GAOUA REALIZATIONS OF THE CELESTIAL REFERENCE FRAME

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ABSTRACT. Short overview of the activity of the Main Astronomical observatory of National Academy of Science of Ukraine for maintenance and extension of the International Celestial Reference Frame (ICRF) is presented. Special attention is paid on the time stabilities of positions of radio sources (RS) and on the selection of a subset of RS to be used for maintenance of the ICRF. It is shown that seven RS qualified by the IERS as defining sources are unstable.

1. INTRODUCTION

Main Astronomical Observatory of the National Academy of Sciences of Ukraine (MAO NASU, GAOUA is the acronym used by the IERS) is engaged in construction of realizations of the International Celestial Reference System (ICRS) at optical and radio wavelengths. This activity is concentrated on:

- the extensive use of the Hipparcos catalogue as reference for the ICRS in works of densification and extension to fainter stars according to the FON-project;
- the construction of two different series of catalogues of radio source (RS) positions as realizations of the ICRS, namely initial catalogues of RSC(GAOUA)YY R NN and combined catalogue of RSC(GAOUA)YY C NN;
- the establishment of tie between the International Celestial Reference Frame (ICRF) and the reference frame at optical wavelengths according to the KMAC project.

2. THE FON ASTROGRAPHIC CATALOGUE (FONAC)

FONAC is the catalogue of positions, proper motions and B_J-magnitudes for $2,004,701$ stars of the Astrographic Catalogue (AC) including the $(B-V)_J$-magnitudes for $1,712,420$ stars and $(B-R)_J$-values for $1,779,442$ stars covering the northern sky between declinations $+90$ and -2 degrees (Kislyuk et al., 2000). The average epoch of positions is 1988.19. The catalogue is based on measurements of more than 1700 plates which were taken with the wide-angle astrograph of the Main Astronomical Observatory in Kiev within the FON (Photographic Survey of the Northern Sky) project. The AC data were used both as the input catalogue for

measuring machine PARSEC (Programming Automatic Radial-Scanning Coordinatometer) and as the first epochs for determination of proper motions of stars. The ACT Reference Catalogue as well as the Guide Star and USNO A2.0 catalogues were applied for the reductions of positions and determination of photometric characteristics of stars. Median precision of the FONAC data are $\pm 0.2''$, $\pm 0.003''/yr$ and $\pm 0.18^m$ in positions, proper motions and magnitudes of stars, respectively.

The catalogue FONAC is available on the MAO NASU home page (ftp://ftp.mao.kiev.ua/pub/astro/fonac). It was transfered to the Strasbourg Centre of Stars Data (http://vizier.u-strasbg.fr/viz-bin/Vizie?-source=I/261).

3. THE FIRST KYIV MERIDIAN AXIAL CIRCLE CCD CATALOGUE (KMAC1) OF STARS IN FIELDS WITH EXTRAGALACTIC RADIO SOURCES

KMAC1 is the catalogue of astrometric (positions, proper motions) and photometric (B, V, R, r', J) data of stars in fields with the ICRF objects which has been compiled by MAO NASU in cooperation with the Kyiv University Observatory (Lazorenko et al., 2004). All fields are located in declination zone from 0 to +30 degrees; nominal field size is $46'$ (right ascension) $\times$ $24'$ (declinations). The observational basis of this catalogue is 1100 CCD scans deep to $V = 17$ mag which were obtained with the Kyiv meridian axial circle in 2001-2003 and which contains one million of images. Astrometric reduction has included the correction depending on image size fluctuations and position of a star on the CCD along the declination axis. A special approach was used for correction of magnitude-dependent errors since images of bright stars were oversaturated. The catalogue KMAC1 is presented in two versions. The first version named as KMAC1-T which contains 156 fields (106417 stars) was obtained with use of the Tycho2 catalogue as reference one. Astrometric reduction for another 36 fields was found to be unreliable due to a low sky density of Tycho2 stars. Therefore the second version KMAC1-CU was made for 192 fields using UCAC2 and CAMC13 catalogues as reference ones; it contains 115032 stars and has a slightly better accuracy. Proper motions have been found using the USNOA2.0 catalogue as a first epoch catalogue. An "external" uncertainty (based on comparison to UCAC2 and CAMC13) of one catalogue position is about 60-70 mas for 14-15 mag stars. An average error of photometry is better than 0.1 mag for stars up to 16 mag.

4. THE GAOUA INITIAL CATALOGUES OF RS POSITIONS

Series of the initial catalogues RSC(GAOUA)YY R NN has been constructed using several versions of the SteelBreeze software for reduction of the VLBI observations (Bolotin, 2001). The overview of these catalogues is given in (Yatskiv, Kur'yanova and Bolotin, 2004). The latest version of the catalogue of this type RSC(GAOUA)03 R 01 is based upon a solution for all applicable VLBI data since 1979 till July 2003. In total $3,550,143$ dual frequency delays acquired on $2,970$ astrometric and geodetic sessions have been processed. The initial values of RS positions have been taken from the ICRF-Ext.1. Orientation of constructed reference frame was defined by a No-Net-Rotation condition between the ICRF-Ext.1 and the derived catalogue using 35 defining radio sources. The catalogue contains the positions of 1558 RS, including 211 defining RS. The average internal positional precision of these RS is about 0.1 mas (Bolotin, 2004).

The relative orientation between this initial frame and the ICRF-Ext.1 is given in Table 1 (first line).

5. GAOUA COMBINED CATALOGUES OF RS POSITIONS

The Kyiv arc length method proposed by Ya. Yatskiv and A. Kur'yanova, 1990, was used for construction of catalogues of type RSC(GAOUA)YY C NN since 1991. This method combines a geometrical arc length calculation with a statistical evaluation of uncertainties of initial and combined catalogues. Several combined solutions based upon initial catalogues of RS positions provided by IERS and/or IVS were constructed (Yatskiv, Molotaj, Kur'yanova and Tel'nyuk-Adamchuk, 2003). The latest version of such combined catalogue is RSC(GAOUA)03 C 02 which contains the positions of 1667 RS, including 211 defining sources (Yatskiv, Kur'yanova, Bolotin, 2004). The positional accuracy of the defining RS is better than about 0.1 mas. The relative orientation between the RSC(GAOUA)03 C 02 and the ICRF-Ext.1 is given in Table 1 (second line).

Frame	N_d	A_1	A_2	A_3
RSC(GAOUA)03 R 01	211	$+24 \pm 30$	$+20 \pm 30$	-15 ± 35
RSC(GAOUA)03 C 02	211	$+4 \pm 26$	-13 ± 26	-11 ± 30

Table 1: Relative orientation between initial frame RSC(GAOUA)03 R 01, combined catalogue RSC(GAOUA) 03 C 02 and ICRF-Ext.1. A_1, A_2, A_3 are the rotation angles (in μas); N_d is the number of common defining sources

IERS Des.	RSC(GAOUA)										St.
	98 C 01		99 C 03		00 C 01		01 C 01		03 C 02		
	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	
$0138-097$	2.22	—	1.63	—	1.64	—	2.34	—	2.03	—	D
$0259+121$	—	—	—	4.70	—	1.25	—	1.45	—	1.39	C
$0440-003$	—	-1.11	—	-1.25	—	-1.08	—	-1.26	—	-1.00	D
$0454-463$	—	—	—	-6.56	—	-17.97	—	-16.73	—	—	C
$0529+075$	-1.38	—	—	—	-1.31	—	—	—	-1.01	—	C
$0600+219$	—	—	—	—	—	1.18	—	1.22	—	2.26	O
$0823-500$	-1.48	—	-1.40	—	-1.32	—	-1.67	—	-7.09	—	C
$1156-094$	1.42	—	1.33	—	1.36	—	1.11	—	1.04	—	C
$1323+321$	-10.74	—	-1.10	—	—	—	-2.36	—	—	—	C
$1328+307$	—	—	-1.01	—	-0.97	—	-0.98	—	-1.32	—	C
$1402-012$	—	1.04	—	0.97	—	0.94	—	2.47	—	2.77	C
$1409+218$	—	—	—	1.10	—	0.99	—	0.91	—	—	C
$1540-828$	2.04	—	2.24	—	2.44	—	1.01	—	—	—	C
$1604-333$	—	—	—	—	0.94	—	1.08	–	0.76	–	D
$1718-649$	—	1.06	—	1.08	—	—	—	1.62	—	1.34	D
$1733-565$	—	—	0.86	—	0.80	—	1.30	—	1.57	—	C
$1740-517$	-2.57	—	-1.71	—	-2.46	—	—	—	—	—	C
$1806-458$	-2.76	—	-1.93	—	-0.92	—	—	—	-1.38	—	C
$1934-638$	-1.95	—	-1.99	—	-2.30	—	-1.08	—	—	—	C
$1951+355$	—	-2.05	—	-1.89	—	-1.79	—	-1.75	—	-1.26	C
$2128+048$	—	—	1.05	—	0.96	—	1.02	—	1.20	—	O
$2312-319$	—	-0.98	—	-1.14	—	-1.19	—	-0.79	—	—	D

Table 2: Statistics of large differences of type "Combined catalogue − ICRF-Ext.1" (in mas). D is defining RS, C is candidate RS and O is other RS

IERS Des.	RSC(GAOUA)									
	98 C 01		99 C 03		00 C 01		01 C 01		03 C 02	
	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$	$\Delta\alpha_*$	$\Delta\delta$
$0039+230$	—	—	—	—	—	0.54	—	0.53	—	0.68
$0123+257$	—	—	—	-0.47	—	—	—	-0.68	—	-0.57
$0131-522$	—	—	—	0.71	—	0.58	—	—	—	1.53
$0138-097$	2.22	—	1.63	—	1.64	—	2.34	—	2.03	—
$0437-454$	-0.54	—	-0.48	—	-0.47	—	-0.44	—	—	—
$0440-003$	—	-1.11	—	-1.25	—	-1.08	—	-1.26	—	-1.00
$0458+138$	—	-0.76	—	-0.97	—	-0.84	—	-0.85	—	-0.39
$0518+165$	—	0.69	—	0.56	—	0.48	—	0.47	—	0.36
$0537-286$	0.40	—	0.42	—	0.46	—	0.51	—	0.63	—
$0733-174$	-0.30	—	-0.52	-0.48	-0.50	—	-0.52	-0.51	-0.60	-0.93
$0812+367$	—	—	—	0.72	—	0.71	—	0.73	—	0.52
$0829+046$	—	—	—	0.52	—	0.52	—	0.47	—	0.48
$1038+064$	—	-0.60	—	-0.62	—	-0.58	—	-0.54	—	-0.47
$1143-245$	—	—	-0.79	—	-0.87	—	-0.90	—	-0.74	—
$1448+762$	0.75	—	0.84	—	0.88	—	0.98	—	0.72	—
$1604-333$	—	—	—	—	0.94	—	1.08	—	0.76	—
$1616+063$	—	—	—	-0.66	—	-0.61	—	-0.60	—	—
$1718-649$	—	1.06	—	1.08	—	—	—	1.62	—	1.34
$1727+502$	—	—	—	—	-0.53	—	-0.57	—	0.89	—
$2059+034$	—	-1.03	—	-0.76	—	-0.66	—	-0.63	—	-0.62
$2312-319$	—	-0.98	—	-1.14	—	-1.19	—	-0.79	—	-0.46

Table 3: Statistics of large differences of type "Combined catalogue − ICRF-Ext.1" for common defining RS (in mas)

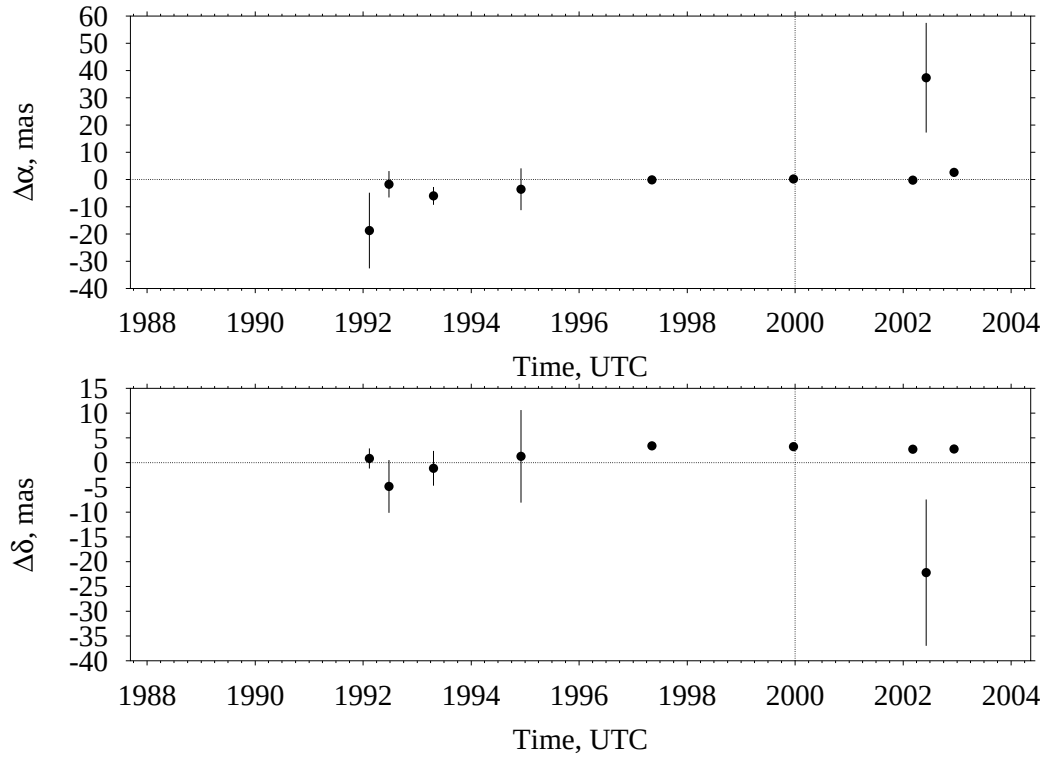

Figure 1: Estimated variations of the coordinates of radio source 1402-012, right ascension (upper figure) and declination.

IERS Des.	A_α mas	V_α mas/yr	A_δ mas	V_δ mas/yr	σ_α mas	σ_δ mas	σ mas	N_s	N_d	St.
$0039+230$	-0.06	0.02	0.89	0.16	0.16	0.27	0.32	5	350	D
$0123+257$	0.17	0.02	-0.84	-0.08	0.18	0.26	0.32	9	477	D
$0138-097$	1.85	-0.01	0.03	-0.04	0.14	0.18	0.23	3	232	D
$0259+121$	0.11	-0.03	1.67	-0.02	0.55	0.20	0.58	4	228	C
$0437-454$	-0.11	0.06	-0.73	-0.21	0.27	0.81	0.85	6	46	D
$0440-003$	-0.46	-0.11	-1.53	-0.09	0.23	0.23	0.32	11	459	D
$0458+138$	-0.09	-0.08	-0.07	-0.10	0.16	0.51	0.53	4	272	D
$0518+165$	-3.45	-0.45	5.39	0.55	0.97	1.71	1.97	6	64	D
$0529+075$	3.36	0.84	0.21	0.11	1.01	1.72	1.99	7	63	C
$0537-286$	0.79	0.03	-0.58	-0.00	0.27	0.43	0.50	14	305	D
$0733-174$	-0.61	-0.11	-1.69	-0.22	0.23	0.55	0.59	7	182	D
$0812+367$	0.37	-0.01	0.77	0.04	0.26	0.45	0.52	7	286	D
$0829+046$	0.00	-0.02	0.50	0.04	0.36	0.38	0.52	13	426	D
$1038+064$	-0.05	-0.04	-0.47	0.04	0.30	0.52	0.60	38	752	D
$1143-245$	-1.19	-0.14	0.42	0.03	0.51	0.37	0.63	9	299	D
$1156-094$	0.78	-0.00	0.25	-0.30	0.09	1.01	1.01	4	96	C
$1323+321$	15.34	3.92	-9.60	-2.26	3.23	1.37	3.51	5	119	C
$1328+307$	-1.31	0.15	-0.66	0.05	0.83	0.55	0.99	4	149	C
$1402-012$	0.08	0.10	3.05	-0.08	0.63	0.39	0.74	6	218	C
$1409+218$	0.69	0.12	1.15	-0.14	0.33	0.30	0.44	4	218	C
$1448+762$	0.88	-0.09	0.11	0.01	0.22	0.17	0.28	29	3530	D
$1604-333$	0.24	-0.04	-0.75	-0.10	1.02	0.88	1.35	8	159	D
$1616+063$	0.08	-0.01	-0.57	-0.03	0.16	0.49	0.51	7	384	D
$1718-649$	-2.12	-0.31	4.52	0.62	0.73	1.03	1.26	3	29	D
$1727+502$	1.31	0.36	-0.53	0.03	0.38	0.47	0.60	3	96	D
$1951+355$	-0.08	-0.03	-1.29	0.08	0.48	0.52	0.71	5	164	C
$2059+034$	-0.31	0.01	-0.65	-0.01	0.18	0.29	0.35	13	750	D
$2128+048$	-0.66	-0.32	-2.91	-0.35	0.78	0.59	0.97	4	35	O
$2312-319$	-0.49	0.04	-0.63	0.30	0.35	0.77	0.85	6	262	D

Table 4: Statistics of time series of coordinates of radio sources, unstable or suspected of instability according to adopted criterion; N_s is number of sessions, N_d is number of observations

6. MAINTENANCE OF THE TIME STABILITY OF THE ICRF

The IAU has charged the IERS with the responsibility of monitoring the ICRS and maintaining its current realization. The MAO NASU being involved in the IERS activity has undertaken the study of the time stabilities of RS coordinates. With this end in view we have analyzed the year-to-year differences between positions of RS in the combined frames RSC(GAOUA) constructed since 1998, and the ICRF-Ext.1 (Yatskiv et al. 2004). The large differences in RA and Dec were identified with the help of simple criteria, namely the differences larger then 1 mas (for all RS) and 0.45 mas (for defining RS) were considered as large ones in case that they occur not less than three times. Table 2 and 3 summarize the results of this study.

Based on this study we concluded that there were about 22 RSs which have exhibited large systematic differences. Four of these RSs are defining sources, namely 0138-097, 0440-003, 1718-649 and 2312-319. These RS are suspected of instabilities and should be excluded from a subset of objects that is used for the maintenance of the ICRF.

To reach a final conclusion on this problem we have analyzed the time stabilities of coordinates of these "unstable" RS using the approach proposed by M. Feissel (Feissel-Vernier, 2004).

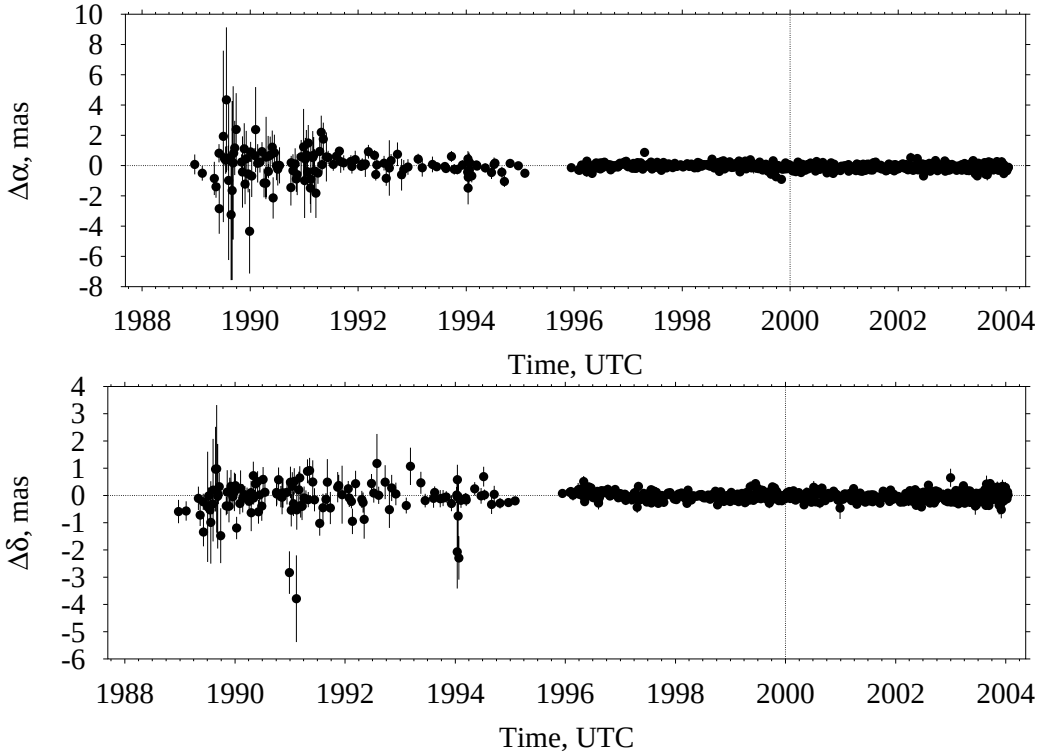

Figure 2: l Estimated variations of the coordinates of radio source 0133+476, right ascension (upper figure) and declination.

IERS Des.	A_α mas	V_α mas/yr	A_δ mas	V_δ mas/yr	σ_α mas	σ_δ mas	σ mas	N_s	N_d
$0014+813$	-0.07	-0.01	0.19	0.03	0.15	0.18	0.23	629	41870
$0133+476$	-0.04	-0.01	-0.03	-0.01	0.11	0.14	0.18	658	58061
$0642+449$	0.01	0.00	0.02	-0.01	0.13	0.16	0.21	641	39146
$0804+499*$	0.08	-0.00	-0.01	-0.01	0.13	0.16	0.21	825	57321
$0955+476$	-0.09	-0.03	0.01	0.00	0.13	0.16	0.21	1157	71070
$1128+385$	-0.03	-0.01	0.01	0.00	0.14	0.21	0.25	713	39793
$1308+326*$	0.04	0.00	0.07	0.01	0.23	0.23	0.33	1189	70529
$1606+106*$	0.08	0.02	0.01	-0.00	0.19	0.22	0.29	1339	64916
$2037+511*$	-0.13	-0.01	-0.14	-0.00	0.15	0.20	0.25	443	17602
$2145+067*$	-0.18	-0.03	0.03	0.01	0.29	0.27	0.39	1535	64450

Table 5: Estimates of trends of coordinates of defining RS (considered as sufficiently stable)

For this purpose all applicable VLBI data since 1988 were reduced using the SteelBreeze software. Firstly the standard solution for terrestrial and celestial frames as well as for ERP was made. Then solved for parameters obtained on this stage were used for determination of the year-to-year variations of coordinates of those RS which were suspected to be unstable. These variations were approximated by linear trends

$$\begin{aligned} \Delta\alpha_i cos\delta_i &= A_\alpha + V_\alpha(t_i - t_o) \\ \Delta\delta_i &= A_\delta + V_\delta(t_i - t_o), \end{aligned}$$

where t_o is a mean epoch of observations.

The estimates obtained are given in Table 4, where σ_α and σ_δ are rms of the post-fit residuals in $\Delta\alpha_i cos\delta_i$ and $\Delta\delta_i$ respectively and σ is the modulus of their vectorial sum.

On the basis of these results we come to a conclusion that the coordinates of some of RS exhibit considerable time variations. An example of such variations for RS 1402-012 is shown on Fig. 1.

To answer the question on a reality of the coordinate variations of RS given in Table 4 we have to define the stability level σ_0. Then we will consider the sources as unstable for which the values σ are larger than σ_o. We derived $\sigma_o = 0.40mas$ on the basis of analysis of the year-to-year variations of the coordinates of those RS which is known are sufficiently stable ones (see Table 5 and Fig. 2).

One can see that there are 23 RS for which $\sigma > \sigma_o$. Among them there are two defining RS which were suspected to be unstable on the first step of analysis, namely 1718-649 and 2312-319.

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