Russian Academy of Sciences
Central Astronomical Observatory at Pulkovo

Connecting terrestrial to celestial reference frames

Zinovy Malkin
Pulkovo Observatory and St. Petersburg University
St. Petersburg, Russia
malkin@gao.spb.ru

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Motivation

The latest ITRF realizations are derived from combination of normal equations obtained from four space geodesy techniques: VLBI, GPS, SLR, and DORIS, whereas ICRF is a result of global VLBI solution.

The latter includes a procedure to tie the VLBI solution to ITRF using an arbitrary set of reference stations. Thus VLBI serves as the only technique that can connect ITRF and ICRF in a single solution.

But VLBI relies on ITRF origin provided by satellite techniques and shares responsibility with SLR for ITRF scale.

And all the techniques contribute to positions and velocities of ITRF stations.

This situation causes complicated mutual impact of ITRF and ICRF, which should be carefully investigated in order to improve the accuracy of both ICRF and ITRF and the consistency between each other and EOP.

Motivation

(EOP)
CRF ⟷ TRF

We are striving to satisfy this equations with accuracy at the level of 1 mm (30 µas), but cannot yet. Why?

- Poor ITRF network, i.e. number and distribution of active and stable (systematically and geologically) stations, VLBI and SLR in the first place.
- Insufficient number of suitable radio sources (VLBI).
- Incompleteness of the theory/models (e. g. reference systems definition, geophysics).
- Not fully understood and agreed all the details of processing strategy (parameterization, constraints).

As a consequence, we faced with systematic errors and mutual impact of CRF and TRF realizations, which cannot be fixed by datum correction during current combination.

Consistency between TRF, CRF, and EOP

In fact, consistency between TRF and CRF we are talking about is consistency between TRF, CRF, and EOP. Systematic EOP differences are the functions of the reference frames rotational differences:

$$\Delta x = R2$$

$$\Delta y = R1$$

$$\Delta \mathrm{UT1} = (-R3 + A3) / f$$

$$\Delta \mathrm{dX} = A2$$

$$\Delta \mathrm{dY} = -A1$$

For GNSS, TRF rotation should also be consistent with the orbit rotation thus involving the dynamical frame rotational errors.

Consistency between TRF, CRF, and EOP

- **Old optical era:**
  ► CRF from astrometry.
  ► TRF and EOP from geodesy, time and latitude services.

- **Space geodesy era**
  ► VLBI provides internally consistent CRF-TRF-EOP solution NNR/NRT linked to external TRF.
  ► Satellite technique provides internally consistent TRF-EOP-Geopotential solution.
  ► IERS provides ITRF consistent TRF-EOP solution using all space geodesy techniques; TRF-EOP-CRF .

- **New optical era:**
  ► Independent CRF from space astrometry.
  ► Link with space geodesy techniques under discussion.

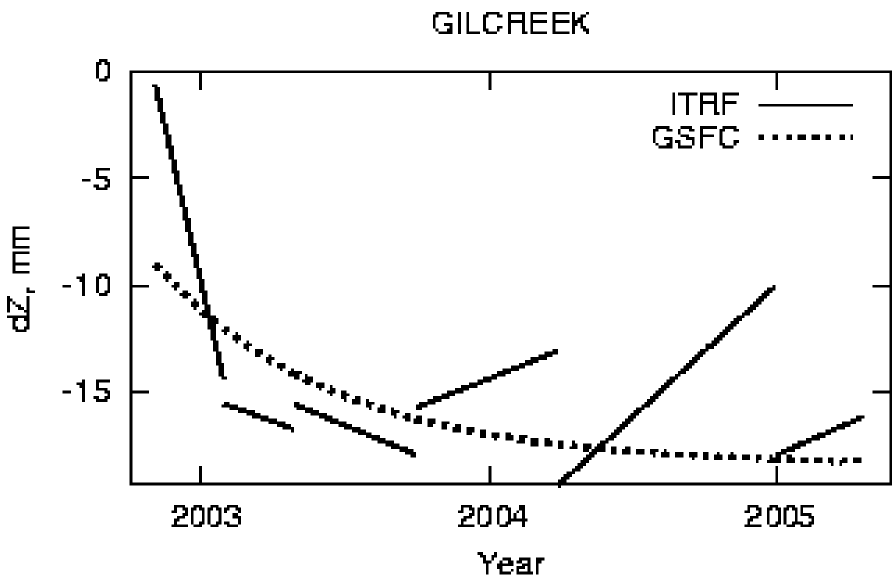
ITRF problems at the mm level

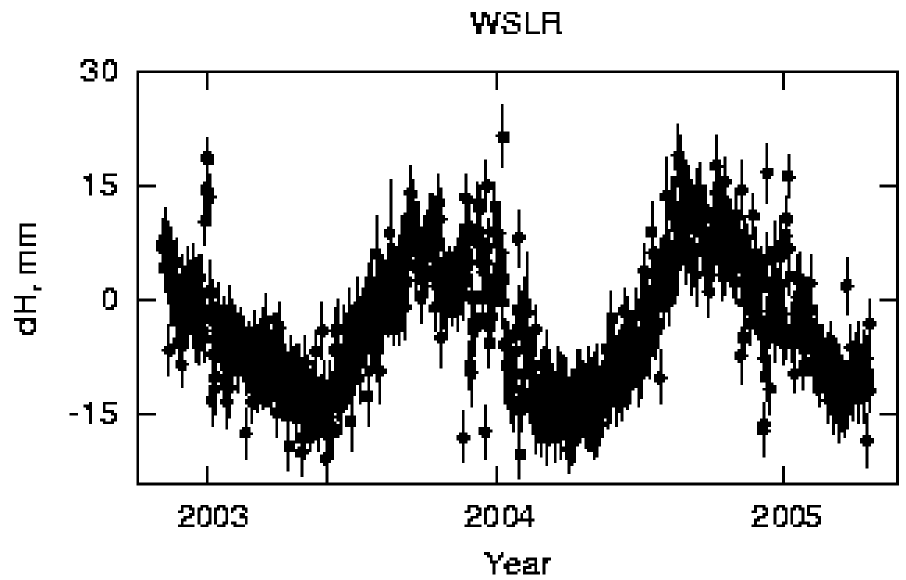
- **Inconsistency between techniques.**
  - Technique-specific systematic errors.
  - Technique-specific analysis standards.
- **Station ties.**
- **Non-linear station movement.**
- **Connection between regional networks.**
- **Geocenter motion.**
- . . . (see more in ITRF2008 papers)

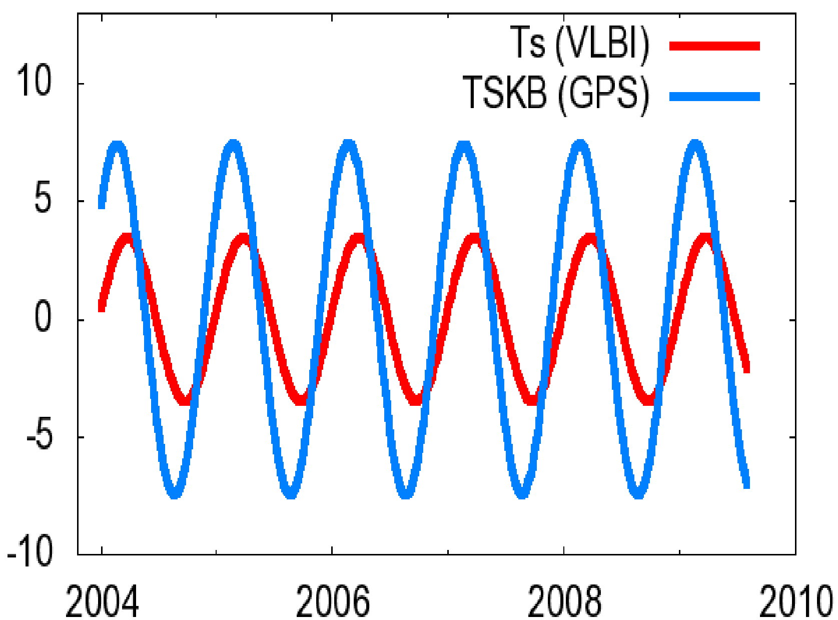
Impact of ITRF on ICRF

- **Dependence on ITRF datum**
  - ► seems to be not significant at the cm-level
  - ► needs further investigation at the mm-level
- **Dependence on the set of reference stations used**
  - ► needs further investigation (currently different ACs used to use different set of reference stations)
- **Dependence on modeling of station non-linear motion**
  - ► needs further investigation

Non-linear station movement







- Can impacts station and site velocities.
- Can impacts arc (daily/weekly/session) EOP+TRF solutions, in particular, VLBI Intensives UT1 (Malkin 2012, J. of Geodesy, submitted).

Modeling of station movement

Goal:

modeling of station daily-averaged position at the mm-level of accuracy for any arbitrary epoch inside of the operational period and for extrapolation to the real time and near future

- **"ITRF model": linear drift with occasional jumps**
  ► not generally suitable
- **"IGS model": linear + jumps + seasonal + exponential**
  ► performs much better
  ► model parameters must be provided along with catalog describing basic linear model
- **"IVS model": using B-splines**
  ► the best approximation to the computed movement
  ► physical meaning?
  ► problems with reproduction and extrapolation?

Impact of ICRF on ITRF

Seems to be not fully understood yet.

Possible mechanisms:

- Global VLBI solution
- Orbit computation (rotational errors)
- ???

ICRF problems at the µas-level

- Uncertainty in ICRS definition (?)
- Uneven distribution of sources over the sky
- Uneven distribution of errors in source position over the sky
- Proper (physical) and apparent (instrumental and analysis) source motions
- Source structure and its variability
- Dependence of source positions on:
  - the wavelength
  - analysis strategy
  - models used during analysis
  - observing network (=> baseline diversity is needed)

ICRF2 – What we have got and what we still need

Achieved (2009)

- Increasing of total # of sources from 717 to 3414
- Increasing of # of the defining sources from 212 to 295
- More uniform distribution of the defining sources
- Improvement in the source position uncertainties
- Elimination of large systematic error at the level of 0.2 mas

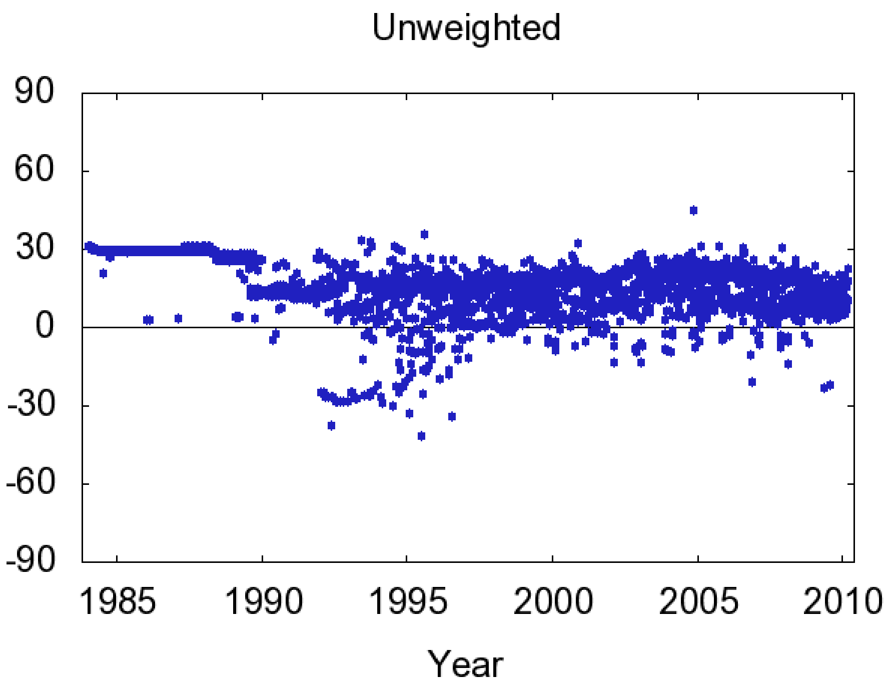
To do (till ~2018)

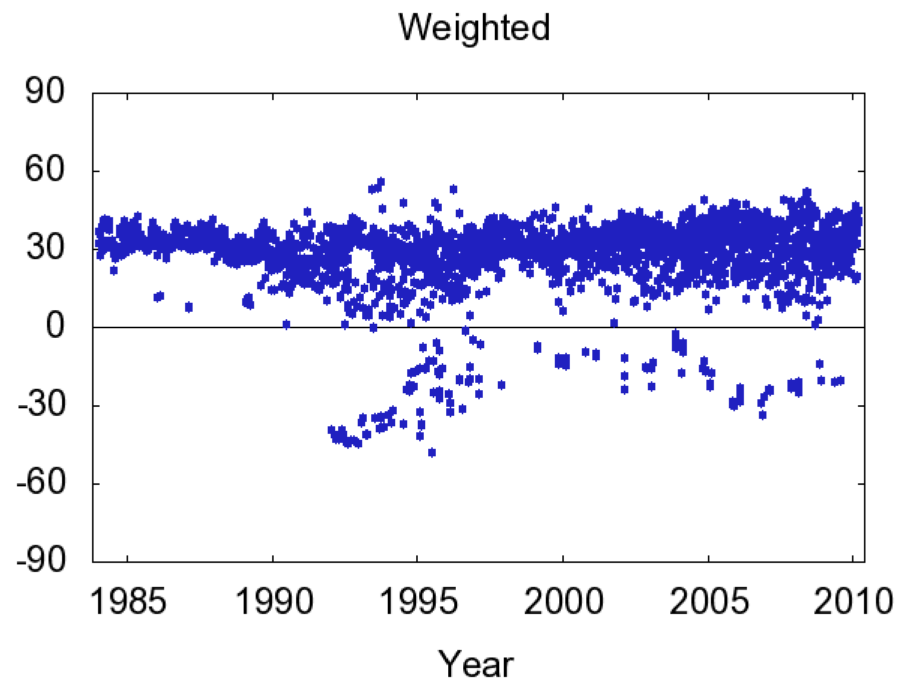
- Increase # of ICRF multi-session sources up to 4100 (one per 10 sq. deg.)
- Increase # of the core sources up to 410 (one per 100 sq. deg.)
- Much more uniform distribution of all and core sources.
- Improve the source position uncertainties and accuracy
- Much more uniform distribution of source position errors

Asymmetry in the average declination

Average declination for 24h sessions:

unweighted (*left*): simple average DE for all observed sources
weighted (*right*): average DE with weights equal to # of observations



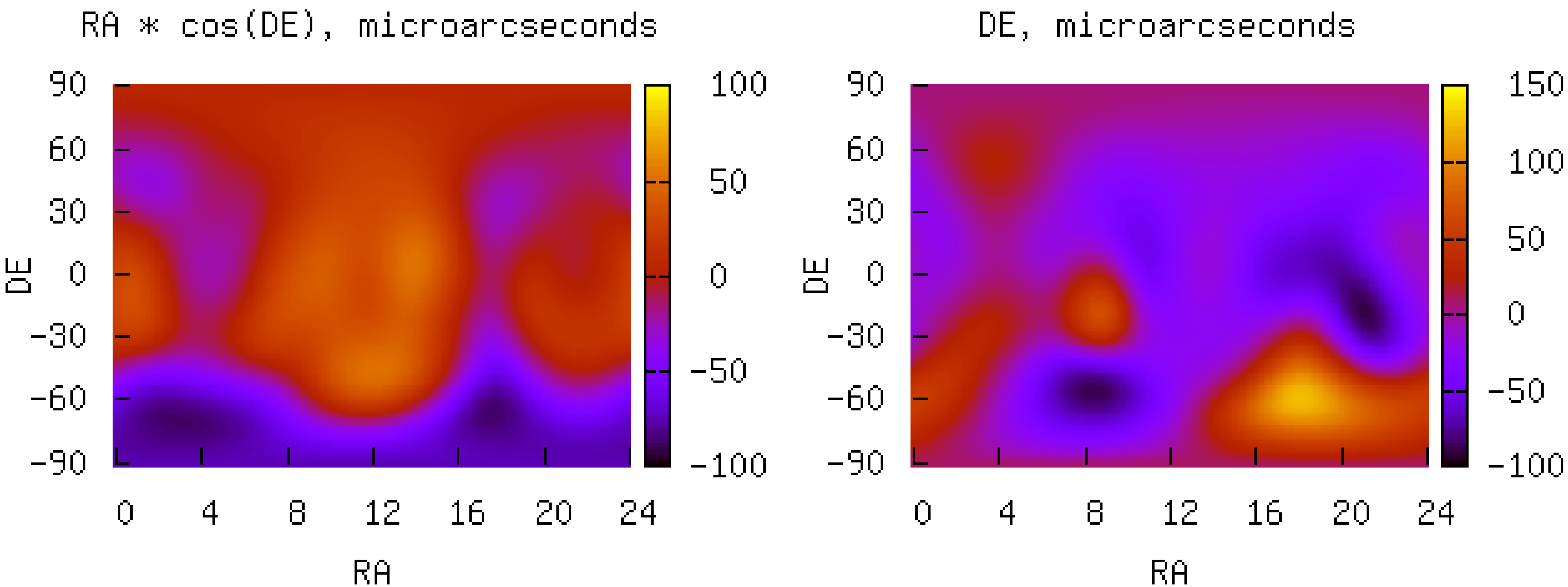


A consequence of scheduling strategy based on local sky coverage criteria

Number of observations in DE bands, thousand

Epoch	Region		
	Southern –90... –30	Equatorial –30...+30	Northern +30...+90
ICRF2 (Mar 2009)	160 (**2.3%**)	3,113 (45.0%)	3,633 (52.7%)
Current (Aug 2012)	225 (**2.7%**)	3,776 (45.0%)	4,388 (52.3%)

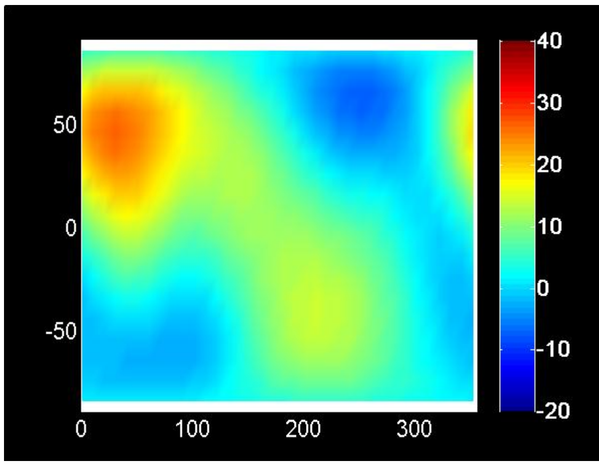
Smoothed differences ICRF2 – ICRF, µas



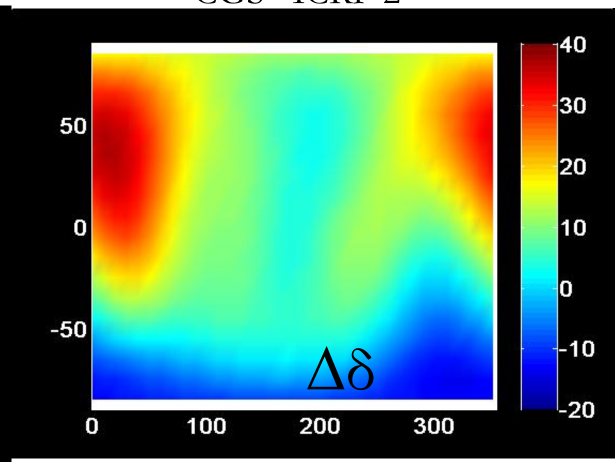
Systematic errors are not rotation only, much more!

Smoothed differences between individual catalogs and ICRF2, $\Delta\alpha$, , μas

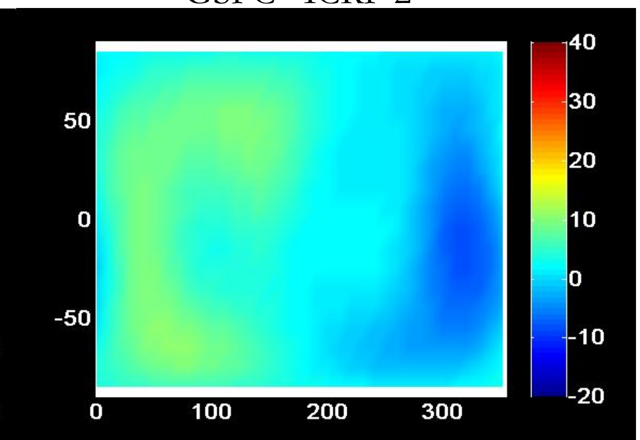
BKG – ICRF 2



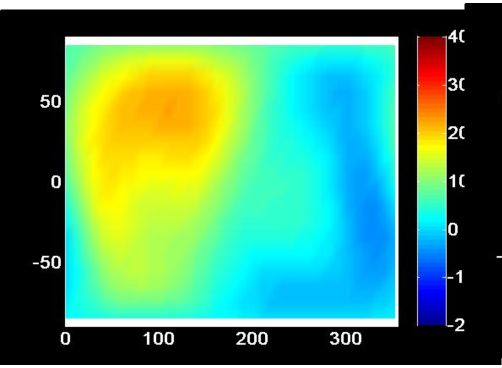
CGS– ICRF 2



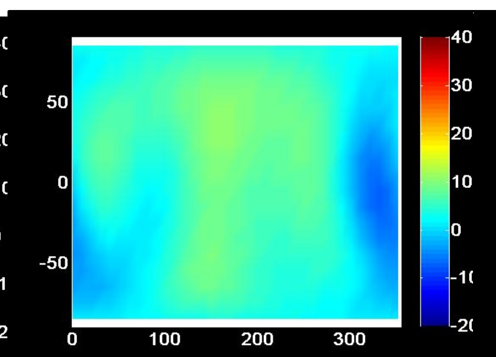
GSFC– ICRF 2



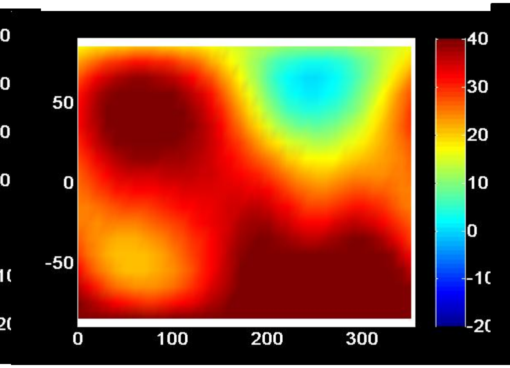
OPA– ICRF 2



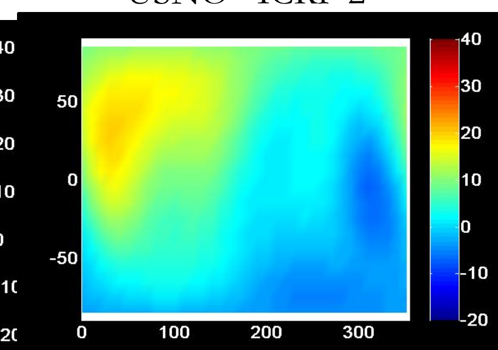
SHA– ICRF 2



IGG– ICRF 2



USNO– ICRF 2

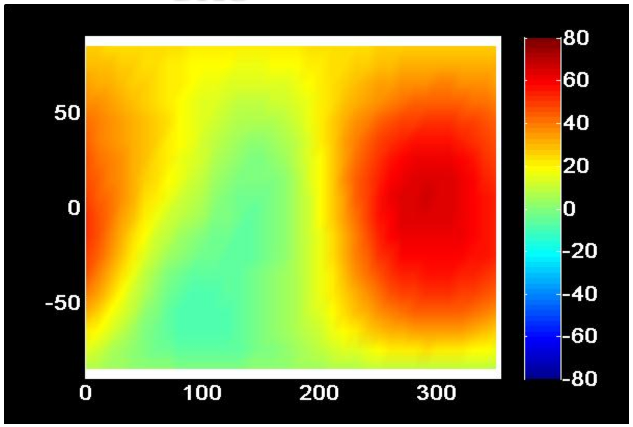


(Sokolova, Malkin, this session)

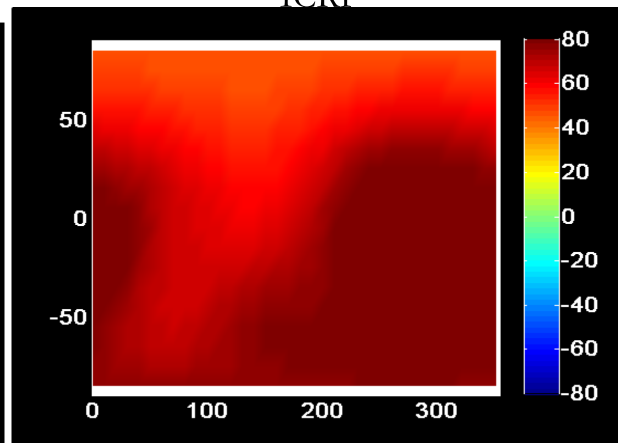
Note common features!

Smoothed differences between individual catalogs and ICRF2, $\Delta\delta$, μas

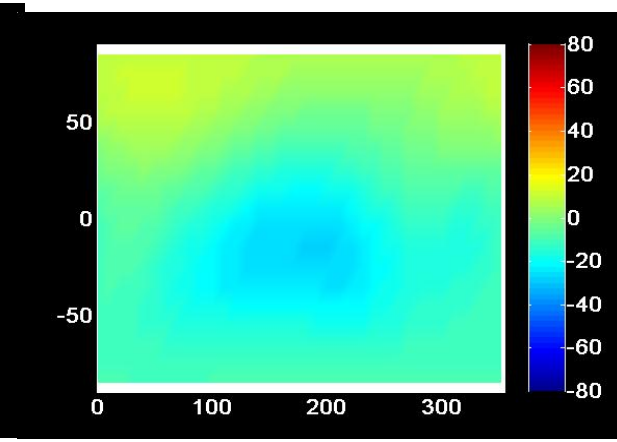
BKG – ICRF 2



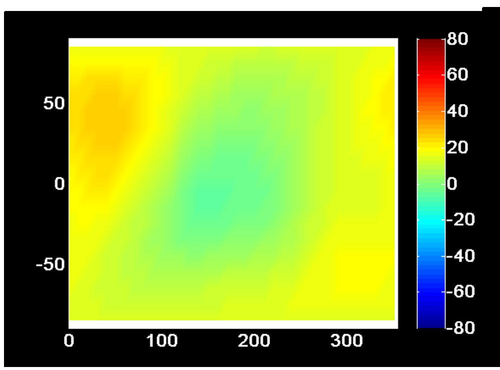
ICRF



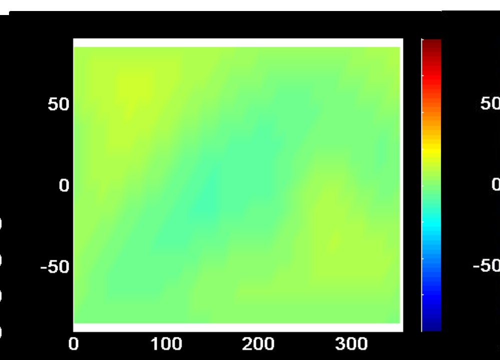
GSFC– ICRF 2



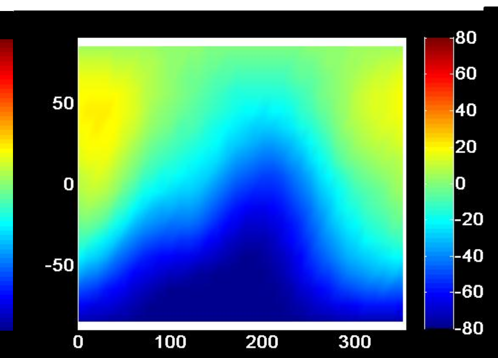
OPA– ICRF 2



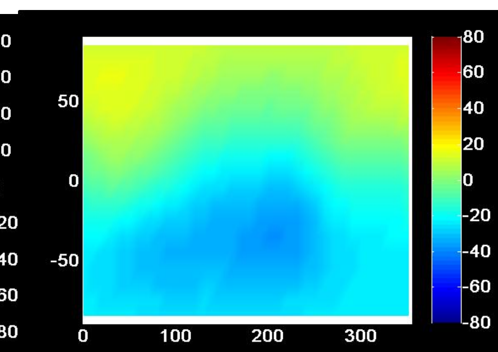
SHA– ICRF 2



IGG– ICRF 2



USNO– ICRF 2



(Sokolova, Malkin, this session)

Note common features!

ICRF history and prospect

ICRF release	Year	Nobs, mln	Δt, yr	
ICRF	1995	1.6		
			4	
ICRF-Ext.1	1999	2.2		
			5	
ICRF-Ext.2	2004	3.4		
			5	
ICRF2	2009	6.5		
			(5)	
(ICRF3)	(2014)	(9-9.5)		8.4 today
			(5)	
(ICRF4)	(2019)	(12-13)		**<=> Gaia**

Motivation for the ICRF release in 2014

Keep a tradition of ICRF updates with 5 years interval.

Most of the latest catalogs show similar systematic differences with ICRF2, most probably in result of adding 2 mln of new observations made after ICRF2 release.

In 2014, there will be 1.5 times more observations than used for computation of ICRF2.

In ICRF3 we could (hopefully) mitigate an ICRF2 systematic errors at a level of few tens μas.

It's still sufficient time to activate observations of new and old poorly observed Southern sources.

ICRF3 – What we want to reach?

- Increasing of # of sources up to > 4100
  (one source per 10 sq. deg.)
  mostly by southern sources
- Increasing of # of the core(defining) sources up to > 410
  (one source per 100 sq. deg.)
- Much more uniform distribution of all and core sources
  (as a result of previous steps)
- Much more uniform distribution of source position errors
- Improvement of the source position uncertainties and accuracy
- Mitigation of the systematic errors to a level of 20-30 μas.

ICRF4 – What we want to reach?

- Substantial increasing of # of all multi-session and core sources.
- Near-uniform distribution of all and core sources over the sky.
- Near-uniform distribution of position errors for all and core sources over the sky.
- Substantial improvement in the source position uncertainties and accuracy.
- Mitigation of the systematic errors to a level of 10-15 μas.
- Preparation to the comparison with the Gaia CRF.

It is expected that these goals will be achieved in the framework of regular VLBI2010 operations with active participation of the southern stations.

ICRF3 core sources

Up to now, a decision on a list selection of defining sources was made, in fact, during ICRF computation.

However, it seems to be much more reasonable to compile a list of planned defining sources beforehand, i.e. just now for ICRF3, and start their observations.

Taking into account a limited observational resources in the Southern hemisphere, IVS observing strategy should be revised, in particular with inclusion of more observations of prospective ICRF sources in the R1 and R4 regular sessions.

Conclusions (1)

1. It seems to be urgent to identify new core ICRF sources in the southern hemisphere and start their observations along with poorly observed ICRF2 ones. A way ought to be found to improve funding of CRF operations at existing (Auscope, HartRAO, TIGO, maybe Antarctic station) and new (Mendoza) stations, maybe in the framework of International cooperation.

2. A possibility worth investigating of a trade-off between local and global sky coverage, at least for CRF programs.

3. One of the simplest and effective ways to improve the situation with the Southern sources would be inclusion of more ICRF sources in the regular IVS sessions R1 and R4. A trade-off between practically insignificant degradation of the EOP precision and ICRF interests can be easily found.

Conclusions (2)

4. A method of uniform description of TRF (and CRF?) objects non-linear movement at the μas/mm level of accuracy allowing to better describe the actual motion and being reproducible and predictable is needed.

5. An agreement on a standard set of VTRF core stations is needed.

Thank you for your attention!