Residual HCRF Rotation relative to the Inertial Coordinate System

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Abstract—VLBI measurements of the absolute proper motions of 23 radio stars have been collected from published data. These are stars with maser emission, or very young stars, or asymptotic-giant-branch stars. By comparing these measurements with the stellar proper motions from the optical catalogs of the Hipparcos Celestial Reference Frame (HCRF), we have found the components of the residual rotation vector of this frame relative to the inertial coordinate system: \((\omega_x, \omega_y, \omega_z) = (-0.39, -0.51, -1.25) \pm (0.58, 0.57, 0.56)\) mas yr\(^{-1}\). Based on all the available data, we have determined new values of the components of the residual rotation vector for the optical realization of the HCRF relative to the inertial coordinate system: \((\omega_x, \omega_y, \omega_z) = (-0.15, +0.24, -0.53) \pm (0.11, 0.10, 0.13)\) mas yr\(^{-1}\).

INTRODUCTION

The present-day standard astronomical coordinate system, the International Celestial Reference System (ICRS), has been an official one since January 1, 1998, by the IAU decision. The directions of the principal plane and the coordinate origin at the epoch J2000.0 were fixed in the IAU decision.

This system is realized as a catalog of the positions of 212 compact extragalactic radio sources uniformly distributed over the entire sky. The catalog was compiled from very long baseline interferometry (VLBI) observations, which is reflected in Ma et al. (1998). This specific realization of the International Celestial Reference System is designated as ICRF (International Celestial Reference Frame).

The current version of the catalog, ICRF2, already uses 295 most reliable radio sources, and the total number of objects in it is 3414 (Ma et al. 2009). The parameters of the third version, ICRF3, are now being discussed (Jacobs et al. 2014). The selection of candidates for ICRF3 is planned to be finished by 2018 in order that the catalog be ready before the completion (by about 2021) of the GAIA optical space experiment.

The first realization of the ICRS in the optical range was the Hipparcos (1997) Catalogue, which is usually designated as HCRF (Hipparcos Celestial Reference Frame). As was shown by Kovalevsky et al. (1997), the Hipparcos system was tied to the extragalactic reference frame with an accuracy of \(\pm 0.6\) mas for the coordinates at the epoch 1991.25 and with an error of \(\pm 0.25\) mas yr\(^{-1}\) for the rotation around three axes. The difficulty of tying Hipparcos to the ICRF lies in the fact that there are virtually no
common objects, because in the optical range the quasars turned out to be too faint to be directly observed in the Hipparcos experiment. Therefore, the main observing program for tying Hipparcos to the ICRF was the program of VLBI observations of 12 radio stars located near quasars (Lestrade 1999). The programs to determine the absolute proper motions of stars relative to galaxies and quasars (Kovalevsky et al. 1997) also served to check the tying.

The application of various analysis techniques shows that there is a slight residual rotation of the HCRF relative to the inertial coordinate system with $\omega_z \approx -0.4$ mas yr$^{-1}$ (Bobylev 2004a, 2004b). To check whether the HCRF is inertial, VLBI observations of 46 radio stars are being performed (Boboltz et al. 2003, 2007) in the USA using the “Very Large Array” (VLA) in combination with the Pie Town antenna (New Mexico) at 8.4 GHz.

In this paper, we want to focus our attention on the VLBI observations of masers and Mira variables that are performed to study the Galaxy (Reid et al. 2014; Nakagawa et al. 2014). The VLBI observations of such sources carried out in the last 5–6 years show that the absolute proper motions of radio stars have a very high accuracy, 0.5–0.05 mas yr$^{-1}$. This accuracy has been achieved, first, owing to the long interferometer baselines and, second, owing to the observations at high frequencies, 22.2 GHz and even 43.2 GHz (SiO masers). The goal of this work is to study the possibility of using such observations to determine the residual rotation of the HCRF relative to the present-day realization of the inertial coordinate system.

**VLBI DATA**

One of the projects to measure the trigonometric parallaxes and proper motions is the Japanese VERA (VLBI Exploration of Radio Astrometry) project devoted to the observations of H$_2$O masers at 22.2 GHz (Hirota et al. 2007) and SiO masers at 43.2 GHz (Kim et al. 2008).

Methanol (CH$_3$OH, 6.7 and 12.2 GHz) and H$_2$O masers are being observed in the USA on the VLBA (Reid et al. 2014). Similar observations are also being carried out within the framework of the European VLBI network (Rygl et al. 2010). These two programs enter into the general BeSSeL$^1$ (Bar and Spiral Structure Legacy Survey) project (Brunthaler et al. 2011).

For the same purpose, the VLBI observations of radio stars are being carried out in continuum at 8.4 GHz (Torres et al. 2007; Dzib et al. 2012). The radio sources located in the local arm (Orion arm) that are associated with young low-mass protostars are being observed within the framework of this program.

Mira variables at the asymptotic-giant-branch (AGB) stage are being observed in the VERA program. Such stars manifest themselves in the radio band as masers (Nakagawa et al. 2014). Thus, our sample includes young massive supergiants, intermediate-mass giants, and low-mass T Tauri stars.

An important peculiarity of all the listed observations is that the stellar positions have always been determined using two or three extragalactic sources, i.e., the parallaxes and

\[ 1 \text{http://www3.mpifr-bonn.mpg.de/staff/brunthaler/BeSSeL/index.shtml} \]
| Star       | HIP/UCAC | Type       | Frequency, GHz | Program | Emission       | Ref   |
|------------|----------|------------|----------------|---------|----------------|-------|
| T Lep      | HIP 23636| Mira       | 22.2           | VERA    | H$_2$O masers  | (1)   |
| S Crt      | HIP 57917| SRb        | 22.2           | VERA    | H$_2$O masers  | (2)   |
| W Hya      | HIP 67419| SRa        | 1.6            | NRAO    | OH masers      | (3)   |
| RX Boo     | HIP 70401| SRa        | 22.2           | VERA    | H$_2$O masers  | (4)   |
| S CrB      | HIP 75143| Mira       | 1.6            | NRAO    | OH masers      | (5)   |
| U Her      | HIP 80488| Mira       | 1.6            | NRAO    | OH masers      | (5)   |
| RR Aql     | HIP 98220| Mira       | 1.6            | NRAO    | OH masers      | (5)   |
| R Aqr      | HIP117054| Mira       | 43.2           | VERA    | SiO masers     | (6)   |
| R Cas      | HIP118188| Mira       | 1.6            | NRAO    | OH masers      | (3)   |
| SY Scl     | UCAC4    | Mira       | 22.2           | VERA    | H$_2$O masers  | (7)   |
| UX Cyg     | UCAC4    | Mira       | 22.2           | NRAO    | H$_2$O masers  | (8)   |
| SS Cyg     | UCAC4    | D. Nova    | 8.4            | NRAO    | continuum      | (9)   |
| IM Peg     | HIP112997| RS CVn     | 8.4            | VLBI    | continuum      | (10)  |
| S Per      | HIP 11093| SRc        | 22.2           | NRAO    | H$_2$O masers  | (11)  |
| V773 Tau   | HIP 19762| T Tau      | 8.4            | NRAO    | continuum      | (12)  |
| HDE 283572 | HIP 20388| T Tau      | 8.4            | NRAO    | continuum      | (13)  |
| T Tau N    | HIP 20390| T Tau      | 8.4            | NRAO    | continuum      | (14)  |
| LSI +61 303| HIP 12469| XMXRB      | 8.4            | VLBI    | continuum      | (15)  |
| Cyg X-1    | HIP 98298| XMXRB      | 8.4            | NRAO    | continuum      | (16)  |
| Cyg OB2#5  | HIP101341| EB         | 8.4            | NRAO    | continuum      | (17)  |
| IRAS 22480+6002 | UCAC4 | —          | 22.2           | VERA    | H$_2$O masers  | (18)  |
| PZ Cas     | HIP117078| SRa        | 22.2           | VERA    | H$_2$O masers  | (19)  |
| $\theta^1$ Ori A | UCAC4 | —          | 8.4            | NRAO    | continuum      | (20)  |

SR—semiregular pulsating stars; RS—eruptive variables of the RS Canum Venaticorum type; EB—eclipsing binaries; XMXRB—high-mass X-ray binaries; D. Nova—dwarf novae.

(1): Nakagawa et al. (2014), (2): Nakagawa et al. (2008), (3): Vlemmings et al. (2003), (4): Kamezaki et al. (2012), (5): Vlemmings and van Langevelde (2007), (6): Min et al. (2014), (7): Nyu et al. (2011), (8): Kurayama et al. (2005), (9): Miller-Jones et al. (2013), (10): Ratner et al. (2012), (11): Asaki et al. (2010), (12): Torres et al. (2012), (13): Torres et al. (2007), (14): Loinard et al. (2007), (15): Dhawan et al. (2006), (16): Reid et al. (2011), (17): Dzib et al. (2013), (18): Imai et al. (2012), (19): Kusuno et al. (2013), (20): Menten et al. (2007).
proper motions of these radio stars are absolute.

Table 1 presents some characteristics of the radio stars. Columns 1, 2, 3, 4, 5, 6, and 7 give, respectively, the star name, the number in the Hipparcos Catalogue, the type of variability, the observation frequency, the name of the observing program or observatory, the type of emission characterizing the VLBI observations (for example, they were performed in maser lines or in continuum), and references. Note that the Hipparcos proper motions are very unreliable for the massive O star $\theta^1$ Ori A (HIP 26220), a member of the famous Orion Trapezium; therefore, we used the data from the UCAC4 (2012) catalog. It can be seen from the second column of Table 1 that there are four more stars (absent in the Hipparcos Catalogue) with the UCAC4 proper motions.

We did not include the red supergiant VY CMa (HIP 35793) in our list, for which high-accuracy VLBI observations are available (Zhang et al. 2012). For this star, the absolute values of the “Hipparcos minus VLBI” proper motion differences are about 8 mas yr$^{-1}$ in each of the coordinates. Such a large difference stems from the fact that slightly different parts of the extended asymmetric envelope of this star are observed in the optical and radio bands.
Note that long-term observations in maser lines are difficult to carry out, because the maser spots are highly unstable; therefore, the periods of observations for such stars are 1.5–2 years (the minimum period required to determine the annual parallax). The situation is different for continuum observations. For example, the period of observations for IM Peg was about 8 years (Ratner et al. 2012).

Table 2 presents the proper motions of the radio stars measured by the VLBI technique (according to the references in Table 1) and the proper motions of these stars from the version of the Hipparcos Catalogue revised by van Leeuwen (2007). Van Leeuwen (2007) showed that the new version of the Catalogue completely reproduces the previous system, i.e., it has no residual rotation relative to the Hipparcos-1997 version, while it excels considerably the Hipparcos-1997 version in terms of random errors (especially in the region of bright stars). It is of interest to check this using the available material.

Figure 1 presents the “HIP-1997 minus VLBI” and “HIP-2007 minus VLBI” stellar proper motion differences. It can be clearly seen from our comparison of the graphs that the dispersion of the “HIP-1997 minus VLBI” differences exceeds considerably that of the “HIP-2007 minus VLBI” differences. For some of the stars, the absolute values of the “HIP-1997 minus VLBI” differences in right ascension exceed 6 mas yr\(^{-1}\).

In Fig. 2, the “HIP-2007 minus VLBI” stellar proper motions are plotted against the equatorial coordinates \(\alpha\) and \(\delta\). It can be seen from the figure that a wave in \(\alpha\) and a slight trend in \(\delta\) are noticeable in the differences \(\Delta \mu_{\alpha} \cos \delta\), while the differences \(\Delta \mu_{\delta}\) are distributed quite symmetrically relative to the horizontal axis.

The following coupling equations can be used to determine the three angular velocities of mutual rotation of the two systems \(\omega_x, \omega_y, \omega_z\):

\[
\begin{align*}
\Delta \mu_{\alpha} \cos \delta &= -\omega_x \cos \alpha \sin \delta - \omega_y \sin \alpha \sin \delta + \omega_z \cos \delta, \\
\Delta \mu_{\delta} &= \omega_x \sin \alpha - \omega_y \cos \alpha,
\end{align*}
\]

where the “Hipparcos minus VLBI” differences are on the left-hand sides of the equations.

Having solved the system of conditional equations (1) by the least squares method for the “HIP-1997 minus VLBI” difference, we obtained the following rotation components (in mas yr\(^{-1}\)):

\[
\begin{align*}
\omega_x &= -0.85 \pm 0.63, \\
\omega_y &= +0.05 \pm 0.61, \\
\omega_z &= -1.33 \pm 0.61,
\end{align*}
\]

where the error per unit weight, which characterizes the dispersion of the residuals, is \(\sigma_0 = 2.37\) mas yr\(^{-1}\). For the “HIP-2007 minus VLBI” difference, we obtained the following rotation components (in mas yr\(^{-1}\)):

\[
\begin{align*}
\omega_x &= -0.39 \pm 0.58, \\
\omega_y &= -0.51 \pm 0.57, \\
\omega_z &= -1.25 \pm 0.56,
\end{align*}
\]

where the error per unit weight is \(\sigma_0 = 2.19\) mas yr\(^{-1}\). We see that it is more advantageous to use the HIP-2007 version.
Table 3 presents almost all of the results of comparing the individual programs with the HCRF catalogs known to date. The first seven rows of Table 3 give the results used by Kovalevsky et al. (1997) to calibrate Hipparcos and to estimate its residual rotation relative to the system of extragalactic sources.

1. The “VLBI-1999” solution was obtained by comparing the absolute proper motions of twelve radio stars with the Hipparcos Catalogue. A detailed description of the observations can be found in Lestrade et al. (1999). In total, 21 antennas of various diameters in the USA and Europe were involved in the observations. The period of observations for each star was from 2 to 11 years. The observations were performed at 5.0 and 8.4 GHz. The coordinates, parallaxes, proper motions, and even accelerations in the proper motions of stars were determined. According to the estimates by Lestrade et al. (1999), the error in the stellar proper motion for some of the stars was about 0.05 mas yr\(^{-1}\).

2. As the “NPM1” solution, we used the results of comparing the stellar proper motions from the NPM1 (Klemola et al. 1994) and Hipparcos Catalogues by the Heidelberg team. We took the parameters of this solution from Table 2 in Kovalevsky et al. (1997). This solution was obtained in the range of magnitudes 10\(^\text{m}.5–11\(^\text{m}.5, where (Fig. 1 in Platais et al. (1998a)) the “HIP minus NPM1” stellar proper motion differences have a “horizontal” character, near zero. In our opinion, the proper motions from the NPM1 Catalogue in this magnitude range are free to the greatest extent from the magnitude equation, which is considerable in this Catalogue.

3. The “KIEV” solution. The stellar proper motions from the GPM1 (Rybka and Yatsenko 1997) and Hipparcos Catalogues were compared by Kislyuk et al. (1997).
\( \Delta \mu'_{\alpha} = \Delta \mu_{\alpha} \cos \delta \).

(4) The “POTSDAM” solution was taken from Hirte et al. (1996).

(5) The “BONN” solution was obtained by performing the Bonn program, which is reflected in Geffert et al. (1997) and Tucholke et al. (1997).

(6) The “EOP” solution was obtained as a result of the analysis of the Earth Orientation Parameters (EOPs) by Vondrák et al. (1997). Only two orientation parameters, \( \omega_x \) and \( \omega_y \), are determined in this method.

(7) The “HST” solution was obtained by Hemenway et al. (1997) using the Hubble Space Telescope (HST). Note that this solution has virtually no influence on the calculation of the weighted average because of the large random errors in the comparison parameters.

(8) The “SPM2” solution was obtained by Zhu (2001) by comparing the stellar proper motions from the SPM2 (Platais et al. 1998b) and Hipparcos Catalogues.

(9) The “PUL2” solution was found by comparing the PUL2 Pulkovo photographic catalog (Bobylev et al. 2004) and the Hipparcos Catalogue.

(10) The “XPM” solution is based on the Kharkov catalog of absolute stellar proper motions, XPM (Fedorov et al. 2009). It was absolutized using \( \approx 1.5 \) million galaxies from the 2MASS catalog of extended sources (Skrutskie et al. 2006). Thus, the XPM catalog is an independent realization of the inertial coordinate system. The proper motions from the XPM and UCAC2 (Zacharias et al. 2004) catalogs were compared in Bobylev et al. (2010), where the parameters \( \omega_x, \omega_y, \) and \( \omega_z \) were calculated using \( \approx 1 \) million stars.

(11) The “MINOR PLANETS” solution. Chernetenko et al. (2008) estimated the orientation parameters of the Hipparcos system relative to the coordinate systems of the DE403 and DE405 ephemerides by analyzing a long-term series of asteroid observations. This result leads to the conclusion that either the DE403 and DE405 dynamical theories need an improvement or the Hipparcos system needs a correction. We reduced the weight
of this solution by half because of the possible contribution from the inaccuracy of the DE403 and DE405 dynamical theories.

(12) The “VLA + PT-2007” solution was obtained by Boboltz et al. (2007) by analyzing the positions and proper motions of 46 radio stars. The VLBI observations were performed in the USA using the “Very Large Array” (VLA) in combination with the Pie Town antenna (New Mexico) at 8.4 GHz. In comparison with the observations by Lestrade et al. (1999), these observations have a considerably lower resolution in positional observations, because the interferometer size is smaller. On average, the positional errors are 13 mas in right ascension and 16 mas in declination (Boboltz et al. 2003). To achieve a high accuracy of determining the proper motions, they used long series of observations, about 20 years for each star. Only the coordinates and proper motions of radio stars were the quantities being determined. According to the estimates by Boboltz et al. (2007), the error in the stellar proper motion in this program is, on average, $\approx 1.7 \text{ mas yr}^{-1}$ in each coordinate.

(13) The search for the “VLBI-2014” solution is described in the first part of this paper. Note that the three solutions under consideration based on the VLBI observations of radio stars, “VLBI-1999”, “VLA + PT-2007”, and “VLBI-2014”, have significant differences in observing techniques; therefore, we consider them as independent solutions.

The weight assigned to each comparison catalog is inversely proportional to the square of the mean error $e_\omega$ in the corresponding quantities $(\omega_x, \omega_y, \omega_z)$ and was calculated from the formula

$$P_i = e_{\text{kiev}}^2 / e_i^2, \quad i = 1, \ldots, 13.$$  \hspace{1cm} (4)

Equations of the form (1), where the “Hipparcos minus Catalogue” differences are on the left-hand sides, can serve to determine $\omega_x$, $\omega_y$, and $\omega_z$. Lindegren and Kovalevsky (1995) proposed a slightly different form of these equations:

$$\Delta \mu_\alpha \cos \delta = \omega_x \cos \alpha \sin \delta + \omega_y \sin \alpha \sin \sin \delta - \omega_z \cos \delta,$$

$$\Delta \mu_\delta = -\omega_x \sin \alpha + \omega_y \cos \alpha,$$  \hspace{1cm} (5)

where the “Catalogue minus Hipparcos” differences are on the left-hand sides of the equations. Zhu (2001) and Boboltz et al. (2007) published the parameters that they determined with a change in the form of either the left-hand sides or the righthand sides of Eqs. (1) or (5). In these two cases, we brought the signs of the quoted parameters to the necessary standard form.

The last rows of Table 3 present “Average 1” that was calculated as a simple average but without using the HST solution and “Average 2” that was calculated from all data as a weighted mean and is the main result of our analysis. It is important to note that the rotation component $\omega_z = -0.53 \pm 0.13 \text{ mas yr}^{-1}$ in the solution obtained differs significantly from zero.

**DISCUSSION**

By comparing the XPM stars with catalogs extending the HCRF to faint magnitudes, such as PPMXL (Roeser et al. 2010), UCAC3 (Zacharias et al. 2009), Tycho-2 (Hog et al. 2000), and XC1 (Fedorov and Myznikov 2006), Fedorov et al. (2011) showed that the two
Tabelle 3: Components of the residual rotation vector of the optical realization of the ICRS/Hipparcos system relative to the inertial coordinate system.

| Method         | $N_*$ | $N_{\text{area}}$ | $\omega_x$, mas yr$^{-1}$ | $\omega_y$, mas yr$^{-1}$ | $\omega_z$, mas yr$^{-1}$ |
|----------------|-------|-------------------|----------------------------|---------------------------|---------------------------|
| VLBI-1999      | 12    |                   | $-0.16 \pm 0.30$          | $-0.17 \pm 0.26$          | $-0.33 \pm 0.30$          |
| NPM1           | 2616  | 899               | $-0.76 \pm 0.25$          | $+0.17 \pm 0.20$          | $-0.85 \pm 0.20$          |
| Kiev           | 415   | 154               | $-0.27 \pm 0.80$          | $+0.15 \pm 0.60$          | $-1.07 \pm 0.80$          |
| Potsdam        | 256   | 24                | $+0.22 \pm 0.52$          | $+0.43 \pm 0.50$          | $+0.13 \pm 0.48$          |
| Bonn           | 88    | 13                | $+0.16 \pm 0.34$          | $-0.32 \pm 0.25$          | $+0.17 \pm 0.33$          |
| EOP            |       |                   | $-0.93 \pm 0.28$          | $-0.32 \pm 0.28$          | $-$                       |
| HST            | 78    |                   | $-1.60 \pm 2.87$          | $-1.92 \pm 1.54$          | $+2.26 \pm 3.42$          |
| SPM2           | 9356  | 156               | $+0.10 \pm 0.17$          | $+0.48 \pm 0.14$          | $-0.17 \pm 0.15$          |
| PUL2           | 1004  | 147               | $-0.98 \pm 0.47$          | $-0.03 \pm 0.38$          | $-1.66 \pm 0.42$          |
| XPM            | $1 \times 10^6$ | 1431           | $-0.06 \pm 0.15$          | $+0.17 \pm 0.14$          | $-0.84 \pm 0.14$          |
| Minor Planets  | 116   |                   | $+0.12 \pm 0.08$          | $+0.66 \pm 0.09$          | $-0.56 \pm 0.16$          |
| VLA+PT-2007    | 46    |                   | $-0.55 \pm 0.34$          | $-0.02 \pm 0.36$          | $+0.41 \pm 0.37$          |
| VLBI-2014      | 23    |                   | $-0.39 \pm 0.58$          | $-0.51 \pm 0.57$          | $-1.25 \pm 0.56$          |
| Average 1      |       |                   | $-0.29 \pm 0.12$          | $+0.06 \pm 0.10$          | $-0.55 \pm 0.20$          |
| Average 2      |       |                   | $-0.15 \pm 0.11$          | $+0.24 \pm 0.10$          | $-0.53 \pm 0.13$          |

$N_*$ is the number of stars/asteroids, $N_{\text{area}}$ is the number of areas on the celestial sphere, average 1 is a simple average (without HST); average 2 is a weighted average.

The rotation components $\omega_x$ and $\omega_y$ do not differ significantly from zero, while the $Z$ rotation component has a measurable value, $\omega_z = -1.8 \pm 0.16$ mas yr$^{-1}$.

Note the result by Bobylev and Khovritchev (2011) obtained from the “proper motions” of about 8000 galaxies from the UCAC3 catalog (Zacharias et al. 2009). These authors found the residual rotation of the HCRF with respect to the inertial coordinate system $(\Omega_x, \Omega_y, \Omega_z) = (0.58, -1.02, -0.59) \pm (0.15, 0.15, 0.17)$ mas yr$^{-1}$ in Galactic coordinates. The corresponding rotation components around the equatorial axes (in mas yr$^{-1}$) are

\begin{align*}
\omega_x &= -0.02 \pm 0.15, \\
\omega_y &= +0.06 \pm 0.15, \\
\omega_z &= -1.31 \pm 0.17.
\end{align*}

Fedorov et al. (2011), Wu et al. (2011), and Grabowski et al. (2014) showed the “proper motions” of galaxies and quasars from the PPMXL catalogs to have measurable values. The proper motions averaged over all galaxies and quasars are $\approx -2$ mas yr$^{-1}$ in each of the coordinates ($\mu_\alpha \cos \delta$ and $\mu_\delta$). Wu et al. (2011) and Grabowski et al. (2014) did not determine the global rotation parameters, but they proposed to perform an additional absolute calibration of the stellar proper motions from the PPMXL catalog using a table of corrections.

Another interesting example of allowance for the additional absolute calibration of the stellar proper motions from the PPMXL catalog using galaxies is given in López-Corredoira et al. (2014). These authors studied the parameters of such a large-scale
phenomenon as the Galactic warp using red giant clump stars. It can be clearly seen from Fig. 3 in the cited paper that the corrections to the vertical stellar velocities reach about 70 km s$^{-1}$ at a heliocentric distance of about 8 kpc toward the Galactic anticenter. In other words, this distribution can be interpreted as the existence of residual rotation of the PPMXL stars around the Galactic $Y$ axis with an angular velocity $\Omega_y \approx -1.5$ mas yr$^{-1}$, in good agreement with the result of analyzing the PPMXL catalog obtained by Fedorov et al. (2011).

All of the aforesaid leads us to conclude that although the values of $\Omega_z$ that we derived from radio stars in solutions (2) and (3) have fairly large errors, they are in agreement with the results of the analysis of large catalogs with galaxies presented above, in particular, with the result (6) and the result from Fedorov et al. (2011).

Having analyzed the individual solutions but using a smaller amount of data, Bobylev (2010) found the following rotation components: $(\omega_x, \omega_y, \omega_z) = (-0.11, +0.24, -0.52) \pm (0.14, 0.10, 0.16)$ mas yr$^{-1}$. The advantage of the result of this study obtained in a similar way (“Average 2” in Table 3) is that the random errors in the parameters decreased. Thus, each result of the individual comparison of catalogs is of great importance for the solution of our problem.

CONCLUSIONS

We collected highly accurate VLBI determinations of the absolute proper motions of 23 radio stars from published data. The observations of the parallaxes and proper motions of these stars have been performed by various scientific teams in the last five or six years. The stars have a different evolutionary status. Some of them are very young stars with maser emission ($\text{H}_2\text{O}$ and CH$_3$OH masers). AGB stars observed as OH, $\text{H}_2\text{O}$, and SiO masers constitute the other part of the sample. Several stars were observed in continuum.

By comparing these measurements with the proper motions from the HCRF catalogs, we found the components of the residual rotation vector of this system with respect to the present-day realization of the inertial coordinate system, namely: $(\omega_x, \omega_y, \omega_z) = (-0.39, -0.51, -1.25) \pm (0.58, 0.57, 0.56)$ mas yr$^{-1}$. This estimate is a completely new result of the individual comparison of the sample of radio stars with the Hipparcos Catalogue.

Based on all the available individual results, we determined new, most probable values of the components of the residual rotation vector for the optical realization of the HCRF with respect to the inertial coordinate system: $(\omega_x, \omega_y, \omega_z) = (-0.15, +0.24, -0.53) \pm (0.11, 0.10, 0.13)$ mas yr$^{-1}$.

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