南京大學
NANJING UNIVERSITY

Reference Frames in the era of Gaia

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28/09/2020

Outline

1. Astrometry, reference system & reference frame
2. Celestial reference frames in the history
3. Why should we pursue a better reference frame?
4. Gaia's contribution to reference frame

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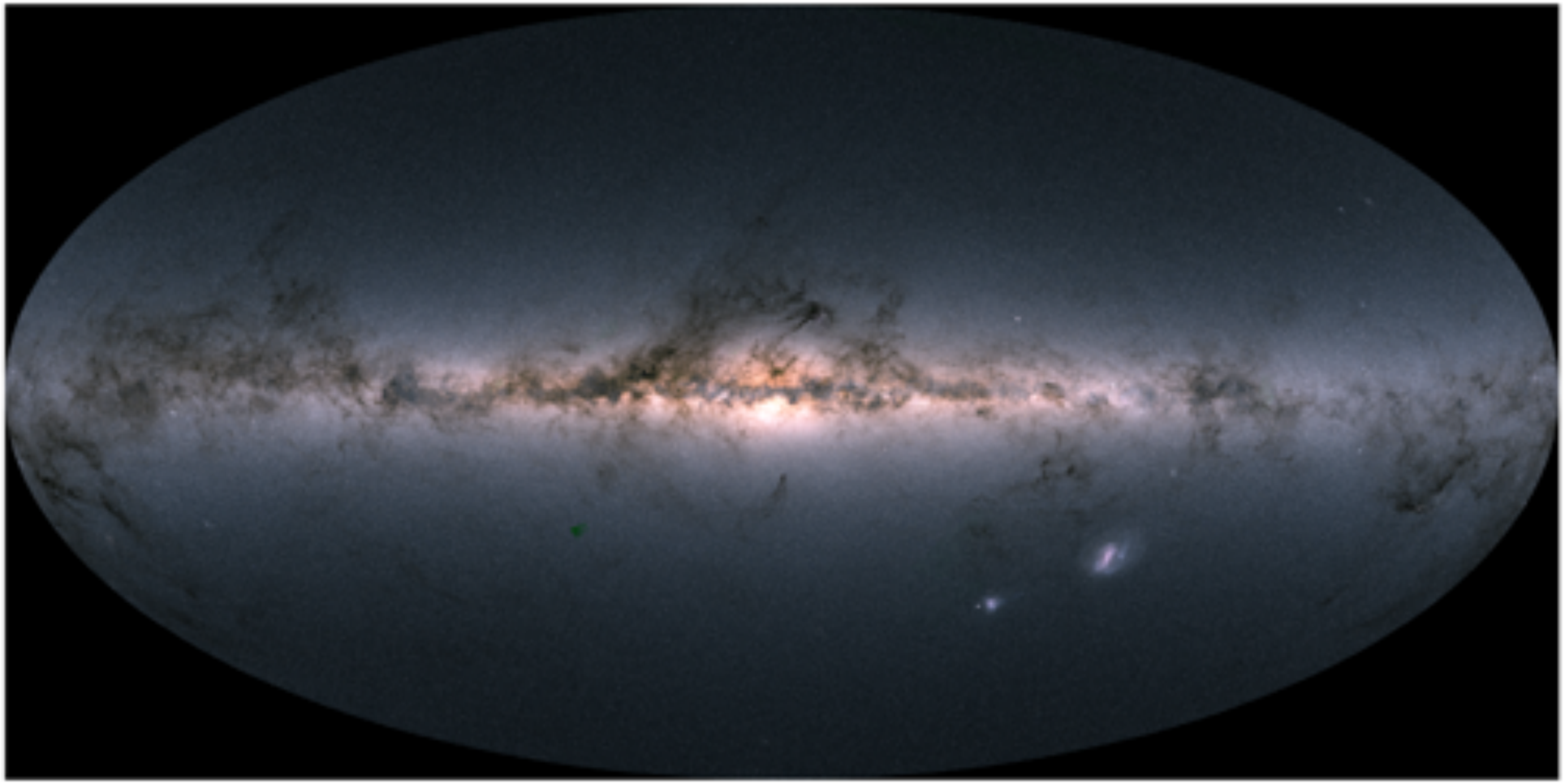
All-sky map



Gaia DR2, Gaia Collaboration (Brown, A. G. A., et al.)
A&A 616, A1 (2018)

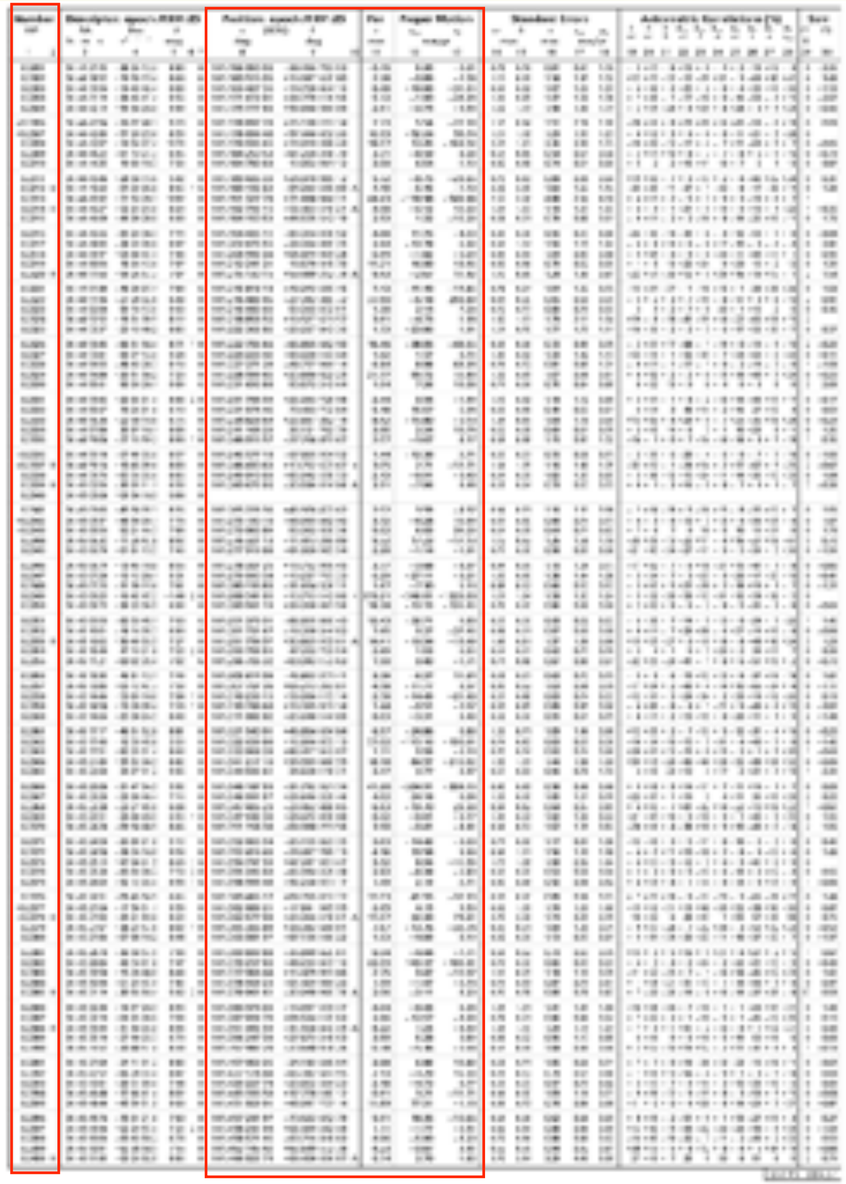
👈

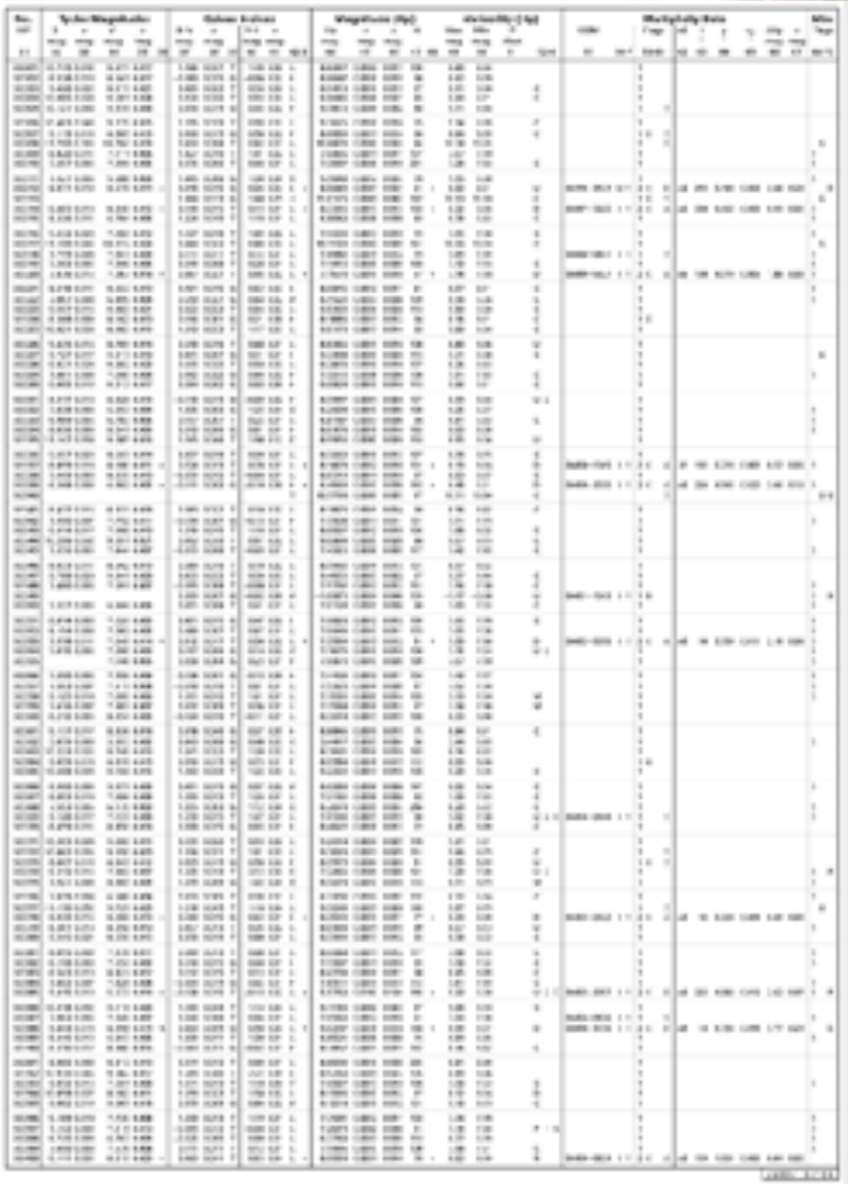
~ 1.7 billion objects

How to tell them apart?

Position and motion (coordinate, proper motion, parallax, radial velocity)

Astrometry — Chart the sky



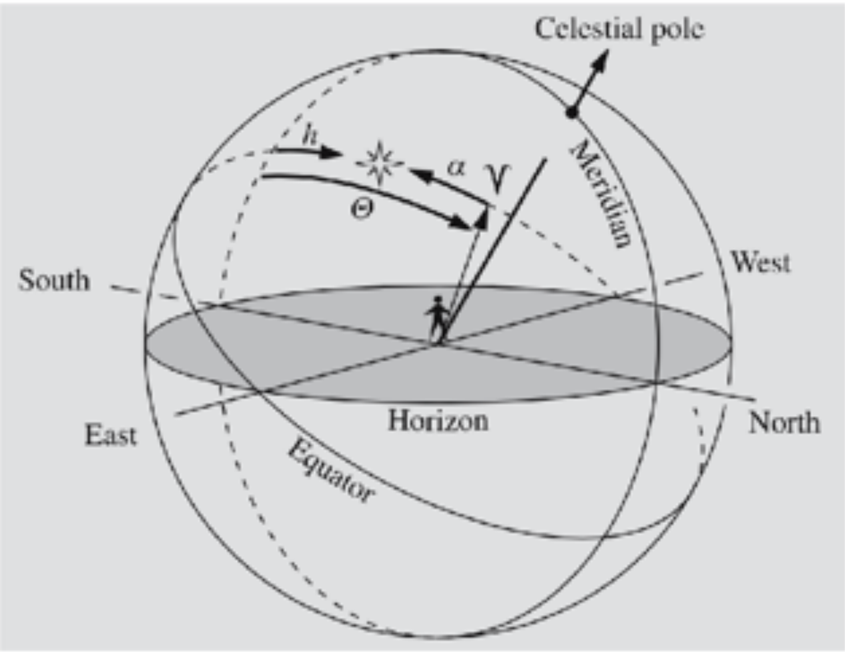


Hipparcos catalog (Michael Perryman 2013)

How to measure positions on the sky?

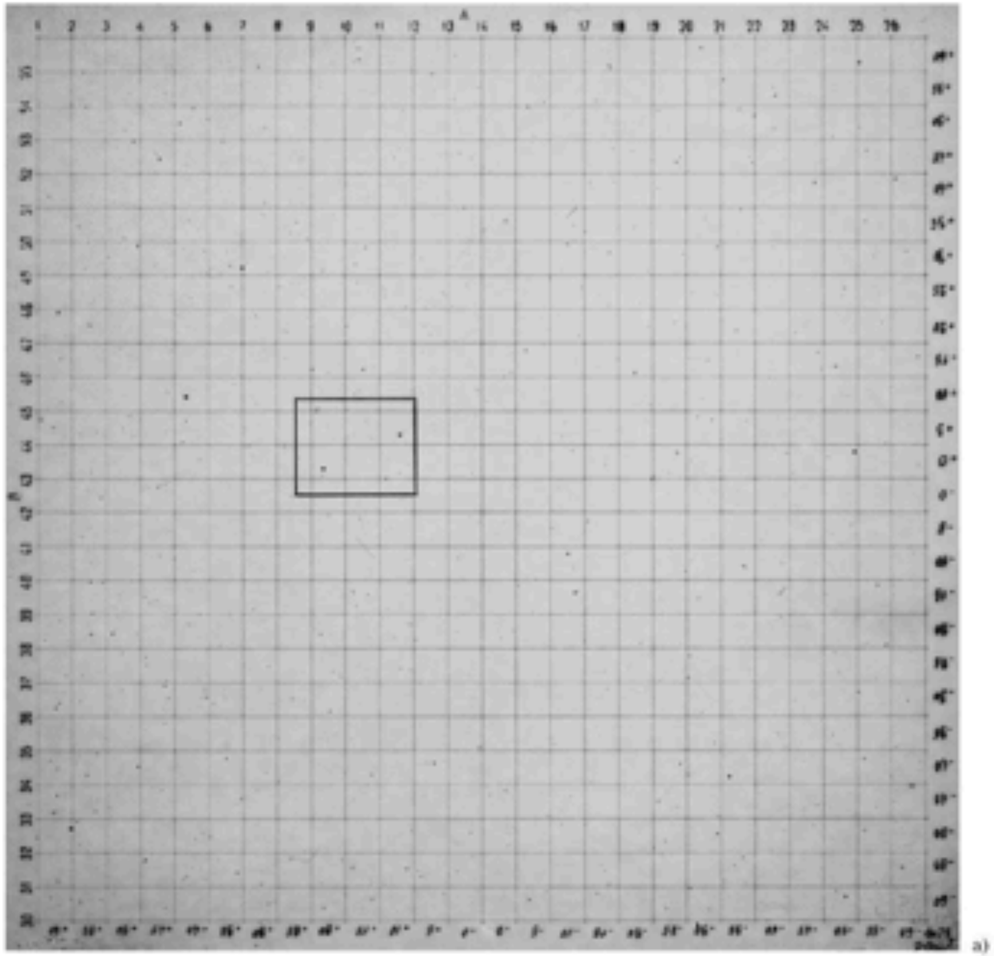
- First we need to build a coordinate system on the celestial sphere
- Rotation of Earth => Equatorial coordinate
- Orbital motion of Earth => Ecliptic coordinate
- Orbital motion of Sun => Galactic coordinate
- Local observer => Horizontal coordinate

Fig. 2.10. At night, stars seem to revolve around the celestial pole. The altitude of the pole from the horizon equals the latitude of the observer. (Photo Pekka Parviainen)

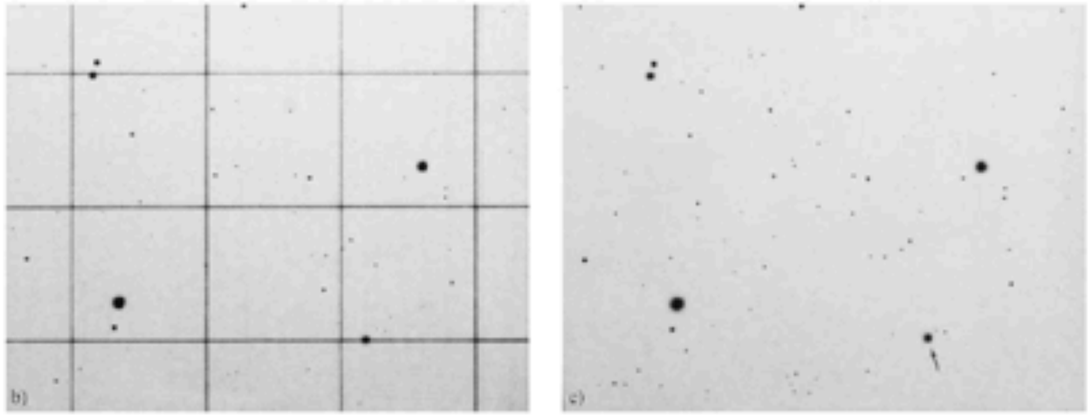


Fundamental Astronomy (2007)

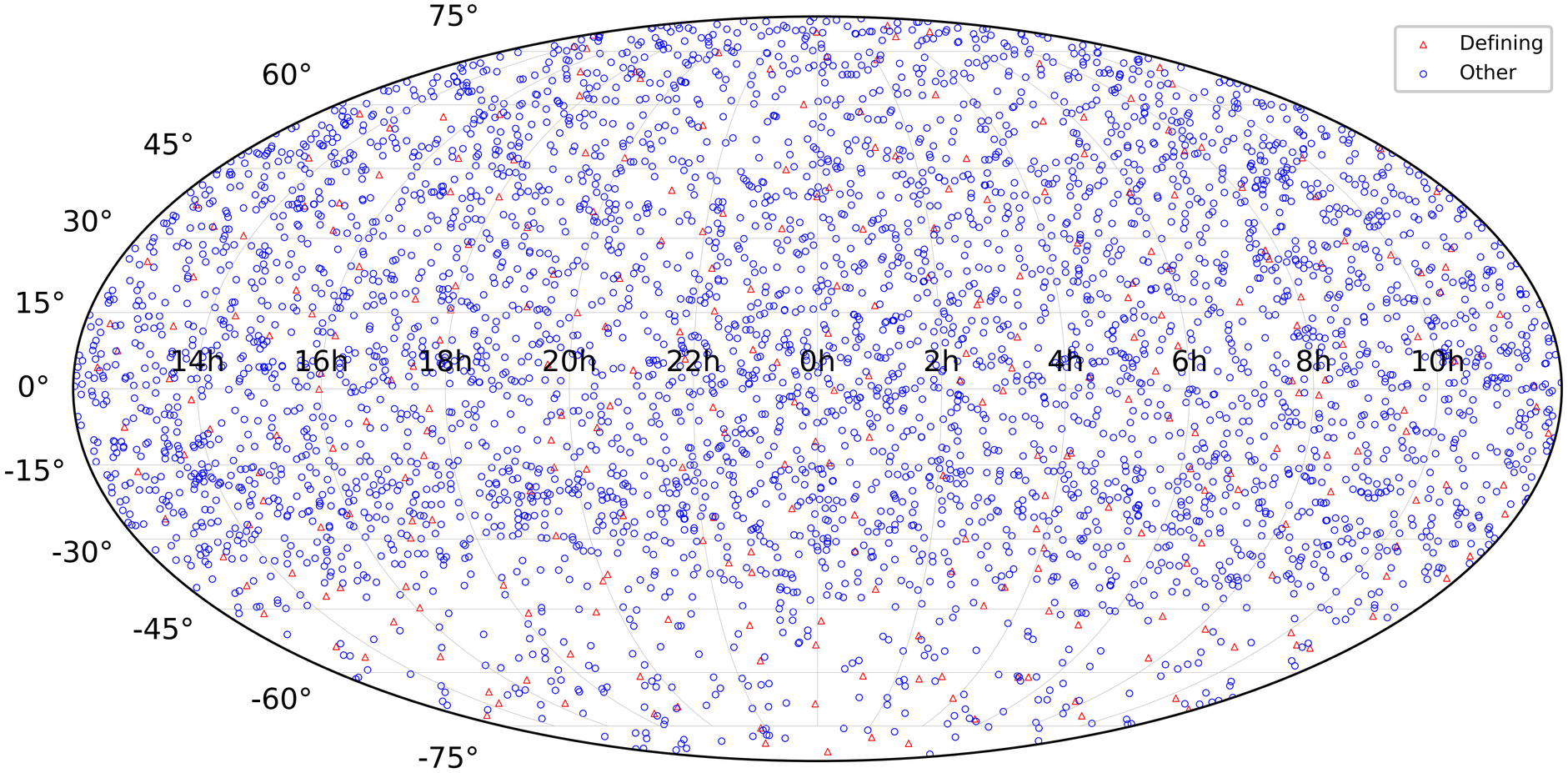
How to measure positions on the sky?



- Then we need some reference grids



Reference ‘grid’

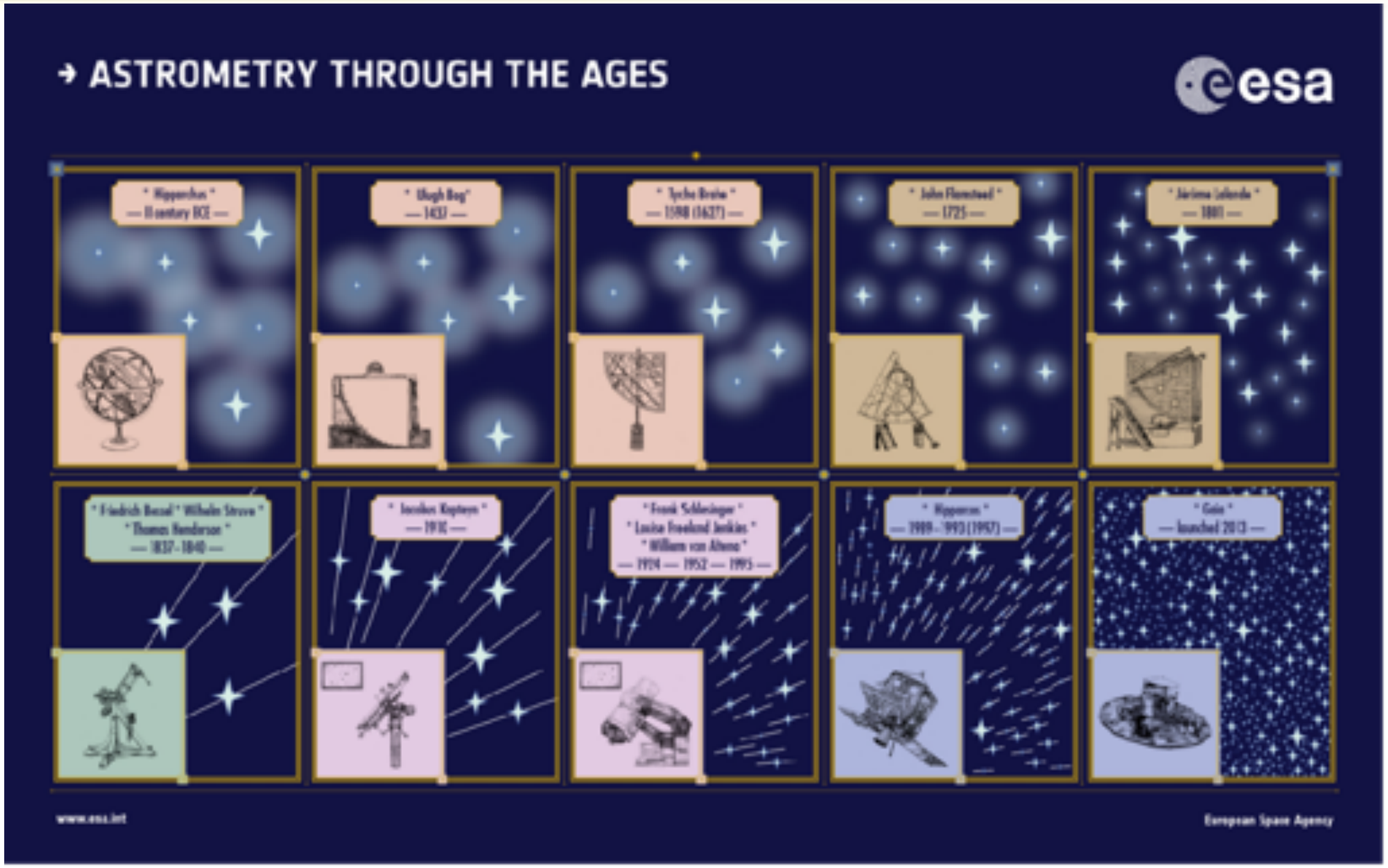


ICRF3 S/X-band catalog

Celestial reference system & frame

- Celestial reference system (CRS), also known as astronomical reference system
    a. inertial reference system within accuracy of current knowledge and observations under some kinematical or dynamical non-rotating assumptions
    b. consist of conventional concepts or definition and physical theories
    c. guide to observational data reduction
    d. requiring knowledge of motions of Earth and Sun and reference objects
- Celestial reference frame (CRF): product derived from observations, usually catalog (目录 ✖ 星表 ✔) or ephemeris
- CRS & CRF: core of astrometry

History of Astrometry



战国

时代

Table 28.1 The major astrometric catalogs

Year	Catalog	Number of objects
360 DC	Chinese	?
260 DC	Aristillus & Timocharis	850?
129 DC	Hipparchus	850 (1080?)
150	Ptolemy's Almagest	1080
1252	Alfonsine Tables	?
1437	Ulugh-Beg	1018
1594	Tothmen & Whilhem	1004
1601	Tycho Brahe	1005
1690	Hevelius	1564
1725	Flamsteed	3310
1751	Lacaille	9766
1760	Lalande	50 000
1792	Piazzi	7646
~1846	Bessel	72 000
1847	British Association	47 390
1850	Durchmusterung	300 000
1887	Astrographic Catalogue	~4 000 000
1910	Preliminary General Catalogue	30 000
1926	Yale Zones	~150 000
1937	General Catalogue	33 000
1950	N30	5000
1960	SAOC	257 997
1975	AGK3	183 145
1984	FK5	1535
1990	GSC 1.0	~20 000 000
1992	4 Million	4 000 000
1993	PPM	350 000
1994	NPM1	149 000
1995	Yale Trigonometric Parallaxes	8112
1996	USNO A1.0	488 000 000
1997	Hipparcos	118 218
1997	Tycho	1 058 332
1998	USNO A2.0	500 000 00
1998	AC2000	4 500 000
2000	GCS II	1 000 000 000
2000	Tycho-2	2 500 000
2001	SPM	30 000 000
2002	UCAC 1	40 000 000
2002	SuperCosmos Sky Survey	~1 000 000 000
2003	USNO B1.0	~1 000 000 000
2003	NPM2	400 000
2004	Pulkovo Catalog	58 483
2004	UCAC2	48 330 571
2004	UCAC2 Bright Star Supplement	430 000

(cont.)

Carlos, E. Lopez, P26

Astrometry for Astrophysics (2013)

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FK5 system and frame

- FK5 = Fifth Fundamental Catalogue
- used until replaced by ICRF in 1997
- position of 1535 stars derived from ground-based observations
- observations since beginning of 20th century

Dr. Walter Fricke

vice president of IAU (1964 -1967)

Image from Wikipedia

International Celestial Reference System – ICRS

-Origin to be barycenter of the solar system (SSB) within the frame of general relativity

-Extra-galactic object is assumed to have no measurable proper motion => fiducial point

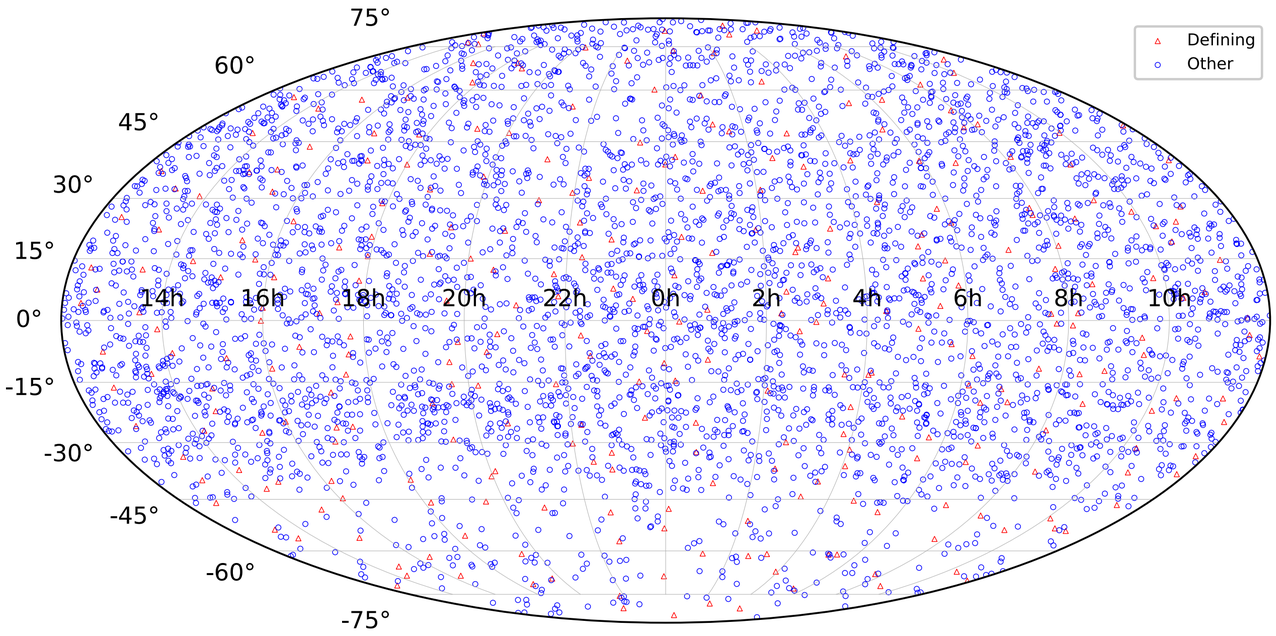
-(kinematically) Assume that whole universe does not rotate => quasi-inertial

-Underlying assumption: enough to model motion of Sun as a linear motion

-Mainly realized by ICRF (radio) and Hipparcos/Gaia (optical) catalog

International Celestial Reference Frame – ICRF

- based on VLBI observations since 1979
- current version (ICRF3) contains positions for 4536 sources
- orientation of ICRF3 axes determined by so-called defining sources
- lack of sources in region of decl. < -45 deg



ICRF3 S/X-band

Very long baseline interferometry (VLBI)

A Simple technique connects heaven and earth.

source direction

$$\tau_g = -\frac{\mathbf{b}\cdot\mathbf{s}_0}{c} = t_2 - t_1$$

baseline vector

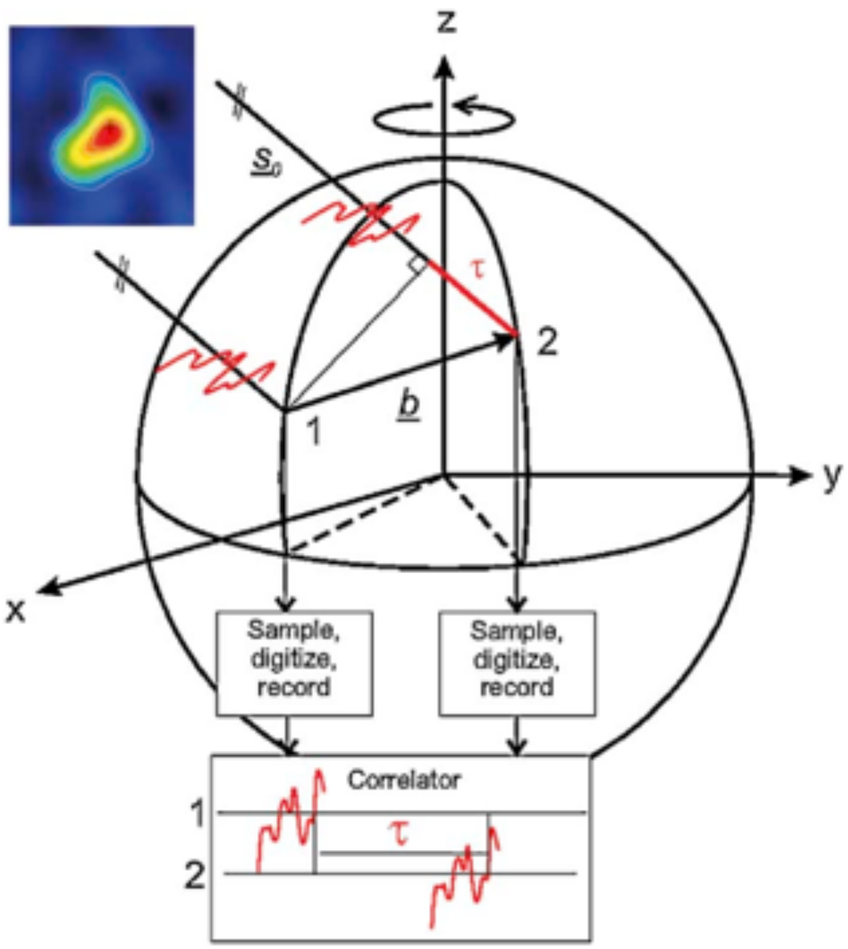


Fig. 2. Basic concept of Very Long Baseline Interferometry.

Global observing network of VLBI

- Mostly in the north
- Baseline: Earth-West component longer than North-South component
- Most sources are observed exclusively by the VLBA

Gaia−CRF

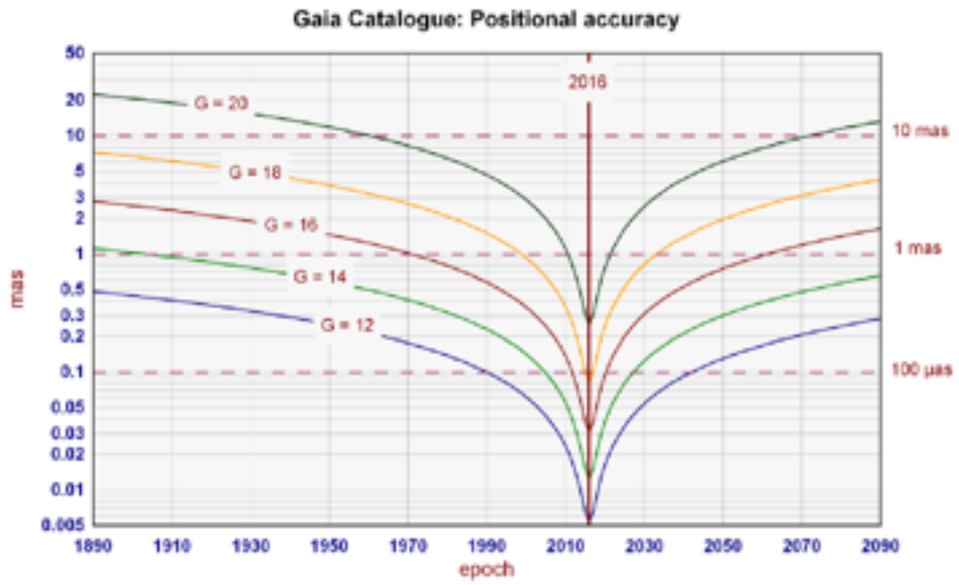


Figure 4: Evolution of the accuracy of the Gaia positional stellar catalogue with time due to the uncertainty in the annual proper motions of stars. The diagram refers only to the stars, not to the QSO-tied reference frame.

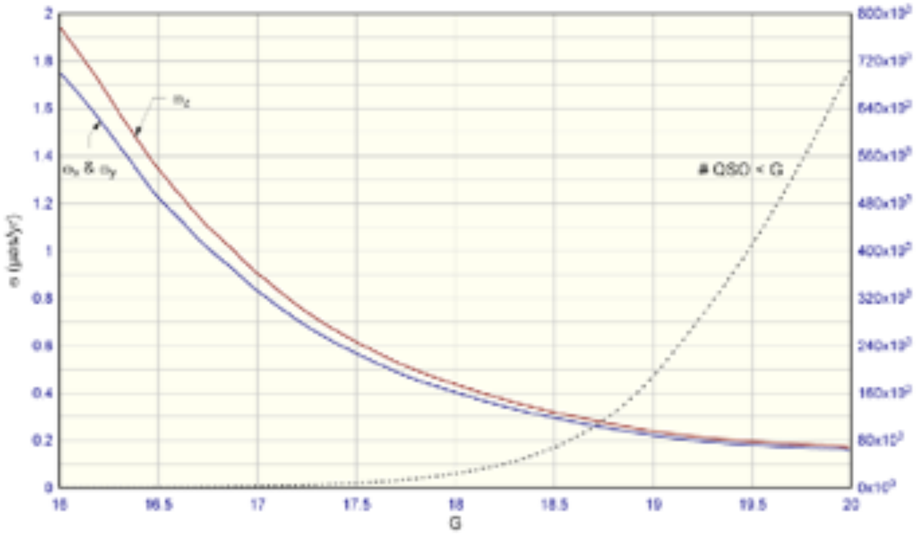


Figure 5: Inertiality of the final Gaia Celestial Reference Frame based on the QSO observations, expressed by the accuracy of the residual rotation in galactic coordinates, compared to an ideal non-rotating frame. The precision for a G magnitude is computed with only sources brighter than G. A random instability has been taken equal to 20 μas yr^{-1} and added (quadratic sum) to the single star noise. The right scale gives the number of sources found brighter than G.

Mignard EVN 2014

Gaia/Hipparcos astrometry

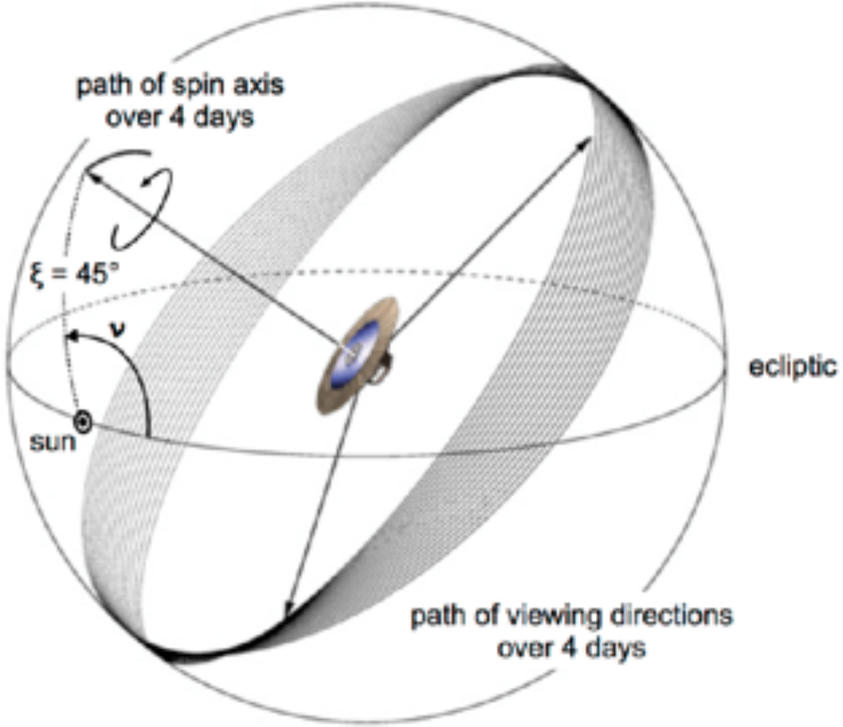
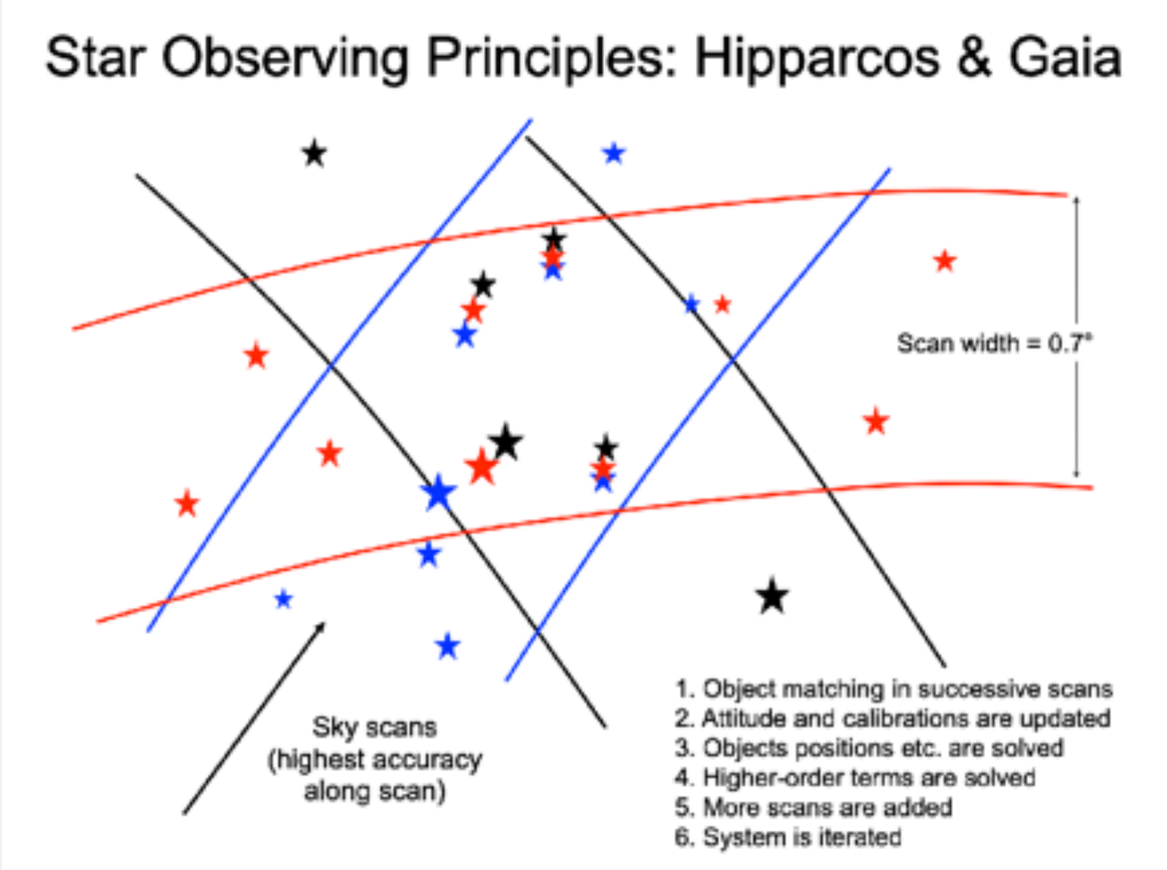


Fig. 6. Illustration of the scanning law of *Gaia*, showing the path of the spin axis (z), and the corresponding path of the preceding viewing direction, during four days. For clarity, the path of the following viewing direction is not shown. Image courtesy Lennart Lindegren.

Gaia Collaboration (Prusti, T., et al.) ,
A&A 595, A1 (2016)



Michael Perryman, 2013

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What’ s a good CRF? – precision

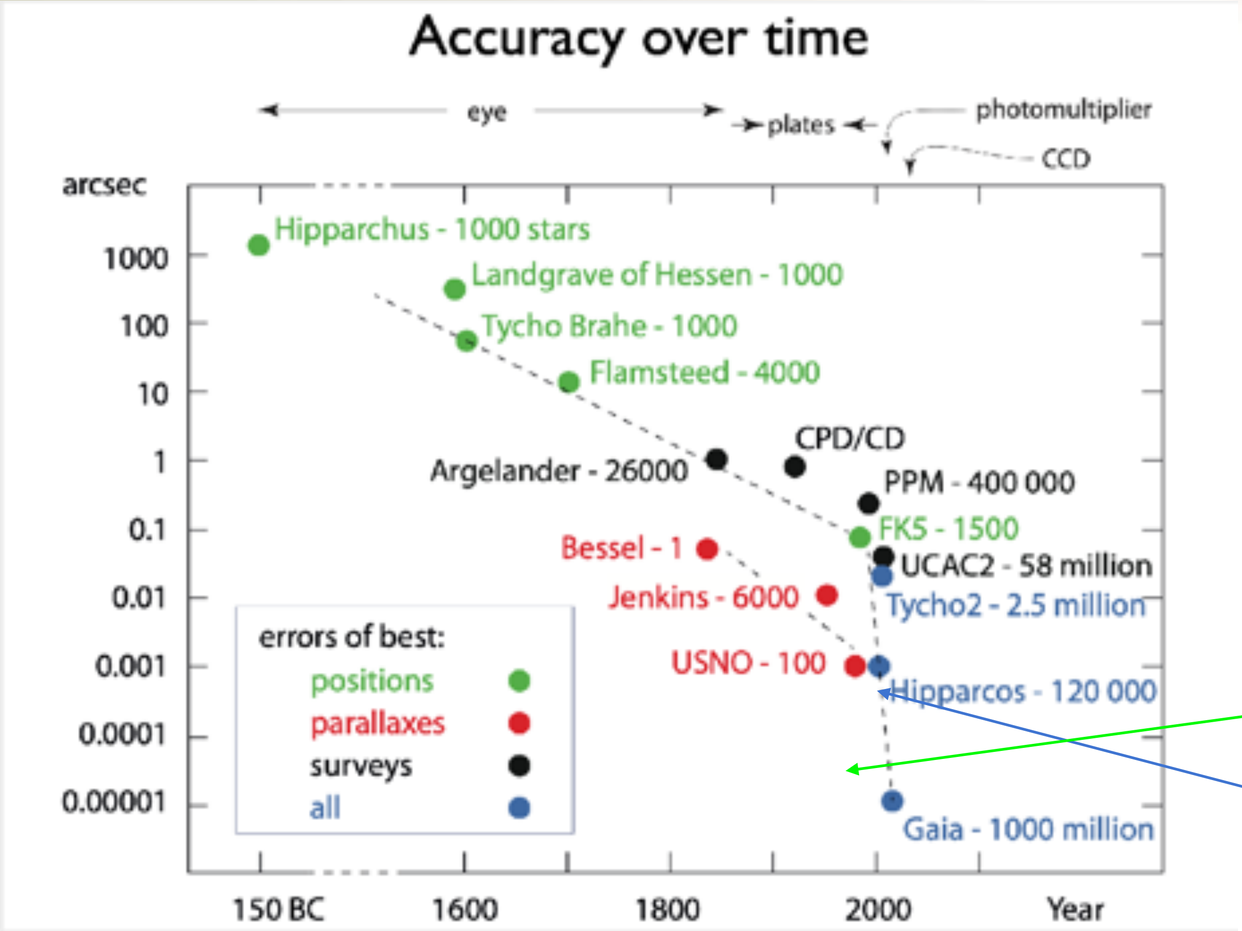
👈

Michael Perryman (2013)

👉

1 mas ~ Neil on the Moon

1 μas ~< width of hair in Nanjing seen from Kunming



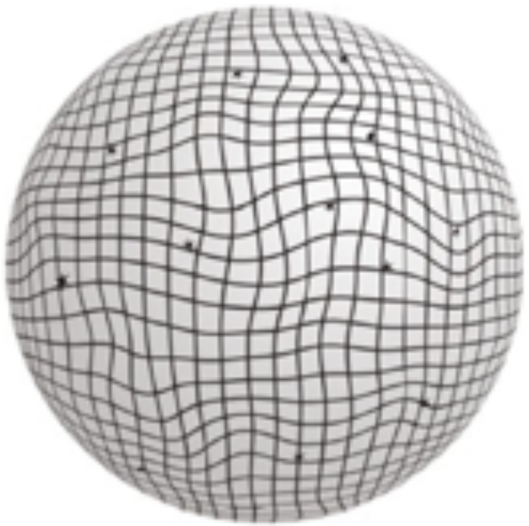
ICRF3 (30 μas)

Gaia-CRF2 (~0.1 mas)

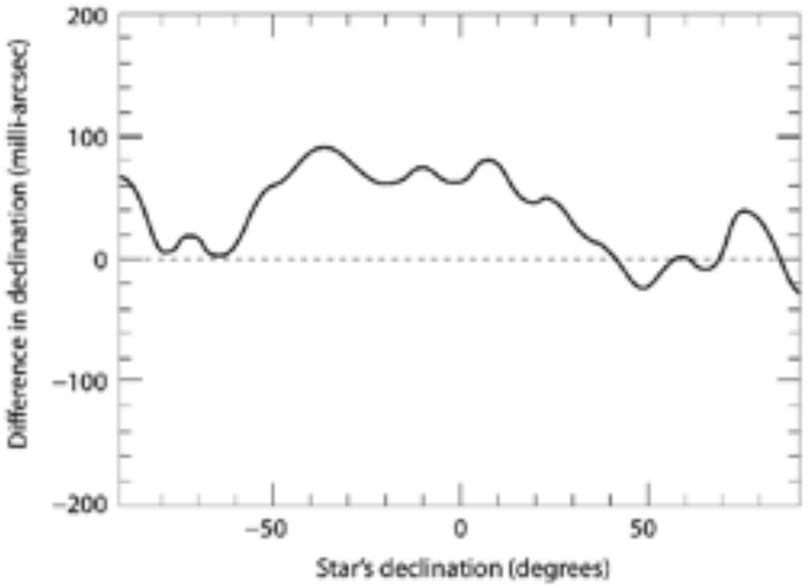
What’ s a good CRF? – systematics

Zonal error

(deformation)



(a)



(b)

Fig. 9. (a) Schematic of star positions on the sky within a warped reference system. (b) example of the systematic differences between star positions measured by the Hipparcos satellite and those from the best ground-based positional catalogue, the FK5, at the comparison epoch 1968.5. This example (adapted from Schwan, 2002) shows the positional difference in declination, as a function of the star's declination on the sky. Compared with the accuracy of the Hipparcos positions, of around 1 milli-arcsec, the warps in the FK5 catalogue reach 100 milli-arcsec or more.

Michael Perryman, Eur. Phys. J. H (2013)

“Is There a Need for an Improved Celestial Reference Frame ? ”

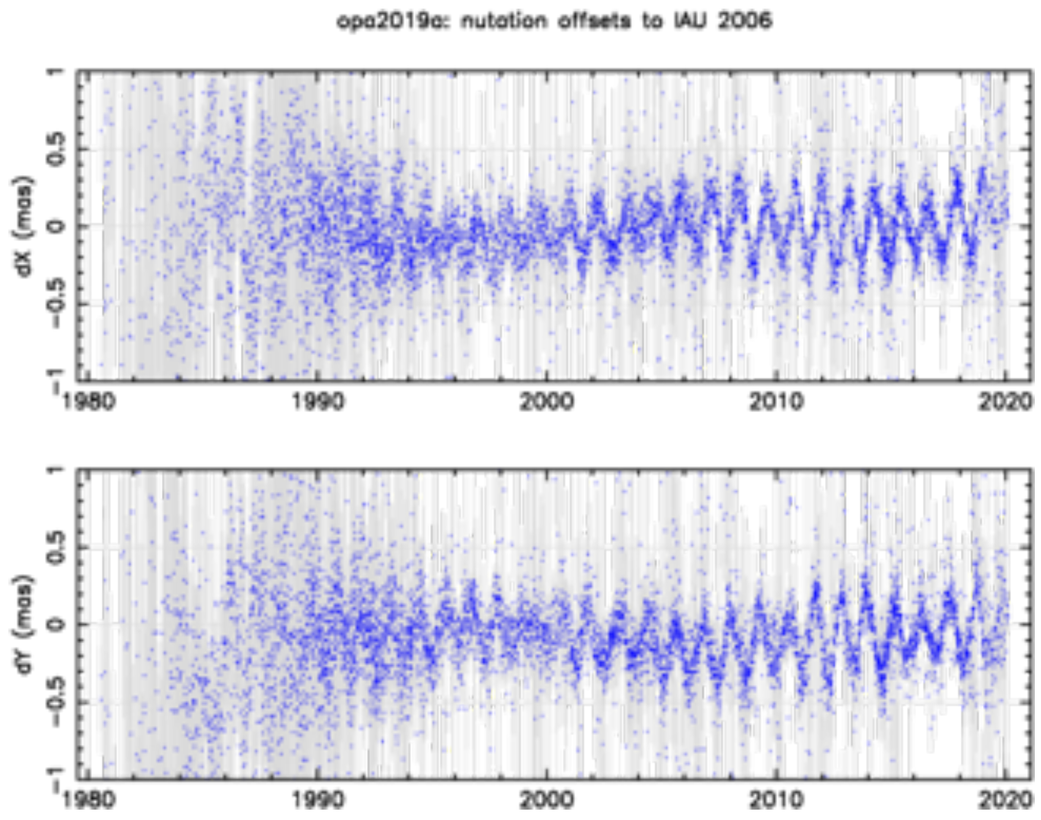
Kenneth Johnston et al., Astro2010 Science White Paper

“

1. direct detection of the acceleration of the Solar System within the Milky Way and the Local Group toward the Virgo cluster
2. meaningful experimental constraints will be put on the broadband power of the relic gravitational waves
3. constrain the mass function of free-floating planets and comets
4. resolve the puzzles of the origin of radiation from radio-loud quasars
5. obtain more accurate tests of alternative gravitation theories

”

Study inner structure of Earth



from SYRTE, Paris Observatory

👈Orientation change of Earth spin axis

Free core nutation (mantle, outer core)

Period: 427~ 434 day

Amplitude: ~ 0.1−0.5 mas (3−15 mm)

Free inner core nutation (outer & inner core)

Period: 995−1028 day

Amplitude: ~ 10 μas (~0.3 mm)

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Gaia-CRF — a big step forward for optical CRF

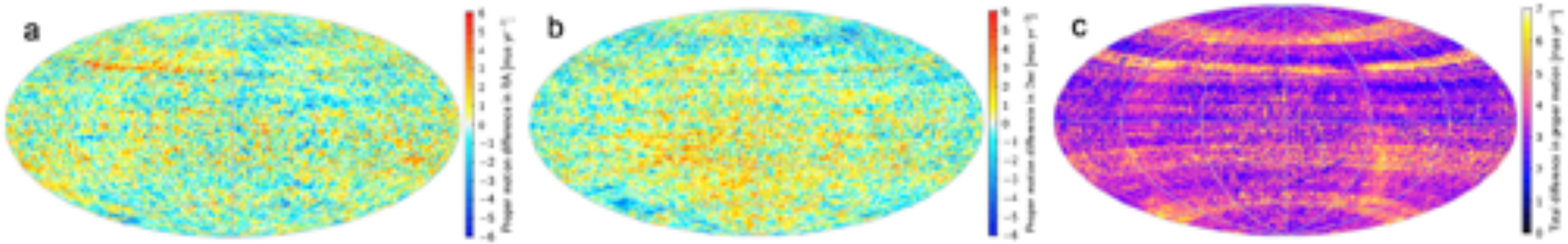


Fig. C.7. Differences in proper motion between the primary (TGAS) solution and the Tycho-2 catalogue for 1 997 003 sources: **a)** differences in $\mu_{\alpha*}$; **b)** differences in μ_δ; and **c)** total differences $(\Delta\mu_\alpha^2 + \Delta\mu_\delta)^{1/2}$. Differences are taken in the sense TGAS minus Tycho-2, after rotation of the latter to the *Gaia* DR1 reference frame. Median differences are shown in cells of about 0.84 deg^2. Some empty cells are shown in white. The maps use an Aitoff projection in equatorial (ICRS) coordinates, with origin $\alpha = \delta = 0$ at the centre and α increasing from right to left.

L. Lindegren et al., A&A 595, A4 (2016)

Tycho-2 — Gaia: reveal zonal errors (systematics) in ground-based optic astrometry

Improve stellar position precision

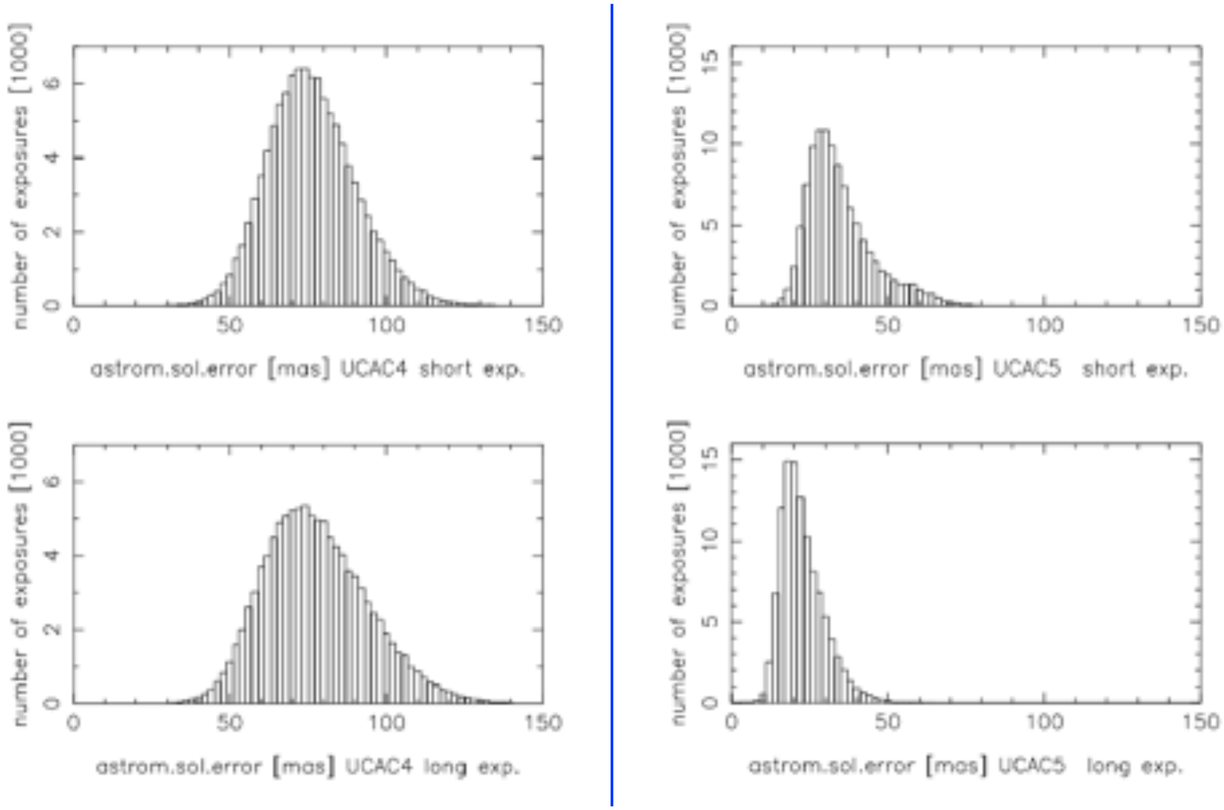
Same observation data and reference stars

UCAC4 solution error

- ~70 mas

Reference catalog

- Tycho-2



UCAC5 solution error

- ~20-30 mas

Reference catalog

- Gaia DR1

(TGAS)

Zacharias et al., AJ 153:166 (2017)

Improve position precision for solar system body

Also same observation data

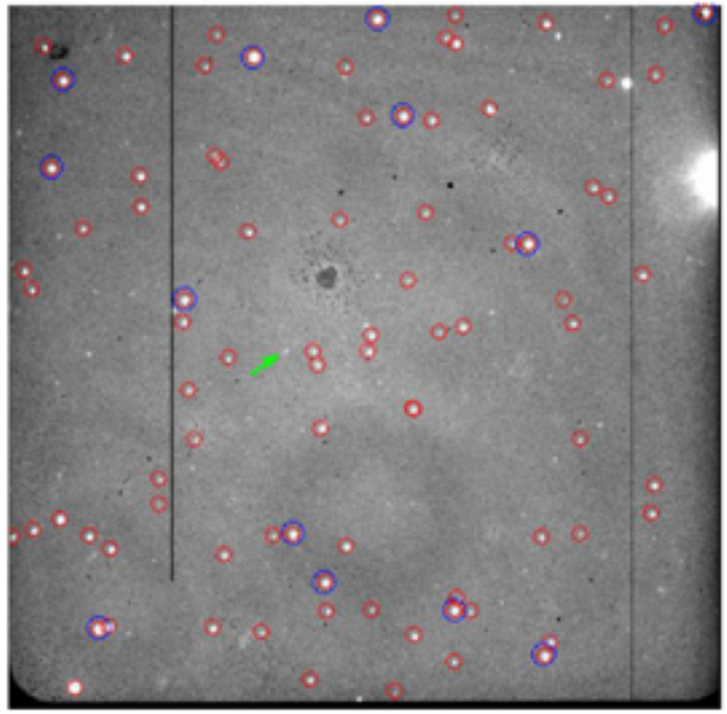


Fig. 1. An example of CCD images of Nereid where the Gaia DR2 reference star is marked by the red circle, the UCAC2 reference star by the blue, and Nereid is pointed by a green arrow. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Re-reduction of Nereid(海卫二) CCD data shows an improvement of ~2 times in position precision due to

- More reference stars
- More accurate reference position

Blue: UCAC2 reference star

Red: Gaia reference star

Y. Yu et al., Planetary and Space Science 165 (2019)

Declination bias in ICRF

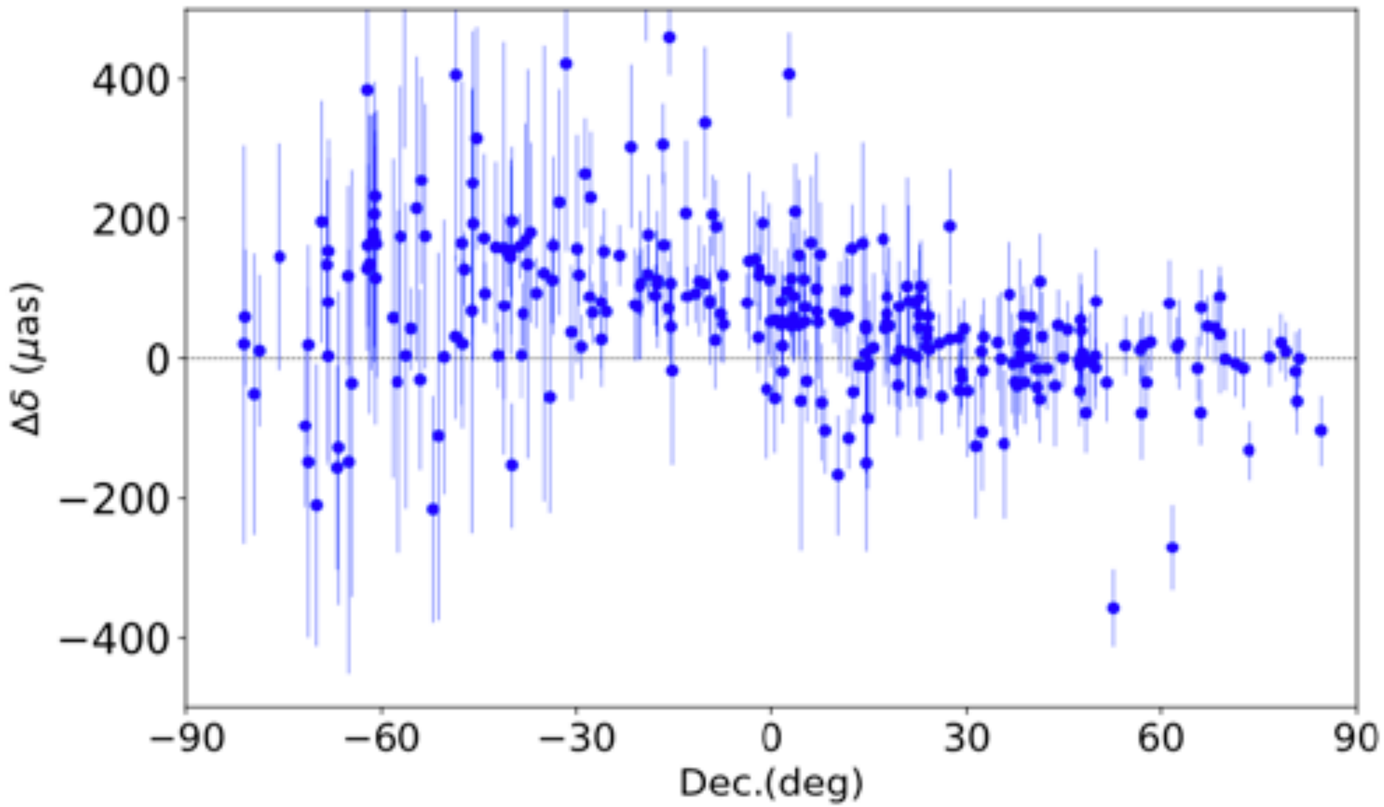


Fig. 3. Declination differences between gsf2016a and ICRF2 catalogs for 290 common ICRF2 defining sources, in the sense of ICRF2 minus gsf2016a. A clear positive offset can be seen from the south side of the equator.

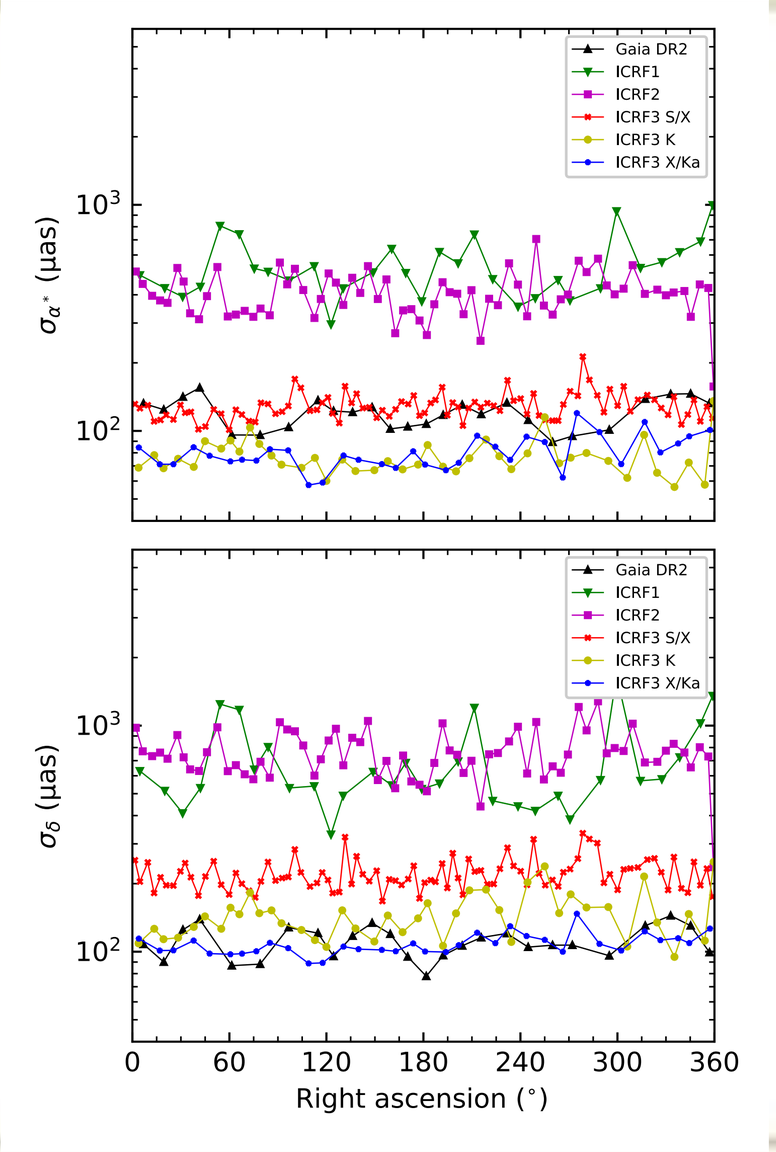
Difference in VLBI catalogs

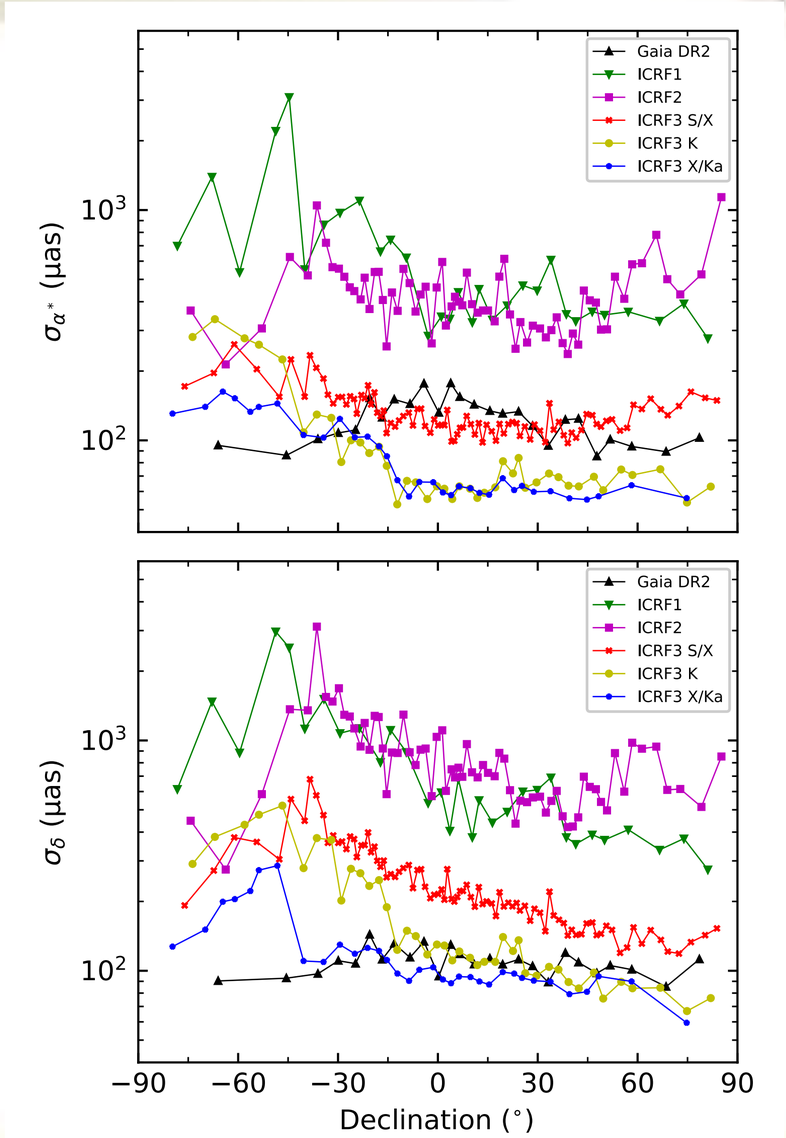
gsf2016a: 1979–2015

ICRF2: 1979–2008

Liu et al., A&A (2017)

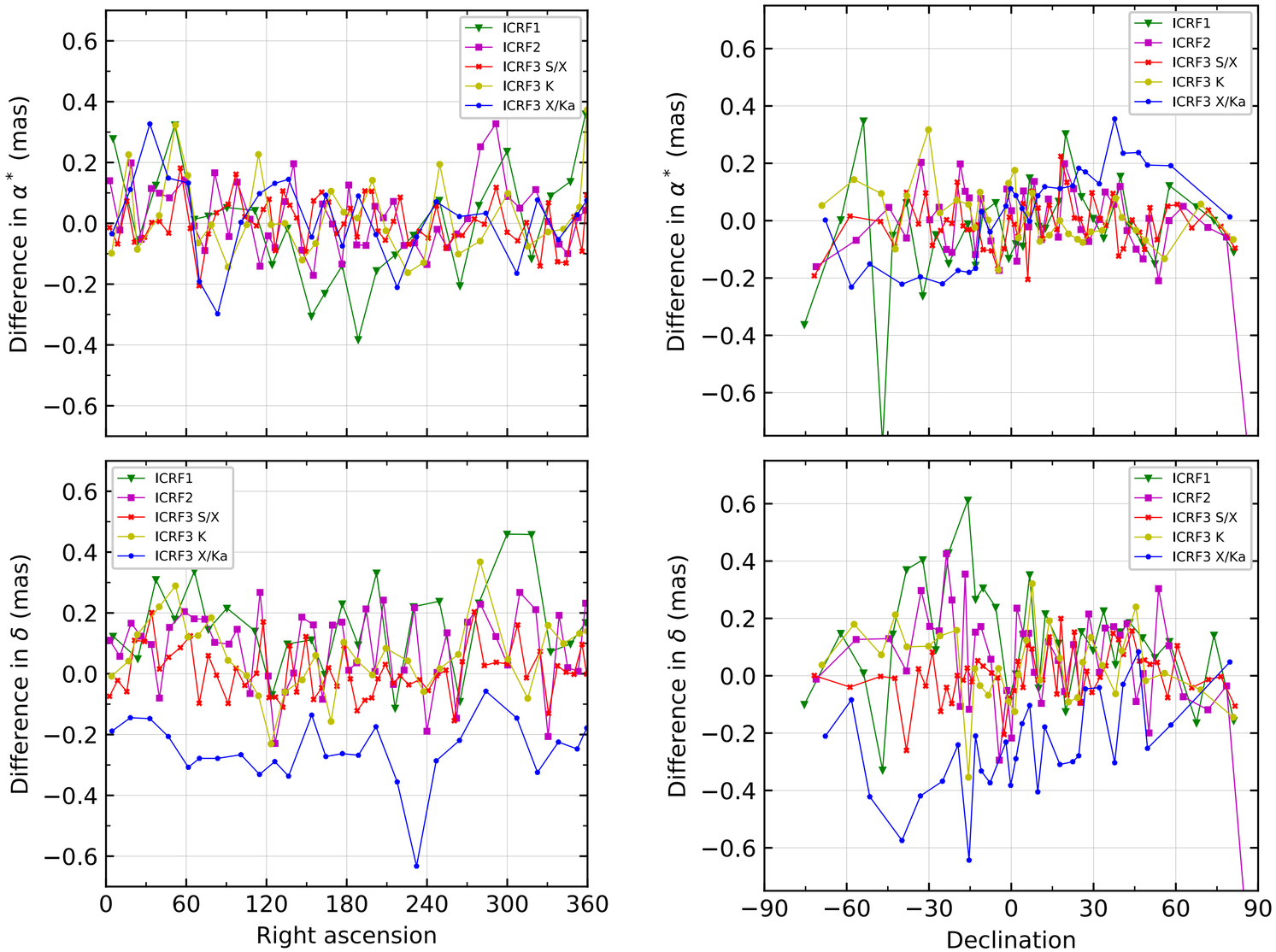
Gaia-CRF helps to see systematics in ICRF





Liu et al. AA (2020)

Gaia-CRF helps to see systematics in ICRF



Systematics in ICRF1, ICRF2, and ICRF3 X/Ka

Liu et al. AA (2020)

Back to VLBI global network

S/X band

(IVS website)

K band

(de Witt et al. 2018)

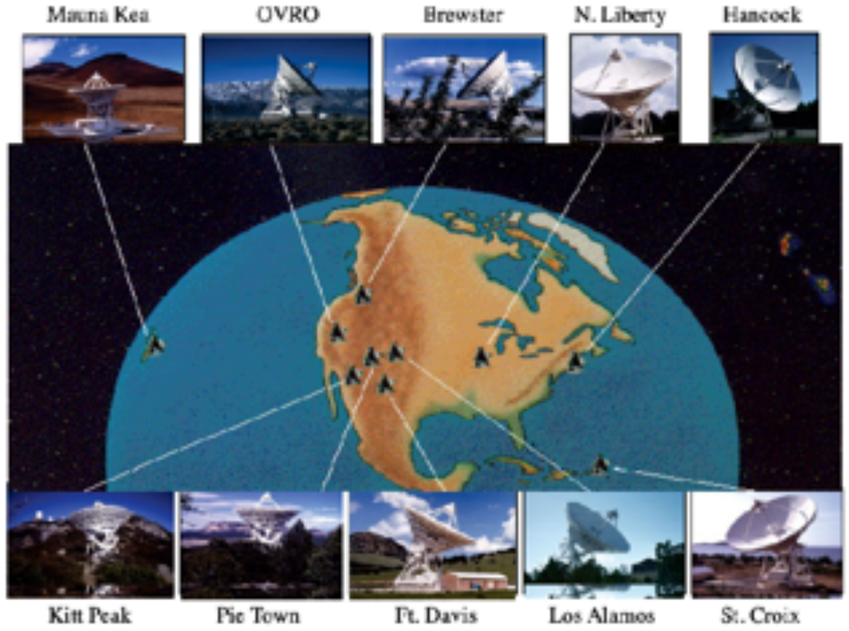
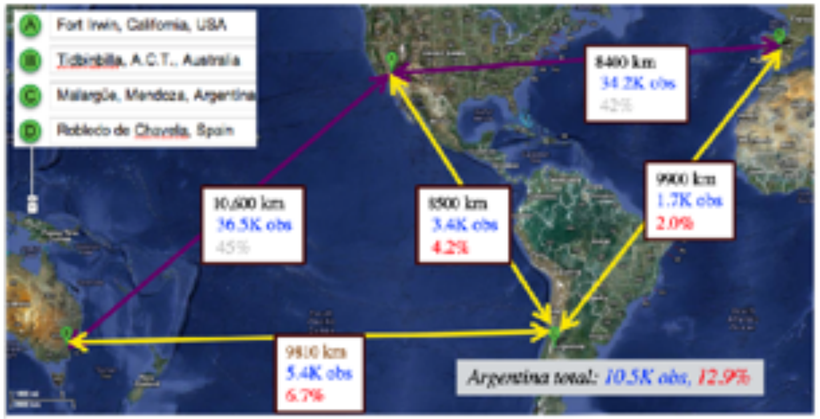


Fig. 1 Very Long Baseline Array of 25m antennas observed from δ +90 to about -40 deg.
credit: NRAO/AUI

X/Ka band

(Jacobs et al. 2018)

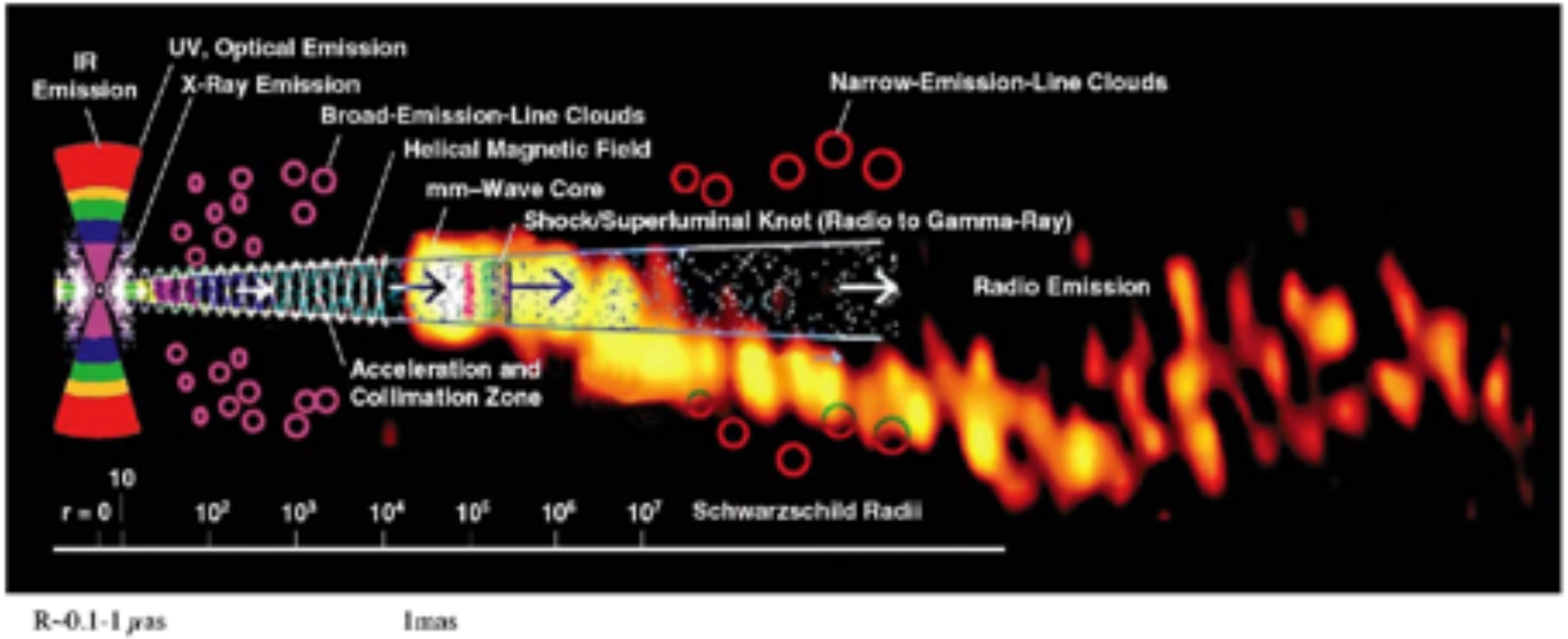


AGN astrophysics with Gaia &VLBI

Gaia

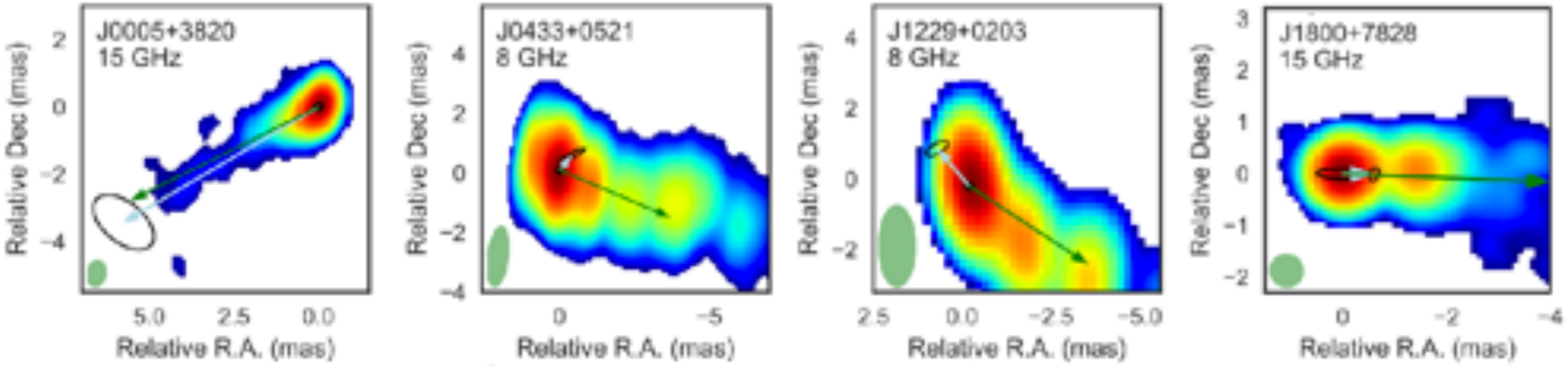
VLBI VLBI VLBI

XKa K SX



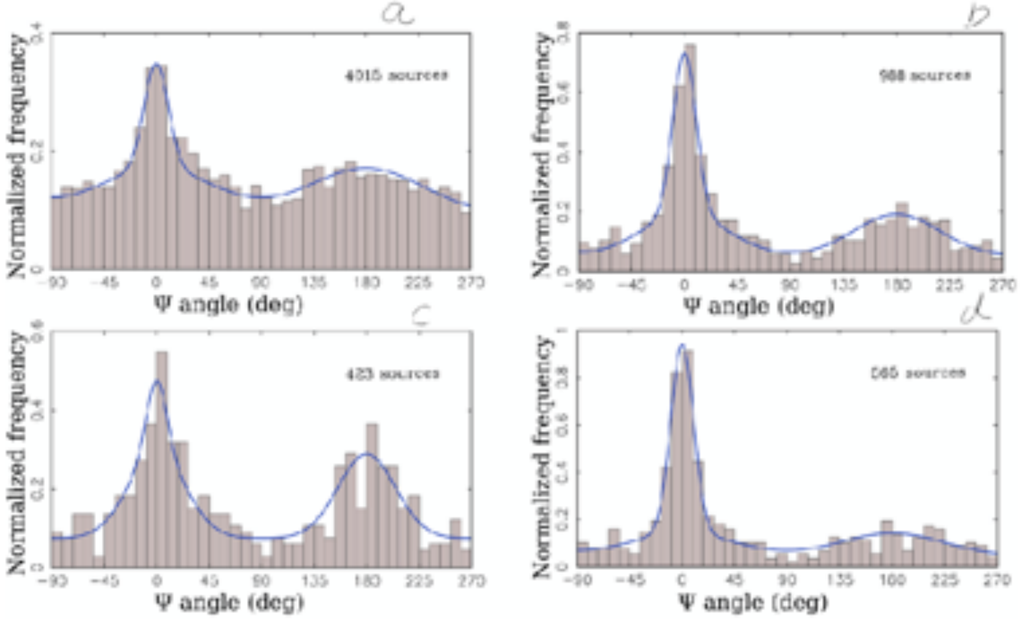
C. S. Jacobs, Journees 2013

Existence of parsec-scale optical jet in AGN



Kovalev et al, AA (2017)

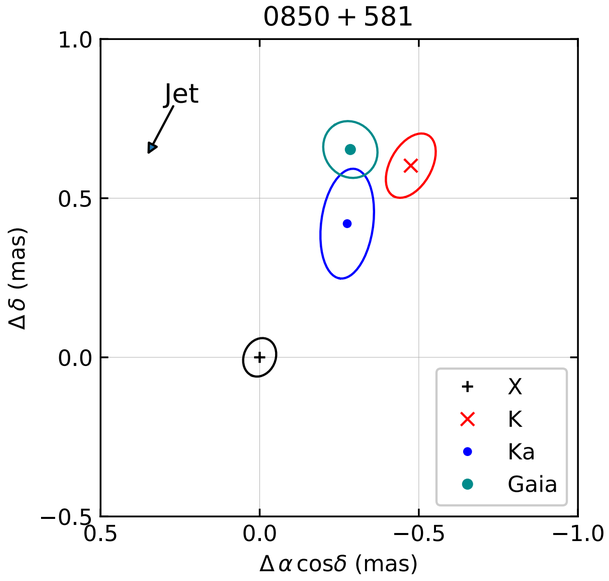
Petrov et al, MNRAS (2019)

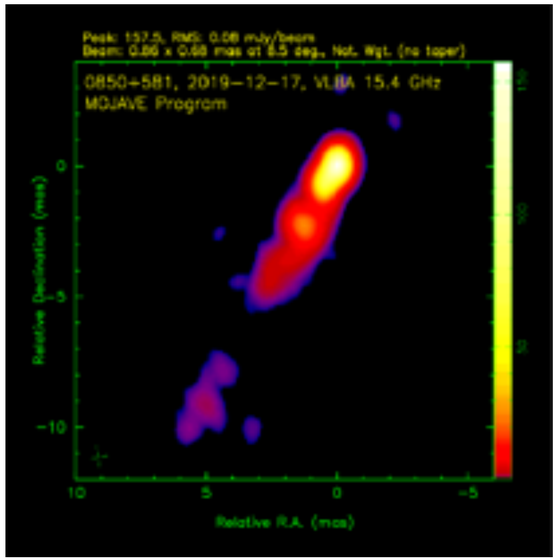


~60% sources showing a parallel orientation between VLBI-Gaia offset and jet

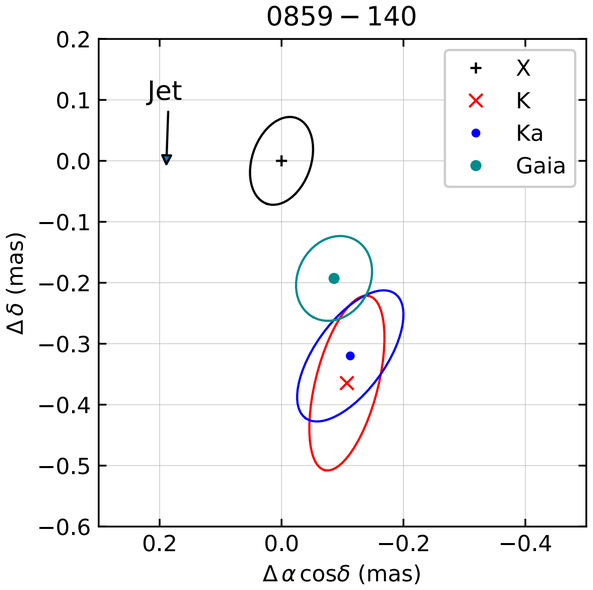
Gaia/VLBI offset to study position–frequency relation

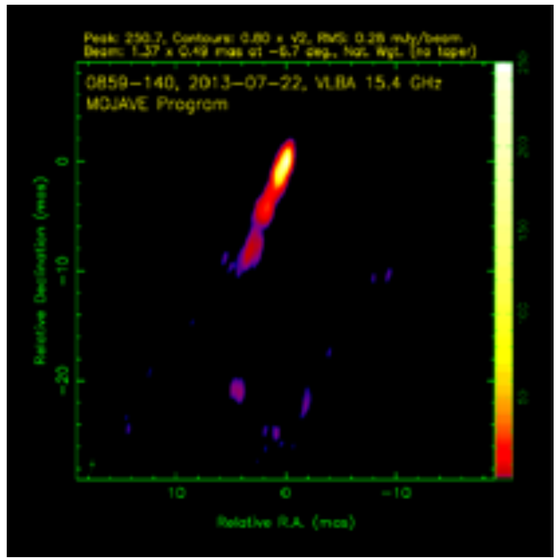
High-frequency position in the upstream direction of jet





High-frequency position in the downstream direction of jet





Liu et al, 2020, submitted

Global signals in extra-galactic proper motion

Table 1. Various perspective effects.

Effect	Origin	Description	Measurement method	Expected magnitude	Redshift dependence
Acceleration of the solar system	o	Acceleration of the solar system assumed to be towards the Galactic centre resulting in patterns of proper motion. However, the local group of galaxies and clusters of local supercluster will also contribute to the effect.	Astrometric	~4.3 μas yr^{-1}	None
Cosmological proper motion	o	Instantaneous velocity of the solar system with respect to the CMB can cause distant extragalactic sources to undergo an apparent systematic proper motion.	CMB and astrometric	1–2 μas yr^{-1}	Increases at low z
Gravitational waves	o	Primordial gravitational waves produce systematic proper motions over the sky.	Dedicated detectors/ possibly astrometric	Unknown but probably <1 μas yr^{-1}	None
Transverse redshift drift/ cosmic parallax	c	A temporal shift of the angular separation of distant sources can be used to detect an anisotropic expansion of the Universe and results in a pattern of proper motions.	Astrometric	0.2 μas yr^{-1} (Bianchi) 0.02 μas yr^{-1} (LTB)	Increases at high z, decreases at very high z
Peculiar proper motion	s	Proper acceleration is the observed transverse acceleration of an object due to the local gravitational field.	Astrometric	Can be 10 μas yr^{-1} for Galactic clusters	None
Quasar microlensing	s	Weak microlensing can induce apparent motions of quasars.	Astrometry photometry	10's of μas yr^{-1} but is extremely rare	None

Notes. o refers to an effect that is due to the observer's motion, s refers to an effect that is due to the source's motion, and c refers to an effect that is of cosmological origin. We arbitrarily define the boundary between low and high z as a redshift of 1.0.

Bachchan et al., A&A (2016)

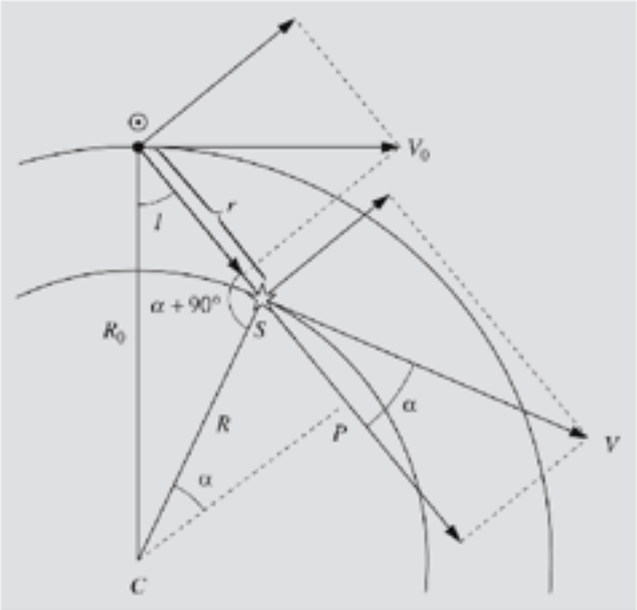
Problems in Gaia-CRF

Within an ideal inertial (non-rotating) frame, stellar motion contains

- Stellar proper motion
- Solar system motion
- Galactic rotation
- Noise

Assumption: K-M giant, only in-plane rotation

From Gaia DR1, rotation around Y_G axis



Fundamental Astronomy (2007)

$$\omega_{Y_G} = D_{13}^{-} = -0.38 \pm 0.15\,\mathrm{mas\,yr^{-1}}$$
$$\omega'_{Y_G} = D_{13}^{+} = -0.29 \pm 0.19\,\mathrm{mas\,yr^{-1}}$$

Residual rotation in the Gaia-CRF1?

Liu et al., A&A (2017)

Gaia Early Data Release 3

Scheduled on 3 December 2020

	# sources in Gaia EDR3	# sources in Gaia DR2	# sources in Gaia DR1
Total number of sources	≈ 1,800,000,000	**1,692,919,135**	**1,142,679,769**
Number of 5-parameter sources	≈ 1,500,000,000	1,331,909,727	2,057,050
Number of 2-parameter sources	≈ 300,000,000	361,009,408	1,140,622,719
Sources with mean G magnitude	≈ 1,800,000,000	1,692,919,135	1,142,679,769
Sources with mean G_{BP}-band photometry	≈ 1,500,000,000	1,381,964,755	-
Sources with mean G_{RP}-band photometry	≈ 1,500,000,000	1,383,551,713	-
Gaia-CRF sources	≈ 1,500,000	556,869	2,191
Sources with radial velocities	expected with Gaia DR3 / ≈7,210,000 from Gaia DR2 in Gaia EDR3	7,224,631	-
Variable sources	expected with Gaia DR3 / see Gaia DR2	550,737	3,194
Known asteroids with epoch data	expected with Gaia DR3 / see Gaia DR2	14,099	-
Effective temperatures (T_{eff})	expected with Gaia DR3 / see Gaia DR2	161,497,595	-
Extinction (A_G) and reddening ($E(G_{BP}-G_{RP})$)	expected with Gaia DR3 / see Gaia DR2	87,733,672	-
Sources with radius and luminosity	expected with Gaia DR3 / see Gaia DR2	76,956,778	-
and more...	expected with Gaia DR3	-	-

Summary

- Astrometry is all about position: question to address is simple but hard to solve.
- Gaia catalog will surpass all astrometric catalogs in the range of 6-21 mag
- Gaia solution helps to evince systematics in current (fundamental) ICRF catalog
- Gaia/VLBI position at micro-arcsecond level might bring more insights to AGN fine structure
- Global patterns in extra-galactic proper motion from Gaia data is still biased by systematics but maybe be studied with future data release (Gaia EDR3?)

Some references

- History of Astrometry: Perryman, M. 2012, European Physical Journal H, 37, 745
- Gaia-CRF2: Gaia Collaboration, Mignard, F., Klioner, S.A., et al. 2018, A&A, 616, A14
- ICRF3: Charlot, P. et al. 2020, A&A, in press
- Nonrotating astronomical relativistic reference frames: Klioner, S.A. & Soffel, M. 1998, A&A, 334, 1123
- proper motion patterns in the Gaia reference frame: Bachchan, R.~K., Hobbs, D., & Lindegren, L. 2016, A&A, 589, A71