PROPERTIES OF THE GAIA - ICRF3 RADIO - OPTICAL REFERENCE FRAME

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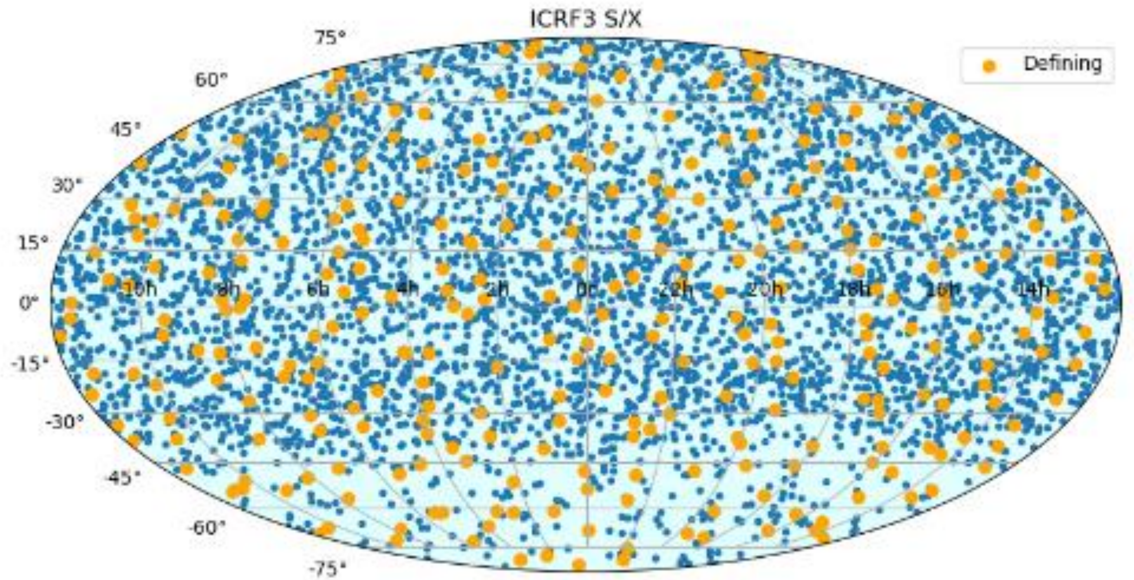
Motivation

- Bottom line : USNO has a long time interest in radio – optical tie sources, Gaia is definitely providing a unique opportunity to realize a good link between these reference frames but this is NOT TRIVIAL
- Coordination: ICRF continues to improve so there should be coordination between the strategies: what Gaia should do best for the alignment and what VLBI can do to improve the link
- Comparison : Comparing the radio and optical frames at similar accuracies is the ONLY way to check for zonal errors (just remember how the older optical catalogs looked like when TGAS came out!). This is the first time the optical accuracies are getting close to radio.
- Astrophysics: Radio and optical probe different emission regions, both VLBI and Gaia have the required accuracies (parsec level) to determine where the emission is coming from. This is very important for the radio – optical tie but also for the astrophysics of quasars (nobody cares about astrometry until they actually need it!)

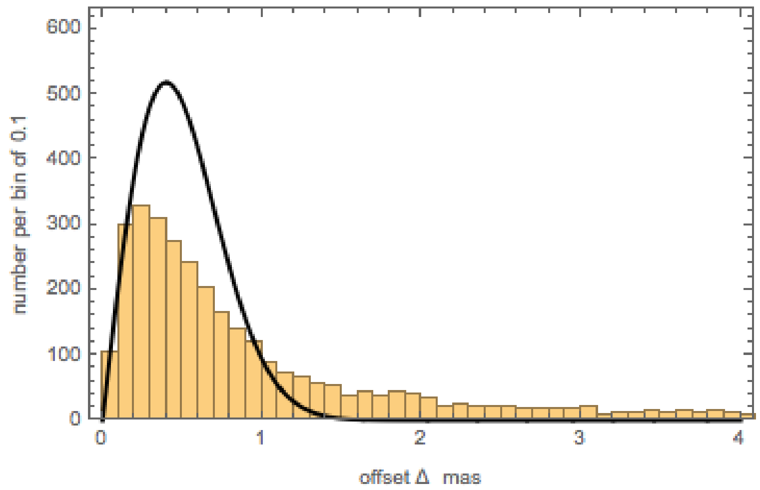
Building the RORFO sample

- RORFO – Radio-optical reference frame object
- ICRF3 – International Celestial Refence Frame #3, a collection of 4536 radio sources observed with VLBI, mostly quasars and AGNs
- Gaia DR2 – well, you know what it is
- ICRF3 establishes the most accurate radio frame in J2000, while Gaia realizes the most accurate optical frame
- They are aligned to each but otherwise independent



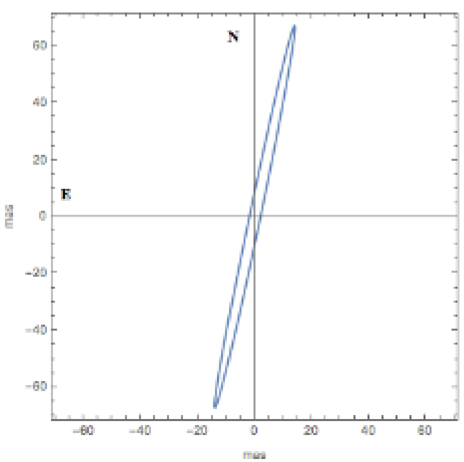
Gaia/ICRF3 crossmatch

- Cone search radius of 1 arcsec around each S/X position -> 3414 cross-matched sources
- Quasars are not supposed to move around on the sky, so crossmatch by position is trivial except…
- Error ellipses for both positions can be elongated, so full covariance matrix is needed to estimate the uncertainty *u* of observed offset Δ



Histogram of absolute position offsets Gaia-ICRF3 for initial 3413 cross-matched objects

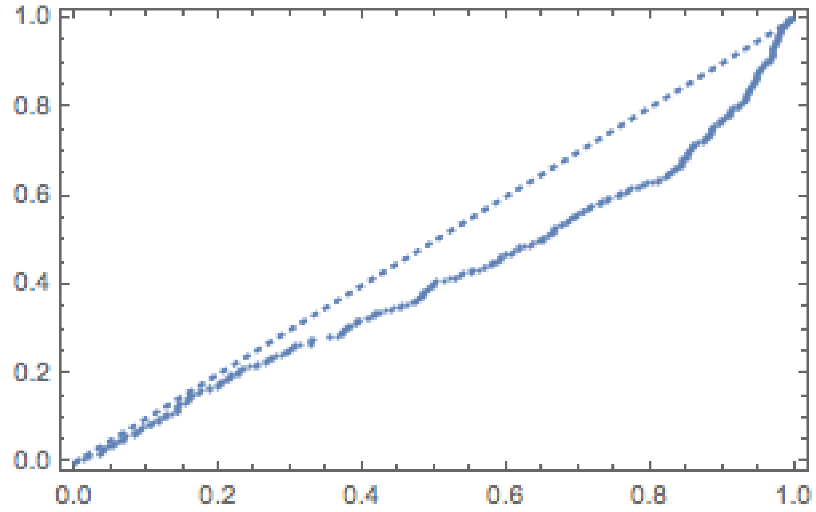
$$\mathbf{C} = \mathbf{C}_{\mathrm{ICRF3}} + \mathbf{C}_{\mathrm{Gaia}}$$
$$u_{\Delta}^{2} = \Delta^{T}\ \mathbf{C}^{-1}\ \Delta$$



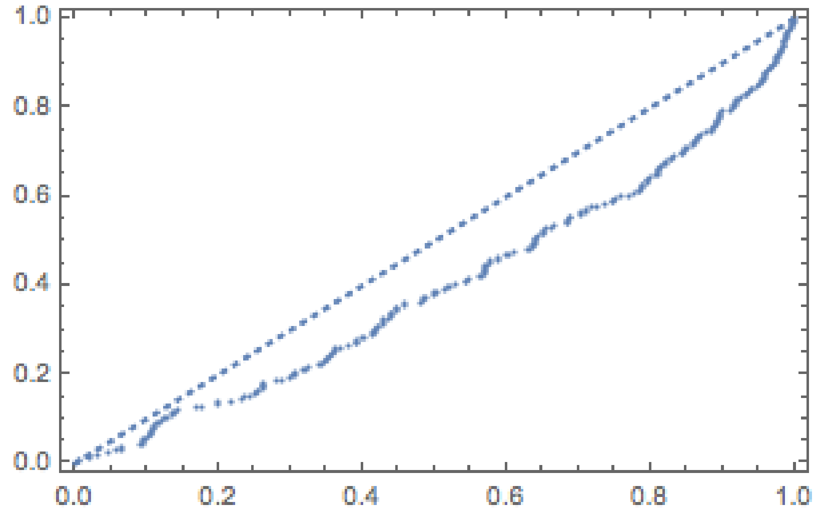
Gaia error ellipse for an ICRF3 source counterpart

Cleaning the sample

- Remove all known extended galaxies and Seyfert galaxies labeled in OCARS catalog (Optical Characteristics of Astrometric Radio Sources, Malkin 2018) or NED
  ⋙ 3020 sources
- Remove duplicate matches (by nearest neighbor principle), and apply the astrometric χ^2 filter to remove astrometrically perturbed sources (e.g. Arenou+2018)
  ⋙ 2763 sources
- Use Cumulative Distribution Functions (CDF) to asses the usefulness of these filters

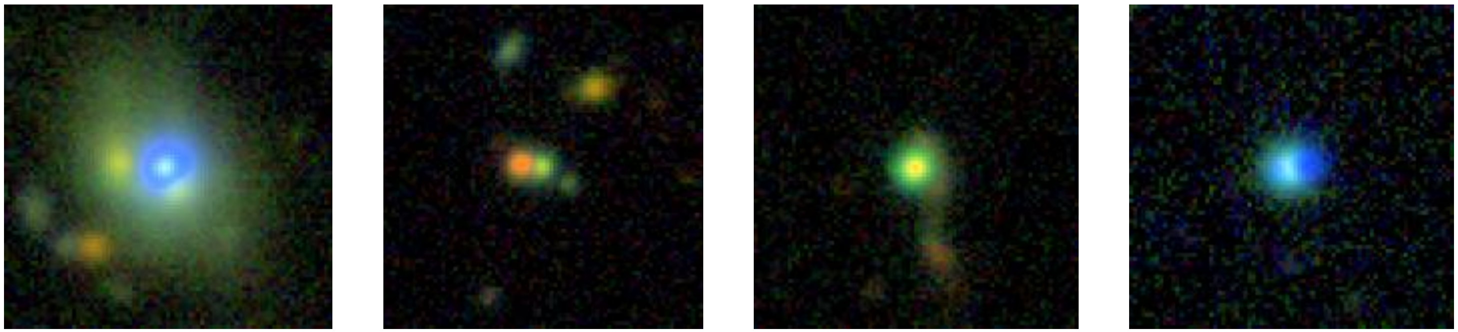


Probability plot (CDF vs. CDF) of u for known galaxies and Seyferts versus other sources

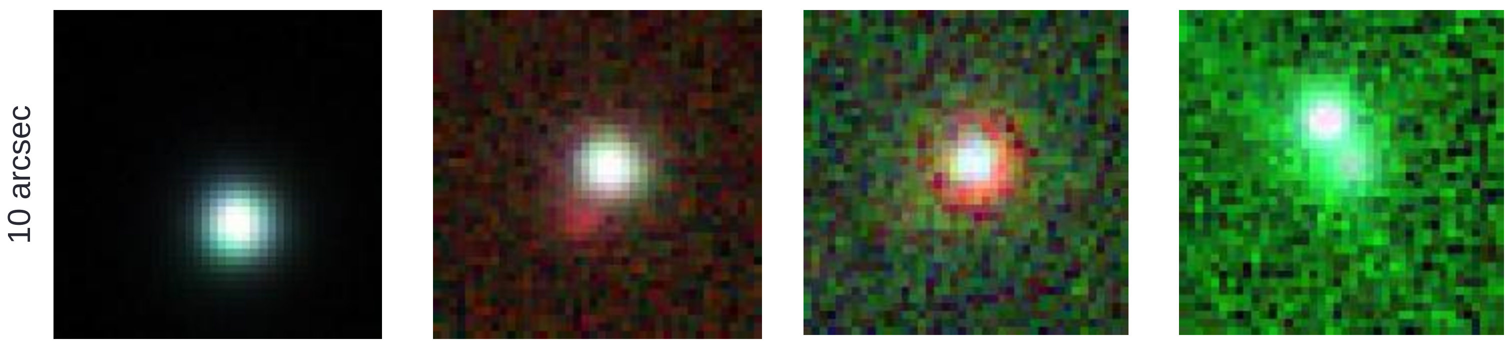


Probability plot (CDF vs. CDF) of u for astrometrically perturbed versus other sources

Images of ICRF3 counterparts



Dark Energy Survey images of ICRF3 sources

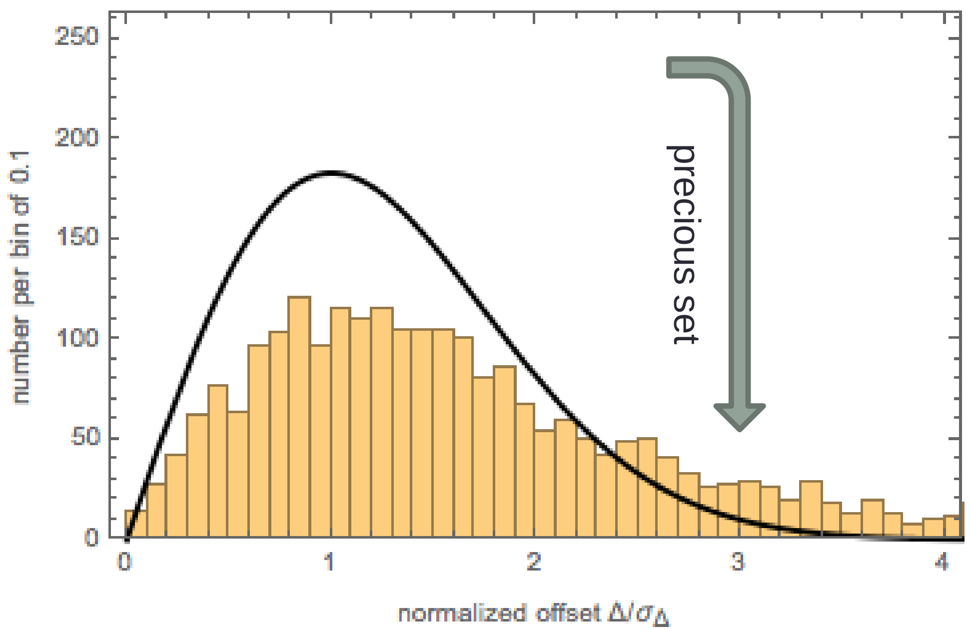


Pan-STARRS-1 3pi survey images of ICRF3 sources (from STSCI archive)

Review ~3000 available Pan-STARRS, DES and HST images to filter out remaining categories to be avoided: galaxies, double and multiple sources, misses and optical pairs, and other perturbed cases. 2643 sources remain.

The final cut on normalized residual

- The Δ/σ_Δ normalized position offset is distributed remarkably differently from the expected Rayleigh[1] curve with a deficit of values around the mode and a long tail of outliers
- The outliers are useless for the RORF tie, so remove them by clipping at $\Delta/\sigma_\Delta \geq 3$ where the confidence level for Rayleigh[1] equals 0.99 (>20%)
- This leaves 2119 objects in the sample we recently published (Makarov, Berghea +, 2019, ApJ, 873, 132)



Histogram of normalized position differences GaiaDR2 – ICRF3. The Rayleigh[1] distribution is shown with thick line.

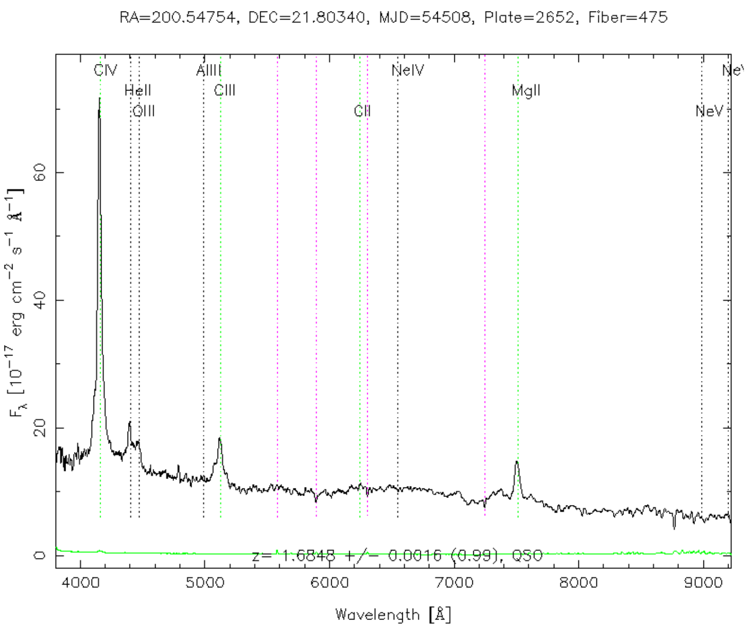
Discussed origin of the observed radio-optical offsets:

distribution of light between core and unresolved jet (Petrov+ 2018, Plavin+ 2019)

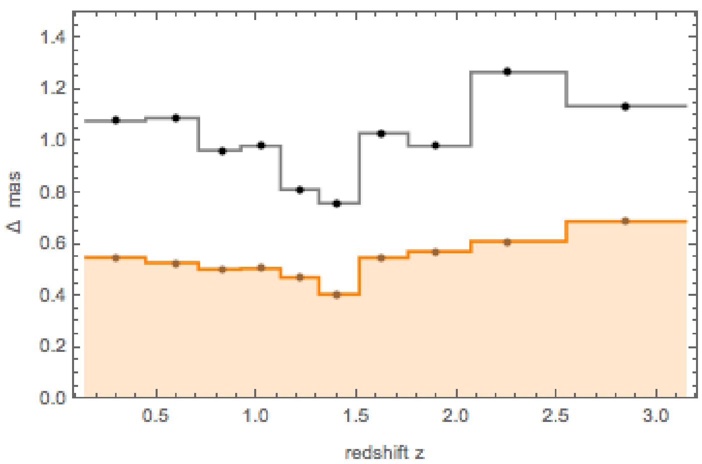
physical displacement of AGNs from host galaxy centers (Makarov+ 2018)

Offsets versus redshift

- High-redshift quasars are more distant and also younger that the nearby AGNs, so do they have different radio-optical offsets? E.g., if unresolved jets have the same typical size, the offsets can be smaller at high z
- There is a bump at $z \approx 1.6$ but it may be caused by the emergence of the bright CIV line in the astrometric bandpass of Gaia



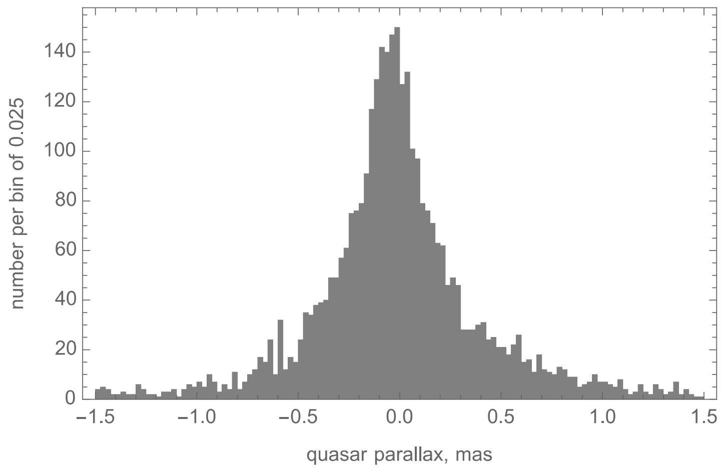
SDSS spectrum of the ICRF3 quasar ICRF J132211.4+214812 at $z = 1.68$



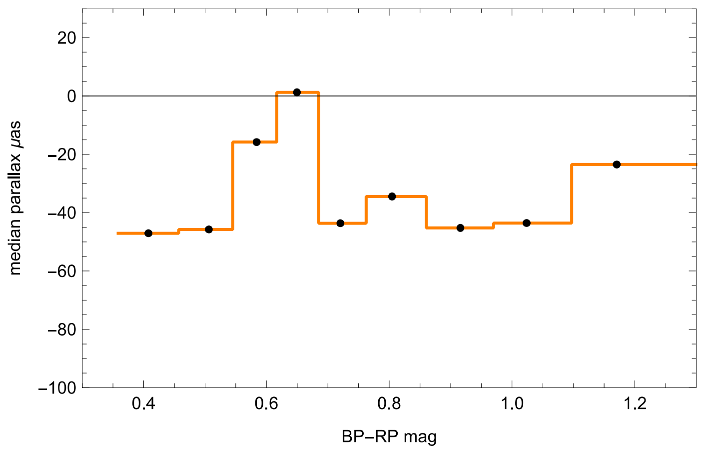
50th (median) and 75th percentiles of binned radio-optical position offsets versus redshift

Gaia parallax bias

- Quasar parallaxes should be zero
- The sample distribution shows an obvious bias (zero-point error)
- Robust location estimators:
  - Median = -0.035 mas
  - BiweightLocation(6) = -0.035 mas
- Estimates in the literature starting form the Gaia DR2 release vary a lot around this value (between 0 and -100 μas), being possibly color, positional, etc. – dependent
- Dependence on the BP – RP color is also clearly shown in our sample



Distribution of Gaia DR2 parallaxes for 3782 ICRF3 QSOs



Spherical harmonics of ICRF 3 - Gaia DR2 offsets

Using vector spherical harmonic (VSH) functions
to fit the observed vector field on the unit sphere

1) solve the weighted least-squares problem

$$\mathbf{A}\,\mathbf{x} = \mathbf{d}$$

where **d** is the data vector composed of east and north tangential components

2) solve by least-squares

$$\hat{\mathbf{x}} = (\mathbf{A}^{\mathrm{T}}\,\mathbf{A})^{-1}\,\mathbf{A}^{\mathrm{T}}\,\mathbf{d}$$

3) singular value decomposition

$$\mathbf{A} = \mathbf{U}\,\mathbf{S}\,\mathbf{V}^{\mathrm{T}}$$

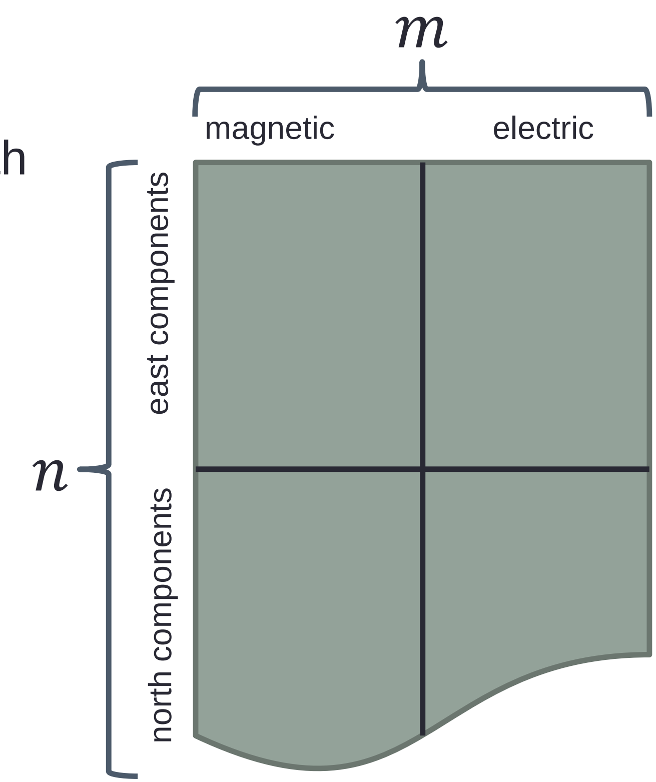
4) robustness of fit

$$R = \frac{\sqrt{n}\,s_1^{-1}}{\sqrt{\sum_{j=1}^{m} s_j^{-2}}}$$

5) confidence

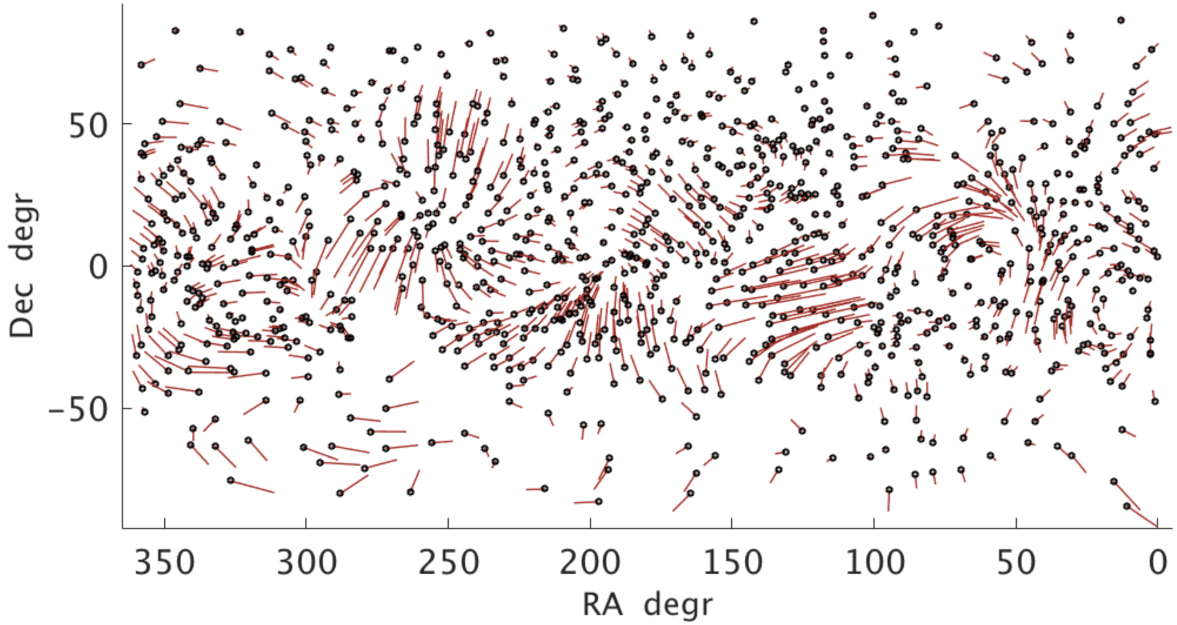
$$F_{\mathrm{CDF}}\left(\frac{(\chi^2_{data}-\chi^2_{fit})(n-m)}{\chi^2_{fit}\cdot m}, m, n-m\right)$$

6) least significant eigenvector = worst distortion = $\mathbf{u}_m$



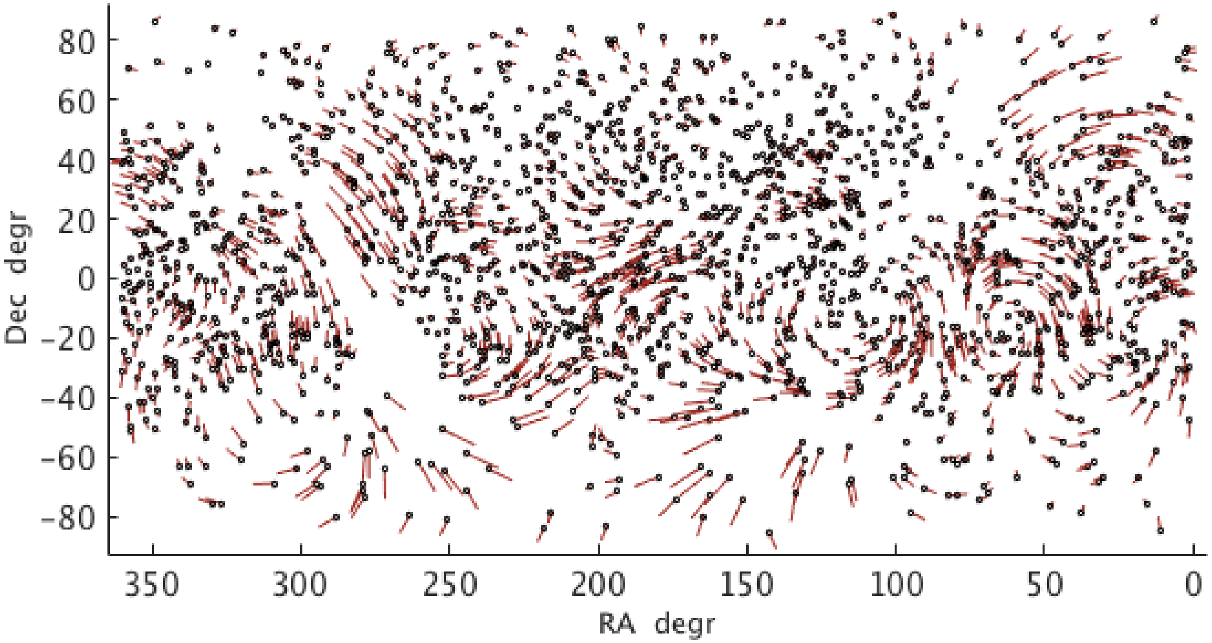
structure of VSH design matrix **A**

GaiaDR2 – ICRF3 position difference field



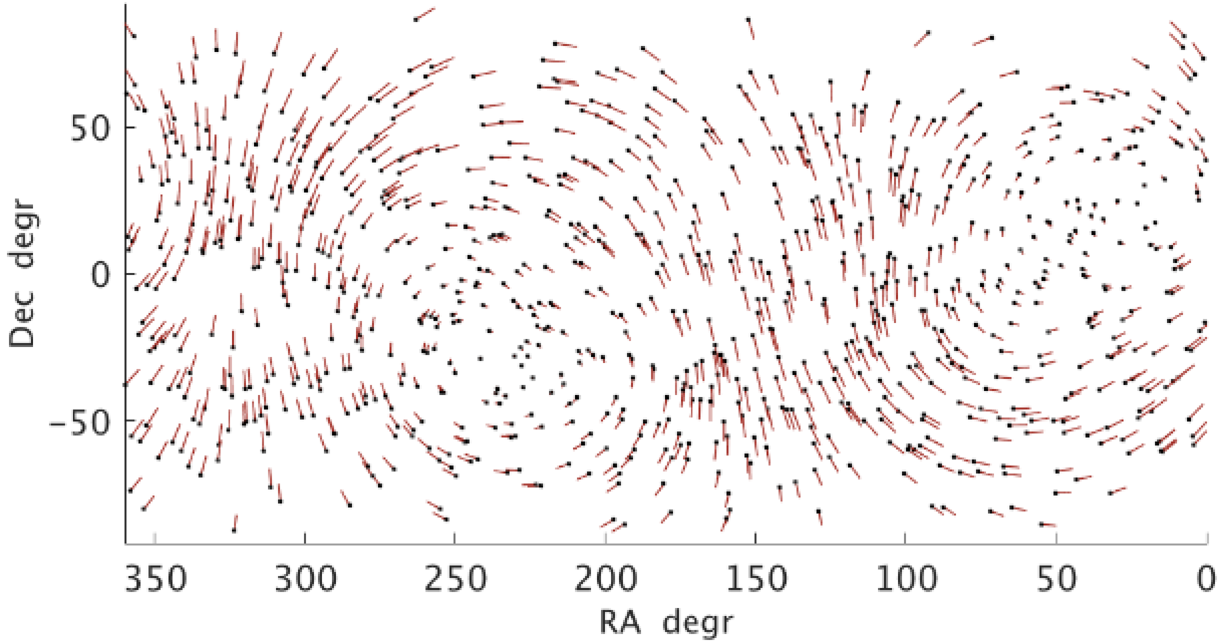
The vector field of position offsets of 2119 ICRF3 quasars measured by Gaia, represented by 96 (l=6) vector spherical harmonics. The median length of arrow is 0.285 mas. Black circles indicate the objects positions at the origins of offset vectors. Robustness of this fit is 4.24 (pretty good). F-test confidence of this fit is 1.000 (excellent). The pattern likely reflects zonal errors in GaiaDR2 or ICRF3.

Proper motion field of ICRF quasars



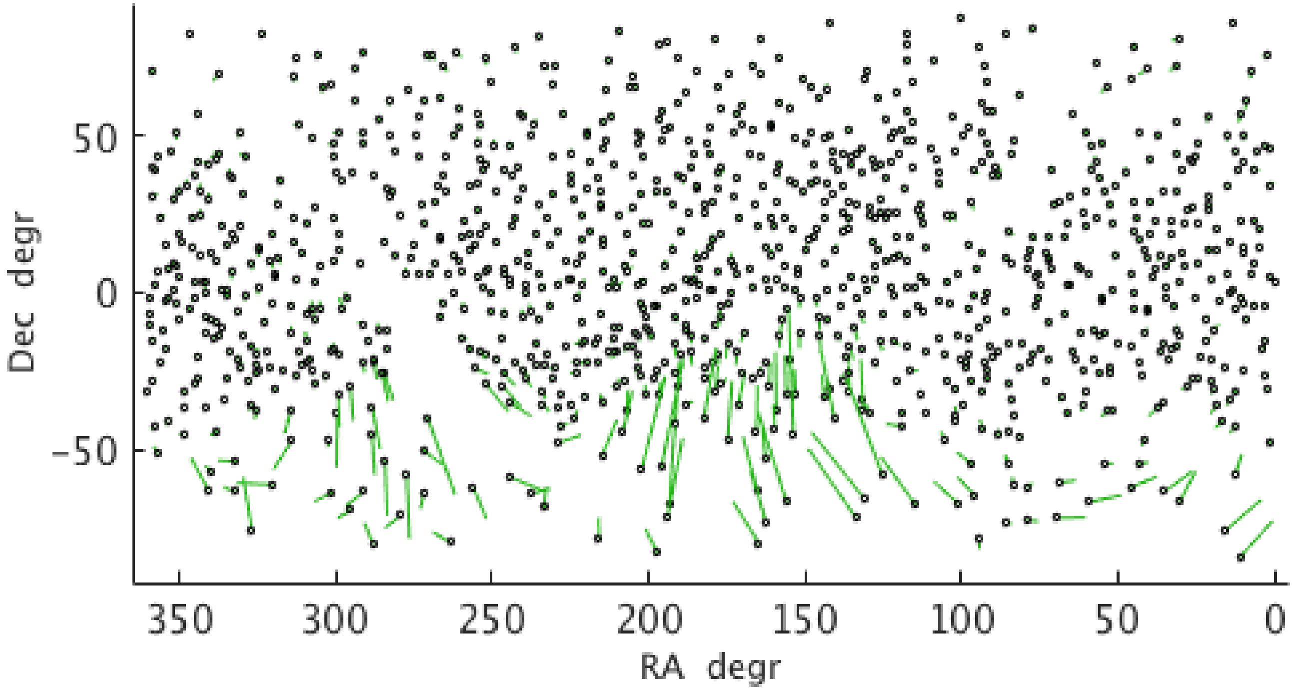
The vector field of proper motions of 1954 ICRF3 quasars measured by Gaia, represented by 96 (l=6) vector spherical harmonics. The median length of arrow is 0.157 mas/yr. Black circles indicate the objects positions at the origins of proper motion vectors. Robustness of this fit is 4.38 (pretty good). F-test confidence of this fit is 0.545 (low). No Solar system acceleration (~0.005 mas/yr) or other interesting astronomical effects are present or can be inferred.

Hipparcos – Gaia position difference field



For comparison, the differences in positions between Hipparcos and Gaia at the mean epoch of Hipparcos (1991.25) show a clear zonal pattern with high confidence. This means that either the Gaia proper motion systems are very different for brighter stars and fainter ICRF sources, or Hipparcos suffers from a large systematic error in positions.

The worst distortion of RORF



The vector field of the least significant eigenvector of the vector spherical representation of ICRF3 – Gaia DR2 position differences, which also represents the worst-case distortion of the radio-optical reference frame tie. The fundamental reference frame can be most significantly improved by adding additional RORFO in the ICRF by observing quasars in the areas where the arrows are large.

Conclusions

- With about 35% of cross-matched Gaia-ICRF3 sources not passing the quality criteria, quasars are far from perfect for setting up a radio-optical reference frame – but there is no viable alternative
- Only 2119 ICRF3 sources are currently deemed suitable for establishing the tie
- Some medium-scale zonal errors seem to be present in Gaia DR2 positions of ICRF quasars but not in proper motions
- The systematics of the Gaia proper motion system for faint sources may be different from that of brighter (Hipparcos) stars
- The best way of improving the radio-optical reference frame tie is to add more good-quality objects in ICRF in the areas where the least-significant eigenvector of the vector field is large, mostly south of Decl.= $-35°$ and around the Galactic plane