SESSION C

RADIO ASTROMETRY

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RADIO ASTROMETRY USING CONNECTED-ELEMENT INTERFEROMETERS

(Invited Paper)

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Abstract. The basic techniques of conventional radio interferometry are explained and a review given of the achievements and limitations of the methods as applied to radio astrometry.

The application of radio astronomy techniques to establish an astrometric system based on extragalactic radio sources has important consequences both in radio astronomy and in optical astrometry. In radio astronomy it will provide a reference frame of high accuracy for source catalogues and for the calibration of instruments for positional measurements. In optical astrometry, a comparison between the positions of compact, extragalactic objects determined by radio and optical methods may lead to a reduction in the errors in fundamental optical catalogues that arise from effects due to proper motion of individual stars and of galactic rotation, and hence, to the elimination of large scale inhomogeneities (Fricke, 1972).

Unlike the situation in optical astronomy, no radio astronomy instrument has yet been designed primarily for astrometric purposes but two distinct interferometer techniques exist that provide sufficient precision in measuring the positions of radio sources to merit the use of the term 'astrometric'.

One method, that uses interferometers of very large baselines, sometimes as much as a few thousand kilometres, has necessitated the development of a timing and recording technique to enable the signals to be recorded separately at each end of the baseline and compared at a later time. The accuracy of this VLBI system is potentially extremely high, but it has not yet been fully realized in practice; one serious limitation being caused by the difficulty in knowing precisely the delay due to the ionosphere and atmosphere above each of the two widely separated aerials. In addition to astrometric uses, VLBI measurements have important applications in geodesy.

Another interferometric technique, which is my main concern here, uses a baseline of a few kilometres, so that the aerials may be linked by cables to a receiving system that instantly measures and records the difference in phase between the signals arriving at the aerials. From measurements of this difference of phase at two aerials, fixed on the surface of the rotating earth, the positions of radio sources may be derived. This conventional type of interferometer has been widely used in recent years and an estimate of the accuracies that have been achieved may be obtained from an examination of Table I. It should be noticed that none of these measurements has been made in the southern hemisphere.

Gliese, Murray, and Tucker, 'New Problems in Astrometry', 111–117. All Rights Reserved.

As the methods used in radio astronomy are very different from those of classical optical astrometry, an attempt will be made to give a broad outline of the principles involved.

The method of relating the measured phase difference to the position of a source on the sky clearly depends upon the orientation of the interferometer baseline and

TABLE I

Highest accuracies claimed for various instruments

			″(arc)
NRAO Greenbank	Wade	(1970)	0.6
Cambridge One Mile	Smith	(1971)	0.2
RRE Malvern	Adgie *et al.*	(1972)	0.4
NRAO Greenbank	Brosche *et al.*	(1973)	0.1
Cambridge 5 km	Ryle and Elsmore	(1973)	0.02

the geometry involved is perhaps the simplest when the interferometer baseline lies east-west. In the early days of radio interferometry, when the aerials were large fixed arrays, unable to track radio source, observations were made only at transit and the east-west interferometer was then analogous to the meridian circle, being subject to the usual level, azimuth and collimation errors. Now that much shorter radio wavelengths are used, and aerials track the sources as the earth rotates, the R.A. and Decl. may be determined independently.

If a vector represents the baseline spacing between two aerials on the Earth's surface as shown in Figure 1a, it can be seen that the vector, due to the assumed uniform

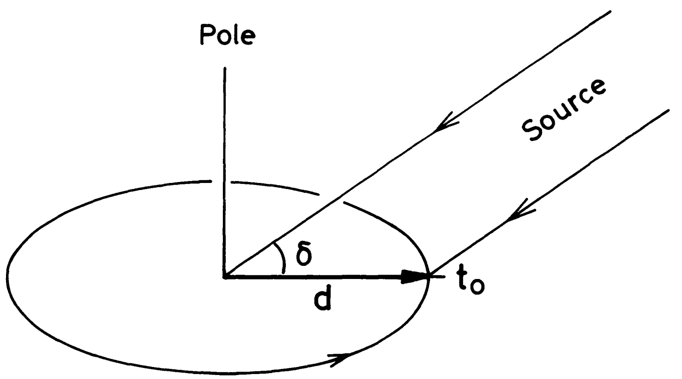

Fig. 1a. A vector representing the baseline spacing of an east-west interferometer is shown to sweep out a circle due to the rotation of the Earth. The measured phase difference at any instant is proportional to the component of this vector in the line of sight from the source.

rotation of the earth, rotates in a plane at right angles to the polar axis; the sideways motion is of no consequence as it only produces an aberration. The path difference at any instant is the component of the vector in the line of sight, and hence, the measured phase difference is

$$\phi(t)=\frac{2\pi}{\lambda}\,d\cos(t-t_0)\cos\delta+C$$

where C is the electrical collimation error; a delay within the receiving system caused, for example, by unequal cables connecting the aerials to the receiver. If we now plot the measured ϕ against time we obtain a curve of the form shown in Figure 1b.

Declination may be derived from the amplitude of the sinusoidally varying component, provided that the spacing d is known. A disadvantage can be seen of the east-west interferometer system in that the accuracy of measuring declination

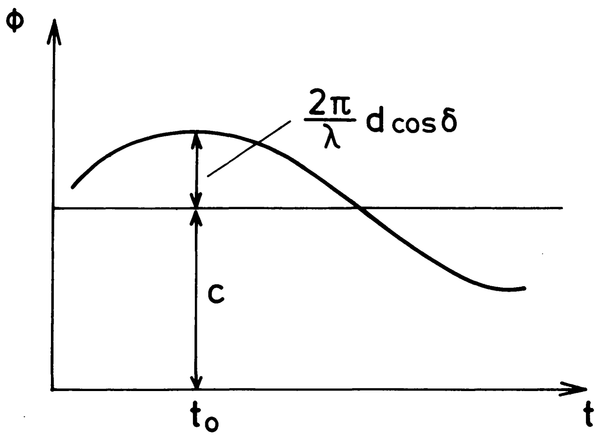

Fig. 1b. The measured phase difference, plotted against time, for an east-west interferometer system.

varies with $\sin\delta$. However, with the 5 km telescope at Cambridge (Ryle, 1972) this fact has been put to an advantage and used to determine the aerial spacing independently of the initial land survey of the instrument, by observing radio sources of only approximately known declinations lying near the equator. Thus the distance, for example, between two of the aerials has been measured to be $3\,430\,828.7 \pm 0.25$ mm (i.e. to 1 in 10^7 which is about 10 times more accurate than that available for the measurement of 3.4 km by conventional means). Using this value for spacing, declinations of other sources may then be determined absolutely.

Hour angle may be derived from the phase of the $\phi(t)$ plot, but the relation between hour angle and right ascension presents more difficulty. The lack of suitable bright and compact radio objects in the solar system makes it difficult to establish the ecliptic and hence the equinox from radio observations, and so for the 5 km telescope the zero point of R.A. has been established from observations of β Persei (Algol) which intermittently radiates sufficiently strongly at cm wavelengths, thereby enabling the RA scale to be related directly to FK4 (Ryle and Elsmore, 1973). A redetermination of the optical position of β Persei at the Royal Greenwich Observatory and at the Institute of Astronomy, Cambridge has shown the FK4 right ascension to be in error by less than 3 ms (Tucker *et al.*, 1973).

With an interferometer not aligned east-west, the baseline vector sweeps out a cone as the Earth rotates as shown in Figure 2a. This fact has been utilised ingeniously by Wade (Wade, 1970; Brosche *et al.*, 1973) of NRAO to determine declinations without prior knowledge of the baseline or of any source declinations. As before, the phase difference is $2\pi/\lambda$ times the component of the vector in the line of sight. As B

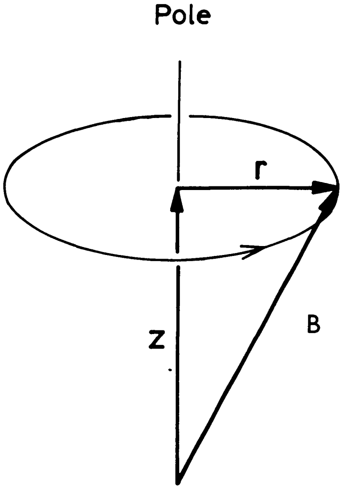

Fig. 2a. The baseline vector for a non east-west system describes a cone as the Earth rotates. The vector may be resolved into a component z, parallel to the polar axis, and a rotating component r.

describes a circle, the phase varies sinusoidally, hence

$$\phi(t)=\frac{2\pi}{\lambda}\left[z \sin\delta+r \cos\delta \cos(t-t_0)\right]+C.$$

Three measured parameters may be derived from a plot of $\phi(t)$, as shown in Figure 2b.

(1) A constant term, $\phi_c=(2\pi/\lambda)\, z \sin\delta+C$.

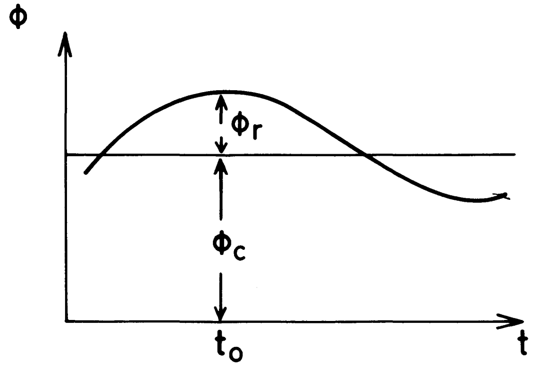

Fig. 2b. The measured phase difference, plotted against time, for a non east-west system.

(2) The amplitude of the oscillatory term, $\phi_r = (2\pi/\lambda)\, r \cos\delta$.
(3) The time t_0, which is related to hour angle.
For several sources, say N, with δ_i, z, r and C unknown. Solving for declination:

$N+3$ unknowns: δ_i, z, r and C
$2N$ equations from (1) and (2) (i.e., from ϕ_c and ϕ_r).

Therefore, a solution may be obtained for declinations using observations of three sources, and furthermore, the method remains accurate at low declinations. Relative right ascensions may be derived from the phase of the $\phi(t)$ plot and at NRAO, the zero of R.A. has been established for their instrument from observations of four extragalactic radio sources for which there are accurate optical positions, (Brosche *et al.*, 1973).

On careful examination of the properties of these two differently orientated interferometers, it can be seen that there is another difference, in that for the east-west system, the measurement of declination and right ascension is independent of the instantaneous position of the pole.

Consider an east-west interferometer situated on the Greenwich meridian. The x component of polar motion changes the latitude, which has no effect on the phase difference between the two ends of the baseline. The y component will rotate the baseline to give a small displacement parallel to the mean polar direction that contributes to C, the electrical collimation term, but will, to first order, make no change in the component parallel to the equatorial plane. Therefore, the measurement of R.A. and Decl. remains unchanged. The polar motion that occurs during the observations is sufficiently small as to not affect the measurements. For an interferometer not at Greenwich a similar argument holds, since the instantaneous polar coordinates can be resolved in, and at right angles to the local meridian.

This is not the case for a non east-west interferometer that has an appreciable component of the baseline vector parallel to the polar direction.

An advantage over all other methods of the technique that utilize moderately spaced interferometers stems from the fact that only *differences* between the paths to the two aerials are involved, hence atmospheric corrections are only of second order and are typically 1″. With a horizontally stratified atmosphere the path differences, and hence the corrections, would be zero, although the individual aerials would have to be steered to allow for refraction. However, in practice, path differences occur due to the curvature of the atmosphere and ionosphere, for which correction is possible. Although the aerials of an interferometer may only be a few kms apart, irregularities in the water vapour content of the troposphere produce phase variations for which no correction is possible. These effects, which are most severe during the daytime in summer, are the dominant factor that limit the accuracy that can be achieved by the 5 km telescope (Ryle and Elsmore, 1973). The magnitude of effects arising from various external causes for different interferometer spacings are shown in Table II (from Hinder and Ryle, 1971).

What of the future? The 5 km telescope at Cambridge has some features that make

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TABLE II

Uncertainties of differential path in mm at 30° elevation for Cambridge

Baseline (km)	Troposphere irregularities		Troposphere curvature	Ionosphere irregularities at 5 GHz
	Summer	Winter		
1	2.6	0.66	0.12	0.03
10	2.8	0.71	1.2	0.35
100	2.8	0.71	12	2.8

Note: 1 mm at 1 km = 0.″2.

it especially suitable for astrometry, (for example, the declination and hour angle axes intersect at a point), but the instrument has been designed primarily as a fully automated instrument for providing high resolution maps of radio sources. For this reason, four of the eight aerials are mobile and are mounted on rails which renders them less stable, and so for astrometric observations, only the fixed aerials are used, giving spacings up to 3.4 km. From preliminary observations of much of the 3*C* catalogue north of Decl. 10°, only 12 sources have so far been found to be sufficiently compact for the highest precision astrometric purposes; all the other sources examined are either extended or complex. The positions of these 12 sources, with an accuracy of about ±0.″03 are about to be published (Ryle and Elsmore, 1973). It is estimated that there are another 100 suitable sources in the N hemisphere brighter than 0.2 f.u. In this connection, it is noted that a working party of Commission 40 has been set up to compile a list of sources suitable for positional calibration purposes.

It is particularly desirable that sources at low declinations should be observed so that the positions of sources in the N hemisphere may be linked to those which it is hoped will be measured in the S hemisphere. This cannot be done with east-west interferometer systems, such as those at Cambridge and Westerbork.

The contribution to astrometry from connected-element radio interferometry is only just beginning, now that large angles on the sky can be measured with great precision and that the positions of radio sources may be determined with comparable, if not greater accuracy than those of optical observations of stars. It is very important, in addition, to appreciate that the factors that limit the accuracies fortunately have different effects in radio and in optical astrometry, thus making the two types of observations complementary.

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DISCUSSION

Tucker: Does the solution for three sources need three distinct δ values? Also there is a diurnal term in latitude variation that amounts to 0.″006.

Elsmore: The method does, in fact, rely upon the use of three different declinations. Concerning the second point, I am grateful to Mr Tucker for making me aware of this effect and one must consider what result it will have on the positional measurements.

Eichhorn: Will it sometimes be possible to use the radio emissions from Jupiter and Saturn to establish the position of the vernal equinox – should this be deemed desirable – or are their diameters too large for this purpose?

Elsmore: The difficulty here is that the sources are extended and furthermore the centre of radio emission may not coincide with that of the figure of these planets.

Fricke: Could our colleagues from Greenwich or Cambridge, England, tell us how they succeeded in checking the right ascension of β Persei?

Murray: Algol was observed photographically at Herstmonceux and Cambridge relative to AGK3 stars, and also on the Herstmonceux Transit Circle relative to about fifteen FK4 stars on 20 different nights between September and December, 1972.

Teleki: We must compare, very carefully, the optical and radio observations. I suppose that there are many problems in this comparison including refractional problems. For this reason Prof. Fricke proposed to me, last year, the inclusion of a radio-astronomer in the Study Group on Astronomical Refraction. Dr W. J. Altenhoff (Max-Planck-Institut für Radioastronomie, Bonn), radioastronomer, has accordingly become a member of this Study Group. In his report prepared for the Study Group, I find this conclusion:

"In my feeling the astronomical refraction is not fully understood in the radio range. For single dish investigations one could think of some differential methods to measure the total refraction (with a dual beam system of fixed separation), the ionospheric refraction (with simultaneous observations at two frequencies) etc. Even though these measurements might help us to understand the refraction, it is not clear if they could help to improve positional (interferometric) work in radio astronomy."

Do you agree with this conclusion?

Elsmore: In interferometric work, the atmosphere does not present such a serious problem as you suggest, as only the difference between the paths to the two aerials is involved, and hence corrections are only of second order.

Murray: Could Mr Elsmore say something about the effect of the orbital motion of Algol? I believe you detected it at Cambridge.

Elsmore: Although the radio observations do not yet cover a complete period of the 1.ʸ9 orbit, it is clear that the emission is almost certainly related to the *AB* system rather than to component *C*, which is separated from *AB* by 0.″1.