12. W. Marshall, *Atom (U.K.) No. 282* (April 1980), p. 88.
13. U.S. Public Law 95-242 (10 March 1978).
14. At the completion of Argentina's gaseous diffusion uranium enrichment facility at Pilcaniyeu in Río Negro province 660 miles south of Buenos Aires on 18 November 1983, Carlos Castro Madero, president of the National Atomic Energy Commission, made the following public statement: "The significant decision of launching this project was made in 1978 in the light of the unexpected decision of our supplier of enriched uranium to interrupt the supply of this material which is required for the operation of our research and isotope-production reactors, at the time when we were starting a policy of exporting reactors to Latin America and when we could foresee very promising possibilities with the use of slightly enriched fuel elements in our power reactors. . . . . Once again, as Argentina has stated in several international fora, it has been proven that such policy of denials, enforced by the great powers to the extent of suspending supply of safeguarded materials needed to produce radioisotopes, fails to give the expected results. Such policy will always fail because of its discriminatory nature, particularly when a country is prepared to face with its own technical resources the development of technologies to assure its autonomy and independence."
15. According to Munir Ahmad Khan [*Nucl. News* **26**, 95 (December 1983)], "the policy of denial of nuclear technology and of using technical fixes to promote acceptance of non-proliferation has not worked, and in fact, has been counterproductive. . . . . The existing insecurity of supplies has actually encouraged the proliferation of the nuclear fuel cycle and has compelled countries to seek a greater degree of self-reliance in the nuclear field."
16. International Nuclear Fuel Cycle Evaluation (INFCE), *Summary and Overview* (IAEA, Vienna, 1980).
17. H. Blix, "International nuclear fuel cycle: Some problem areas" in proceedings of the joint (U.S.) Atomic Industrial Forum and FORATOM (European Nuclear Forums) Conference, 31 May to 3 June 1983.
18. Nuclear Non-Proliferation Act goals include improved assurance of fuel supply; establishment of an international nuclear fuel authority; establishing repositories for spent fuel; defined sanctions for violations or abrogation of agreements; determination of national interest in repurchase, transportation, or storage of spent fuel; aid to developing countries in meeting energy needs "consistent with economic factors"; and "procedures to facilitate the timely processing of requests . . . to enhance the reliability of the United States in meeting its commitments to supply nuclear reactors and fuel to nations which adhere to effective non-proliferation policies."
19. Report to Congress, "The NNPA of 1978 should be selectively modified" (OCG 81-2, General Accounting Office, Washington, D.C., 1981).

RESEARCH ARTICLE

Variations in the Rotation of the Earth

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As recently as a few decades ago, the diurnal rotation of the earth served to define the basic unit of time. Clocks were adjusted to agree as closely as possible with the length of day (LOD) determined from observations of successive transits of stars across the meridians of optical astronomical observatories. In 1912 the Bureau International de l'Heure (BIH) was founded at the Paris Observatory to establish a "unified" time system by publishing the offsets between the radio time signals broadcast by various observatories. As technology progressed and clocks became ever more precise, questions arose concerning the uniformity of the LOD. By 1936 the performance of pendulum clocks had so advanced that the director of the BIH, N. Stoyko, suggested that the LOD in January actually exceeded the LOD in July by approximately 2 msec (*1*). A change in the LOD of 1 msec represents a change in the earth's rate of rotation of approximately 1 part in 10^8. Detecting a change in the rotation rate of a few parts in 10^8 over periods of months with mechanical clocks was a remarkable achievement. As quartz crystal clocks became operational and were refined to achieve stabilities of the order of parts in 10^{11} to 10^{12}, it became obvious that the LOD varied in a complex manner, with periodic components at annual, semiannual, lunar-monthly, and fortnightly periods and amplitudes of a few to several tenths of a millisecond. There were also suggestions of irregular variations in the LOD including sudden jumps on the scale of a millisecond per day. Because only optical (stellar) astrometric observations were available, it was impossible at that time to decide whether these apparent high-frequency variations were real or the result of observational errors.

Abstract. *Variations in the earth's rotation (UT1) and length of day have been tracked at the submillisecond level by astronomical radio interferometry and laser ranging to the LAGEOS satellite. Three years of regular measurements reveal complex patterns of variations including UT1 fluctuations as large as 5 milliseconds in a few weeks. Comparison of the observed changes in length of day with variations in the global atmospheric angular momentum indicates that the dominant cause of changes in the earth's spin rate, on time scales from a week to several years, is the exchange of angular momentum between the atmosphere and the mantle. The unusually intense El Niño of 1982–1983 was marked by a strong peak in the length of day.*

With the development by 1955 of atomic frequency standards having stabilities of a few parts in 10^{13} and sufficient portability to allow accurate comparison of clocks at widely separated observatories, man-made clocks finally displaced the diurnal rotation of the earth as the basic unit of time. At that time the primary purpose of LOD observations changed from defining the fundamental time scale to monitoring the variations in the rotation of the earth for applications in geodetic surveying, navigation, and astrometry, and for basic research in the dynamics of the earth. For most applications it is generally the change in the rotational orientation of the earth over some time interval, that is, the accumulated effect of variations in the LOD, that is required. The rotational orientation of the earth is referred to as UT1.

Early attempts to identify the causes of the observed variations in the LOD were severely hampered by a lack of basic data such as global meteorological measurements. Nonetheless, it was generally accepted as early as 1960 that the seasonal variations were caused primarily by changes in wind patterns (*1*). A study by Lambeck and Cazenave published in 1973 showed the dominant effect to be the periodic exchange of angu-

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lar momentum between the atmospheric zonal wind circulation and the earth's mantle (*2*). Some evidence suggested that atmospheric circulation might also be important at longer periods, perhaps up to the order of a decade. For periods longer than a decade, mass transport within the fluid core and coupling between the core and mantle were generally thought to be the primary sources of changes in LOD. The question of variations with periods of days to a few months remained an open issue, awaiting improved measurements made by new observational techniques (*3*).

During the 1960's and 1970's, three new observational techniques were developed; these techniques were based on advanced technology stimulated by space exploration efforts. These were lunar laser ranging (LLR), satellite laser ranging (SLR), and very long baseline interferometry (VLBI). In the two laser-ranging techniques, very short pulses of light (typically a billionth of a second or less) generated by lasers are transmitted to retroreflectors placed on the moon or mounted on the surface of artificial satellites. One measures the round-trip travel time of each light pulse and converts that measurement to the distance from the observatory to the reflectors, using the known speed of light. A series of such measurements eventually allows the orbital parameters and perturbations of the satellite to be estimated well enough to produce a precise ephemeris for the reflector package, which then serves as a reference frame for measuring a number of geodetic and geophysical quantities, including variations in the LOD. In the VLBI technique, radio telescopes are used to collect extremely faint radio signals emitted by radio sources (typically quasars) that are believed to be located billions of light-years from the earth. The arrival times of the signals at the radio telescopes are recorded on magnetic tapes. The tapes are transported to a special-purpose correlator, which extracts the differences in the arrival times of the signals at the various telescopes (delays). The delays from several quasars can then be used to determine both the relative directions of the quasars, which then serve to define a quasi-inertial reference frame, and the length and direction of the vector baseline connecting each pair of telescopes. A series of determinations of the baseline directions can then be used to determine the changes in the orientation of the earth as a function of the uniform atomic time scale and thereby UT1. One can then determine the LOD by dividing the deviation of UT1 from the adopted uniform time scale by the interval in days between the observations.

In this article we compare series of VLBI and SLR determinations of UT1 and LOD over a 3-year period from October 1980 through September 1983. Since the two observing techniques are fundamentally dissimilar (different classes of objects are observed at different wavelengths from different locations), there is only a very low probability that both series of measurements will be contaminated by common systematic errors. Variations in UT1 and LOD observed by both techniques therefore almost certainly reflect actual variations in the rotation of the earth. We also compare these direct measurements of changes in LOD to values derived from atmospheric zonal-wind data. The comparisons show conclusively that the atmospheric winds play a dominant role in variations of the LOD at periods as short as a few weeks. Our results agree with the results of similar studies based on LLR observations of LOD and atmospheric angular momentum by Langley *et al.* (*4*).

POLARIS Estimates of UT1

During the 1960's and 1970's, the National Aeronautics and Space Administration (NASA) and the National Science Foundation supported the development of three generations of VLBI instrumentation and computer software. The third-generation MARK III system, developed by a consortium of engineers and scientists at the Massachusetts Institute of Technology, Haystack Radio Observatory, NASA Goddard Space Flight Center, and the National Radio Astronomy Observatory (*5*), brought the state of the art to the level where a VLBI-based, earth-rotation monitoring system became practical. In 1977, the National Geodetic Survey (NGS), a component of the National Oceanic and Atmospheric Administration (NOAA), launched Project POLARIS (polar-motion analysis by radio interferometric surveying) (*6*). POLARIS replaces the obsolete optical polar motion monitoring observatories which NGS had operated for more than 80 years in conjunction with the International Latitude Service by establishing a three-station network of VLBI observatories. The POLARIS network was designed to improve both the temporal and spatial resolution of measurements of the earth's rotation by more than an order of magnitude. The project grew almost immediately into a truly national effort as first NASA and then the U.S. Naval Observatory agreed to participate.

The first two POLARIS observatories, the George R. Agassiz Station (GRAS, formerly the Harvard Radio Astronomy Station) near Fort Davis, Texas, and the Westford Observatory, near Boston, Massachusetts, became operational in September 1980 and April 1981, respectively. The third POLARIS observatory, located at the U.S. Naval Observatory timing substation near Miami, Florida, began operations at the close of 1983. As soon as the GRAS POLARIS facility was operational, the NGS began regular observations. The Haystack Radio Observatory was used until the Westford facility was completed. In June 1981, the GRAS-Westford interferometer began routine operations. That interferometer is more than 3100 km in length and is oriented predominantly east-west (the baseline is inclined to the earth's equatorial plane by only 20 degrees) and is therefore very sensitive to changes in the rotational orientation of the earth (*7*).

The POLARIS observing sessions are 24 hours in duration. In a typical observation, the telescopes simultaneously observe a radio source for 2 to 3 minutes before shifting to another source. More than 200 observations on a set of 14 sources may be accumulated during a session. Observations are made at 14 different frequency channels, six near 2200 MHz (S-band) and eight near 8400 MHz (X-band), recording 4 million bits per second on each channel. A single observation consists of the collection of approximately 10 billion (10^{10}) bits at each station. Each two-station POLARIS session therefore requires the recording and processing of 4 trillion (4×10^{12}) bits of data. Without an efficient computerized system, we would be quickly inundated with data. However, the MARK III system is so well designed that the observational data can be processed through the correlator in a fraction of the time required to make the observations (*8*), and the final reductions and analysis to extract the information on the earth's rotation are routinely completed by one person in a few hours.

The methods and procedures used by the NGS to process the POLARIS observations have been described in detail by Robertson and Carter (*9, 10*). Briefly, calibration factors accounting for variations in cable lengths and phase instabilities in the electronics are applied, the S- and X-band observations are used to compute and remove ionospheric effects, and surface meteorological data are used to compute corrections for the effects of the troposphere. A least-squares adjustment is performed to estimate source positions, clock parameters, atmosphere zenith heights, and geodetic information, including polar motion and UT1. The individual observations typically have a root-mean-square scatter of about 0.1 to 0.15 nsec, equivalent to a range difference of 3 to 5 cm. The estimates of UT1 usually have a formal uncertainty (1 σ) of a few tenths of a millisecond or less and, as we shall see from comparisons with other techniques, have an accuracy no worse than a fraction of a millisecond.

SLR Estimates of UT1

In contrast to the VLBI instrumentation, SLR systems are diverse in design. The earliest systems used ruby lasers, which produced one pulse of red (6943 Å) light every 2 to 5 seconds. The pulses typically had an energy of a few joules and a duration of 3 to 10 nsec. The round-trip travel time was usually measured with interval timers having resolutions of 1 nsec. There are still a few of these first-generation systems operating, but most have been upgraded by the replacement of various components as the technology has evolved. Nearly all systems built within the past several years use neodymium:yttrium-aluminum-garnet lasers frequency-doubled to produce green light (5320 Å), at repetition rates as high as ten pulses per second, pulse lengths of a few hundred picoseconds, and energy levels of tens to hundreds of millijoules per pulse. The timing is typically done with an event timer or a multiple-stop interval timer with resolution at the 100-psec level. The single-shot precision of these advanced systems is 2 to 3 cm, and a normal point, formed from tens of individual range measurements, typically has a precision of better than 1 cm.

The high precision of the SLR systems can be translated to highly precise information on the earth's rotation only if the orbit of the satellite can be computed with comparable precision. In order to achieve a high level of orbital stability, NASA launched the Laser Geodynamics Satellite (LAGEOS) in 1976. This satellite is a solid sphere 60 cm in diameter weighing 407 kg and covered with 426 retroreflectors, each with an aperture of 3.8 cm (*11*). The high altitude (5900 km) and low surface-to-mass ratio of this satellite allow its position to be determined to an accuracy of a few decimeters over intervals of 30 days. However, even with LAGEOS there will be anomalous long-period motions of the ascending node of the orbit relative to inertial space arising from unmodeled variability of the geopotential. These motions limit the ability of the technique to produce an accurate UT1 time series over long periods. Only when the LAGEOS UT1 solution is compared with corresponding estimates from data sources independent of a detailed knowledge of the geopotential can the estimates of UT1 from the LAGEOS observations be properly interpreted (*12*). Indeed, the anomalous variations observed in the LAGEOS UT1 estimates are a valuable source of information about the geopotential and especially about time variations in the geopotential (*13*).

The SLR observations to the LAGEOS satellite, which were analyzed by the University of Texas to produce the

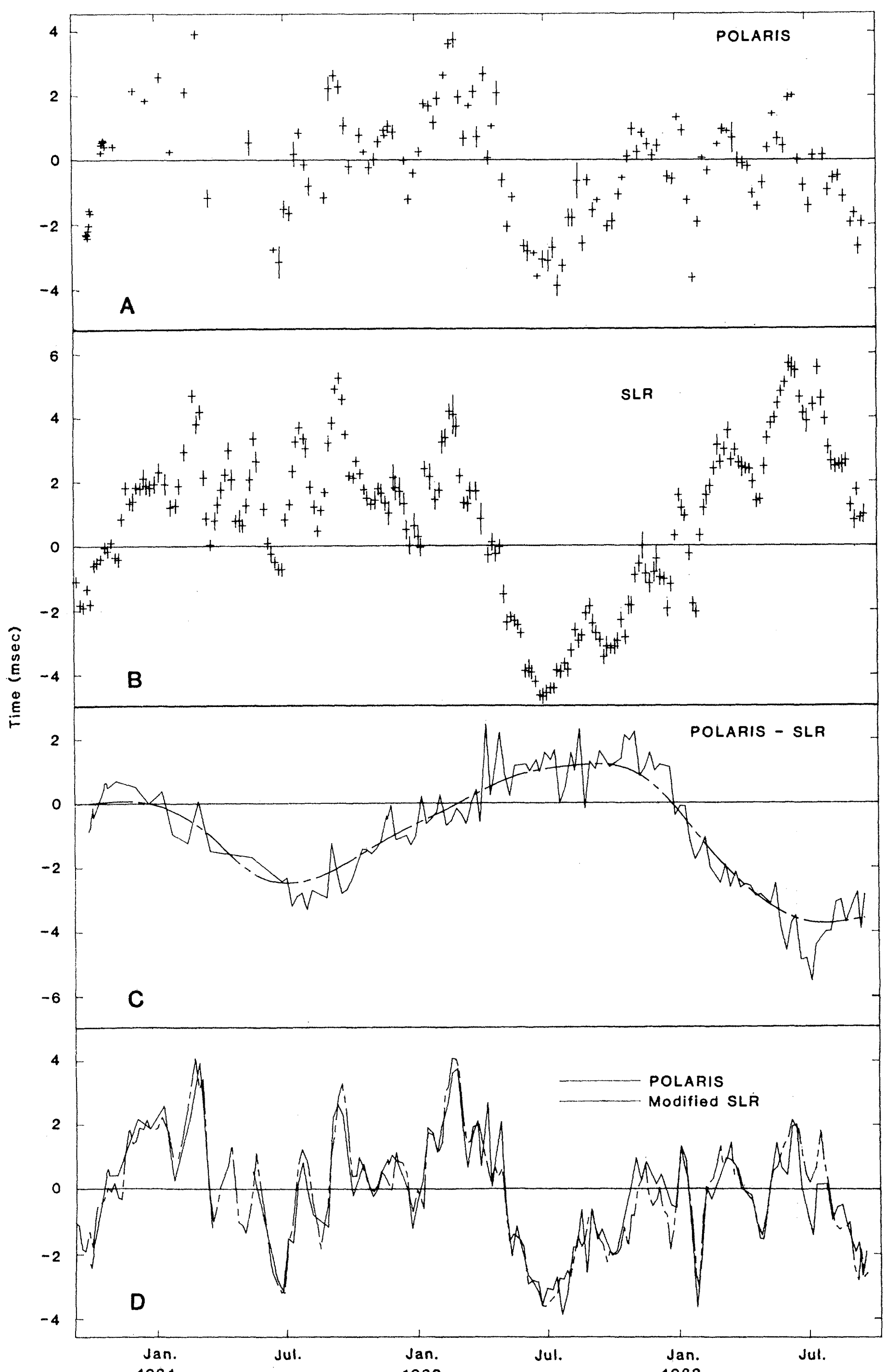

Fig. 1. (A) The UT1 determinations from the POLARIS observations. (B) The UT1 determinations from the SLR observations. Both series are shown as differences from the BIH Circular D series; the vertical bars represent the formal standard errors of the determinations. (C) Differences between the SLR and POLARIS determinations and the curve generated as a result of smoothing the differences. (D) The POLARIS and SLR series after removal of the smoothed differences shown in (C). The POLARIS line is discontinuous during April and May 1981, when equipment failures caused a gap in the VLBI observations.

UT1 estimates, were obtained by the NASA Crustal Dynamics Project (*14*). This project was initiated by NASA in 1978 to apply the rapidly maturing space technology to the study of geodynamics. Several observatories in foreign nations also cooperate and exchange data with the Crustal Dynamics Project.

Comparison of the VLBI and SLR UT1 Series

Figure 1 compares the POLARIS VLBI and the University of Texas SLR UT1 series. In order to accentuate short-term variations in UT1, we have subtracted the BIH Circular D series and the short-period tidal terms (*15*) from both the VLBI and the SLR series and plotted only the residuals. The Circular D values are not the most definitive BIH values, but they are convenient to use because they are widely available with a delay of only about 2 months.

The differences between the VLBI and BIH series are plotted in Fig. 1A. The error bars on the VLBI points represent the formal (1 σ) estimates of the precision of the UT1 determinations. Instrumentation malfunctions caused the loss of a few scheduled sessions and during March, April, and September 1982 caused a significant loss of observations that resulted in degraded UT1 values.

The differences between the SLR and BIH series are plotted in Fig. 1B. The error bars have the same meaning as in Fig. 1A. For purposes of comparing the VLBI and SLR results, UT1 values for the exact dates of the VLBI observations were computed by linear interpolation between the SLR values. The root-mean-square difference computed in that manner was found to be 1.8 msec. However, the SLR series can be expected to contain secular and long-period variations due to errors in the coefficients of the LAGEOS force model. As one example, errors in the adopted ocean tide model will lead to long period errors in the SLR UT1 time series.

In order to remove these long-term effects, we smoothed the differences between the VLBI and the SLR values by convolution with a Gaussian function with a full width at half maximum of 90 days. The difference between the VLBI and SLR series and the resulting smooth curve are plotted in Fig. 1C. We then modified the SLR values by subtracting the smoothed values. This procedure is equivalent to passing the SLR data through a high-pass filter; it yields an SLR UT1 time series that still contains useful information about the high-frequency variations in UT1 but no longer contains the spurious low-frequency variations.

Figure 1D is a plot of the VLBI and modified SLR series. The root-mean-square difference is 0.7 msec. The seasonal-scale variations clearly are in general agreement, and there is qualitative agreement in the variations for time scales of a few weeks. The large short-period variations in February and March 1981, June through September 1981, and January and February 1983 are examples of this agreement.

Variations in LOD Implied from Atmospheric Angular Momentum

The National Meteorological Center (NMC) of NOAA routinely produces 12-hour global summaries of the state of the atmosphere for use in weather forecasting. The data are compiled from several sources, including rawinsonde (radiosonde with wind velocity measurements) balloons launched at the upper-air stations of the World Weather Watch network, satellites, commercial aircraft, and ocean vessels. The NMC processes these temporally and spatially nonuniformly distributed observations to produce, among other items, the zonal (east-west) wind velocities at the intersections of 2.5° intervals in latitude and longitude, at 12 levels of barometric pressure beginning at 1000 mbar and extending outward to 50 mbar.

The atmospheric angular momentum is computed for each 12-hour interval at the NGS by numerical integration of the zonal wind data. Assuming conservation of angular momentum for the atmosphere-mantle system, one can use changes in atmospheric angular momentum to derive expected variations in the rotation rate of the earth. A detailed discussion of the formulations and procedures used to compute the atmospheric angular momentum and derive the implied variations in LOD has been presented by Rosen and Salstein (*16*).

Comparison of the Three LOD Series

Although the SLR and atmospheric angular momentum LOD series go back farther in time, we will limit our discussion to the period from June 1981 through September 1983 when the VLBI observing sessions were conducted routinely at weekly intervals. We derived daily estimates of the LOD from the VLBI data by sequentially differencing the UT1 determinations and then smoothing and interpolating the resulting series by convolving it with a Gaussian function having a full width at half maximum of 10 days. The SLR and atmospheric angular momentum series were smoothed in the same manner. All three LOD series are plotted in Fig. 2. An offset has been removed from the atmospheric angular momentum curve. The

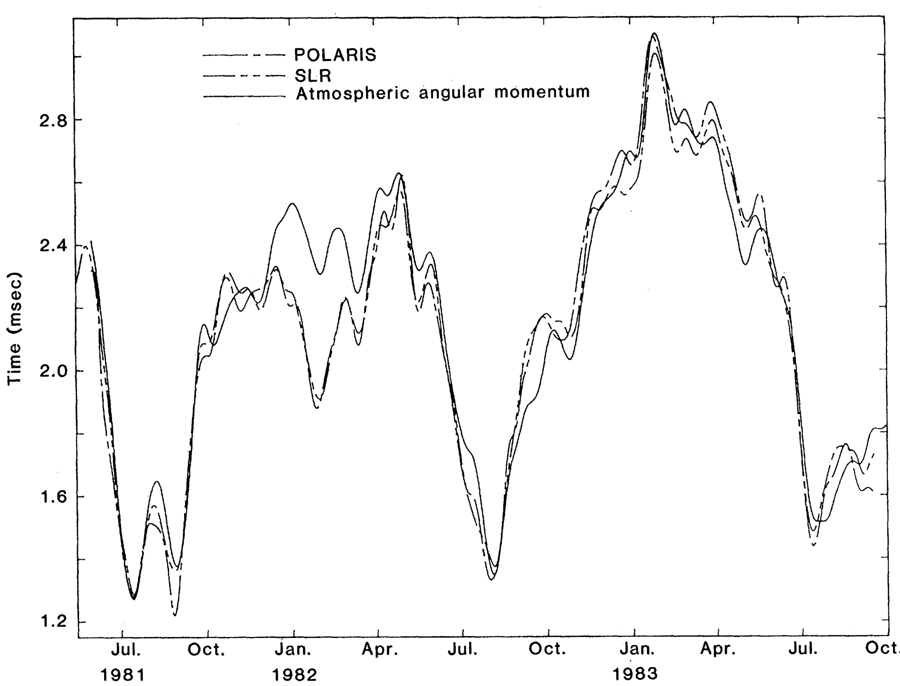

Fig. 2. Excess length of day as measured by POLARIS VLBI and SLR observations and as inferred from observed changes in the global atmospheric angular momentum.

root-mean-square differences between the VLBI and SLR data, the VLBI and atmospheric angular momentum data, and the SLR and atmospheric angular momentum data are 0.06, 0.13, and 0.12 msec, respectively.

The discrepancies between the LOD implied from the atmospheric angular momentum data and either the VLBI or SLR results do not vary randomly. Both contain an obvious cyclic component with a period of approximately 6 months and an amplitude of about 0.1 msec. The source of this systematic variation is not known and may simply reflect inaccuracies in the meteorological data or may be a result of deficiencies in the algorithm used to derive LOD from the atmospheric angular momentum values. For example, it is possible that the angular momentum of the portion of atmosphere above 50 mbar is large enough to account for the discrepancy or that a significant amount of the atmospheric angular momentum is transferred to the oceans rather than to the mantle.

The rapid change in UT1 during January and February 1983 is reflected as a strong peak in the plot of LOD (Fig. 2). This extremity in LOD, reaching nearly 3.1 msec, was occasioned by extraordinary oceanic and atmospheric conditions associated with the strongest episode of the Southern Oscillation–El Niño phenomenon to have occurred in the past 40 years, perhaps in this century (*17*). The VLBI and SLR LOD series certainly contain information about the interactions between the earth's mantle, atmosphere, and oceans, and may contribute to the attempt to understand phenomena such as the Southern Oscillation–El Niño sufficiently well to predict their occurrences and attendant effects on year-to-year fluctuations in climate.

Concluding Comments

The improved series of earth-rotation measurements presented here represent some of the early results of a concerted international effort to apply advanced technology to the study of geodynamics. In September 1983 Project MERIT (monitor earth rotation and intercompare techniques of observation and analysis), jointly sponsored by the International Astronomical Union and the International Union of Geodesy and Geophysics, launched a 14-month observing campaign to study the earth's rotation (*18*). The VLBI, SLR, and LLR observations collected under Project MERIT are expected to yield the most detailed and accurate records of variations in the earth's rotation ever compiled. Special efforts are also being made to improve both the observational and analytical aspects of monitoring variations in the atmospheric angular momentum with the goal of improving our understanding of the interactions among the oceans, atmosphere, and solid earth. Plans are already under way to ensure that the international cooperation generated by Project MERIT does not wither at the completion of the current campaign. The improved observational capabilities may well allow questions that have dominated the study of geodynamics for more than a century to be answered within the next decade. Even more exciting is the expectation that previously undetectable signals will pose new and more challenging questions.

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