Reports

Polar Motion Measurements: Subdecimeter Accuracy Verified by Intercomparison

Abstract. *An important bound on the accuracy of modern techniques for monitoring polar motion is established by intercomparison of measurement series from two different observing techniques, very long baseline interferometry and satellite laser ranging. The root-mean-square differences between the estimates of the pole position from both techniques are shown to be only 2 milliseconds of arc (about 6 centimeters at one Earth radius). In the absence of common systematic errors, these differences bound the total errors in both sets of estimates. An initial investigation did not reveal any clear signature in the pole position that seems to be associated with major earthquakes. Continued measurements at this level of accuracy hold promise for resolving long-standing arguments over such questions as the nature of the excitation mechanism required to maintain the motion of the pole.*

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The wobble of Earth's spin axis relative to its solid crust was discovered in 1891 by the American astronomer and geodesist, S. C. Chandler. At that time it was realized that measurements of this motion were important not only for correcting systematic errors in astrometric and astrogeodetic observations but also for determining the rheological properties of the solid Earth, and an international effort to monitor polar motion by optical techniques commenced in 1895. However, the usefulness of these measurements for determining geophysical parameters was compromised by meter-level systematic and random errors (*1*).

Recent advances in measurement techniques have opened a new era in the history of the measurement of polar motion. Satellite laser ranging (SLR) and very long baseline interferometry (VLBI) provide an improvement of about one order of magnitude in accuracy over conventional optical techniques in addition to substantially better time resolution. To exploit these new techniques and to derive the maximum amount of geophysical information available from the new data, it is essential to make accurate determinations of the total measurement errors. One of the best methods of placing an upper bound on total measurement errors is by intercomparing the time series that result from the different observing techniques. The importance of such intercomparisons has been recognized by the International Astronomical Union, the International Association of Geodesy (IAG), and the International Union of Geodesy and Geophysics, which have jointly sponsored a project called MERIT (monitor Earth rotation and intercompare techniques of observation and analysis), whose purpose is to foster and encourage such intercomparisons. We now describe the results of an intercomparison.

The VLBI data used for this intercomparison came from an ongoing observing program organized by the IAG–Committee on Space Research joint subcommission on international radio interferometric surveying (IRIS) (*2*). The observations were made every 5 days with the three stations of the U.S. National Geodetic Survey's POLARIS network (the Westford Observatory in Massachusetts, the George R. Agassiz Station in Texas, and the Richmond Observatory in Florida) and at the Wettzell Observatory in the Federal Republic of Germany. The Onsala Space Observatory in Sweden also participated about once per month. Each observing session spanned 24 hours and collected 300 to 400 delay and delay-rate observations on 14 radio sources. All the observations were dual-frequency (S-X band) and were made with the Mark III VLBI observing system (*3*). The data were reduced with algorithms consistent with the standards defined for the MERIT campaign (*4*), except that ocean-loading corrections to solid Earth tide displacements were not used.

The SLR Earth orientation results were computed at the University of Texas Center for Space Research from range observations to the Laser Geodynamics Satellite (LAGEOS) (*5*). The observations were made from more than 20 globally distributed stations that contributed data to the NASA Crustal Dynamics Project and to the MERIT campaign. The ranging data used represent a sample of the full set of data collected that is transmitted to the Center for Space Research via phone line with delays of no more than a few days from the observation time. Earth orientation solutions are performed weekly with consecutive 5-day intervals of data (*6*).

Pole positions estimated from the VLBI and SLR observations are shown

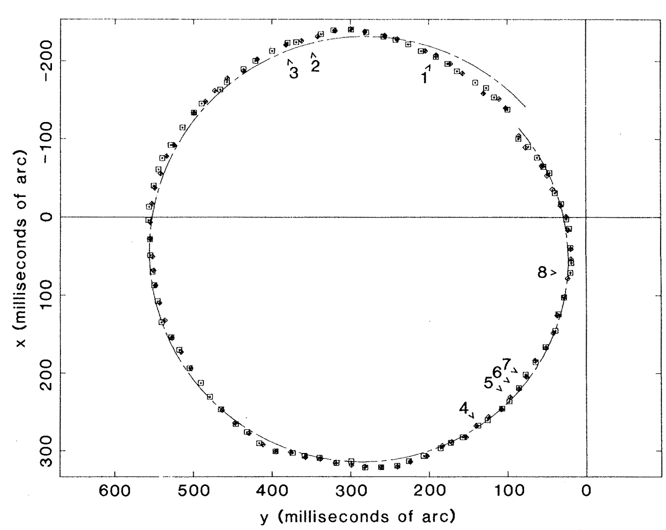

Fig. 1. Pole position determinations from January 1984 to February 1985, from IRIS VLBI observations (◇) and LAGEOS SLR observations (□). The times of the earthquakes listed in Table 1 are indicated by arrows. The dashed line is a best-fit model composed of two uniform circular motions. Because there is an arbitrary origin in the VLBI and SLR determinations, the mean difference between the curves in both the *x* and *y* directions has been removed.

Table 1. Major earthquakes during 1984.

Number	Date	Richter scale magnitude	Location
1	7 February	7.3 to 7.7	Solomon Islands
2	19 March	7.0 to 7.1	Uzbek SSR
3	24 March	6.7 to 7.0	Japan
4	1 November	7.1 to 7.4	Central Mid-Atlantic Ridge
5	17 November	7.2 to 7.4	Sumatra
6	20 November	7.1	Mindanao
7	23 November	6.7 to 7.1	Vanuatu
8	28 December	7.0	Kamchatka

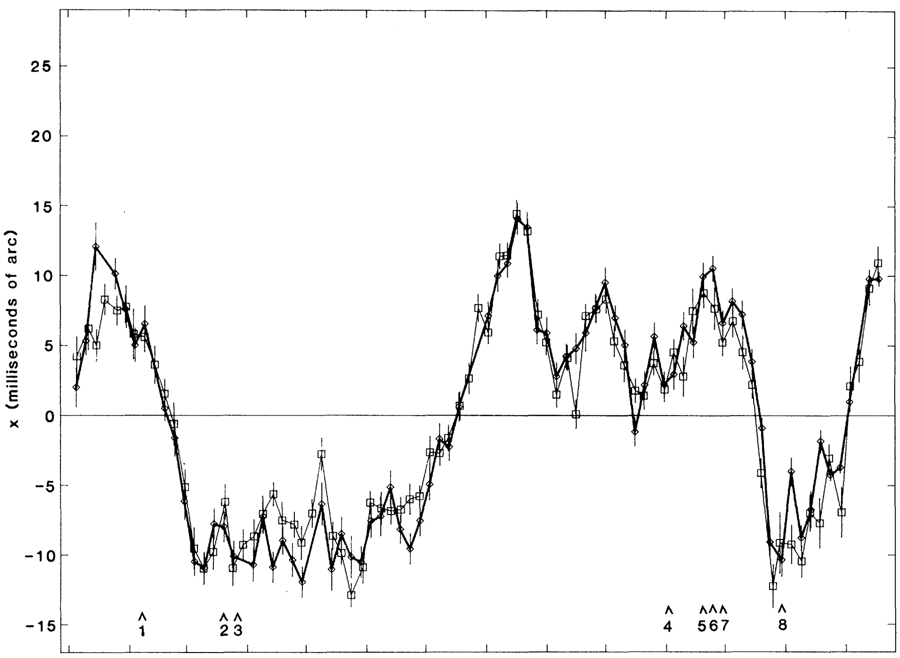

Fig. 2. The x component of the pole position determinations, shown as differences from the dashed line in Fig. 1. Symbols are as described in Fig. 1.

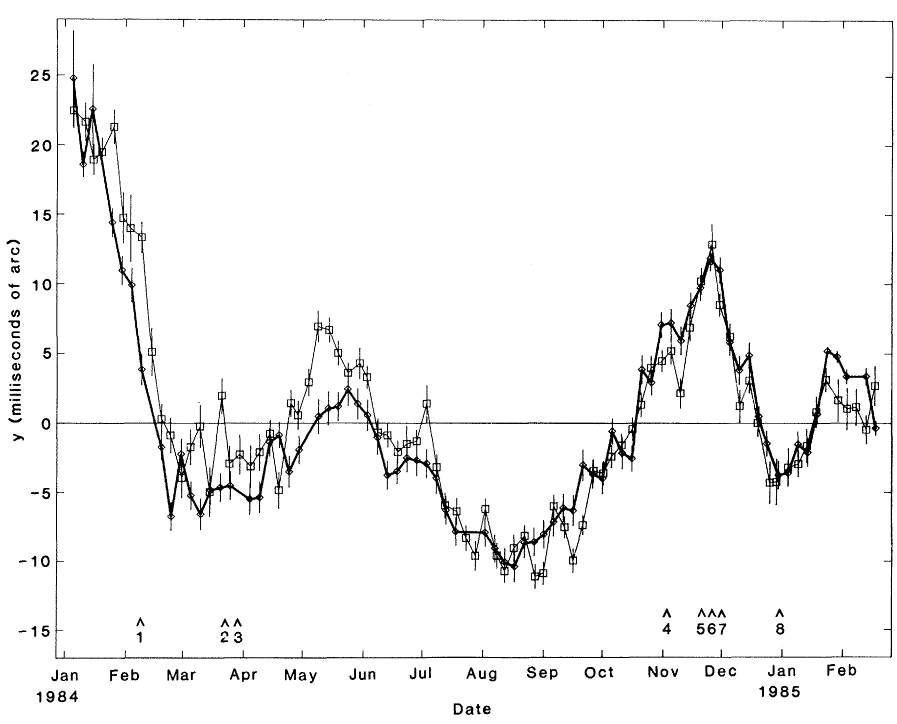

Fig. 3. Same as Fig. 2 for the y component of the pole.

in Fig. 1. The crosses in the center of each symbol in Fig. 1 indicate the sizes of the formal standard errors for each determination. The SLR errors were calculated on the assumption of normally distributed range measurement errors with a uniform standard deviation, which was chosen so that the formal errors roughly predict the observed internal precision of the SLR polar motion series. The VLBI formal errors were calculated from observation weights adjusted so that the χ^2 value per degree of freedom of the observation residuals is close to unity. On the scale of Fig. 1, the error bars are often indistinguishable from points at the centers of the symbols.

The differences between the two sets of estimates of pole position were so small that the two corresponding determinations were difficult to separate; the two points were often plotted on top of each other. To display better the differences between the series, we subtracted a smooth curve from each set of determinations. The curve was calculated by fitting to the data two superposed uniform circular motions (representing the annual and Chandler components) plus a constant offset in each direction. The differences from the resulting curve for both x and y are plotted against time in Figs. 2 and 3. The scale in Figs. 2 and 3 is large enough that the differences between the two determinations and the error bars can be discerned.

The weighted root-mean-square (rms) differences between the VLBI and SLR determinations are only 2 milliseconds of arc (~6 cm) in both the x and y directions. Since it is unlikely that these two different types of observations contain common systematic errors, this rms difference places a strong bound on the sum of all the errors in both series, which must be of the order of 2 milliseconds of arc. The average formal standard error for these determinations was about 1 millisecond of arc for both the VLBI and SLR determinations, and the average systematic error for these determinations must therefore be of the order of 1.5 milliseconds. How this systematic error is distributed between the two measurement series cannot be determined from this intercomparison, but its magnitude is so small that even if it is totally contained in one series (which is unlikely) that series still produces excellent determinations of pole position.

The routine determination of pole position with verified accuracy at the subdecimeter level has important implications for resolving long-standing arguments about the nature of the excitation mechanism responsible for maintaining polar motion (*1*). As an initial check to determine whether earthquakes have a discernible effect on the motion of the pole at the time of the earthquake, we plotted the times of all earthquakes of magnitude 7.0 (Richter scale) or larger that occurred in 1984 (*7*). The magnitudes of the earthquakes (Table 1) were calculated from surface-wave measurements. No significant changes in the motion of the pole are seen near the time of these quakes. Only the first earthquake in Table 1 was as large as magnitude 7.5, and it occurred in the middle of one of the smoothest parts of the pole path (Fig. 1). If earthquakes of this magnitude do not produce effects discernible with the subdecimeter accuracy of these determinations, then it seems unlikely that such effects would be found in the older, optically determined series whose accuracy is an order of magnitude poorer (*8*). Continued monitoring of the pole position with subdecimeter accuracy should eventually produce a series that overlaps a sufficient number of large earthquakes so that we can definitively characterize the relations of such quakes to the motions of the pole.

The smooth changes in the motion of the pole have a character similar to the atmosphere-dominated variations in the length of day; for example, there are broad, flat extrema with sharp peaks in winter and summer (*5*). There is considerable disagreement on the question of whether meteorological excitation is sufficient to cause the observed polar motion. Barnes and coworkers (*9*) have argued that most of the polar motion can be explained in terms of meteorological effects, whereas Wahr (*10*) has claimed that meteorological effects are too small to excite all the observed polar motions. Resolution of the question of the excitation of the pole will depend on continued high-accuracy monitoring of the pole position coupled with improved atmosphere sensing.

References and Notes

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Geochemical Indicator of Tectonic Stress Resulting in an Earthquake in Central Japan, 1984

Abstract. *Conspicuous changes in gas composition were observed at a fumarole and a mineral spring just before the occurrence of an inland earthquake (magnitude, 6.8) in central Japan in September 1984; the fumarole and spring were 9 and 50 kilometers, respectively, from the earthquake's epicenter. Deep-seated fluids emitted as a result of the compressional stress of the earth tide had been observed previously at this mineral spring and at a lava lake in Hawaii. By analogy, the gas anomaly observed before the earthquake in Japan probably resulted from deep-seated fluids being squeezed to the surface by the tectonic stress that caused the earthquake.*

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An inland earthquake (magnitude, 6.8; focal depth, 3.8 km), called the western Nagano prefecture earthquake, occurred in central Japan on 14 September 1984 (Fig. 1). Although this earthquake occurred in a sparsely populated, mountainous region, it resulted in 29 deaths. Five years earlier, on 28 October 1979, the Ontake volcano (Fig. 1) suddenly began to erupt on its southwestern flank near the summit, forming several new craters. Up to that time, the volcano had been believed to be dormant, and any precursory signs for the eruption such as seismic activity had not been observed, although weak geothermal activities had been detected around it.

The craters formed from the Ontake eruption were 9 km northwest of the epicenter of the Nagano prefecture earthquake. We have been analyzing volcanic gases from one of these craters at least once a year since the Ontake eruption and, for the purpose of predicting earthquakes, have been testing subsurface gases at several locations in central Japan. Gas bubbles from mineral springs have been analyzed four times a day by means of gas chromatography at our field laboratories (*1*). When we started the project, an earthquake of the magnitude experienced in 1984 had never occurred in this region. Our observations revealed a conspicuous gas anomaly at a fumarole and a mineral spring (epicentral distance, 9 and 50 km, respectively) just before the event. Because this anomaly probably occurred as a result of stress changes that gave rise to the earthquake, it can be considered a precursor event.

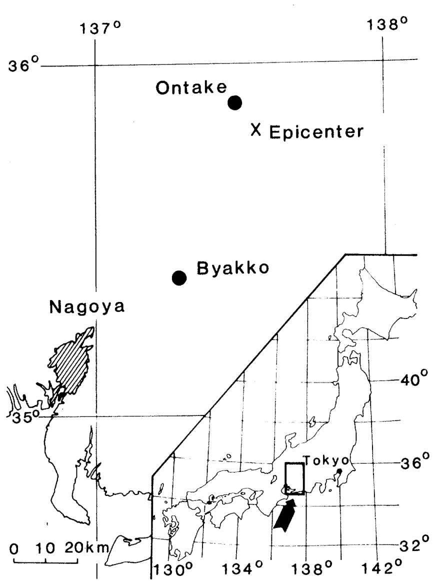

Fig. 1. Location and index maps showing observation sites (Byakko Spa and the Ontake volcano) and the epicenter of the western Nagano prefecture earthquake, 1984.

The He : Ar and CH_4 : Ar ratios as well as H_2 concentrations in subsurface gases have been proposed as useful geochemical indicators for earthquake prediction (*2–5*). Figure 2 shows the variation of these parameters in bubble gases from the mineral spring at Byakko (Fig. 1), the monitoring station nearest to the epicenter. Both He : Ar and CH_4 : Ar ratios had been increasing with small fluctuations until March 1984 and dropped abruptly in July 1984. They showed a minimum value at the beginning of August 1984. About 40 days later, the earthquake occurred.

At Byakko, Sugisaki (*3*) had previously observed a regular, cyclic variation in the He : Ar ratio that was caused by the earth tide. The gas analyzed at this station was characterized by a high He : Ar ratio and was dissolved in deep-seated waters of the mineral spring, which were then squeezed out of fissures under the tidal compression. Subsequent observations showed that the CH_4 : Ar ratio fluctuated synchronously with the He : Ar ratio (*3*). If deep-seated gases are similarly squeezed out by stresses preceding an earthquake (*3*), then the temporal varia-