“Observations” of jets with geodetic VLBI, celestial reference frames, and link with Gaia

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Outline

Geodetic VLBI: what it is, what we do with it

The multiwavelength extragalactic reference frame

The radio source coordinate time series

Conclusion

Geodetic VLBI

2+ radio telescopes observing an extragalactic source

$$F_{12} = \mathrm{e}^{-2i\pi\hat{k}_0.\vec{B}/\lambda} \int I(x,y)\mathrm{e}^{-2i\pi(ux+vy)}\mathrm{d}x\mathrm{d}y$$

Delay of reception between telescopes

Strongly depends on the orientation of the Earth and on the telescope position on the ground

Brightness distribution

Sampling of the spatial frequencies

SYRTE
IERS
IVS

Analyze delay τ = k.B/c to infer "geometric products"

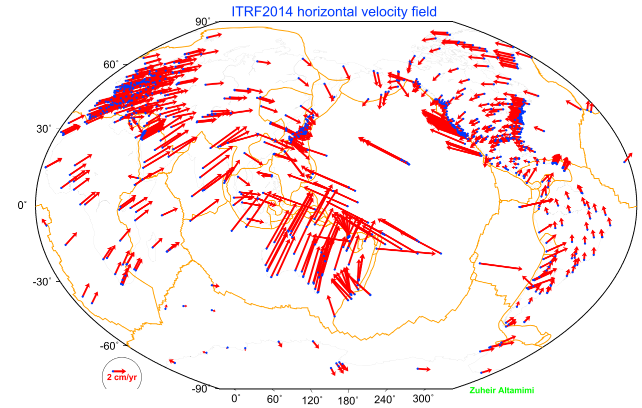
Geodetic VLBI

Frame of IAG and IAU: International Earth Rotation and Reference Systems Service (IERS) and **International VLBI Service for Geodesy and Astrometry** (IVS)

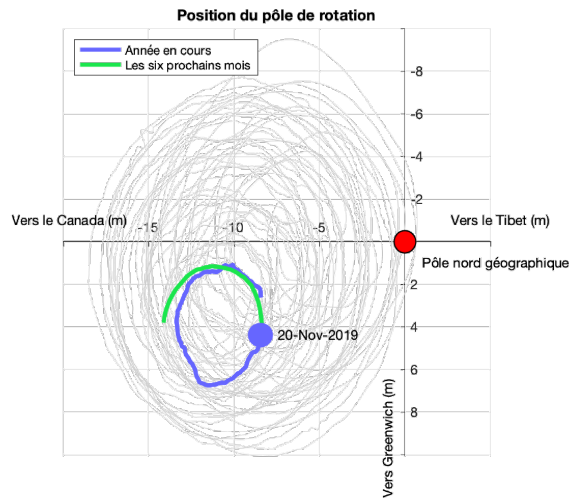
- Combination center (VLBI, GNSS, Laser, DORIS) @SYRTE: reference Earth rotation series
- ICRS center @SYRTE: maintenance of the ICRF
- Analysis center @SYRTE: operational treatment of geodetic VLBI observations and contribution to ITRF, ICRF, and Earth orientation
- “Operational”: new observations every day

Geodetic VLBI

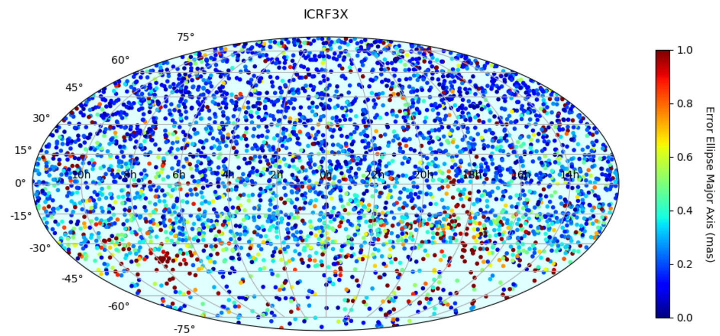
- Three pillars of geodesy
  - Terrestrial reference frame (ITRF)
  - Celestial reference frame (ICRF)
  - Transformation between them: Earth rotation
- Applications
  - Reference frames
  - Geophysics
  - Fundamental physics



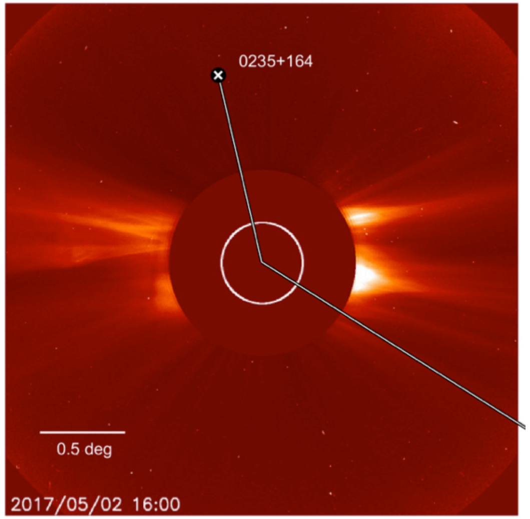
Altamimi et al 2016



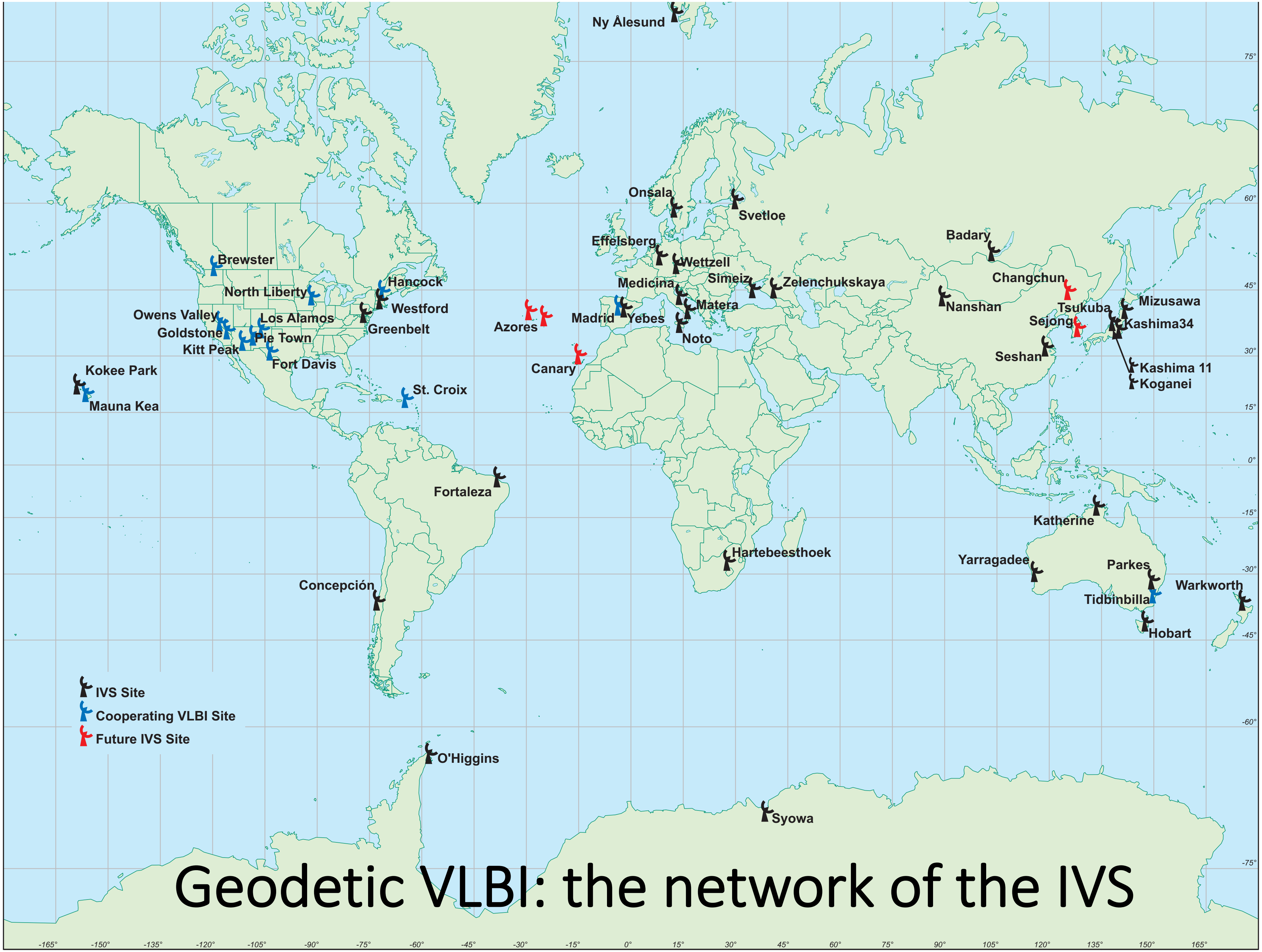
Bizouard et al 2019



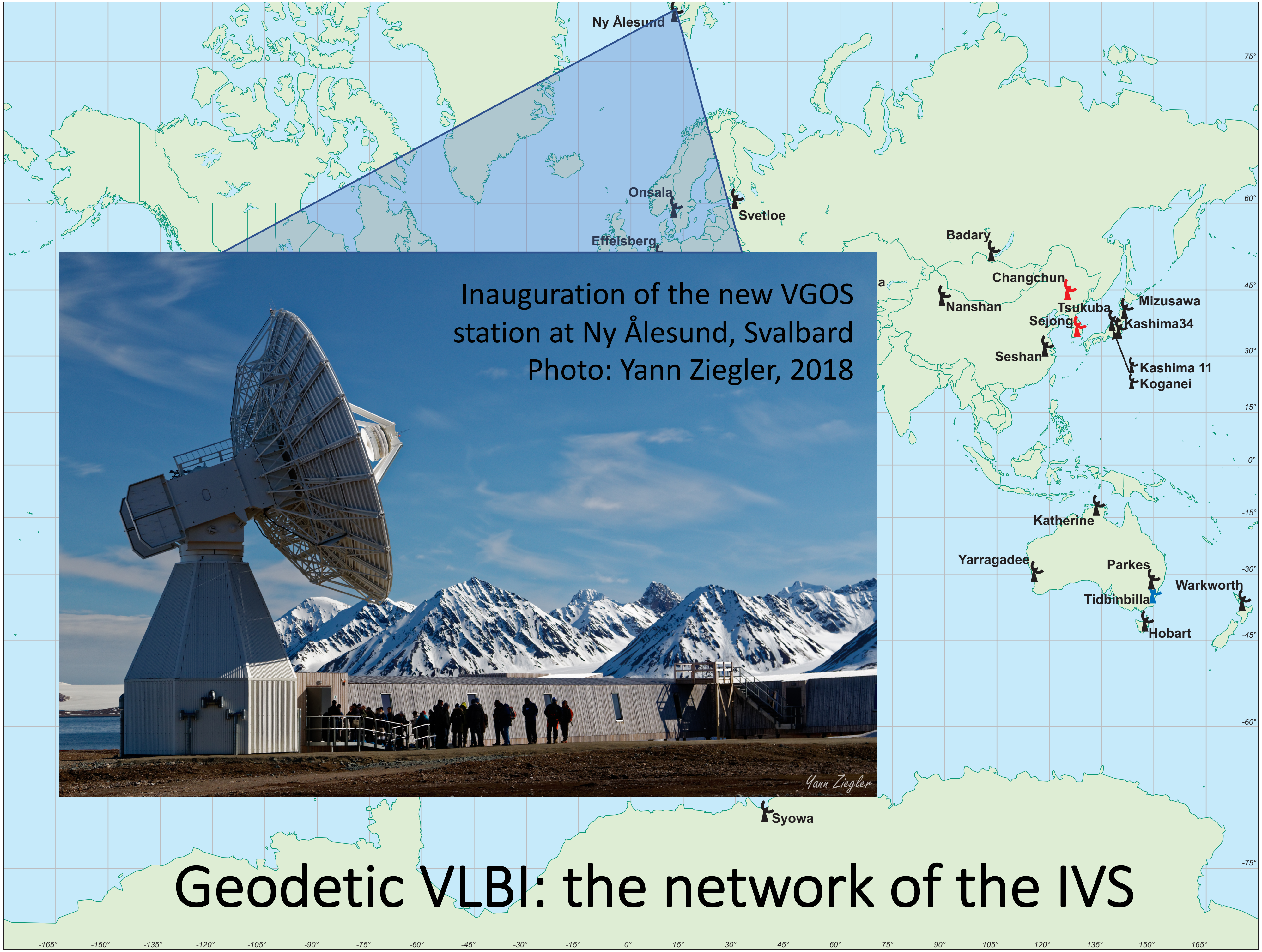
Charlot et al 2020



Titov et al 2019



Geodetic VLBI: the network of the IVS



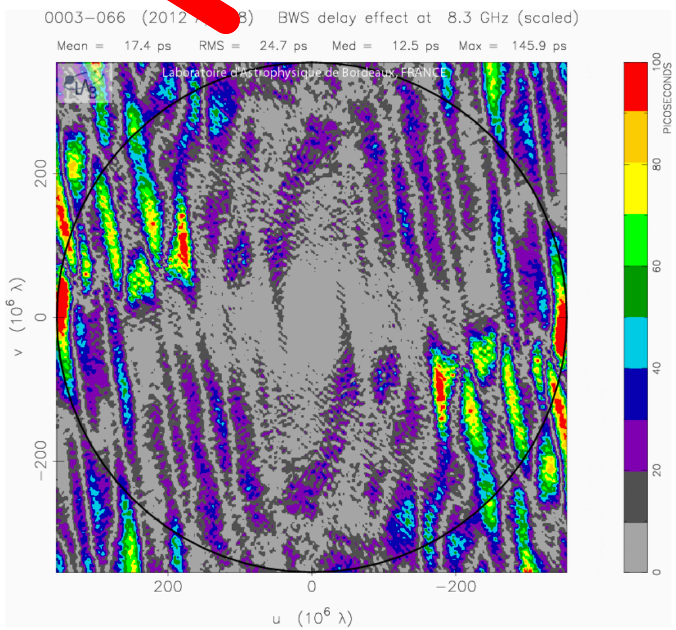
Geodetic VLBI: the network of the IVS

Radio sources with geodetic VLBI

- Geodetic point of view
  - They are points
  - Structure is ignored to some extent

$$F_{12} = \mathrm{e}^{-2i\pi\hat{k}_0.\vec{B}/\lambda} \int I(x,y)\mathrm{e}^{-2i\pi(ux+vy)}\mathrm{d}x\mathrm{d}y$$

- Delay and structure
  - $\tau = \tau_{geom} + \ldots + \tau_{structure}$
  - Geodetic VLBI observing strategy not suitable for imaging
  - How much structure perturbs the geodetic products is still an unsolved problem
  - Structure delay: Charlot 1990, Fey and Charlot 1997, 2000, BVID



The extragalactic reference frame

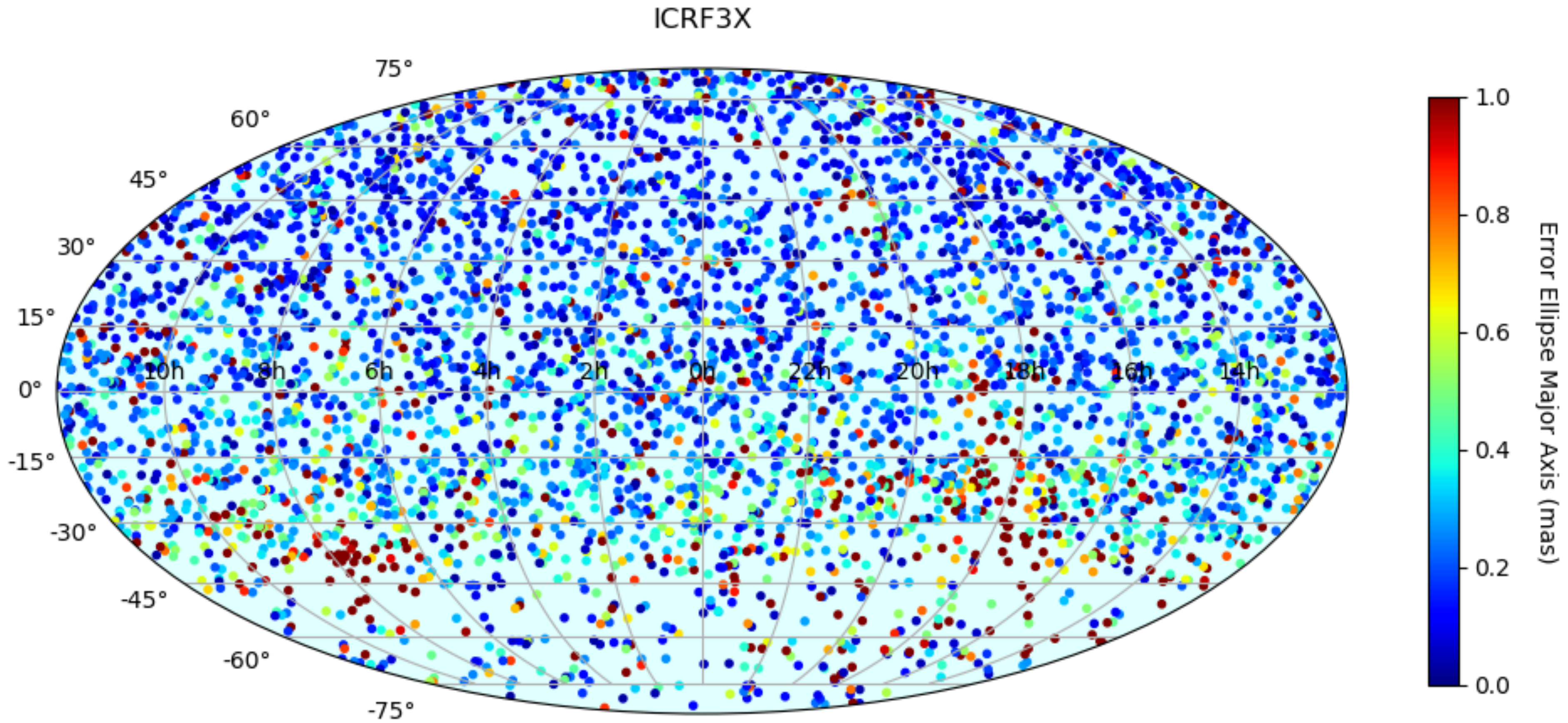
ICRF3

ICRF3 and Gaia: linking radio and optical

The ICRF3 (Charlot et al 2020)

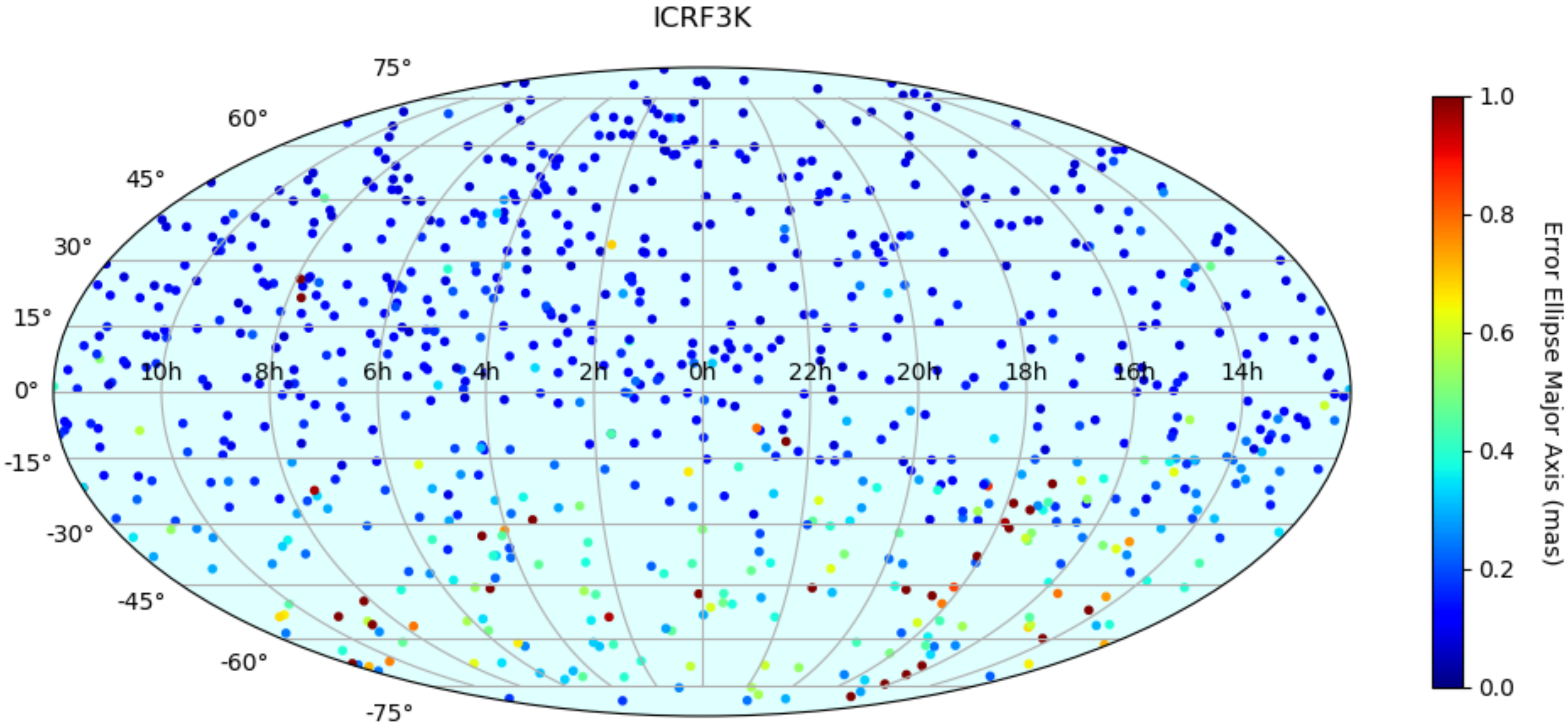
- Astrometry at 8 GHz (4536 sources), 22 GHz (824 sources) and 32 GHz (678 sources)
- IAU fundamental frame since 1 January 2019
- Precision for X-band: 0.03 mas
- Other estimated parameters
  - TRF and Earth orientation
  - Tropo and clocks
- Models
  - Tides and nonlinear station position variations
  - Galactic aberration (MacMillan et al 2019)
- Frame orientation
  - No-net rotation applied onto 295 defining sources
  - “Absolute” astrometry (“in the ICRS”)

The ICRF3 @ 8 GHz



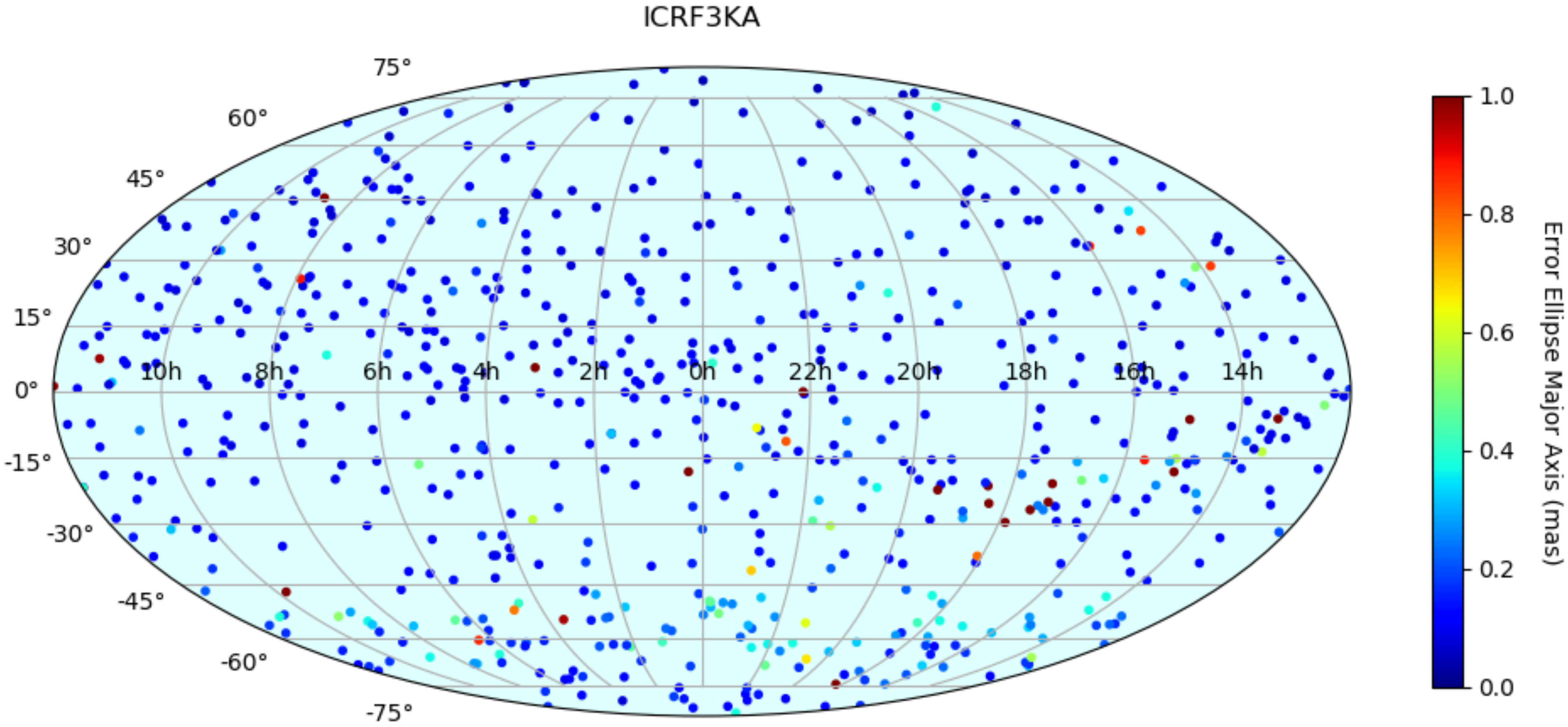
4536 sources

The ICRF3 @ 22 GHz



824 sources

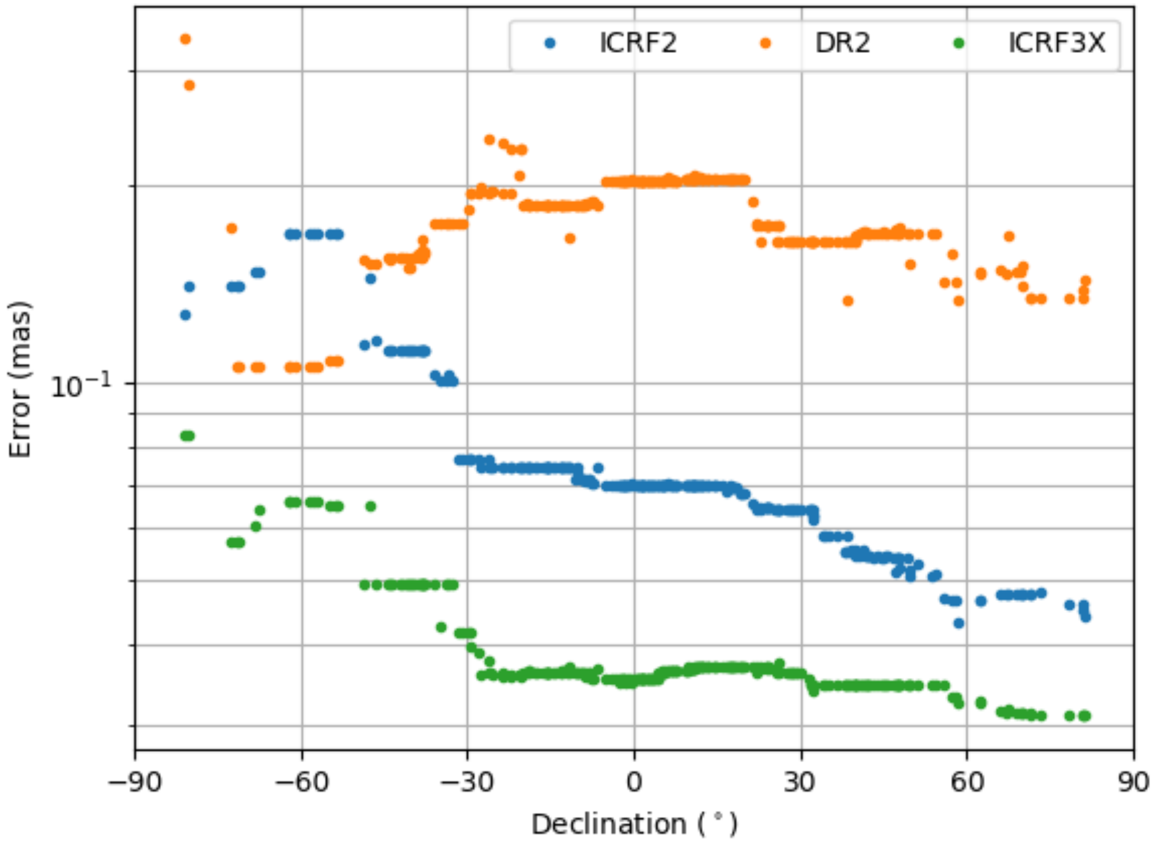
The ICRF3 @ 32 GHz



678 sources

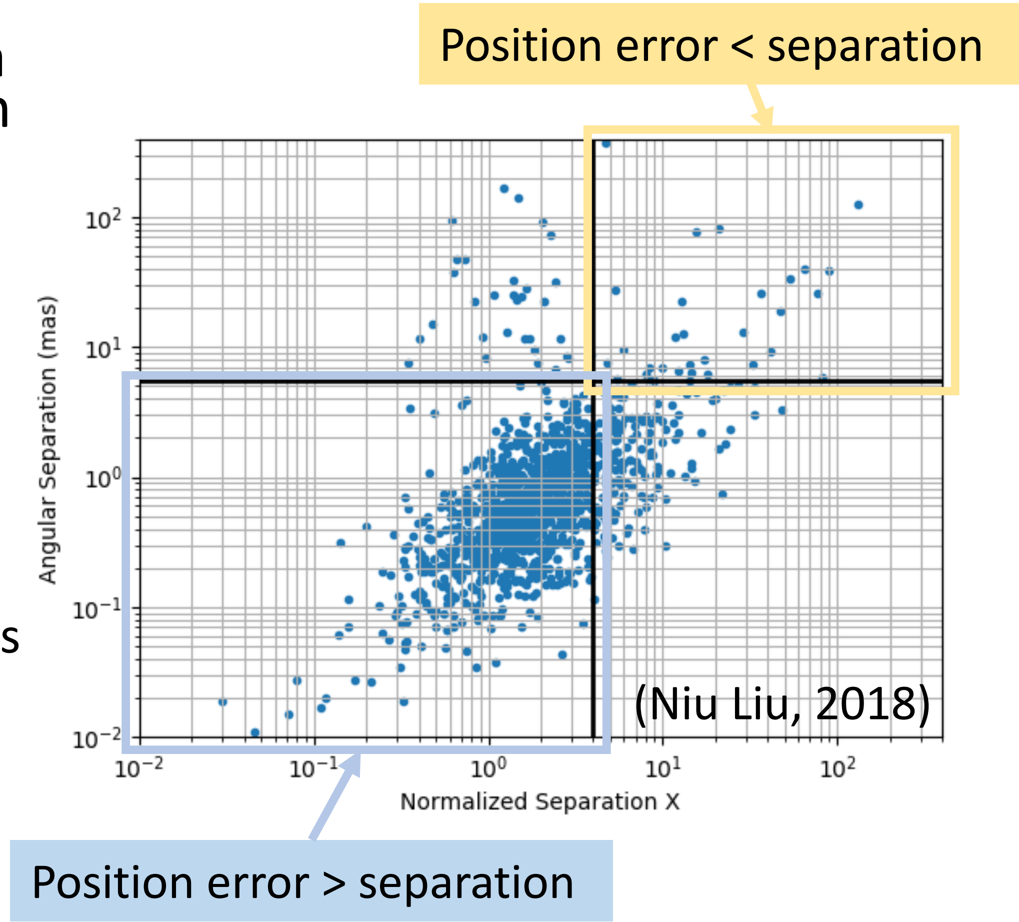
The ICRF3 vs Gaia DR2 and ICRF2

Precision vs declination: VLBI is “better” than Gaia but has different systematics: strong declination-dependent error



Linking radio to optical

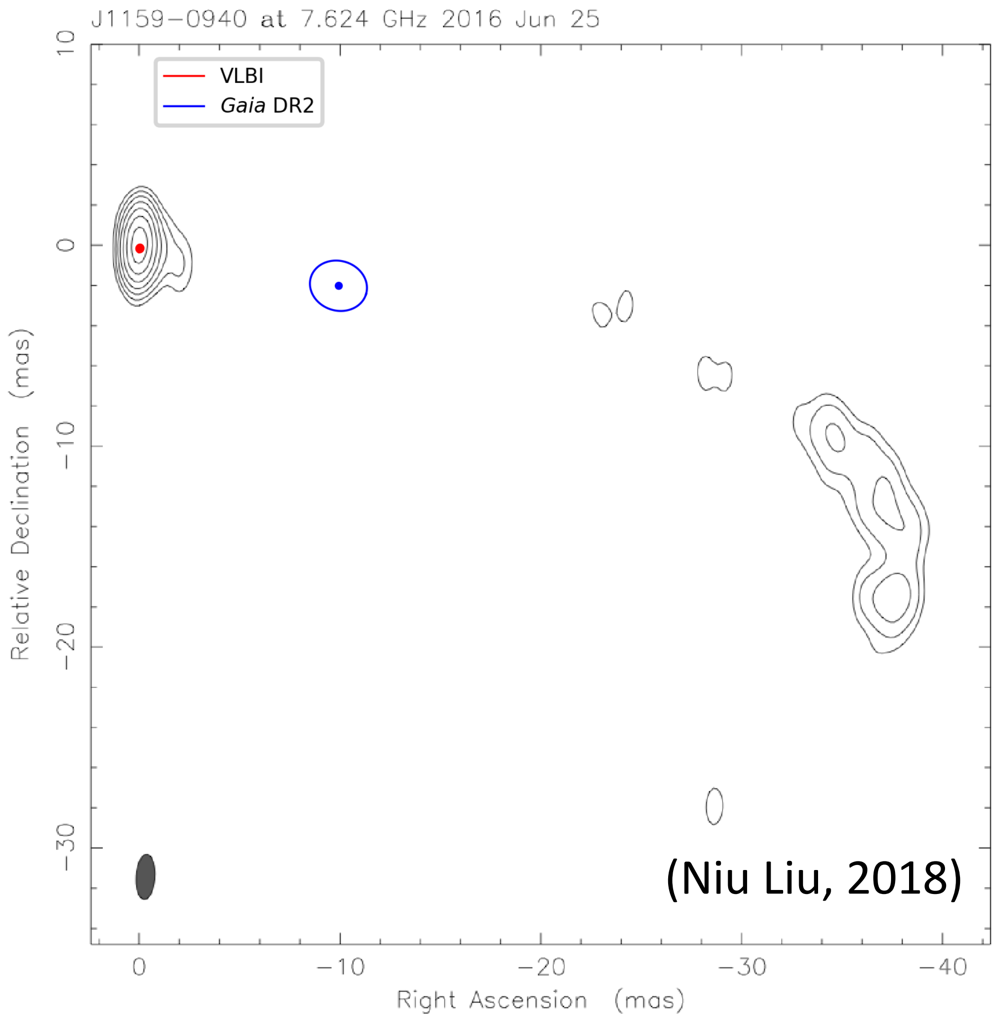
- Comparison of VLBI with Gaia allows to pick up sources with significant radio-optical (RO) separation
- Kovalev et al 2017: favor jet direction
- Liu et al 2020
  - Analyzed 1200+ Gaia-VLBI differences
  - 53 sources w/ normalized separation > 4 and RO > 1 mas
- Then, questioning about
  - Orientation of RO wrt jet?
  - Implications for the sources?



Angular sep vs normalized sep;
Significance level determined following Mignard et al 2016

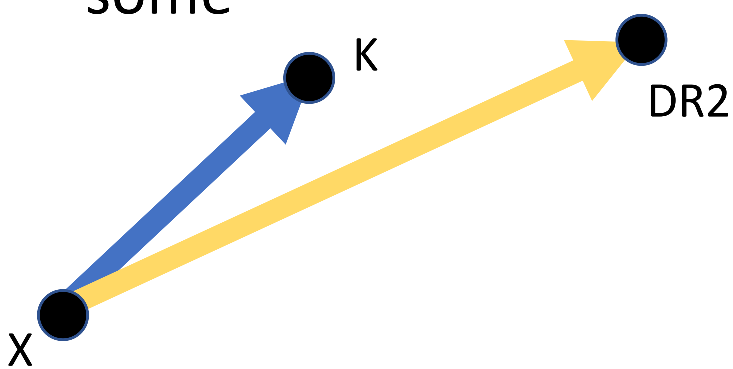
Linking radio to optical

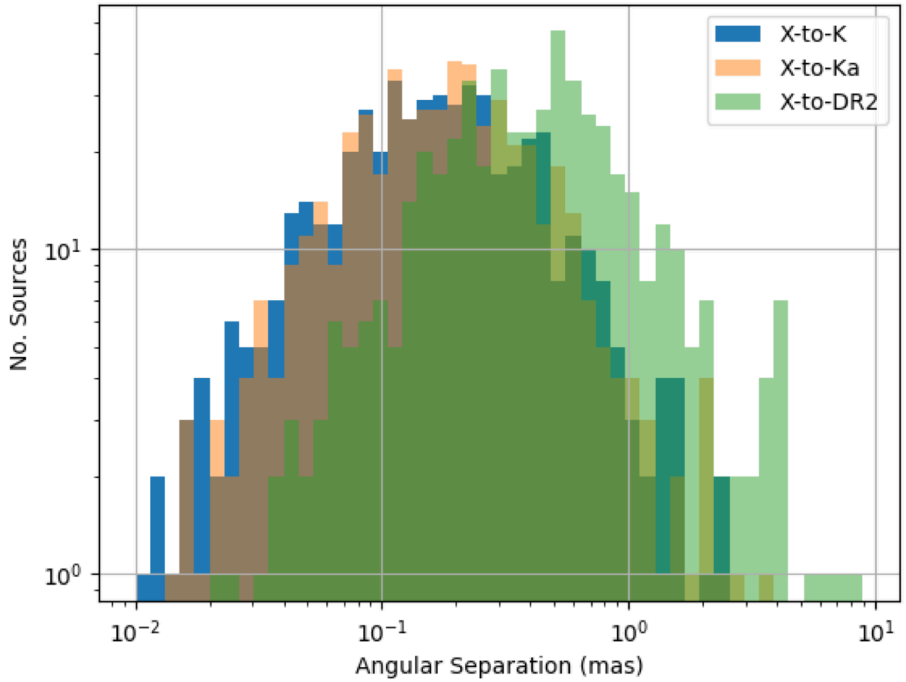
- Individual approach: for each source, where are the radio and optical centers? (with respect to the structure...)
- Alignment of the VLBI center onto the structure not rigorous ~ 0.1 to 1 mas (Kovalev et al 2017)

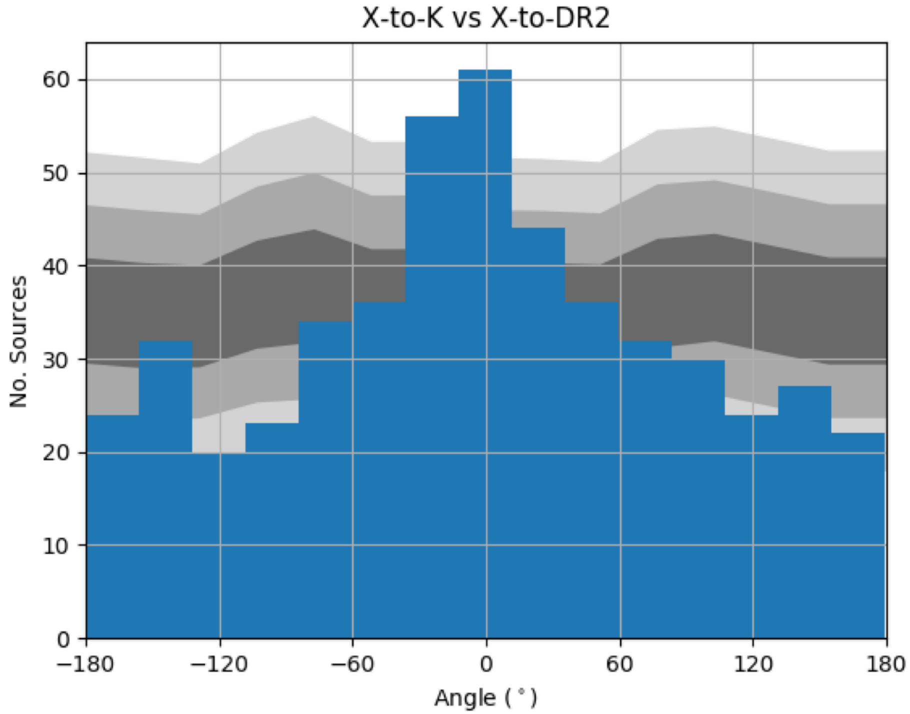


Linking radio to optical

- 3 radio wavelengths (X, K, Ka) + Gaia (ongoing work)
- 501 sources available
- X, K, Ka, optical: are they aligned? This seems verified for most of the source but not true for some







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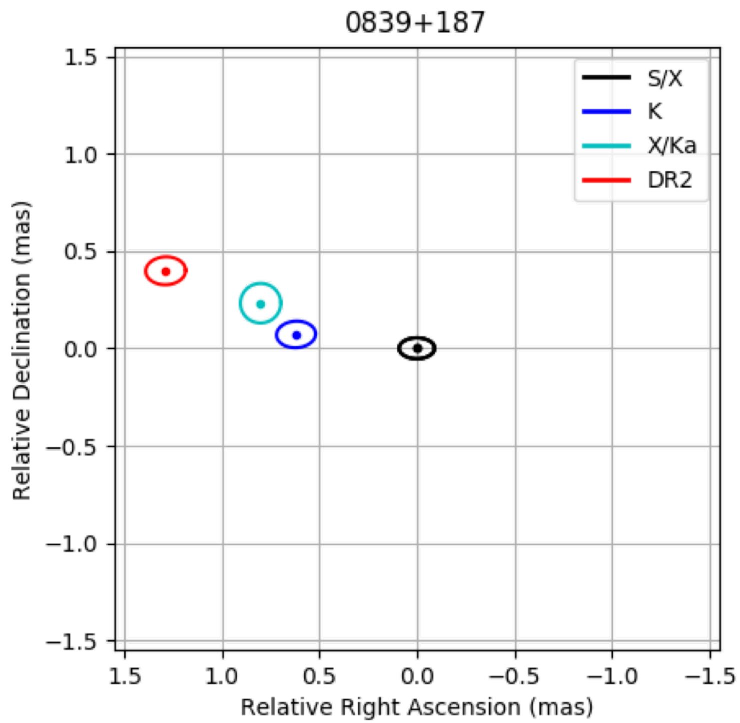

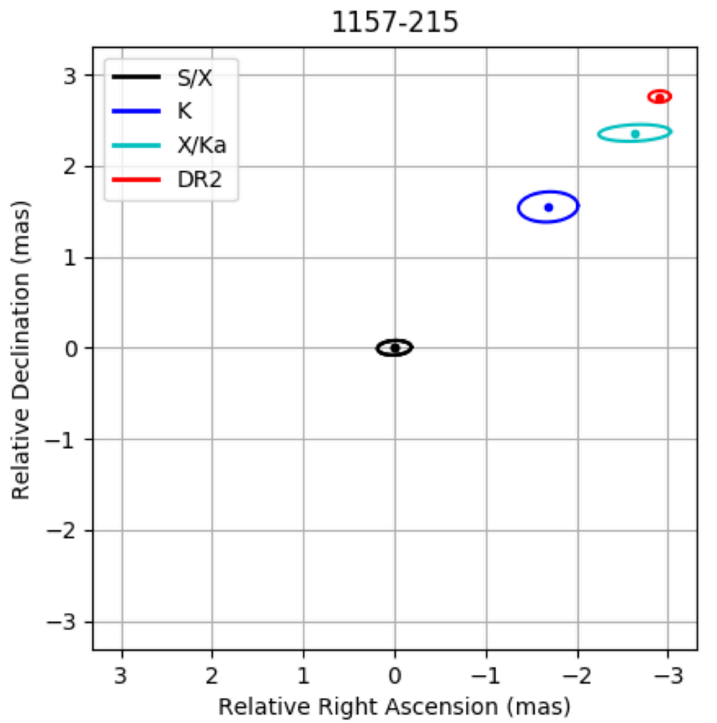

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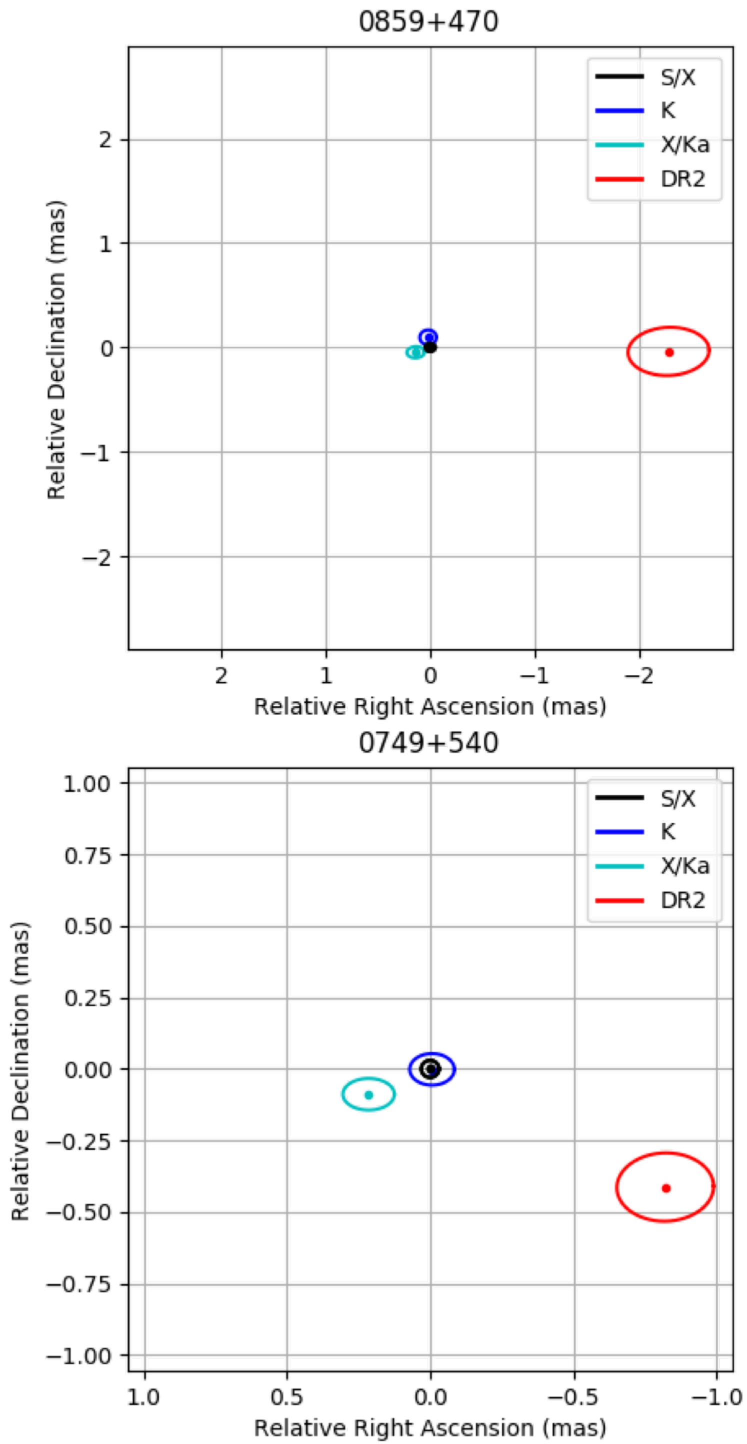
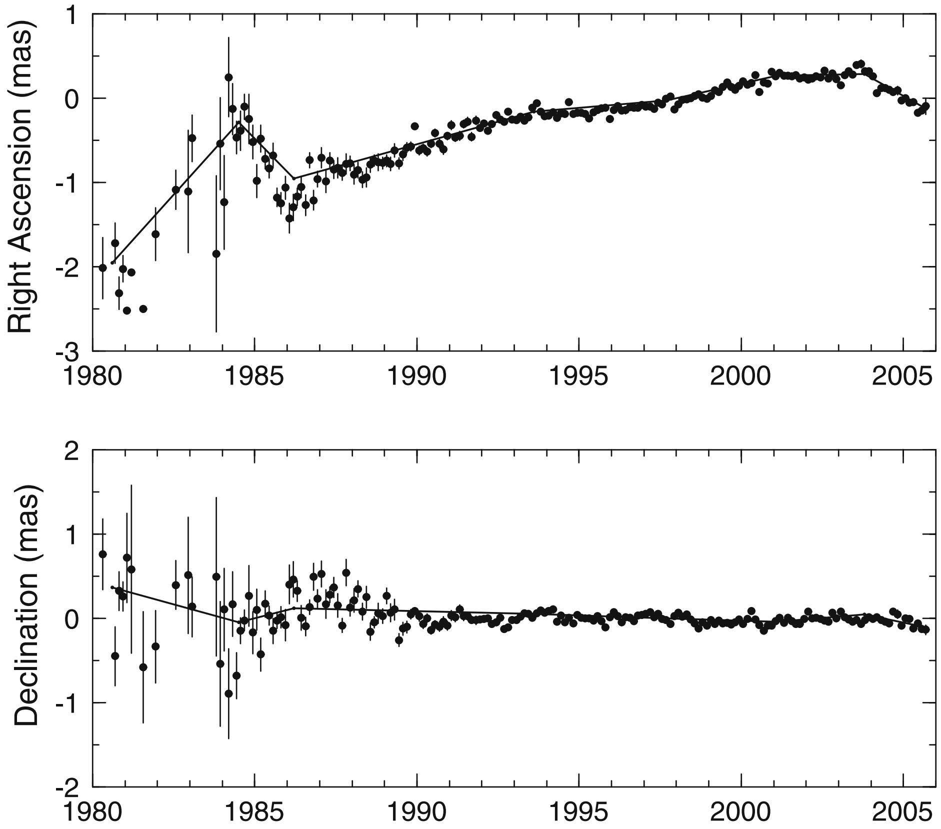


The radio source coordinate time series

Position time series

- ICRF reference points are assumed to have **no proper motion**
- They do have nonlinear motions within 1 mas
- But thought to be mainly driven by structure evolution
- Session-wise estimates of the position



4C 39.25 (MacMillan and Ma 2007)

Non sécurisé — ivsopar.obspm.fr/radiosources/index.php

Paris Observatory Geodetic VLBI Center

Radio source coordinate time series

The coordinate time series of radio sources are computed with a specific analysis configuration. The source name color indicates the length of the observational history (darker means longer). The ICRF3 defining sources are highlighted in yellow. Plots are available for sources observed in more than 100 sessions. The full set of time series is available in a single file in SOLVE *lso* format. These data are constantly updated.

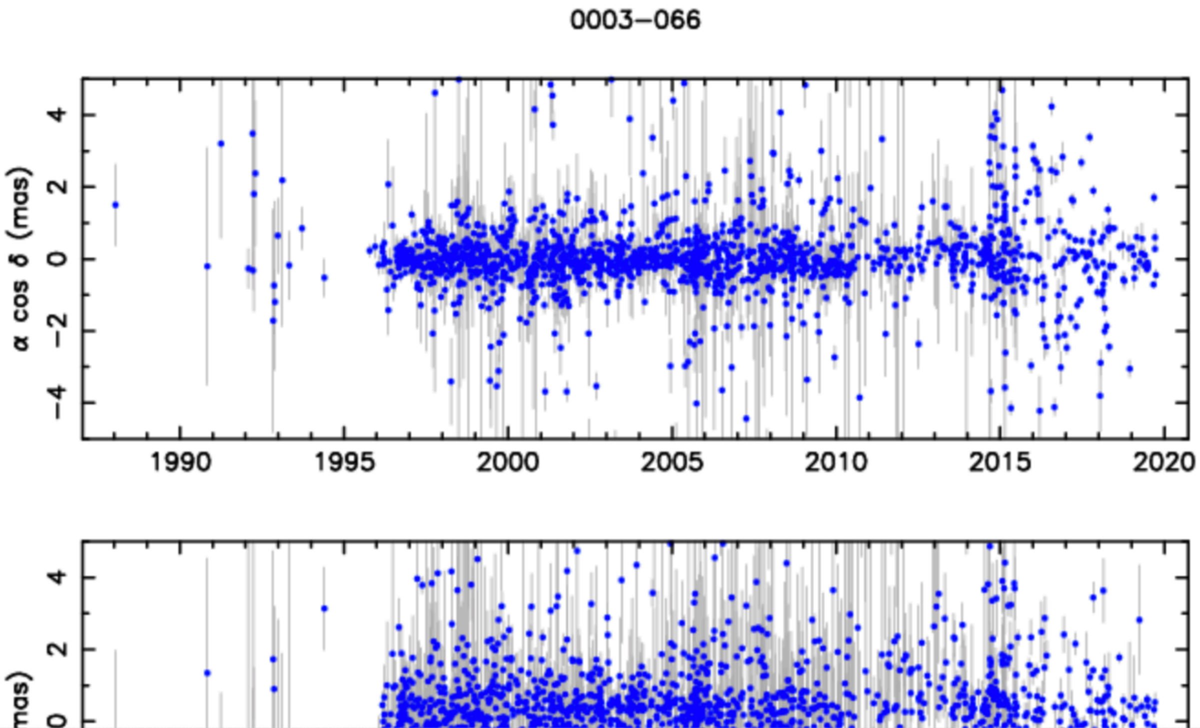
0001+478	0001-120	0002+051	0002+200	0002+541	0002-170	0002-350	0002-478
0003+123	0003+158	0003+340	0003+380	**0003-066**	0003-302	0004+240	0005+114
0005+568	0005+683	0005-239	0005-262	0006+061	0006+397	0006+771	0006-363
0007+016	0007+106	0007+171	0007+205	0007+439	0007+757	0007-048	0007-325
0008+006	0008+704	0008-222	**0008-264**	0008-300	0008-307	0008-311	0008-421
0009+081	0009+467	0009+655	0009-148	0010+336	0010+405	0010+463	0010-155
0010-401	0011+189	0011-046	0012+077	0012+319	0012+610	0012-184	0013-005
0013-184	0013-240	**0014+813**	0015+145	0015+529	0015-054	0015-280	**0016+731**
0017+200	0017+257	0017+296	0017-307	0018+715	0018+729	**0019+058**	0019+451
0019-000	0020+015	0020+446	0021+243	0021+464	0021-084	0022+390	0022-044
0022-227	0022-423	0023-263	0023-354	0024+092	0024+224	0024+348	0024+597
0024-114	**0025+197**	0025+449	0026+048	0026+346	0026-015	0027+056	0027+703
0027-024	0027-426	0028-396	0029-147	0030+196	0032+276	0032+612	0032-011
0033+142	0033+143	0033-088	0034+078	0034+108	0034+393	0034-220	0035+121

Paris Observatory Geodetic VLBI Center

Radio source coordinate time series for 0003-066

Data - BVID - NED - MOJAVE

Right ascension: 1.5578870534456°
Declination: -6.3931487310015°
No. sessions: 1562
No. delays: 45018
Defining: No
RMS(α cos δ) = 0.9816 mas
RMS(δ) = 2.8313 mas



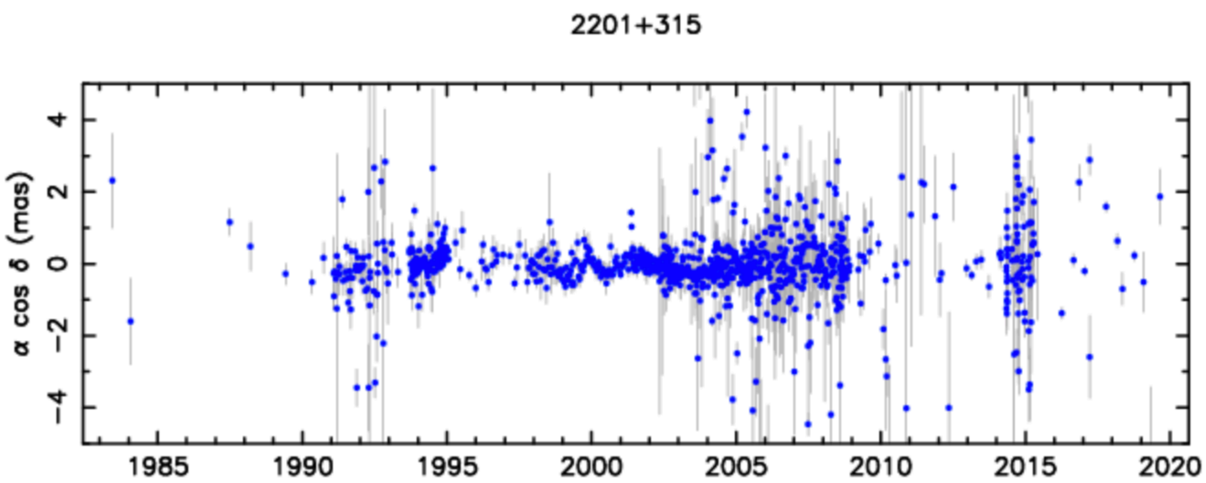
Non sécurisé — ivsopar.obspm.fr/radiosources/search.ph

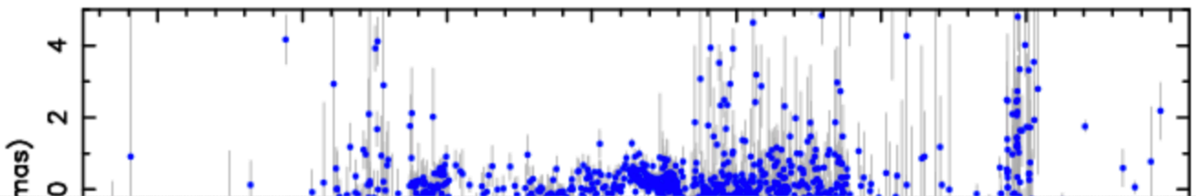
Paris Observatory Geodetic VLBI Center

Radio source coordinate time series for 2201+315

Data - BVID - NED - MOJAVE

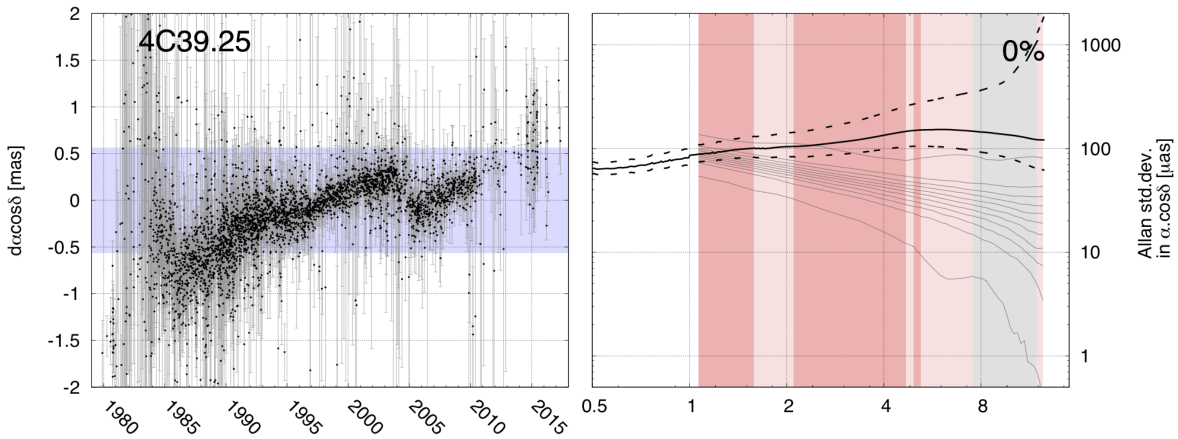
Right ascension: 330.8123991326349°
Declination: 31.7606305652751°
No. sessions: 945
No. delays: 29059
Defining: No
RMS(α cos δ) = 0.6468 mas
RMS(δ) = 1.0524 mas





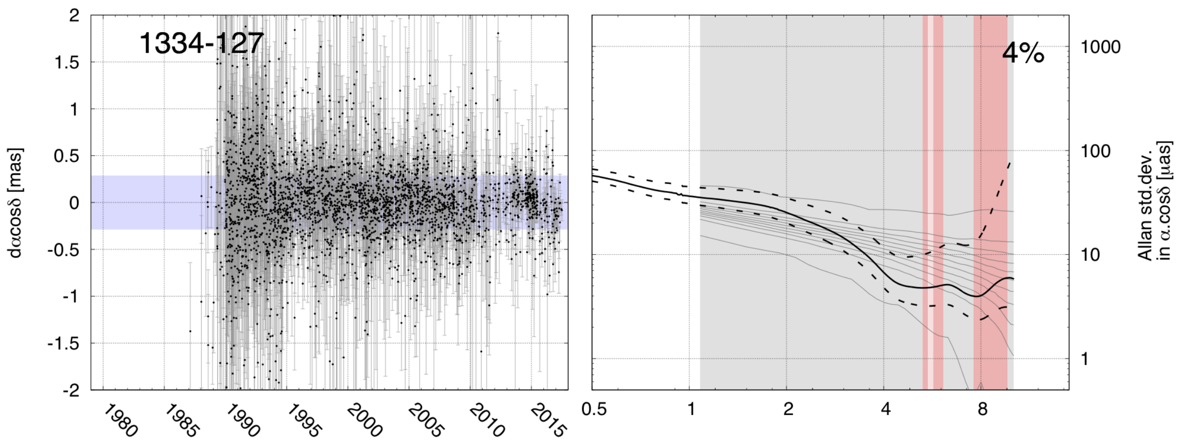
Position time series

- Important product to monitor the frame axis stability (Lambert 2014)
- The frame should be defined using the most stable sources (Feissel-Vernier 2003)
- Gattano et al 2018 showed that even "stable" sources show tiny nonlinear motions at the level of few 0.01 mas



From very unstable...

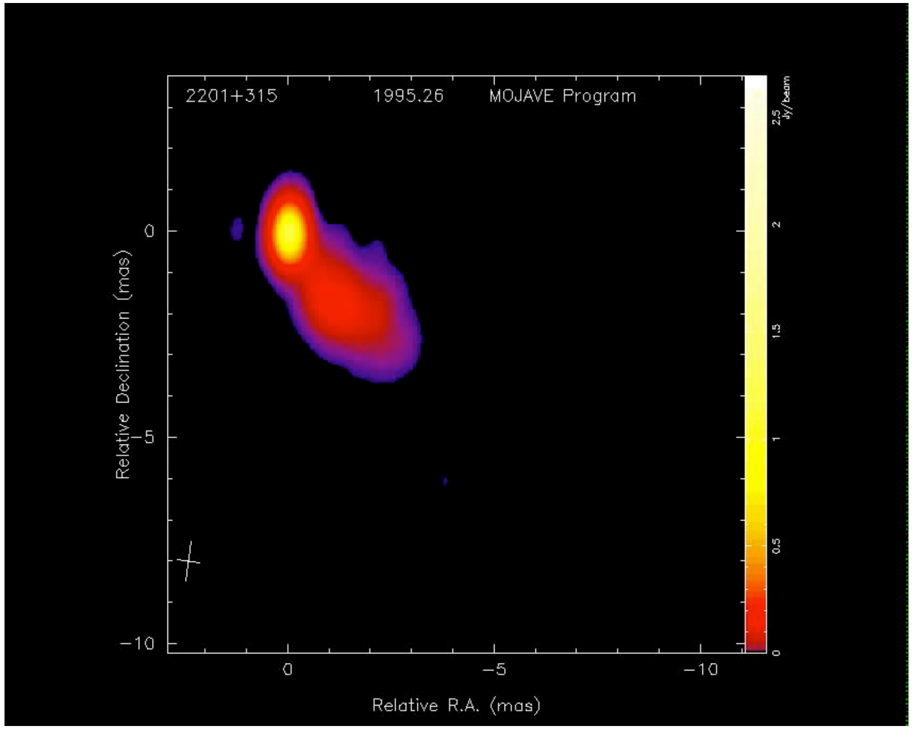
... to quite stable

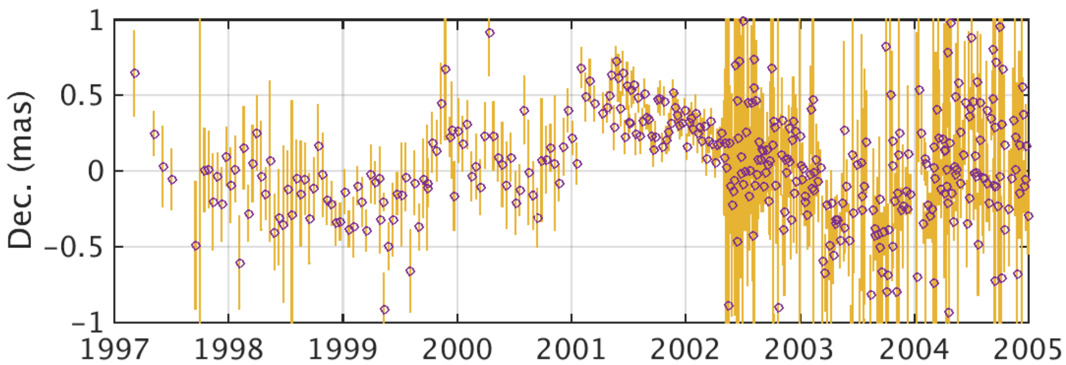


Gattano et al 2018 used the Allan variance to characterize the noise in the time series →

Position time series

- Unclear meaning of what "radio center" is
- Barycenter of the brightness distribution...
- ... mitigated by the network effect
- Different for two different networks
- Can hardly be deduced from a "standard" map generated by another network (Petrov 2007)



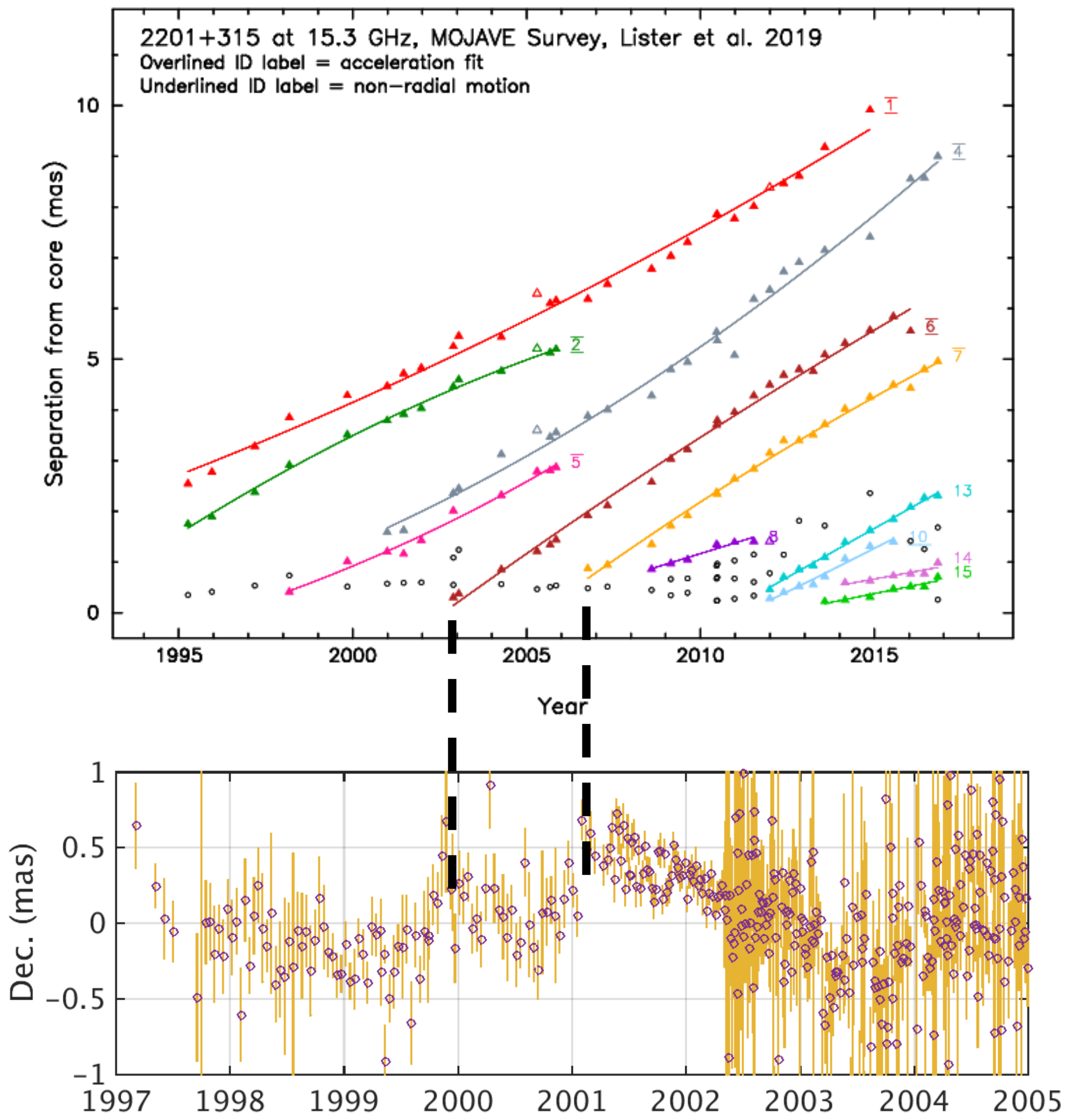


2201+315, Lister et al 2019, Roland et al 2020 →

Position time series

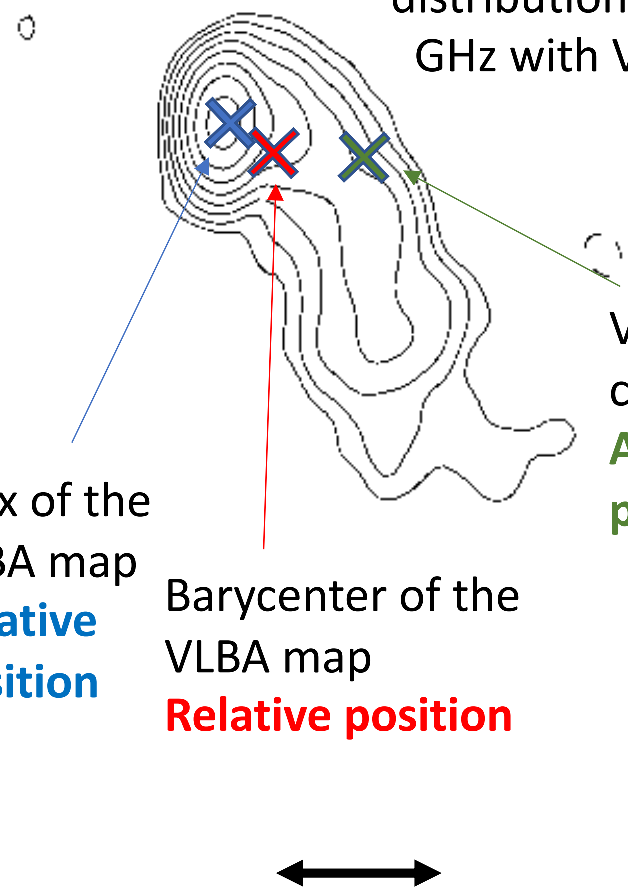
- Features of time series related to motion/flux variations of components
- A bright, stationary component would result in a stationary radio center
- The sudden ejection of a bright, moving component would shift the radio center

2201+315, Lister et al 2019,
Roland et al 2020 →



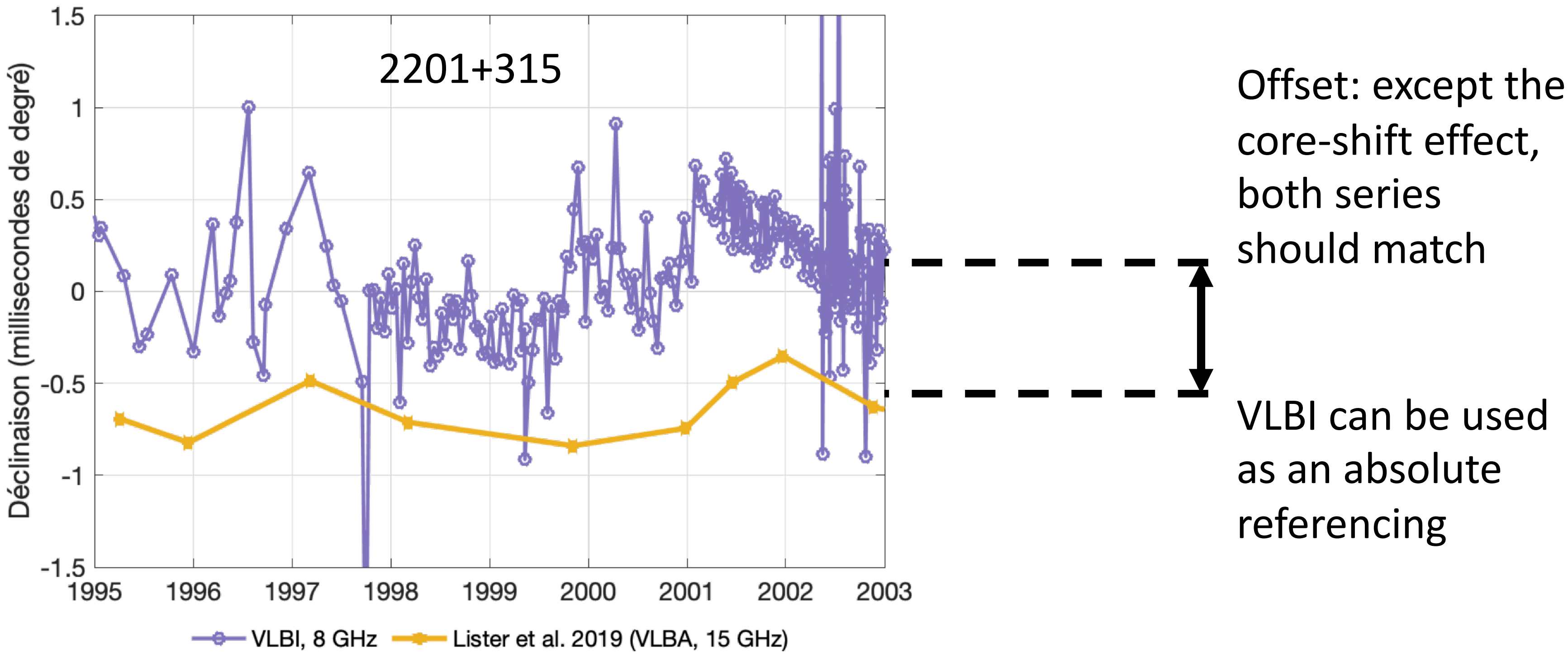
Position time series

- Ambiguity barycenter/radio center
- The radio center is not
  - The max of the brightness distribution
  - The barycenter of the brightness distribution
  - But it is close...
  - The closeness is still debated
- The motion of the radio center is absolute while the motions of the components are relative



Position time series

- Comparing radio centers given by VLBI and reconstructed from MOJAVE model-fitted component positions
- Consistent time variations



Conclusion

Concluding remarks

- ICRF
  - Now: VLBI, 10M+ delays, 4500+ radio sources, 3 wavelengths
  - Future: Gaia will likely be associated → ICRF radio and optical
- VGOS will continue to be deployed
  - Improve sky coverage
  - Improve precision and accuracy (lower systematics)
- Ongoing work on radios and optical alignments
  - Though the four are generally “within the jet”, there are cases for which the optical is emitted from a different place
  - Need individual comparisons with maps...
- Can the coordinate time series have an astrophysical interest?
  - Never clearly explored yet ... probably because it is not obvious how the radio center position can be linked to maps since they are obtained from different networks
  - Large number of sources: possible individual and population approaches
  - They are signature of the structure: can they be used in addition to maps to assess the signature of (simulated) jets?

Thank you for your attention!

June 2018, on the road to Ny Ålesund VLBI station