RADIO ASTROMETRY +

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ABSTRACT

Radio astrometry is now the premier astrometric technique for measuring the positions of celestial objects. The precision with which absolute positions can be determined is approaching a few milliarcseconds. The progress towards establishing an almost inertial reference frame based upon the positions of extragalactic radio sources is reviewed as of June 1983. The outlook for relating this reference frame to optical reference frames is also reviewed.

INTRODUCTION

Astrometry is the measurement of the precise positions and motions of celestial objects. It is usually divided into the measurement of the relative positions of objects over small ($< 1°$) and large ($\sim 360°$) angles. The latter is usually referred to as the absolute position of the coordinates of the object in right ascension (relative to the first point of Aries) and declination. This paper reviews the status of astrometric positions as regards to large angles. However before reviewing large angle astrometry, let me address how astrometry is associated with many aspects of this symposium.

Stellar kinematics and dynamics may be considered a subfield of astrometry. Stellar kinematics deals with the space motions of stars leading to studies of precession, solar motion, galactic rotation, statistical and secular parallaxes. Stellar dynamics deals with tidal effects in clusters and associations, and the effects of the overall gravitational potential on objects. Papers in this symposium volume deal with the motions of plasma ejected in a strong gravitational field from a central compact object. The measurement of relative positions over very small angles (milliarcseconds) is the topic of many papers in this symposium discussing "superluminal" motion. They also deal with the evolution of "beams" from these objects which in the case of SS433 display precessional motion. It is unfortunate that as yet there is no strong spectral line in the radio spectrum which can yield the radial velocities of this ejected plasma. Other papers in this symposium deal with maser emission. These may be considered studies of the "stellar" dynamics of clusters where the internal motions lead to the determination of the distances to the maser cluster.

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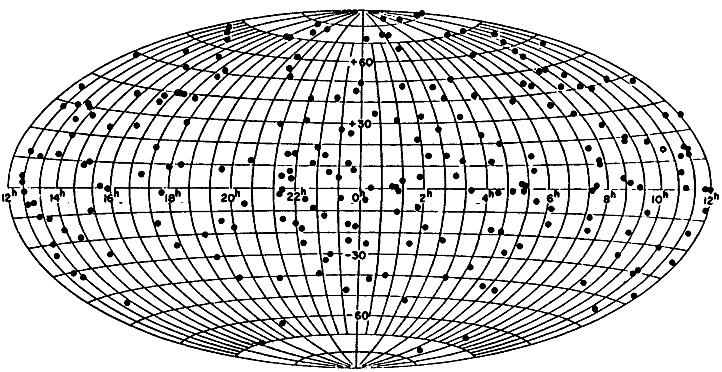
AN INERTIAL REFERENCE FRAME

Extragalactic radio sources, since they are the furtherest known celestial objects, display very little motion on the celestial sphere. As such, a catalog of precise radio source positions of extragalactic sources may be used to define an almost inertial reference frame against which motions of objects on the earth, motions of the earth, objects in the near earth environment (satellites), and objects on the celestial sphere (planets, stars, and galaxies) may be defined. This leads to applications in the fields of astrophysics, astronomy, and geophysics.

Celestial reference frames are based upon many stars. The FK4 system contains 1535 stars while the proposed FK5 system will contain over 5000 stars. There is an ample number of compact radio sources for a fundamental reference frame (Johnston and Ulvestad 1982). A working group of IAU Commission 24 for the Identification of Candidate Radio/Optical Sources has selected 236 sources of flux density > 1 Jy (Argue et al. 1983). The distribution of these sources is shown in figure 1. There is a paucity of sources south of -40° declination, but work is progressing on selecting sources. The initial reference frame will probably consist of $\sim$ 100 sources of flux density > 1 Jy. If a denser grid of sources is needed, over a thousand sources of flux density 0.2 Jy are available.



Extragalactic Radio/Optical Reference Frame: IAU Com#24 W.G.

Fig. 1 The distribution of radio/optical sources proposed by the working group of IAU Commission #24 to establish an almost inertial reference frame (Argue et al. 1983).

PROGRESS TOWARD MEASURING PRECISE POSITIONS

The measurement of the positions of compact extragalactic radio sources has progressed very well over the past ten years. The promise of high accuracy for Very Long Baseline Interferometric measurements made in the late 60's are now being fulfilled. In 1972, positional accuracies of $0\overset{''}{.}1$ were considered good. At this time precision is approaching $0\overset{''}{.}001$. Here we will deal only with precision because radio interferometric measurements of celestial source position are made with respect to the instantaneous pole of rotation of the earth at the time of the measurements. The celestial positions reported depend upon the models for earth motions such as polar motion, spin axis motion such as precession and nutation, revolutionary motions about the earth moon barycenter, as well as solar system and solar galactic motions. Until these motions are known on the 0".001 level, it is difficult to compare the accuracy of catalogs.

TABLE 1

CATALOG OF RADIO SOURCE POSITIONS

Authors	Instrument	Number of Sources	Precision	Observing Epoch	Reference Epoch
Connected Element Interferometry					
Elsmore & Ryle (1976)	Cambridge	55	0".03	1973.1; 1974.2	1950
Elsmore (1982)	Cambridge	25	0.03	1979.8	1950
Hilldrup et al.(1982)	VLA	29	0.02	1980.0	1950, 2000
Kaplan et al. (1982)	Green Bank	16	0.01	1979.9	1950, 2000
Perley (1982)	VLA	393	0.05	1981.0	1950
Wade and Johnston (1977)	Green Bank	34	0.03	1975.4	1950, 2000
Ulvestad et al. (1981)	VLA	250	0.10	1979.10	1950
Very Long Baseline Interferometry					
Clark et al. (1976)	US-Europe	18	0.04	1973.9	1950
Purcell et al. (1980)	Madrid-Goldstone-Tidbinbilla	117	< 0.01	1978.0	1950
Shaffer et al. (1982)	US-Europe	48	0.005	1981.5	2000
Ma et al. (1983)	US-Europe	21 Mk II	0.002	1975.2	2000
		71 Mk III	0.001	1981.2	2000
Sovers et al. (1982)	Madrid-Goldstone-Tidbinbilla	117	0.002	1977; 1978	2000

The improvement in positional precision and in the number of sources measured since 1970 is shown in Table 1. Included are catalogs with a large number of sources with accuracies better than 0".1 or catalogs of higher accuracies with over ten sources. The precision of the catalogs varies from 0".1 to 0".001. The radio frequencies of the measurements are between 2-9 GHz. Earlier measurements were made at only one frequency. The later catalogs of Hilldrup et al. (1983), Kaplan et al. (1982), Purcell et al. (1980), Shaffer et al. (1982), and Ma et al. (1983) were made at two frequencies between 1.4-2.6 and 4.9-8.4 GHz in order to eliminate the delay path length in the ionosphere as a cause of systematic error. It is very difficult to compare the catalogs because the earlier work was expressed in terms of the standard B1950 epoch. The constants involved in precession, nutation, other earth rotation parameters, as well as time scales are not expressed as exactly in this system, which is based upon the fundamental catalog FK4, as in the new FK5 system which has the new standard epoch J2000. For example, the precession constant in the earlier system differs by 0".01/year from that of the FK5 system. The IAU adopted resolutions during the General Assemblies of 1976 and 1979 establishing the FK5 fundamental reference frame. However exact transformation to the FK5 system cannot be performed until the catalog containing the stars defining the reference frame is available. One can see from the epoch of observations of the different catalogs that this effect is very important. Before attempting to directly compare catalogs, one should look for rotations between the coordinate reference frames. This will occur even when positions are expressed in the standard J2000 epoch of the FK5 reference frame. These rotations will lead to improved knowledge of the effects of earth rotation parameters and of motions of the earth, sun, and galaxy. The precision of the "best" catalogs in Table 1 is about a milliarcsecond. These VLBI catalogs were made from observations obtained over a period of several years. In contrast, the connected element catalogs are made from only three or less observing epochs spaced at most by a year. The catalog claiming the highest precision (Ma et al. 1983) was reduced in a manner compatible with the J2000 reference epoch. The positions of the common sources from the Ma et al. (1983) catalog compares favorably with those of other catalogs within the errors of the other catalogs. For example, the root sum of the squares of the differences for sixteen common sources in the Ma et al. (1983) and the Sovers et al. (1982) catalogs is at the 3 milliarcsecond level.

Evidence for the stability of the reference frame defined by extragalactic radio sources can be demonstrated by the repeatability of the positions in the various catalogs. The position of the very variable source BL Lac appears to be stable at the 2 milliarcsecond level for the period 1978-1982. The flux density from this source has recently undergone variations in intensity by a factor of 5, indicating several outbursts in the 1980-1981 time frame. The mas structure has been shown by Phillips and Mutel (1983) to be that of a typical superluminal source in which the radio core dominates the emission with emission moving away from the central core with an apparent velocity in excess of the velocity of light.

REFERENCE POINT OF RIGHT ASCENSION

The celestial coordinate system based upon our rotating earth uniquely defines the source declination but leaves the zero point of right ascension to be defined. Radio interferometric measurements of source positions, as long as they are carried out by earth based antennas also need to define a zero point of right ascension. In order to align the radio coordinates with the zero point of right ascension as defined by optical methods, the position of a radio source, or several, are made to coincide with their optical counterparts. This has been done in some cases by using the position of quasars such as 3C273B or of radio stars such as Algol. More will be said later about the detailed relationship and suitability of sources for relating the optical and radio reference frames.

NEEDS FOR FUTURE VLBI MEASUREMENTS

As stated by Johnston (1983), future VLBI measurements aimed at the high precision astrometric work should be made as follows:

1. These observations should be expressed in a uniform manner on the standard J2000 reference epoch of the FK5 reference frame defined by the IAU system of astronomical constants as stated in the resolutions

passed at the 1976 and 1979 IAU General Assemblies. A convenient definition of this system for radio astronomers is found in Kaplan (1981). The data should be expressed so that the complete observable can be reconstructed. This data must contain the epoch of observations, the delay, and delay rates, etc. This is extremely important because only with this knowledge can the data be analyzed for precise determination of earth rotation parameters, precession, nutation, etc.

2. The observations should be made using: a) dual radio frequencies to eliminate ionospheric effects, b) wide radio bandwidths (400 MHz) to insure highest accuracy, and c) incorporate water vapor radiometers and weather stations to calibrate atmospheric effects.

3. Source structure should be measured at timely intervals in order to remove this effect from the catalog positions.

4. A core list of approximately fifty sources should be established. These sources should be primarily used as the calibrators for measuring precise baselines and comparing the reference frames defined by individual source catalogs.

5. The right ascension zero point should be established by a single extragalactic source.

RELATIONSHIP OF OPTICAL/RADIO REFERENCE FRAMES

As stated earlier, the optical FK4 or FK5 reference frames may be related to the radio reference frame by measuring the positions of objects that display both optical and radio emission. Some objects that have been proposed are a) stars that display associated radio emission, b) solar system objects such as asteroids, planetary satellites, and artificial orbiters, and c) optical counterparts of compact extragalactic radio sources.

The problem with the radio emission associated with stars is that the emission mechanisms are not thermal and are located in a circumstellar region that may have a diameter of several A.U. Optical positions are centered on the stellar photosphere. Flare stars such as the RS CVn variables appear to be one of the best candidates for coincident optical/radio emission. Recent VLA measurements by Johnston, Wade, and Florkowski (1983) indicate that for the star HR1099 the optical and radio emission is probably coincident to 0".01. Further measurements will indicate whether this can be extended to 0".001.

Maser emission from OH, H_2O, and SiO are also associated with late type Mira variable stars. The position of the OH and H_2O masers can be measured using the VLA. Recent VLA measurements by Johnston, Spencer, and Bowers (1983) of R Aql and RR Aql show the H_2O emission is distributed over 0".1-0".2. The H_2O emission from the symbiontic star RX Boo is shown in figure 2 and is distributed over 0".3. Since these masers are pumped by energy from the star, the most intense masers hopefully will be located in close proximity to the star ($\sim$ few A.U.). The star's optical emission may be located in the maser cloud by modeling the geometry and velocity gradients of the H_2O maser emission hopefully to an accuracy of 0".02. The SiO masers may be superior to H_2O masers as they are located closer to the star (Soulie and Baudry 1983).

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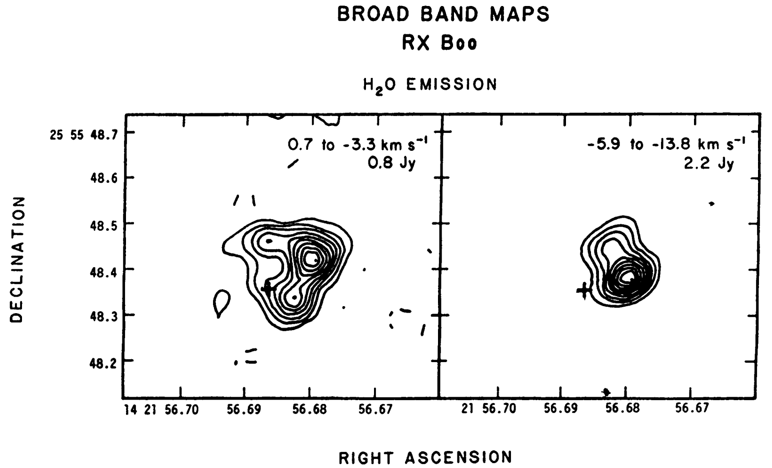

Fig. 2 The H_2O emission associated with the late type star RX Boo. This is the emission averaged over the velocity ranges 0.7 to -3.3 km s^{-1} and -5.9 to -13.8 km s^{-1}. The position of the strongest spectral feature at 6 km s^{-1} is marked by a +.

Mass loss from early type stars allows these objects to be radio sources. This emission is from ionized hydrogen close to the star. However in most cases this emission displays spatial structure on arc second scales. Again here one may obtain radio positional accuracies of a few hundredths of an arc second.

The dynamical reference frame of the planets may be related to extragalactic radio sources through radio measurements of solar system objects. The asteriods and satellites of planets have finite sizes of order 0".1 to 1".0 and are also not very intense at radio frequencies. Measurements of the centroid of emission are possible at the 0".01 level.

Direct optical measurements of the radio sources making up the reference frame have also been made. The accuracy of the radio positions presented in Argue et al. (1983) are already adequate. Precise optical positions of 28 extragalactic radio sources north of 0° which are referred to the FK4 system through the AGK 3RN indicate that there are no significant differences larger than up to 0".2 (de Vegt and Gehlick 1982) between the radio and FK4 reference frame. The accuracies of the optical positions are at the 0".05 level. The positions of more optical counterparts are needed.

Therefore at this time measurements are progressing which will relate the optical to radio reference frame for individual sources at the 0".05 level (the accuracies of optical positions). Improvement in the optical reference frame can be made through comparison with the radio reference frame. Future improvements in optical astrometric methods such as HIPPARCOS or optical interferometry may achieve individual optical positional accuracy at the milliarcsecond level. The radio positions relative to background extragalactic radio sources of approximately 100 stellar objects at ∿ the 0".01-0".001 level should be available by 1988.

CONCLUSION

Radio astrometry now appears to have the capability of determining celestial positions over large angles to precisions of a few milliarcseconds. Over small angles (< 1°), relative positions are at the submilliarcsecond level. A large number of radio sources (∿ 100) have now been measured with high precision and thus an almost inertial reference frame based upon extragalactic source positions is close to reality. This reference frame may be related to the optical reference frame at the 0".05 level which is now the accuracy of optical positions. Future observations of sources which display coincident optical/radio emission may improve this relationship as the precision of optical position determination improves.

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