THE PRECISION OF J2000.0 RADIO SOURCE POSITIONS FROM MARK III VLBI

C. Ma
NASA/Goddard Space Flight Center

A celestial coordinate frame defined by extragalactic radio sources has been developed from Mark III VLBI data. 33 000 delay and delay rate pairs acquired between August 1979 and December 1982 have been analyzed to give positions for 82 radio sources. Standard J2000.0 astronomical models were applied. 90% of the formal errors for arc lengths between sources are less than 0"003. Arc lengths estimated from separate one-year data sets are consistent at the 0"001 to 0"004 level.

Data from very long baseline interferometry (VLBI) have significantly improved radio source positions in recent years (Clark et al., 1976; Rogers et al., 1983; Fanselow et al., submitted to Astron. J.). The improvement in precision arises from new instrumentation, progressing through the Mark I, Mark II, and Mark III systems with increasing sensitivity and flexibility. The increasing number of VLBI positions is a result of applications to geodesy and spacecraft tracking. With further work, particularly in the southern hemisphere, the catalog of extragalactic radio sources could provide the fixed basis of the celestial coordinate system.

The Mark III VLBI system was developed cooperatively by the National Aeronautics and Space Administration (NASA) for geodetic measurements and the National Radio Astronomy Observatory (NRAO) for astronomical observations. Rogers et al. (1983) describe the instrumentation in some detail. The system integrates all aspects of data acquisition, processing, analysis, and archiving. A wide bandwidth, dual-frequency receiver allows precise determination of the group delay observable in each frequency band and calibration of the ionosphere using a combination of the two delays. The 28 recorded tracks, each capable of 2 MHz, provide much greater sensitivity than earlier systems. Control of all data acquisition is entirely automatic, including the logging of meteorological and calibration data, and the only manual operation is changing data tapes. A dedicated hardware correlator designed, built and operated by the Haystack Observatory reduces the raw data from each pair of stations to the observables of group delay and phase delay rate. Both the correlator and the data analysis system use

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HP 1000 minicomputers. The core of the Mark III data analysis system is a data base handler which provides the interface between programs as well as a permanent archive and catalog of VLBI data. The analysis system provides considerable flexibility in the selection, calibration, and editing of data, the choice of parameterization, and the retention of results.

The VLBI observations made by the NASA Crustal Dynamics Project and the National Geodetic Survey (NGS) POLARIS program which are presented here differ from normal astronomical observations. All the data are dual-frequency with eight channels spanning 360 MHz near 8.4 GHz and six channels spanning 85 MHz near 2.3 GHz. Thus 14 tracks are recorded simultaneously. The radio telescopes and sources observed require integration times between 100 and 400 seconds. The sources are chosen for sufficient radio flux at both observing frequencies and for compactness. The observing schedule is distributed in machine-readable form to all stations before an experiment. A typical 24-hr experiment includes 10 to 14 sources, each observed at least ten times during the period of mutual visibility for a total of 140 to 220 scans. The limiting factor on the number of scans is the slewing speed of the slowest telescope. Measurements of pressure, temperature, humidity, and timing cable length are logged during each scan. The observing network uses from two to six stations, forming up to fifteen baselines. It is therefore possible to acquire over 2000 delay/rate pairs in a single day of observing.

The Goddard J2000.0 radio source catalog was derived from 33 000 delay/rate pairs taken with the Mark III system between August 1979 and December 1982 using nine stations in North America and Europe. 82 sources above -13 degrees declination were successfully observed, many in three survey sessions designed to identify new sources with appropriate characteristics. All the points were calibrated using dual-frequency ionospheric measurements and real-time meteorological data. Data from water vapor radiometers were available for some experiments in 1982 but were not used because of incompleteness and difficulties in interpretation.

The physical models applied in the data analysis generally follow the MERIT standards. The orientation of the Earth in space is modeled using J2000.0 precession and 1980 IAU nutation, as summarized by Kaplan (1981). The orbital motion is taken from the M.I.T. PEP planetary ephemeris. The motions of the Earth's surface are modeled with BIH Circular D polar motion and UT1 values, corrected for short period UT1 variations, and solid Earth tides determined from lunar and solar ephemerides. The Marini model for the troposphere is applied using local pressure, temperature and humidity. The ionospheric delay is modeled from by a simple inverse frequency squared relationship. Other models include antenna axis offset, relativistic gravitational deflection by the sun, a transformation from atomic to coordinate time (Moyer, 1981), and a theoretical delay and delay rate model. Further details are given in Robertson (1975) and Ma (1978).

A single large solution was accumulated using a sequential least-squares estimator. The global adjusted parameters were the telescope locations, except for the Haystack 37-m, and the source positions, except for the right ascension of 3C273B (1226+023). (Fixing a single right ascension is a simple method for defining the right ascension origin, a fiducial point to which VLBI measurements have no sensitivity. A different value for the reference right ascension merely rotates all the catalog positions.) For each day and station, polynomials and 24-hr sinusoids were adjusted to model the station clock behavior relative to the reference station clock. The atmosphere thickness at zenith for each station was adjusted for each day. Earth orientation parameters were also adjusted for each day. On days having only a single baseline, UT1 and one component of polar motion were adjusted. Parameters which were not adjusted in order to maintain standard models were Earth tide lag and Love numbers, the precession constant, and nutation angles and coefficients. The weighted RMS fit of the solution was 0.1 ns in delay and 0.1 ps/s in delay rate.

The precision of the estimated source positions is shown in figure 1. The histogram plots the one-sigma formal errors for the 3321 arc lengths between all 82 sources. 90% are less than 0".003. The slight excess at the 0".010 value arises from lumping together all larger errors in this bin. It should be noted that the arcs extend across the entire northern sky and are not grouped by length. However, the longest arcs have larger errors.

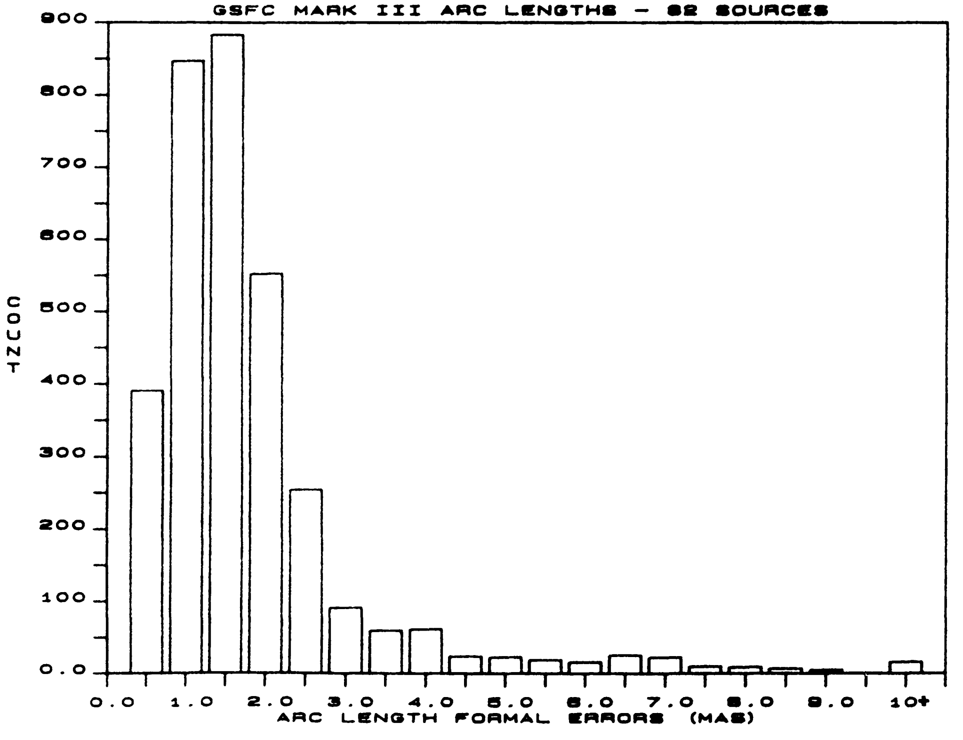

Figure 1. Histogram of one-sigma arc length formal errors. Each bin is 0".0005. 10+ bin includes all larger errors.

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The consistency of the solution was tested internally and externally. Table 1 shows the distribution of observations by year. The small number of observations from 1979 have been included with 1980. It can be seen that the regular observing catalog has approximately 20 sources. Table 2 shows the comparison of those arcs which are common to two years. For all sources the RMS scatter is between 0".002 and 0".004. For the most frequently observed sources the consistency is better by a factor of two. The year-to-year variation of common arc lengths indicates that the formal errors are optimistic.

Table 1. Observations and arcs by year.

	1980	1981	1982
Total number of sources observed	49	49	37
Number of arcs formed	1176	1176	666
Number of sources with >50 observations	20	21	18
Number of arcs formed	190	210	153
Total number of observation pairs	12300	8300	12000

Table 2. Comparison of individual year arc lengths.

All sources:	80-81	80-82	81-82	
Number of common arcs	231	190	253	
Mean arc length difference	-0.8	-0.7	0.7	x 0".001
RMS difference	3.3	2.0	4.3	x 0".001
Sources with >50 observations:				
Number of common arcs	105	66	105	
mean arc length difference	-1.3	-0.7	1.2	x 0".001
RMS difference	1.9	1.1	1.9	x 0".001

The external check used the JPL 1983-3 catalog of Fanselow *et al.* (submitted to Astron. J.). It should be emphasized that the Goddard and JPL catalogs have completely disjoint origins. The latter uses a mixture of 2.3 GHz, 8.4 GHz, and dual-frequency Mark II observations taken between 1971 and 1980, a total of approximately 2 400 data pairs. The three primary stations are in California, Spain, and Australia so that better southern hemisphere coverage and declination precision are possible. The JPL planetary ephemeris is used. Because of a narrower synthesized bandwidth, the RMS fit is somewhat worse, 0.5 ns in delay and 0.3 ps/s in delay rate.

There are 45 sources common to the Goddard and JPL catalogs. The weighted mean offset parallel to the equator is 0"0025 in the sense of Goddard - JPL. The weighted mean offset perpendicular to the equator is -0"0002. With the offsets removed, the unweighted RMS differences are 0"0032 and 0"0065, respectively. The scatter in declination is dominated by six sources whose declinations are poorly determined in one or the other catalog. Without these sources the unweighted RMS scatter in declination is 0"0037. The level of agreement suggests that the realistic uncertainty of the Goddard catalog positions is larger than the formal error by a factor of approximately two.

The precision of radio source positions from VLBI indicated by internal and external consistency is certainly better than 0"010 on average and perhaps as good as 0"004. The quality of the source positions determined from single survey sessions indicates that this level of precision can be attained with a small number of observations for each source. With observations from a longer interval, the limiting factor may not be the uncertainty of each measurement but the models of the Earth's motion with which observations are transformed into a fixed coordinate system. On the basis of recent results, it is clear that VLBI observations of extragalactic radio sources can be used to define a fixed celestial coordinate system and to study the Earth's movements in this reference frame.

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Discussion:

WALTER: The precisions quoted by you and preceding speakers are impressive. When pushing the accuracy of radio source positions further and further the number of system unknowns to be solved for simultaneously increases considerably, thus diminishing the overall accuracy aimed at. Under these circumstances, is it actually possible to reach accuracies of 0.″001?

MA: The internal consistency from year to year furnishes at this time the best indication of the true precision. There are sources whose formal errors are quite small. If you take the angles between those sources and regard their constancy over time, you get some variations of about 0.″001, rather than 0.″3 or so. But these are angles all over the sky, whereas Herring was talking about very small separations.

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