# PART IV : RADIO INTERFEROMETRY

# AN INTRODUCTION TO RADIO INTERFEROMETRIC TECHNIQUES

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At this symposium we are to hear a great deal about new techniques for the measurement of earth rotation and polar motion that have come into being in the last decade and I am privileged to give a short introduction to one of these new techniques, that of radio interferometry.

The wavelengths currently used for high precision measurements of positions of sources in radio astronomy are typically 100 000 times longer than those of light. This immediately leads to the fact that in order to obtain the same theoretical resolution, limited only by diffraction, as that achieved by the classical optical instruments for measuring earth rotation, a radio telescope several kilometres in diameter would be required. Because of the impossibility of constructing such a large, single parabolic antenna, other means must be sought to obtain high resolution. This has led to the development of the radio interferometer which, in its most simple form, consists of two antennas spaced apart on the earth's surface. The two antennas are used simultaneously to observe the same source in the sky, the source position being derived from measurements of the difference between the radio frequency phase of the two signals received and from geometrical considerations as the earth rotates. The manner in which the two radio signals are compared has led to two distinct types of system. Details of both types are given elsewhere, see for example, the review of radio astrometry by Counselman (1976), and only some points will be mentioned here.

In the conventional interferometer system, known as the connected interferometer, the signals from the two antennas are brought together through cables or a radio link and are compared instantaneously. As the accuracy of the phase measurements depends upon the stability of the electrical length of the cables or link connecting the antennas to the phase comparison receiver, there is a practical limit to the maximum separation that can be successfully used; this amounts to about 10-20 kms using cables or a few hundred kms for a radio link.

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To overcome this limitation, another interferometer type has been developed, known as VLBI, where the signals are tape recorded separately at the two sites, together with time marks, and at some later time the two recordings are brought together, are replayed and crosscorrelated. At first examination it seems that the use of larger and larger baselines operating at ever shorter wavelengths should provide more and more accuracy of measurements of source positions or earth rotation. An advantage of the VLBI system is that the baseline may be extended to several thousand kilometres, but there are some technical problems and the great potential of the VLBI system has yet to be fully realised in practice.

One difficulty is the very high stability demanded for the frequency standard at each observing station. The atomic hydrogen masers currently used have stabilities of 1 part in $10^{13}$ over a $10^{3}$ or $10^{4}$ second period, giving rise to phase instabilities at the signal frequency equivalent to a path length of 3 to 30 cms.

In the interpretation of all radio interferometric observations the observable quantity is the phase difference between the signals arriving at the two antennas, and hence there exists an ambiguity of $2\pi n$ of phase. Resolving this ambiguity is relatively simple in connected interferometers but is difficult in VLBI. It has been done in some VLBI applications by making, for example, simultaneous observations of an additional source with a pair of antennas at each end of a long baseline and using a common frequency standard to supply signals to both antennas at a given end. When observations cannot be phase connected unambiguously it is simple to measure the time derivative of the interferometer phase, giving rise to "fringe-rate" measurements. These have the disadvantage of being insensitive to declination near the equator and so to overcome this yet another technique has been developed (Rogers 1970) whereby wide radio frequency bandwidth observations are made and analysed to determine the group-delay which is effectively the derivative with respect to the angular frequency, $2\pi f$, of the phase difference.

Radio interferometers are affected by the atmosphere to a degree which depends partly on the baseline spacing. The steady atmosphere produces a delay which, for a source at the zenith, amounts to about 2 metres of extra path. It is sufficient with interferometers of small spacings to assume that the atmosphere above each of the antenna is substantially the same and hence only a small differential correction is needed to take account of the spherical structure of the atmosphere. This is not the case when spacings of thousands of kilometres are used and uncertainties of path length of the order 10-20 cms are then encountered. This uncertainty may be reduced by separate measurements made to determine the atmospheric path length at each site. In addition to the effects caused by the steady atmosphere, irregularities, mainly of water vapour in the troposphere, cause short term fluctuations of path length. One class of non-uniformity has a typical scale of

0.7 km and is associated with solar heating of the ground, whilst a second class has a scale 10-20 km and there is evidence that still larger scales exist (Hinder & Ryle 1971, Hargrave & Shaw 1978). It is these fluctuations that limit the positional accuracy attainable with the Cambridge 5 km connected interferometer. It is interesting to note that excellent conditions occur during widespread winter fog, when distortions to the incident wavefront may be less than 0.2 mm over 5 kilometres leading to a source positional accuracy of 0".02 arc; this illustrates a striking difference between requirements for optical and radio observations.

The effects of the ionosphere are in general less troublesome for two reasons; firstly, at short wavelengths the effects are small for moderate baselines and secondly, the delay introduced, unlike that due to the troposphere, is wavelength dependent and may therefore be eliminated by making observations at two wavelengths.

We are to hear later how determinations of positions of radio sources lead to measurements of earth rotation and polar motion and of the accuracies currently achieved. It should be noted that an interferometer orientated east-west cannot be used to measure polar motion but can provide measurements of UT1 without the knowledge of the instantaneous position of the pole (Elsmore 1973)

The radio sources themselves are fortunately distributed approximately uniformly across the sky, but they appear in all shapes and sizes with many of them having a double or complex structure. Only those sources that are compact, having an angular extent of less than about 0".2 arc, are ideal for astrometry or earth rotation measurements. These objects are nearly all extragalactic and include the very distant radio galaxies and quasars which provide an excellent inertial frame against which measurements of earth rotation may be made. So far radio astrometric measurements have been published for about 75 such sources in the northern hemisphere and whilst these must include the most intense sources, it seems probable that there may be a total of about 150 suitable sources in each hemisphere within reach of modest size antennas, i.e. one source every 140 square degrees. The highest precision claimed in recent surveys for measurements of right ascension are given in Table 1. It should be noted that the VLBI measurements are not significantly better than those of connected interferometers.

Table 1

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| Rogers et al. (1973) | VLBI | ± 4 ms |
| Elsmore & Ryle (1976) | 5 km interferometer | ± 2 ms |
| Clark et al. (1976) | VLBI | ± 2 ms |
| Wade & Johnston (1977) | 35 km interferometer | ± 2 ms |

The radio emission from these objects is broad-band and, over the wavelength range 2-20 cms, currently used for high accuracy measurements, the emission is approximately uniform, apart from a tendency to be less at the shortest wavelengths. By way of a contrast, their optical emission is very feeble. Most of these objects have an optical magnitude in the range 16 to 20, which puts them out of reach of the conventional optical instruments used for the measurement of earth rotation.

In conclusion, it must be pointed out that radio interferometers provide an almost all weather, day and night facility for measuring earth rotation, but they are very expensive compared with, for example, a PZT, especially if we are considering the installation of an interferometer system at a site previously equipped only for optical observations. Of the two systems, the connected interferometer is cheaper and much simpler, but the VLBI system is capable of higher precision. It seems that interferometer measurements of earth rotation will only be made at existing radio observatories and speaking for one such observatory, it is disappointing that owing to the pressure of other commitments, it is not possible for us at present to make measurements on a regular basis. In addition to improved measurements with VLBI systems, I would also like to see a connected interferometer devoted entirely to astrometry and measurements of earth rotation.

## References

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DISCUSSION

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| A.R. Robbins: | How do you establish the zero point of RA and connect it with that of the FK4? |
| B. Elsmore: | Three of the surveys have used 3C273B to establish the zero point, adopting the position derived by Hazard et al. from lunar occultations. The Cambridge survey is based on the FK4 position of Algol; this incidentally gives a 6 ms difference when compared with the other surveys. The precision with which the zero point is established relative to an adopted source is better than 2 ms. |