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

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ABSTRACT

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 However, data usually used in radio astrometry is often incomplete and outdated.

Aims. Our purpose is to study the optical characteristics of more than 4000 radio sources observed by the astrometric VLBI technique since 1979. We also studied the 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 degrees.

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 were 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 OCARS (optical characteristics of astrometric radio sources) of 4261 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 the 667 common sources. Finally, we found that asymmetry in the radio source distribution between hemispheres could cause significant correlation between the vector spherical harmonics, especially in the case of sparse distribution of the sources with high redshift. We also identified radio sources having a many-year observation history and lack of redshift. These sources should be urgently observed with large optical telescopes.

Conclusions. The list of optical characteristics created in this paper is recommended for use as a supplementary 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 optical wavelength.

Key words. astrometry – techniques: interferometric – astronomical data bases: miscellaneous – cosmology: miscellaneous

1. Introduction

Information on the physical characteristics of astrometric radio sources is important for the planning of VLBI experiments and analysis of VLBI data for a research in cosmology, kinematics of the Universe, etc. In particular, the primary motivation for this work was support for 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,b).

The official list of 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 by internet¹. However this list has some deficiencies:

- The characteristics of some sources in the IERS list are outdated or doubtful.

To overcome these problems, we compiled new list of the physical characteristics of astrometric radio sources using the most recent information available. 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 catalogues², version 2007c, with the addition of the two absent ICRF-Ext.2 (Fey et al. 2004) sources 1039-474 and 1329-665 (hereafter we will use 8-character IERS designation HHMMsDDd which is an abridged version of the IAU-compliant name “IERS BHMMsDDd”). In the latest version, the source list was updated using the 2009a_astro.cat catalogue computed by Petrov³. It gives 4261 radio sources in total.

At this stage mainly the NASA/IPAC extragalactic database⁴ (NED) was scoured. Characteristics of the gravitational lenses were checked with the CfA-Arizona Space Telescope LENS Survey⁵ (CASTLES). Several sources were checked with

[★] OCARS catalog is only available in electronic form at the CDS via anonymous ftp to [cdsweb.u-strasbg.fr](ftp://cdsweb.u-strasbg.fr) (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/506/1477>

¹ http://hpiers.obspm.fr/icrs-pc/info/car_physique_ext1

² <http://vlbi.gsfc.nasa.gov/solutions/astro>

³ <http://astrogeo.org/vlbi/solutions>

⁴ <http://nedwww.ipac.caltech.edu/>

⁵ <http://cfa-www.harvard.edu/glensdata/>

SIMBAD⁶ and HyperLeda⁷ databases. In the OCARS list we have included only the optical characteristics of 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 investigate statistical properties of the list in more detail and study their impact on the kinematic analysis of radio source motion.

An analysis of the radio source apparent motion revealed some statistically significant systematic effects described by the vector spherical harmonics of the first and second orders (dipole and quadrupole effects, respectively) (Titov 2008a,b). The dipole effect could be caused by the Galactocentric acceleration of the Solar system (Gwinn et al. 1997; Sovers et al. 1998; Kovalevsky 2003; Klioner 2003; Kopeikin & Makarov 2006) or a hypothetical acceleration of the Galaxy relative to the reference quasars. The quadrupole harmonic, considered in detail by Kristian & Sachs (1966), could be caused either by the primordial gravitational waves or by 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 gravitational waves having a 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 the 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 supplementary material for the second realization of the International Celestial Reference Frame (ICRF2), as well as for kinematic studies of the Universe and other related works, including scheduling of dedicated IVS (International VLBI Service for Geodesy and Astrometry, Schlüter & Behrend 2007) programs.

2. Description of the OCARS

Our primary interest is to obtain the redshift (z) for astrometric radio sources to develop previous studies (Gwinn et al. 1997; MacMillan 2005; Titov 2008a,b). In these papers, redshift values were taken from the ICRF list (Archinal et al. 1997). However, as very small effects on the source motions are to be investigated, it is important to increase the number of sources used during 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.

The only direct way to determine the redshift for other frequently observed astrometric sources is through a dedicated observing program with large optical telescopes. To help in the preparation of such a program, we also collect the source type and its visual magnitude if this information is available. Also,

we include in this observational program those sources with existing but uncertain redshift values.

Unfortunately, not all astrometric radio sources have been reliably identified in the NED. We use the following procedure for identification. First, we search for sources by source name using the “ICRF” and “IVS” prefix (i.e., at this stage, 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 for by position. We take into account both the angular distance between the VLBI and NED positions as well as their uncertainty. For some sources, multiple NED objects within the error were found. For 16 sources no appropriate object was found in the NED, which is mentioned in the comments. The problem of source identification in the NED and other astrophysical databases hopefully will be resolved 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 shows the magnitude of the sources for which a redshift has not yet been determined. Therefore, large observational projects for spectroscopy of astrometric radio sources are very important. Such a program is quite laborious, taking into account necessity of observations of mostly rather weak sources and their careful identification (search for an optical counterpart of radio sources). Thus, it is useful to have a list of radio sources which were intensively observed during astrometric and geodetic VLBI programs, and with no known redshift, to establish an order of priority for optical observations. Our 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/ac_vlbi/. The list was sorted using the number of observations marked as good in the observational NGS cards. On the other hand, we give observation priority to sources with reliably determined redshift, especially in the Southern hemisphere, and sources already having a good observational history.

⁶ <http://simbad.u-strasbg.fr/>

⁷ <http://leda.univ-lyon1.fr/>

Fig. 1. Distribution of the redshift (*top*) and cumulative number of sources (*bottom*).

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

Fig. 2. Distribution of the redshift over declination.

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 IERS list. Comparison of these two lists reveals large discrepancies.

- The first difference is in the number of radio sources. The OCARS list contains 40 extra ICRF sources plus several hundred 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 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, the redshift differs by more than 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 by more than 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 the discrepancies found between two lists. To provide more information for users, we included in our list a detailed comment in cases of doubtful or ambiguous published data.

5. Comparison with the LQAC

We also performed a comparison of the OCARS list with the recently published Large Quasar Astrometric Catalogue (LQAC) (Souhay et al. 2009). This catalogue contains information on redshift and luminosity at optical and radio wavelengths for 113 666 quasars.

First, it should be noticed that more than one third of the astrometric sources are not quasars (see Sect. 3), hence not all of them are contained in the LQAC. Nevertheless, this comparison is useful because the information sources used to compile both lists have a large overlap, but are not fully the same. Also, such a check allows us to identify possible mistakes, overlooked literature, etc.

Table 1. High-priority list of radio sources lacking known redshift.

Source	Nobs	Source	Nobs	Source	Nobs
1357+769	202005	0426+273	994	0017+200	356
1300+580	75748	0019+058	941	0206+136	342
0749+540	67718	1706-174	919	2051+745	337
0718+792	35867	1922-224	908	1651+391	326
0300+470	25613	1746+470	850	0459+135	323
1923+210	25324	2337+264	723	1647-296	313
0735+178	16356	0134+311	708	1243-160	310
0556+238	12553	0826-373	693	0729+259	310
1057-797	6623	0554+242	635	1036+054	310
0656+082	5278	0818-128	633	1951+355	304
2229+695	4759	0458+138	617	0332+078	303
0657+172	4667	0524+034	592	0822+137	301
0454+844	4296	1754+155	567	0602+405	300
1657-261	2735	1823+689	536	1909+161	296
1221+809	2258	1926+087	531	1424+240	293
1929+226	2087	0759+183	530	1734+508	291
2000+472	2086	1656-075	517	0437-454	281
0430+289	2047	1639-062	516	1251-713	277
0648-165	1973	0055-059	509	0743+277	268
0109+224	1954	1604-333	502	0601+245	267
1751+288	1906	1443-162	497	0259+121	263
0420+417	1893	1817-254	490	0951+268	260
2150+173	1789	1327+321	488	0723+219	250
1815-553	1789	2013+163	479	2302+232	248
1459+480	1782	0341+158	472	0613+570	242
0302+625	1660	0415+398	470	0302-623	232
0544+273	1634	0733-174	468	0700-197	226
0920+390	1575	0854-108	453	1433+304	225
0159+723	1508	1602-115	447	1830+139	222
0440+345	1467	0854+213	446	1705+135	215
1738+476	1413	1922+155	438	0629+160	215
2021+317	1335	1947+079	435	1013+127	215
1307+121	1296	2000+148	433	0728+249	214
1213-172	1285	0115-214	424	0025+197	213
0308-611	1280	1101-536	405	1344+188	205
0722+145	1269	1409+218	400	1451+270	200
0506+101	1233	0912+297	397	0516-621	200
1932+204	1128	0627-199	376	1156-094	198
0039+230	1123	0530-727	375	1412-368	196
2030+547	1056	0725+219	369	0627+176	195

Table 2. Statistics of comparison of OCARS (1) with LQAC (2).

Number of sources ...	Search radius, arcsec				
	1	2	5	10	30
not found in (2)	669	650	641	635	631
without z in both catalogues	1809	1811	1814	1817	1821
with z in (1) only	547	548	532	526	520
with z in (2) only	8	8	8	10	10
with different z in (1) and (2)	44	48	47	47	50

Since LQAC has no source names, the source identification was made using their position in both catalogues, which corresponds to the method used by the authors of LQAC. Table 2 shows a summary of comparison results for five different search radii. Here we compared only redshift values as the most important parameter. The z values in the two catalogs that differ by 0.01 or more were considered as different.

The most interesting results are sources having redshifts in the LQAC and lacking them 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. A first analysis showed that the sources 0003-302 and 1026-084 are located in a very populated sky region, and more careful

identification is needed. The redshift value for the former is from 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.

It is interesting that about 85% of OCARS objects were found in the LQAC, which is much greater than the number of OCARS objects with known type. On the other hand, the number of 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.

6. Vector spherical functions

The paucity of radio sources with declination less than -30° (Fig. 2) may result in difficulties for astrometric analysis of radio catalogues. The poorer precision of 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 a 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 techniques. The observed radio sources are very distant, therefore when the ICRF is made, their physical proper motion is assumed to be negligible (less than $1 \mu\text{as}/\text{year}$) 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 $0.5 \text{ mas}/\text{yr}$) (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,b). A study of these apparent proper motions is an important part of the development of future fundamental reference frame.

The dipole and quadrupole systematic effect in the radio source apparent motion have been studied previously (Gwinn et al. 1997; MacMillan 2005; Titov 2008a,b) using the expansion of the apparent motion field in vector spherical harmonics. Unfortunately, due to uneven distribution of the reference radio sources over the sky, the results may 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 of systematic effect on the proper motion of celestial objects (see e.g. Mignard & 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 ($\mu_\alpha \cos \delta, \mu_\delta$)

$$F(\alpha, \delta) = \mu_\alpha \cos \delta e_\alpha + \mu_\delta e_\delta, \quad (1)$$

where e_α, e_δ are unit vectors. A vector field of spherical functions $F(\alpha, \delta)$ can be approximated by the vector spherical functions as follows

$$F(\alpha, \delta) = \sum_{l=1}^{\infty} \sum_{m=-l}^l (a_{l,m}^E Y_{l,m}^E + a_{l,m}^M Y_{l,m}^M), \quad (2)$$

Table 3. Statistics of the model and real distributions of the radio sources over four redshift intervals.

Zone	Model		Real	
	<i>N</i>	Max corr	<i>N</i>	Max corr
$0 < z < 1$	1431	0.15	835	0.27
$1 < z < 2$	1183	0.15	671	0.33
$2 < z < 3$	398	0.18	240	0.34
$3 < z < 4$	100	0.19	57	0.51

The number of radio sources and the maximum correlation between the thirteen estimated parameters are shown.

where $Y_{l,m}^E$, $Y_{l,m}^M$ are the “electric” and “magnetic” transverse vector spherical functions, respectively:

$$Y_{l,m}^E = \frac{1}{\sqrt{l(l+1)}} \left(\frac{\partial V_{l,m}(\alpha, \delta)}{\partial \alpha \cos \delta} e_\alpha + \frac{\partial V_{l,m}(\alpha, \delta)}{\partial \delta} e_\delta \right),$$

$$Y_{l,m}^M = \frac{1}{\sqrt{l(l+1)}} \left(\frac{\partial V_{l,m}(\alpha, \delta)}{\partial \delta} e_\alpha - \frac{\partial V_{l,m}(\alpha, \delta)}{\partial \alpha \cos \delta} e_\delta \right). \quad (3)$$

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

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

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

The coefficients of expansion $a_{l,m}^E$, $a_{l,m}^M$ can be estimated as follows

$$a_{l,m}^E = \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} \mathbf{F}(\alpha, \delta) Y_{l,m}^{E*}(\alpha, \delta) \cos \delta \, d\alpha \, d\delta,$$

$$a_{l,m}^M = \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} \mathbf{F}(\alpha, \delta) Y_{l,m}^{M*}(\alpha, \delta) \cos \delta \, d\alpha \, d\delta, \quad (5)$$

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 the model, we initially created a set of 4000 radio sources uniformly distributed over the sky. Then we assigned redshifts to all simulated objects in a such way that the assigned 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 a $\pm 15^\circ$ zone along the Galactic equator, to obtain an “avoidance zone” similar to the real distribution. These distributions are shown in Fig. 4.

A comparison of the correlation matrices corresponding to the two modelled distributions 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 radio sources below a declination of -30° (for the real distribution) results in a further increase of the correlation to the maximum absolute value 0.28.

Once the separation in different zones of redshift is applicable, we also considered the correlation between observables in four zones for the model and real distributions (Figs. 5 and 6, respectively). The model distribution without a decrease in the number of sources around the South Celestial Pole produces almost equal maximum correlation parameters for all four redshift zones (from 0.15 to 0.19). A deficit of the real radio sources around the South Celestial Pole is more crucial. Figure 6 demonstrates the impact of the North-South asymmetry on the real distribution of 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 a level of 0.8–0.9, especially if not all the sources are observed. While the individual apparent motion due to intrinsic structure reaches $500 \mu\text{as/yr}$ (Feissel-Vernier 2003; MacMillan & Ma 2007; Titov 2007), these values could be propagated systematically to the estimated parameters, if the number of objects is not sufficient, i.e. for the case of high redshift.

7. Conclusion

The “historic” deficit of radio sources (and, additionally, radio sources with measured redshift) might cause problems in further investigations of the barely detectable systematic effects in the proper motion of the reference radio sources. Therefore, large observational projects obtaining spectroscopy of astrometric radio sources in the Southern hemisphere are very important. Nonetheless, some observations in the Northern 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 ranges (optical and radio) characteristics such as visual magnitude and redshift in optical wavelengths, and flux density in several radio bands have to be measured. We also need to be sure that the same source is observed by optical and radio instruments. Due to possible misalignment between optical and radio positions, the physical characteristics might help to solve the problem of identification.

For this, a new list of optical characteristics of 4261 astrometric radio sources, OCARS, 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 to understand incomplete, contradictory and controversial astrophysical data. The OCARS may serve for various VLBI tasks, for instance:

- As supplemental material for the second ICRF realization ICRF2 (Fey & Gordon 2009).
- As a database for VLBI data analysis.

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.

- 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 half of the common sources, suggesting that the IERS list is 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, and, in particular, included in the ICRF2.

We also compared OCARS with the newest Large Quasar Astrometric Catalogue (LQAC), and found discrepancies worth further investigation. Most of the 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 missing and ambiguous characteristics through literature and astronomical databases.
- To organize photometric and spectroscopic observations of astrometric radio sources with large optical telescopes. In particular, such an observational program was started at Pulkovo Observatory in 2008. Observations are being made on the 6-m BTA telescope of the Special Astrophysical Observatory in North Caucasus.

	$a_{1,1}^E$	$a_{1,-1}^E$	$a_{1,0}^E$	$a_{2,1}^E$	$a_{2,-1}^E$	$a_{2,2}^E$	$a_{2,-2}^E$	$a_{2,0}^E$	$a_{2,1}^M$	$a_{2,-1}^M$	$a_{2,2}^M$	$a_{2,-2}^M$	$a_{2,0}^M$
$a_{1,1}^E$	1.00												
$a_{1,-1}^E$	0.03	1.00											
$a_{1,0}^E$	-0.10	-0.04	1.00										
$a_{2,1}^E$	-0.01	0.04	0.03	1.00									
$a_{2,-1}^E$	0.03	-0.01	-0.01	-0.04	1.00								
$a_{2,2}^E$	-0.01	-0.01	-0.01	0.03	0.08	1.00							
$a_{2,-2}^E$	0.02	0.00	0.00	0.04	0.10	0.00	1.00						
$a_{2,0}^E$	0.00	0.02	0.03	-0.01	-0.03	0.00	0.07	1.00					
$a_{2,1}^M$	-0.07	-0.04	-0.09	0.00	0.01	0.00	-0.02	-0.01	1.00				
$a_{2,-1}^M$	0.04	-0.15	0.04	-0.02	0.00	-0.02	-0.04	-0.02	-0.04	1.00			
$a_{2,2}^M$	0.13	0.09	-0.19	0.00	-0.01	0.00	0.00	0.00	-0.02	-0.03	1.00		
$a_{2,-2}^M$	-0.12	0.03	0.07	-0.01	-0.01	0.00	-0.01	-0.01	0.00	-0.05	-0.03	1.00	
$a_{2,0}^M$	-0.06	0.17	0.00	0.01	0.02	0.01	-0.01	0.00	-0.02	-0.06	0.01	0.09	1.00

	$a_{1,1}^E$	$a_{1,-1}^E$	$a_{1,0}^E$	$a_{2,1}^E$	$a_{2,-1}^E$	$a_{2,2}^E$	$a_{2,-2}^E$	$a_{2,0}^E$	$a_{2,1}^M$	$a_{2,-1}^M$	$a_{2,2}^M$	$a_{2,-2}^M$	$a_{2,0}^M$
$a_{1,1}^E$	1.00												
$a_{1,-1}^E$	0.03	1.00											
$a_{1,0}^E$	-0.09	-0.01	1.00										
$a_{2,1}^E$	-0.01	0.02	0.03	1.00									
$a_{2,-1}^E$	0.03	-0.02	-0.02	-0.03	1.00								
$a_{2,2}^E$	0.03	-0.03	-0.02	0.01	0.06	1.00							
$a_{2,-2}^E$	-0.02	-0.03	0.01	0.04	0.10	-0.03	1.00						
$a_{2,0}^E$	0.02	-0.02	-0.01	-0.02	-0.03	0.00	0.03	1.00					
$a_{2,1}^M$	-0.06	-0.03	-0.08	0.00	0.04	0.00	-0.01	0.02	1.00				
$a_{2,-1}^M$	0.03	-0.11	0.00	-0.04	0.00	0.00	0.01	0.02	-0.03	1.00			
$a_{2,2}^M$	0.13	0.08	-0.15	-0.02	-0.02	0.00	-0.03	0.00	-0.01	-0.01	1.00		
$a_{2,-2}^M$	-0.09	0.04	0.07	0.01	-0.03	-0.03	0.01	-0.02	-0.02	-0.04	-0.05	1.00	
$a_{2,0}^M$	0.00	0.15	0.00	-0.02	-0.03	-0.01	-0.02	0.00	-0.02	-0.06	0.02	0.04	1.00

	$a_{1,1}^E$	$a_{1,-1}^E$	$a_{1,0}^E$	$a_{2,1}^E$	$a_{2,-1}^E$	$a_{2,2}^E$	$a_{2,-2}^E$	$a_{2,0}^E$	$a_{2,1}^M$	$a_{2,-1}^M$	$a_{2,2}^M$	$a_{2,-2}^M$	$a_{2,0}^M$
$a_{1,1}^E$	1.00												
$a_{1,-1}^E$	0.04	1.00											
$a_{1,0}^E$	-0.09	0.01	1.00										
$a_{2,1}^E$	-0.05	-0.06	0.08	1.00									
$a_{2,-1}^E$	-0.06	-0.02	-0.01	-0.01	1.00								
$a_{2,2}^E$	0.01	0.01	-0.06	-0.01	0.02	1.00							
$a_{2,-2}^E$	0.02	0.02	-0.01	0.03	0.13	-0.04	1.00						
$a_{2,0}^E$	-0.01	0.05	-0.08	-0.02	-0.05	0.06	-0.02	1.00					
$a_{2,1}^M$	-0.05	-0.04	-0.07	0.00	-0.03	-0.09	-0.03	-0.02	1.00				
$a_{2,-1}^M$	0.04	-0.09	-0.01	0.03	0.00	-0.07	-0.02	-0.06	0.00	1.00			
$a_{2,2}^M$	0.18	0.04	-0.13	-0.04	0.00	0.03	0.03	0.02	0.02	0.02	1.00		
$a_{2,-2}^M$	-0.03	0.09	0.08	0.00	0.00	0.02	-0.02	-0.06	-0.01	-0.06	-0.05	1.00	
$a_{2,0}^M$	0.03	0.15	-0.01	0.01	0.04	0.02	-0.05	0.01	-0.02	-0.06	0.06	0.00	1.00

	$a_{1,1}^E$	$a_{1,-1}^E$	$a_{1,0}^E$	$a_{2,1}^E$	$a_{2,-1}^E$	$a_{2,2}^E$	$a_{2,-2}^E$	$a_{2,0}^E$	$a_{2,1}^M$	$a_{2,-1}^M$	$a_{2,2}^M$	$a_{2,-2}^M$	$a_{2,0}^M$
$a_{1,1}^E$	1.00												
$a_{1,-1}^E$	0.11	1.00											
$a_{1,0}^E$	-0.11	0.03	1.00										
$a_{2,1}^E$	-0.04	-0.03	0.09	1.00									
$a_{2,-1}^E$	0.03	-0.03	-0.05	-0.11	1.00								
$a_{2,2}^E$	0.04	-0.04	0.00	0.03	0.00	1.00							
$a_{2,-2}^E$	-0.06	-0.06	0.04	0.08	0.19	0.01	1.00						
$a_{2,0}^E$	0.02	-0.02	0.06	0.09	-0.14	0.02	-0.08	1.00					
$a_{2,1}^M$	0.00	-0.09	-0.11	0.00	-0.01	-0.02	0.06	0.04	1.00				
$a_{2,-1}^M$	0.10	-0.03	-0.03	0.03	0.00	0.09	-0.05	0.02	-0.12	1.00			
$a_{2,2}^M$	0.19	0.11	-0.03	-0.05	-0.03	0.01	0.07	-0.06	0.01	-0.01	1.00		
$a_{2,-2}^M$	-0.07	0.07	0.18	0.03	-0.06	0.09	-0.01	0.00	-0.03	-0.01	0.01	1.00	
$a_{2,0}^M$	0.08	0.21	-0.02	-0.06	-0.02	-0.09	-0.03	-0.01	0.07	-0.13	0.06	-0.05	1.00

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.

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

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