CONSISTENCY OF NUTATION MODELING IN RADIO SOURCE POSITION COMPARISONS

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ABSTRACT. Comparisons between sets of radio source coordinates determined from independent VLBI measurements show that rotational offsets can be as large as several milliarcseconds (mas), and are considerably larger than the positional uncertainties ($\leq$1 mas). The 1 to 2 mas discrepancies remaining after removal of the rotational offsets indicate the present true level of accuracy. Analyses of DSN and CDP astrometric data are performed to explore the effects of alternative schemes of nutation modeling on such catalog comparisons. It is concluded that rotations between different source catalogs are minimized or eliminated if the nutation models employed are consistent. Intrinsic source coordinate discrepancies, however, remain at the 1 mas level.

1. Introduction

During the past several years, frequent comparisons have been made between radio source positions determined from Deep Space Network (DSN), Crustal Dynamics Project (CDP), and International Radio Interferometric Surveying (IRIS) VLBI data. Such comparisons serve to establish the level of systematic errors. Comparisons for recent data are considered in Section 2. Typically, the three-dimensional rotational offsets that are required to bring these three source catalogs into best coincidence range up to several milliarcseconds (mas), and are considerably larger than the positional uncertainties ($\leq$1 mas). Section 3 presents analyses of DSN and CDP astrometric data that were performed in an effort to understand orientational and intrinsic source coordinate discrepancies. All parameter estimation employs the JPL VLBI modeling and estimation software MODEST. Variants of nutation modeling include estimates of daily angles, estimates of precession and nutation amplitudes, and adoption of the recent Zhu *et al.* (1990) revision of 1980 IAU nutation.

2. Comparisons of Source Catalogs

The IERS Annual Report for 1989 (IERS, 1990) reports a radio reference frame based on combinations of four independently determined sets of radio source coordinates. These are based on the VLBI observing programs of the Goddard Space Flight Center (Crustal Dynamics Project (CDP), Ma *et al.*, 1990), the Jet Propulsion Laboratory Deep Space Network (DSN) (Sovers *et al.*, 1988), the National Geodetic Survey (International Radio

Interferometric Surveying (IRIS), Robertson *et al.*, 1986), and the U.S. Naval Observatory (USNO, Eubanks *et al.*, 1990). Although the modeling of VLBI observables in all four projects largely conforms to the IERS Standards (IERS, 1989), there is one major exception. It has been known for a number of years that VLBI data clearly demonstrate the inadequacy of the IAU models for the Earth's nutation and precession (Herring *et al.*, 1986). Consequently routine VLBI data analysis includes some means of correcting this deficiency. This usually takes the form of estimating the nutation angles in longitude and obliquity for each 24-hour observing session. In order to fix the relative orientations of the terrestrial and celestial coordinate systems, one session is adopted as the "reference day", for which the 1980 IAU nutation angles are adopted and not allowed to vary. In the past, there has been no agreement on a common reference day between the various observing programs, partly due to scarcity of overlapping experiments. This has contributed to some obscurity in interpreting comparison of results, and thus in assessing the true accuracies of the VLBI-measured coordinates of radio sources.

Table 1. Typical Source Position Comparisons

Pair	N_s	A_1	A_2	A_3	$\chi_\nu{}^2$	Δ arc
IERS90 - IERS89	169	0.1	0.3	0.1	2.1	2.2
IERS88	163	0.6	0.0	0.5	2.0	2.9
IERS90 - JPL90	175	-0.4	-0.6	0.0	1.6	1.3
GSFC90	71	-1.3	-2.5	0.3	0.7	0.6
NGS90	69	-1.4	-0.9	0.2	0.9	0.9
USNO90	74	-1.6	-2.4	-0.0	0.7	2.0
JPL90 - GSFC90	52	-1.9	-3.1	0.7	1.8	1.2
NGS90	51	-2.2	-1.4	0.5	2.1	1.6
USNO90	61	-1.9	-2.9	0.3	1.6	3.2

To give some examples of comparisons of various radio reference frames, Table 1 presents three groups of results. The first two pairs are comparisons of the three IERS combined catalogs for 1988, 1989, and 1990. Here, N_s is the number of common sources, A_{1-3} are the x, y, z rotation angles (applied to the second member of each pair) that bring the two catalogs into best coincidence, χ^2_ν is the chi-square per degree of freedom in coordinate differences after removal of the rotational offset, and Δarc is the RMS arc length difference for all pairs of sources. Since special pains are taken to ensure stablity of the IERS catalogs from year to year, it is not surprising that the rotational offsets between the current one and the 1988 and 1989 versions are only a few tenths of mas. The second group of comparisons in Table 1 are between the current IERS catalog and its four constituents. Here it is obvious that a number of rotational offsets can exceed the mean formal source coordinate uncertainties, and can be larger than 2 mas. The last group of results shows comparisons between the four constituents of the IERS90 catalog, with rotations ranging up to 3 mas. The accuracy level of present VLBI source coordinates (for 50 to 60 of the best-determined objects) appears to be 1-2 mas. Normalized chi-squares exceed unity, indicating that the formal uncertainties may be underestimates of the true accuracies.

3. Effects of Alternative Nutation Modeling

The four component catalogs of IERS90, whose mutual rotational offsets were shown in the last three rows of Table 1, all employ different nutation models. For GSFC90, NGS90, and USNO90, daily nutations in longitude and obliquity were estimated, with separate reference days, while the JPL fit estimated precession and amplitudes of selected nutation components. Exploratory fits were performed in order to determine whether the large rotational offsets and RMS arclength discrepancies are connected to the disparate nutation modeling. Subsets of the observations entering the determinations of JPL90 (9000 delay-delay rate pairs, 1978-89) and GSFC90 (25000 intercontinental D-DR pairs, 1979-89) were studied. All parameter estimation employed the JPL VLBI modeling and estimation software MODEST (Sovers and Fanselow, 1987). Fits were performed to obtain positional coordinates of radio sources, time rates of station motion, and the usual clock and troposphere parameters (one every 3 hours for the latter). Corrections to the IAU nutation model took various forms: separate as well as identical nutation reference days for separate fits, estimates of nutation amplitudes and precession, and a nutation model fixed at the results of Zhu *et al.* (1990).

Table 2. Source Position Comparisons
(Variants of Nutation Modeling)

Pair	N_s	A_1	A_2	A_3	$\chi_\nu{}^2$	Δ arc
JPL (B) - GSFC(A)	36	1.9	-1.1	-0.8	1.5	1.2
GSFC (C) - GSFC(A)	49	4.2	1.3	-0.7	(0)	(0)
JPL (C) - GSFC(C)	36	0.2	0.3	0.0	1.2	1.2
JPL (S) - GSFC(S)	36	-0.3	0.5	0.2	6.2	1.9
JPL (Z) - GSFC(Z)	36	-0.0	1.2	0.3	6.9	2.1
JPL (N) - GSFC(N)	36	0.0	0.0	0.0	3.1	1.4

A = 1980.9 reference day
B = 1983.4 reference day
C = 1983.9 reference day
S = Standard 1980 IAU nutation model
Z = Zhu *et al.* nutation model
N = Nutation amplitudes + precession estimated

Table 2 summarizes the results of source coordinate comparisons between selected pairs of catalogs yielded by the analyses. The first pair of catalogs was generated by fits estimating daily nutation angles, with separate reference days 2.5 years apart. To give an indication of the quality of the source coordinates, the RMS formal uncertainties for the 36 sources in common are 0.6 mas for RA and 0.7 mas for declination for JPL(B), and (0.5, 0.6) mas for GSFC(A). Average observation epochs are substantially different for some sources: the RMS epoch difference is 1.6 years. The rotations A_1 and A_2 are qualitatively consistent with the known differences in corrections to $\Delta\psi$ and $\Delta\varepsilon$ between 1980.9 and 1983.4.

To give an even clearer demonstration of the role of the nutation reference day in catalog comparisons, the second pair in Table 2 is a comparison of two catalogs derived from identical data and identical modeling, with the sole exception of a different nutation reference day. A large rotational offset is seen. As the last of fits estimating nutation angles, the third pair in Table 2 compares JPL and GSFC source positions with the same nutation reference day. This day is 18 November 1983, when both JPL and GSFC had observing sessions between North America and Europe. The angles A_i are seen to be much reduced; they amount to only fractions of the catalog uncertainties.

The last three JPL-GSFC pairs were generated by fits that fixed the nutation model as either the 1980 IAU or the Zhu *et al.* series, or estimated precession and selected nutation amplitudes. With nutation fixed either at the 1980 IAU (S) or Zhu *et al.* (Z) series, the rotational offsets are small. The exception is the angle A_2, which is caused by the precession model defect in combination with source coordinate observation epoch differences. The normalized chi-square values with either the S or Z nutation models show that fits to the VLBI data are not as good as those in which daily angles are estimated. The last line in Table 2 shows a comparison between source positions derived from fits in which the precession constant and a number of in- and out-of-phase nutation amplitudes are estimated. Three nearly mutually orthogonal coordinates (RA and declination of OJ 287, declination of CTD 20) are constrained to the IERS90 values, and small rotations around the x and y axes are estimated, as in the procedure of Steppe *et al.*, 1989. Such fits ensure that any rotational offsets are eliminated internally, and the resulting source catalogs show zero relative rotation.

In conclusion, significant rotations between different source catalogs are minimized or eliminated if care is taken to ensure that the nutation models used in the analyses are consistent. Intrinsic source coordinate discrepancies are presently of the order of 1 mas.

4. Conclusions

Rotational offsets between catalogs of independently determined source positions may be eliminated either by adopting the same model of nutation, or by estimating precession and nutation amplitudes in the original data analyses. If daily nutations in longitude and obliquity are to be estimated instead, then source catalog rotational offsets are minimized if the same reference day is adopted. In the latter case, the rotation is not completely eliminated, but reduced to well below the level of formal catalog uncertainties. With either scheme, for the sample data considered here, the coordinate discrepancies after removal of the rotation are of the order of 1 mas (somewhat larger than the RMS catalog uncertainties.) Normalized chi-squares exceed unity, indicating that the formal σs are underestimates of the true accuracies. As additional experiments reduce formal uncertainties to the 0.1 mas level, improved modeling of source structure (Charlot, 1990) and dynamic troposphere variations (Treuhaft and Lanyi, 1987) will be imperative to bring accuracy to the same level.

Acknowledgments

I thank Dr. Chopo Ma for providing the GSFC VLBI observations. The research described in this report was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

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