PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Establishment of Scale and Orientation for Satellite Doppler Positions

W. E. Strange and L. D. Hothem

Phil. Trans. R. Soc. Lond. A 1980 **294**, 335-340
doi: 10.1098/rsta.1980.0040

Phil. Trans. R. Soc. Lond. A **294**, 335–340 (1980)
Printed in Great Britain

Establishment of scale and orientation for satellite Doppler positions

By W. E. Strange and L. D. Hothem

National Geodetic Survey, National Ocean Survey, NOAA,
Rockville, Maryland 20852, *U.S.A.*

The scale of satellite Doppler results and the orientation of the coordinate system in which the results are obtained, relative to more conventional coordinate systems, need to be known for many applications. Sources of this information are comparisons with external standards. Comparisons indicate that Doppler positions obtained by the National Geodetic Survey of the National Ocean Survey (with the use of its standard program and the precise ephemeris) require a longitude rotation of $0.8 \pm 0.05''$ eastward and a decrease in scale of 0.4 ± 0.1 parts/10^6 to be compatible with results of other space systems. This rotation is compatible with results obtained by comparisons of astro-Doppler and gravimetric deflexions. To apply these results to those of other investigators, by using other reduction programs and techniques, will require intercomparison of programs with the use of standard data sets such as those used by Special Study Group 2.44 of the International Association of Geodesy.

Introduction

To use Doppler satellite derived positions in conjunction with conventional geodetic information or with data from other space systems, it is necessary to reference all positional information to a common coordinate system and to establish a common definition of scale. In achieving this objective, Doppler stations were established at the site of very long baseline interferometry (v.l.b.i.), lunar laser ranging (l.l.r.) and deep space net (d.s.n.) tracking stations. This paper presents a status report on Doppler scale and coordinate system intercomparisons with these systems.

The Doppler positions used for intercomparisons are those derived by using the precise ephemeris, in conjunction with the computer program DOPPLR used by the National Geodetic Survey (NGS) of the National Ocean Survey (NOS).

The scale and orientation of Doppler positions are obtained from the ephemeris used. Ephemeris scale is established through the use of a particular value of GM (G = gravitational constant; M = mass of Earth). The orientation of the pole to which Doppler positions are referenced is based on minimization of the difference between Doppler and BIH pole positions for a period in 1971 (Anderle 1976). This reference pole has been maintained by continuous solution for a Doppler pole position. The longitude origin for a Doppler coordinate system is arbitrary. In practice the longitudes of Doppler tracking stations were fixed to produce, as nearly as possible, agreement with the zero longitude as defined by BIH.

Early investigations

Early comparisons of Doppler results with ground survey and other space systems (Anderle 1974; Strange *et al.* 1975) had indicated that Doppler scale should be decreased by 1 part/10^6. Studies by R. J. Anderle (1976, personal communication, 1978) identified an explanation for a scale reduction of about 0.4 part/10^6. The 0.4 part/10^6 scale reduction arose in part from a 1.7 m offset between the centre of mass of the Transit satellites and the phase centre of the satellite antenna. The remainder resulted from the use of GM = 398601 km^3/s^2 in orbit determination rather than the currently accepted value of GM = 398600.5 km^3/s^2.

The Doppler longitude origin, which was established early in the Transit programme, had been critically examined by the U.S. Defense Mapping Agency (DMA). Through comparisons between astro-Doppler and gravimetric deflexions at a number of stations in the United States, a widely quoted rotation of 0.26″ was derived as applicable to Doppler longitudes to correctly reference Doppler results to the BIH longitude origin (Seppelin 1974). Later it was found that, owing to a misunderstanding between DMA and the NGS (NOS) which provided the astronomic data, the astronomic data used in the comparisons were referenced to an earlier longitude origin rather than the BIH zero longitude. After referencing the astronomic data to the BIH zero longitude, the rotation required for the Doppler longitudes was 0.77″ eastward. This is in good agreement with earlier comparisons between Doppler longitudes and d.s.n. and l.l.r. longitudes of 0.864″ and 0.792″ derived by Strange *et al.* (1975) and the v.l.b.i. comparisons of Petrochenko *et al.* (1977).

Early coordinate system comparisons indicated agreement between the Doppler and CIO poles to within ±0.15″ or better (Mueller 1974; Strange *et al.* 1975).

Results of intercomparisons

Recently, comparisons between Doppler and other space systems based on observations taken before 1978 were presented by Hothem *et al.* (1978). Table 1 *a–c* summarizes the more important comparisons of scale and coordinate system orientation from that paper. Figure 1 indicates the location of the various stations.

Table 1*a*. Comparisons of Doppler and fixed v.l.b.i.†

stations		chord distance/m			declination	longitude
from	to	Doppler‡	v.l.b.i.	diff.	difference	difference
Haystack	Goldstone§	3899798.61	3899798.84	−0.23	+0.036″	−0.818″
Haystack	Owens Valley	3928931.74	3928931.67	+0.07	+0.053″	−0.743″
Greenbank	Owens Valley	3324620.54	3324620.08	+0.46	+0.059″	−0.824″

† With the use of pre-1978 Doppler results and pre-1978 v.l.b.i. measurements.
‡ Doppler distance corrected for scale of −0.38 part/10^6 (Anderle 1978).
§ V.l.b.i. distance corrected for scale of −0.14 part/10^6 to adjust for currently accepted value for velocity of light of 292792.458 km/s.

Table 1*b*. Comparisons of Doppler and lunar laser†

	radius vector/m			geocentric latitude	longitude
station	Doppler‡	lunar laser	diff.	difference	difference
McDonald observatory	6374664.25	6374664.66	−0.42	−0.159″	−0.746″

† With the use of pre-1978 Doppler and pre-1978 lunar laser measurements.
‡ Doppler distance corrected for scale of −0.38 part/10^6 (Anderle 1978).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Table 1c. Comparisons of Doppler and d.s.n.†

station		spin axis distance/m: Doppler‡	d.s.n.	diff.	longitude difference
Goldstone DSN 4	DSS 14	5203997.53	5203996.99	+0.54	−0.858″

† With the use of pre-1978 Doppler and pre-1978 d.s.n. data.
‡ Doppler distance corrected for scale of −0.38 part/10^6 (Anderle 1978).

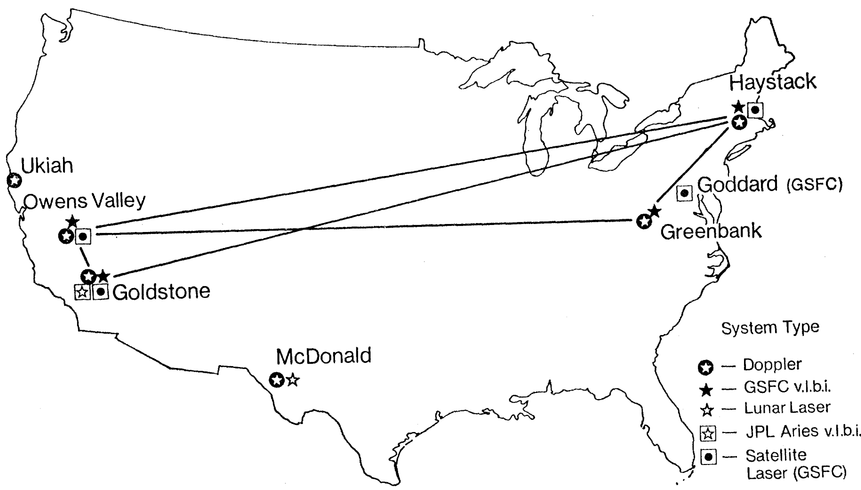

Figure 1. Space Systems Validation Project, January–March 1978.

In early 1978, some 400 additional Doppler passes were observed at the Haystack, Greenbank (NRAO), McDonald, Goldstone and Owens Valley space system sites. Also additional v.l.b.i. measurements and satellite laser observations were carried out at the Haystack, Goldstone and Owens Valley sites. Table 2a–c indicates comparisons with the use of the 1978 Doppler data together with the data from other space systems used in deriving table 1. Also included in table 2a is a comparison of the 1978 Doppler data with one set of 1978 v.l.b.i. determinations obtained by using data taken by the Mark I v.l.b.i. system.

Table 2a. Comparisons of Doppler and fixed v.l.b.i.

stations: from	to	chord distance/m: Doppler†	v.l.b.i.	diff.	declination difference	longitude difference
(With the use of 1978 Doppler results and pre-1978 v.l.b.i. measurements.)						
Haystack	Goldstone‡	3899798.74	3899798.84	−0.10	+0.049″	−0.824″
Haystack	Owens Valley	3928931.74	3928931.67	+0.07	+0.078″	−0.737″
Greenbank	Owens Valley	3324620.17	3324620.08	+0.09	+0.109″	−0.846″
(With the use of 1978 Doppler results and 1978 v.l.b.i. measurements.)						
Haystack	Owens Valley	3928931.74	3928931.76	−0.02	+0.024″	−0.793″

† Doppler distance corrected for scale of −0.38 part/10^6 (Anderle 1978).
‡ V.l.b.i. distance corrected for scale of −0.14 part/10^6 to adjust for currently accepted value for velocity of light of 299792.458 km/s.

TABLE 2*b*. COMPARISONS OF DOPPLER AND LUNAR LASER†

station	radius vector/m			geocentric latitude difference	longitude difference
	Doppler‡	lunar laser	diff.		
McDonald observatory	6374664.31	6374664.66	−0.35	−0.161″	−0.808″

† With the use of 1978 Doppler results and pre-1978 lunar laser measurements.
‡ Doppler distance corrected for scale of −0.38 part/10^6 (Anderle 1978).

TABLE 2*c*. COMPARISONS OF DOPPLER AND D.S.N.†

station		spin axis distance/m			longitude difference
		Doppler‡	d.s.n.	diff.	
Goldstone					
DSN 4	DSS 14	5203997.91	5203996.99	+0.92	−0.853″

† With the use of 1978 Doppler results and pre-1978 d.s.n. data.
‡ Doppler distance corrected for scale of −0.38 part/10^6 (Anderle 1978).

Several comments are appropriate with regard to the comparisons given in table 2. Table 2 demonstrates that the latest Doppler, v.l.b.i., l.l.r. and d.s.n. results are in agreement with regard to scale to within ±0.1 part/10^6. There is also agreement with the other three space systems at the ±0.03″ level as to the longitude rotation that should be applied to the Doppler results.

With regard to the origin of the pole, the situation is somewhat more complex. The agreement for the v.l.b.i. lines Haystack–Goldstone and Haystack–Owens Valley are within ±0.05″ of zero. The v.l.b.i. Owens Valley–Greenbank line and the l.l.r. results indicate larger disagreements. However, several factors must be noted. The v.l.b.i. result for the Owens Valley–Greenbank line is not well determined; v.l.b.i. data were taken several years ago at a time when there were clock stability problems at the Greenbank observatory.

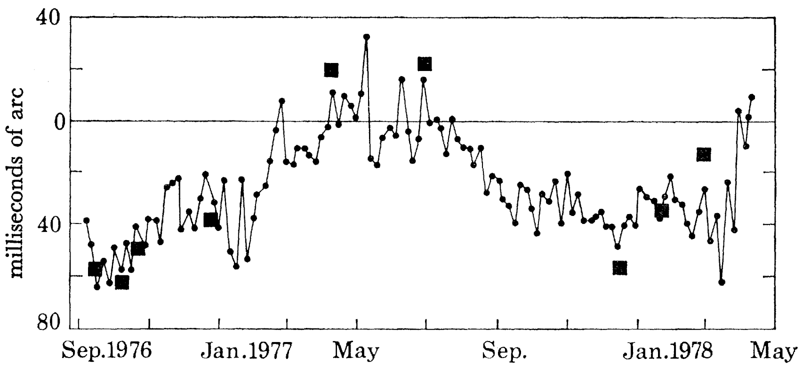

FIGURE 2. *X*-component of polar motion. Reference value: BIH polar motion; •, Doppler polar motion; ■, v.l.b.i. polar motion.

In the l.l.r. results the equatorial plane is defined by the lunar ephemeris selected; therefore a difference may exist between this definition and the definition derived by using the CIO pole.

For these reasons the two v.l.b.i. lines Haystack–Goldstone and Haystack–Owens Valley are considered best for determining possible pole origin differences.

However, it is still necessary to recognize that there are known differences between the Doppler pole and the BIH pole used in deriving the v.l.b.i. results (Anderle 1976). The difference is primarily a periodic annual term with the Doppler results considered correct (Guinot 1978). V.l.b.i. determinations of the *X* component of pole position for the period September 1976–February 1978 are in excellent agreement with the Doppler results (Robertson *et al.* 1978) and support the correctness of Doppler polar motion. Figure 2, which is a modification of figure 3 in the paper by Robertson *et al.*, illustrates this. Since v.l.b.i. data are taken over 1 or 2 days, the short period differences in polar motion are important. At present there is no evidence to indicate that the Doppler pole origin needs correction. If, in the future, any correction is found to be needed, it is unlikely to exceed $\pm 0.05''$.

Comments on results

The comparisons so far carried out between Doppler positional information and that derived from other space systems indicate that a scale decrease of 0.4 ± 0.1 part/10^6 and a longitude rotation of $0.8 \pm 0.05''$ eastward should be applied to the Doppler results. No systematic pole error is detectable.

There are several factors to keep in mind in applying these results. The results refer to Doppler positions obtained by using a particular reduction program and the precise ephemeris. It is known that coordinate system differences occur between precise ephemeris and broadcast ephemeris results. Also, up to 1 m of systematic difference exists between results obtained with different Doppler programs. These result from differences in methods of refraction correction as well as differences in applying other small corrections.

To obtain a more universally applicable set of scale and orientation corrections, it is important to intercompare Doppler results obtained by different reduction programs. This is best done by the use of standard data sets, such as those provided by Special Study Group 2.44 of the International Association of Geodesy. In this way, different reduction programs can be applied to a common data set.

Finally, it is clear that, with data sets of reasonable length (200 passes or more) and with use of the precise ephemeris, geocentric Doppler positions can be derived with a precision of ± 20–30 cm. To obtain scale and orientation with a commensurate level of accuracy will require a number of improvements in procedure. First, present polar motion and Earth rotation measurements are not sufficiently accurate to locate the CIO pole and BIH longitude origin to the required accuracy. Secondly, the relation between coordinate systems, which depend on a lunar and/or planetary ephemeris or on radio stars, are not related sufficiently accurately to the optical star coordinate system. Thirdly, at the few decimetre level, the differences between Doppler reduction systems and the long-term stability of the coordinate system, to which the precise ephemeris is referred, must be considered. However, it seems possible that, with sufficient work, orientation of Doppler results to $\pm 0.01''$ and scale accurate to ± 0.03 part/10^6 are possible.

References (Strange & Hothem)

Anderle, R. J. 1974 Transformation of terrestrial survey to Doppler satellite-datum. *J. geophys. Res.* **79**, 5319–5331.
Anderle, R. J. 1976 Polar motion determination by Doppler satellite observations. *Bull. géod.* **50**, 377–390.
Anderle, R. J. 1978 Mean Earth's ellipsoid based on Doppler satellite observation (abstract). *Trans. Am. geophys. Un.* **59**, 807.
Hothem, L. C., Robertson, D. S. & Strange, W. E. 1978 Orientation and scale of satellite Doppler results based on combination and comparison with other space systems. In *Proceedings of the Second International Symposium on Problems Related to the Redefinition of North American Geodetic Networks*, pp. 167–180. U.S. Government Printing Office.

Guinot, B. 1978 Irregularities of the polar motion, In *I.A.U. Symposium* no. 82 (*Time and the Earth's rotation*) (ed. Ridell). (In the press.)

Mueller, I. I. 1974 Global satellite triangulation and trilateration results. *J. geophys. Res.* **79**, 5333–5348.

Petrochenko, W. I., Langley, R. B., Cannon, W. H. & Kouba, J. M. 1977 Geodesy and astronomy by trans-atlantic long base line interferometry. *J. geophys. Res.* (Submitted for publication.)

Robertson, D. S., Carter, W. E., Corey, B. E., Cotton, W. D., Counselman, C. C., Shapiro, I. I., Wittels, J. J., Hinteregger, H. F., Knight, C. A., Rogers, A. E. E., Whitney, A. R., Ryan, J. W., Clark, I. A., Coates, R. J., Ma, C. & Moran, J. M. 1978 Recent results of radio interferometric determinations of a trans-continental base line, polar motion, and Earth rotation. In *I.A.U. Symposium* no. 82 (*Time and the Earth's rotation*) (ed. Riddell). (In the press.)

Seppelin, T. O. 1974 *The Department of Defense World Geodetic System 1972. International Symposium on Problems Related to the Redefinition of North American Geodetic Networks*, Fredericton, New Brunswick, Canada, May 1974 (43 pages).

Strange, W. E., Hothem, L. D. & White, M. B. 1975 *The satellite Doppler station network in the United States, XVI General Assembly, International Association of Geodesy*, Grenoble, France, August 1975.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF