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Determination of optical positions for 23 extragalactic radio sources

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ABSTRACT

The optical counterparts of 23 extragalactic radio sources, of which 13 are in the southern hemisphere, have been observed by three telescopes equipped with CCDs. By reference to the Astrographic/Tycho (ACT) Reference, Carlsberg Meridian (CMC), Positions and Proper Motions (PPM), *Hipparcos* (HIP) and Lick Northern Proper Motion (NPM) catalogues, the positions of the 23 objects have been obtained. The mean standard errors in right ascension and declination are better than 0.2 arcsec. The differences from the radio positions are given, and a comparison between our results and those of other studies is also made.

Key words: catalogues – astrometry – reference systems.

1 INTRODUCTION

With compact extragalactic radio sources as fiducial points, the radio reference frame may be said to be a quasi-inertial reference frame (Ma et al. 1998). Because the sources are very remote, their proper motions (approximately a few μas yr$^{□1}$) are negligible compared with the observational accuracy. Adopted by the 23rd General Assembly of the International Astronomical Union (IAU) (held in 1997 in Koyto, Japan), the International Celestial Reference System (ICRS) has been the fundamental celestial reference system since 1998 January 1, replacing the FK5 optical system. The ICRS is realized by the International Celestial Reference Frame (ICRF), which is combined from various radio catalogues by the International Earth Rotation Service (IERS). The *Hipparcos* stellar reference frame provides the primary realization of the ICRS at optical wavelengths. The Working Group (WG) on the ICRS, set up at the 23rd General Assembly of the IAU, is concerned with all aspects of the approved ICRS, including its use, its extension and its promotion to the astronomical community (Mignard 1998). The WG has the following tasks: maintenance and extension of the ICRS; densification in optics; linkage to dynamical systems, and so on. The construction of an extragalactic radio reference frame and the establishment of the link between radio and optical reference frames have moved to the forefront of astrometry.

The most direct method to realize the linkage between the conventional ground-based optical reference frame or *Hipparcos* reference frame and the radio reference frame is a precise determination of the optical positions for radio sources referred to the optical catalogue. As compared with photographs, CCDs have three advantages: higher quantum efficiency, higher linearity and greater convenience. The optical counterparts of radio sources, generally fainter than 18 mag which is too faint to be photographed by small-aperture telescopes, can be observed by CCDs, and the optical positions of radio sources with respect to reference stars can be determined more accurately.

In the work of Wang & Tang (1997) and Tang, Wang & Jin (1998a,b), the optical positions of six sources have been obtained. Besides these six sources, we present here the optical positions of another 17 radio sources (13 of them in the southern hemisphere), obtained with reference to the Astrographic/Tycho (ACT) Reference Catalogue (Urban, Corbin & Wycoff 1997), the Carlsberg Meridian Catalogue (CMC) (1997) and the Lick Northern Proper Motion (NPM) catalogue (Arnold, Robert & Burton 1993). The observations were completed with the 1-m telescope equipped with a CCD at the Yunnan Astronomical Observatory.

The results for the six sources published previously are given in Section 2 of this paper. The observations and data reduction for the 17 additional sources are presented in Section 3. Differences from the radio positions are given in Section 4. The comparison between our results and those of other studies is made in Section 5, and a discussion is also presented in that section.

The 17 sources are 0405□123, 0528□250, 0607□157, 0723□008, 0735□178, 0736□017, 0818□128, 0859□140, 1034□293, 1040□123, 1045□188, 1127□145, 1145□071, 1219□285, 1237□101, 1302□102 and 1510□089. Only the text of this paper is included in the printed version; the full paper, complete with tables and figures, is available in the electronic version of the article on *Synergy* (http://www.blackwell-synergy.com/issuelist.asp?journal=mnr).

2 RESULTS FOR THE SIX PREVIOUSLY OBSERVED SOURCES

Among the six previously observed sources, the observations of four sources (0851□202, 1228□126, 1442□101 and 1749□701)

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were carried out with the 60/90-cm Schmidt telescope at the Xinglong station of Beijing Observatory, equipped with a 2048 × 2048 CCD (15 μm pixel$^{\square 1}$), while the other two sources (0716□714 and 0839□187) were observed with the 60-cm telescope at the Xinglong station of Beijing Observatory, equipped with a 1024 × 1024 CCD. The focal length of the first telescope was 1800 mm and the field of view was about 1 deg^2; for the latter telescope, the focal length was 2400 mm and the field of view was 16.6 × 16.6 $arcmin^2$.

The data reduction for the six sources is similar to that introduced in the next section. The final results for the four sources, obtained from five reference catalogues, are listed in Table 1 (in the electronic version of the article on *Synergy*). In the table, the first column gives the object name, the second column the mean epoch of the observations, the third column the name of the reference catalogue, the fourth column the number of reference stars, the fifth and sixth columns the right ascension (J2000.0) and its standard error (i.e. rms), and the seventh and eighth columns the declination (J2000.0) and its the standard error (i.e. rms). The differences between the results obtained with the CMC, the Positions and Proper Motions (PPM) Catalogue (Röser & Bastian 1991), the NPM catalogue and the *Hipparcos* (HIP) catalogue (ESA 1997), and those obtained with the ACT Reference Catalogue are summarized in Table 2 (on *Synergy*).

For a comparison between our results and those of other studies, we took the catalogues of de Vegt & Gehlich (1978), Geffert et al. (1989), Li & Jin (1996), Ma et al. (1990) and Russell et al. (1991) and the IERS Annual Report (1996) into account. The catalogue published in the 1996 IERS Annual Report gives the radio positions of sources, which were obtained from highly accurate very long baseline interferometry (VLBI) observations. The results of the comparison are given in Table 3 (on *Synergy*); here we choose the positions obtained from the ACT Reference Catalogue as representative of our results.

Tables 4 and 5 (on *Synergy*) list the results of positions and comparisons for the two sources 0716□714 and 0839□187; the contents are the same as those of Tables 1 and 2. Here the data from the CMC are kindly provided by Drs Argyle and Morrison.

3 OBSERVATIONS AND REDUCTION

The observations for the 17 sources were carried out with the 1-m reflector ($F = 13$ m) at Yunnan Astronomical out(at)-896.932(Y)97.999(19968925(unJ1d(F434(6Tf941499.9d)--162.9434(outon)]TJsob8.715-C(9 sources were obtained and are listed in Table 7 (on *Synergy*) where the first column is the object name (IERS designation); the second and the third columns are right ascension and its standard error; the fourth and fifth columns are declination and its standard error; the sixth column is the name of the reference catalogue; and the seventh and eighth columns are the differences between our results and the radio positions of Table 6 (our results – radio positions). The observation epoch of all positions is J1999.11. For the three sources referred to the ACT Reference Catalogue, the mean standard errors of right ascension and declination are 0.049 and 0.056 arcsec respectively; for the eight sources referred to the CMC, the corresponding values are 0.039 and 0.043 arcsec; for the six sources referred to the NPM catalogue, the corresponding values are 0.027 and 0.028 arcsec.

The method of computing the standard error of the position is based on the following equation:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n - 1}}. \tag{2}$$

Here x_i is the position reduced from the ith CCD, $\bar{x}$ is the mean value of the positions, and n is the number of observations.

The formal error of the stellar image centre is typically better than 0.1 pixel, about 0.04 arcsec, so the results obtained with different reference catalogues are mainly influenced by the systematic features of the reference catalogues. With source 0405−123 as an example, Figs 1–3 (on *Synergy*) show the differences of positions and proper motions for stars common to the three catalogues in an area around the source of $2^\circ\!.5 \times 2^\circ\!.5$. Fig. 1 shows the differences between the ACT Reference Catalogue and the CMC; Fig. 2 shows the differences between the ACT Reference Catalogue and the NPM catalogue; Fig. 3 shows the differences between the CMC and the NPM catalogue. In each figure, panel (a) shows the differences of positions ($\Delta\alpha \cos\delta$, $\Delta\delta$) as functions of the positions; (b) shows the differences of proper motions ($\Delta\mu_\alpha \cos\delta$, $\Delta\mu_\delta$) as functions of the positions; (c) shows $\Delta\alpha \cos\delta$ versus magnitude; (d) shows $\Delta\delta$ versus magnitude; (e) shows $\Delta\mu_\alpha \cos\delta$ versus magnitude; and (f) shows $\Delta\mu_\delta$ versus magnitude. Here the magnitude is referred to B magnitude, and the results of a straight line fitted by the least-squares method are also drawn in panels (c)–(f). Table 8 (on *Synergy*) gives the mean values of the differences in positions and proper motions and their standard errors for common stars around the source; here the NPM catalogue has also been converted from the FK4 to the FK5 system. Many stars in the NPM catalogue are fainter than 14 mag; it seems from Fig. 2 that there exist obvious systematic differences in positions and proper motions as functions of magnitude between the NPM catalogue and the ACT Reference Catalogue.

The mean observational epochs of positions of the three reference catalogues (ACT, CMC and NPM) are 1991, 1990 and 1967 respectively. In comparison with the ACT Reference Catalogue, the CMC not only has the same positional epoch and stellar density, but also has the same magnitude range, so the results obtained from the two catalogues do not have large differences, as shown in Table 8 and Fig. 1. The observational epoch of the NPM catalogue is more than 30 years ago, and the accumulated errors caused by the uncertainty in the proper motions are fairly large; this can explain the larger differences between it and the ACT Reference Catalogue and CMC in Table 8 and Figs 2 and 3.

5 COMPARISON AND DISCUSSION

For a comparison between our results and those of other authors, we took the catalogues of Assafin et al. (1997), Costa & Loyola (1992), Li & Jin (1996), Ma et al. (1990), Véron-Cetty & Veron (1996) and Walter & West (1986) into account. The results of the comparison ($\Delta\alpha \cos\delta$, $\Delta\delta$) are given in Table 9 (on *Synergy*).

The field of view of the CCD that we used is only $6.5 \times 6.5\,\mathrm{arcmin}^2$. There are few reference stars in such a small field of view, so accidental errors in the positions and proper motions of individual reference stars will have a large effect on the final results. To have more reference stars and obtain more reliable position results, a larger CCD and reference catalogues with more stars are needed. In addition, images of faint sources on CCDs cover few pixels, and it is difficult to determine the centre precisely, so longer exposures and a larger telescope will be beneficial to improving the results. Linking the optical and radio reference frames generally requires a combination of transit circle, astrographic and large-aperture telescope observations in order to cover the large range of magnitude between bright stars and extragalactic objects (Stone 1994).

To link the optical and radio reference frames more precisely, long-term and regular observations of optical counterparts of radio sources with respect to optical reference catalogues are especially important. We are carrying out a programme with the purpose of obtaining the optical positions of about 100 compact extragalactic radio sources in the optical reference frame, using telescopes equipped with CCDs.

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