New Pulkovo combined catalogues of the radio source positions

Julia Sokolova, Zinovy Malkin

Pulkovo Observatory, Russia

Context:

- Introduction
- **Investigation of a possibility to improve the ICRF by means of combining individual CRF catalogues**

  - Comparison of WRMS differences between catalogues and ICRF 2
  - Determination of systematic differences between input catalogues and ICRF2 with accounting for correlations
  - Construction of a combined catalogue in the ICRF2 system *(*stochastic improvement of the ICRF2*)*
  - Construction of a final combined catalogue (stochastic and systematic improvement of the ICRF2)

Introduction:

- Catalogues of radio source positions obtained from Very Long Baseline Interferometry (VLBI) observations serve as the realizations of the IAU International Celestial Reference System (ICRS) since 1998.
- One of the commonly used method of improving the accuracy of the source position catalogues is construction of a combined catalogue. In this paper, we present new Pulkovo combined catalogues which have been constructed mainly following the strategy developed by Sokolova & Malkin (2007, A&A, 474, 665).
- The PUL(2012)C01 catalogue is aimed at stochastic improvement of the ICRF2, the PUL(2012)C02 catalogue is constructed in the independent system.

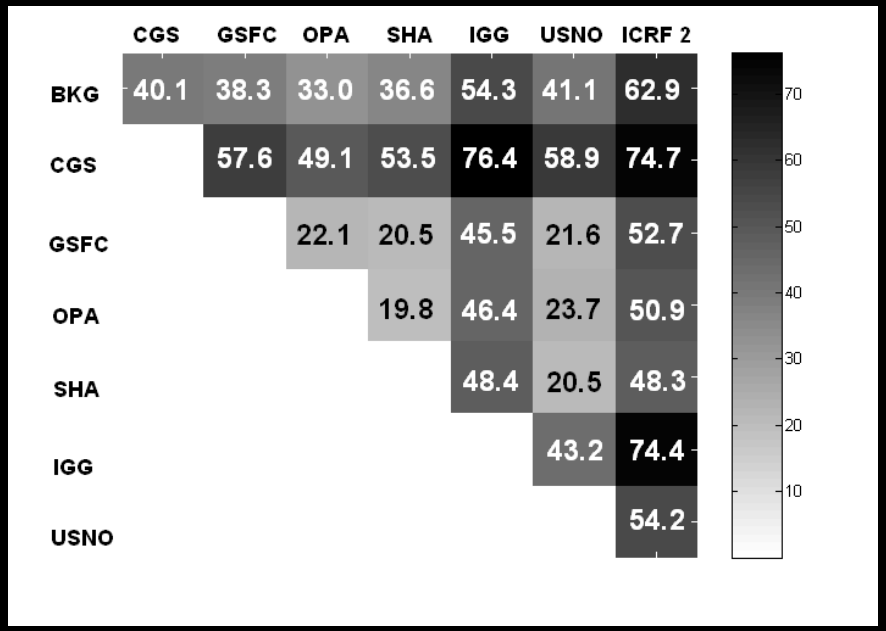
Input Catalogues :

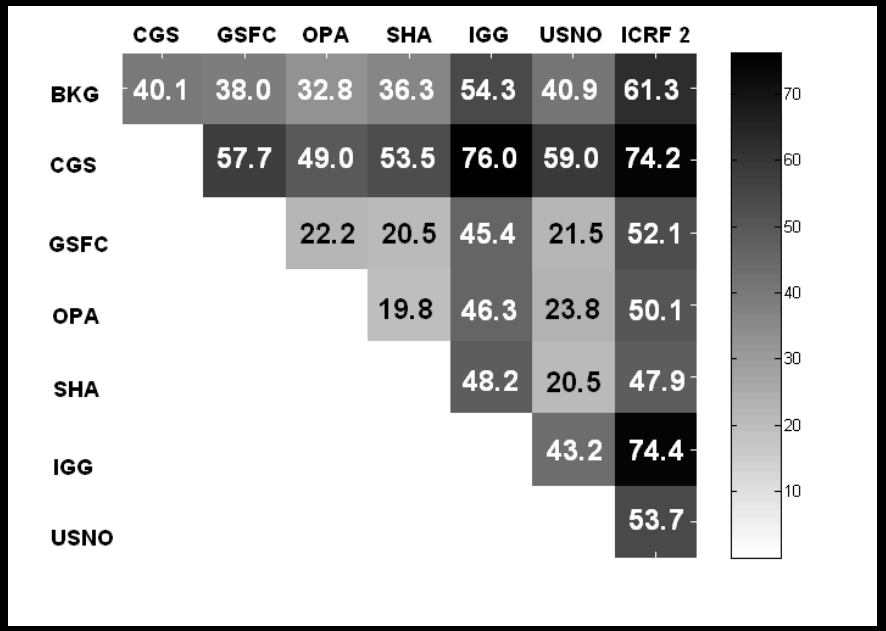
Input catalogues. The last column shows number of the sources in the catalogue we used and number of reference sources used to tie the orientation of the catalogue to ICRF.

Catalogue	Centre	Software	Time-Span month/year	Number of Sources
bkg2011a	BKG, Germany	CALC / SOLVE	01/1984 – 09/2011	3214 / (283)
cgs2012a	CGS, Italy	CALC / SOLVE	04/1980 – 12/2011	842 / (281)
gsf2011b	GSFC, USA	CALC / SOLVE	- /2011	3518 / (295)
opa2012a	OPA, France	CALC /SOLVE	08/1979-01/2012	3482 / (295)
sha2012b	SHA, China	CALC /SOLVE	08/1979-04/2012	3470 / (295)
igg2012a	TU Vienna, Austria	VieVS	1984 - 2011	840 / (277)
usn2012a	USNO, USA	CALC /SOLVE	08/1979-02/2009	793 / (295)

We will use 271 radio sources–common ICRF 2 defining sources for ALL catalogues.

WRMS differences between catalogues :





WRMS differences between input catalogues and ICRF 2. Unit: μas

(without accounting for correlation (α,δ) left, and with correlation(α,δ) on a right)

Accounting for Correlation (α/δ)

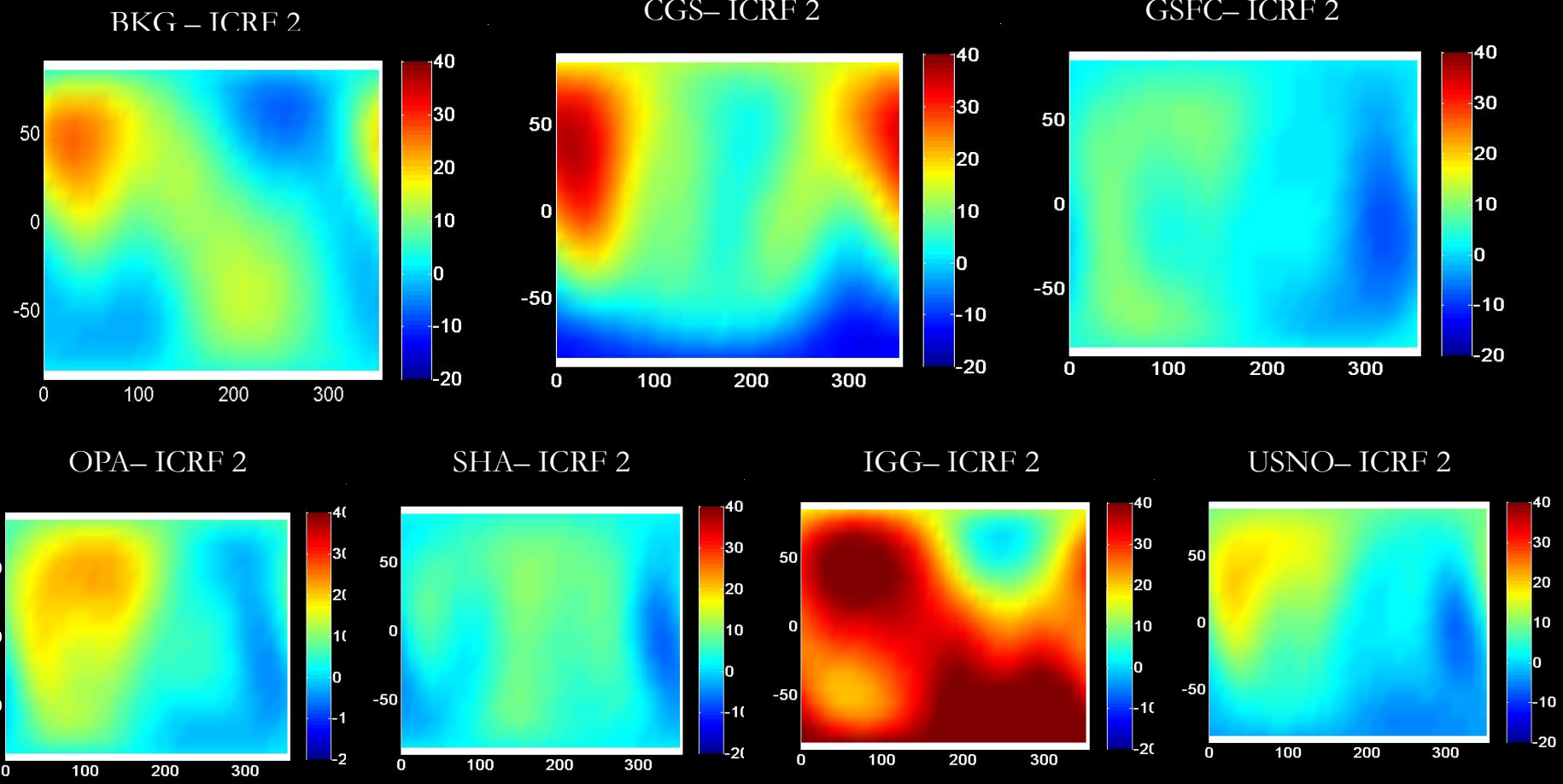
Table 2: Rotation Parameters and WRMS residuals between the input catalogues and ICRF2 , (μas)

Catalogue	A1	A2	A3	Wrms		ΔWrms
				before	after	
bkg2011a	25.17 ± 4.27	17.14 ± 4.29	-08.67 ± 3.75	62.9	59.9	3.0
	25.38 ± 4.13	17.53 ± 4.17	-10.66 ± 3.63	61.3	58.0	3.3
cgs2012a	14.03 ± 5.23	-05.34 ± 5.28	-12.82 ± 4.62	74.7	73.6	1.1
	14.14 ± 5.17	-03.99 ± 5.22	-17.31 ± 4.56	74.2	72.8	1.4
gsf2011b	-03.52 ± 3.71	06.55 ± 3.74	-02.48 ± 3.28	52.7	52.5	0.2
	-03.89 ± 3.67	06.50 ± 3.70	-01.56 ± 3.24	52.1	51.8	0.3
opa2012a	-04.56 ± 3.54	11.18 ± 3.57	-08.60 ± 3.14	50.9	49.9	1.0
	-04.99 ± 3.48	11.44 ± 3.51	-09.16 ± 3.08	50.1	49.1	1.0
sha2012b	-03.66 ± 3.40	03.16 ± 3.43	-04.51 ± 3.02	48.2	48.0	0.2
	-03.68 ± 3.38	03.24 ± 3.41	-04.58 ± 2.99	47.9	47.7	0.2
igg2012a	0.53 ± 4.82	34.32 ± 4.90	-27.89 ± 4.36	74.4	68.7	5.7
	0.53 ± 4.84	34.11 ± 4.94	-26.73 ± 4.38	74.4	69.1	5.3
usn2012a	-03.61 ± 3.80	10.61 ± 3.83	-05.37 ± 3.37	54.2	53.7	0.5
	-04.08 ± 3.76	10.89 ± 3.80	-04.47 ± 3.33	53.7	53.1	0.6

Without accounting for correlation (α/δ)
With accounting

Smooth differences between catalogues and ICRF2

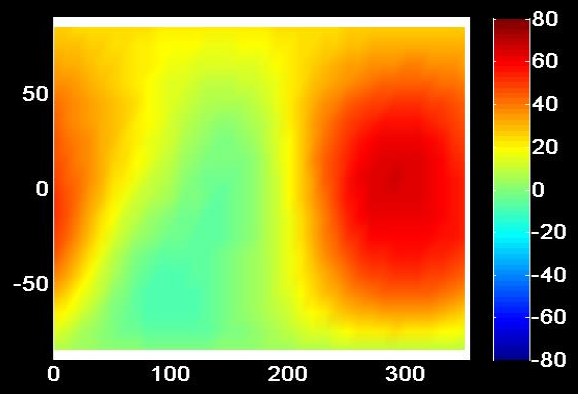
$\Delta\alpha$ (μas)



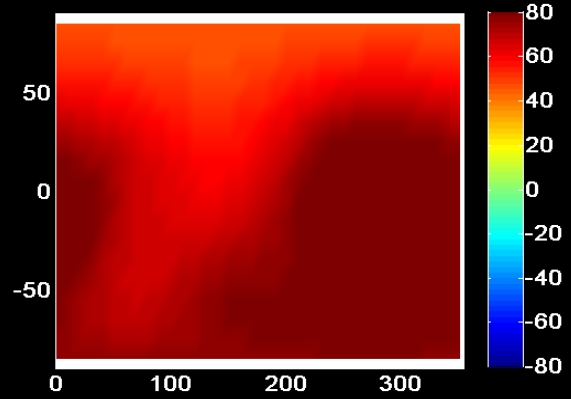
Smooth differences between catalogues and ICRF2

$\Delta\delta$ (μas)

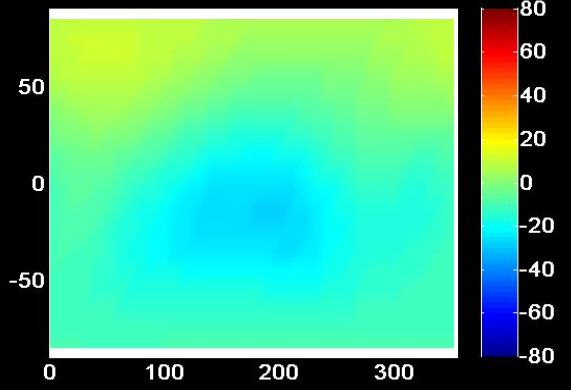
BKG – ICRF 2



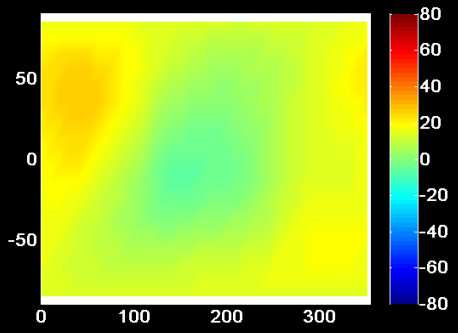
CGS– ICRF 2



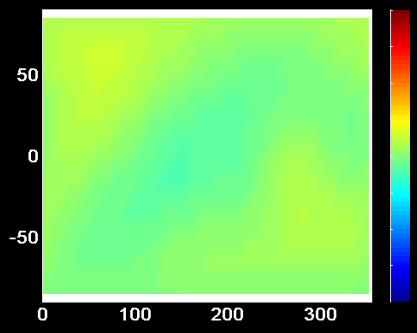
GSFC– ICRF 2



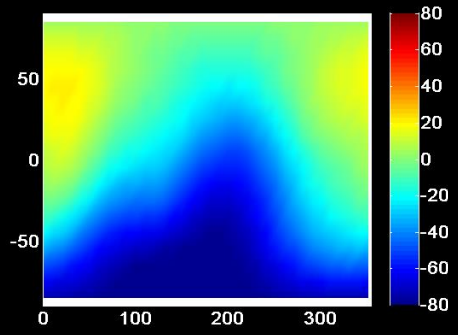
OPA– ICRF 2



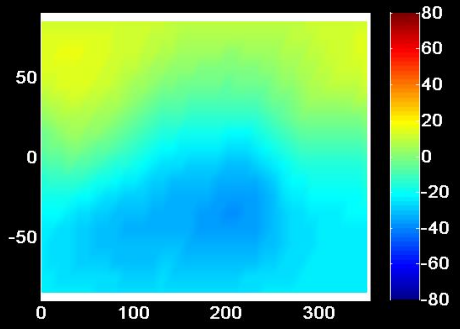
SHA– ICRF 2



IGG– ICRF 2



USNO– ICRF 2



Analytical representation of systematic differences

1. Simple Rotation Model:

$$\Delta\alpha = A_1 \tan\delta\cos\alpha + A_2 \tan\delta\sin\alpha - A_3,$$
$$\Delta\delta = -A_1 \sin\alpha + A_2 \cos\alpha.$$

2. Rotation with Deformation Model:

$$\Delta\alpha = A_1 \tan\delta\cos\alpha + A_2 \tan\delta\sin\alpha - A_3 + D_\alpha(\delta - \delta_0),$$
$$\Delta\delta = -A_1 \sin\alpha + A_2 \cos\alpha + D_\delta(\delta - \delta_0) + B_\delta.$$

3. Brosche's Method:

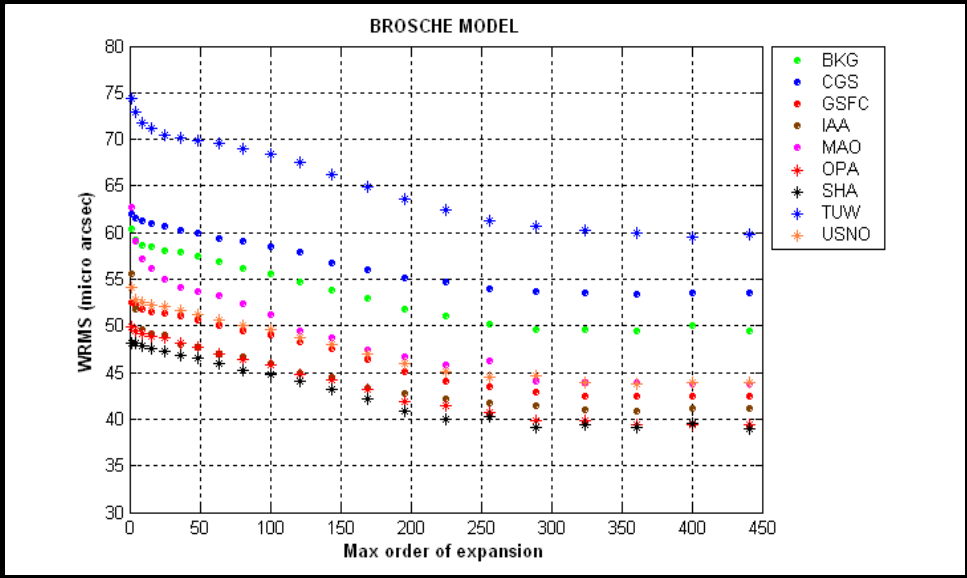
$$\begin{Bmatrix}\Delta\alpha\\ \Delta\delta\end{Bmatrix} = \sum_{j=0}^{g} b_j Y_j(\alpha,\delta) + \varepsilon$$

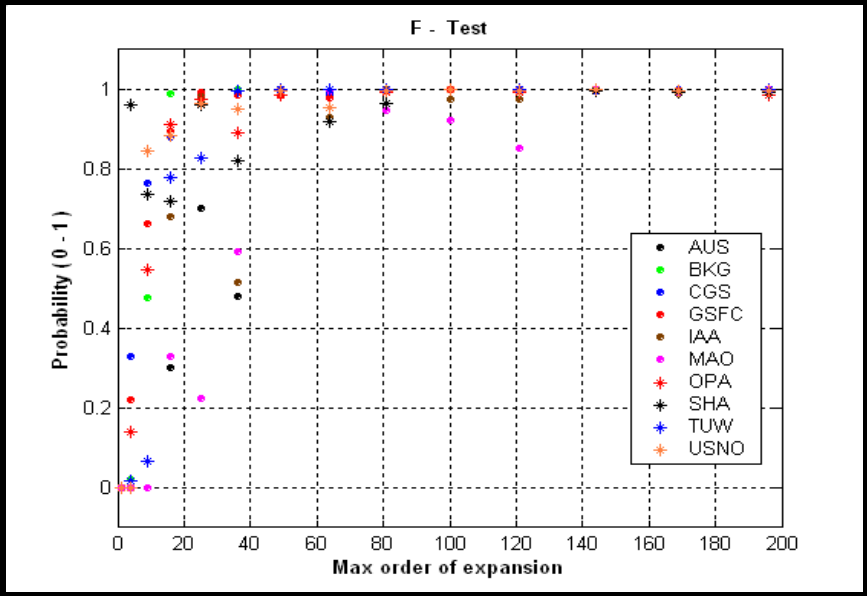
$$Y_j = K_i(\alpha,\delta) = \begin{cases} P_{n0}(\delta), & k=0, l\neq 1\\ P_{nk}(\delta)\sin(k\alpha), & k\neq 1, l=0\\ P_{nk}(\delta)\sin(k\alpha), & k\neq 1, l=0\end{cases}$$

$$P_{nk}(\delta) = \cos^k(\delta)\left[\sin^p(\delta) + \sum_{\mu=1}^{[p/2]} \frac{(-1)^\mu \prod_{\nu=0}^{2\mu-1}(p-\nu)}{\prod_{\nu=1}^{\mu} 2\nu(2n-2\nu+1)} \sin^{p-2\mu}(\delta)\right], \quad \begin{matrix} n=0,1,2,\ldots\\ k=0,1,2,..n\end{matrix}$$

Choosing the maximum order of expansion.

Picture. Number of parameters vs WRMS





Picture. F-Test
Probability vs number of expanison parameters

WRMS residuals between the input catalogues and ICRF2 before (Raw) and after approximation by one of the 3 models.

	BKG	CGS	GSFC	OPA	SHA	IGG	USNO
Not accounting for correlations							
RAW	62.9	74.7	52.7	50.9	48.3	74.4	54.2
ROT	59.9	73.6	52.5	49.9	48.0	68.7	53.7
ROT+DEF	56.0	53.3	51.5	49.1	48.0	65.1	51.5
BROSCHE	51.8	53.1	45.0	41.7	40.8	63.5	45.8
Accounting for Correlations							
RAW	61.3	74.2	52.1	50.1	47.9	74.4	53.7
ROT	58.0	72.8	51.8	49.1	47.7	69.1	53.1
ROT+DEF	54.1	52.3	50.8	48.2	47.6	65.4	50.9
BROSCHE	48.9	52.6	43.6	40.6	39.9	62.7	44.5
ROT+DEF+ BROSCHE	47.1	45.0	44.5	42.0	41.2	57.6	44.6

Unit: micro arcsec.

Construction of a combined catalogues

1. $CRF_k \xrightarrow{Model} CRF_k^{ICRF}$
2. Calculate a combined catalogue in the ICRF system (stochastic improvement of the ICRF)

$$\alpha_i^{C1} = \frac{\sum_k \alpha_i'^k \cdot P_{\alpha i}^k}{\sum_k P_{\alpha i}^k},$$

$$\delta_i^{C1} = \frac{\sum_k \delta_i'^k \cdot P_{\delta i}^k}{\sum_k P_{\delta i}^k},$$

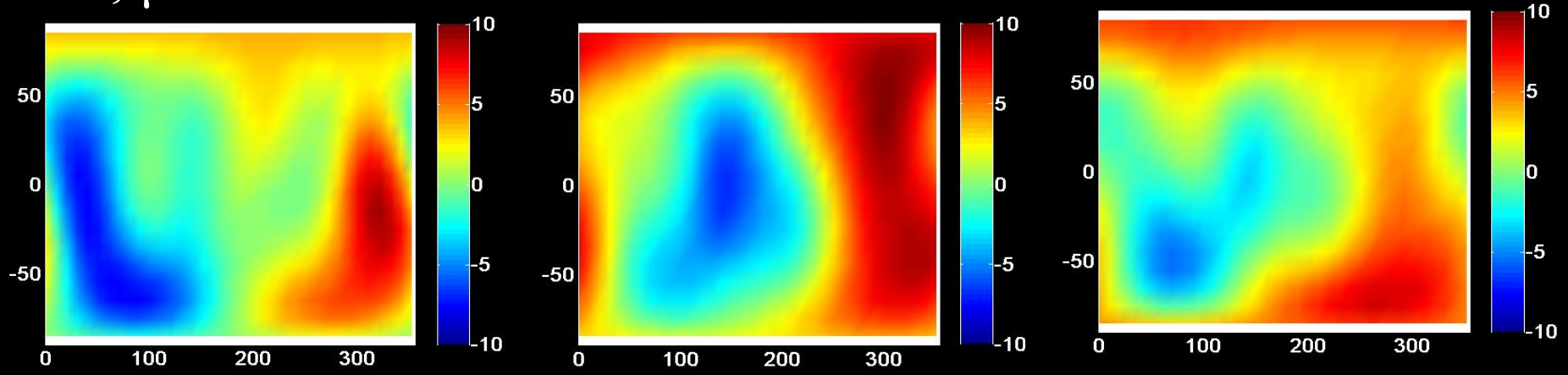
$$P_{\alpha i}^k = \frac{1}{\left(\sigma_{\alpha i}^k\right)^2 + \left(\sigma_{\alpha i}^{ICRF}\right)^2},$$

$$P_{\delta i}^k = \frac{1}{\left(\sigma_{\delta i}^k\right)^2 + \left(\sigma_{\delta i}^{ICRF}\right)^2}$$

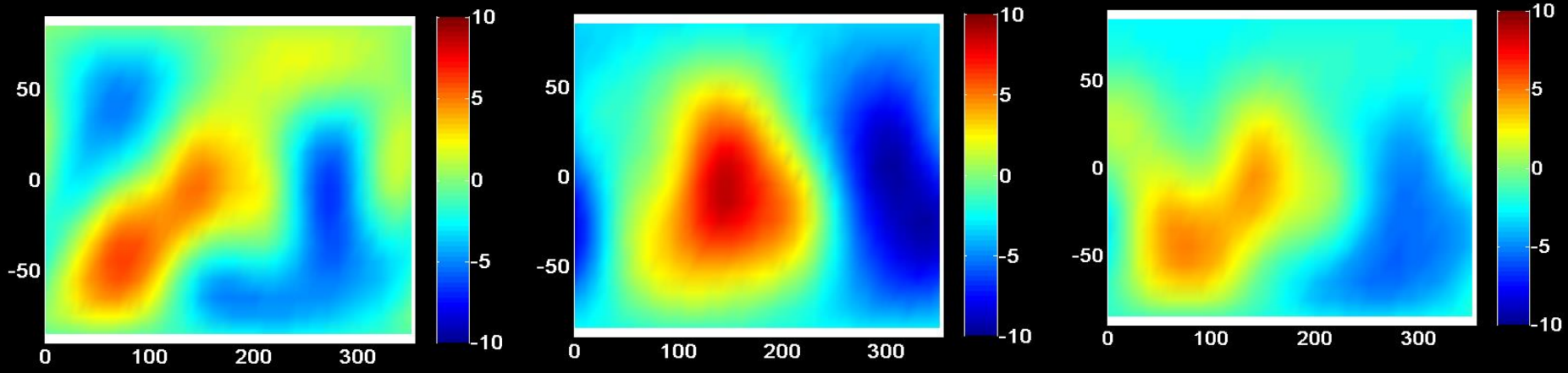
PULC01 (in the ICRF2 sytem) — ICRF 2

ROT+DEF, Brosche, ROT+DEF + Brosche (left to right)

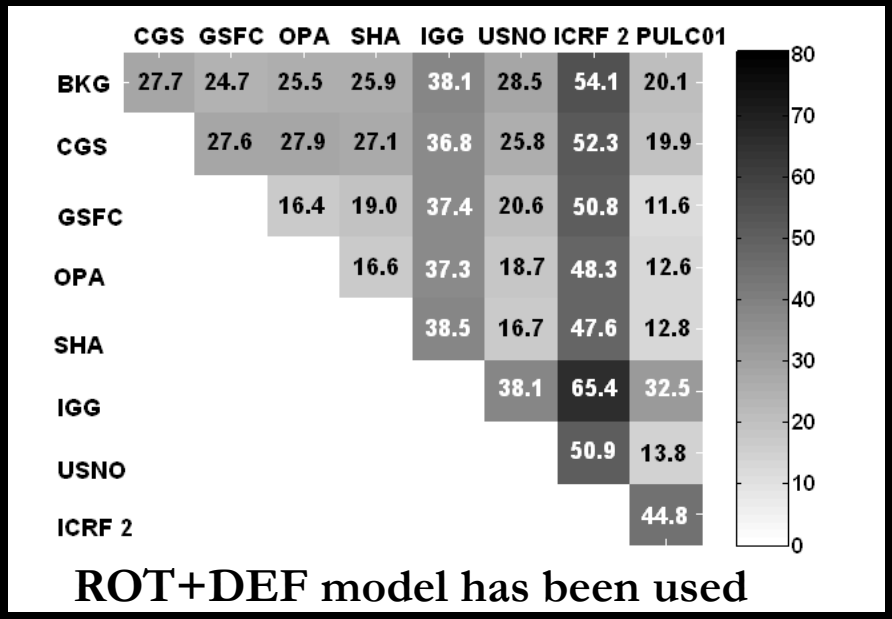
$\Delta\alpha$, μas



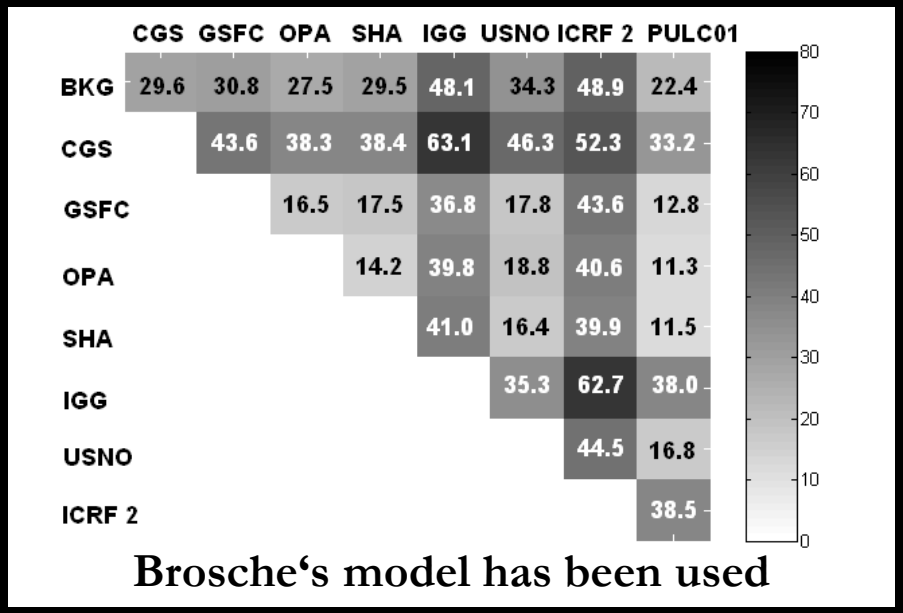
$\Delta\delta$, μas



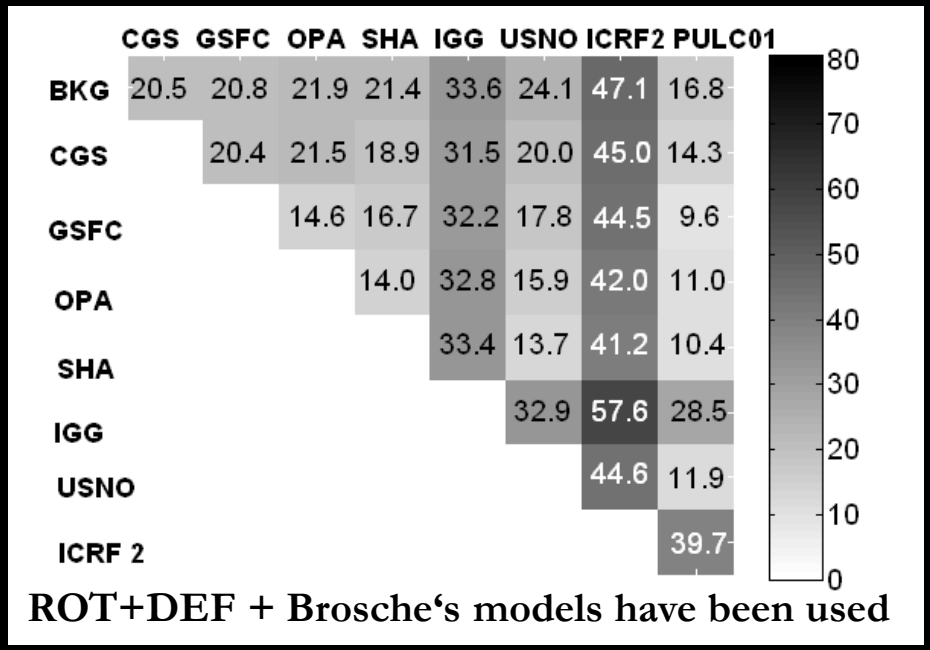
WRMS differences between catalogues :



ROT+DEF model has been used



Brosche‘s model has been used



ROT+DEF + Brosche‘s models have been used

Construction of the final combined catalogues

3. Calculate a mean system $(\Delta\alpha', \Delta\delta')$

$$\begin{Bmatrix} \Delta\alpha'_i \\ \Delta\delta'_i \end{Bmatrix} = \frac{1}{M} \sum_m \sum_{nkl} b^{im}_{nkl} R_{nkl} \cdot L_n(\sin\delta_i) \cdot F_{kl}(\alpha_i)$$

4. Calculate a weighted mean system $(\Delta\alpha'', \Delta\delta'')$ using CRF weights for the bins $10°(\alpha) \times 5°(\delta)$

Weights of the input CRF normalized and averaged over the sky

BKG	CGS	GSFC	OPA	SHA	TUW	USNO
0.72	0.39	1.00	0.57	0.98	0.25	0.90

5. Calculate a final combined catalogue

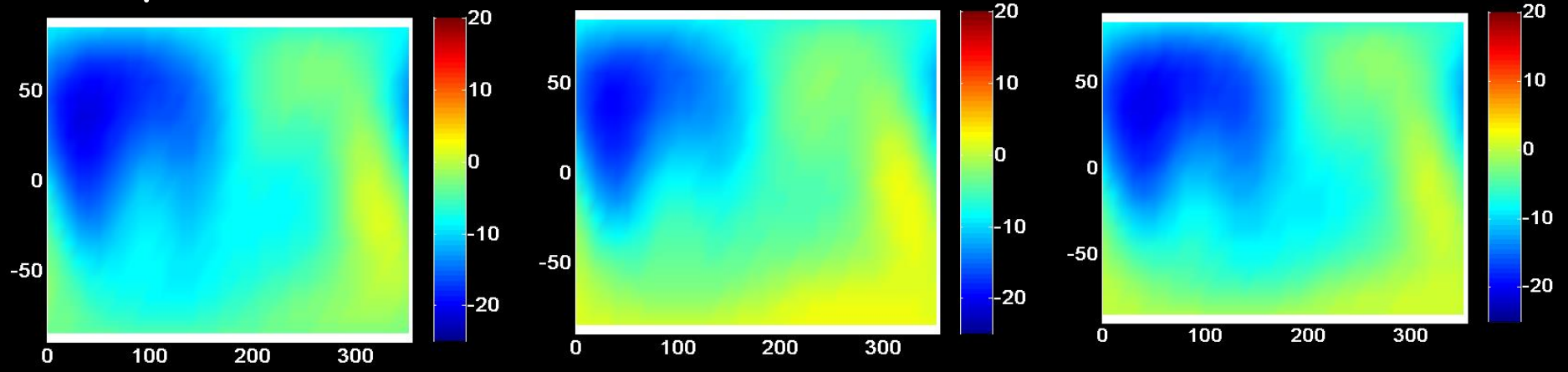
(stochastic and systematic improvement of the ICRF)

$$\alpha_i^{C2} = \alpha_i^{C1} + \Delta\alpha''_i, \qquad \delta_i^{C2} = \delta_i^{C1} + \Delta\delta''_i$$

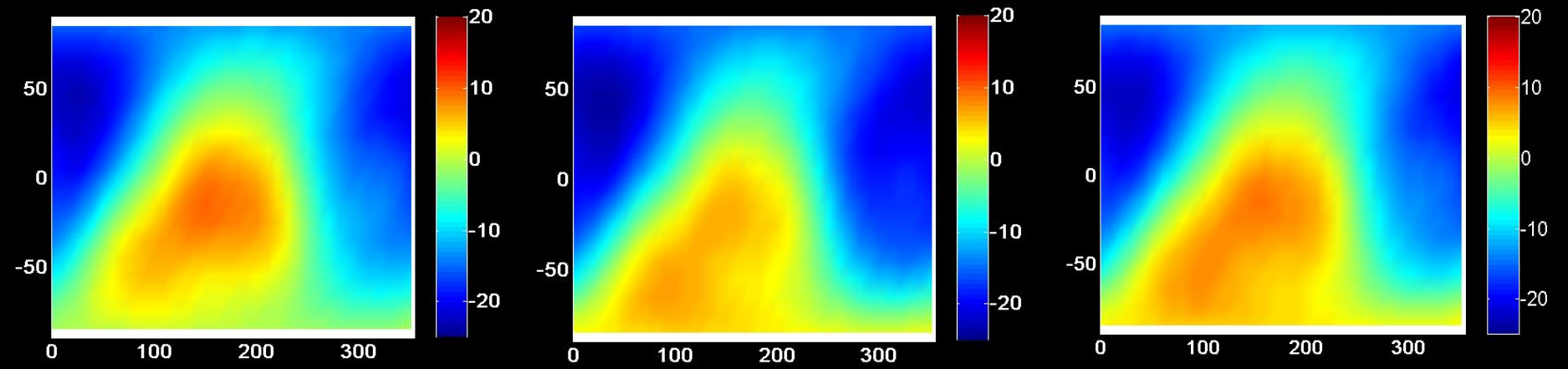
PULC02 — ICRF 2

ROT+DEF, Brosche, ROT+DEF + Brosche (left to right)

$\Delta\alpha$, μas



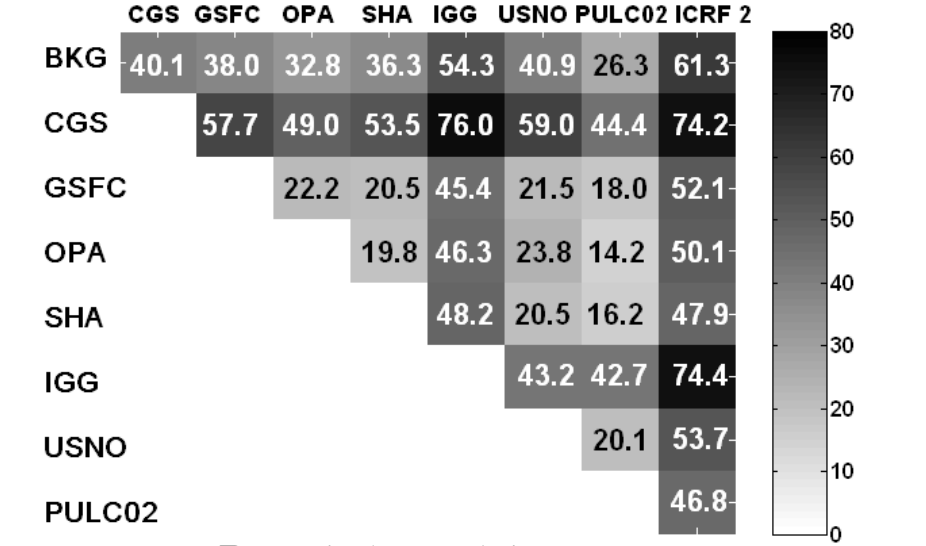
$\Delta\delta$, μas



WRMS differences between catalogues :

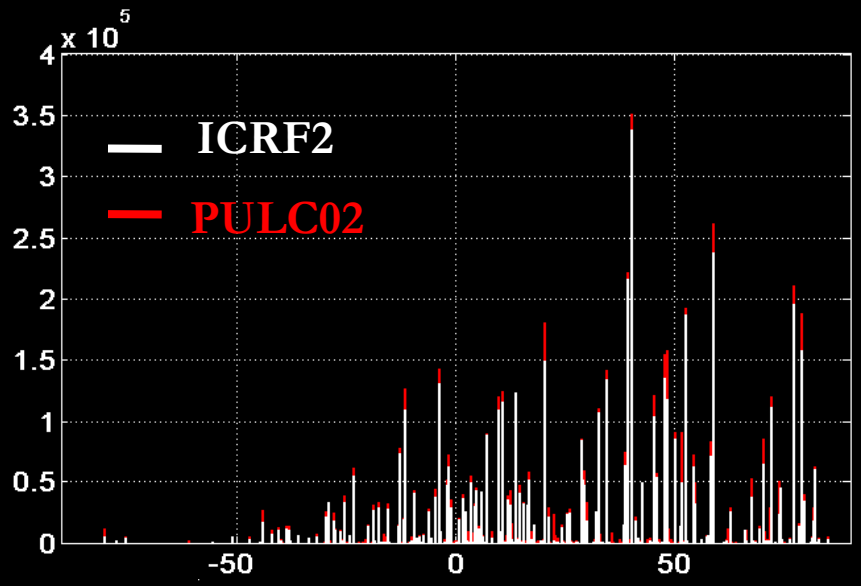
Differences between PULC02 and catalogues

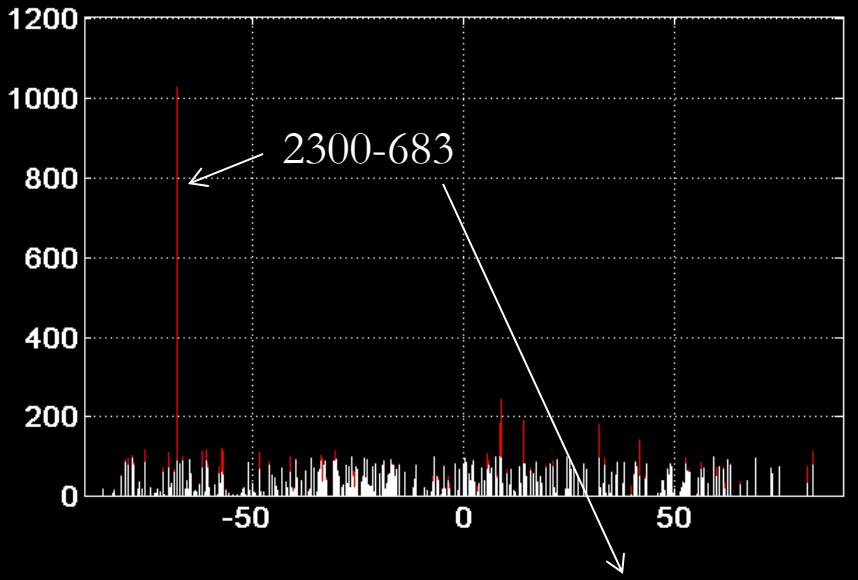
MODEL	BKG	CGS	GSFC	OPA	SHA	IGG	USNO	ICRF2
ROT+DEF	27.6	45.7	17.6	13.5	15.8	41.7	18.8	46.4
BROSCHE	26.3	44.4	18.0	14.2	16.2	42.7	20.1	46.8
ROT+DEF+ BROSCHE	27.4	45.8	18.0	13.6	15.8	41.2	19.1	46.5

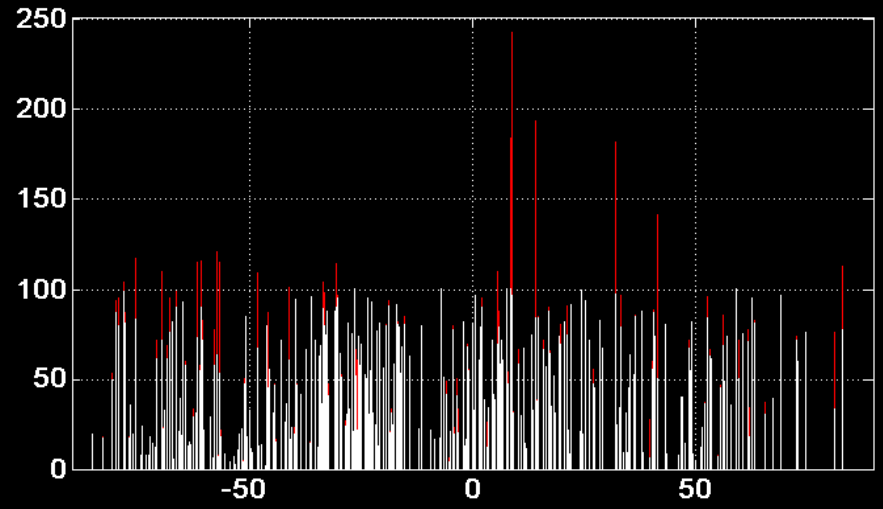


Brosche's model

Number of observation in ICRF2 and PULC02

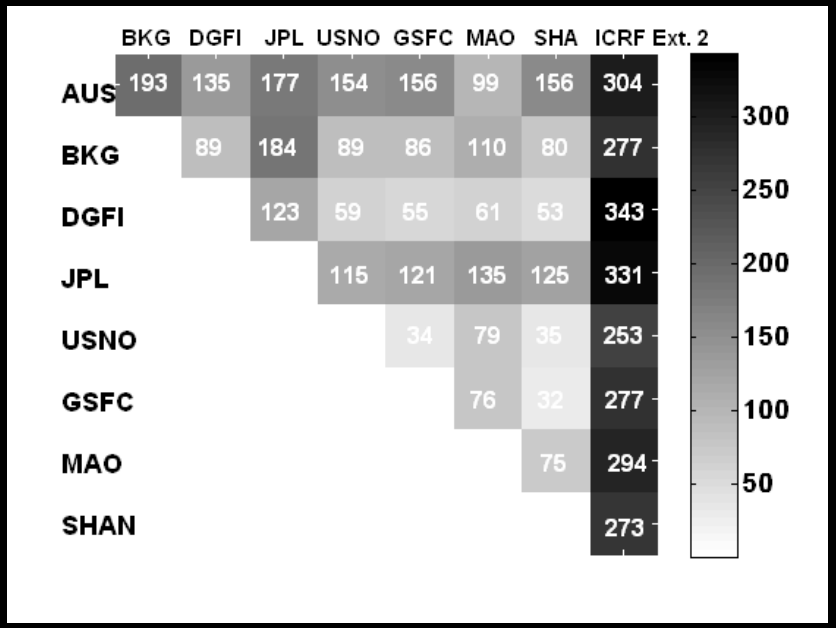




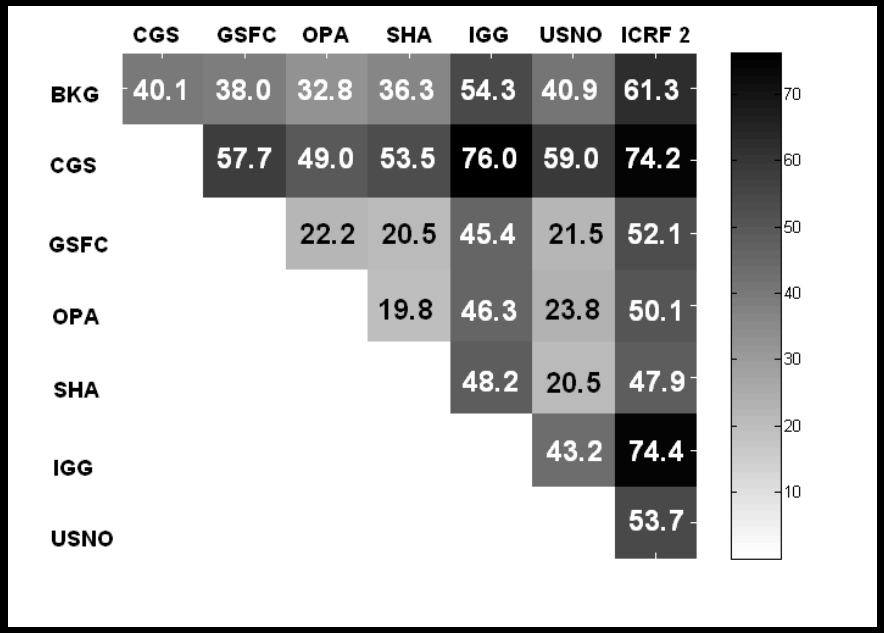


Catalogues	Nobs
ICRF2	91
BKG 2011a	282
CGS 2012a	786
GSFC 2011b	1013
OPA 2012a	981
USNO	1025

Catalogues (2004-2005) and catalogues (2011-2012)



WRMS differences between catalogues (2004-2005) and ICRF Ext.2



WRMS differences between catalogues (2011-2012) and ICRF2

Summary:

- **Accounting for correlation:**
  - Slightly Imrovement, (допишу потом)
- **Catalogues**
  - Need more catalogues obtained by various software
- **Approximation models**
  - For input catalogues models ROT+DEF and Brosche both work on approximately the same level
- **Comparison and combination of catalogues allow fast and efficiently find problems in ICRF and estimate apropriate time for ICRF update.**

Thank you for your attention.