# Is It Possible To Bring the Gaia-CRF2 Into the VLBI Data Reduction?

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# Outline

- Motivation
- Implementation of Gaia-CRF in VLBI solution
- Comparison of VLBI solutions
- Concluding remarks

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# Motivation

- VLBI can determine the celestial reference frame (CRF) , Earth orientation parameters (EOP), and terrestrial reference frame (TRF) simultaneously
    - north-south VLBI network asymmetry leads to large scale (declination-dependent) systematics
    - also some possible unknown dependency between TRF and CRF
- Gaia is a unique instrument that is principally able to build a CRF on itself
    - free of declination-dependent systematics
    - precision of DR2 is comparable to ICRF3, but we can expect a better precision (positional error) and accuracy (lower systematics) in the future release
- If considering Gaia-CRF in the VLBI analysis
    - A possible way for radio-optical reference frame tie?
    - Any new information to the nutation/UT1?
    - An interesting option for VLBI data analysis?

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# Geodetic/Astrometric VLBI analysis

- Taking Calc/Solve@GSFC for example: Least square method
  - $\tau_{\text{obs}} = \tau_{\text{mod}} + \epsilon \Rightarrow \tau_{\text{obs}} - \tau_{\text{mod}} = \frac{\partial \tau}{\partial \vec{x}} \cdot \Delta \vec{x} + \epsilon$
  - Normal equation: $N \Delta \vec{x} = \vec{b}$

- Due to degeneracies amongst CRF, TRF, and EOP, special constraint equations should be added to normal equation.

- Maintenance of the reference frame
  - No-Net-Rotation (NNR) constraint to position of radio sources (also possible for proper motion but not used)
  - No-Net-Translation (NNT) and No-Net-Rotation (NNR) constraint to station positions and velocities

# NNR constraint on radio source positions

- NNR constraint equation of CRF
  - $\sum_i \Delta\vec{s}_i \times \vec{s}_{i,0} = \vec{0}$
  - Average rotation for a special ensemble of radio sources to be 0
- Rewrite the equation as
  - $\vec{s}_i = \vec{r}, \Delta\vec{s}_i = \Delta\alpha \cos\delta \cdot \vec{p} + \Delta\delta \cdot \vec{q}$
  - $\vec{p} = (-\sin\alpha, \cos\alpha, 0)^{\mathrm{T}}, \vec{q} = (-\sin\delta\cos\alpha, -\sin\delta\sin\alpha, -\cos\delta)^{\mathrm{T}}, \vec{r} = (\cos\delta\cos\delta, \cos\delta\sin\delta, \sin\delta)^{\mathrm{T}}$
  - $\Rightarrow \sum_i -\Delta\alpha_i \cos\delta_i \cdot \vec{q}_i + \Delta\delta_i \cdot \vec{p}_i = \vec{0}$
- State-of-art VLBI solution
  - ICRF3 (S/X) positions of 303 defining sources

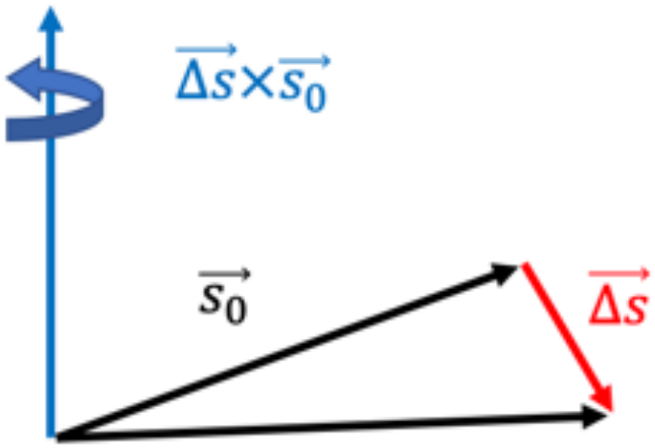


Fig. 1 Rotation needed to align the adjusted position to a priori position

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- State-of-art VLBI solution
  - ICRF3 (S/X) positions of 303 defining sources => Gaia DR2 position?

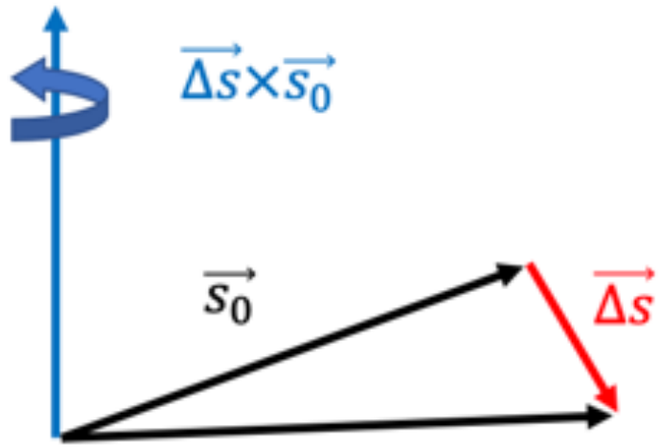


Fig. 1 Rotation needed to align the adjusted position to a priori position

# Gaia-CRF2

- 250 common sources between Gaia DR2 IERS subset and ICRF3 defining source set

- Most precise position in the ICRF3 but not in the Gaia DR2

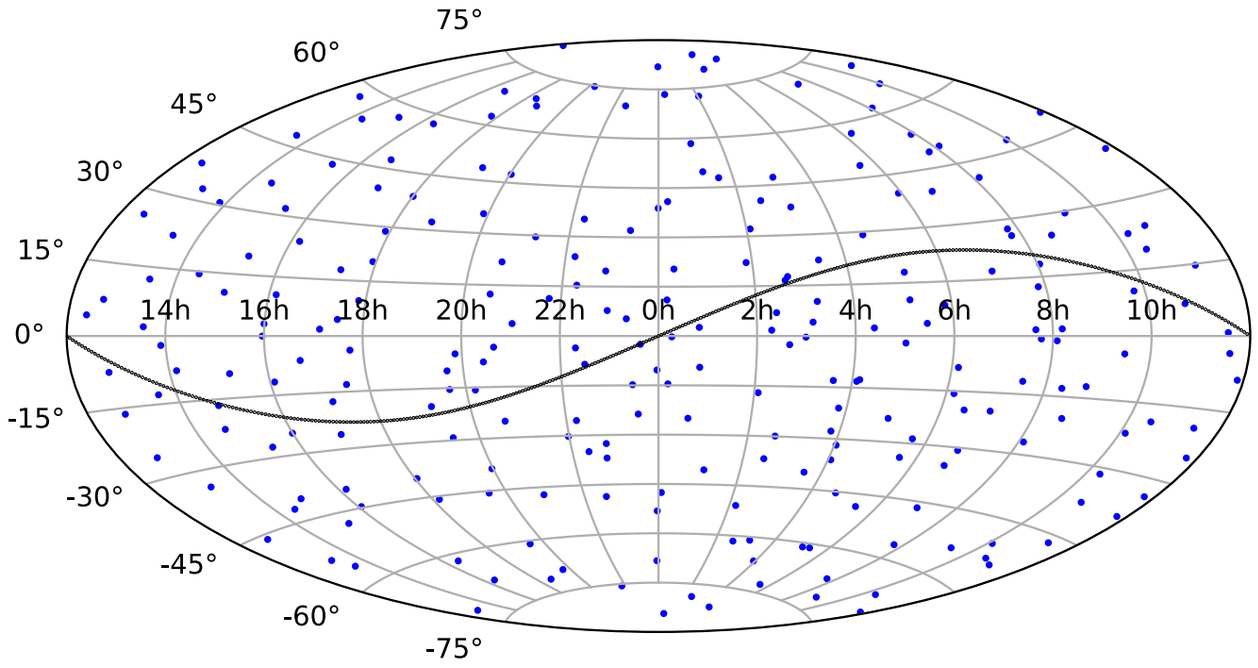


Fig. 2 Distribution of 250 sources

# Interesting sources

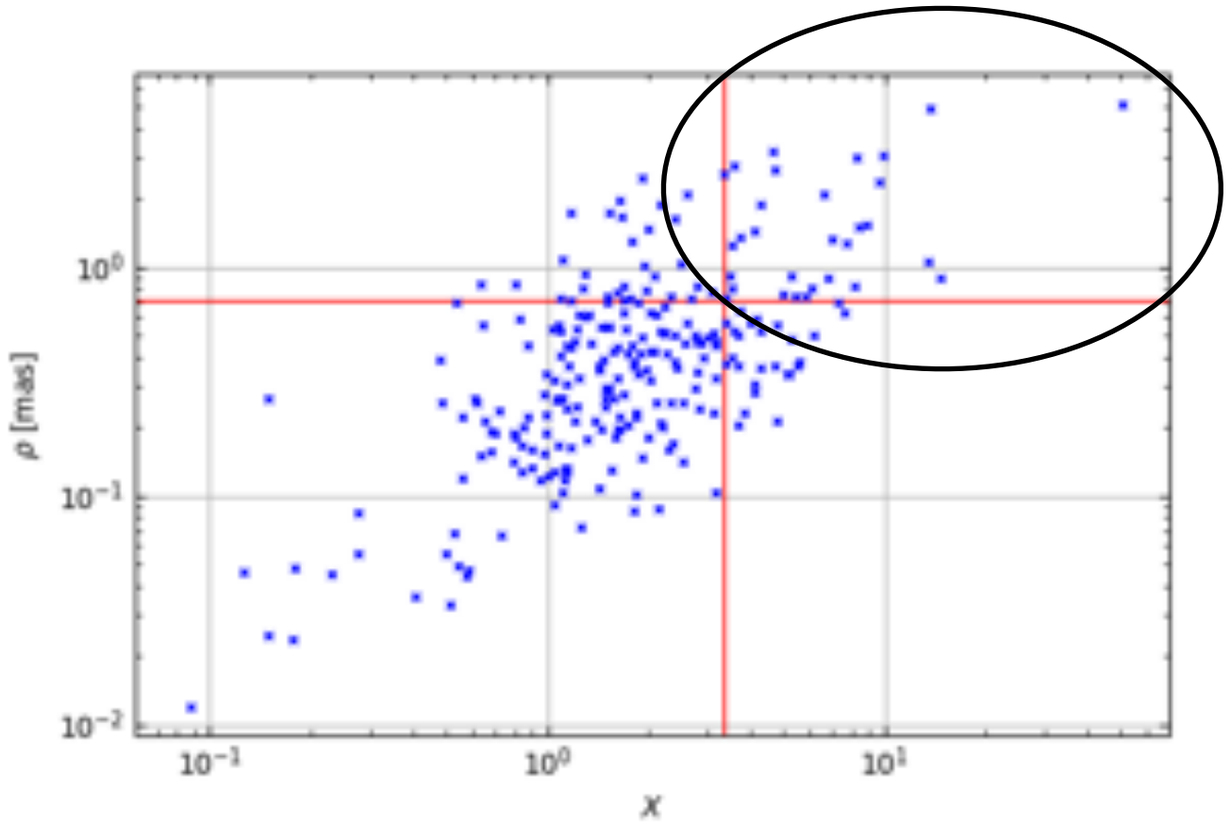


Fig. 3 Angular separation $\rho$ and normalized separation $X$

| iers_name | ra | dec | rho | X |
|---|---|---|---|---|
| | deg | deg | mas | |
| 0010+405 | 3.38 | 40.86 | 1.332 | 6.98 |
| 0013-005 | 4.05 | -0.25 | 1.244 | 3.54 |
| 0235-618 | 39.22 | -61.60 | 1.449 | 4.12 |
| 0305+039 | 47.11 | 4.11 | 4.943 | 13.70 |
| 0312+100 | 48.84 | 10.21 | 3.105 | 9.86 |
| 0615+820 | 96.51 | 82.04 | 0.820 | 8.22 |
| 0642-349 | 101.11 | -34.99 | 0.911 | 5.28 |
| 0743-006 | 116.48 | -0.74 | 1.054 | 13.43 |
| 0749+540 | 118.26 | 53.88 | 0.889 | 6.85 |
| 0818-128 | 125.24 | -12.98 | 2.333 | 9.60 |
| ... | ... | ... | ... | ... |
| 1642+690 | 250.53 | 68.94 | 2.803 | 3.61 |
| 1730-130 | 263.26 | -13.08 | 0.760 | 4.98 |
| 1806-458 | 272.49 | -45.88 | 2.077 | 6.58 |
| 1908+484 | 287.44 | 48.58 | 2.560 | 3.35 |
| 1921-293 | 291.21 | -29.24 | 1.273 | 7.73 |
| 2209+236 | 333.02 | 23.93 | 0.723 | 3.39 |
| 2214+350 | 334.08 | 35.30 | 0.812 | 6.13 |
| 2254+074 | 344.32 | 7.72 | 1.490 | 8.34 |
| 2325-150 | 351.95 | -14.80 | 1.869 | 4.31 |
| 2331-240 | 353.48 | -23.73 | 0.752 | 5.44 |

Length = 30 rows

- Outliers for reference frame construction
- interesting objects for astrophysical studies

# Global difference between Gaia DR2 and ICRF3 S/X

- Vector spherical harmonics (VSH) of degree-1

- Rotation

$$\Delta\alpha^* = -R_x \cos\alpha \sin\delta - R_y \sin\alpha \sin\delta + R_z \cos\delta$$
$$\Delta\delta = +R_x \sin\alpha - R_y \cos\alpha$$

- Dipole or Glide

$$\Delta\alpha^* = -D_x \sin\alpha + D_y \cos\alpha$$
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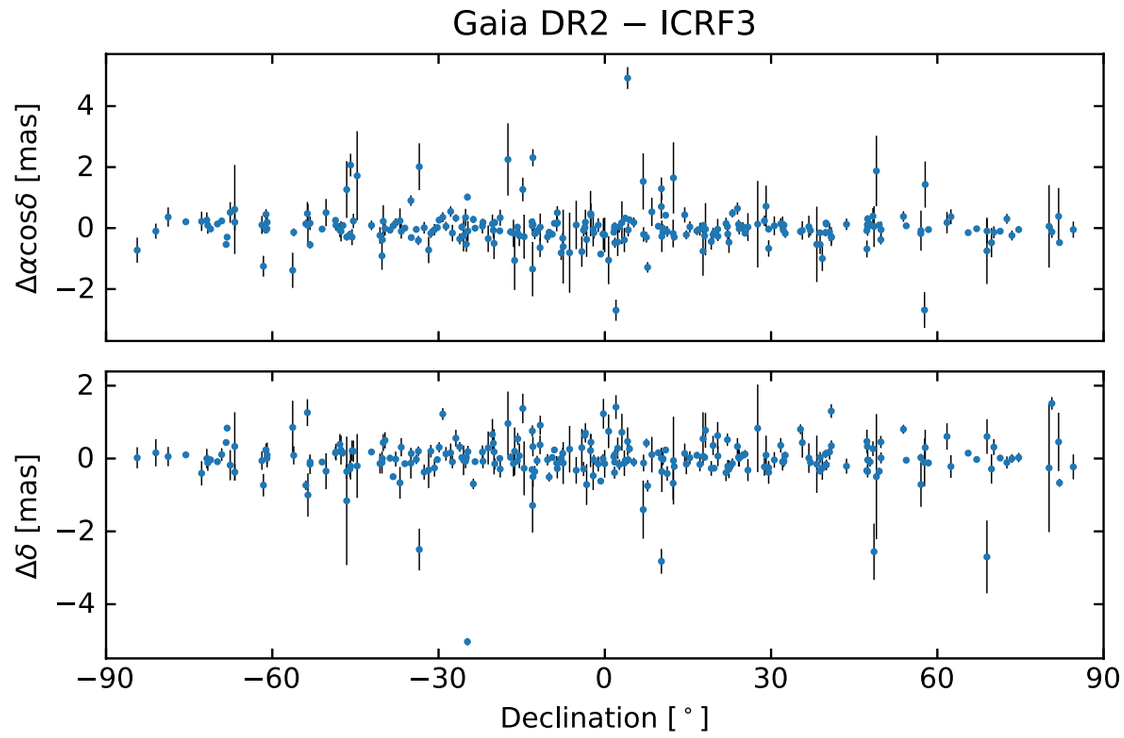


Fig. 4 ICRF3—Gaia DR2 for 250 sources

| $N$ | Rotation ($\mu$as) | | | Dipole ($\mu$as) | | |
|---|---|---|---|---|---|---|
| | $x$ | $y$ | $z$ | $x$ | $y$ | $z$ |
| 250 | $-74 \pm 32$ | $-16 \pm 31$ | $-9 \pm 35$ | $+47 \pm 31$ | $-48 \pm 32$ | $-47 \pm 32$ |
| 2820 | $-26 \pm 32$ | $+32 \pm 30$ | $+41 \pm 28$ | $+32 \pm 30$ | $-37 \pm 28$ | $-30 \pm 30$ |

Table 1 VSH parameters of ICRF3—Gaia DR2

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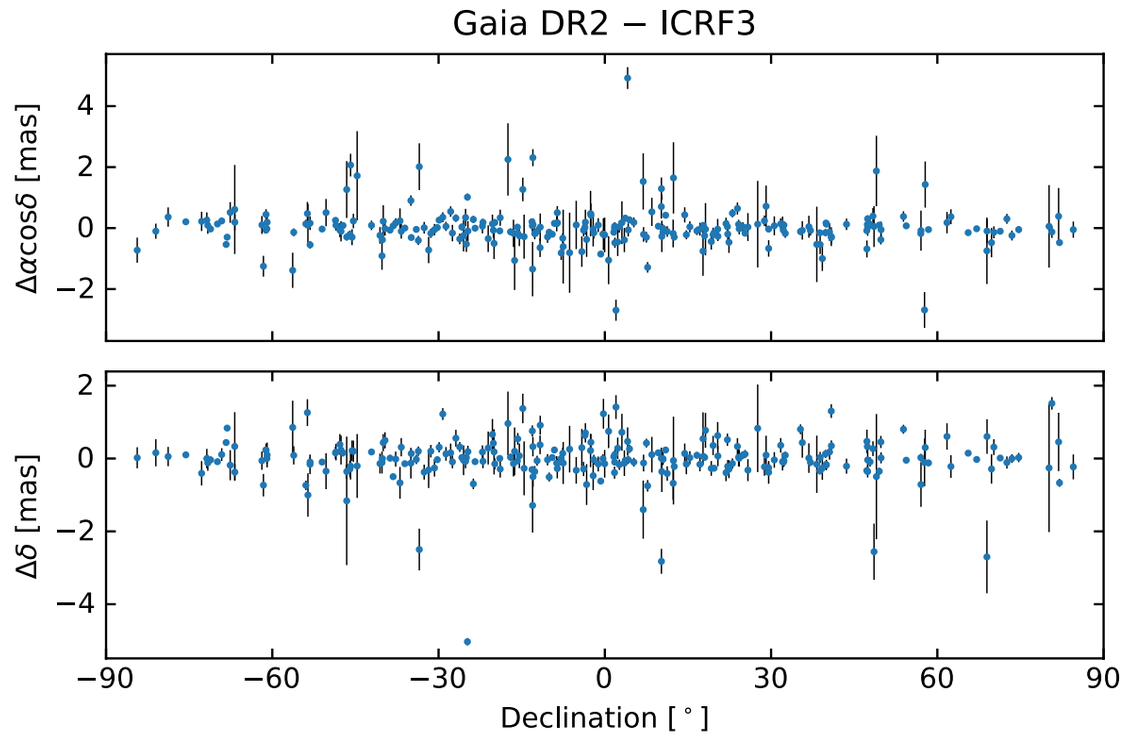


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# Solution configuration

- Test on
  - different a priori source position (ICRF3 S/X or Gaia DR2)
  - adjusting or fixing positions of defining source
- VLBI solutions @SYRTE/Paris Observatory

Table 2 VSH Configuration of VLBI solutions

| Label | Name | A priori catalog | Defining Source position | NNR rad | Post-fit rms ps | Reduced-$\chi^2$ |
|---|---|---|---|---|---|---|
| A | gcrf250 | Gaia DR2 | adjusted | $10^{-10}$ | 26.37 | 1.19 |
| B | icrf250 | ICRF3 SX | adjusted | $10^{-10}$ | 26.37 | 1.19 |
| C | gcrf250-fix | Gaia DR2 | fixed | $10^{-10}$ | 28.03 | 1.34 |
| D | icrf250-fix | ICRF3 SX | fixed | $10^{-10}$ | 26.44 | 1.20 |

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# Only changing a priori positions of radio sources

Fig. 5 Positional difference vs. R.A.

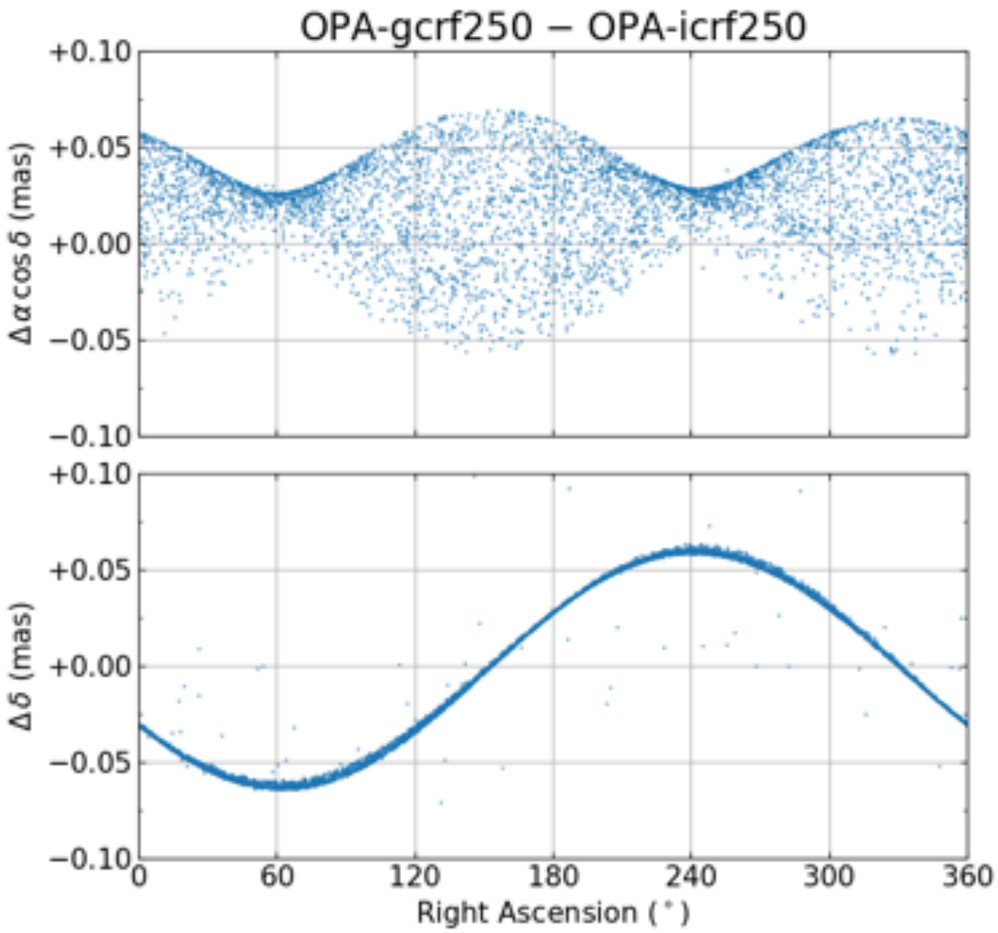
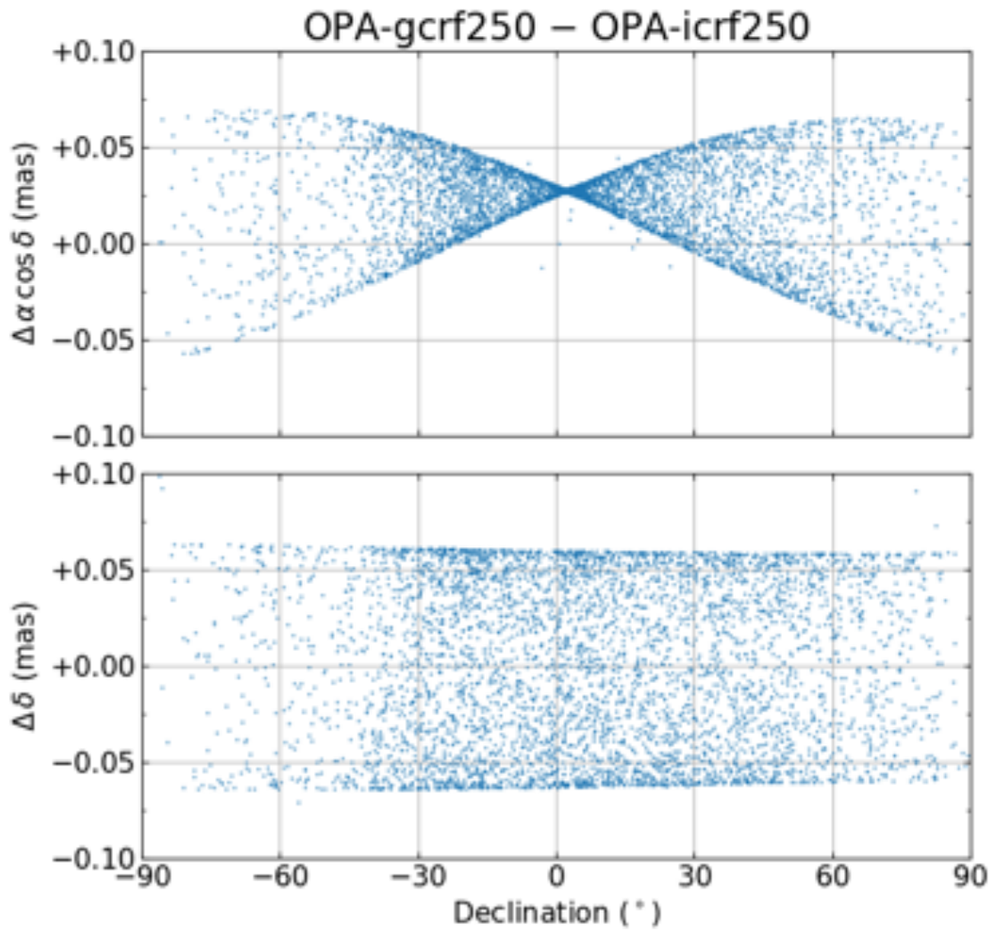



Fig. 6 Positional difference vs. decl.




Rotation ($\mu as$): $R_x \sim -54, R_y \sim +29, R_z \sim +27$

No dipole found

# Only changing source positions

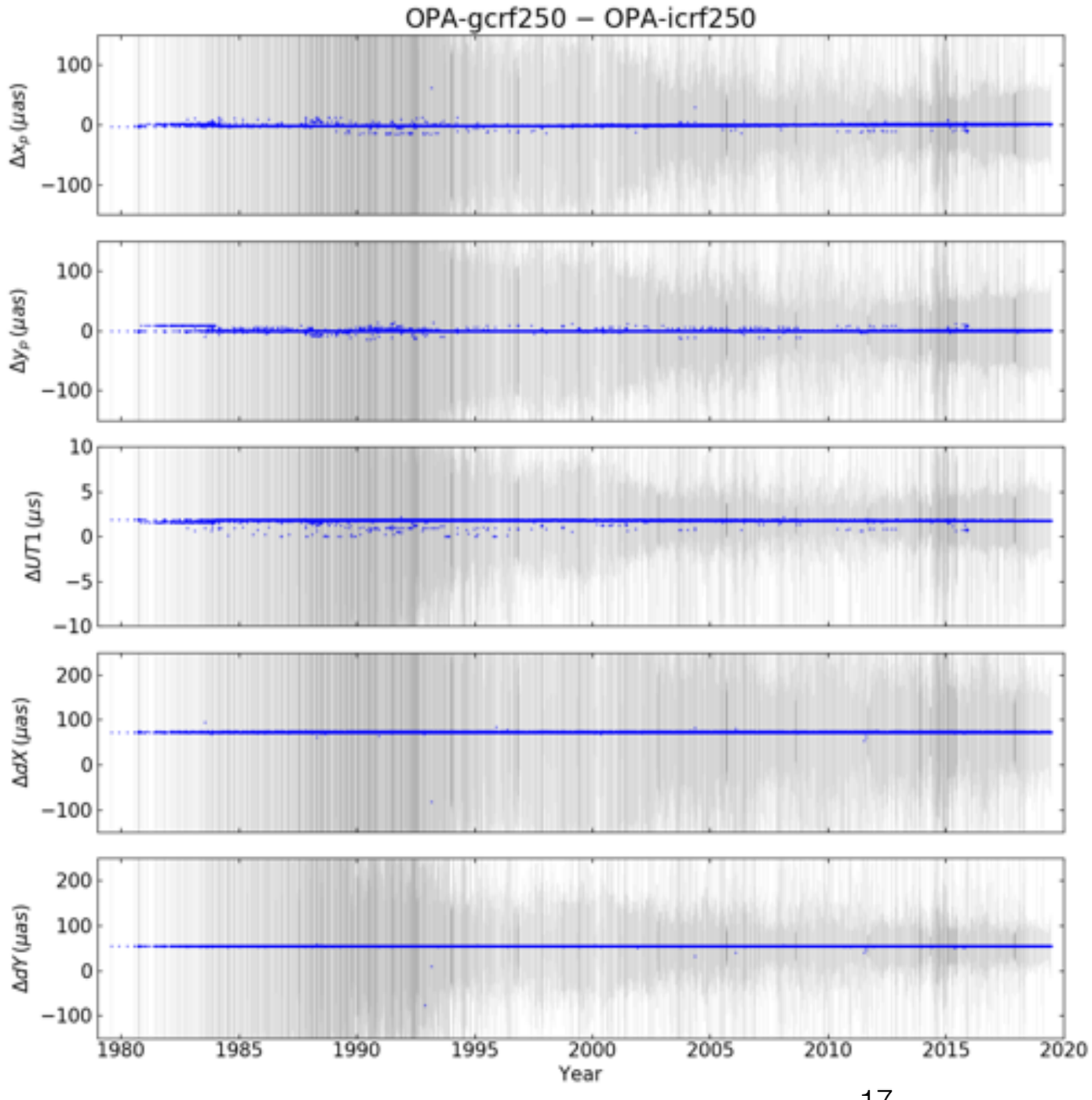



Fig. 7 EOP differences.
From top to bottom:
polar motion ($x_p$ and $y_p$);
UT1;
Nutation offset (d$X$ and d$Y$)

No influence on polar motion

→ $R_z \sim +27\mu as$

→ $R_y \sim +29\mu as$?

→ $R_x \sim -54\mu as$

# Fixing defining source positions

Fig. 8 Positional difference vs. R.A.

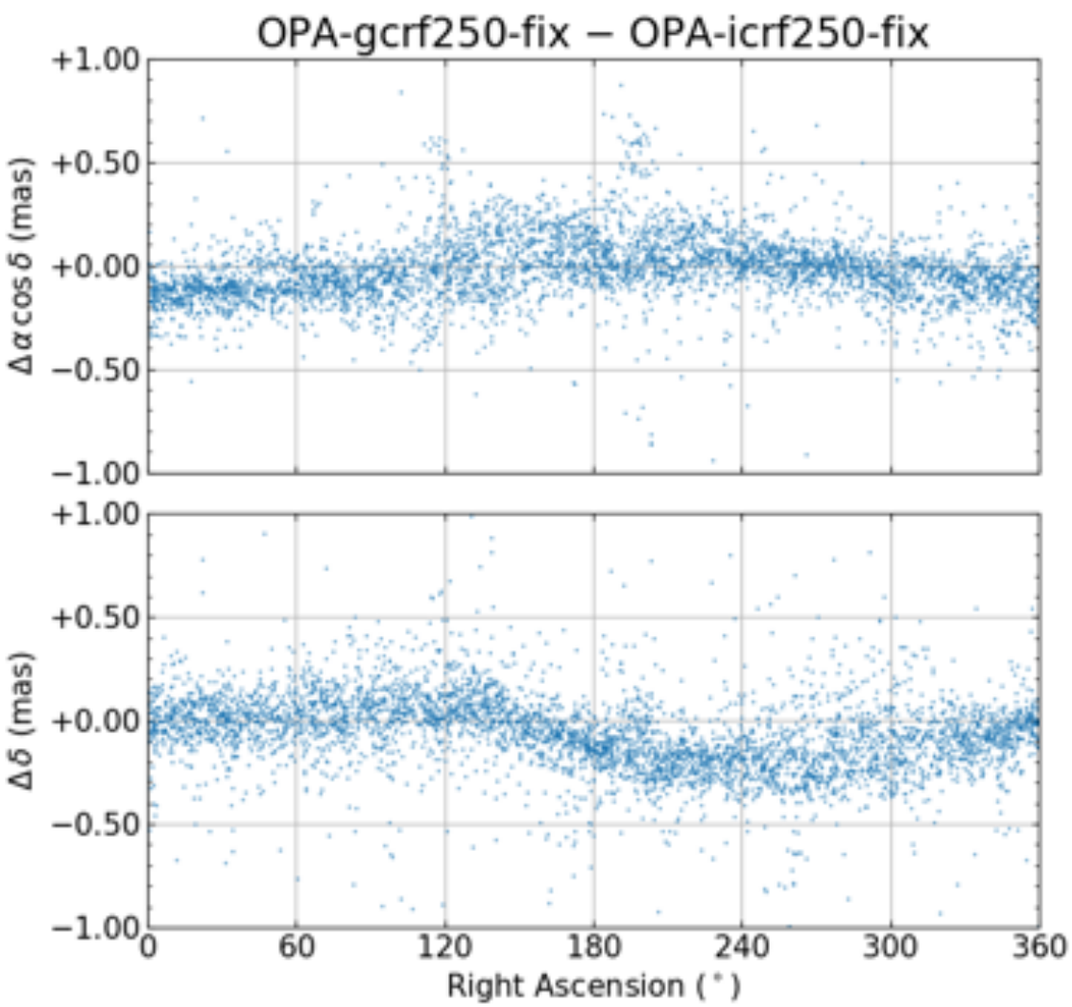
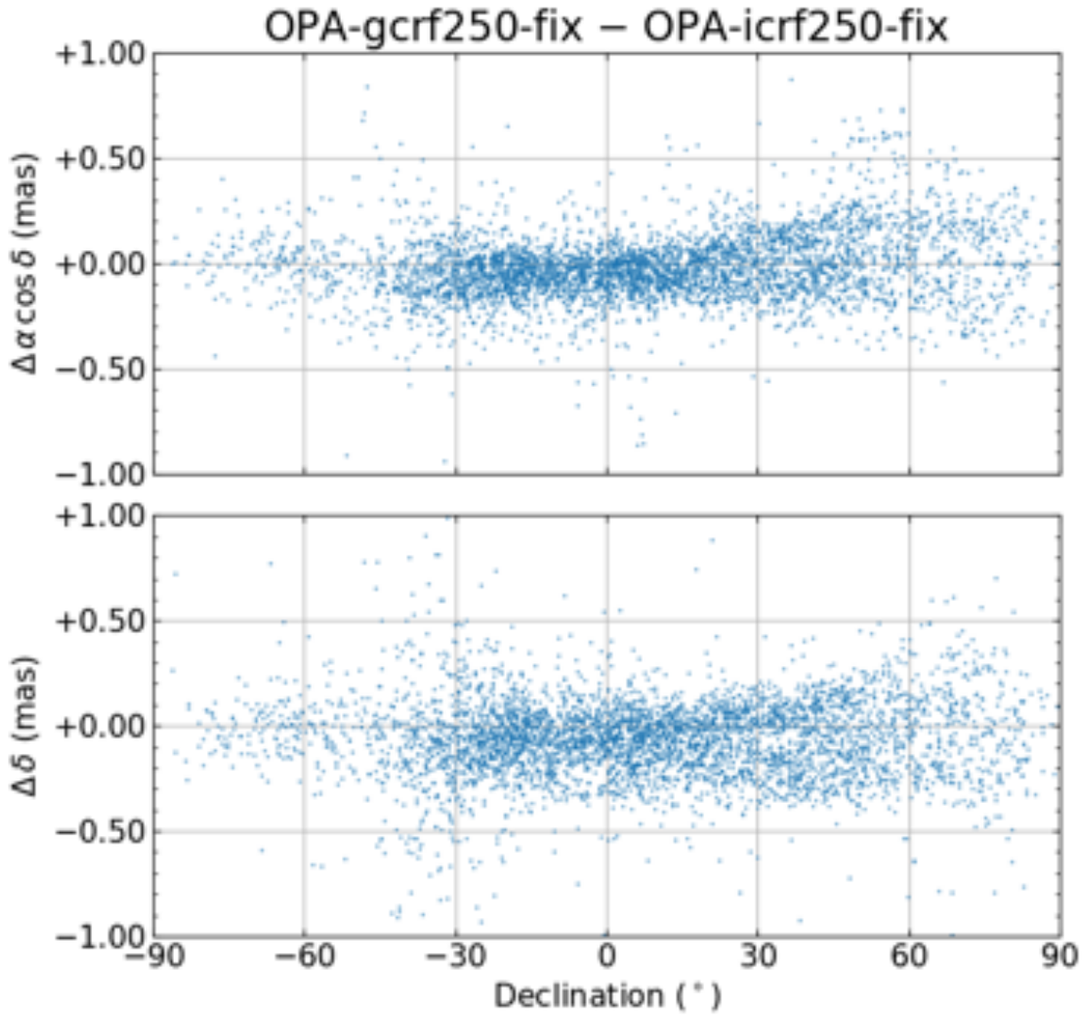



Fig. 9 Positional difference vs. decl.




Rotation ($\mu as$): $R_x \sim +148, R_y \sim -87, R_z \sim -17$

Dipole ($\mu as$): $D_x \sim +86, D_y \sim -104, D_z \sim -95$

# Fixing defining source positions

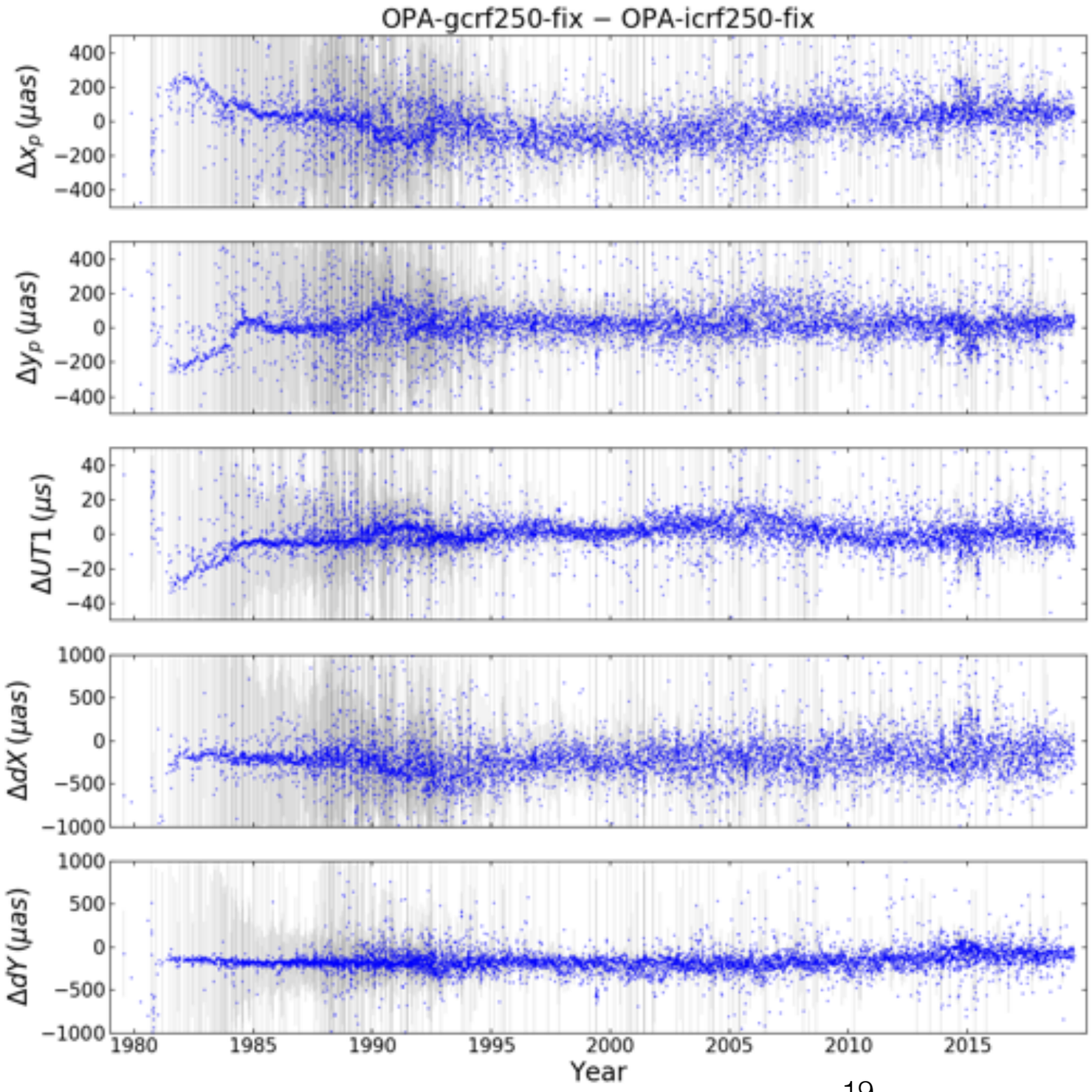



Fig. 10 EOP differences.
From top to bottom:
polar motion ($x_p$ and $y_p$);
UT1;
Nutation offset (d$X$ and d$Y$)

Irregular offset

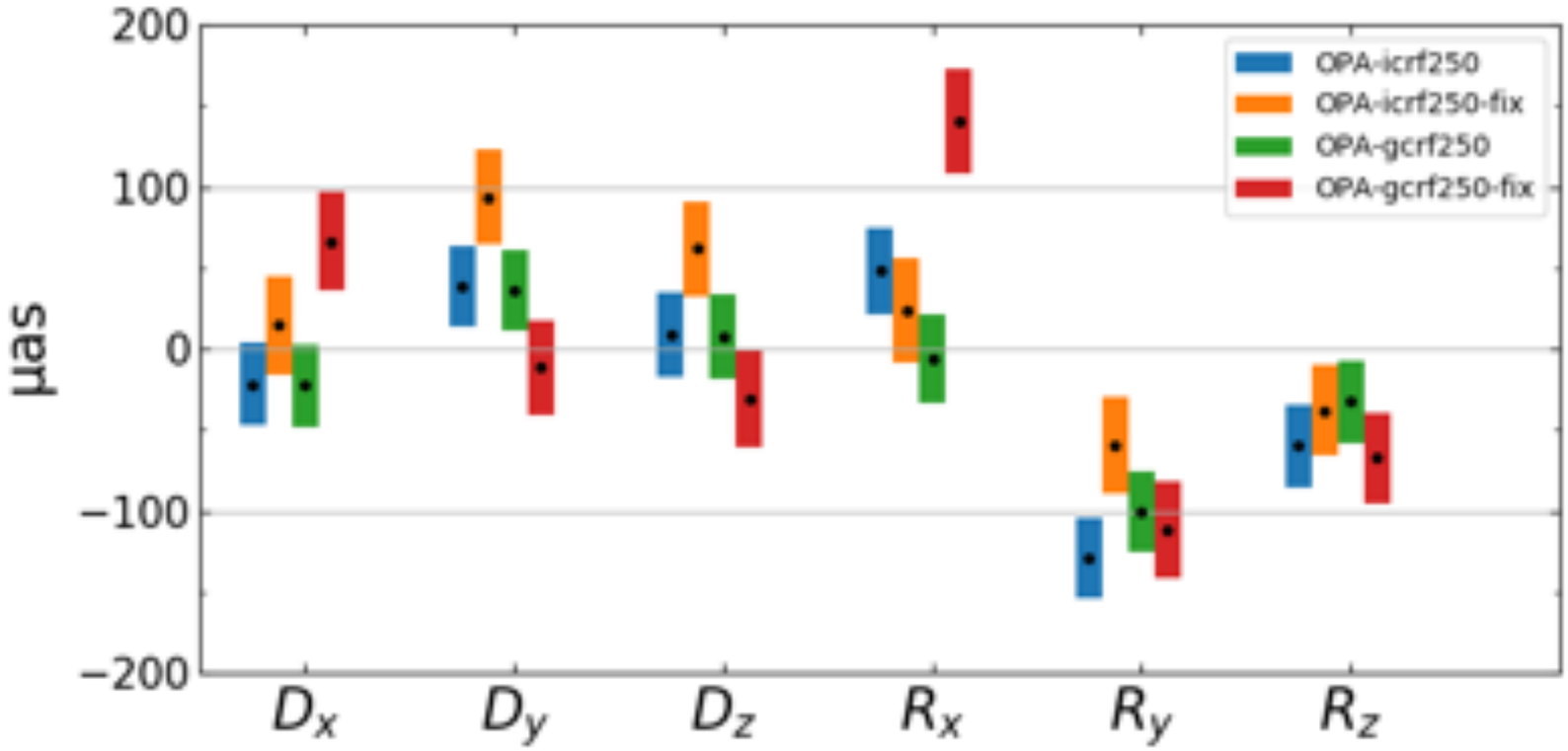
$R_z \sim -95\mu as$

$R_y \sim -87\mu as$?

$R_x \sim +148\mu as$

# Comparison with Gaia DR2

Fig. 11 VSH parameters between solutions and Gaia DR2




- Rotation generally agrees with each other

- Fixing defining source position to Gaia DR2 (*OPA-gcrf250-fix*) reduces the dipole with Gaia DR2 than fixing to ICRF3 positions (*OPA-icrf250-fix*)

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# Concluding remarks

- We present a possible method to analyze VLBI observations within the frame of Gaia-CRF2
- We found
    - taking ICRF3 or Gaia DR2 positions as a priori &adjusting the celestial frame introduces only orientation and corresponding offsets in UT1/Nutation
    - fixing defining source position to Gaia DR2 bring the estimated source position closer to Gaia DR2 in terms of dipole. However, it is a bad choice. We should better fix them to the ICRF3.
- Outlooks
    - Choose a suitable set of radio sources for radio-optical frame tie
    - Also consider the proper motion of Gaia DR2?