Optical Celestial Reference Frame

From Hipparcos to Gaia

A tribute to J. Kovalevsky

F. Mignard

Observatoire de la Côte d'Azur/Lagrange

Summary

- J. Kovalevsky: scientist and science manager
- CRF before Hipparcos
- The HCRF
- The ICRS/ICRF context
- The Gaia-CRF2
- Conclusions

Jean Kovalevsky (1929-2018)

- Born in Paris area in 1929 from Russian emigrates
- Educated at the Ecole Normale Supérieure in Paris
- PhD in Yale with D. Brouwer in Celestial Mechanics
- Founded and headed the Service de Calculs et de Mécanique Céleste of the Bureau des Longitudes
- Structured the Space Geodesy in France
- Build the CERGA in 1974, director to 1982, and 1988-1992
- Pioneer of Space Astrometry with Hipparcos
- Head of the FAST consortium
- President of the CIPM at the BIPM (1997-2004)
- Author of fundamental astronomy and geodesy textbooks

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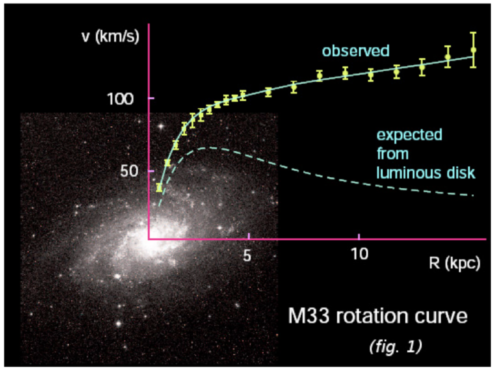
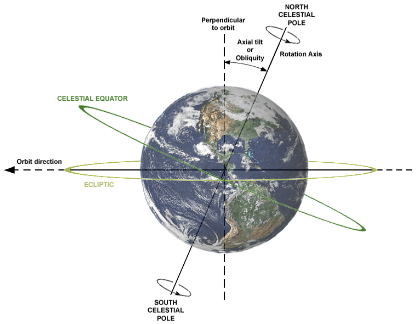
Why a reference frame ?



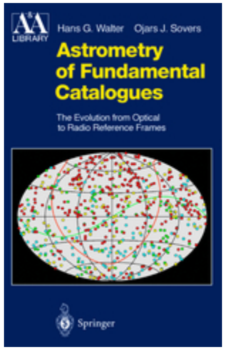
- To refer positions of fixed or moving sources
- To detect tiny motions
- To quantify without bias the motion of sources
  - modelling the galactic kinematics
  - investigate rotational and translational motion of external galaxies
- To monitor the rotation of the earth
  - fix the timescale
  - study the plate motions



- Angular positions (and distances) of Quasars, galaxies, stars, planets, spacecraft

Stellar Reference Frames < 1990

Name	Epoch	N. sources	mag <	Precision	Comment
Lacaille	1760	397	7	$10''$	
Maskelyne	1774	36	5	$5''$	zodiacal stars
Piazzi	1818	220	6	$2''$	No PM
Bessel	1830	36	5	$1''$	with PM
Argelander	1869	160	6	$1''$	
Auwers	1879	539	6	$0.5''$	
FK3	1937	873	7.0	$0.5''$	1st IAU supported
FK4	1963	1535	7.5	$0.2''$	
FK5	1988	1535	7.5	40 mas	



Main features: small catalogues, bright sources, hard work !

~ 1980 : A new approach

- New Concepts: Ideal and Practical realisations
- New tools: Geodetic VLBI, astrometry in space
- New sources: extragalactic sources
- Better precision: stepping in the mas realm

A landmark monograph

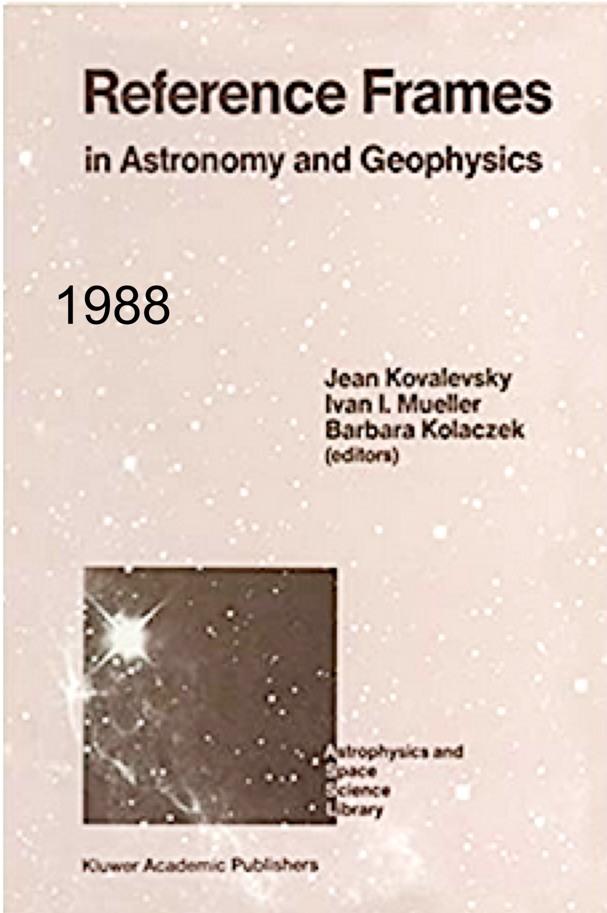


TABLE OF CONTENTS

Space Astrometry: key steps

- First concepts from P. Lacroute to CNES in 1966
- A presentation at the IAU GA 1967 in Prague
- Feasibility study at CNES in 1969-70 within a national program

P. Lacroute

"Nearly all fields of astronomy will be concerned"

" …this experience would completely revolutionize astrometry"

- Submitted to ESRO and major symposium to form the community around scientific objectives, 22-23 October 1974 in Frascati
  - initiated by J. Kovalevsky

J. Kovalevsky

- Road to success: combination of astrometry and astrophysics
- ESA launched early studies for space astrometry

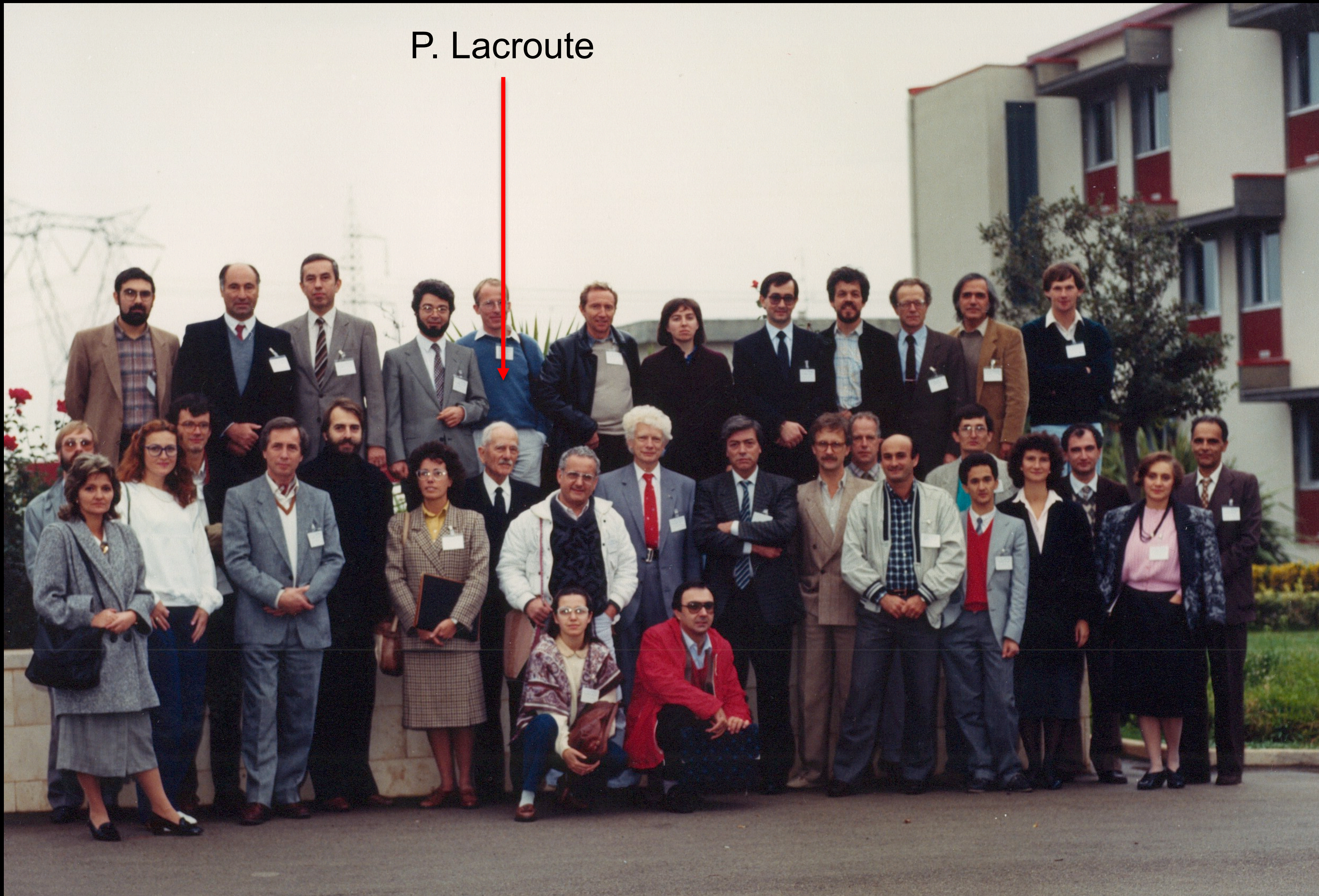
NEWS IN BRIEF

ESA chooses Hipparcos

THE Scientific Programme Committee of the European Space Agency decided last week to fund the astrometry mission Hipparcos as the next ESA mission after Exosat which is to be launched in 1981. Designed to improve the measurements of stellar positions by two orders of magnitude, the satellite will be launched by Ariane in mid-1986, and placed in a geostationary orbit for its lifetime of two and a half years. The total estimated cost of the project is 139.3 MAU ($185 million).

Hipparcos was the Programme Committee's final choice in spite of a recommendation by the Scientific Advisory Committee to fund a dual mission consisting of experiments to measure the Earth's magnetospheric tail and a deep space flyby of Halley's comet. By a vote of 10 votes for and one abstention, the 11 member committee, consisting of delegates from each ESA country, decided to overturn the Scientific Advisory Committee's recommendation.

Nature, March 1980, 284, 116



FAST Consortium Nov 1986

Credit : M. Perryman

Lecture in Delft

16 Dec 1986

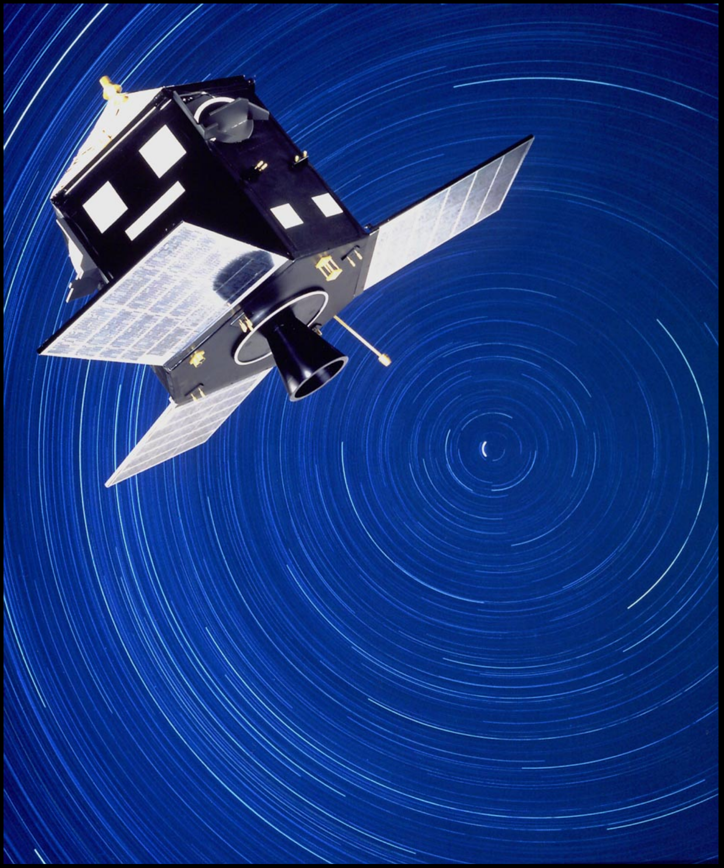
Credit : M. Perryman

R. Lüst M. Perryman xx
xx, H. Hassan, C.Turon, P. Lacroute, R. Bonnet, E. Hoeg, J. Kovalevsky, xx

11 April 1988

Credit : M. Perryman

8 August, 1989



Credit : ESA

HIPPARCOS

Bad day for astronomers

Kourou, French Guiana

AFTER a perfect launch in French Guiana on 8 August, the European astronomy satellite Hipparcos ran into trouble when the apogee motor failed three times to respond to commands to fire. The motor is responsible for lifting the satellite into geostationary orbit around the Earth. As *Nature* goes to press, there are still hopes that the motor will eventualiy fire.

Two more attempts to fire the motor are planned for 15 and 16 August. For the moment, the satellite remains in an elliptical orbit moving between 208 kilometres and 35,000 kilometres from the Earth. As a last resort, the motors used to orient the satellite will be used to push it into a higher orbit. Many of the experiments could still be carried out, but using the fuel for this purpose would leave the satellite with a much shorter working life.

The Ariane rocket left the launch pad carrying a West German direct broadcasting television satellite, TV-SAT 2, as well as Hipparcos. The first launch attempt was stopped seven seconds short of ignition by an overzealous computer. But then the mission got off to a good start with the perfect positioning of Hipparcos and TV-SAT 2 in their transfer orbits. Just 37 hours later the problems began.

The easy part: the 9 August lift-off from Kourou went well (AP).

IMAGE UNAVAILABLE FOR COPYRIGHT REASONS

Hipparcos, named after the Greek astronomer who drew up the first star catalogue during the second century BC, is the world's first astronometry mission, designed to measure the precise positions, parallaxes and proper motions of stars. During its two and a half years of life, the satellite is expected to measure the positions of 100,000 stars with a precision of 0.002 arc seconds. The results, as well as those of the Tycho experiment, designed to measure 400,000 stars with an accuracy of 0.03 arc seconds, should be ready by 1995. And the data should be 50 times more accurate than the best available today, according to Michael Perryman of the European Space Agency (ESA).

The satellite is a 23-year-old dream of a French astronomer, Pierre Lacroute, who was one of the guests at the launch last week along with the French minister for research and technology, Hubert Curien. It was built by the French company Matra and the Italian company Aeritalia at a cost of about $360 million, and is not insured, according to Roger Bonnet, director of ESA's scientific programmes. A spokesman for Matra said that to build a replacement would take more than three years.

Ricardo Bonalume Neto

Nature, 17/08 1989, 340, 491

Credit : F. Mignard

HIPPARCOS

ESA tries to salvage Hipparcos

Munich

AFTER nearly two weeks of unsuccessful attempts to fire the apogee motor on the European astronomy satellite Hipparcos, project leaders have reluctantly begun to design a salvage operation for the mission. The 1,140-kg satellite is currently in an elliptical orbit between 200 km and 35,000 km from the Earth. Project scientist M.A.C. Perryman says the chances are "very small" that Hipparcos can be brought into a geostationary orbit by the motor, as was originally intended (see *Nature* **340**, 491; 1989).

One or two more attempts to fire the motor will be made on 24 or 25 August. If they fail, small thrusters on the satellite will be fired early next week to bring the satellite into a higher orbit at a minimum distance of about 600 km from Earth. The thrusters were originally meant to be used to correct for nutation (wobbling) once the satellite was in geostationary orbit.

Hipparcos was designed to measure the precise positions, parallaxes and proper motions of stars. It was expected over two and a half years to measure the positions of 120,000 stars with a precision of 0.002 arcseconds. A second mission on board, called Tycho, was meant to measure the positions of 400,000 stars with an accuracy of 0.03 arcseconds by 1995.

In the current orbit, Hipparcos could last from six months to two years, depending on how fast the solar cells that power the satellite degrade. In six months, the satellite could achieve only one-third the accuracy initially projected, although this would still improve on ground-based results by a factor of 15.

ESA has not decided to ask its 13 member states for the money to build and launch a second Hipparcos satellite identical to the first. But a preliminary decision is expected "in one month", said Roger Bonnet, director of the ESA scientific programmes, after the extent of the degradation of the solar cells has been determined. The ESA council would have to approach the scientific programme committee to request more money. A replacement satellite would cost an estimated £114 million ($182 million).

It would be difficult to reapportion the money out of the existing ESA science programme budget, which would require a two-thirds majority vote in the committee. But it would be even more difficult to gain a new appropriation for a second Hipparcos, which would require unanimous support. The length of time in orbit is crucial. In six months, only 8 or 10 observations of each star would be possible instead of the 80 originally planned. If Hipparcos were to survive longer, say for a year or a year and a half, proper motions of stars and parallaxes could begin to be measured. But Perryman said that was not a "realistic" expectation.

In its elliptical orbit, the satellite passes every ten hours through the Van Allen belts, where it is subject to irradiation by protons and electrons in the solar wind 5,000 km above the equator. This radiation degrades the solar panels which power the satellite. **Steven Dickman**

Nature, 24/08 1989, 340, 581

NEWS

HIPPARCOS

Original mission abandoned

Munich

THE European Space Agency (ESA) gave up hope last week of bringing the astronomy satellite Hipparcos into its intended orbit. Instead, project leaders were to sign an agreement on 4 September to try to salvage the mission by raising slightly the current elliptical orbit. They expect to begin this by 7 or 8 September. The new orbit would yield a sharply reduced amount of data.

The Hipparcos mission, named after the second century BC Greek astronomer who drew up the first star catalogue, was intended to measure the precise positions, parallaxes and proper motions of stars. After a perfect launch on 8 August, ESA was unable to fire the apogee motor in order to raise the $360-million satellite into a geostationary orbit 36,000 km from the Earth (see *Nature* 340, 491 and 581; 17 and 24 August 1989).

If the rescue mission succeeds, Hipparcos is expected to last just six months before its solar panels succumb to the bombardment of protons and electrons in the Van Allen belts, 5,000 km up. This decrease from the original 30-month mission would sharply reduce the accuracy of the data that could be collected.

The salvage operation will attempt to use the hydrazine thrusters on the satellite to boost its perigee (closest approach to Earth) from 208 km to 460 km This would reduce aerodynamic drag on the satellite and, researchers hope, give it a longer lifetime.

Nature, 07/09 1989, 341, 3

Credit : F. Mignard

Happy Ending

Bern , 20 May, 1999

Credit : M. Perryman

Stellar Reference Frames - 1996

Name	Epoch	N. sources	mag <	Precision	Comment
Lacaille	1760	397	7	10 $''$	
Maskelyne	1774	36	5	5 $''$	zodiacal stars
Piazzi	1818	220	6	2 $''$	No PM
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FK5	1988	1535	7.5	40 mas	
Hipparcos	1996	100 000	11.5	1 mas	HCRF

Astron. Astrophys. 323, 620–633 (1997)

ASTRONOMY AND ASTROPHYSICS

The Hipparcos Catalogue as a realisation of the extragalactic reference system

J. Kovalevsky[1], L. Lindegren[2], M.A.C. Perryman[3], P.D. Hemenway[4], K.J. Johnston[5], V.S. Kislyuk[6], J.F. Lestrade[7], L.V. Morrison[8], I. Platais[9], S. Röser[10], E. Schilbach[11], H.-J. Tucholke[12], C. de Vegt[13], J. Vondrák[14], F. Arias[15], A.M. Gontier[16], F. Arenou[7], P. Brosche[12], D.R. Florkowski[5], S.T. Garrington[17], R.A. Preston[18], C. Ron[14], S.P. Rybka[6], R.-D. Scholz[11], and N. Zacharias[5]

A&A 392, 341–351 (2002)
DOI: 10.1051/0004-6361:20020931

Astronomy & Astrophysics

Application of the new concepts and definitions (ICRS, CIP and CEO) in fundamental astronomy

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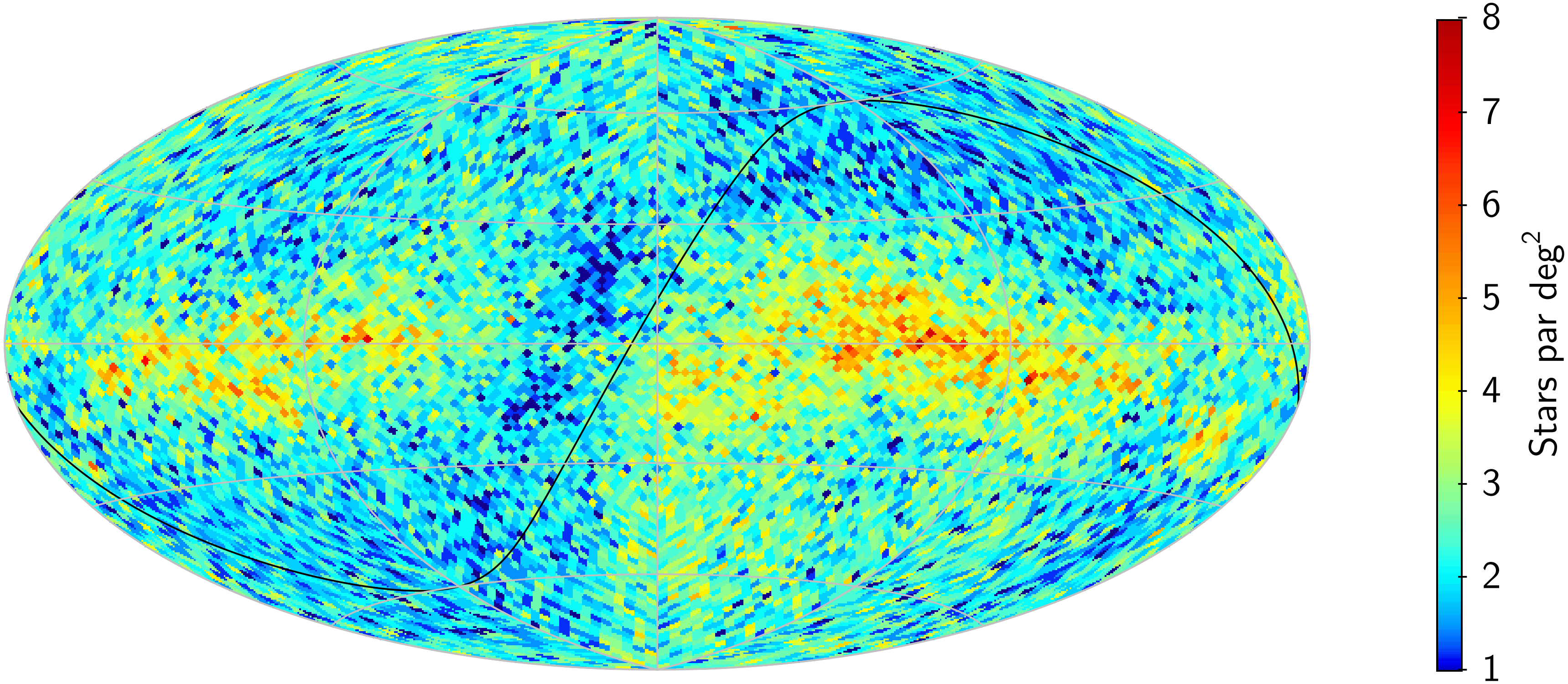
Received 8 March 2002 / Accepted 17 May 2002

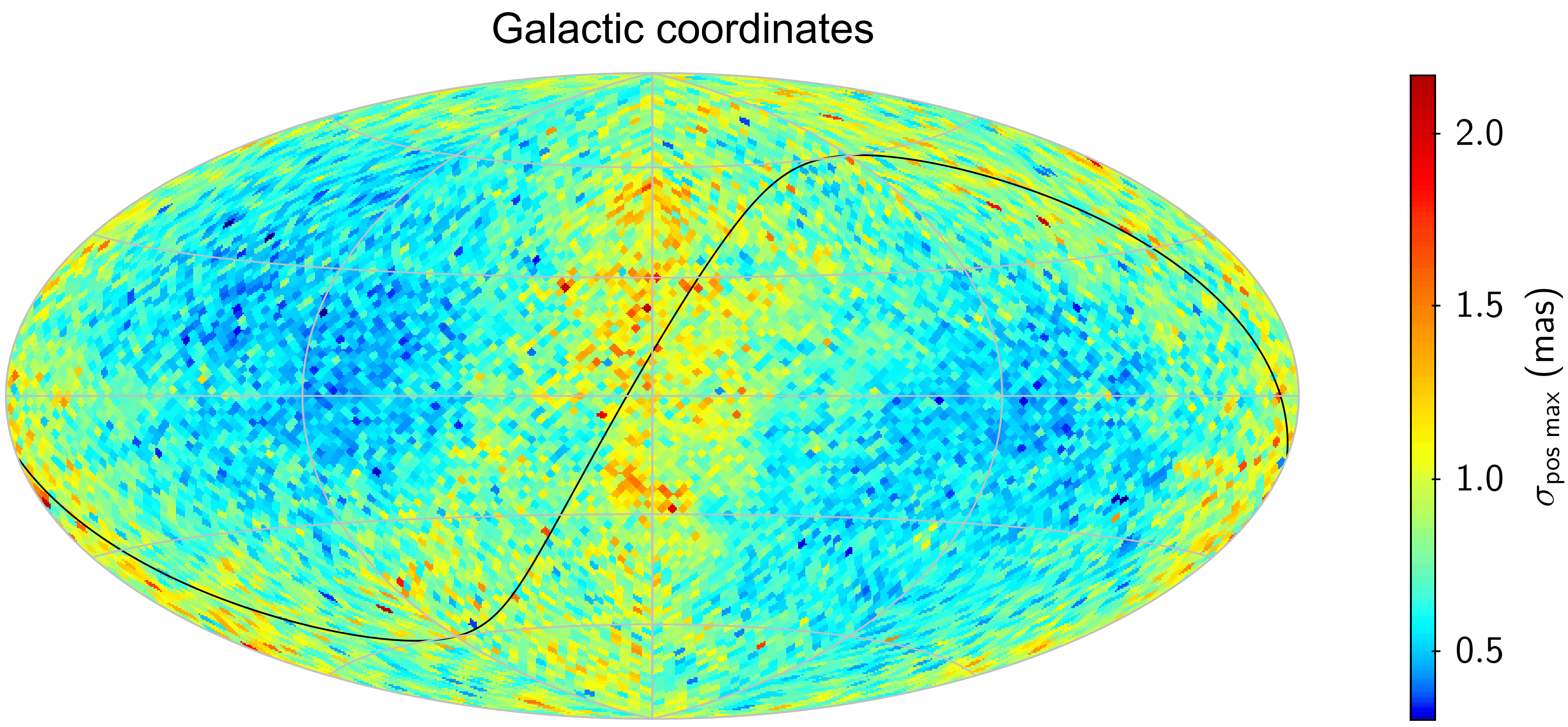
HCRF – Source distribution

HCRF - 100,000 single stars – Galactic coordinates



HCRF – Positional uncertainty 1991.25

HCRF - 1991



Resolution No B2

On the international celestial reference system (ICRS)

Sur le système céleste international de référence (ICRS)

HCRF at IAU 1997

The XXIIIrd International Astronomical Union General Assembly

Considering

a. That Recommendation VII of Resolution A4 of the 21st General Assembly specifies the coordinate system for the new celestial reference frame and, in particular, its continuity with the FK5 system at J2000.0;

b. That Resolution B5 of the 22nd General Assembly specifies a list of extragalactic sources for consideration as candidates for the realization of the new celestial reference frame;

c. That the IAU Working Group on Reference Frames has in 1995 finalized the positions of these candidate extragalactic sources in a coordinate frame aligned to that of the FK5 to within the tolerance of the errors in the latter (see note 1);

d. That the Hipparcos Catalogue was finalized in 1996 and that its coordinate frame is aligned to that of the frame of the extragalactic sources in (c) with one sigma uncertainties of ± 0.6 milliarcseconds (mas) at epoch J1991.25 and ± 0.25 mas per year in rotation rate;

Noting

That all the conditions in the IAU Resolutions have now been met;

Resolves

a. That, as from 1 January 1998, the IAU celestial reference system shall be the International Celestial Reference System (ICRS) as specified in the 1991 IAU Resolution on reference frames and as defined by the International Earth Rotation Service (IERS) (see note 2);

b. That the corresponding fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on Reference Frames;

c. That the Hipparcos Catalogue shall be the primary realization of the ICRS at optical wavelengths;

d. That IERS should take appropriate measures, in conjunction with the IAU Working Group on reference frames, to maintain the ICRF and its ties to the reference frames at other wavelengths.

HCRF at IAU 2000

Resolution No. B1.2

Hipparcos celestal reference frame

Le repère de référence céleste Hipparcos

The XXIVth International Astronomical Union General Assembly,

Noting

1. that Resolution B2 of the XXIIIrd General Assembly (1997) specifies, "That the Hipparcos Catalogue shall be the primary realisation of the International Celestial Reference System (ICRS) at optical wavelengths",

2. the need for this realisation to be of the highest precision,

3. that the proper motions of many of the Hipparcos stars known, or suspected, to be multiple are adversely affected by uncorrected orbital motion,

4. the extensive use of the Hipparcos Catalogue as reference for the ICRS in extension to fainter stars,

5. the need to avoid confusion between the International Celestial Reference Frame (ICRF) and the Hipparcos frame, and

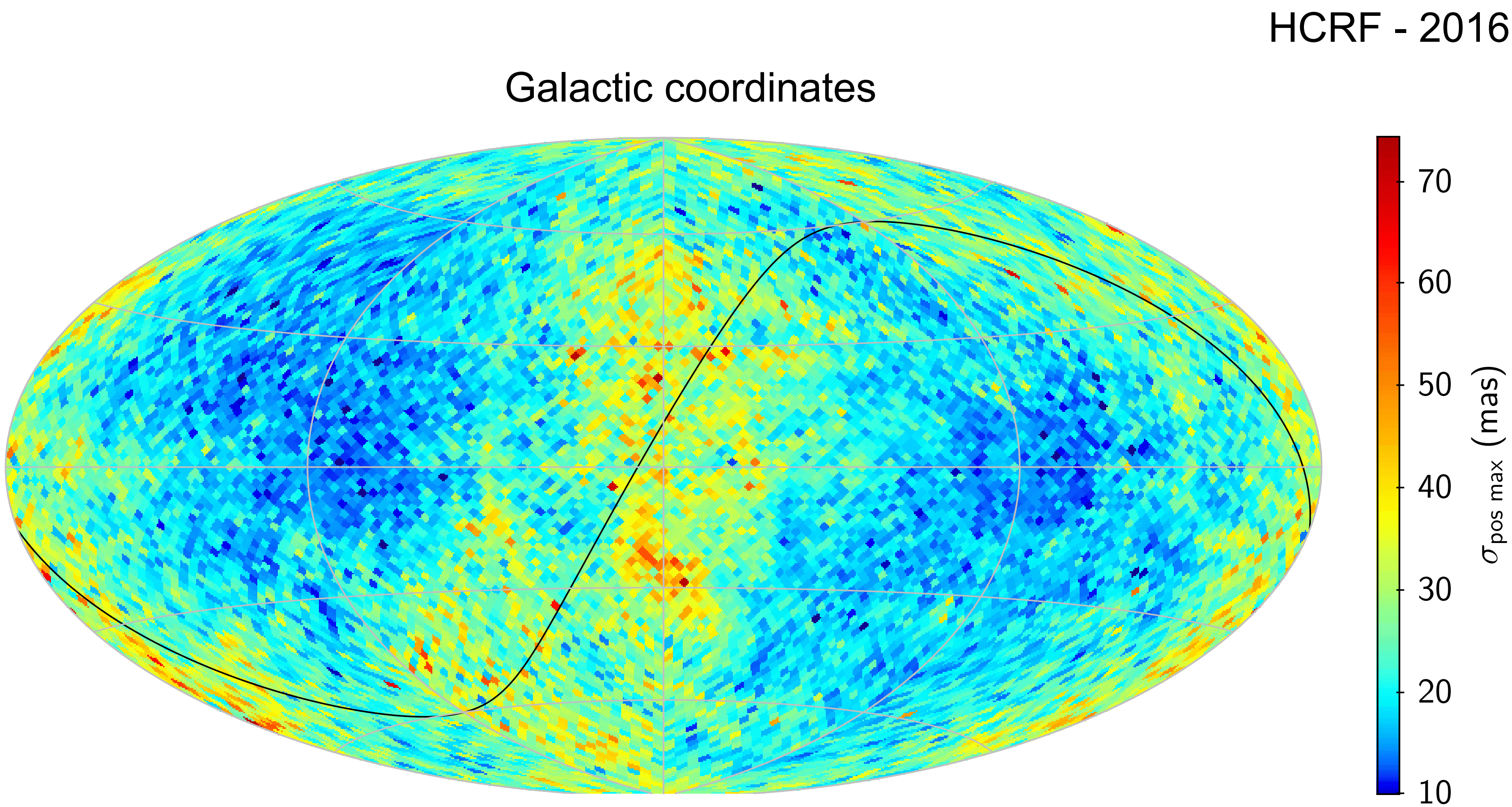
6. the progressive shift between the Hipparcos frame and the ICRF,

Recommends

1. that Resolution B2 of the XXIIIrd IAU General Assembly (1997) be amended by excluding from the optical realisation of the ICRS all stars flagged C, G, O, V and X in the Hipparcos Catalogue, and

2. that this modified Hipparcos frame be labelled the Hipparcos Celestial Reference Frame (HCRF).

HCRF – Positional uncertainty 2016.0



Celestial Reference Frames – 1998 - 2018

Name	Epoch	N. sources	mag <	Precision	Comment
Lacaille	1760	397	7	10 ″	
Maskelyne	1774	36	5	5 ″	zodiacal stars
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Bessel	1830	36	5	1 ″	with PM
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FK4	1963	1535	7.5	0.2 ″	
FK5	1988	1535	7.5	40 mas	
Hipparcos	1996	100 000	11.5	1 mas	HCRF (stars)
ICRF1 (radio)	1998	620	-	2 mas	ext. galact. sces.
ICRF2 (radio)	2009	3400	-	0.6 mas	
ICRF3 (radio)	2018	4500	-	0.23 mas	median uncert.
	2018	302	-	0.04 mas	def. sources

ICRF3 – source distribution

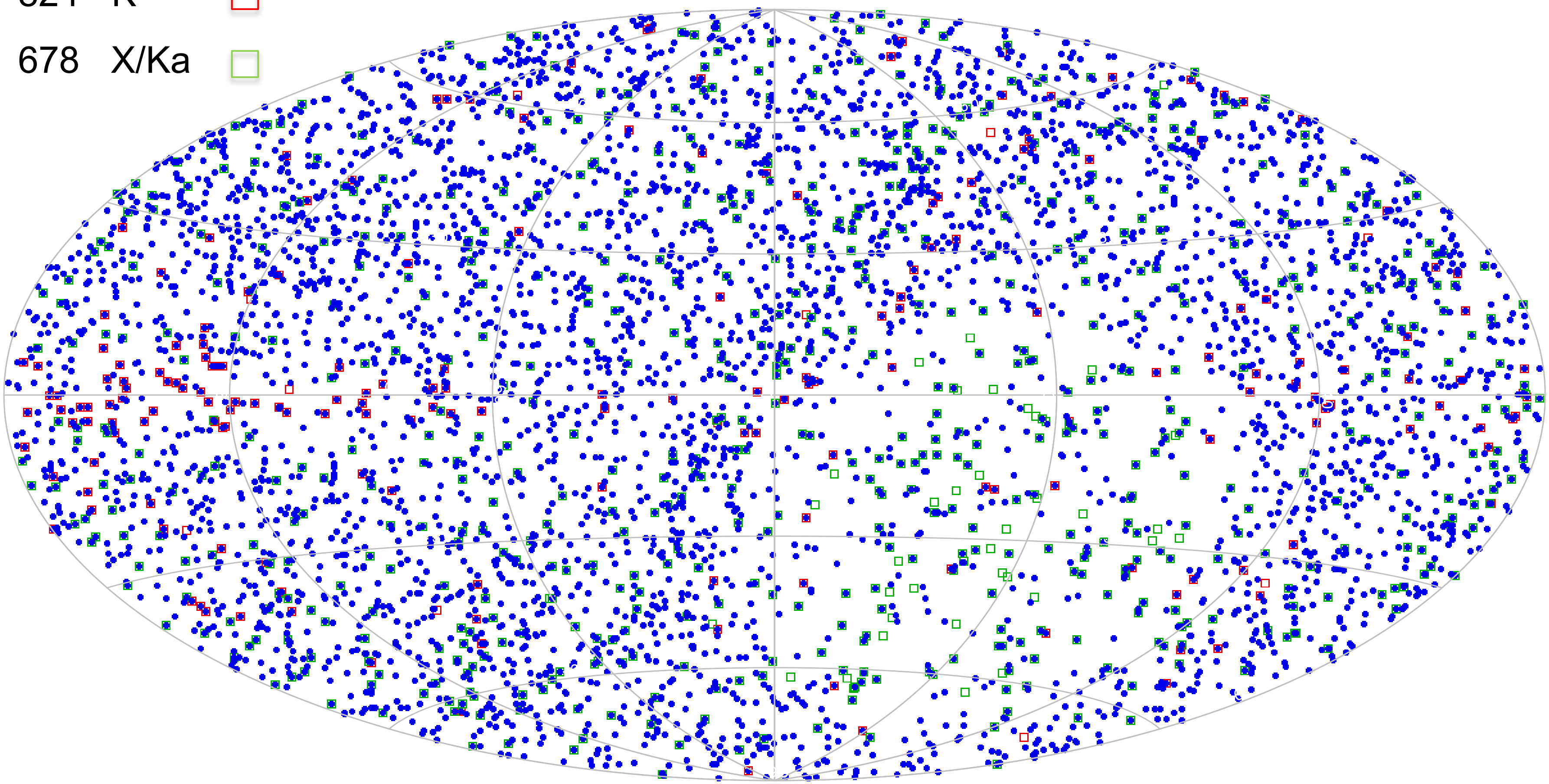
4588 QSOs – Galactic coord.

ICRF3

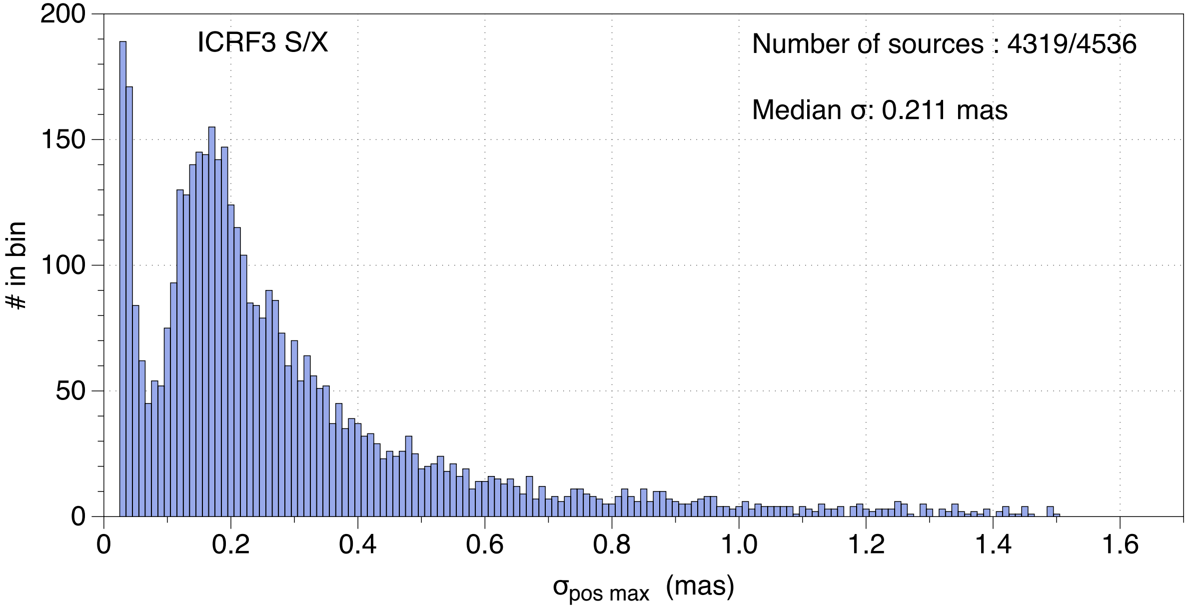
4536 S/X

824 K

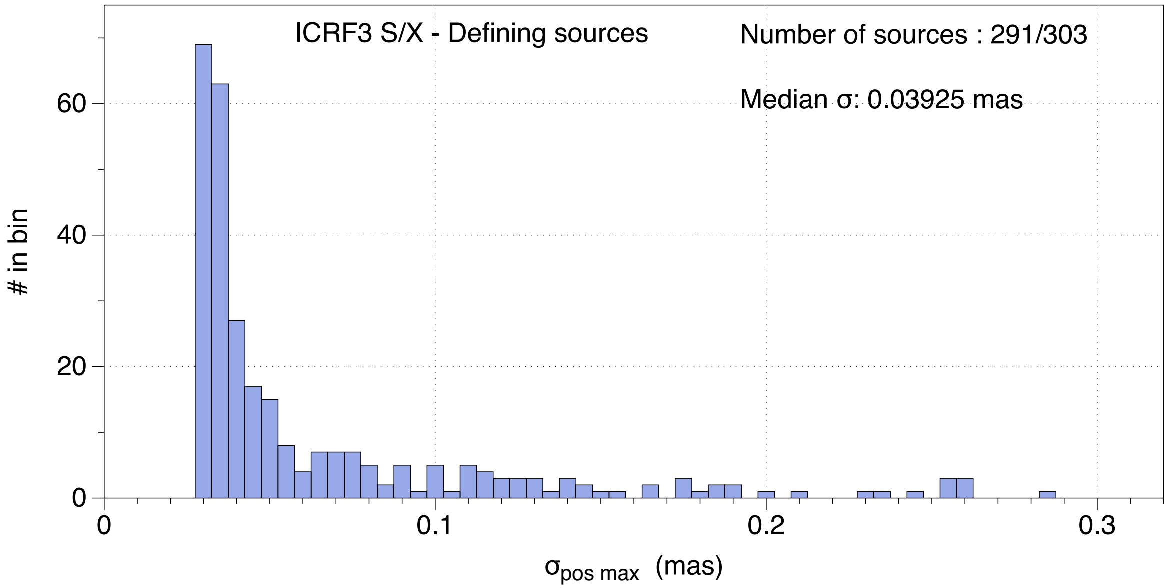
678 X/Ka



ICRF3 S/X– Accuracy

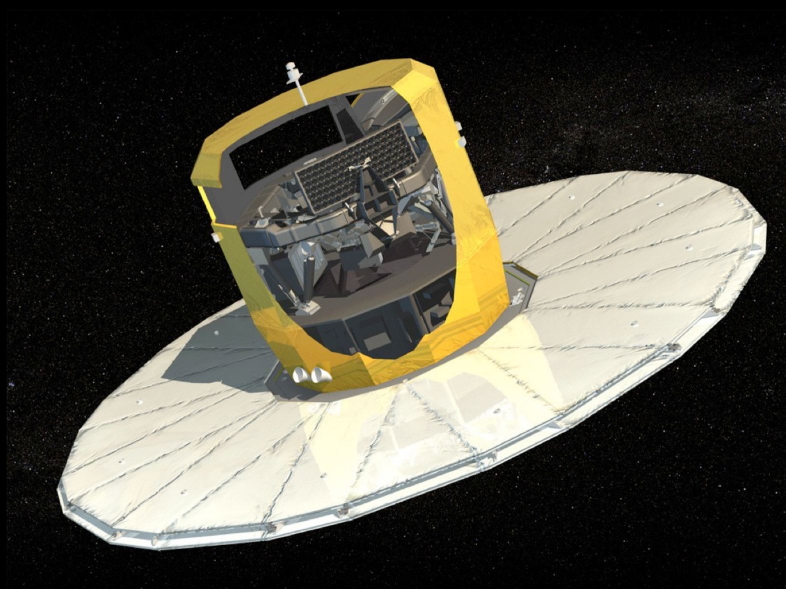


- two regimes
- 5% outside the wing

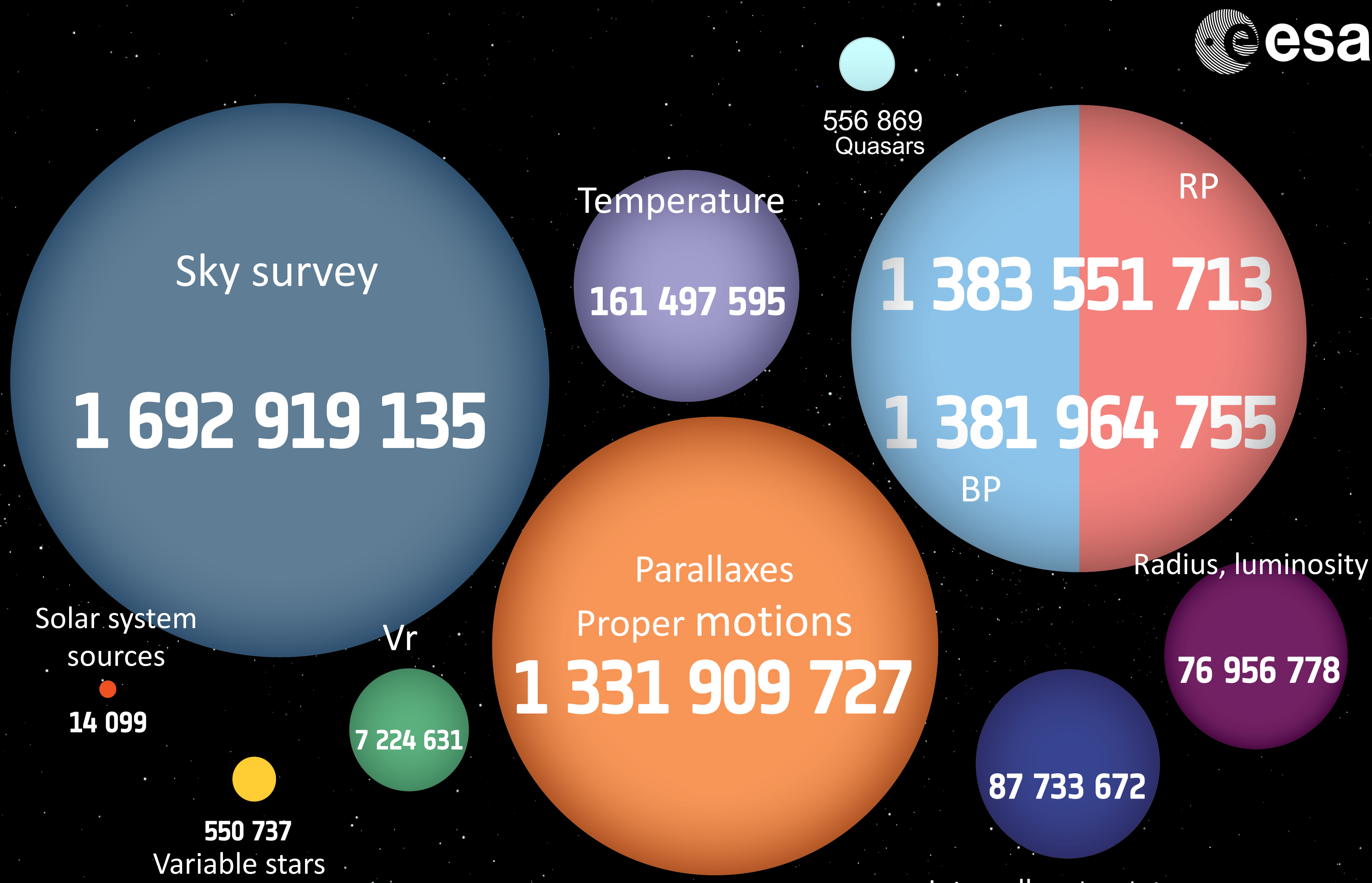


- remarkable accuracy

And ESA said, Let there be Gaia …



THE GAIA DR2: quantity, quality, diversity



Reference frame with Gaia

J. Kovalevsky, Ch. Le Poncin-Lafitte, M. Lattanzi, S. Klioner, D. Hestroffer, G. Anglada, P. Teyssandier

J. De Bruijne, A. Vecchiato, F. Mignard, M.T. Crosta

Relativity and Reference frame working group

Gaia - CRF2

Gaia DPAC

A&A 616, A14 (2018)
https://doi.org/10.1051/0004-6361/201832916

Gaia Data Release 2

Astronomy & Astrophysics

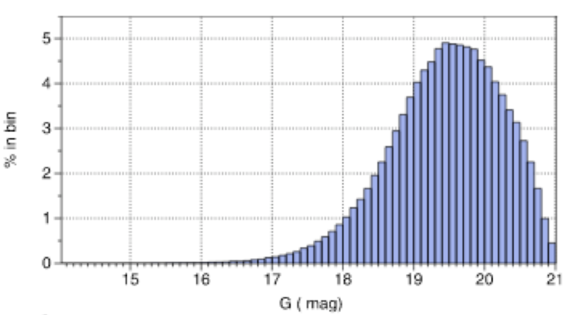
Special issue

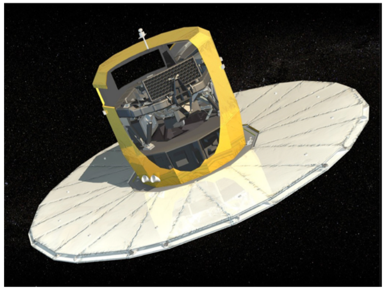
Gaia Data Release 2

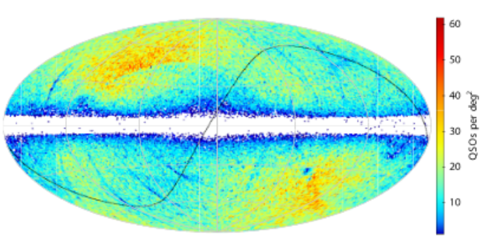
The celestial reference frame (*Gaia*-CRF2)

Gaia Collaboration, F. Mignard[1,⋆], S. A. Klioner[2], L. Lindegren[3], J. Hernández[4], U. Bastian[5], A. Bombrun[6], et al.

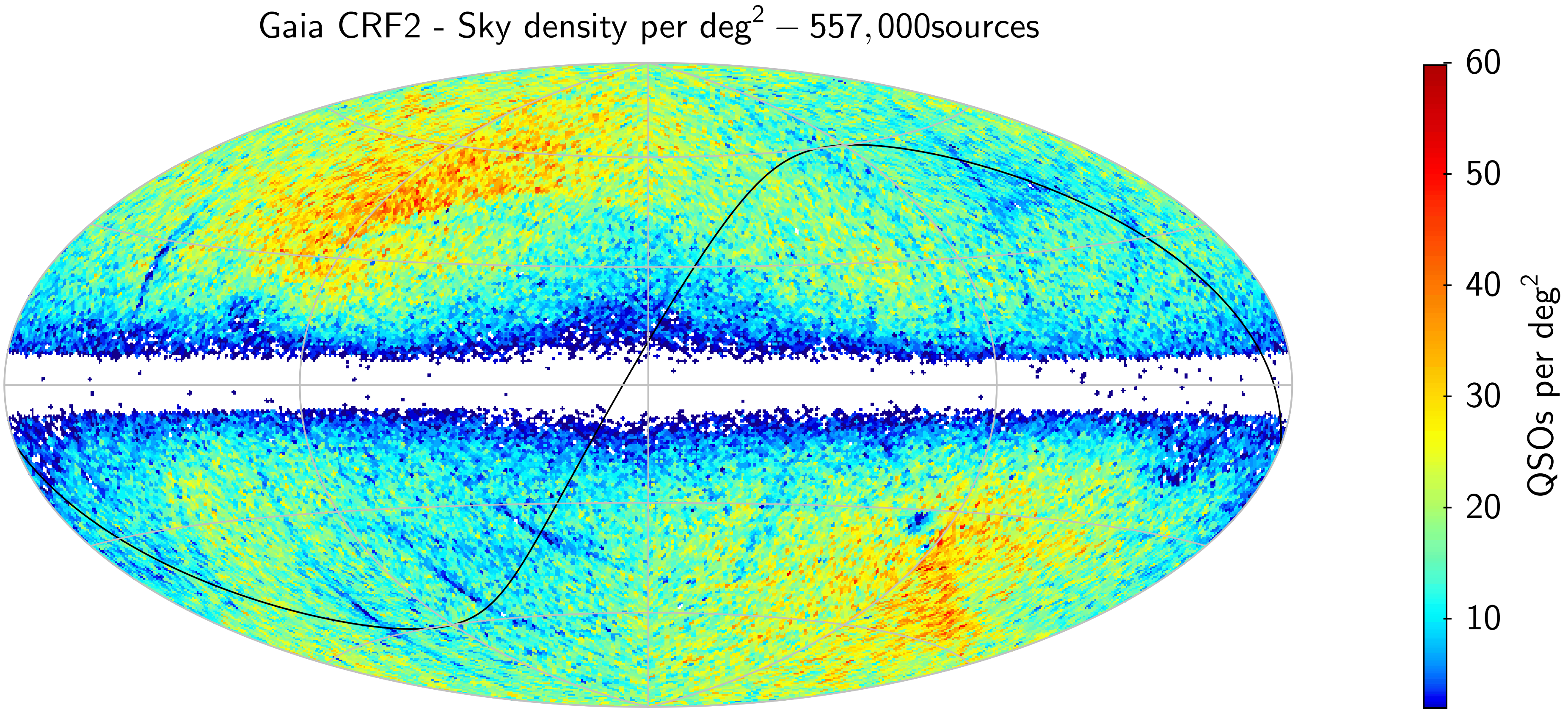
Received 27 February 2018 / Accepted 16 April 2018





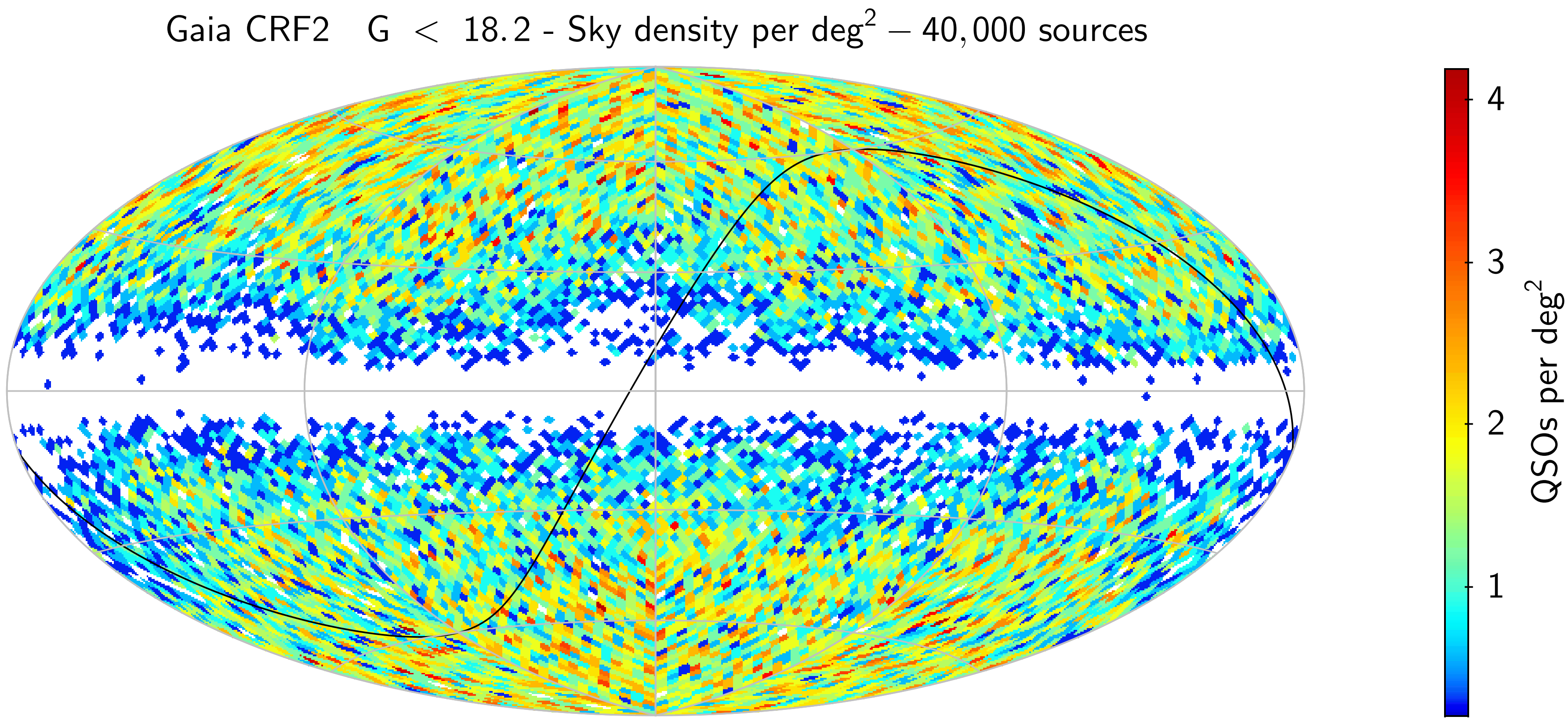


Gaia CRF2 : source distribution



Gaia collaboration, DR2 , 2018

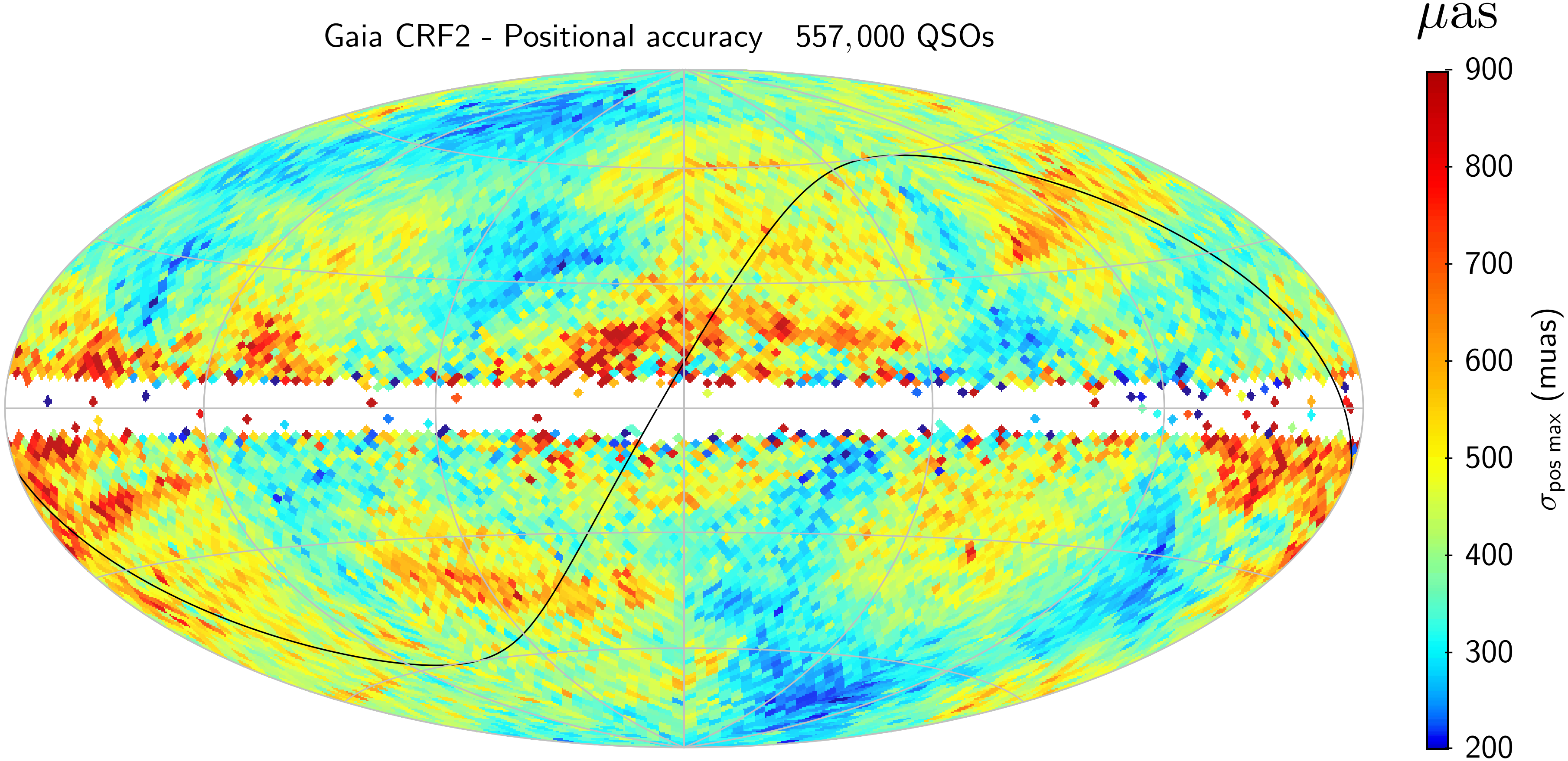
Gaia CRF2 : source distribution G <18.2



Gaia collaboration, DR2 , 2018

Gaia CRF2 : astrometric uncertainty G < 21

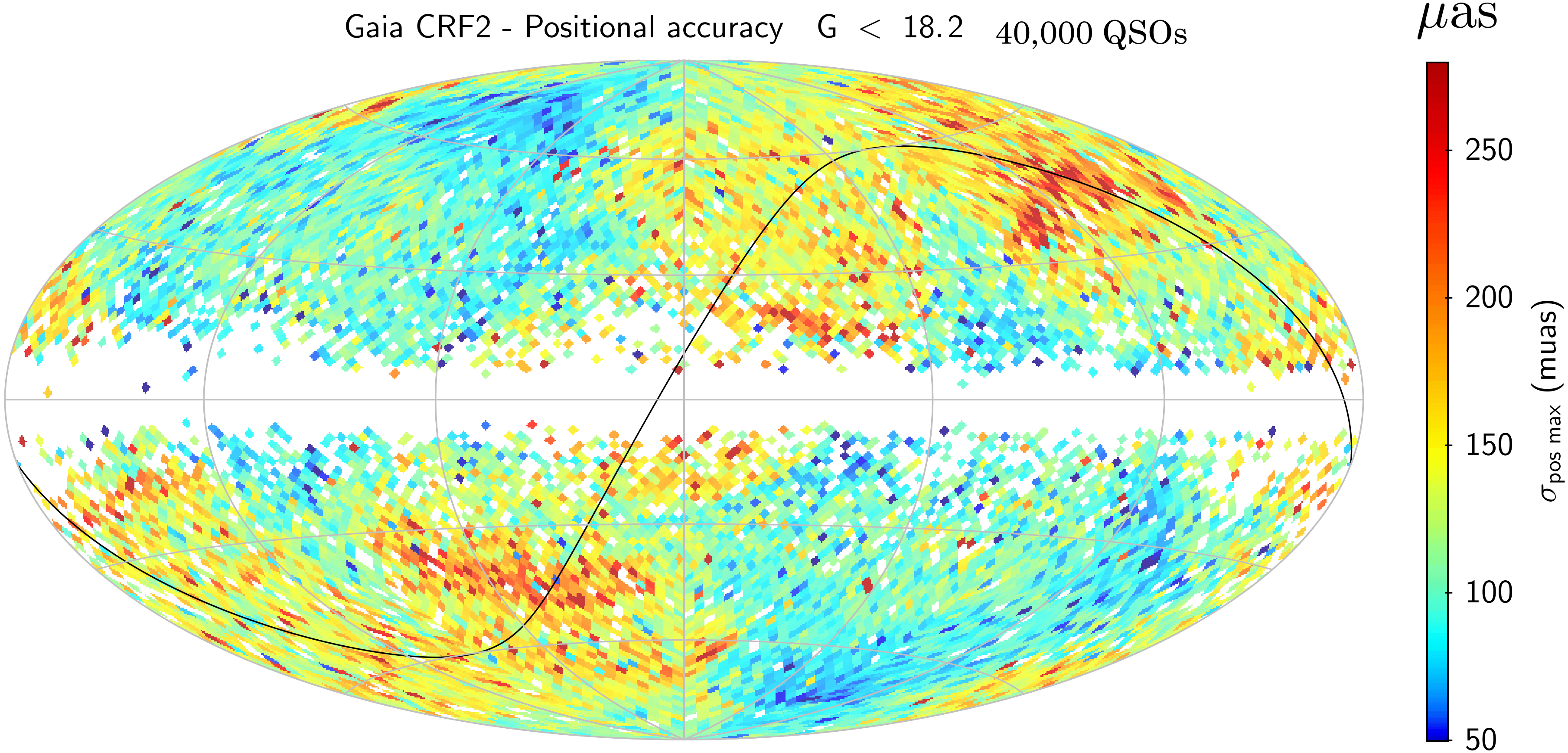
GCRF2



Gaia collaboration, DR2 , 2018

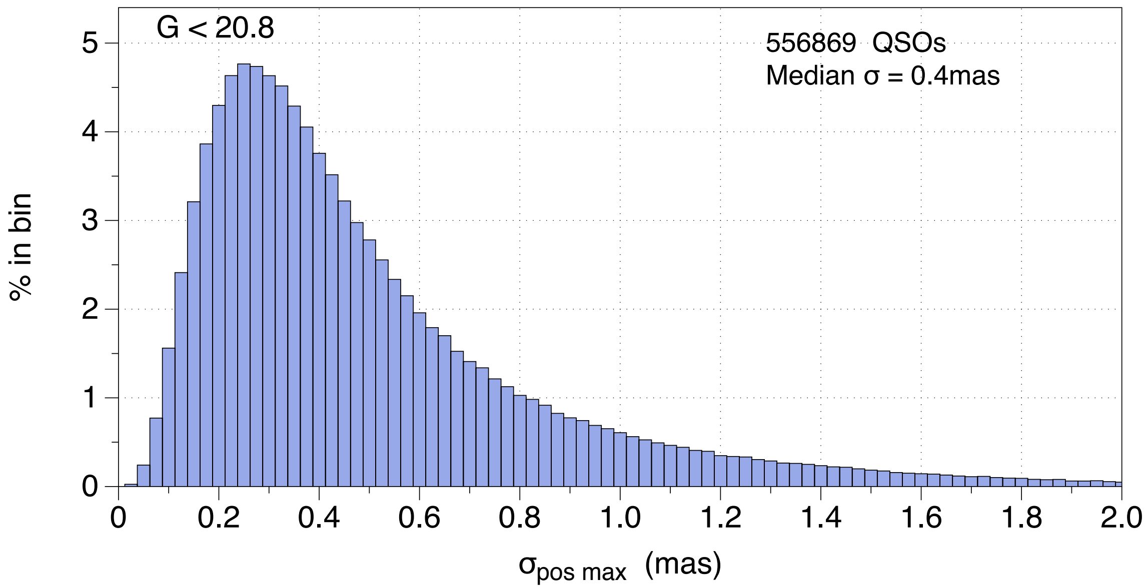
Gaia CRF2 : astrometric uncertainty G < 18.2

GCRF2

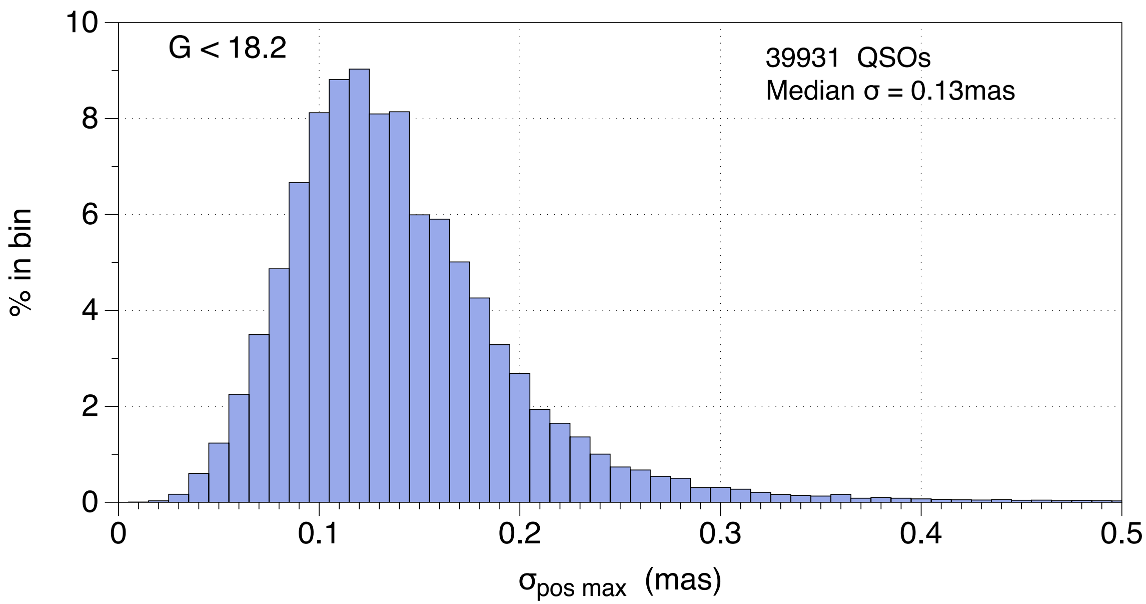


Gaia collaboration, DR2 , 2018

Gaia CRF2 – accuracy distribution



- very smooth distributions
- no outliers (removed !)
- $\approx 10,000 \ \sigma_{pos} < 100 \, \mu as$



- Excellent subset with 1 QSO/deg^2
- More to come with DR3 & DR4

Gaia collaboration, DR2 , 2018

Celestial Reference Frames today

Name	Epoch	N. sources	mag <	Precision	Comment
Lacaille	1760	397	7	10 $''$	
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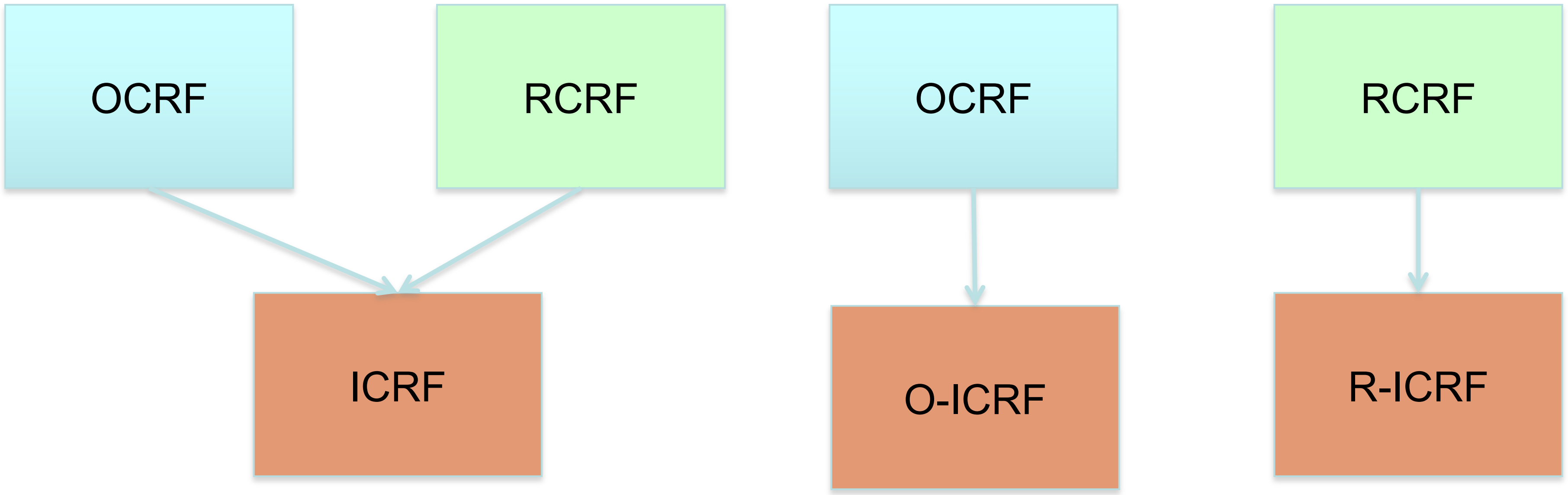
ICRF1 (radio)	1998	620	-	2 mas	ext. galact. sces.
ICRF2 (radio)	2009	3400	-	0.6 mas	
ICRF3 (radio)	2018	4500	-	0.23 mas	median uncert.
	2018	302	-	0.04 mas	def. sources
Gaia QSOs	2018	550 000	20.8	0.4 mas	Gaia-CRF2
Gaia $G < 18.2$	2018	40 000	18.2	0.13 mas	

ICRF after Gaia : to be discussed

- There are at least two options according as the alignment between optical and radio frames is achievable with the required accuracy
- OCRF = Optical Celestial Reference Frame → new versions shortly
- RCRF = Radio Celestial Reference Frame → no major revision soon



ICRF after Gaia : to be discussed

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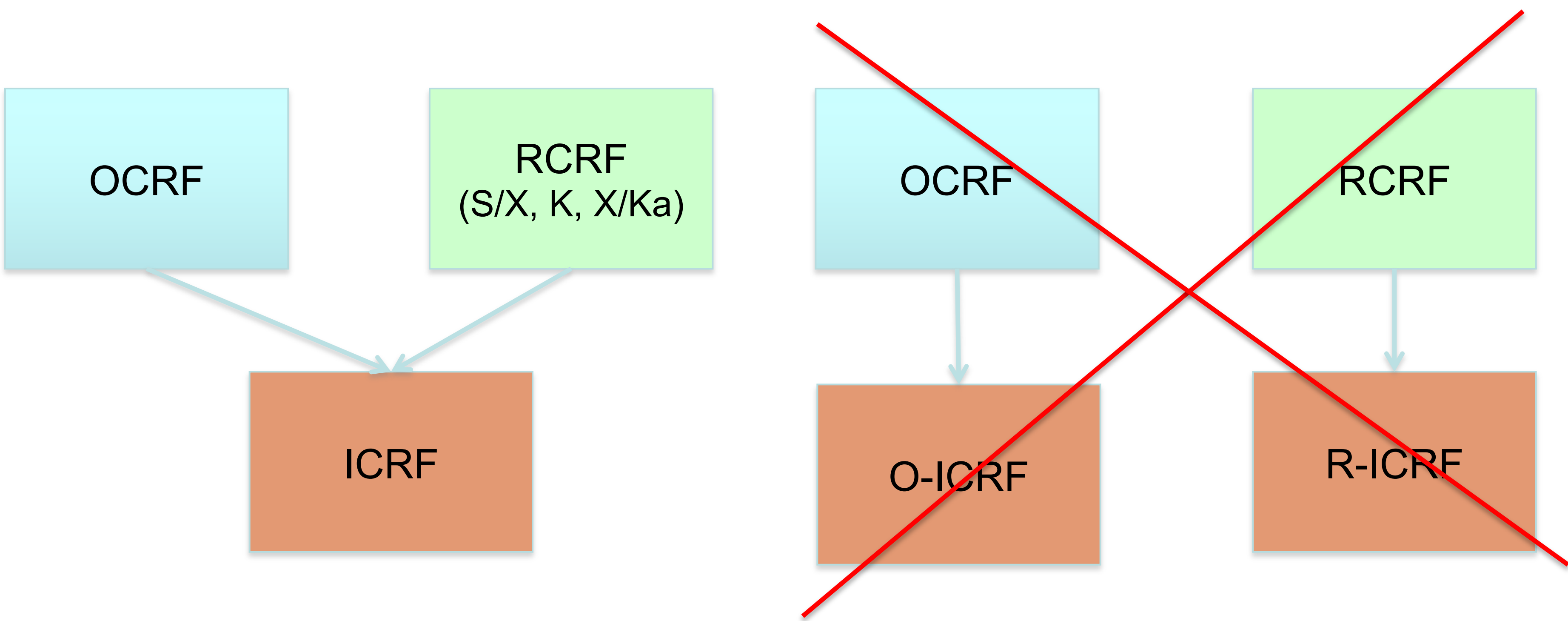

J. Kovalevsky : From astronomy to metrology

Gaia DPAC

Thanks for your attention