Notes for Summer Student Lecture on Precise Radio Astrometry

22 July 1977, by C. M. Wade

I. What is astrometry?

Astrometry is the precise measurement of the positions of astronomical objects on the celestial sphere. "Precise" in this context can be taken to mean an accuracy of 2" ($\sim 10^{-5}$ radian) or better. The best radio and optical astrometry achieve results accurate to a few hundredths of an arc second (say $\sim 10^{-7}$ radian).

The positions are expressed as coordinates in a spherical reference frame. Normally this is the equatorial system (right ascension and declination). All reference frames used in astrometry are defined kinematically, through the earth's rotation about its axis and its orbital motion about the barycenter of the solar system. Since the earth's rotational axis is not fixed in space, and since the parameters of the earth's orbit vary because of gravitational perturbations by the moon and the other planets, the reference frames change continually with time. Hence astrometry must determine the instantaneous orientation of the coordinate axes in space as well as the directions of celestial objects with respect to these axes. Moreover, the objects have intrinsic motions of their own, and their positions change with time regardless of how the coordinate systems are established.

For most purposes, astrometry treats celestial objects as if they were infinitely distant. It is concerned primarily with directions in space. In the case of relatively nearby objects, however, one must sometimes make allowance for parallax (the difference in direction as seen from opposite sides of the earth's orbit).

II. Why is astrometry important?

Astrometry today is something of an orphan. Few graduate schools treat it seriously. It is not "exciting", in that it does little to one's adrenalin flow. With a little care, even a mediocre lecturer can turn it into a marvelously soporific subject. Nevertheless, astrometry is "basic" to an extent matched by few other branches of astronomy. Astrometry underlies celestial mechanics, and hence our quantitative knowledge of the structure and dynamics of the solar system. Without astrometry, we would know virtually nothing about the distances, masses and luminosities of the stars, or about the motion of the sun relative to its neighbors, or about the dynamics and mass of the Galaxy. We would lack the calibrations which are used to estimate the distances to other galaxies. Most contemporary astrophysics depends on the quantitative foundation which astrometry provides.

III. Where does radio astronomy come in?

Optical astrometry goes back some 2000 years, to the work of Hipparchus in Greece and Claudius Ptolemy in Egypt. The measurements of Tycho Brahe in the late 16th century led to the discovery of the laws of planetary motion by Johannes Kepler, and this in turn led to Sir Isaac Newton's Principia and the systematic development of celestial mechanics. By the early 18th century, James Bradley at the Royal Greenwich Observatory was doing work of accuracy respectable by modern standards. Since Bradley's time, the subject has developed steadily to the point of diminishing returns; significant further improvements in accuracy are unlikely without some fundamentally new principles of measurement. In other words, optical astrometry has "matured", and unless something new is added, senility may be next.

Radio astrometry is providing this rejuvenation. It hasn't had much effect yet, since it is so new. But it will be very important, for the following reasons:

(i) Radio measurements will probably reach an accuracy in the near future which exceeds that of the best optical work by a factor of 10 or more. This is because the radio measurements depend on the relative times of arrival of a signal at widely separated points (the essence of interferometry) rather than on the apparent direction of arrival. Thus the sources of systematic error are different for radio and optical astrometry, and these errors happen to be smaller in the radio case.

(ii) The accuracy with which an angle can be measured by radio methods is independent of the size of the angle. In optical work, the uncertainty is proportional to the size of the angle. For this reason optical astrometry has always had trouble in tying widely separated parts of the sky together--there have always been zonal errors which have been difficult to detect and eliminate.

(iii) At any given level of accuracy, the radio measurements are much easier to make and reduce. The radio work is easy to automate, the optical is not.

By determining very precise positions for a large number of sources with optical counterparts, well distributed over the sky, radio astrometry will provide a greatly improved net of standards for optical astrometry. It will not replace optical astrometry, of course, since most of the stars which the optical astrometrist measures are not radio sources. But I expect that in a few years most optical astrometry will depend on differential measurements referred to radio standards.

IV. What accuracy is now attainable?

There are at present three lists of radio position measurements which claim accuracies of the order of $0''.03$ or better. They depend on different measurement techniques, so a detailed comparison of them should be instructive. First, Elsmore and Ryle (Monthly Notices 174, 111, 1976) used the Cambridge 5-km telescope as a set of simultaneous interferometers for astrometric measurements. Second, there are the very careful VLBI measurements by Clark et al. (AJ 81, 599, 1976). Finally, there is the work by Wade and Johnston (to be published in the October 1977 issue of AJ; there is a copy on the preprint shelf in the library) with the 35-km radio link interferometer at Green Bank.

In each case, the source declinations were determined absolutely, i.e., without any reference to previously established calibration sources. Similarly, the right ascension differences between sources were found absolutely. With each method, the right ascension zero-point has to be fixed by reference to some optically established standards. The use of different standards by various observers causes their right ascension results to differ systematically by a small amount.

There are 17 sources common to the Green Bank and VLBI lists. The weighted mean difference of the right ascensions is $-0^{s}.0001 \pm 0^{s}.0006$. The small value of the mean is forced, since the Green Bank zero-point was chosen to match that of the VLBI work. The very small standard error of the mean, on the other hand, attests to the very small scatter in the results for the individual sources. The weighted mean declination difference is $+0''.002 \pm 0''.009$. Thus the Green Bank and VLBI results are consistent in both coordinates at the $0''.01$ level, even though the methods of measurement are very different.

There are 17 sources common to the Green Bank and Cambridge lists. The weighted mean right ascension difference is $-0^{s}.0060 \pm 0^{s}.0015$. The apparent disagreement is an artifact of the differing methods used to fix the right ascension zero-point. The weighted mean declination difference ($+0''.049 \pm 0''.016$) appears to be significantly larger than its standard error. So far, we have no good explanation for the discrepancy, which is small in magnitude anyway.

Thus it appears that the various radio astrometric techniques give results whose agreement ranges from good to excellent. For perspective, one should remember that the best optical position measurements are good to no better than $\pm 0''.04$. Indeed, in most optical work an error of $\pm 0''.2$ is regarded as quite good.

V. What does the future hold?

We expect that systematic astrometry accurate to $0\rlap{.}''01$ will be possible with the VLA. The high sensitivity of the VLA will also permit observations of the minor planets, which will let us fix the right ascension zero-point kinematically, thus avoiding the need for an optically fixed reference.

It is likely that accuracies near $0\rlap{.}''001$ eventually will be achieved by VLBI methods. Differential (not absolute) measurements of this accuracy already have been made.

References

1. An excellent review of contemporary astrometry, particularly optical: W. Fricke, Annual Review of Astronomy and Astrophysics, vol. 10, pp. 101-128, 1972.

2. Overview of radio astrometry:
C. C. Counselman, Annual Review of Astronomy and Astrophysics, vol. 14, pp. 197-214, 1976.

3. The following two papers, both from "New Problems in Astrometry" (Proc. IAU Symposium No. 61, Reidel, 1974), provide a general review of the methods and results of radio astrometry:

B. Elsmore, "Radio Astrometry Using Connected-Element Interferometers", pp. 111-117.

C. M. Wade, "Radio and Optical Astrometry", pp. 133-139.

4. The methods of radio astrometry are developed in detail in the following papers:

M. Ryle and B. Elsmore, Monthly Notices Royal Astron. Soc., 164, 223, 1973.
C. M. Wade, Astrophys. J., 162, 381, 1970.

P. Brosche, C. M. Wade and R. M. Hjellming, Astrophys. J., 183, 805, 1973.

5. Basic information on time, coordinate systems, and the general background underlying practical astrometry can be found in the following books. The first two are the "holy scriptures"--very complete, very accurate and definitely not light reading. The third is meant as an undergraduate text, but is meaty enough to be profitable reading for the Ph.D.

"Explanatory Supplement to the Ephemeris", Her Majesty's Stationery Office, London, 1961.

E. W. Woolard and G. M. Clemence, "Spherical Astronomy", Academic Press, New York and London, 1966.

D. McNally, "Positional Astronomy", John Wiley & Sons, New York, 1974.

A Further Reference

6. An excellent discussion of time and astronomical coordinate systems can be found in Chapters 3-5 of:

   I. I. Mueller, Spherical and Practical Astronomy as Applied to Geodesy, Frederick Ungar Publishing Co., New York, 1969.

   Since this book was written by a non-astronomer for the enlightenment of other non-astronomers, it has the rare merit of being comprehensible – even to astronomers.