review, see 44]. Both U.S. and foreign meteorological services maintain global atmospheric models for weather forecasting; surface and upper-air wind data and other meteorological measurements are assimilated into these models on a regular basis. Certain atmospheric variables, including pressure and horizontal wind velocity, are estimated at each model grid point at twelve-hour intervals by combining measurements of these variables with their forecasted values in a statistically optimal fashion. Calculation of an effective atmospheric excitation function, χ, a three-dimensional pseudo-vector including Love number corrections for rotational and surface loading deformation of the Earth, can be made directly from the meteorological data [1]. From intercomparisons between fluctuations in χ_3 (the axial component of χ) and length-of-day (LOD), it has been established that non-tidal rotation rate variations over time scales less than several years are largely due to atmospheric effects [44]. Also evident is a dominant seasonal cycle (Figure 2d) and additional variability on the intraseasonal (30 to 60 day—Figure 2e) and interannual time scales [Figure 2c; see also, 5, 16, 18, 22, 54, 61, 66]. The correlation between short-period variations in length-of-day and AAM is so well established that numerical forecasts of atmospheric angular momentum are now being used for the purpose of predicting Earth rotation variations [26]. There are also short-period fluctuations in the LOD due to solid Earth and ocean tides which arise because of tidal perturbations in the Earth's inertia tensor. The largest tidally induced LOD fluctuations occur for the fortnightly, monthly, semi-annual, and annual tides [80]. The amplitudes of these oscillations are sensitive to mantle anelasticity, which is not well constrained in this frequency range.

On interannual time scales (Figure 2c), length-of-day changes are related to atmospheric and climatic phenomena such as the Quasi-Biennial Oscillation and the El Niño/Southern Oscillation [7-9, 15, 17, 18, 21, 67]. However, at periods of more than several years (Figure 2b), the "decade" fluctuations are most likely caused by torques exerted by the core on the overlying mantle [40, 47]. In addition, the effects of long-period variability in the global ice and water budget may affect the rotation rate over periods of several decades or more [51, 53].

Because we have no direct access to the core, Earth rotation observations are of prime importance in the study of the structure and dynamics of the Earth's deep interior. In general, torques can be produced at the core-mantle boundary by viscous, electromagnetic, topographic and gravitational coupling. Two candidate mechanisms under investigation for these decade variations are (1) topographic torques due to dynamic pressure forces associated with core motions acting on undulations of the core-mantle boundary and, (2) torques of electromagnetic origin arising through Lorentz forces in the weakly-conducting lower mantle, which could be significant if the unknown electrical conductivity of the lower mantle, were sufficiently high. Estimates of topographic torques can be made from core motion deduced from geomagnetic secular variation, in combination with core-mantle boundary topography deduced either directly from seismic tomography or from dynamic models of the lower mantle based on tomographic and long-wavelength gravity anomaly data [43, 45]. Geodetic torque estimates inferred from the LOD provide a means of checking results from seismology and geomagnetism and imposing constraints on the models used.

3.2. Polar Motion

Polar motion is dominated by nearly circular oscillations at periods of one year (the annual wobble) and about 434

TABLE 1. Moments of Inertia of the Earth's Subsystems

A (mantle)	7.0999 x 10^{37} kg m^2;
A (fluid core)	0.90583 x 10^{37} kg m^2;
A (solid inner core)	0.0058531 x 10^{37} kg m^2;
A (atmosphere)	0.0000138 x 10^{37} kg m^2 [71];
(C-A) mantle	0.02377 x 10^{37} kg m^2;
(C-A) fluid core	0.002328 x 10^{37} kg m^2 [57 for the PREM model].

*A, B and C are the principle moments of inertia. In many applications the two smallest moments of inertia are assumed equal and the minimum of inertia is taken to be the average of A and B. In the separation of Equation 2, the changes in the orientation of the rotation axis depends on (C-A) and therefore the orientation changes (polar motion and nutations) are generally two orders of magnitude larger than the rotation rate changes. The effects of each of subsystems in the Earth (i.e., fluid core, oceans and atmosphere) depends not only on its moment of inertia (relative to the mantle) but also the velocity changes of the subsystem. Therefore, although the atmosphere has a very small moment of inertia, its rapid velocity variations produce large rotation variations.

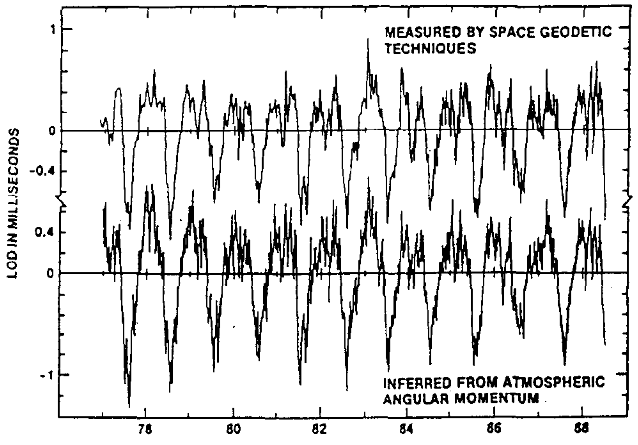

Fig. 4. Time series of the sum of the seasonal and intraseasonal LOD components, with the upper curve measured by space geodetic techniques (see Fig. 2d and e) and the lower curve inferred from routine daily determinations of changes in the axial component of the atmospheric angular momentum made by the U. S. National Meteorological Center.

days (the Chandler wobble), with amplitudes of about 100 and 200 milliarcseconds (mas), respectively, together with a long-term drift of a few milliarcseconds per year (1 and Figure 3]. In addition, astrometric data sets exhibit decade time-scale polar motion of amplitude less than 50 mas, while analysis of geodetic data reveals rapid polar motion with peak-to-peak variations of approximately 2 to 20 mas, fluctuating on time scales between two weeks and several months. Comparisons with meteorological data (Figure 5) suggest that these latter motions are at least partially driven by surface air pressure changes, as modified by the response of sea level to atmospheric loading and by wind variations [23, 34].

The atmosphere and oceans, together with the effect of variable ground water storage, are clearly responsible for exciting a large portion of the annual wobble [10, 50, 60, 76]. However, the entire annual wobble excitation is not fully accounted for. The Chandler wobble is a free oscillation of the Earth [70, 79] whose source of excitation is uncertain. Since polar motion is assumed to be a linear response to geophysical excitation, the problem is to find an excitation source with enough power near the Chandler period of about 434 days. The major candidates are the atmosphere and the redistribution of ground water. Other proposed sources, such as earthquakes, are probably too small in magnitude although great earthquakes may contribute [30]. A complication in determining the amount of excitation needed is that we do not know what the dissipation of the mode (or Q) is. The current estimates of Q assume a white noise excitation which may not be valid. If the Q is increased sufficiently, the current excitation mechanisms may be enough to explain its amplitude. Continual and improved monitoring of polar motion combined with improved models of atmospheric wind and pressure and ground water variations may resolve the degree to which the atmosphere drives polar motion.

The changing distribution of water in the ground and oceans is likely to be important at periods of a year and longer. On time scales of hundreds to thousands of years, water storage variations in the polar ice caps and the associated loading deformation of the solid Earth is a dominant influence on polar motion. Although one must account for other secular variations in these calculations, much of the observed secular drift of the pole in this century can be explained by redistributions of water and ice together with the post-glacial rebound following the last deglaciation around 20,000 years ago [51]. Contributions from plate motions, seismic deformation and present day melting of glaciers are also present; the study of these long-period polar motions is hampered by systematic errors in the optical astrometric data which must be relied on prior to 1976.

3.3. Nutations and Precession

Torques on the oblate Earth from the Sun, Moon and other bodies in the solar system cause a change in the direction of the Earth's rotation and figure axes, resulting in the precession of the Earth's equator along the ecliptic with superimposed oscillations. These motions are defined as the nutations. The response of the Earth to these externally applied torques is largely that of a rigid body. However, there are observable effects that arise because the Earth is deformable, with a solid-inner core, fluid-outer core, anelastic mantle, fluid oceans, and an atmosphere. It is these effects of the Earth's deformability that make nutations geophysically interesting [for a review, see 56].

From an inertial coordinate system, the Earth's nutations have periods much longer than a day. The largest such motion is the long-period precession, a nutation of the spin axis with a period of about 26,000 years. The precession is caused by the gravitational torque on the Earth's equatorial bulge from the Sun, Moon and the planets and thus has an angular amplitude of 23.5°, the angle between the equator and the plane of the Earth's orbit (the ecliptic). The inclination of the Moon's orbit with respect to the Earth's equator induces a lunar nutation on the Earth. The Sun perturbs the lunar orbit and causes it to precess (rotate in the plane of the ecliptic) with a period of 18.6 years, with

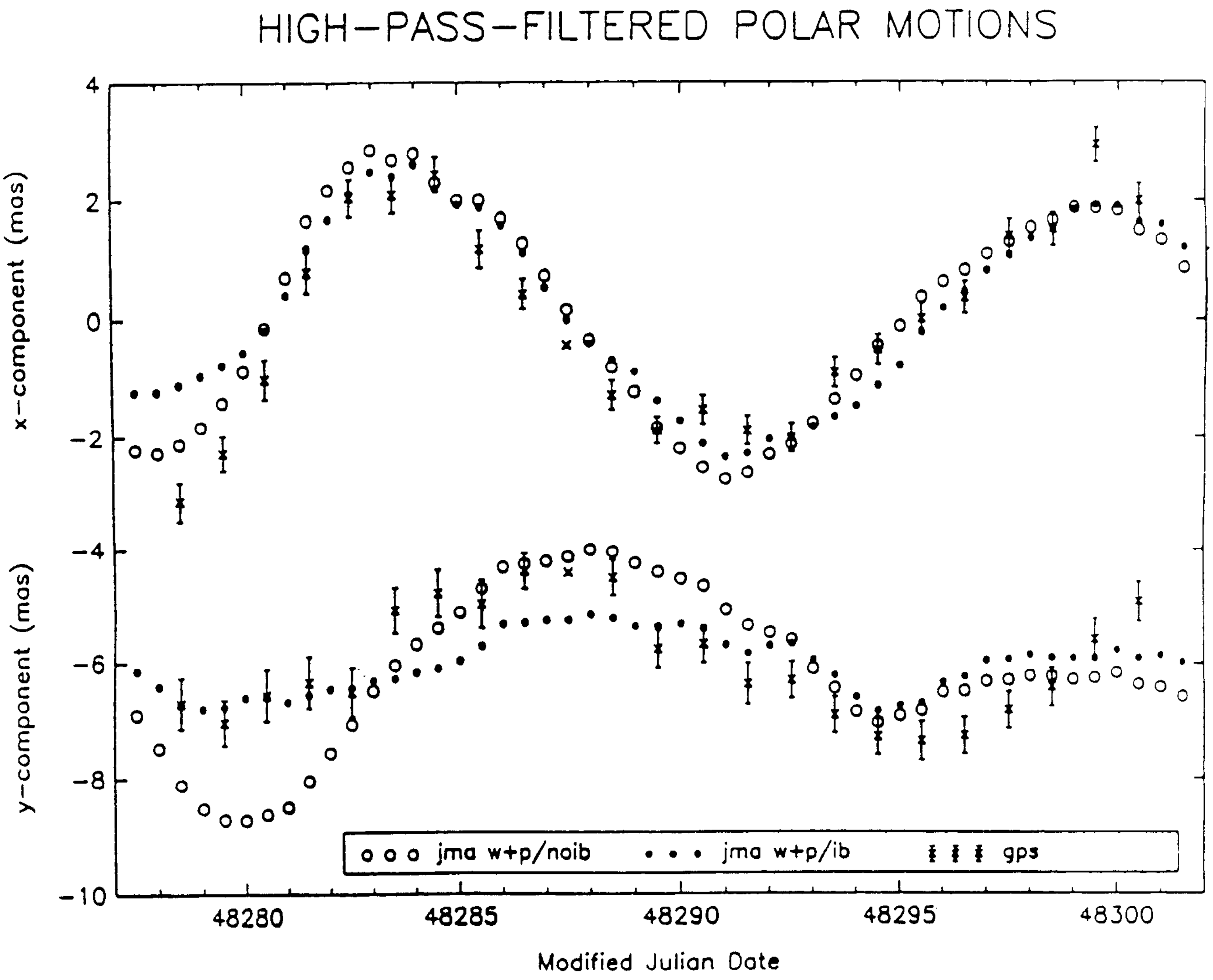

Fig. 5. The x-component (top) and y-component (bottom) of the observed and Japanese Meteorological Agency (JMA) AAM-induced polar motion series (both series have been high-pass-filtered using a cutoff period of 23 days). The crosses with error bars represent the observed series (one data point is plotted without error bars indicating that it is an interpolated point). The open circles represent the polar motion series induced by the JMA AAM χ-functions formed by summing the wind term with the pressure term computed under the rigid ocean approximation. The filled circles represent the polar motion series induced by the JMA AAM χ-functions formed by summing the wind term with the pressure term computed under the inverted barometer approximation, after [34].

the induced nutation having the same period and an amplitude of about 9 s of arc. There are also nutations with periods of one solar year, one lunar month and at the harmonics of the dominant frequencies with smaller nutations occurring at periods of half a solar year and a half-month and the harmonics of these. The half period is caused by the torque being symmetric about the equatorial plane. Nutation series are calculated assuming that the individual periodic components can be linearly summed and that the motion of the body axis with respect to inertial space can be obtained from the addition of the periodic nutations, precession, and the motions due to polar motion. The currently recommended nutation model, the IAU 1980 Theory of Nutation [69] is based on the work of Kinoshita

[48] for the rigid Earth series and of Wahr [75] for the perturbing effects of elasticity on a rigid Earth model. Analyses of the data from the space techniques have indicated that sizable corrections are required to the standard nutations models, which are a consequence of the incompleteness of the geophysical models (see Figure 6). The largest of these (~ 2 mas) is the correction to the retrograde annual nutation, caused by the closeness to the free core nutation (FCN) response frequency [37], which has been interpreted as being due to the flattening of the core-mantle boundary which deviates from its hydrostatic equilibrium by about 5% [36]. A similar discrepancy between theory and observations has also been observed in tidal gravity data [65], with results which are consistent with this increased flattening of 5%. Although the real parts of the FCN frequency agree well in both analyses, the tidal results have a significantly larger imaginary part (that is, smaller Q than the geodetic results), the reason for which is under current investigation.

3.4. Reference Frames

In general, each space geodetic system defines a reference frame based on technique-dependent considerations. Furthermore, each technique makes some unique contribution to reference frame considerations. For example, the VLBI technique provides a direct link to the already adopted inertial reference frame, but it has no sensitivity to the Earth's center of mass. Conversely, SLR and GPS are sensitive to the center of mass but are nearly independent of the adopted reference frame. Thus, SLR and GPS, for example, are not inertial sources of UT1 and must be tied periodically to an inertial system. LLR is sensitive to the center of mass, defines its own reference frame, the lunar ephemeris, which is a component of the planetary ephemeris, and is of great importance in spacecraft navigation and in the unification of reference systems. The interested reader is referred to the text [49] which is entirely devoted to reference frames.

Commonly used frames are the IERS (International Earth Rotation Service) Celestial and Terrestrial Reference Frames (ICRF and ITRF, respectively). The ICRF is derived from the VLBI measured positions of ~400 quasars as reported by various analysis centers, while the ITRF is based on ~120 IERS observing sites [25].

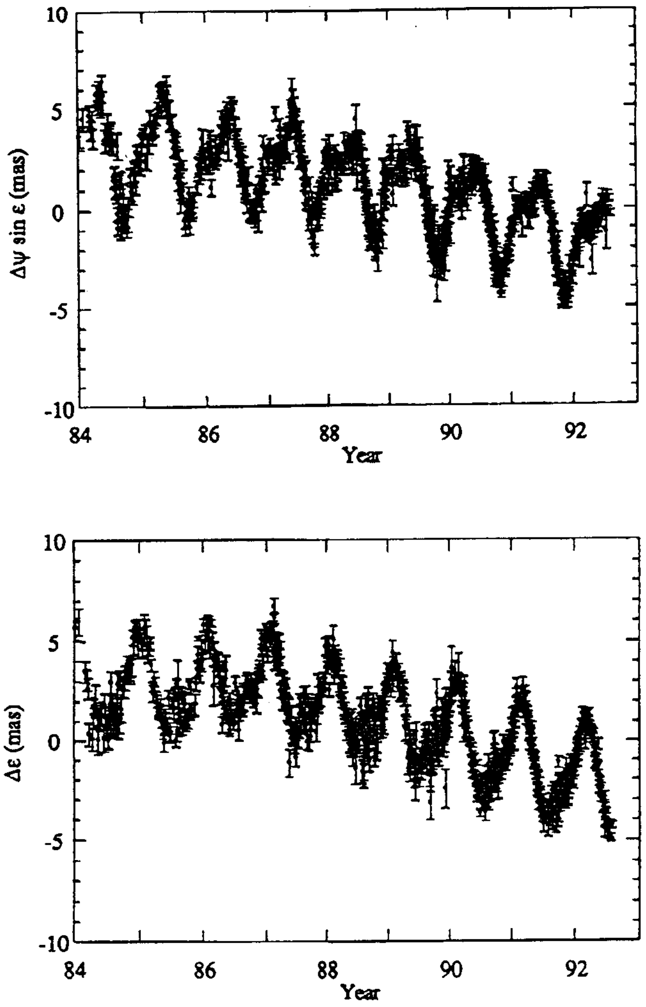

Fig. 6. Estimates of corrections, (a) $\delta\Delta\psi \sin \varepsilon_0$ and (b)$\delta\Delta\varepsilon$ to the IAU 1980 values for the nutation in longitude, $\Delta\psi \sin \varepsilon_0$ and the nutation in obliquity, $\Delta\varepsilon$ (T. Herring, Priv. Comm., 1993).

4. CONSTANTS AND MODELS UTILIZED IN EARTH ROTATION REDUCTION AND ANALYSIS

A variety of models and constants are used in the reduction and analysis of Earth rotation. The International Earth Rotation Services (IERS—see Section 5) has published the *IERS Standards* as an IERS Technical Note [58, 59], which provides guidance to the international community on the use of constants and models. Numerical standards [adapted from 61] are given in Table 2; a short description and relevant references for the main model being utilized are listed below:

4.1. Nutation Model

The currently recommended nutation model, IAU 1980 Theory of Nutation [69], is based on the work of Kinoshita [48] for the rigid Earth series and of Wahr [75] for the

TABLE 2. Numerical Standards [adapted from 59]

Astronomical Constants	Recommended Value
Defining Constants	
• Gaussian Gravitational Constant	$k = 0.01720209895$
• Velocity of Light	$c = 2.99792458 \times 10^8 ms^{-1}$
Primary Constants	
• Astronomical Unit in Light-Seconds	$\tau_A = 499.00478353$ s
• Equatorial Radius of the Earth	$a_e = 6378136.3m$
• Dynamical Form Factor for Earth	$J_2 = 0.0010826362$
• Geocentric Constant of Gravitation	$GM_\oplus = 3.986004415 \times 10^{14} m^3 s^{-2}$
• Constant of Gravitation	$G = 6.67259 \times 10^{-11} m^3 kg^{-1} s^{-2}$
• Earth-Moon Mass Ratio	$\mu = 0.012300034$
• General Precession* in Longitude Per Century for J2000.0	$p = 5029''.0966$
• Obliquity of the Ecliptic for J2000.0	$\varepsilon_0 = 23°26'21''.4119$
• Mean Angular Velocity of the Earth	$\omega = 7.292115 \times 10^{-5}$ rad s^{-1}
Derived Constants	
• Astronomical Unit	$c\tau_A = 1.4959787061 \times 10^{11} m$
• Solar Parallax	$\pi = \sin^{-1}(a_e / A) = 8''.794142$
• Earth Flattening	$f^{-1} = 298.257$
• Heliocentric Constant for Gravitation	$GM_\odot = 1.32712440 \times 10^{20} m^3 s^{-2}$
• Ratio of the Solar Mass to the Mass of the Earth	$GM_\odot / GM_\oplus = 332{,}946.045$
• Ratio of the Solar Mass to the Mass of the Earth-Moon System	$GM_\odot / GM_\oplus (1 + \mu) = 328{,}900.56$
• Solar Mass	$M_\odot = 1.9889 \times 10^{30} kg$

*General precession includes planetary and geodetic precession.

perturbing effects of elasticity on a rigid Earth model. VLBI and LLR observations have shown that there are deficiencies in both the currently accepted IAU 1976 Precession and the IAU 1980 Theory of Nutation [11, 38, 39]. For users requiring accuracies of 2 mas (the error in the annual term, the dominant correction term) at best, the current model may be employed. It should be noted that the resulting error due to the adaptation of this series will grow as the time span increases, reaching, for example, 10 mas in a decade. However, for those with more stringent requirements, the series regularly reported by the IERS (see Section 5) is recommended. Another alternative is to utilize empirically derived correction series [see for example 38, 82].

4.2. Tidal Variations in Earth Rotation

Tidal variations in Earth rotation are caused by the periodic changes in the inertia tensor produced by the gravitational attraction of the Moon, Sun and other astronomical bodies. These variations (with amplitude up to 0.5 ms in UT1) must be substracted from the series before further geophysical analysis is performed. The Yoder *et al.* model [80] is in current use to calculate the periodic variations in UT1 due to modification of the polar moment of inertia by tidal deformation of the Earth with a decoupled core. Oceanic tides also cause variations in UT1 and are an active area of research [2, 3, 19, 33]. They make a significant contribution at the fortnightly period and dominate sub-daily variations.

4.3. Geopotential Model

An accurate geopotential model is required, particularly in the analysis of satellite laser ranging data; the recommended model is the GEM-T3 Model [55].

4.4. Solid Earth Tide Model

A solid Earth tide model is required in the reduction of all geodetic data types. Observatories and sites are displaced by the solid Earth tides, and if not properly accounted for, the resulting systematic error would corrupt Earth rotation measurements. The current generally used model [59, Ch. 7] is an abbreviated form of the Wahr model [75] using the Earth model 1066A of Gilbert and Dziewonski [29].

4.5. Ocean Tide Model

An ocean tidal model is required, particularly in analysis of satellite laser ranging data [20]. The currently recommended model is that of Schwiderski [68].

4.6. Plate Motion Model

Observatories are located on plates and thus Earth rotation series are corrupted if plate motion is improperly modeled. The NUVEL NNR-1 Model [13] is now commonly used.

4.7. Lunar and Planetary Ephemeris

The planetary and lunar ephemerides recommended by the IERS Standards are the JPL Development Ephemeris DE200 and the Lunar Ephemeris LE200 [72, 73].

5. The International Earth Rotation Service and Data Availability

An important development has been the introduction in 1988 of the International Earth Rotation Service (IERS) centered in Paris, to consolidate the earlier activities of the BIH (Bureau Internationale de l'Heure, based in Paris) for determining UT1 and of the International Polar Motion Service (IPMS), based in Japan, for determining polar motion. The IERS is charged with defining and maintaining both conventional terrestrial and celestial reference systems, determining the Earth orientation parameters connecting these systems (the terrestrial and celestial coordinates of the pole and the universal time), organizing operational activities for observation and data analyses, collecting and archiving data and results, and the dissemination of the results [63].

The IERS results are based primarily on the space geodetic techniques of laser ranging to the moon and artificial satellites, and Very Long Baseline Interferometry [63] with the recent addition of GPS as a fourth technique [46]. It is composed of a Coordinating Center and other technical centers for each of the four observing techniques, and a Central Bureau with associated Sub-Bureaus. The Central Bureau combines the various types of data and disseminates to the international community the relevant information on Earth rotation and the terrestrial and celestial reference systems. Two sub-bureaus are associated with the Central Bureau: a Sub-Bureau for Rapid Service and Predictions and a Sub-Bureau for Atmospheric Angular Momentum.

Earth rotation results of the IPMS are archived at the National Astronomical Observatory, Misuzawa, Japan; a copy is also archived at the IERS Central Bureau. The BIH results are archived at the Paris Observatory. The results on Earth rotation and reference frames from the modern techniques (VLBI, LLR, SLR and GPS) are archived at the Central Bureau. In addition, complementary geophysical data sets such as atmospheric angular momentum are also stored there.

Information and data are distributed through a variety of mechanisms, both electronic and hard copy [46]. Typical information disseminated on a regular basis includes polar motion, UT1, and celestial pole offsets (i.e., the combined effect of precession and notation); both combined and individual-technique series are distributed. The weekly *Bulletin A* includes a rapid service and prediction; whereas the monthly *Bulletin B* presents the results of a more comprehensive analysis, taking into consideration more data sets. The Annual Report of the IERS includes further-refined, state-of-the-art solutions with information on Terrestrial and Celestial Reference systems. The nominal precision of the published results depends on the delay of their availability. For the operational solutions of Earth rotation (weekly and monthly bulletins), it is a few mas. The prediction accuracy is in the range of 3 to 20 mas for polar motion and 2 to 15 ms for UT for lead times of 10 to 90 days. For the IERS combined solution of Earth rotation, the nominal uncertainties of polar motion and UT1 are normally better than 0.3 mas (1 cm); those of the celestial pole offsets ($d\Psi \sin \varepsilon$ and $d\varepsilon$) are about 0.3 mas. The individual coefficients from the nutation series are determined (see previous section) with accuracies of about 0.04 mas, and should yield more accurate celestial pole offsets than the daily estimates. The IERS, in addition, publishes Technical Notes, which provide information of relevance to the IERS work on Earth rotation and the reference system. The IERS Standards, published as an IERS Technical Note, provide guidance to the international community on the use of constants and models (see Section 4).

Requests for IERS publications and further information may be addressed to: Central Bureau of IERS, Observatoire de Paris, 61 avenue de l'Observatoire, 75014 Paris, France. Telephone: 33 (1) 4051-24226; Telex: OBS270776P; Fax: 33 (1) 4051-2232; GE Mark III: IERS-CB; EARN/BITNET/SPAN: IERS@FRIAP51.

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