VLBI astrometry in the post-*Gaia* epoch

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VLBI astrometry surveys. Status on 2018.03.01

Statistics:

Number of observed sources: 27,719
Number of detected sources: 14,786
Number of sources imaged: 12,759
Number of images: 63,301

Matches:

γ-ray	Fermi:	15%
X-ray	Chandra	3%
infra-red	WISE:	74%
infra-red	2MASS:	36% (point sources)
optic	*Gaia*:	52%
optic	PanSTARRS:	69% (78%)
optic	known redshifts	42%
radio	NVSS	91% (99.8%)
radio	TGSS	72% (76%)

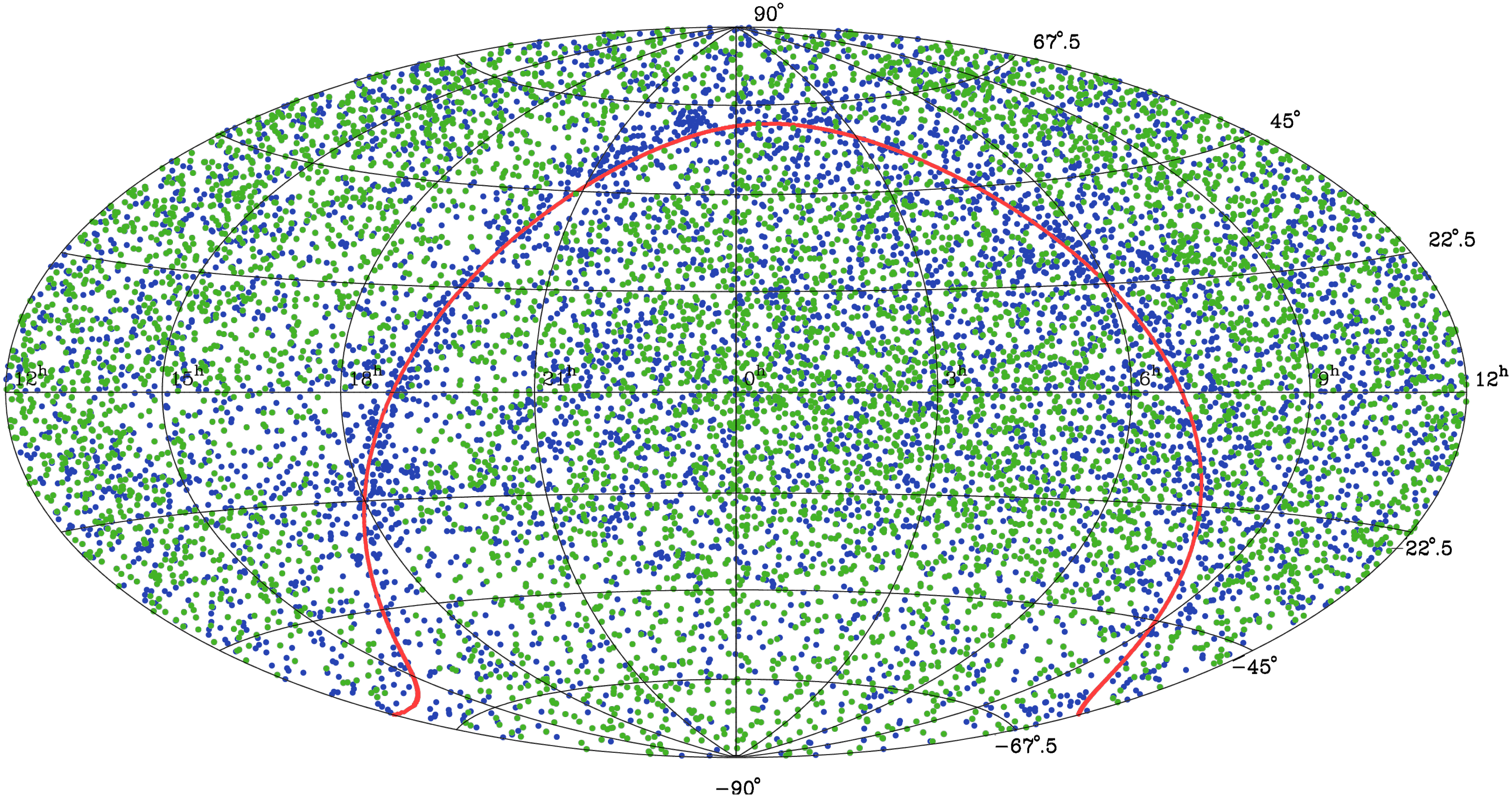
RFC position accuracy

Percentile of accuracy:

20%	< 0.30	mas
50% (median)	< 0.90	mas
80%	< 2.5	mas
90%	< 5.2	mas
94.8%	< 10	mas

Flux density @ X-band: [0.003, 22] Jy, median: 101 mJy

VLBI Radio Fundamental Catalogue (**14,786 sources**) on 2018.03.01 and *Gaia* DR1 ($1.14 \cdot 10^9$ objects)

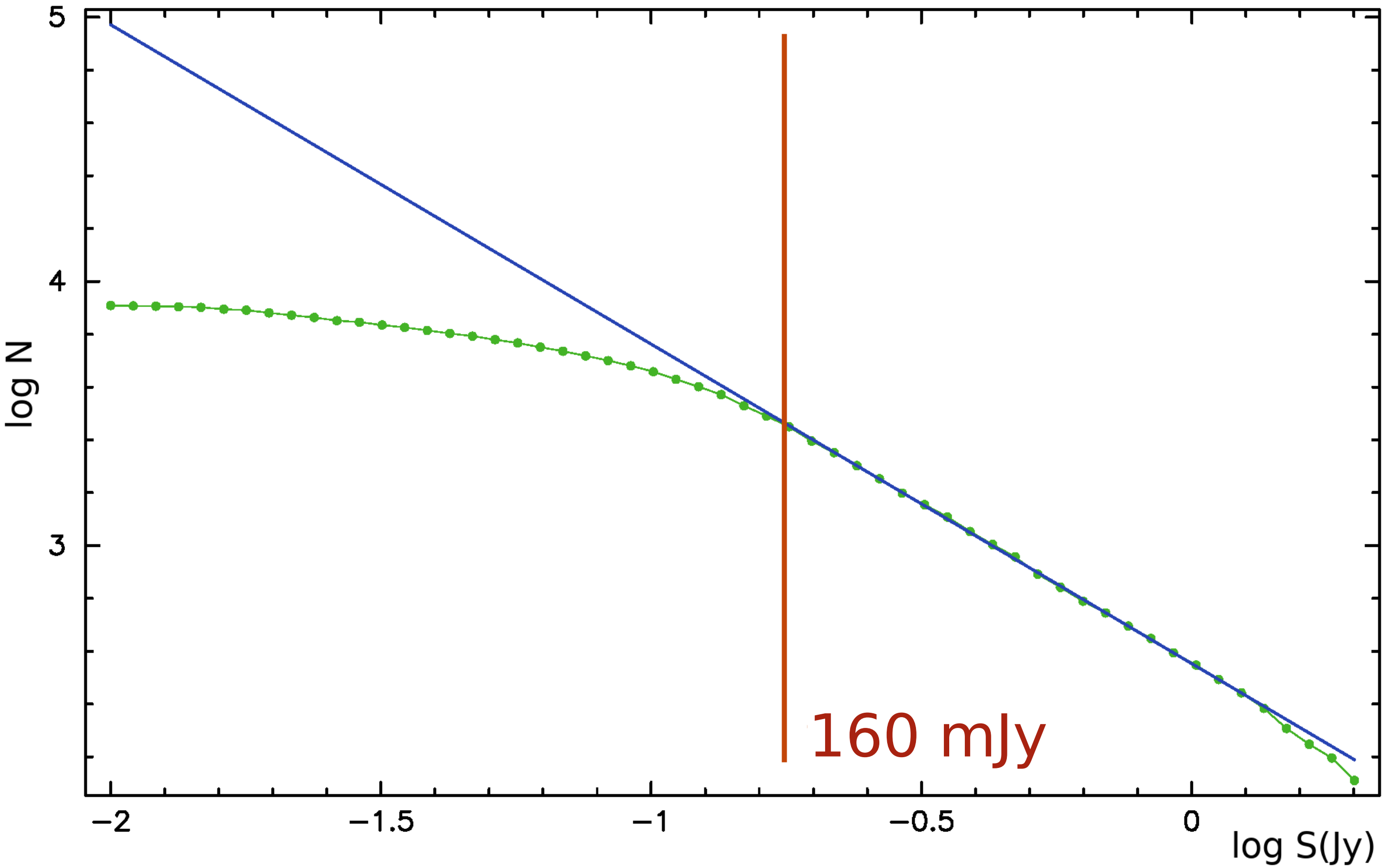


Green: 7,716 VLBI/*Gaia* matches $P < 0.0002$

Blue: VLBI sources without *Gaia* matches

Completeness of the RFC

$\log N$ versus $\log S$ diagram. $S_{\rm corr}$ @ 8 GHz at baselines 200–1000 km



170 mJy	99%
160 mJy	97%
150 mJy	95%
100 mJy	82%
50 mJy	53%
10 mJy	13%

Beyond RFC

Phase-referencing catalogues:

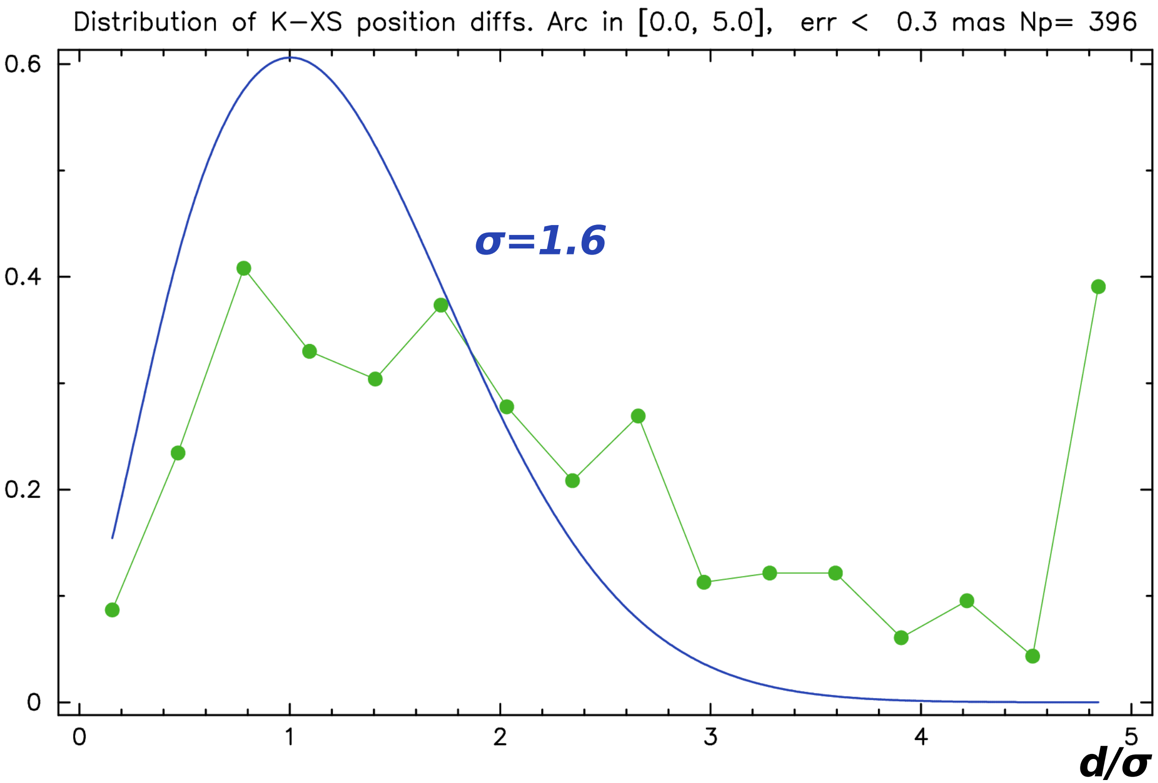
- mJive-20: 4822 source
- Lockman Hole, Hubble Deep Field-North, NOAO Bootes Field: ~ 100 sources

High frequency observations for images/detection:

- K/Q survey Lanyi, et al. 2010
- K-band VLBA, A. de Witt, on-going
- VERA and/or KVN, ~ 1200 sources

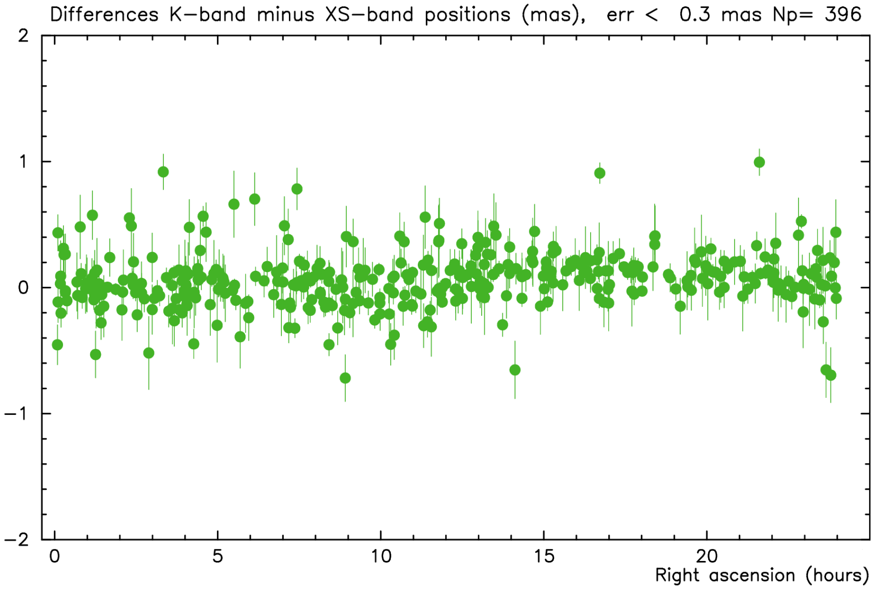
K-band astrometry

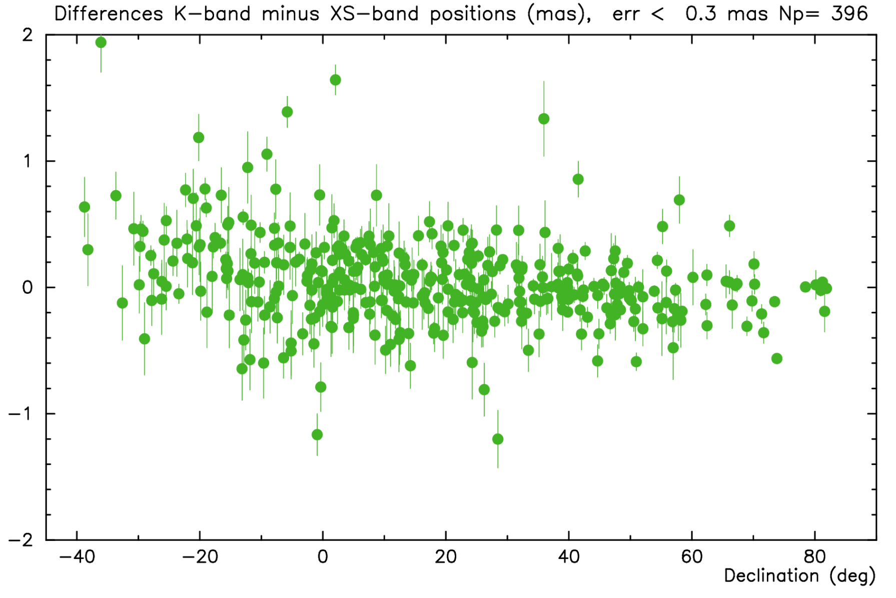
Total number of sources:	1039
With position accuracy < 1 mas:	750
With position accuracy < 0.2 mas:	363
With position accuracy < 0.1 mas:	148



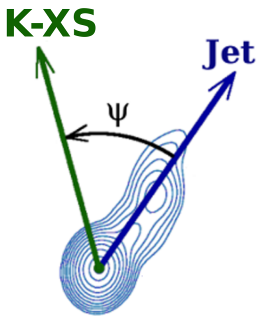
Are there systematic difference?

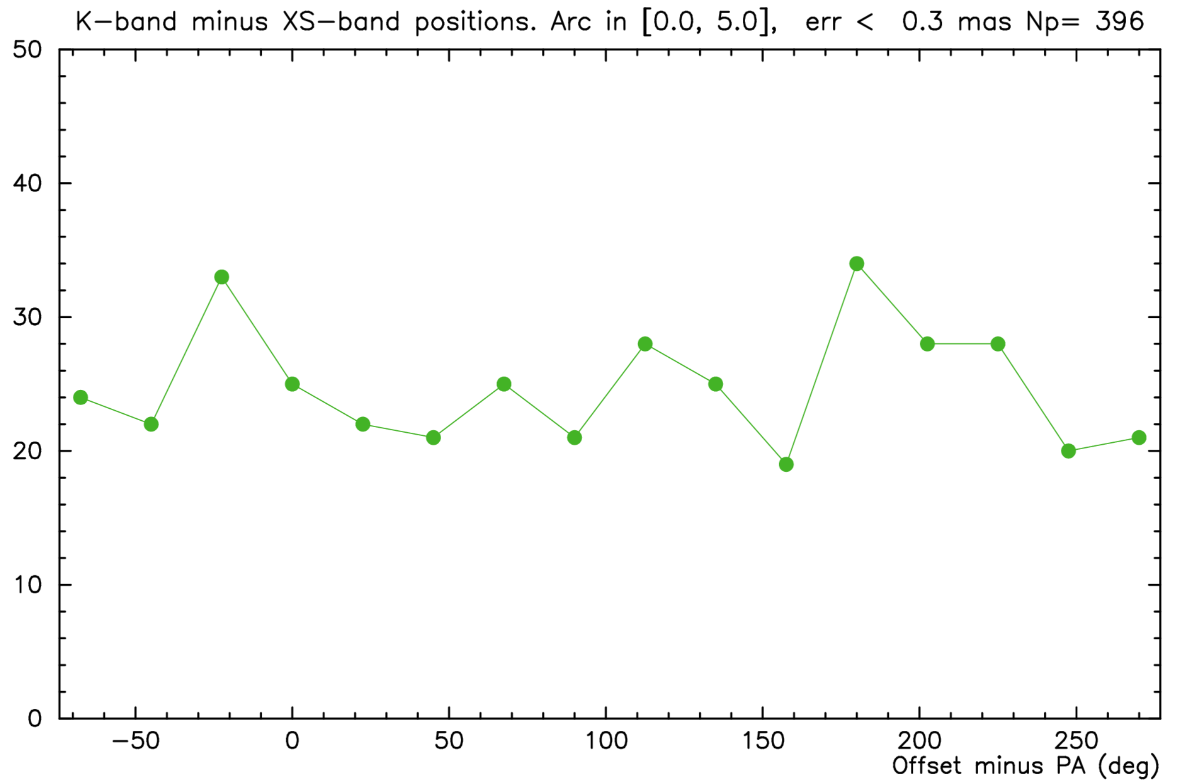
K-XS position differences:





Distribution of K-XS offset directions wrt jet directions





Conclusion: no evidence of systematic K/XS position differences

VLBI survey strategies:

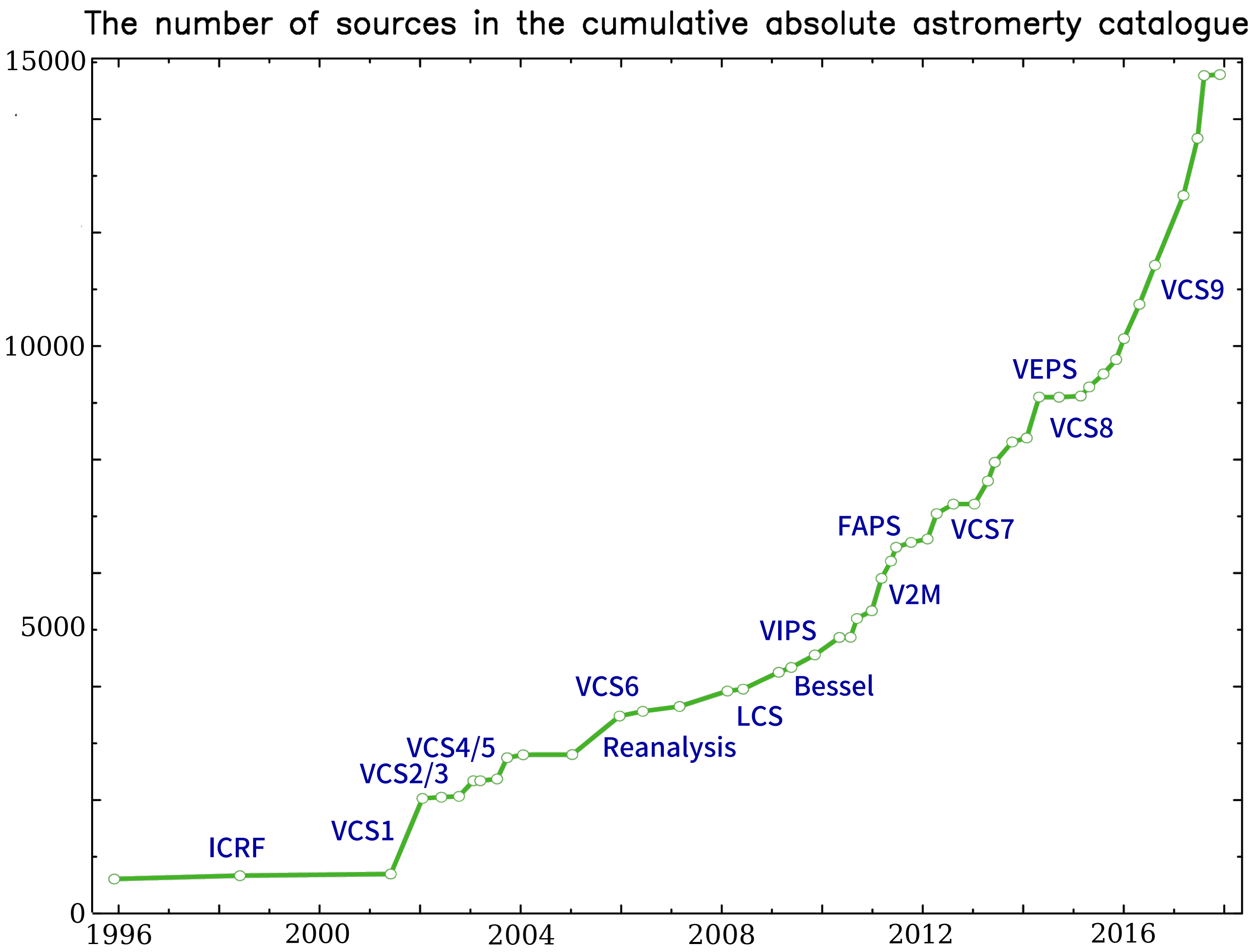
- To observe new VLBI sources
  - To extend the number of calibrators all-sky
  - To extend the number of calibrators in a given zone
  - To fill "empty" zones
  - To observe "interesting" sources
  - To reach completeness
  - To observe all in-beamers in the vicinity of calibrators

- To re-observe known sources
  - To improve position accuracy
  - To improve images
  - To determine core-shift
  - To observe at other (higher) frequencies
  - To follow-up peculiar sources

What is new in modern surveys:

- Gradual increase of field of view from $2''$ to $5'$ (whole beam)
- Gradual lifting selection bias towards flat spectrum
- Wider bandwidth: 64 $\longrightarrow$ 2048 Mbps. Detection limit: 6–20 mJy
- Automatic scheduling
- (semi)Automatic imaging
- X/S $\longrightarrow$ X/C, K-only, X-only, C-only, S-only data
- Rate: VLBA: 20–24 target sources per hour, 50% detection rate.

VLBI absolute astrometry: recent history

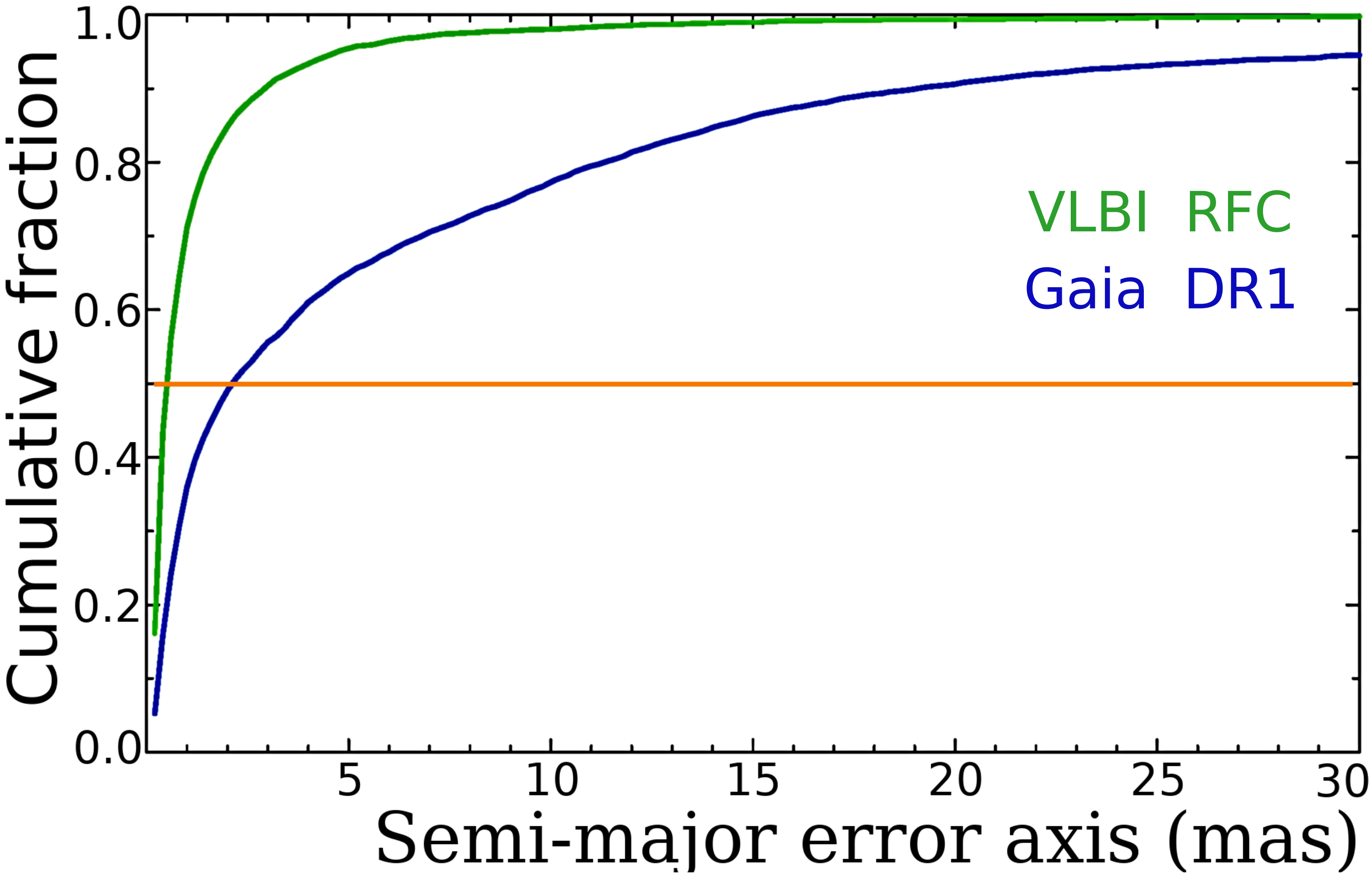


Cost: 4000 hours (excluding RDV and IVS)

VLBI absolute astrometry survey: where to go?

- Get more source?
  - to double # source: 1500 hours VLBA time
  - to double # source density: 5500 hours VLBA time
- To improve position accuracy?
  - to reach 0.2–0.3 mas accuracy for all VLBA sources: 2000 at VLBA
  - to reach 0.2–0.3 mas accuracy for all VLBA/Gaia sources: 1000 at VLBA
- To survey Galactic plane with K-band?
  - Re-observe known sources: 300 hours VLBA time
- To survey ecliptic plane down to 50 mJy?
  - detection survey: 300 hours (CVN)
  - fine astrometry: 300 hours (CVN+IAA, VLBA)
- To re-image interesting source?

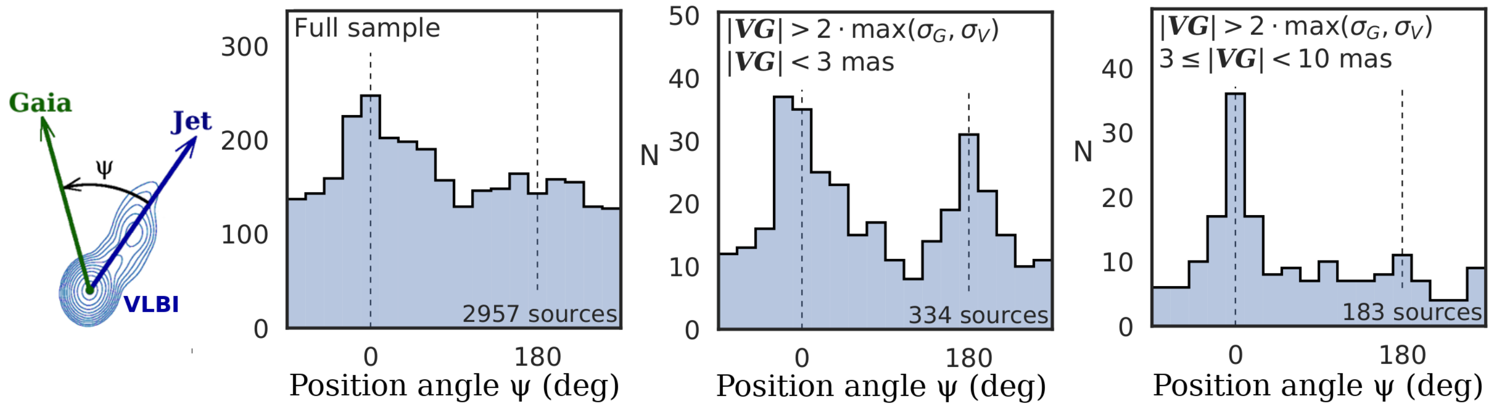
VLBI and *Gaia* position uncertainties



Median error: **VLBI RFC**: 0.5 mas

Median error: *Gaia* **DR1**: 2.2 mas

Discovery of systematic differences VLBI/*Gaia*



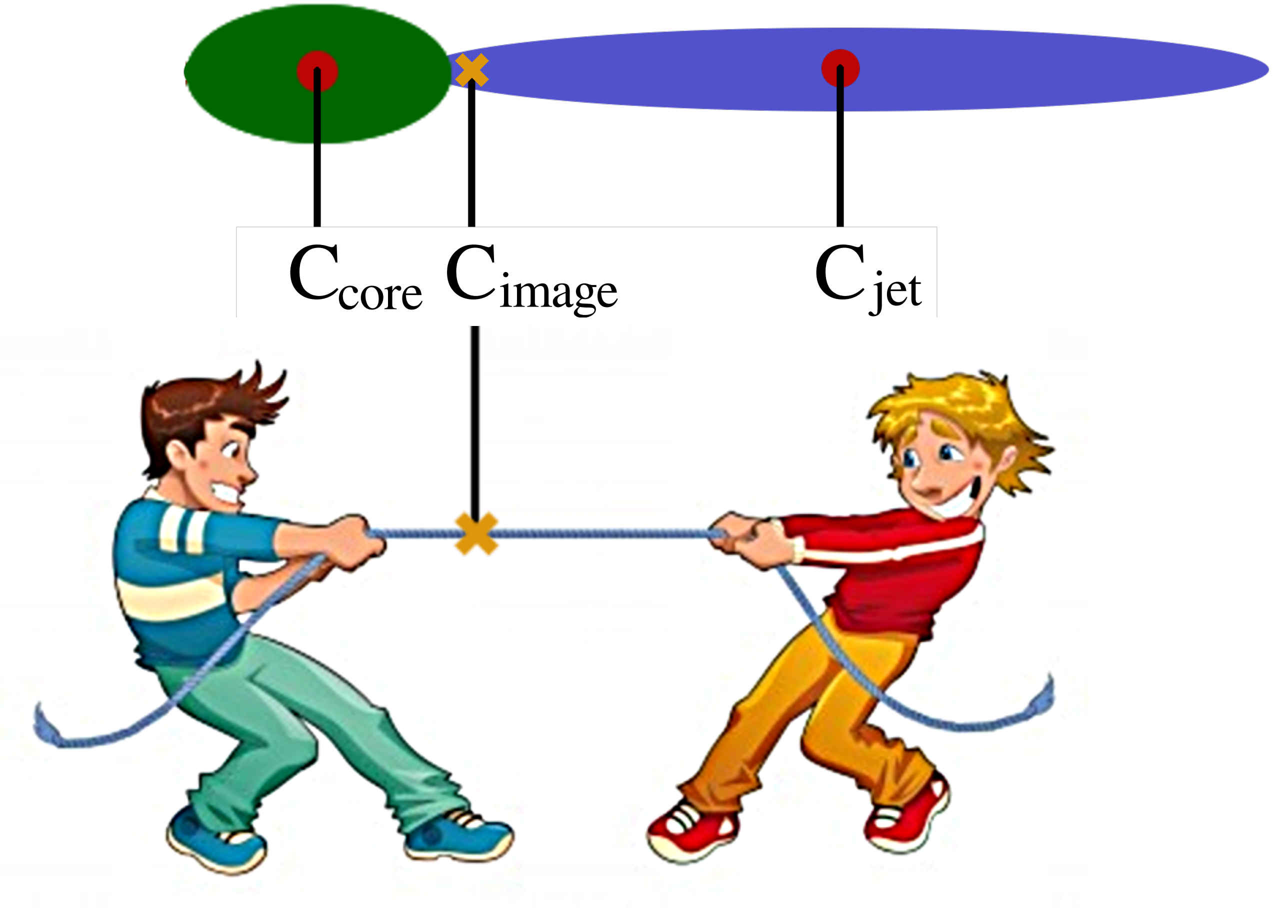
Interpretation: VLBI and *Gaia* see sources differently:

VLBI reports position of the compact component (if there is only one)

Gaia reports position of the centroid

New observable appeared: $\mathcal{O}_\mathrm{j}$

Centroid of a core-jet morphology



$$C_{\text{image}} = \frac{C_{\text{core}}\,F_{\text{core}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}} + \frac{C_{\text{jet}}\,F_{\text{jet}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}} + \frac{C_{\text{stars}}\,F_{\text{stars}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}}$$

Impact of discovery of VLBI/*Gaia* offsets on AGN physics

- Possibility to study optical jets at 1–100 mas resolution a) statistically; b) case-by-case
- Possibility to separate emission in the accretion disk from jet
- Possibility to answer the question where the flares occur: at the accretion disk, at the core base or at the hot spot
- Better understanding the nature of CSO

What is needed?

- better images
- better position accuracy
- applying source structure contribution in data analysis

Impact of discovery of VLBI/*Gaia* offsets on astrometry

- We still do not know unmovable sources (AGNs are not);
- There is a limit beyond that positions from technique A and B are not comparable;
- For VLBI/*Gaia* this limit is 1–2 mas;
- A jitter in *Gaia* AGN positions is predicted;
- The fundamental coordinate systems from different techniques have to coexist;
- Impossible to say which is the best: *Gaia*-DR99, or RFC, or ICRF-2100;
- Future comparison of VLBI/optic will focus on astrophysics interpretation.

Wide impact of *Gaia* on fundamental astronomy

- Is VLBI astrometry for study of Galaxy kinematics competitive with *Gaia*?

  - VLBI stellar parallax determination —
    can VLBI compete? ●
  - VLBI maser parallax/proper motion determination —
    can VLBI compete? ●

- Ground astrometry of Galactic plane objects is limited to
  - objects weaker 21 mag (telescope larger 2m);
  - objects not visible in optical range, like pulsars, masers;

- VLBI/*Gaia* AGN program is emerging;

Radio absolute astrometry: where to go — my view

- Field of "extensive astrometry":
  - ecliptic plane (50 and 30 mJy);
  - unassociated sources (f.e. *Fermi*)

  Expected growth rate: 200–500 new sources per year.

- Extensive era of radio astrometry is followed by with intensive era

  The areas that need nanorad level accuracy:
  1. $\mathcal{O}_\mathrm{j}$, $\mathcal{O}_\mathrm{t}$ observables;
  2. space navigation;
  3. pulsar timing/VLBI differences.

  Goals:
  - improve positions of ~ 9000 VLBI/*Gaia* matches down to 0.2–0.3 mas.
  - derive source images, apply source structure correction.
  - determine jet direction

Absolute astrometry without imaging is close to junk in post-*Gaia* era.

Summary of debatable items

- Whether the list of VLBI source (15k absolute and 5k differential) should be expanded?
- How deep should we observe ecliptic band?
- Should we get accuracy below 0.3 mas for specific sources?
- Can VLBI compete with *Gaia* for parallax/proper motions of stars?
- Can VLBI compete with *Gaia* for study of Galactic kinematics?
- What is the merit of mjive20-style astrometry?