Determination of the Motion of the Pole, and Comparison with Astrometry

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Phil. Trans. R. Soc. Lond. A 1980 **294**, 329-334
doi: 10.1098/rsta.1980.0039

Phil. Trans. R. Soc. Lond. A **294**, 329–334 (1980)
Printed in Great Britain

Determination of the motion of the pole, and comparison with astrometry

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The Doppler tracking of artificial satellites can provide the coordinates of the pole relative to the Earth, as shown by Anderle: using this method, firstly, the Naval Weapons Laboratory and, subsequently, the U.S. Defense Mapping Agency produced a series of coordinates of the pole since 1967. Apart from the classical astrometric method, the Doppler method is currently the only one that is used on a regular basis. The comparison with astrometry since 1972 shows that the random uncertainties of the Doppler system are currently half those of astrometry, while its systematic errors seem much smaller. Some irregularities of the motion of the pole are found both in Doppler and astrometric observations. Some possible improvements of the Doppler determinations of the pole are considered.

Introduction

The motion of the poles of the Earth relative to the Earth itself, theoretically predicted by Euler, is so small, its amplitude being less than 20 m, that it was experimentally found only at the end of the 19th century. It was then recognized that this motion did not conform to Euler's theory: it was irregular and required continuous monitoring. The motion remains unpredictable and its measurement is necessary for the investigation of its causes and for applications where the angular position of the Earth in space is needed: astrometry, geodesy, space sciences and techniques.

Apart from an uninterrupted series of pole coordinates, obtained by the International Latitude Service (ILS), operating since 1900, from three to six dedicated stations, other series based on up to 80 astronomical instruments have been made available since 1962 by the International Polar Motion Service (IPMS) and the Bureau International de l'Heure (BIH). These series are more precise but there is little hope of further improvement of the classical astrometric network.

For this reason, other techniques are being developed. Among them, the Doppler observation of Transit satellites is the only one which is in current operation and offers the possibility of comparison with astrometry.

In the following, we shall assume that the motion of the pole is expressed in metres in a horizontal plane of a fixed origin near the north pole, referred to the x axis toward Greenwich and the y axis toward longitude 90° W.

Doppler determinations of the motion of the pole

The theory of the motion of an artificial satellite (and of the Moon) is developed in a frame of reference which does not rotate in space. The rotation of the Earth affects the relative

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positions of an Earth observer and of the satellite in two ways: (*a*) some disturbing forces rotate with the Earth, essentially the irregularities of the gravitational field; (*b*) the observer rotates with the Earth but the satellite does not. The disturbing effects can be fairly well estimated with only a rough knowledge of the Earth's rotation. Hence, the disturbed orbit in a non-rotating frame can be computed and it becomes possible to recover from the satellite tracking data the Earth rotation parameters: the coordinates of the pole and also the universal time U.T.1, which cannot be freed from a progressive error owing to the defects of the orbit computation and needs recalibration from time to time. The polar motion can be obtained to a large extent free from systematic errors.

Any type of tracking is convenient, in principle. Laser tracking is being experimented with, and promises to lead to high precision. Currently, however, the only application of satellite methods which has led to an uninterrupted series of coordinates of the pole is Doppler observation of the polar satellites of the Transit navigation system. In that programme, the along-track component of the satellite motion is measured, and U.T.1, which cannot be obtained with valuable precision, is taken from the astrometric determinations.

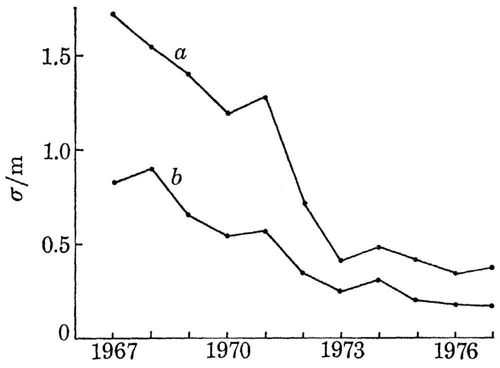

FIGURE 1. Standard deviations of the pole coordinate derived by the DMA (mean for x and y), for 2 day (*a*) and 5 day (*b*) averages.

Initially (Anderle & Beuglass 1970; Anderle 1970), the precise orbits of Transit satellites, required for geodetic purposes, were computed by the Naval Weapons Laboratory (NWL), U.S.A., from the Doppler observations of a fixed network of 13 stations, ignoring polar motion. Owing to the good distribution of the stations on the Earth, the effect of a wrong assumed position of the pole could not be absorbed by the usual unknowns: orbit parameters, drag factor, frequencies. Thus the orbit is correctly represented in space, but not relatively to individual stations, and the pole errors appear as apparent tracking errors, with a period of 24 h. It was then possible to recover the pole coordinates from the station residuals since 1967.

The most important change in the Doppler determination of the pole occurred in August 1971, when a simultaneous 2 day solution for the pole and the other parameters was adopted (Anderle 1972). Doppler results after this date are believed to be homogeneous in spite of other improvements in the station network (now about 20 stations), observation techniques and reduction methods (Oesterwinter 1978). Figure 1 shows, according to Oesterwinter, the standard deviations computed over 2 days and 5 days. These values are confirmed by the independent estimations of the Bureau International de l'Heure (BIH).

In 1975, the responsibility of the derivation of the pole was transferred to the Defense Mapping Agency (DMA) without changes of computational methods, so that the transfer did not affect the results.

The Groupe de Recherches de Géodesie Spatiale (G.R.G.S.) in France began in 1977 to determine positions of the pole by Doppler observations of Transit satellites, with the use of a partly different network of stations and totally independent models of forces and computational methods. The standard errors of the pole coordinates, in the provisional 2 day solutions currently available, is 1–2 m as in the early work of NWL; the general agreement with DMA results is good (Nouel & Gambis 1978). In the following, only the DMA results will be used and denoted by DOP.

Comparison with astrometry

The BIH, in its current work, computes the coordinates of the pole with the use of both astrometric observations and DMA results (since 1972). But for special studies, an astrometric solution is established and published in the Tables 6B of the *BIH Annual Reports*. This solution is used here and denoted by AST. It is based on about 80 instruments.

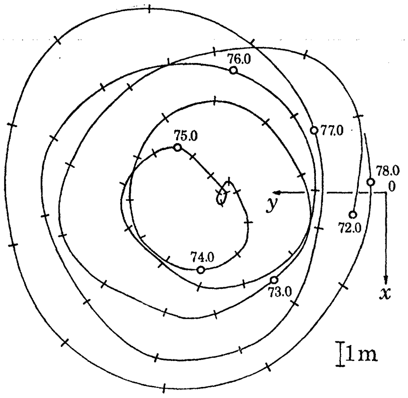

Figure 2. Motion of the pole derived from Doppler observations by the DMA (DOP).

DOP and AST are compared after filtering the high frequency noise which is believed to be mainly due to observational noise: the low-pass filter has a cut-off toward 100 days. Figure 2 shows the motion of pole according to DOP, after filtering. The consideration of filtered data leads to the following results.

Precision of astrometry and Doppler

Figure 3 represents the r.m.s. differences between raw averages over 18.3 days (0.05 year) and filtered data. On account of the filter characteristics, they are a good estimation of the standard errors. The improvement of DOP is confirmed, but AST appears to have reached its optimum level. Since 1975, the random errors of the Doppler system have been half those of astrometry.

Drifts and annual errors

The yearly development of DOP – AST for x and y since 1972, in constant annual and semi-annual sine terms, is shown by table 1.

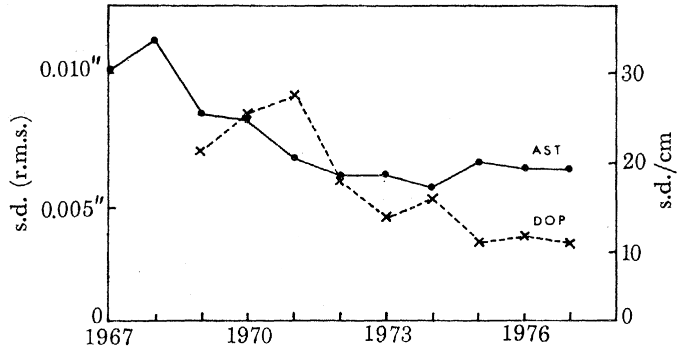

FIGURE 3. Comparison of the standard deviations of the pole coordinates, computed over 0.05 year, for astrometry (AST) and Doppler determinations (DOP) (mean for x and y).

TABLE 1. YEARLY DEVELOPMENT OF THE DIFFERENCES (CENTIMETRES) BETWEEN DOPPLER AND ASTROMETRIC RESULTS

(The equation takes the form DOP − AST $= a+b\sin 2\pi t+c\cos 2\pi t+d\sin 4\pi t+e\cos 4\pi t$, where t is the time in years.)

	x					y				
year	a	b	c	d	e	a'	b'	c'	d'	e'
1972	−27	+10	−64	−37	+1	+12	+18	−2	+14	+25
1973	−38	+20	−18	−14	−16	−25	+17	−19	+16	+11
1974	−41	+25	−35	+3	+20	−15	+27	−3	−2	−5
1975	−71	+54	−65	−16	+23	+5	+32	−2	+7	−12
1976	−80	+42	−74	−19	+17	+29	+16	+15	−16	+10
1977	−59	+48	−75	+1	−1	+22	+40	+11	+26	+1

The computed drift of the DOP pole relative to the AST pole is represented by the rate of variation of a and a'; it is of the order of 3 cm/year, but needs to be confirmed.

There clearly exists a significant and fairly stable annual difference between DOP and AST. The presence of annual errors in the astrometric observations of latitude and Universal Time, which are the basis of AST, is well known. In the BIH solution, there is no means of calibrating the annual term of the derived motion of the pole, but every effort was made to keep the annual error constant from year to year (Feissel 1972). Thus the present annual error in AST represents the mean of the errors of the individual instruments when the BIH system was initiated, in 1967–8. The size of a possible annual error in DOP is not yet known, but the observed difference is probably due to astrometry.

In order to make the comparison of DOP and AST more meaningful, a mean annual correction was applied to AST, to express it in the DOP system.

Irregularities

Some irregularities of the polar motion can be seen in figure 2, for instance the sharp turn at 1972.60. Similar irregularities were observed in the astrometric series before the existence of Doppler determinations, but it was not possible to decide whether they were real or an effect of determination errors. Now, the comparison of AST and DOP clearly shows the reality of the phenomenon, as can be seen in the examples of figure 4.

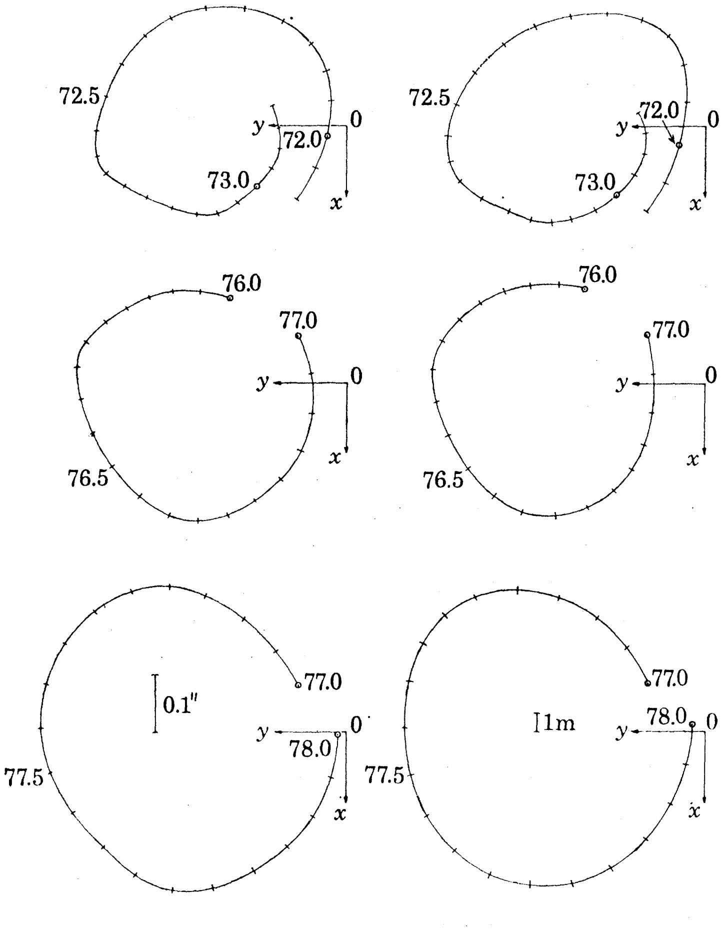

Figure 4. Examples of irregularities of the pole path found in astrometric (AST) and Doppler (DOP) determinations.

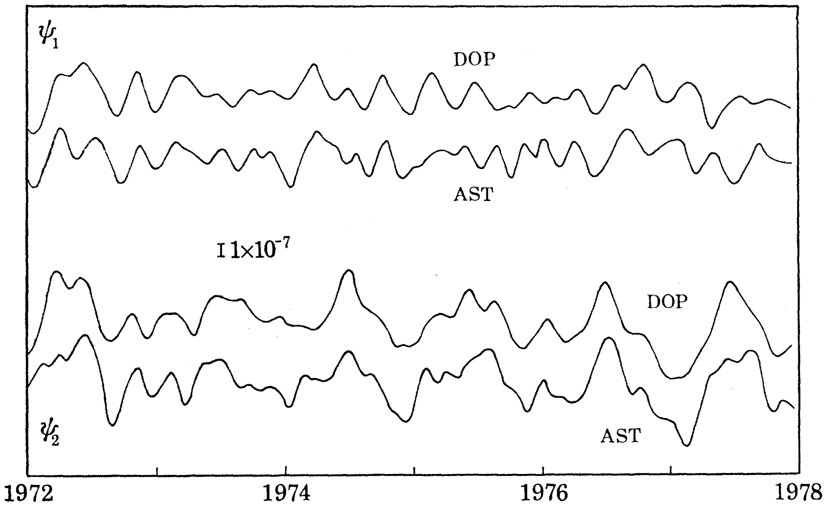

Figure 5. Excitation functions derived from astrometry (AST) and Doppler (DOP) coordinates of the pole.

Another way to consider this problem is to derive the excitation functions of the polar motion from the pole coordinates (Munk & MacDonald 1960). They are shown in figure 5. These functions exhibit common features for DOP and AST, especially for ψ_2 which has larger variations than ψ_1. Remarkably large excitation in ψ_2 appears in 1976–7.

CONCLUSION

The Defense Mapping Agency has proved that the Doppler method can provide, on a regular basis, better coordinates of the pole than the astrometric network, and also with a much shorter delay.

Compared with the other new techniques for the determination of the pole, such as laser ranging and very long baseline interferometry, the Doppler method has the advantage of using automatic low-cost stations, which can be used in fairly large numbers: a safeguard in case of failures and unexpected station motions. Compared with laser ranging, it has the advantage of being an all-weather technique, which can provide a very homogeneous set of results.

However, in the future reorganization of the determination of the Earth rotation parameters, the Doppler method does not appear as a good candidate for several reasons: it gives only the pole, not U.T.1; it requires an active artificial object; its future seems to be linked to the future of the Transit system; and its precision and accuracy are lower than those of other proposed techniques.

This last point, however, deserves further consideration. It is not fair to compare the expected precision of ideal networks with the realized precision of an existing service. Although there is a contradiction in the Doppler method, since precision requires a low satellite and accuracy a high one, some improvements can be imagined, such as better stabilized frequencies in the satellites and in the stations, higher transmitted frequencies and a drag-free satellite. I am not aware of the ultimate limitations, but if a substantial improvement could be obtained, it could be justified to launch dedicated space transmitters for Doppler geodesy and the study of the Earth's rotation. Such transmitters need emit only two carrier frequencies without modulation, and they could be part of other space experiments.

REFERENCES (Guinot)

Anderle, R. J. 1970 Polar motion determinations by U.S. Navy Doppler satellite observations. *Naval Weapons Laboratory tech. Rep.* no. TR-2432, Dahlgren, Virginia.

Anderle, R. J. & Beuglass, L. K. 1970 Doppler satellite observations of polar motion. *Bull. géod.* **96**, 125–141.

Anderle, R. J. 1972 Pole position for 1971 based on Doppler satellite observations. *Naval Weapons Laboratory tech. Rep.* no. TR-2734, Dahlgren, Virginia.

Feissel, M. 1972 La conservation du système de référence de résultats du Bureau International de l'Heure. *BIH A. Rep. for* 1971, part E.

Guinot, B. 1978 Irregularities of the polar motion. In *Proc. I.A.U. Symp.* no. 82. (In the press.)

Munk, W. H. & MacDonald, G. J. F. 1960 In *The rotation of the Earth*, p. 41. Cambridge University Press.

Nouel, F. & Gambis, D. 1978 Very first results on MEDOC experiments. In *Proc. I.A.U. Symp.* no. 82. (In the press.)

Oesterwinter, C. 1978 Polar motion through 1977 from Doppler satellite observations. In *Proc. I.A.U. Symp.* no. 82. (In the press.)