N79-24754

MODERN METHODS FOR THE DETERMINATION OF POLAR MOTION AND UT1

William E. Carter
National Geodetic Survey
National Ocean Survey, NOAA
Rockville, Md. 20852

ABSTRACT

This paper is organized into two major divisions according to the topics: polar motion and UT1. Each division is introduced with a brief review to provide a minimal perspective for readers unfamiliar with the subject area. The applications of Doppler satellite observations, laser ranging to artificial satellites and the Moon, and astronomic radio interferometry to monitoring polar motion and UT1 are discussed. Emphasis is placed on detailing how and what each method is capable of measuring, fundamental limitations are noted, and the present status of the development of each method is reviewed.

The paper concludes with a summary of the author's evaluations of the various methods as candidates for the next generation international polar motion and UT1 monitoring service.

INTRODUCTION

The "classical" methods of monitoring polar motion and UT1 have been based on visual, photographic, and photoelectric observations of optical stars. The temporal and spatial resolutions and accuracies of these methods have been limited by such factors as; an inability to fully correct the observations for the effects of the Earth's atmosphere, inaccuracies in the relative positions and proper motions of the stars, the limited number and poor distribution of observatories, and instrumental imperfections. Further refinements of the classical methods, some of which involve the application of modern technology, are continuing and are expected to yield significant improvements. However, profoundly different methods, which have developed as outgrowths of space exploration activities, promise an order of magnitude improvement in our ability to monitor polar motion and UT1. It is these space-age methods, i.e., Doppler satellite observations, laser ranging to artificial satellites and the Moon, and astronomical radio interferometry that are discussed in this paper.

POLAR MOTION

Review

Polar motion is the motion of the Earth's instantaneous pole (axis of rotation) with respect to a reference point fixed to the crust of the Earth.

The theoretical basis for the existence of polar motion was presented by Euler in 1765, but the motion was not detected observationally until the late 1800's. S. C. Chandler discovered that the observed motion was actually the result of two primary components: a revolution of the true pole around the principal moment of inertia axis counterclockwise when viewed from the north, with a period of 1.2 years; and an annual revolution, also counterclockwise (Chandler, 1891). The 1.2 year period of the first component (now commonly referred to as Chandlerian motion) did not agree well with the much shorter period predicted by Euler's work. The discrepancy was quickly explained by S. Newcomb as being due to the elasticity of the Earth (Newcomb, 1891). The annual term is produced by the continuous redistribution of mass in meteorological and geophysical processes.

The motion of the pole is not totally predictable from a simple two-component model. Unexpected changes in the magnitude and direction of the motion occur, that result in a requirement to monitor the motion on a continuing basis.

Regular monitoring of polar motion was undertaken by the International Latitude Service (ILS) in 1899, and has continued without interruption until today. The ILS system uses the differential zenith distance method (Hoskinson and Duerksen, 1947) of determining latitude with visual zenith telescopes (VZT). The stations are all located very near the same parallel of latitude (39° 08' N) so that the same star pairs can be observed from all observatories. The mean pole position defined by the ILS observatories for the period 1900-1905 has been adopted as the Conventional International Origin (CIO).

In 1962 the ILS was reorganized, according to resolutions of the International Astronomical Union, and the International Polar Motion Service (IPMS) was founded (Yumi, 1964). The IPMS continues to publish polar positions based only on the ILS observatories, but it also publishes values derived from a combination of VZT, Photographic Zenith Tube (PZT), astrolabe, and transit circle observations from approximately 75 observatories.

In 1955, the Rapid Latitude Service (RLS) was established, by action of the IAU, under the direction of the Bureau International de l'Heure (BIH), to predict the coordinates of the pole and provide time corrections with very short delays. The individuality of the RLS has since been abandoned and the rapid service is now provided as a routine function of the BIH.

In 1968, the BIH adjusted the positions of their contributing observatories, predominately the same observatories that are included in the IPMS system, to insure the coincidence of the BIH pole with the CIO. Since that time, the BIH reference system has been maintained independently from the ILS system. In 1972, the BIH began to include pole position information obtained by Doppler satellite observations in their solutions. The Doppler values used are the two-day solutions of the Transit navigational system observations, presently published by the Defense Mapping Agency. The methods used to combine the Doppler data with the optical data are detailed in the BIH Annual Report for 1976.

Pole positions derived from Doppler observations of artificial satellites are available from as early as 1967, but the earliest data are of lower quality than the post 1972 data. The developmental work of the Doppler Polar Motion Service (DPMS) was accomplished at the Naval Weapons Laboratory (Anderle, 1973). The Defense Mapping Agency (DMA) took over operational responsibility in April 1975 (Oesterwinter, 1978). The Doppler polar positions are available directly from DMA, and are also published in U. S. Naval Observatory Time Service Publication Series 7.

To briefly summarize, polar motion values are determined and distributed today by the IPMS, BIH and DMA. The IPMS utilizes only optical data, the BIH utilizes a combination of optical and Doppler satellite data, and DMA utilizes only Doppler data. Monthly means are usually quoted as having uncertainties in the 20 to 40 cm range, but the positions published by the different services often differ by 1 to 2 meters.

Many questions still remain unanswered even after almost 80 years of continually monitoring polar motion. Some of these questions cannot be answered unless significant improvements are made in the spatial and temporal resolutions of the observations. An improved monitoring system, based on more modern methods, is badly needed. Candidate methods are: Doppler satellite observations, laser ranging to the Moon and artificial satellites, and astronomic radio interferometry.

Polar Motion Determinations by Doppler Satellite Observations

The material presented in this section has been extracted primarily from papers by Anderle (1973) and Oesterwinter (1978).

Radio signals suitable for Doppler observations are transmitted by U. S. Navy Navigation System satellites. The satellites are in nearly circular polar orbits at heights of about 1,000 km. They continuously transmit at two carrier frequencies, 399.968 MHz and 149.988 MHz (nominal values). The oscillators typically drift a few parts in 10^{11} per day. Both frequencies are generated from the same oscillator to facilitate the determination of ionospheric refraction effects.

Pole positions are obtained as part of the bi-daily updating of the orbit of each satellite. The gravity field model and the positions of the base stations are held fixed in a least squares solution which estimates the x and y coordinates of the pole, six constants of orbital integration, one drag scaling factor, a frequency and tropospheric scaling factor for each satellite pass, and the coordinates of any new points being surveyed. The bi-daily solutions from as many as five different satellites are combined to derive 5-day mean positions of the pole.

The Doppler pole positions are determined in the "Doppler network" coordinate system. In 1970, an attempt was made to make the origin of the Doppler coordinate system close to the CIO by estimating the coordinates of the base stations in a solution in which the gravity field coefficients and the BIH pole positions were held fixed. The network does vary with time due to station failures, modifications and upgrades, and the augmentation of the 17 to 20 base stations by one to ten, or more, temporary stations during various operational campaigns.

The standard error of the pole positions vary considerably depending upon the distribution and number of observations combined in each solution. Oesterwinter (1978) concludes that the standard deviation of a two-day polar coordinate solution is now better than 40 cm, and for a five-day mean, under 20 cm. The dominant source of error is believed to be residual errors in the gravity field model.

Polar Motion Determinations by Satellite Laser Ranging

The material presented in this section has been extracted primarily from papers by Kolenkiewicz et al. (1977) and Smith et al. (1978).

Many artificial Earth satellites have been equipped with retroreflectors to facilitate tracking by laser ranging systems. Polar motion can be determined from satellite laser ranging from a single station, if an accurate satellite ephemeris is available, or a network of stations.

In the case when only a single tracking station is in operation, only one component of polar motion, i.e., the component along the station meridian, can be monitored. The procedure is to establish a precise reference orbit by tracking the satellite for a reasonable period of time, say a month or so, and then compare subsequent observations made over periods of perhaps 6 to 12 hours, to this reference orbit. Of particular interest is the apparent change in inclination of the orbit, since changes in the latitude of the tracking station are reflected as apparent changes in that parameter. Of course, in order to extract the changes in latitude, any real changes in the inclination of the satellite must be taken into account.

The strongest determination of the inclination of the orbit is obtained when the tracking station is located near the northern or southern apex of the orbit. The satellite is then moving along an east to west (or west to east) track to the north (or south) of the tracking station when it is observed.

Initial experiments to determine polar motion by satellite laser tracking were conducted by the NASA Goddard Space Flight Center during a 5-month period in 1970. The experiment used ranges to the Beacon Explorer C satellite. The pole positions showed residuals, with respect to BIH values, having an rms deviation of about 1 meter. A very fundamental difficulty with the single station method just described is the requirement for a reference orbit that remains very precise over periods of months to years.

If a "network" of ground stations is operated, for which a consistent set of coordinates is known, the requirement for the reference orbit is eliminated and both the x and y components of the pole position can be determined in the "network frame of reference." This multistation case corresponds to the Doppler methods previously described.

Smith et al. (1978) presented the first results of the network approach using the Laser Geodynamics Satellite (LAGEOS) which was launched on May 4, 1976. The LAGEOS satellite was specifically designed to have a very stable orbit. The satellite is in a high orbit (12,265 km) and has a high mass to surface area ratio, which greatly reduces the effects of such perturbing forces as solar radiation, Earth albedo, air drag, and the high frequency components of the Earth's gravitational field.

Smith and Kolenkiewicz analyzed LAGEOS data collected by a network of seven stations during the period of May through December 1976 and derived 5-day mean values of x and y with most of the estimated standard deviations ranging from 0.01 to 0.02 arcsecond ($\sim$30 to 60 cm). These results are available in tabular form (Smith, 1978).

Polar Motion Determinations by Lunar Laser Ranging

The material presented in this section has been extracted primarily from Harris and Williams (1977).

An error in the latitude of a lunar laser ranging observatory results in a range error which is relatively constant near zero hour angle, but does depend on the lunar declination, approximately as the sine of the difference between the latitude of the observatory and the lunar declination.

$$\Delta r = r\Delta\phi \sin(\phi-\delta) \qquad (1)$$

where r is the range from the observatory to the lunar reflector; δ is the declination of the lunar reflector; ϕ is the geocentric latitude of the observatory; $\Delta\phi$ is the change in the geocentric latitude of the observatory due to a change in the position of the pole: and Δr is the change in range.

When the Moon's declination is nearly equal to the latitude of the observatory, the error in latitude contributes little to the range error, but as the Moon's declination moves away from the observatory's latitude, the error in latitude does contribute to the range error. The signature has a period equal to the lunar cycle. Harris and Williams analyzed the McDonald lunar laser ranging data to determine if there was a reasonable chance of extracting daily polar motion values from that single observatory data set. They concluded that there was not. Polar motion values based on lunar laser ranging apparently will have to await multiobservatory operations.

Polar Motion Determination by Radio Interferometry

In radio interferometry the range-difference and the time rate of change of the range-difference from the radio sources to two (or more) observatories are determined. When extra-galactic sources, such as quasars, are observed the sources are at such great distances that the radio wave fronts arriving at the interferometer are essentially planar. Any purely translational motions of the interferometer or rotations about an axis parallel to the interferometric baseline are not detectable. For a single baseline, it is possible to determine two of the three angles necessary to express the orientation of the Earth in the frame of reference defined by the radio sources. To determine all three angles, two nonparallel baselines are required.

The sensitivity of radio interferometry to variations in the orientation of the Earth can be estimated from the following equations:

$$\Delta X = -(\Delta\Theta)\, Y - x\, Z \qquad (2)$$

$$\Delta Y = (\Delta\Theta)\, X + y\, Z$$

$$\Delta Z = x\, X - y\, Y$$

x and y are the components of the pole position, in radians, relative to the CIO; $\Delta\Theta$ represents (UT1-UTC), also in radians; X, Y, Z are the Earth fixed coordinates of the baseline; and ΔX, ΔY, ΔZ are the changes in the baseline vector components caused by x, y and $\Delta\Theta$.

If the baseline has a substantial Z component, changes in the position of the pole will cause significant changes in the equatorial components of the baseline (X,Y) which will be reflected in the sinusoidal signatures of the delay and delay rates.

If the baseline is nearly parallel to the equatorial plane, i.e., $Z \approx 0$, sensitivity to polar motion comes solely from the ΔZ term. A small variation in Z causes a change in the delay that varies with the declinations of the sources. It is therefore quite feasible to determine one component of polar motion from an equatorial baseline. In fact, excellent determinations of the x component of polar motion have been obtained from the nearly equatorial Haystack-Owens Valley radio interferometer. These results are particularly noteworthy because they agree closely with Doppler derived values, the rms of the differences being $\approx$30 cm, and display obvious systematic trends relative to the BIH values (Robertson et al. 1978).

There are two approaches to implementing astronomic radio interferometry; connected element interferometry (CEI), and very long baseline interferometry (VLBI). The underlying principles are not different, but the technological methods used to bring the signals detected at the two telescopes together for processing cause significant differences in the operational characteristics of the interferometers and in the dominant error sources.

CEI baselines are presently limited in length to a few tens of kilometers by the ability to maintain the phase stability of the connecting data link. VLBI baselines are limited in length to a few thousand kilometers by the size and shape of the Earth. The inherent angular resolution of an interferometer is directly proportional to the baseline length - i.e., the longer the baseline the better the angular resolution.

However, the theoretical resolution of the interferometer is not presently the limiting constraint on the accuracy to which the polar motion can be determined. Since polar motion is an angular measurement, any instabilities of the two telescopes forming the interferometer degrade the determination as the ratio of the radius of the Earth to the length of the baseline. For baselines of a few kilometers to a few tens of kilometers, for which CEI is presently feasible, this multiplicative factor is of magnitude 10^2 to 10^3, and antenna distortions due to gravitational and wind loading and temperature variations, and local crustal deformations become critical. Atmospheric "seeing" also appears to be a serious problem (Hargrave and Shaw, 1978). For the much longer baselines used in VLBI these factors decrease in significance and local oscillator instabilities are presently the limiting constraint. As higher performance oscillators are developed, the ultimate limiting constraints are likely to become atmospheric effects, possible variations in the structure of the radio sources and tectonic motions.

In October 1978, the U. S. Naval Observatory (USNO) initiated a program to use the 37 kilometer CEI located at the National Radio Astronomy Observatory (NRAO) at Greenbank, West Virginia. NRAO personnel perform the observations specified by USNO, and the data reduction and dissemination are done by Washington based USNO and Naval Research Laboratory (NRL) personnel. The USNO/NRL group estimates that the NRAO interferometer may eventually be capable of determining polar motion to 0.01 arcsecond (30) cm over an averaging period of a day or so.

The National Ocean Survey of the National Oceanic and Atmospheric Administration has begun a project to establish and operate a three-station network of permanent observatories to monitor polar motion (and UT1) by VLBI. The project designation is POLARIS (POLar-motion Analysis by Radio Interferometric Surveying). Project POLARIS is described in some detail in Carter et al. (1978). Computer simulations indicate that the POLARIS system will be capable of determining the x and y components of polar motion to better than 10 cm over an averaging period of 8 hours.

UT1

Review

The Bureau International de l'Heure (BIH) has monitored the rotation of the Earth since 1912, utilizing observations from a large number of stations (presently about 80) distributed around the world. The BIH is presently the only international service which provides UT1 data. Independently determined values are also published in the USNO Time Service Series 6.

The Earth does not rotate at a constant rate, but exhibits periodic, secular, and irregular variations. The primary periodic terms have annual, semi-annual, 27.55 day and 13.66 day periods. Sudden variations in the length of day of several milliseconds over a period of a few days have been observed (Smylie and Mansinha, 1968).

Just as with polar motion, the present methods of monitoring UT1 do not have sufficient angular or temporal resolutions to satisfy modern scientific requirements. In the following sections, candidate methods for improved UT1 determinations are examined.

UT1 Determinations by Artificial Satellite Observations

In order for the rotational orientation of the Earth to be determined in an inertial frame of reference by artificial satellite observations, it is necessary that any perturbations of the satellites' orbital plane be predictable over the time span of interest. Over time spans of several months to years, the uncertainties for even the most stable satellites, such as LAGEOS, will grow to unacceptable levels. For this reason it is widely agreed that artificial satellite observations by Doppler, laser ranging, VLBI or any other method are not suitable for long term Earth rotation studies. However, satellite observations could be used to monitor short-term variations in the Earth rotation which could then be combined with observations of a different type having the desired long-term stability.

Smith et al. (1978) have investigated the use of LAGEOS laser ranging observations for the determination of UT1. The limiting perturbations appear to be Earth albedo and ocean tides. They estimate that by the early 1980's the modeling capabilities will likely be such that it will be possible to derive UT1 with uncertainties of a few tenths of millisecond over periods of three months. Silverberg (1978) has suggested that the pairing of LAGEOS and lunar laser ranging data would be a reasonable marriage of convenience. The LAGEOS data would provide unbroken short-term coverage, while the lunar data would provide the long-term frame of reference. It would be desirable if the participating observatories could do both types of range measurements.

Another combination that has been suggested is VLBI observations of artificial satellites, such as the NAVSTAR constellation, and extragalactic sources. The satellite signals could be made of sufficient strength that relatively simple and inexpensive ground stations and data processing systems could be used. The more expensive observations of the extragalactic sources would be minimized, and yet still provide the long-term stable frame of reference.

UT1 Determinations by Lunar Laser Ranging

A constant error in the assumed longitude of a lunar laser ranging station will produce a range residual, with respect to the lunar ephemeris which varies as the sine of the lunar hour angle.

$$\Delta r \approx \Delta UT0 \cos \delta \sin H \qquad (3)$$

Δr is the change in range from the observatory to lunar reflector due to an error in longitude (ΔUT0): δ is the declination of the lunar reflector, H is the hour angle of the lunar reflector.

If lunar laser ranging data are available over a large enough span of hour angle to allow the sinusoidal signature to be well estimated, UT0 can be determined for the observatory. Using polar motion information from another source, such as the IPMS or BIH, or observations from two or more properly located lunar laser ranging observatories, it is possible to obtain UT1. Just as in the case of artificial satellites, the lunar ephemeris must not drift, relative to an inertial frame of reference, if the UT1 determinations are to remain accurate over long periods of time.

A significant number of lunar laser range measurements have to date been made from only one observatory - the University of Texas McDonald Observatory. These data have been analyzed by several investigators to extract Earth rotation information (Stolz et al. 1976; Harris and Williams 1977; King et al. 1978).

King et al. compared UT1 determinations by lunar laser ranging to smoothed BIH values, to which fortnightly and monthly corrections had been added to account for tidal effects largely removed by the BIH smoothing procedure. After removal of the mean differences, the rms of the remaining differences was 2.1 msec. It should be noted that the UT1 values derived from the lunar laser ranging data by different investigators, differ significantly. For example, the King et al. vs. Stolz et al. UT1 values have an rms difference of 0.8 msec. The sources of these differences are being investigated.

UT1 Determinations by Radio Interferometry

Elsmore (1973) points out that an equatorial interferometer ($Z \approx 0$) can measure UT1 directly - uncorrupted, to first-order, by polar motion. Equations 2 make this quite apparent. For $Z \approx 0$, the terms containing x and y (the components of the pole position) vanish from the equations for ΔX and ΔY. For this reason, it would be desirable in designing a UT1 monitoring network to utilize equatorial baselines.

Elsmore (1973) reported the results of UT1 determinations with the 5 km equatorial CEI at Cambridge between August 1972 and May 1973. The rms scatter relative to BIH values was approximately 6 msec. The averaging time for each determination was generally 12 hours.

USNO estimates that it will be able to determine UT0 using the NRAO CEI with an accuracy of 1 msec on a daily basis during 1979, and hopes to substantially improve that accuracy over the next few years.

Robertson et al. (1978) reported the results of 14 VLBI experiments conducted between September 1976 and May 1978 using the Haystack-Owens Valley interferometer, in which UT1 values were determined. The rms difference with respect to the BIH values (with added fortnightly and monthly terms) was 1.6 msec, after removal of the mean difference. Comparative studies of the VLBI and lunar laser ranging UT1 values are in progress.

NOS computer simulations for the POLARIS network indicate that it will be capable of determining UT1 to ±0.1 millisecond in an averaging period of eight hours or less. The experimental results of the Haystack-Owens Valley interferometer, reported by Robertson et al. (1978), add credibility to the simulations.

SUMMARY

The only truly operational usage of any of the modern techniques for the determination of polar motion or UT1 has been the Doppler satellite determinations of polar motion. Even in this case, the polar motion information has been a by-product of a program having other primary goals, and very little effort has been made to optimize the network configuration, observing schedules, or instrumentation for determining polar motion. The Doppler satellite method suffers the disadvantages that it relies on the availability of functional satellites, which have limited lifetimes and must be replaced from time to time, and that it would not be an adequate method for the long-term determination of UT1. The author believes that this limits the Doppler satellite method to a transitional role that will prove very useful in verifying the initial results of methods better suited to long-term usage.

Viewed independently, laser ranging to artificial satellites and the Moon, each have serious deficiencies. Even using very special satellites such as LAGEOS, it appears that satellite methods will only be able to provide measurements of UT1 over periods of a few months before errors due to rotation of the orbital plane become excessive. Lunar laser ranging suffers from technological complexities (only one observatory has been made to operate reliably after the first full decade of experiments) and difficulties in obtaining measurements within a few days before or after a new Moon. The combined usage of satellite and lunar laser ranging data, as suggested by Silverberg, certainly offers some promise but the cost of operating enough stations to ensure reliability during periods of poor weather may still disqualify these methods.

Astronomic radio interferometry has several very desirable attributes: a three-station network (the minimum number of stations required to form two baselines) can determine both components of polar motion and UT1; spatial resolutions of 10 cm can be achieved in averaging periods of eight hours or less; observations can be made during inclement weather; the radio sources form the most nearly inertial frame of reference presently known; the radio sources have unlimited lifetimes, and are equally available to all users. The choice between CEI and VLBI techniques depends very heavily on the maximum length of the baseline that can be operated in the CEI mode. For baselines of less than several hundred kilometers the task of cleansing the CEI data of purely local effects appears, in the author's opinion, to be insurmountable.

Of the presently available methods, VLBI observations of extragalactic radio sources appear to be the best choice for use in the next generation international polar motion and UT1 service.

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Questions and Answers

DR. TOM CLARK, NASA Goddard Space Flight Center:

Do we have any questions or comments? I might make one comment regarding Bill's last picture. In addition to the three stations he showed there, the same group is also conducting even earlier prototype observations using a Mark III system personally funded by DMA that will be going into Sweden, and some hardware personally funded by NASA which will be going into a station in California, so there will actually be some FY 79 observations going on at those stations.