Towards an optical-radio frame tie using Gaia and VLBI

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Introduction

Tying Optical and Radio Celestial Frames

- **Motivation:** *Deep Space Navigation in Optical Era* requires an optical celestial reference frame to navigate.

- **Good news:** ESA's $1B Gaia mission has just released DR1 catalog (Gaia Collaboration, Brown et al. 2016) consisting of astrometry and photometry for over 1 billion sources brighter than magnitude 20.7

  bonus: positions/velocities of > 200K solar system objects!

- **Need to tie the existing radio-based frame to the new Gaia frame to better than 200 μas level for numerous astronomy applications.**

Introduction

Methods for Tying Optical and Radio Celestial Frames

- **Radio stars:** galactic stars that emit in radio, difficult to get down to 100 to 200 μas level.

  Lestrade et al. (1995): Tie Hipparcos to ICRF

  Fey, Bobltz, et al. (2006)

- **350 GHz astrometry using ALMA:** thermal emission from regular stars.

  Fomalont et al. (observing proposal)

- **Quasars:** measuring quasars detectable in both radio and optical thus integrating Gaia into radio, down to sub-mas level

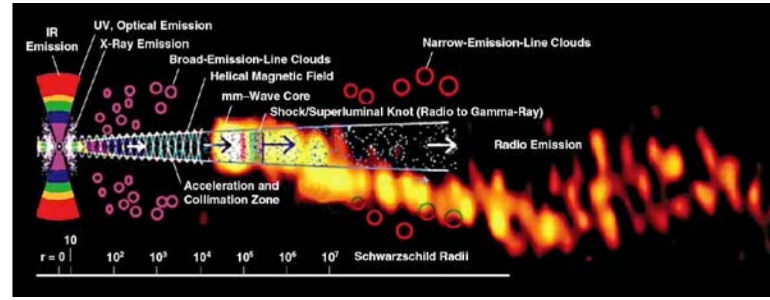
  Mignard et al. (in press): Gaia DR1 vs. ICRF2

  Petrov: http://astrogeo.org/petrov/discussion/vlbi_gaia/

  THIS CONTRIBUTION: S/X-bands and X/Ka-bands DSN campaigns (plus K-band not reported here)

Frame Tie Geometry

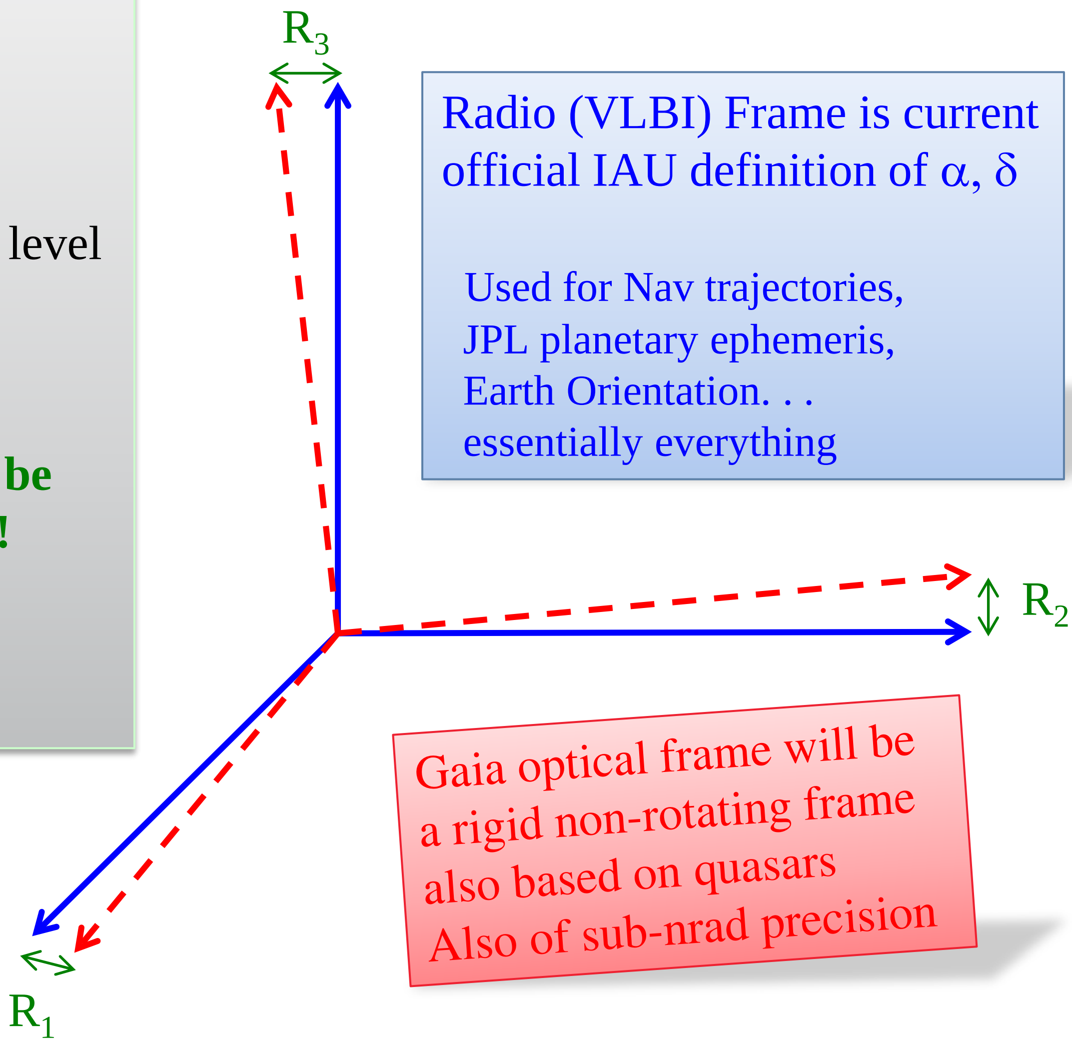
Tying Optical and Radio Celestial Frames



Frame tie task will determine 3 small rotations ($R_{1,2,3}$) between the individually rigid, non-rotating radio and optical frames to sub-nanoradian level

Allows seamless integration into united frame.
More than 1 billion objects will be integrated into common frame!!

Frames objects to < 0.5 nrad. want tie errors 10X smaller.



Radio (VLBI) Frame is current official IAU definition of α, δ

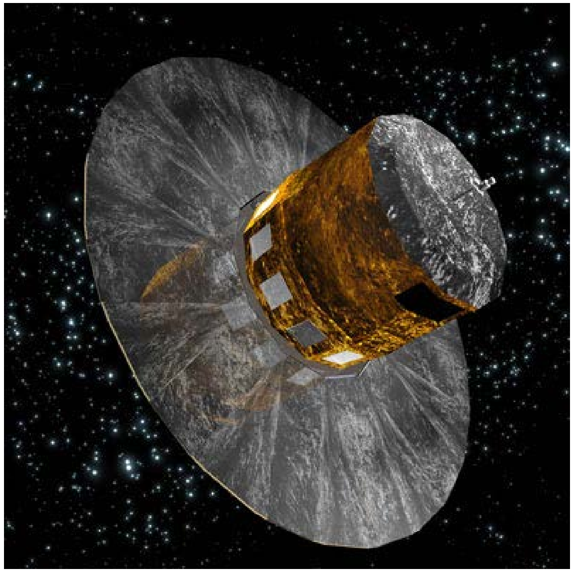
Used for Nav trajectories, JPL planetary ephemeris, Earth Orientation. . . essentially everything

Gaia optical frame will be a rigid non-rotating frame also based on quasars
Also of sub-nrad precision

Motivation and Background

Tying Optical and Radio Celestial Frames

- **VLBI enables precision navigation in the deep space:**
  - VLBI measures spacecraft angular position relative to radio reference frame (MGS, Odyssey, MRO, VEX, Ulysses, Cassini);
  - Critical for precision landing (i.e., MER, MSL, etc.);
  - Current ΔDOR accuracy is ~200 μas;
  - Radio frame at ~100 μas (troposphere, source structure).
- **Optical era in navigation is emerging:**
  - ESA's Gaia mission – astrometry for 10^9 objects to few μas;
  - Gaia will enable optometric navigation that could have the capabilities similar of better compared to radiometric tracking.
- **Urgency to continue:**
  - Gaia has already released DR1 catalog;
  - Need data at over-lapping times to minimize time-dependent errors;
  - Need to assess systematic errors and revise observation strategy before Gaia mission ends.



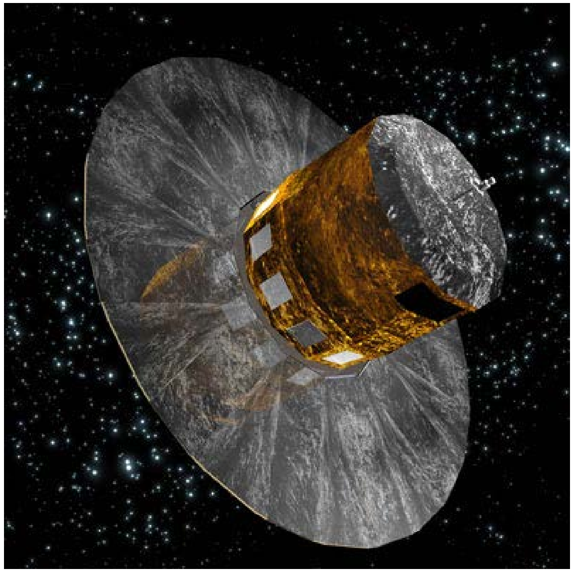
Gaia satellite @ Lagrange-2

- **JPL Ka-band capability provides world class resolution**
  - JPL uniquely pursuing Ka-band (9mm) VLBI: the highest resolution operational capability now in use, Earth based.
  - Ka-band's 4X resolution improvement resolve out extended structure, potential binary black holes, etc.

Gaia optical Astrometry Mission

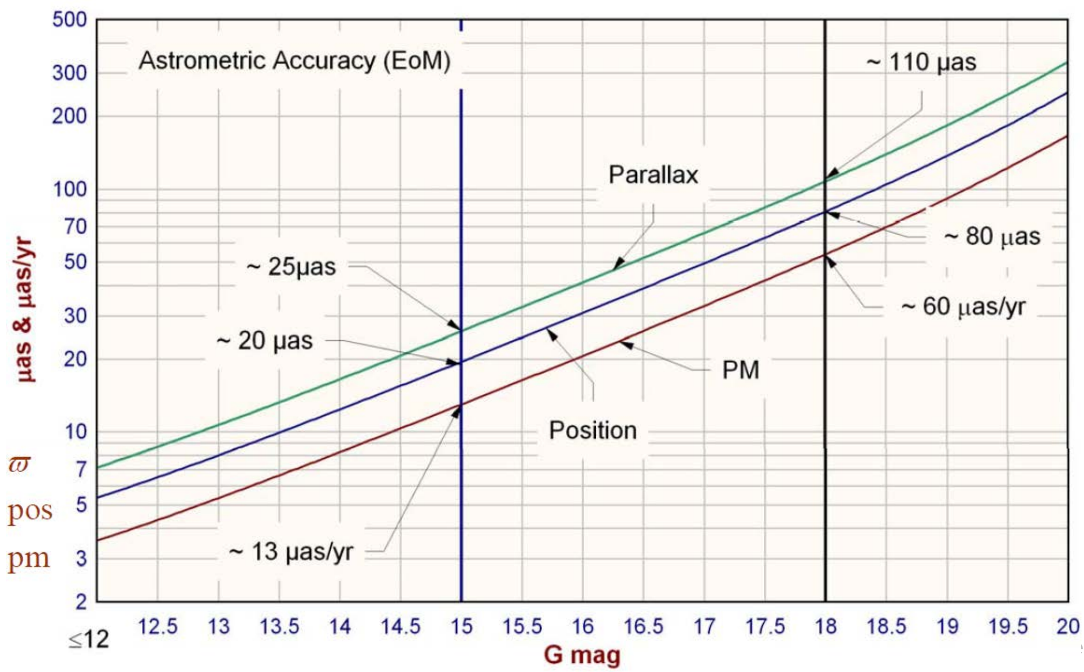
Tying Optical and Radio Celestial Frames

- **Astrometry & photometric survey to V = 20.7^m**
  - ~10^9 objects: stars, QSOs, solar system, galaxies.
  - Need to tie to existing radio frame so that this wealth of objects can be of use to JPL
- **Gaia Celestial Reference Frame (GCRF):**
  - Optically bright objects (V< 18mag) give best precision
  - First release Gaia astrometric catalog DR1 Sep 2016, after 14 months.



Credit: F. Mignard (2013)

Anticipated precision of Gaia catalogue



Gaia DR1:

~0.3 mas in positions and parallaxes for 2 million brightest stars

~10 mas for rest of the stars

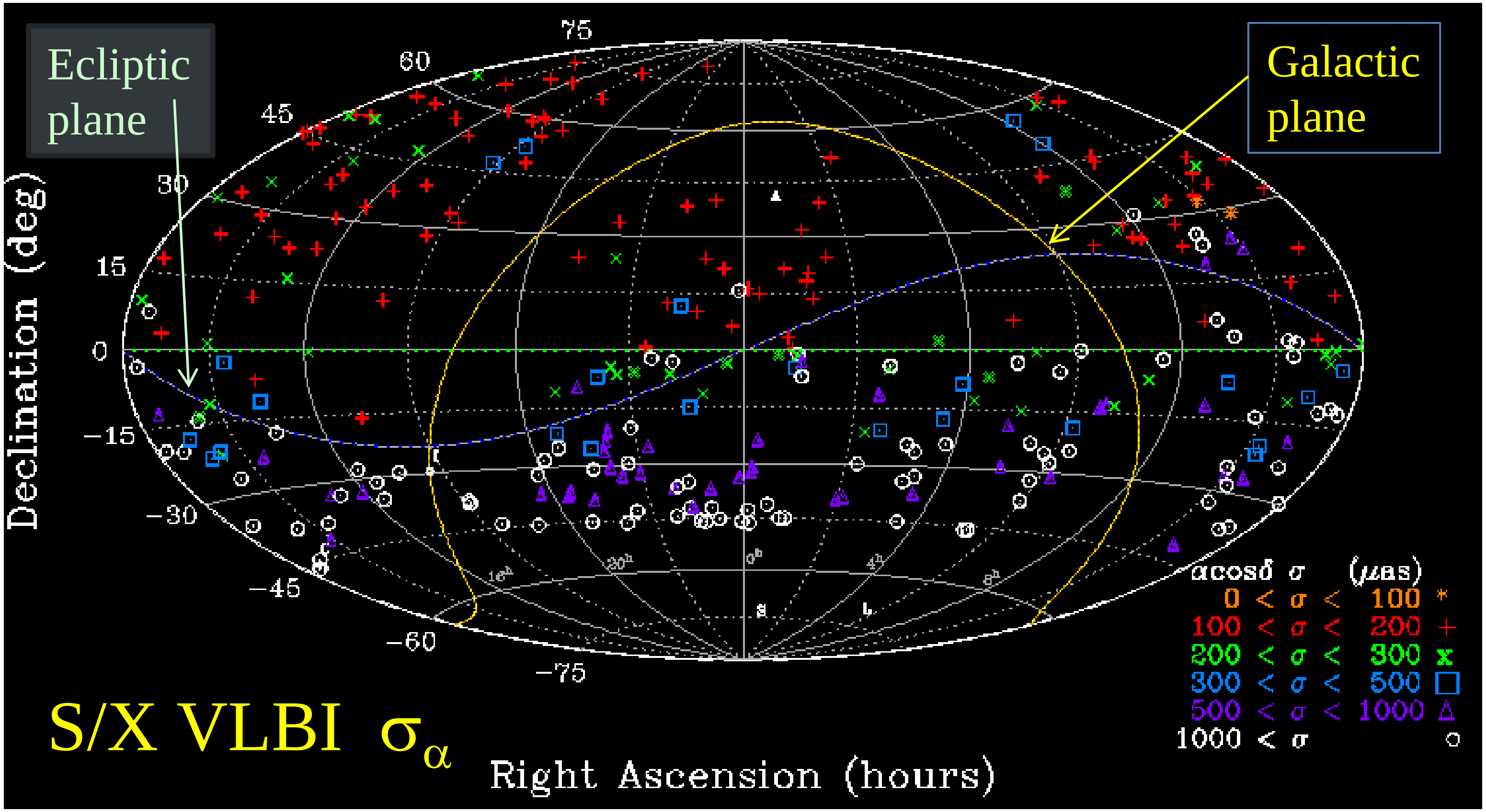
Tying optical and Radio Celestial Frames

S/X DSN campaign

- **Need to maximize number of optically bright quasars also detectable by VLBI in the radio**
  - **ICRF2-Gaia transfer sources:** only 195 existing VLBI sources (6% of ICRF2) optically bright, compact enough for good tie (Le Bail et al. 2016)
  - **Our Goal:** add ~300 frame tie candidate non-ICRF2 sources:
    - 119 well vetted northern sources studied with EVN (Bourda et al. 2010, 2011, 2014)
    - rest of sources, no so well vetted, also includes southern sources
- **Larger set of sources provides for**
  - Attrition as systematic errors uncovered.
  - Statistics to explore zonal errors (Y_{lm}), etc.
- **Improved DSN geometry thanks to collaborators in the South Hemisphere: Hobart (Australia) and HartRAO (S. Africa)**

Initial VLBI S/X-bands Results

Tying Optical and Radio Celestial Frames



- **Collaboration with S. Africa and Australia to extend DSN reach to SPC**
- **Detected 297 sources. 90 TB VLBI data! Achieved 400 µas precision.**

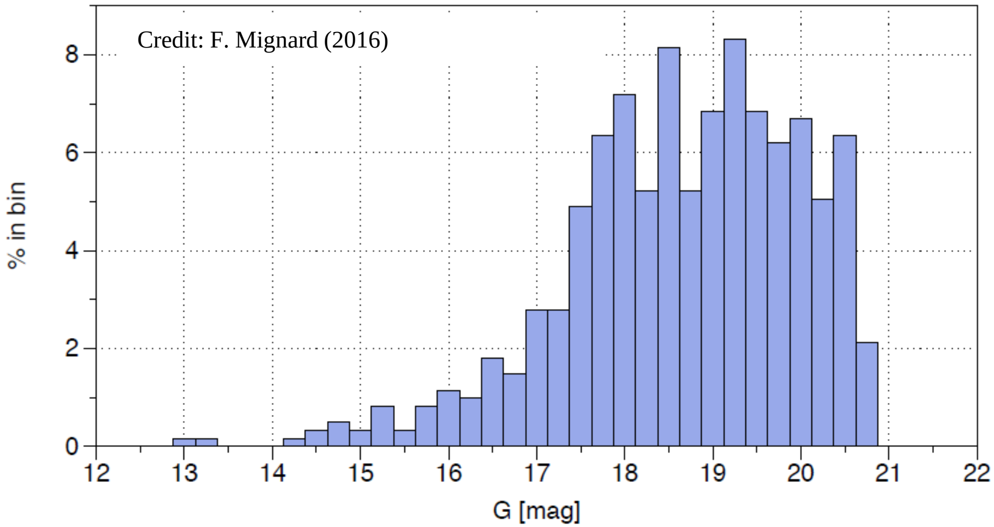
On track for 3 year goal: 4X more data ⟶ 200 µas precision

Tying optical and Radio Celestial Frames

X/Ka DSN campaign

- **Goal:** ~150 frame tie candidate bright sources for VLBI Ka-band radio observations
  - Detected 674 sources with better than 100 µas precision (VCS, Petrov, etc.) with only 50K group delay/phase rate observations.
  - 138 sources detected in south polar cap: 2/3 non-ICRF2, 26 ICRF2 defining sources.

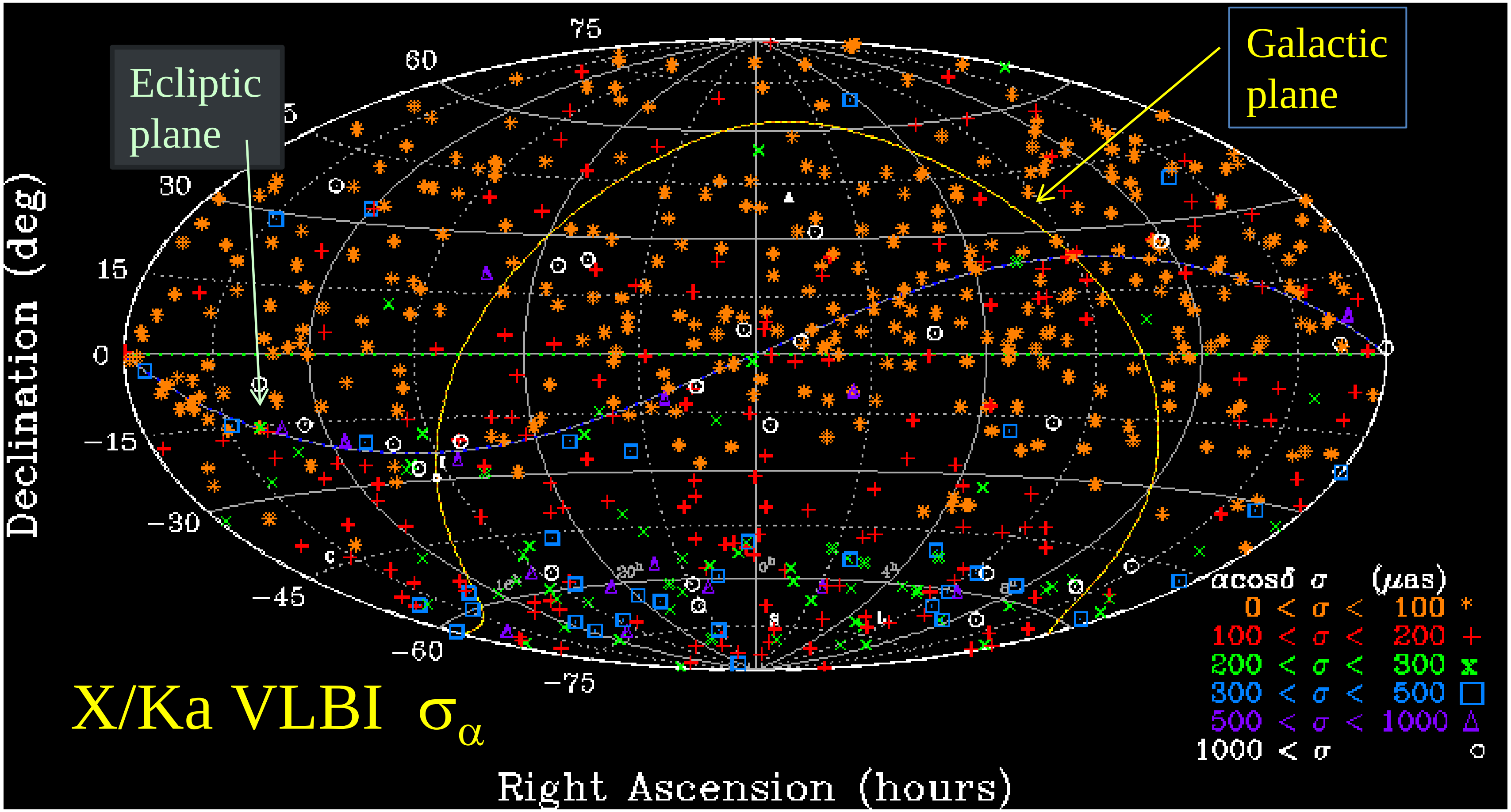
412 out of 674 sources detected by Gaia DR1!!
~25% or ~150 sources optically bright for Gaia



- **Independent check for ICRF2 S/X tie to Gaia but with less source structure and core shift.**

VLBI X/Ka-bands Results

Tying Optical and Radio Celestial Frames



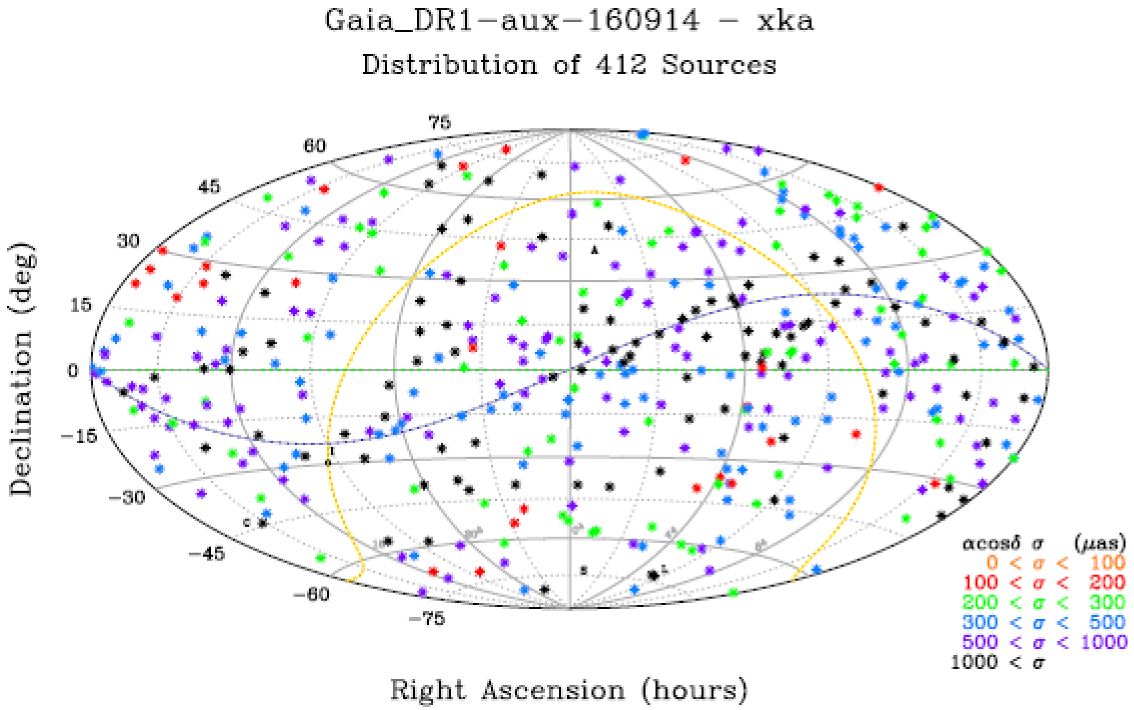
- **Collaboration with Argentina and ESA to extend DSN reach to SPC**
- **Detected 674 sources. 100 sessions, 50K group delay/phase rate obs**

  Better than 100 μas precision

Tying optical and Radio Celestial Frames

Gaia_DR1-aux vs. X/Ka DSN

- **Tying to Gaia's optical frame using Gaia_DR1-aux AUXILIARY QUASAR POSITION (no proper motions, about 2200 sources in ICRF2) aprox 500 μas precision(Gaia archive** http://gea.esac.esa.int/archive/)
  - **412 common sources (-7 outliers), including 184 ICRF2 defining sources**



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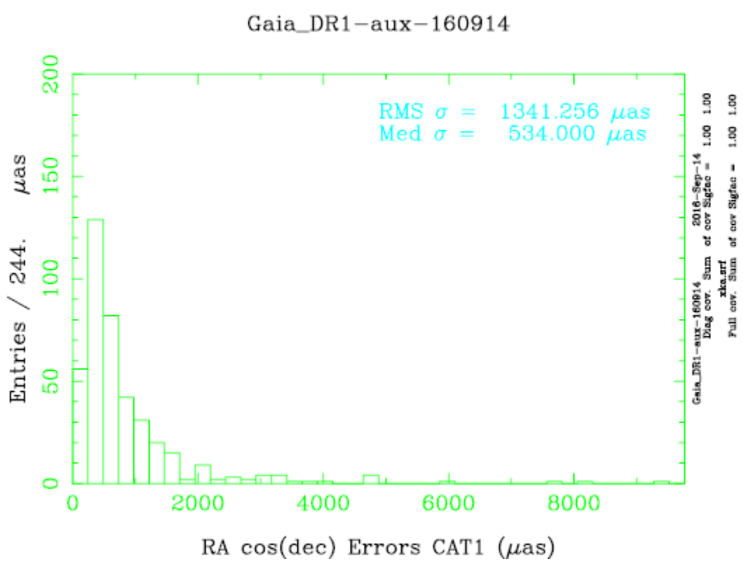
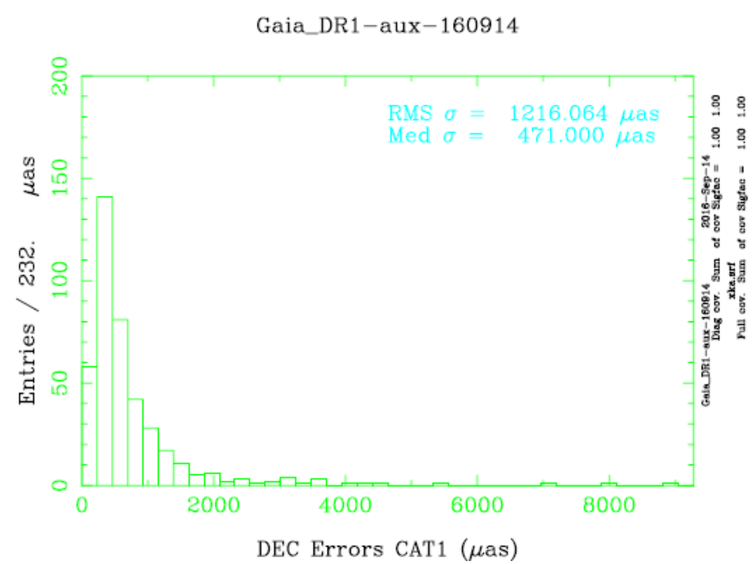
Gaia_DR1-aux median RA sigma 534 μas

Gaia_DR1-aux median Dec sigma 471 μas





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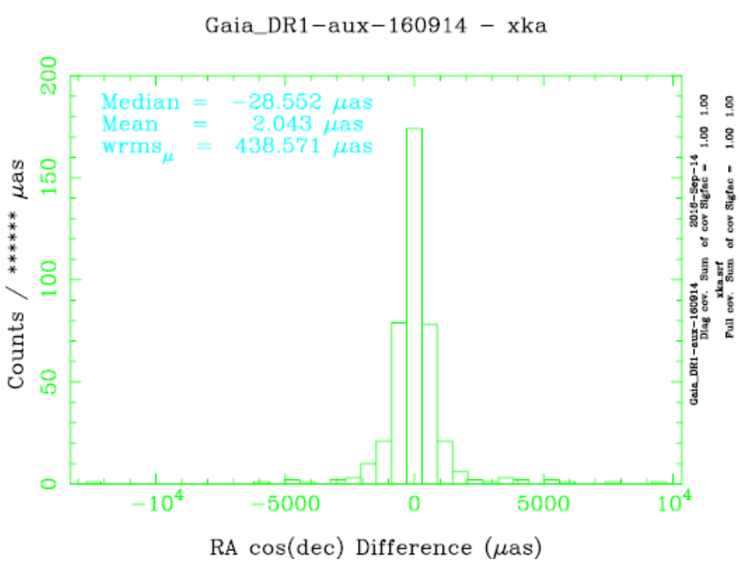
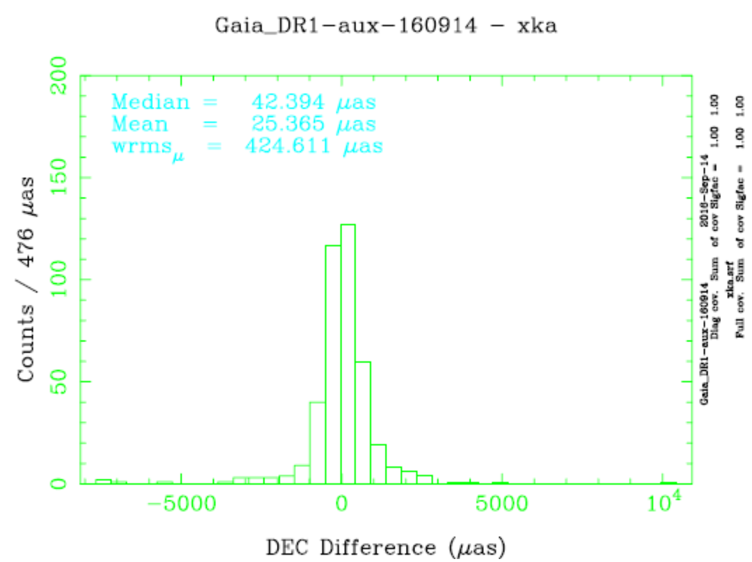
RA cosDec wRMS diff 439 µas, mean 2 µas

Dec wRMS diff 425 µas, mean 25 µas





Tying optical and Radio Celestial Frames

Gaia_DR1-aux vs. X/Ka DSN

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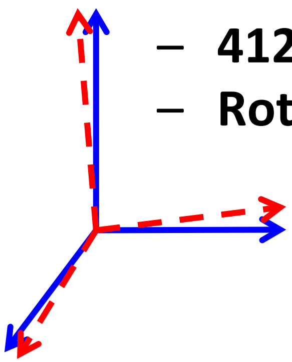


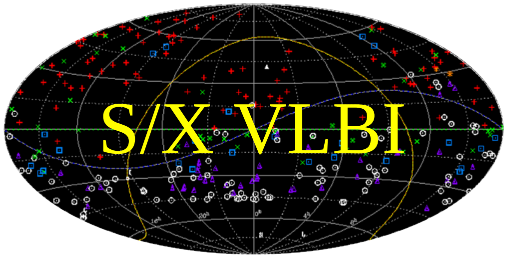
- **412 common sources (-7 outliers), including 184 ICRF2 defining sources**
- **Rotational alignment:**

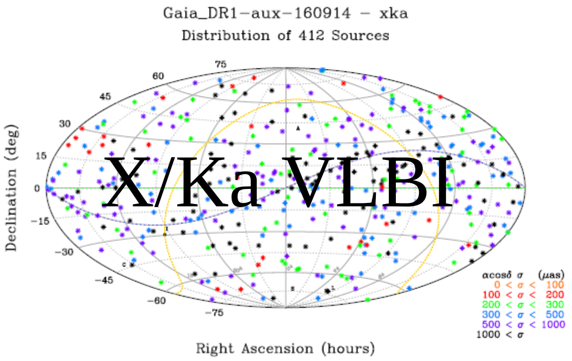
Rotation about X-axis = 71 +- 25 µas
Rotation about Y-axis = 22 22 µas
Rotation about Z-axis = 27 24 µas

- **XKA Rotational alignment at 25 µas level.**
- **Very few outliers so XKa common detection with Gaia is a good indicator of astrometric quality.**
- **412 X/Ka sources vs. ~2000 S/X in ICRF2.**
- **X/Ka uses only 50K observations, ICRF2 6.5 million observations.**
- **To improve need to control systematics with e.g. inclusion of more Ka antennas in the network.**

Summary

Tying Optical and Radio Celestial Frames





- **Goal:** Tie of optical and radio celestial frames for deep space navigation and astronomical applications.
- **Advantage:** use of independent radio catalogs realized in different radio frequencies, with different antennas, processing analysis, etc.
- **Roadmap:** increase number of sources in common between optical and radio catalogs: find radio sources optically bright for Gaia
  - S/X bands: added ~300 frame tie candidate non-ICRF2 sources
  - X/Ka bands: 412 out of 674 sources detected by Gaia DR1-aux
  - K band: similar efforts not reported here
- **Preliminary results: Gaia_DR1-aux alignment vs. X/Ka DSN**
  - X/Ka rotation at 25 µas level precision. Accuracy systematic limited
  - X/Ka very efficient: 412 X/Ka sources vs. ~2000 S/X in ICRF2
  - X/Ka very efficient: X/Ka uses only 50K observations, ICRF2 6.5M
  - Control of systematics including more sources, antennas, etc.

backup

Science Bonus: Binary Black Holes?

Tying Optical and Radio Celestial Frames

- **If all objects are perfect point sources at infinity frame tie will be limited by SNR**

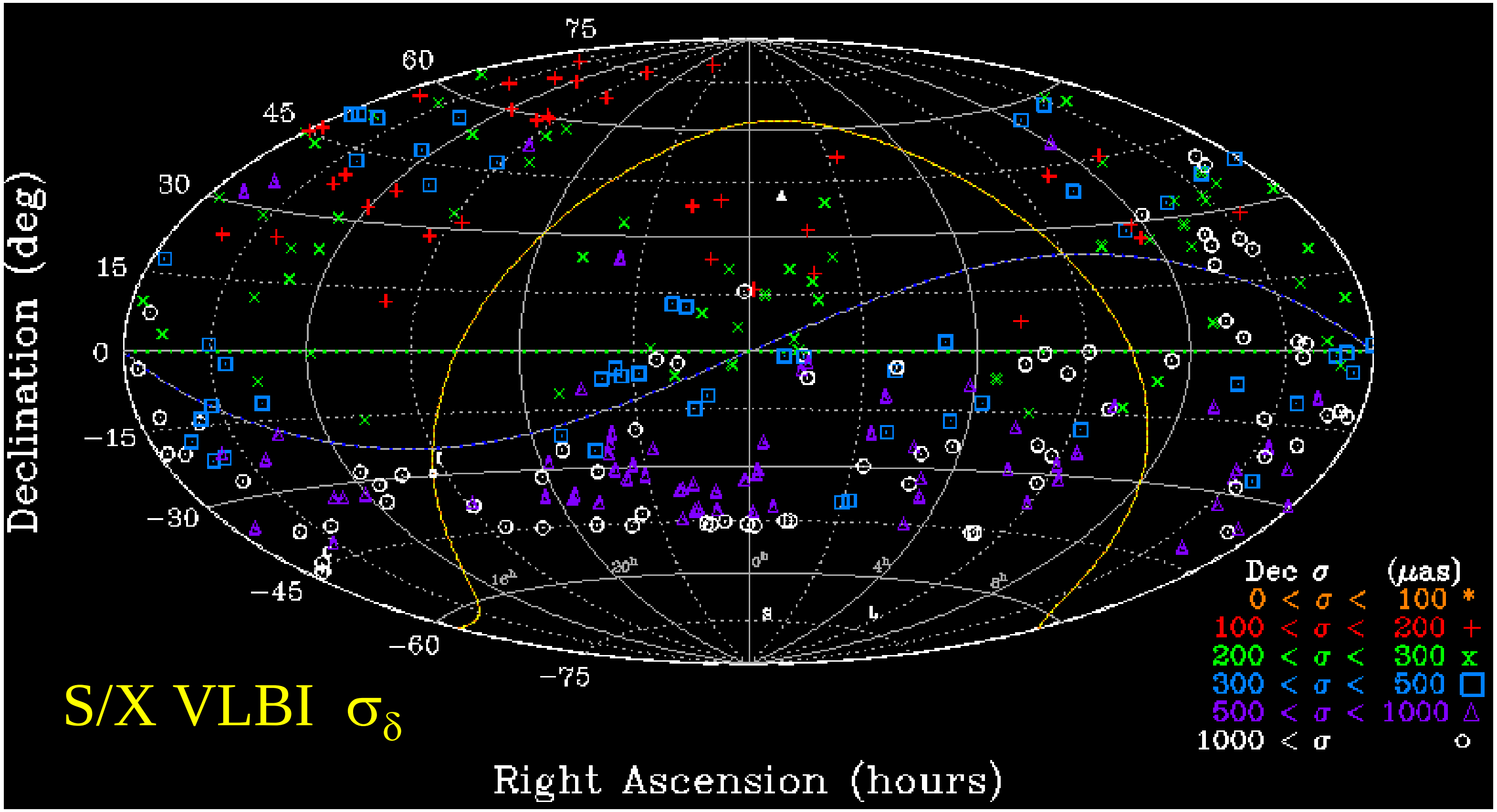
- **However, super-massiveBinary Black Holes at center of quasars may causes positions to oscillate (e.g. J. Roland, Obs. Paris).**
  How frequent? Candidate: PKS 1302-102

- **If frequent, bad for individual frame tie objects @ ~1 nrad level.**

- **Winning the lottery for science research especially in light of advanced LIGO discoveries and gravitational wave research.**

Initial Radio (VLBI) Results

Tying Optical and Radio Celestial Frames



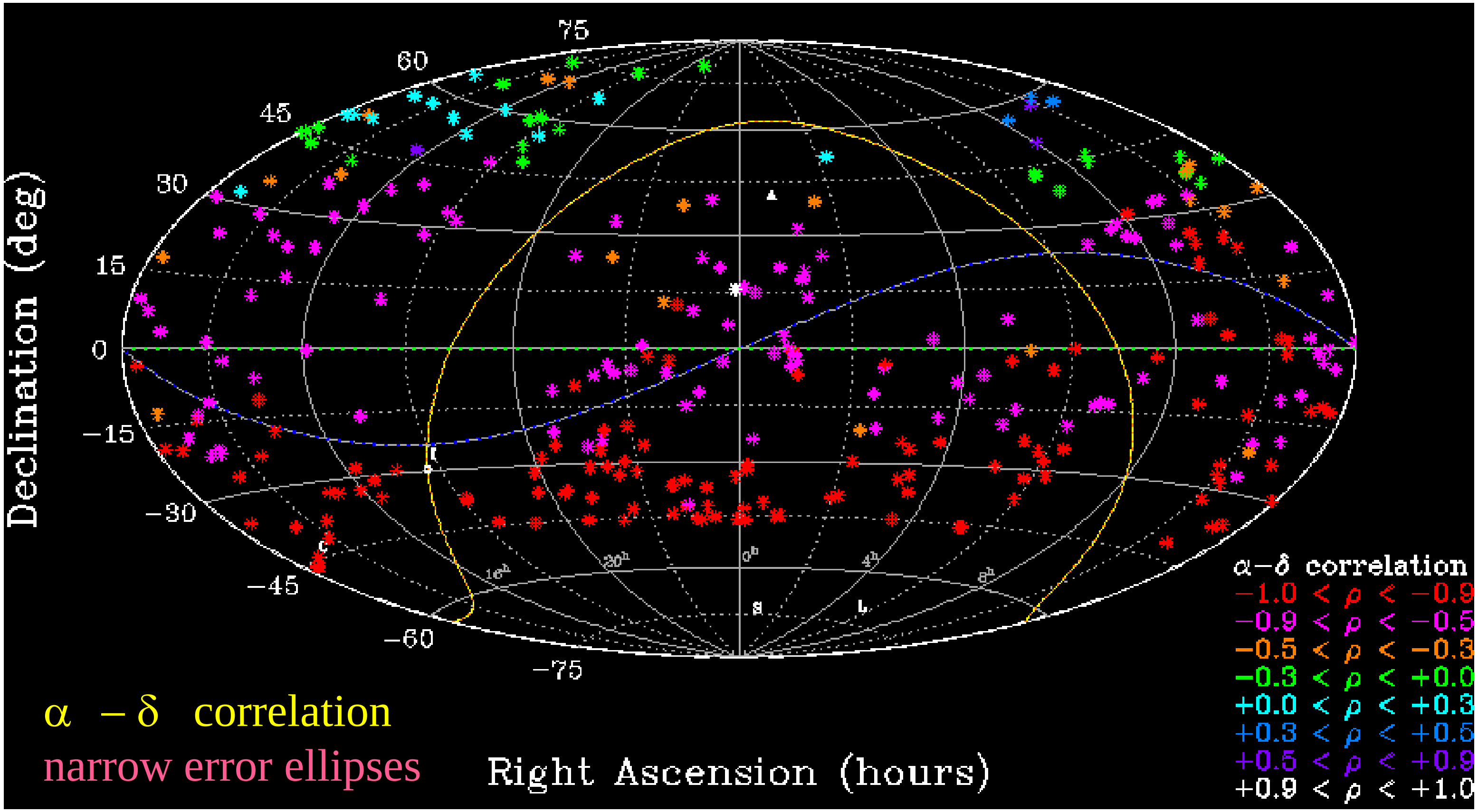
- **Declination precision weaker as one moves south.**

  Need more observations.

  Need 2nd southern antenna (S. Africa, Argentina)

Initial Radio (VLBI) Results

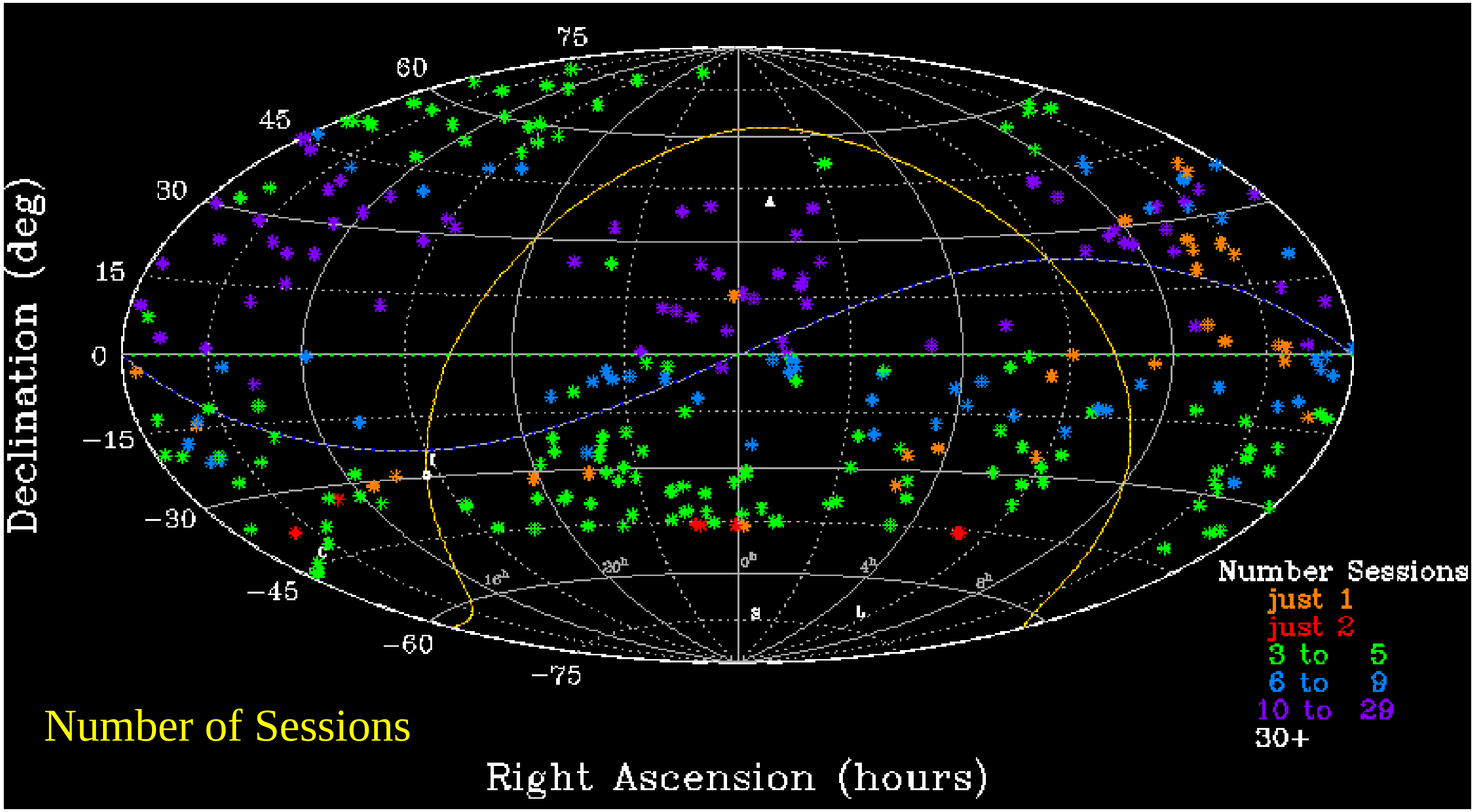
Tying Optical and Radio Celestial Frames



- **Single North-South baseline leads to high RA-Dec correlations i.e. long narrow error ellipses**
- **Building South Africa and Argentina collaborations to resolve**

Initial Radio (VLBI) Results

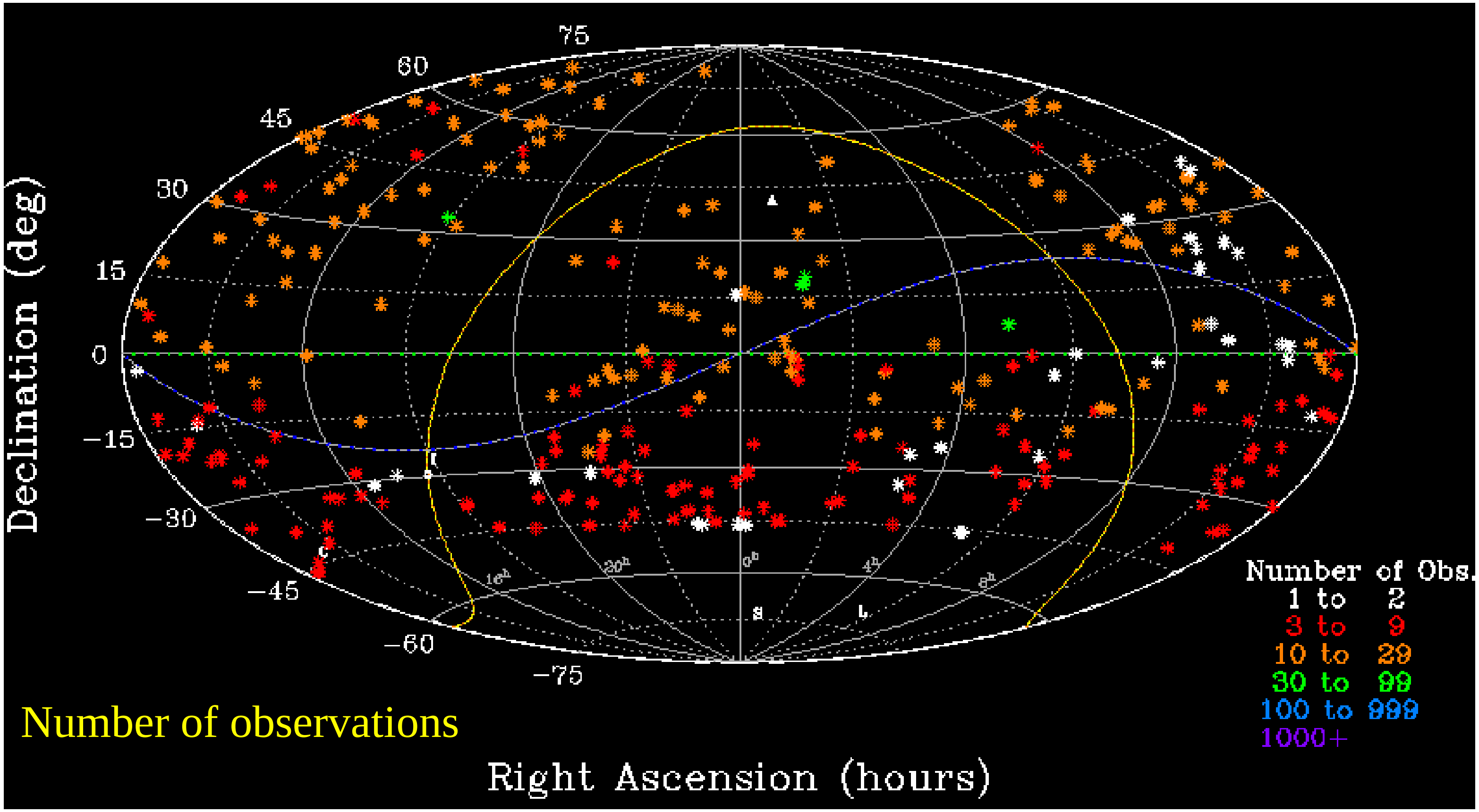
Tying Optical and Radio Celestial Frames



- **Number of sessions in mid-north augmented by archive data**
- **Mid–south (δ = 0 to -30) helped by overlap of two baselines.**
- **Far south/north 1 baseline; need S. Africa, Argentina collaborators**

Initial Radio (VLBI) Results

Tying Optical and Radio Celestial Frames



- **Number of observations in north augmented by archive data**
- **Mid–Declinations (δ +40 to -30) helped by overlap of two baselines.**
- **Far south: 1 baseline; need South Africa, Argentina collaborators**