On Comparison and Combination of Radio Source Catalogues

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Abstract.
In this paper four methods of the representing RSC systematic differences have been examined by comparison of the residuals of the radio source positions between each pair of individual catalogues. Eight radio source catalogues, and the latest ICRF realization, ICRF-Ext.2, were used for comparison. After selection of the best method how representing differences representation we compute the systematic differences between each individual catalogue and the ICRF. Then, these differences were used in the procedure of construction of the combined radio source catalogue. In results, representation of the systematic differences between RSC with Legendre-Fourier functions is proven to be the most accurate method. Using this method, two combined radio source catalogues constructed. The first one provides a stochastic improvement of the ICRF, and the second one allows us to account also for possible systematic errors in the ICRF. Comparison of the celestial pole offsets obtained from processing of VLBI observations using ICRF and combined catalogue has shown improvement of the results obtained with the combined catalogue.

Keywords. VLBI, ICRF, catalogue comparison, catalogue combination

1 Introduction

In 1998, the International Celestial Reference Frame (ICRF) based on the positions of extragalactic radio sources was adopted by the International Astronomical Union (Ma et al. 1998). The first ICRF realization was based on the refined analysis of VLBI observations made at the Goddard Space Flight Center (Ma et al. 1998). In 1999 and 2004 two ICRF extensions ICRF-Ext.1 and ICRF-Ext.2 (hereafter referred to as ICRF) were issued. In those versions, the positions of 212 *defining* sources were kept the same as obtained in the first ICRF.

In the end of 2004, a joint pilot project of the IERS (International Earth Rotation and Reference Systems Services) and the IVS (International VLBI Service for Geodesy and Astrometry) was initiated (Ma 2004, Call for Participation). The goal of the project was to seek after ways to improve the existing ICRF.

In this paper we investigate a possibility of ICRF improvement by means of using advanced methods of comparison of the radio source catalogues (RSC) and RSC combination with the aim of mitigation of stochastic and systematic errors of individual RSC.

2 Input Catalogues

Input catalogues used in this study were submitted by eight IVS Analysis Centers: AUS (Geoscience Australia), BKG (Bundesamt für Kartographie und Geodäsie, Germany), DGFI (Deutsches Geodätisches Forschungsinstitut, Germany), GSFC (NASA Goddard Space Flight Center, USA), JPL (Caltech/NASA Jet Propulsion Laboratory, USA), MAO (Main Astronomical Observatory of National Academy of Sciences of Ukraine), SHAO (Shanghai Astronomical Observatory, China), USNO (U. S. Naval Observatory, USA). Brief description of the input catalogues is given in Table1.

Table 1. Input catalogues. (* - 199 stable sources from M. Feissel – Vernier stable list)

IVS Analysis Center	Software	Number of delays	Number of sources (total /references)
AUS	OCCAM	3208197	737 / 207
BKG	Calc/Solve	4031453	748 / 212
DGFI	OCCAM	3650771	686 / 199*
GSFC	Calc/Solve	4574189	954 / 212
JPL	MODEST	3575847	734 / 2
MAO	SteelBreeze	3773765	685 / 25
SHAN	Calc/Solve	4431503	813 / 212
USNO	Calc/Solve	4252684	943 / 207

For comparison of the catalogues, we used 196 ICRF *defining* sources present in all of the compared catalogues. Weighted root-mean-square (WRMS) differences of the radio source coordinates between the catalogues and the ICRF are shown in Fig. 1.

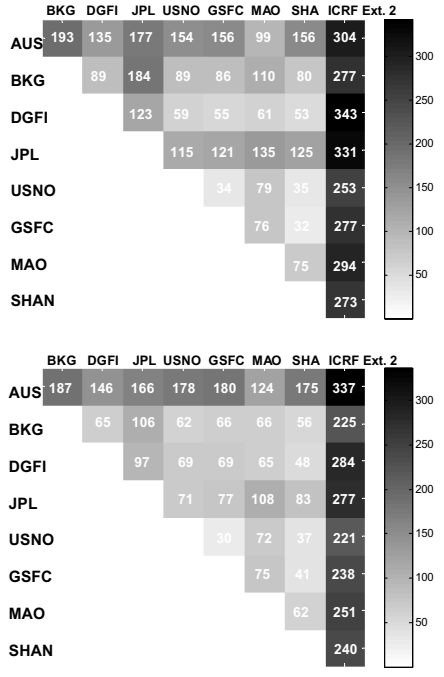

Fig. 1 WRMS differences between the input catalogues and the ICRF (μas). (Δα above, Δδ below).

One can see from Fig.1 that the WRMS differences have the least values for catalogues computed with Calc/Solve software, both for intercomparison of these catalogues and their comparison with the ICRF. The latter is most probably caused by the fact that the ICRF was constructed using the Calc/Solve software. Large WRMS differences between JPL and other catalogues may be caused by its orientation to the ICRF which has been defined by only two reference sources, unlike other catalogues, for which much longer lists of reference sources were used. Catalogue AUS shows the greatest differences with other catalogues, probably, because it is the only catalogue constructed using the Least Squares Collocation method, while other Analysis Centers used conventional Least Squares. One can see that the DGFI catalogue, also constructed using OCCAM software, but Least Squares version, does not stand out against other catalogues.

The most interesting fact is that all input catalogues demonstrate rather large differences with the ICRF, which may indicate significant systematic errors in the latter.

3 Analytical Representation of the systematic differences

In this section, we compare four methods of analytical representation of the systematic differences between RSC.

Simple Rotation. In this simplest method, the differences between catalogues are represented by three rotational angles A_1, A_2, A_3:

$$\Delta\alpha = A_1 \mathrm{tg}\delta \cos\alpha + A_2 \mathrm{tg}\delta \sin\alpha - A_3 \qquad (1)$$
$$\Delta\delta = -A_1 \sin\alpha + A_2 \cos\alpha$$

Rotation with Deformation. In this method currently used by the IERS, the systematic differences between two catalogues are approximated by

$$\Delta\alpha = A_1 \mathrm{tg}\delta \cos\alpha + A_2 \mathrm{tg}\delta \sin\alpha - A_3 + D_\alpha \delta \qquad (2)$$
$$\Delta\delta = -A_1 \sin\alpha + A_2 \cos\alpha + D_\delta \delta + B_\delta$$

Brosche's Method. In this method proposed by Brosche (1966), the differences between catalogues are represented via expansion in spherical harmonics:

$$\begin{Bmatrix} \Delta\alpha \\ \Delta\delta \end{Bmatrix} = \sum_{j=0}^{g} b_j Y_j(\alpha, \delta), \qquad (3)$$

where P_{nk}, are associated Legendre polynomials.

Legendre-Fourier Functions. Bien et al. (1978) proposed expansion in another set of orthogonal functions:

$$\begin{Bmatrix} \Delta\alpha \\ \Delta\delta \end{Bmatrix} = \sum_{j=0}^{g} b_{nkl} R_{nkl} L_n \, sin(\delta) F_{kl}(\alpha), \qquad (4)$$

where L_n are Legendre polynomials, F_{kl} are Fourier functions and R_{nkl} are normalizing functions.

All the four methods described above were applied to the differences between each of eight input catalogues and the ICRF. For this purpose, the coefficients of (1-4) were found by means of Least Squares adjustment. Then we computed the residuals between original differences and those computed by formulae (1-4). The results are presented in Table 2 and Fig. 2.

Table 2. WRMS residuals between the input catalogues and the ICRF before (Raw) and after approximation of the systematic differences (see notation of the methods in text). Unit: μas.

	AUS	BKG	DGFI	JPL	USNO	GSFC	MAO	SHA
				Δα				
Raw	304	277	343	331	253	277	294	273
R	301	271	342	308	249	274	286	271
RD	299	265	342	308	247	273	285	270
B	170	177	237	238	172	191	203	193
LF	**110**	**127**	**167**	**174**	**124**	**146**	**156**	**147**
				Δδ				
Raw	337	225	284	277	221	238	251	240
R	337	225	284	273	221	238	251	240
RD	333	224	283	273	221	237	251	239
B	180	159	178	182	152	158	169	166
LF	**111**	**115**	**116**	**131**	**109**	**111**	**136**	**117**

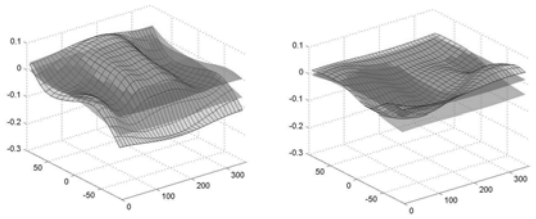

Fig. 2 Analytical representation of the differences between the input catalogues and ICRF: R (dark grey), RD (grey), LF (light grey). Original differences are shown in black lines. Horizontal axes show right ascension (*right*) and declination (*left*) in degrees. Unit: μas.

One can see that expansion in Legendre-Fourier functions provides the least residuals, it i.e. most accurate representation of the systematic differences between catalogues. Expansion in spherical functions (Brosche's method) gives worse accuracy. As to the first two methods, they seem to be not adequate to actual errors of modern RSC.

4 A Combined Catalogue in the ICRF system

At the next step, the systematic differences between the input catalogues and the ICRF found by the LF method were applied to all the input catalogues in order to transform them to the ICRF system. After that, the coordinates of all sources in transformed catalogues were averaged with weights depending on the formal errors of coordinates. In result, the combined catalogue RSC(PUL)07C01 was constructed. This catalogue contains all the 968 sources present in the input catalogues and can be considered as a stochastic improvement of the ICRF.

Fig. 3 shows the systematic differences between the combined catalogue RSC(PUL)07C01 and the ICRF. One can see that the catalogue RSC(PUL)07C01 represents the ICRF system at a level of about 10 μas.

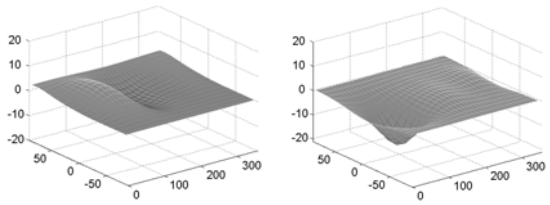

Fig. 3 Differences between RSC(PUL)07C01 and the ICRF. Horizontal axes show right ascension (*right*) and declination (*left*) in degrees. Unit: μas.

For construction of a final catalogue, systematic differences between the input catalogues and the ICRF were averaged with weights depending on the differences between input and combined catalogues. Final weights of the catalogues averaged over the sky are given in Table 3. Thus the computed average system was added to the catalogue RSC(PUL)07C01 to obtain the final combined

catalogue, RSC(PUL)07C02. It can be considered as both stochastic and systematic improvement of the ICRF. Result of comparison of RSC(PUL)07C02 and the ICRF presented in Fig. 4 leads us to the supposition that the ICRF may have significant systematic errors.

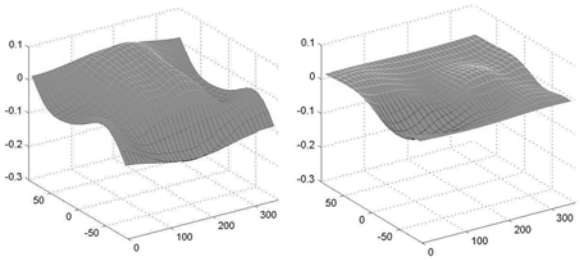

Fig. 4. Differences between RSC(PUL)07C02 and the ICRF. Horizontal axes show right ascension (*right*) and declination (*left*) in degrees. Unit: μas.

Table 3. Weights of the input catalogues applied during combination, averaged over the sky

	AUS	BKG	DGFI	JPL	USNO	GSFC	MAO	SHA
α	0.246	0.671	0.464	0.254	2.062	1.993	0.558	1.792
δ	0.205	1.220	0.586	0.446	1.927	1.921	0.541	1.459

6 Comparison with observation

To assess an actual accuracy of the combined catalogue, we have computed two celestial pole offset time series from processing of IVS R1 and R4 sessions observed in the period 2002–2006 with two RSC, ICRF-Ext.2 and RSC(PUL)07C02. Then we computed two estimates of the scatter for these time series. The first estimate is the WRMS difference between the computed celestial pole offsets and the IAU2000A model supplemented with the Free Core Nutation contribution. The second estimate was computed as weighted Allan deviation of the celestial pole (Malkin, 2007). The results of these tests presented in Table 4 show a clear improvement of the scatter of celestial pole offset estimates when using combined catalogue.

Table 4. Scatter of the celestial pole offset time series obtained with two catalogues. FCN column shows the scatter w.r.t. the FCN model, ADEV column shows Allan variance. Unit: μas.

CATALOGUE	FCN			ADEV		
	X	Y	Mean	X	Y	Mean
ICRF	103	101	102	113	109	111
RSC(PUL) 07C02	98	98	98	105	106	105

7 Conclusion

In this paper, we have examined four different methods of analytical representation of systematic differences between RSC. Expansion of the systematic differences in Legendre-Fourier functions is proven to be the most accurate method. Methods usually used for comparison of the VLBI CRF realizations based on axes rotation and rotation with deformation seem to be not suitable for the investigation of modern radio source catalogues

Two combined radio source catalogues have been constructed. The first of them, RSC(PUL)07C01 can be considered as stochastic improvement of the current realization of the ICRF. The final combined catalogue, RSC(PUL)07C02, provides both stochastic and systematic improvement of the ICRF.

Two tests based on analysis of the scatter of celestial pole offset time series computed using the ICRF and the combined catalogue have shown less scatter of the series based on the combined catalogue.

The results obtained in this paper allow us to make a conclusion that ICRF-Ext.2 may have significant systematic errors, most probably caused by fixing the coordinates of 212 *defining* sources in the successive ICRF realizations.

Acknowledgements. The authors greatly appreciate all IVS Analysis Centers that provided their radio source position catalogues used in this study.

Full version of this paper was submitted to *Astronomy and Astrophysics Journal.*

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