Effect of asymmetry of the radio source distribution on the apparent proper motion kinematic analysis

Oleg Titov\textsuperscript{1} and Zinovy Malkin\textsuperscript{2}

\textsuperscript{1} Geoscience Australia, GPO Box 378, Canberra, ACT 2601, Australia
\textsuperscript{2} Central Astronomical Observatory at Pulkovo of RAS, Pulkovskoe Ch. 65, St. Petersburg 196140, Russia

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ABSTRACT

Context. Information on physical characteristics of astrometric radio sources, magnitude and redshift in the first place, is of great importance for many astronomical studies. However, data usually used in radio astrometry is incomplete and often outdated.

Aims. Our purpose is to study the optical characteristics of more than 4000 radio sources observed by the astrometric VLBI technique since 1979. Also we studied an effect of the asymmetry in the distribution of the reference radio sources on the correlation matrices between vector spherical harmonics of the first and second degree.

Methods. The radio source characteristics were mainly taken from the NASA/IPAC Extragalactic Database (NED). Characteristics of the gravitational lenses were checked with the CfA-Arizona Space Telescope LEns Survey. SIMBAD and HyperLeda databases was also used to clarify the characteristics of some objects. Also we simulated and investigated a list of 4000 radio sources evenly distributed around the celestial sphere. We estimated the correlation matrices between the vector spherical harmonics using the real as well as modelled distribution of the radio sources.

Results. A new list of physical characteristics of 4261 astrometric radio sources, including all 717 ICRF-Ext.2 sources has been compiled. Comparison of our data of optical characteristics with the official International Earth Rotation and Reference Systems Service (IERS) list showed significant discrepancies for about half of 667 common sources. Finally, we found that asymmetry in the radio sources distribution between hemispheres could cause significant correlation between the vector spherical harmonics, especially if the case of sparse distribution of the sources with high redshift. We also identified radio sources having many-year observation history and lack redshift. This sources should be urgently observed at large optical telescopes.

Conclusions. The list of optical characteristics created in this paper is recommended for use as a supplement material for the next International Celestial Reference Frame (ICRF) realization. It can be also effectively used for cosmological studies and planning of observing programs both in radio and optics.

Key words. astrometry – techniques: interferometric – Astronomical data bases: miscellaneous – Cosmology: miscellaneous

1. Introduction

Information on physical characteristics of the astrometric radio sources is important for planning of VLBI experiments and analysis of VLBI data to do a research in cosmology, kinematics of the Universe, etc. In particular, the primary mainspring to this work was a support of the investigation of the systematic effects in apparent motion of the astrometric radio sources observed by VLBI (Gwinn et al. 1997, MacMillan 2005, Titov 2008a, Titov 2008b).

The official list of the physical characteristics of the ICRF radio sources is supported by the IERS (International Earth Rotation and Reference Systems Service) ICRS (International Celestial Reference System) Product Center (Archinal et al. 1997). The latest version of the IERS list is available in the Internet\textsuperscript{1}. However this list has some deficiencies:

- Not all the sources observed in the framework of geodetic and astrometric experiments are included in the IERS list.
- The characteristics of some sources in the IERS list are outdated or doubtful.

To overcome this problems, we performed a compilation of new list of the physical characteristics of astrometric radio sources using the latest information. Hereafter this list is referred to as OCARS (Optical Characteristics of Astrometric Radio Sources).

The list of radio sources with their positions was originally taken from the Goddard VLBI astrometric catalogue\textsuperscript{2} version 2007c, with addition of two absent ICRF-Ext.2 (Fey et al. 2004) sources 1039-474 and 1329-665 (hereafter we will use 8-char IERS designation HHMMsDDd which is an abridged version of the IAU-compliant name 'IERS BHHMMsDDd'). In the last version, the source list was updated using the 2009\textsuperscript{a}astro.cat catalogue computed by Leonid Petrov.\textsuperscript{3} It gives 4261 radio sources in total.

At this stage mainly the NASA/IPAC Extragalactic Database\textsuperscript{4} (NED) was scoured. Characteristics of the gravitational lenses were checked with the CfA-Arizona Space Telescope LEns Survey\textsuperscript{5} (CASTLES). Several sources were checked with SIMBAD\textsuperscript{6} and the HyperLeda\textsuperscript{7} databases. In the OCARS list we have included only the optical characteristics of

\textsuperscript{1} http://aprs.obspm.fr/icrs-pc/info/car\_physique\_ext1
\textsuperscript{2} http://vlbi.gsfc.nasa.gov/solutions/astro
\textsuperscript{3} http://astrogeo.org/vlbi/solutions
\textsuperscript{4} http://nedwww.ipac.caltech.edu/
\textsuperscript{5} http://cfa-www.harvard.edu/glensdata/
\textsuperscript{6} http://simbad.u-strasbg.fr/
\textsuperscript{7} http://leda.univ-lyon1.fr/
astrometric radio sources: source type, redshift and visual magnitude. The flux parameters are not included in our list because they are available from other centers directly working on correlation and primary processing of the VLBI observations.

The OCARS was preliminary presented in (Malkin & Titov 2008). In this paper we investigated statistical properties of the list in more detail and study their impact on the kinematic analysis of radio source motions.

Analysis of the radio source apparent motion revealed some statistically significant systematics described by the vector spherical harmonics of the first and second orders (dipole and quadrupole effects, respectively) (Titov 2008a, Titov 2008b). The dipole effect could be caused by the Galactocentric acceleration of the Solar system (Gwinn et al. 1997; Sovers et al. 1998; Kovalevsky 2003; Kliore 2003; Kopitikin & Makarov 2006) or a hypothetic acceleration of the Galaxy relative to the reference quasars. The quadrupole harmonic, considered in details by Kristian & Sachs (1966), could be caused either of the primordial gravitational waves or anisotropic expansion of the Universe. This result was confirmed by Ellis et al. (1985) although they stated “the major problem is that neither the distortion nor the proper motions are likely to be measurable in practice in the foreseeable future”. In this case the quadrupole effect should be redshift-dependent, and the apparent proper motion will increase with redshift. However, Pyne et al. (1996) and Gwinn et al. (1997) also discussed the gravitational waves with the wavelength shorter than the Hubble length. Thus, the proper motion, induced by the short-wavelength gravitational waves, also might be constant over all redshifts.

Due to asymmetry of the astrometric radio source distribution around the sky, the correlation between the vector spherical harmonic components is not zero. Therefore, we studied the effect of the asymmetry using the real uneven and simulated even distribution of the sources.

The OCARS list can be used as a supplement material for the second realization of the International Celestial Reference Frame (ICRF2), as well as a database for kinematic studies of the Universe and other related works, including scheduling of dedicated IVS (International VLBI Service for Geodesy and Astrometry, Schlüeter & Behrend 2007) programs.

2. Description of the OCARS

Our primary interest is to get the redshift (z) for astrometric radio sources to develop the previous studies (Gwinn et al. 1997; MacMillan 2005; Titov 2008a, 2008b). In those papers, redshift values were taken from the ICRF list (Archinal et al. 1997). However, as rather tiny effects in the source motions are to be investigated, it is important to increase the number of sources involved in the processing. Searching the latest astrophysical databases, primarily the NED, we could considerably augment the list of astrometric radio sources with known redshift. Nevertheless, more than half of the astrometric radio sources have no determined redshift.

Evidently, the only direct way to get the redshift for other most frequently observed astrometric sources is to organize a dedicated observing program with large optical telescopes. To help in preparation of such a program, we also collect the source type and its visual magnitude if this information is available. Also, it makes a sense to include in this observational program those sources with existing but uncertain redshift values.

It should be noted, that not all astrometric radio sources were reliably identified in the NED. We use the following procedure for identification. In the first step, we search for sources by source name using “ICRF” and “IVS” prefix. So, we rely on the source identification used in the literature and by the NED staff. Then about 500 sources, mostly from the VCS6 list, were searched by position. We take into account both the angular distance between the VLBI and NED positions as well as their uncertainty in the VLBI and NED positions. For some sources multiply NED objects within the error level were found. For 16 sources no appropriate object was found in the NED, which is mentioned in the comments. The problem of the source identification in the NED and other astrophysical data bases hopefully will be solved after official publication of the VCS6 catalogue.

The OCARS list is made available along with this paper in electronic form.

3. Statistics

The overall statistics of the OCARS is the following.

| Number of sources: | total | 4261 (100%) |
|--------------------|-------|-------------|
| N                  | 2391 (56.1%) |
| S                  | 1870 (43.9%) |
| with known type    | 2545 (59.7%) |
| AGN                | 1654 (65.0%) |
| galaxy             | 492 (19.3%) |
| star               | 27 (1.1%) |
| other              | 372 (14.6%) |
| with known redshift| 1840 (43.2%) |
| <= 1               | 853 (46.4%) |
| > 1                | 987 (53.6%) |
| N                  | 1195 (64.9%) |
| S                  | 645 (35.1%) |
| with known visual magnitude | 2452 (57.5%) |
| with known both z and magnitude | 1789 (42.0%) |
| with known z or magnitude | 2503 (58.7%) |
| with known magnitude and unknown z | 663 (15.6%) |

Figures 1 and 2 show the distribution of the sources with known redshift.

Figure 3 shows the distribution of the visual magnitude. The bottom part of the figure gives an impression about the magnitude of the sources for which redshift is not yet determined.

Therefore, large observational projects for spectroscopy of the astrometric radio sources are very important. Such a program is quite laborious taking into account a necessity of observations of mostly rather weak sources and their careful identification (search for an optical counterpart of radio sources). So, it makes sense to create a list of radio sources which were intensively observed during astrometric and geodetic VLBI programs, and lack of known redshift to establish an order of priority for optical observations. Such a list of high-priority sources is given in Table 1.

It was compiled using the IVS observation statistics available at http://www.gao.spb.ru/english/as/acvlbi/. The list was sorted using the number of observations marked as good in the observational NGS cards made during 24h sessions (in fact, in sessions of 18 hours and longer). On the other hand, it seems to be reasonable to give a observation priority to sources with reliably determined redshift, especially in the Southern hemisphere, and sources already having a good observational history.

4. Comparison with the IERS list

We have compared the OCARS with the IERS list and found 667 common radio sources. All the sources are present in the
Fig. 1. Distribution of the redshift *(top)* and cumulative number of sources *(bottom).*

Fig. 2. Distribution of the redshift over declination.

Fig. 3. Distribution of the visual magnitude for all sources *(top)* and for sources without known redshift *(bottom).*

IERS list. Comparison of these two lists results in rather large discrepancy.

- The first evident difference is in the number of radio sources. The OCARS list contains 40 extra ICRF sources plus several hundreds other sources, 4261 vs. 667 objects in total, 2503 vs. 555 objects with known redshift or visual magnitude.

- Unlike the IERS list, we did not try to trace all the details of the Active Galactic Nuclei (AGN) classification that are not always stable and unambiguous. So, all the quasars and BL object are designated as AGN.

- Redshift for 55 more ICRF sources were found; redshift for 4 sources presented in the IERS list were not included in our list for various reasons; for 30 sources redshift differs more than by 0.01; the largest differences are 1.26 (1903-802), 1.20 (1600+431), 0.70 (0646-306).

- Visual magnitudes for 70 more ICRF sources were found; magnitudes for 2 sources were not confirmed in our list; for 195 sources magnitude differs more than by 0.5; the largest differences are 5.2 (1758-651), 5.0 (1156-094, 1322-427), 3.9 (0241+622).

Further investigation has to be made to clarify all found discrepancies between two lists. It should be mentioned that we consider as important and useful for a user to provide a detailed comment in case of doubtful or ambiguous published data.

5. Comparison with the LQAC

We also performed a comparison of the OCARS list with recently published Large Quasar Astrometric Catalogue (LQAC) (Souchay et al. 2009). This catalogue contains information on redshift and luminosity at optical and radio wavelengths for 113666 quasars.

First, it should be noticed that more than one third of the astrometric sources are not quasars (see section 3) hence not all of them are contained in the LQAC. Nevertheless, this comparison seems to be mutually interesting because the information
Table 1. High-priority list of radio sources lacking known redshift.

| Source    | Nobs | Source    | Nobs | Source    | Nobs |
|-----------|------|-----------|------|-----------|------|
| 0017-7200 | 356  | 0017-7200 | 356  | 0017-7200 | 356  |
| 0017-7200 | 356  | 0017-7200 | 356  | 0017-7200 | 356  |
| 0017-7200 | 356  | 0017-7200 | 356  | 0017-7200 | 356  |
| 0017-7200 | 356  | 0017-7200 | 356  | 0017-7200 | 356  |

The most interesting result to us are sources having redshift in the LQAC and lack it in the OCARS. Those sources are 0003-302, 0118-283, 1026-084, 1202+527, 1225+028, 1332+031, 1422+231, 1555+030, 1639-062, and 2256-084. The first analysis showed that the sources 0003-302 and 1026-084 are located in very populated sky region, and maybe more careful identification is needed. The redshift value for the former is referred to a private communication. The source 1422+231 is a component of a gravitational lens according to CASTLES. These and other discrepancies found during this comparison will be analyzed during preparation of the next OCARS version.

An interesting point is the number of the OCARS objects not found in the LQAC. One can see that about 85% OCARS objects were found in the LQAC, which is much greater than the number of OCARS object with known type. On the other hand, the number of the OCARS objects not found in the LQAC is less than the number of OCARS non-AGN objects. It may be worth re-visiting the object classification in both catalogues, in fact in LQAC and NED. Such a large work is out of the scope of this study however.

6. Vector spherical functions

The paucity of the radio sources with declination less than −30° (Fig 2) may result in difficulties for astrometric analysis of radio catalogues. A worse precision of the radio source coordinates in the Southern hemisphere has been reported in papers on the International Celestial Reference Frame (Ma et al. 1998). It may cause more dramatic impact on the analysis of the apparent proper motion of the reference radio sources.

The ICRF consists of a set of highly accurate positions of reference radio sources as determined by the VLBI technique. The observed radio sources are very distant, therefore when the ICRF is made, their physical proper motion is assumed to be negligible (less than 1 mas/year) and their positions are practically stable. However, the motion of relativistic jets from the active extragalactic nuclei can mimic the proper motion of the observed radio sources (with a magnitude up to 0.5 mas/yr) (see e.g. Marcaide et al. 1985; Alberdi et al. 1993; Fey et al. 1997, Feissel-Vernier 2003; Titov 2007; MacMillan & Ma 2007). Moreover, some tiny systematic effects (dipole and quadrupole) in the apparent proper motion have been observed (Titov 2008a, 2008b). A study of these apparent proper motion would become an important part of the future fundamental reference frame making up.

The dipole and quadrupole systematic effect in the radio source apparent motion were studied previously (Gwinn et al. 1997; MacMillan 2005; Titov 2008a, 2008b) using the expansion of the apparent motion field on vector spherical harmonics. Unfortunately, due to uneven distribution of the reference radio sources over the sky the results could be corrupted by the correlation between estimated parameters. However, the correlation matrices have not been studied carefully so far.

The vector spherical harmonics Hill (1954) are used to study the systematic effect in a proper motion of celestial objects (see e.g. Migndar & Morando 1990; Gwinn et al. 1997; Vityazev & Shuksto 2004; Vityazev & Tsvetkov 2009).

Let us consider $F(\alpha, \delta)$ as a vector field of a sphere described by the components of the apparent proper motion vector $(\mu_\alpha, \cos \delta, \mu_\delta)$

$$F(\alpha, \delta) = \mu_\alpha \cos \delta \delta \psi + \mu_\delta \cos \delta$$

(1)
Table 3. Statistic of the model and real distributions of the radio sources over four redshift intervals. The number of radio sources and the maximum correlation between the thirteen estimated parameters are shown.

| Zone  | Model | Real |
|-------|-------|------|
| 0 < z < 1 | 1431 | 150 |
| 1 < z < 2 | 1183 | 120 |
| 2 < z < 3 | 398  | 240  |
| 3 < z < 4 | 100  | 57   |

where \( e_a, e_5 \) — unit vectors. A vector field of spherical functions \( F(\alpha, \delta) \) can be approximated by the vector spherical functions as follows

\[
F(\alpha, \delta) = \sum_{l=1}^{\infty} \sum_{m=-l}^{l} (d_{l,m}^E Y_{l,m}^E + d_{l,m}^M Y_{l,m}^M),
\]

where \( Y_{l,m}^E, Y_{l,m}^M \) — the ‘electric’ and ‘magnetic’ transverse vector spherical functions, respectively:

\[
Y_{l,m}^E = \frac{1}{\sqrt{l(l+1)}} \left( \frac{\partial V_{l,m}(\alpha, \delta)}{\partial \alpha} \cos \delta \hat{e}_a + \frac{\partial V_{l,m}(\alpha, \delta)}{\partial \delta} \hat{e}_c \right),
\]

\[
Y_{l,m}^M = \frac{1}{\sqrt{l(l+1)}} \left( \frac{\partial V_{l,m}(\alpha, \delta)}{\partial \alpha} \sin \delta \hat{e}_c - \frac{\partial V_{l,m}(\alpha, \delta)}{\partial \delta} \hat{e}_a \right).
\]

The function \( V_{l,m}(\alpha, \delta) \) is given by

\[
V_{l,m}(\alpha, \delta) = (-1)^m \sqrt{\frac{(2l+1)(l-m)!}{4\pi(l+m)!}} P_l^m(\sin \delta) \exp(i m \alpha),
\]

where \( P_l^m(\sin \delta) \) — the associated Legendre functions.

The coefficients of expansion \( d_{l,m}^E, d_{l,m}^M \) to be estimated as follows

\[
d_{l,m}^E = \int_0^{2\pi} \int_0^\pi F(\alpha, \delta) Y_{l,m}^E(\alpha, \delta) \cos \delta \ d\alpha d\delta,
\]

\[
d_{l,m}^M = \int_0^{2\pi} \int_0^\pi F(\alpha, \delta) Y_{l,m}^M(\alpha, \delta) \cos \delta \ d\alpha d\delta,
\]

where * means a complex conjugation. This system of equations can be solved by the least squares method. In this research the coefficients are estimated as global parameters from a large set of VLBI data.

The three ‘electric’ spherical harmonics for \( l=1 \) produces the dipole effect corresponding to the acceleration of the Solar system. The three \( l=1 \) ‘magnetic’ harmonics describe a rotation of the set of quasars. This rotation is not separable from the Earth’s rotation, and, therefore, not estimated. The five \( l=2 \) ‘electric’ spherical harmonics correspond either to the gravitational waves or to the Universe anisotropic expansion, and, finally, the five \( l=2 \) ‘magnetic’ spherical harmonics correspond only to the gravitational waves. In total, 13 components are to be estimated.

We studied both real and modelled distributions of the radio sources to calculate the correlations between the spherical harmonics (see Fig 4). For modelling, we initially created a set of 4000 radio sources uniformly distributed over the sky. Then we assigned redshift to all simulated objects in a such way that the redshift values have the same distribution as real ones. Another model set of sources was created from the first one by thinning of the sources within \( \pm 15^\circ \) zone along the Galactic equator, to get an ‘avoidance zone’ similar to the real distribution. These distributions are shown in Fig 4.

A comparison of the correlation matrices corresponding to two modelled distribution shown in Fig 4 highlights that the avoidance zone increases the maximum correlation (in absolute values) between the estimated spherical harmonics from 0.03 to 0.16. It is obvious that the paucity of the radio sources under declination \(-30^\circ\) (for the real distribution) results in further increase of the correlation to the maximum absolute value 0.28.

Once the separation on different zones on redshift is applicable, we also considered the correlation between observables in four zones for the both model and real distribution (Figs. 5 and 6 respectively). The model distribution without essential decrease in the number of sources around the South Celestial Pole produces almost equal maximum correlation parameter for all four redshift zones (from 0.15 to 0.19).

In opposite, a deficit of the radio sources around the South Celestial Pole is more crucial. The data presented in Figs. 6 demonstrate the impact of the North-South asymmetry in the real distribution of the radio sources. For the zone of redshift between 3 and 4 the maximum correlation reaches 0.51.

As we learnt from the comparison of correlation matrices for the limited number of radio sources unevenly distributed around the celestial sphere, the correlation between estimated spherical harmonics might increase dramatically to level of 0.8—0.9, especially of not all the sources are observed. Whereas, the individual apparent motion due to intrinsic structure reaches 500 μas/yr (Feissel-Vernier 2003; MacMillan & Ma 2007; Titov 2007), they could propagate systematically to the estimated parameters, if the number of objects is not sufficient, i.e. for the case of high redshift.

7. Conclusion

To conclude, it is necessary to note that this ‘historic’ deficit of the radio sources (and, additionally, the radio sources with measured redshift) might cause problems with further investigation of the hardly detectable systematic effects in the proper motion of the reference radio sources. Therefore, large observational projects for spectroscopy of the astrometric radio sources in the Southern hemisphere are very important. Nonetheless, some observations in the North hemisphere also need to be undertaken.

Independently, the MASIV scintillation survey (Lovell et al. 2003, 2009) also demonstrates a highly significant dramatic decrease in the numbers of scintillators for redshifts in excess of \( z = 2 \). The lack of scintillation at high redshifts is clear evidence for an increase in the source angular sizes with increasing redshift. Such an increase may be cosmological in origin or may be a propagation effect of inter-galactic scattering (Lovell et al. 2009).

To observe and study radio source in both frequency range (optical and radio) characteristics such as visual magnitude, redshift in optic and flux density in several radio bands have to be measured. We also need to be sure that the same source is observed by the optical and radio instruments. Due to possible misalignment between optical and radio positions the physical characteristics might help to solve the problem of identification.

To chase this aim, a new list of optical characteristics of 4261 astrometric radio sources, OCARS, including all 717 ICRF-Ext.2 sources has been compiled. The OCARS list includes source type, redshift and visual magnitude (when available). Detailed comments are provided when necessary, which is especially useful in understanding of incomplete, contradictory and controversial astrophysical data. The OCARS may serve to various VLBI tasks, for instance:
Fig. 4. Sky coverage and correlation matrix for 13 vector spherical harmonics of first and second order for real source distribution of the 1809 radio sources with known redshift for real distribution (top) and two modelled distributions of 3123 radio source with the avoidance zone (middle) and of 4000 radio sources without the avoidance zone (bottom). The circle size corresponds to the redshift value.

- As a supplement material for the second ICRF realization ICRF2 (Ma 2008).
- As a database for VLBI data analysis.
- For planning of IVS and other observing programs, in order to enrich the observational history of the sources with reliable determined redshift.
- For future link between optical (GAIA) and radio (ICRF) celestial reference frames, once the GAIA optical position of about 100,000 quasars will be available.

We performed a detailed comparison of the OCARS list with the official IERS list, and found many discrepancies for about a half of common sources. This comparison showed that the IERS list seems to be outdated and should be used with care. Besides, the IERS list, being intended to provide physical characteristics of the IERS sources only, contains only a small fraction of the whole set of astrometric radio sources used nowadays.

We also compared the OCARS with the newest Large Quasar Astrometric Catalogue LQAC, and found discrepancies which worth further investigating. Most of discrepancies seems to be a result of different object identification.

This is only the first stage of our work. We are planning the following steps:

- To continue searching for the missing and checking out the ambiguous characteristics through literature and astronomical databases.
- To organize photometric and spectroscopy observations of astrometric radio sources with large optical telescopes. In particular, such an observational program started at Pulkovo
Fig. 5. Sky coverage and correlation matrix for 13 vector spherical harmonics of first and second order for modelled source distribution and four redshift intervals. From top to bottom: 0 < z < 1, 1 < z < 2, 2 < z < 3, 3 < z < 4. The circle size corresponds to the redshift value.
Fig. 6. Sky coverage and correlation matrix for 13 vector spherical harmonics of first and second order for real source distribution and four redshift intervals. From top to bottom: $0 < z < 1$, $1 < z < 2$, $2 < z < 3$, $3 < z < 4$. The circle size corresponds to the redshift value.
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Observatory in 2008. Observations are being made on the 6-m BTA telescope of the Special Astrophysical Observatory in North Caucasus.

The list of optical characteristics of astrometric radio sources presented in this paper is publicly available at www.gao.spb.ru/english/as/acvlbi/sou_car.dat and is updated once in several months.

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