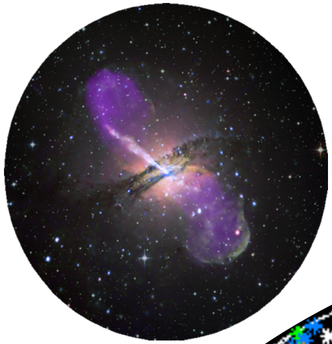
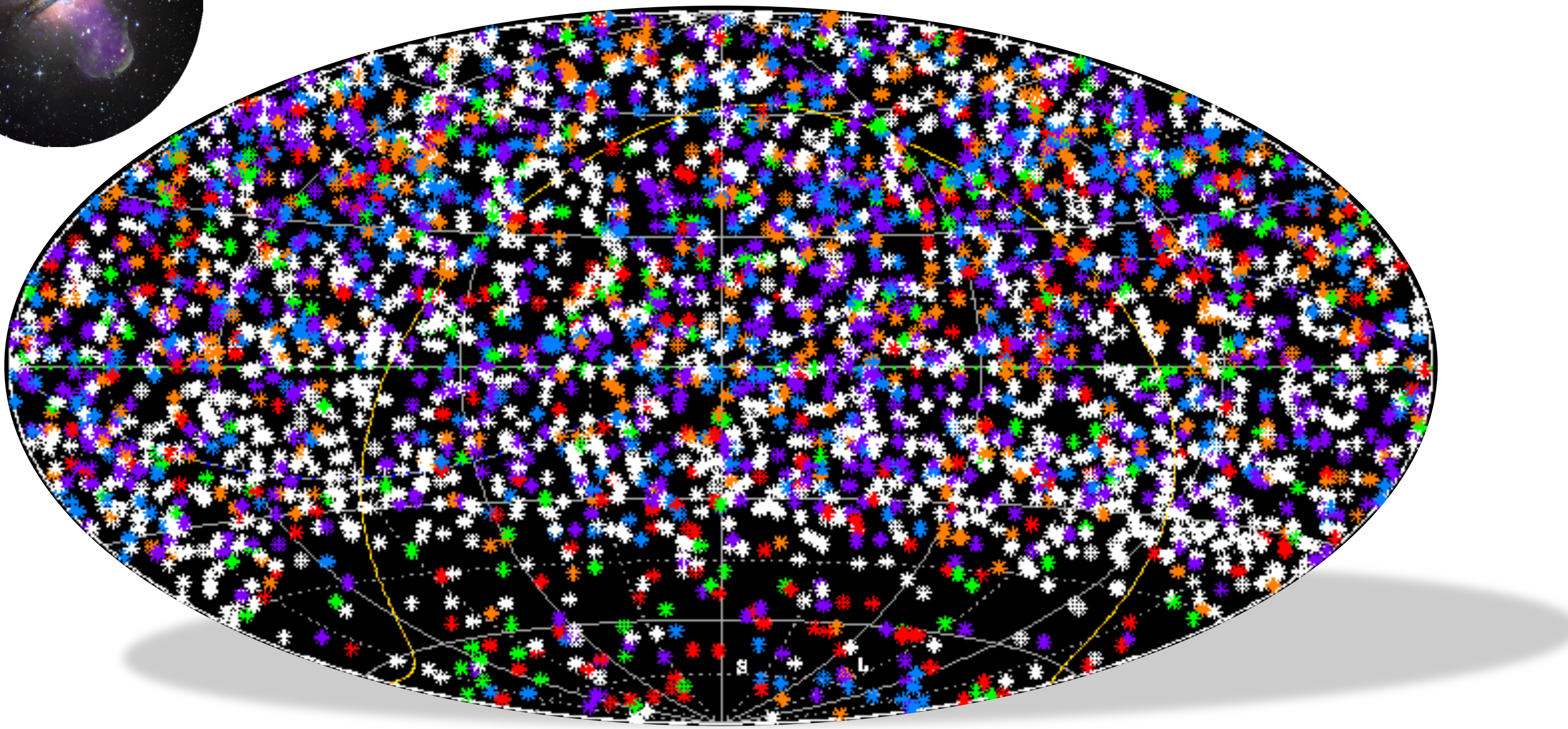


The Radio-based ICRF: Multi-wavelength progress



Christopher S. Jacobs, IAU ICRF-3 working group chair
on behalf of the ICRF-3 working group

10 July 2015

ICRF-3 working group members

- Felicitas Arias, France
- David Boboltz, USA
- Johannes Boehm, Austria
- Sergei Bolotin, USA
- Geraldine Bourda, France
- Patrick Charlot, France
- Aletha de Witt, South Africa
- Alan Fey, USA
- Ralph Gaume, USA
- David Gordon, USA
- Robert Heinkelmann, Germany
- Christopher Jacobs, USA
- Sebastien Lambert, France
- Chopo Ma, USA
- Zinovy Malkin, Russia
- Axel Nothnagel, Germany
- Manuela Seitz, Germany
- Elena Skurikhina, Russia
- Jean Souchay, France
- Oleg Titov, Australia

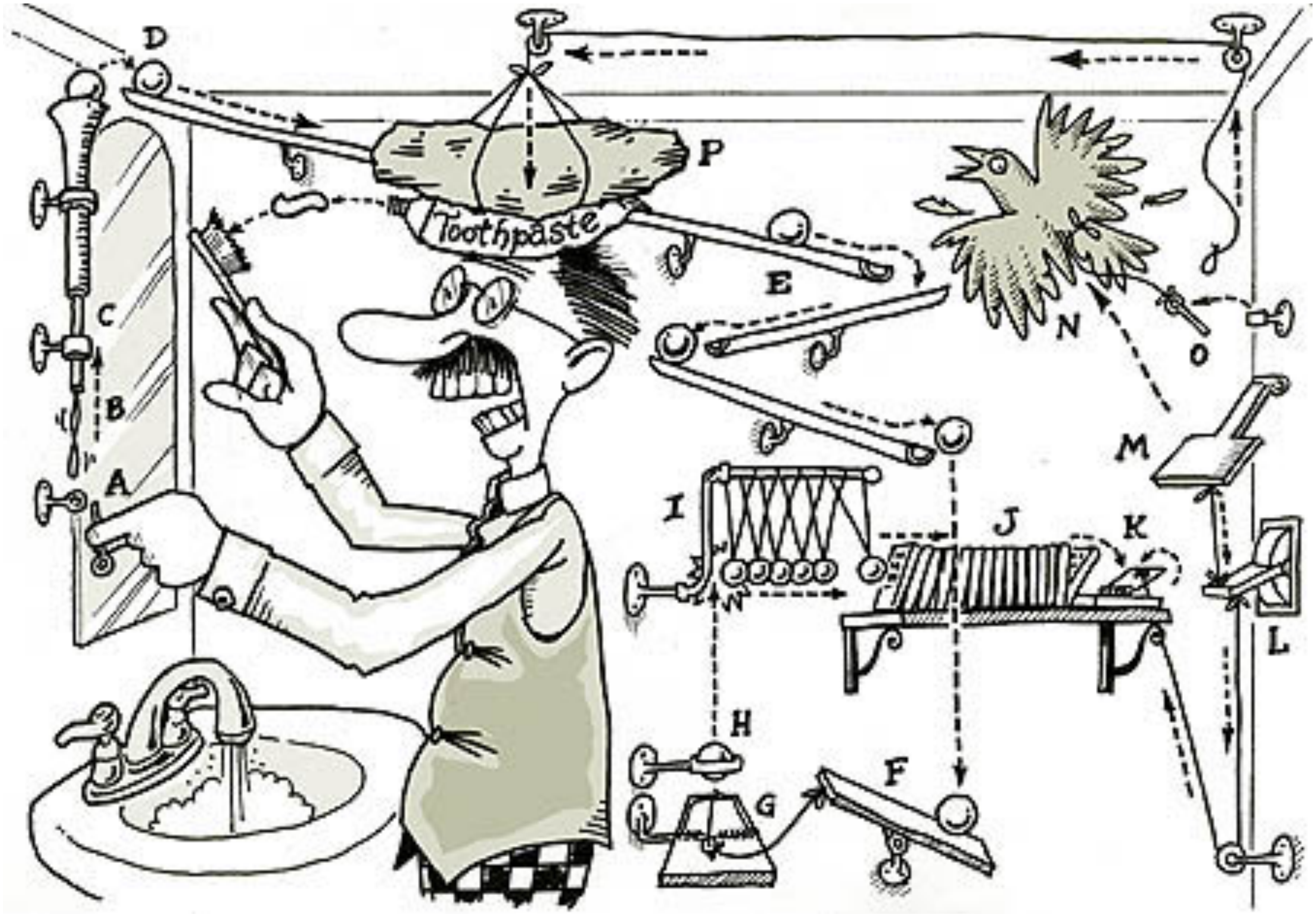
http://www.iau.org/science/scientific_bodies/working_groups/192/members/

Summary of ICRF-3 goals:

- Improving **VLBA Cal Survey's** 2000+ positions
  → More uniform precision for all sources
- Improving **southern observations**
  → More uniform spatial coverage
- Improving number, accuracy, and southern coverage of **high frequency frames** 24, 32, 43? GHz (K, X/Ka, Q?)
  → Improved frequency coverage

- ICRF-3 completed by **Aug 2018** **in time for** comparisons & alignment with **Gaia** optical frame
- Competitive precision with Gaia ~ 70 μas (1-sigma RA, Dec)
- Improving set of **optical-radio frame tie** sources for Gaia

How Does VLBI Work? It's Simple ;-)

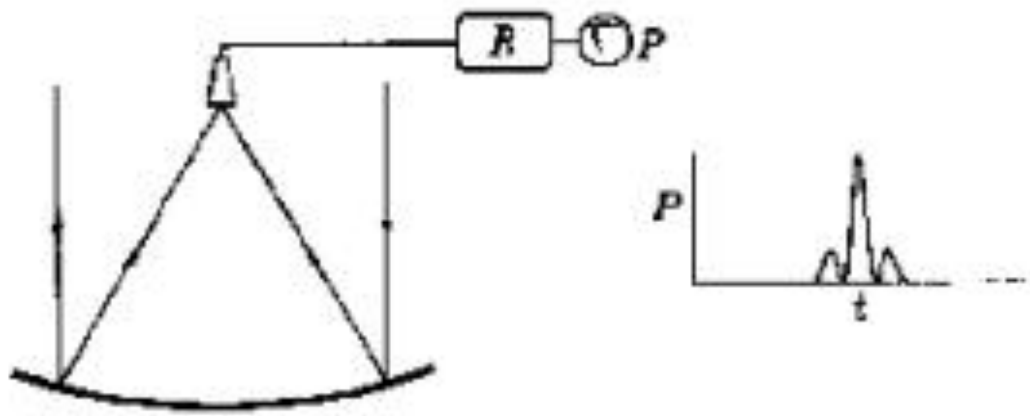


Cartoon credit: Rube Goldberg

Figure: www.vedicsciences.net/intelligent/rube-goldberg.jpg

Antennas are Mechanical Arrays

Single Large Dish is an "array" of panels aligned mechanically. Note side lobes.



beam

Imagine removing inner panels, then beam pattern changes, sidelobes rise, but center lobe still has high resolution ~ wavelength / D

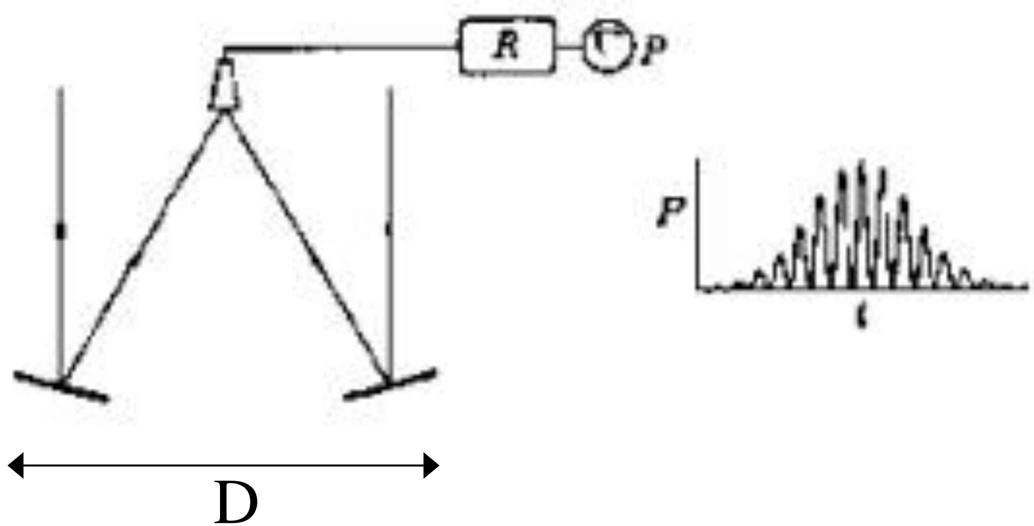
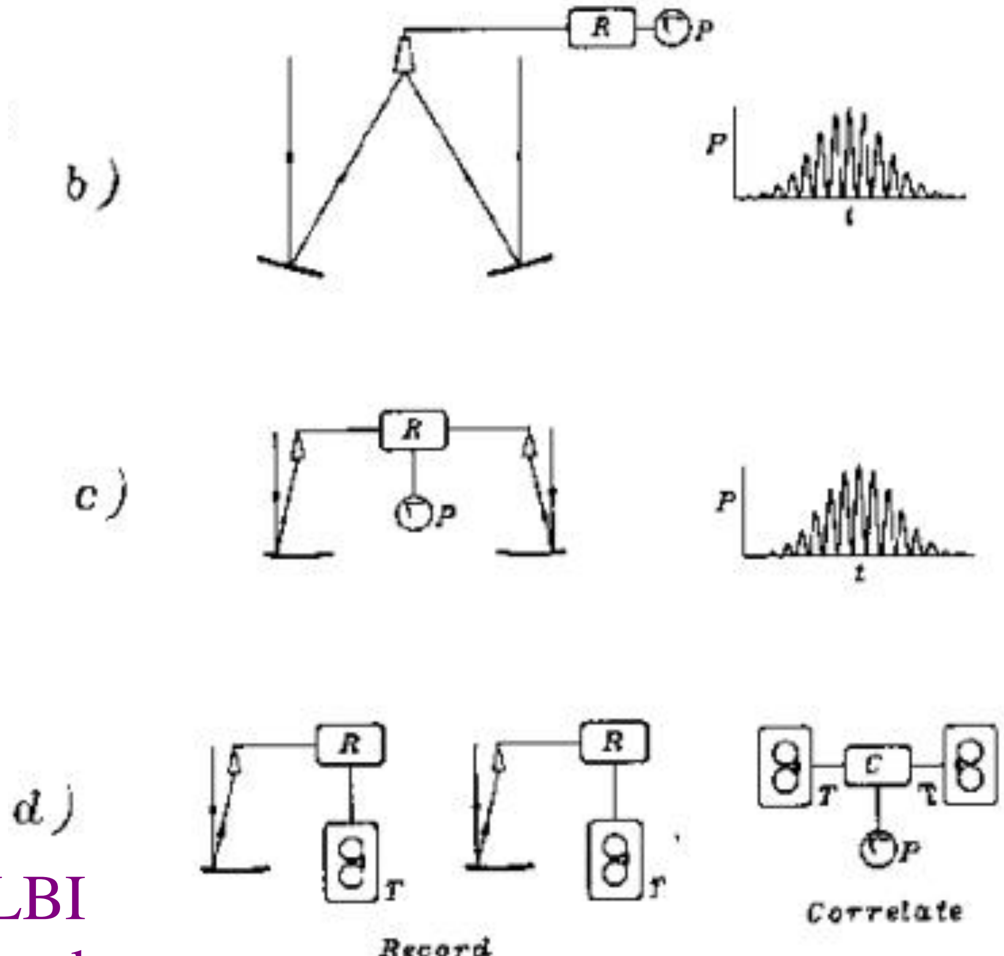


Figure credit: H. Gush

Mechanical → electrical alignment → VLBI

Two segments
of antenna



"Fringes"

Two separate
antennas with
Electrical
Connection

Same fringes
as b).

Unconnected
Antennas = VLBI
Time tag data and
combine signals later at correlator

Same fringes
as b).

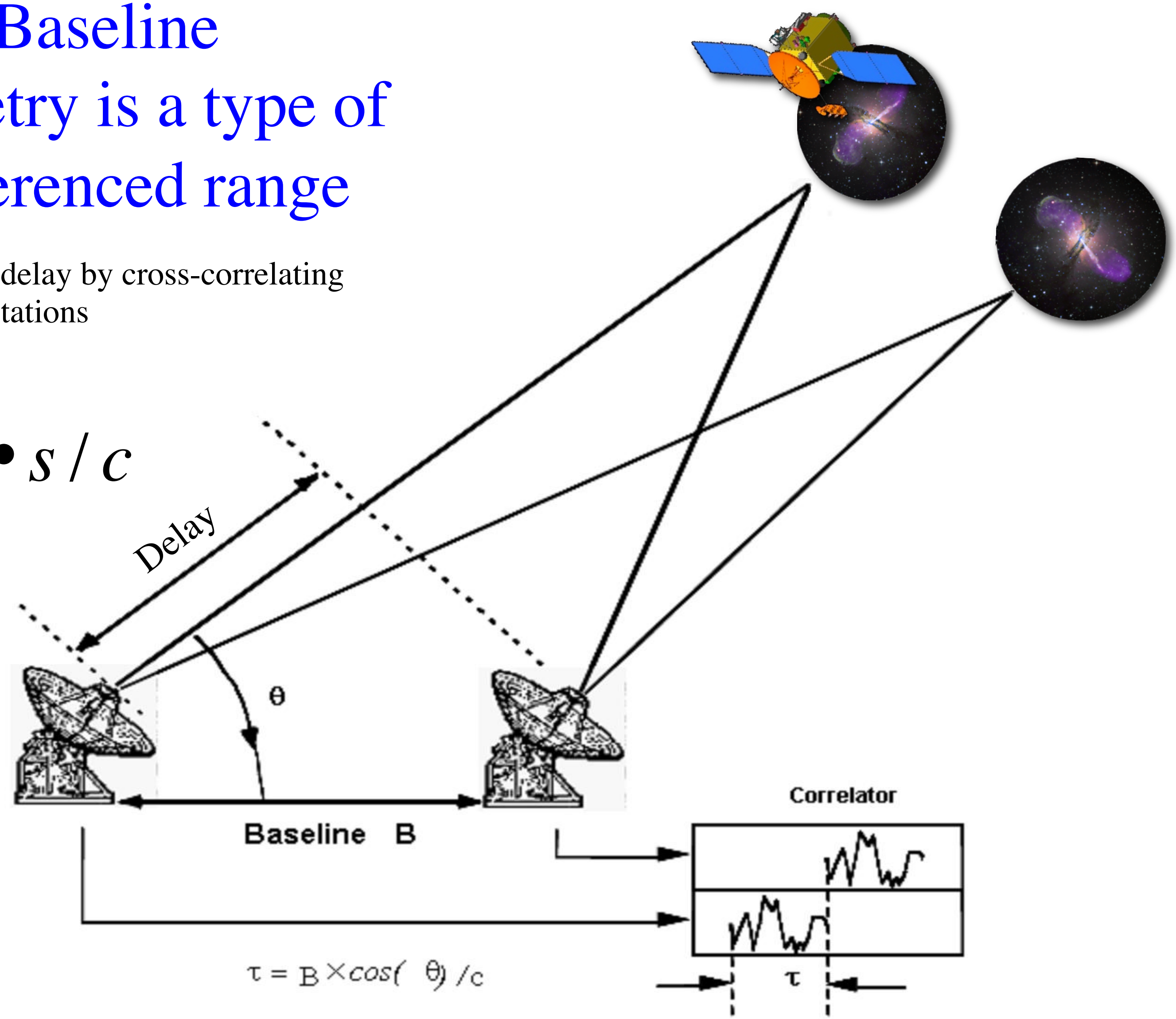
Figure credit: H. Gush

VLBI Delay: $\tau = B \bullet s / c$

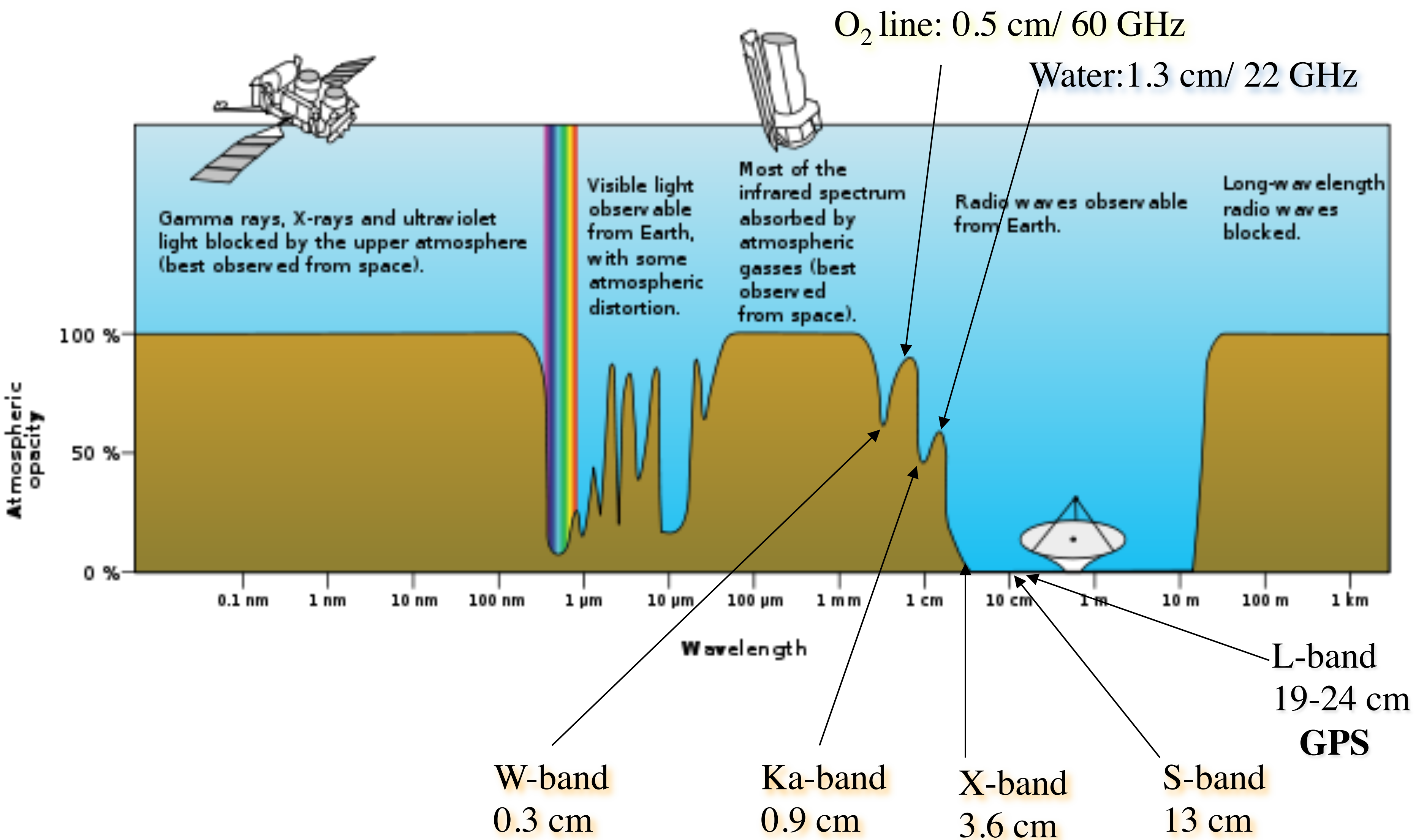
Very Long Baseline Interferometry is a type of station differenced range

- Measures geometric delay by cross-correlating signal from two (2) stations

$$\tau = B \bullet s / c$$



Why observe in Radio? Deep 'Window'



Credit: NASA; http://en.wikipedia.org/wiki/Radio_window

Why observe in Radio? Resolution

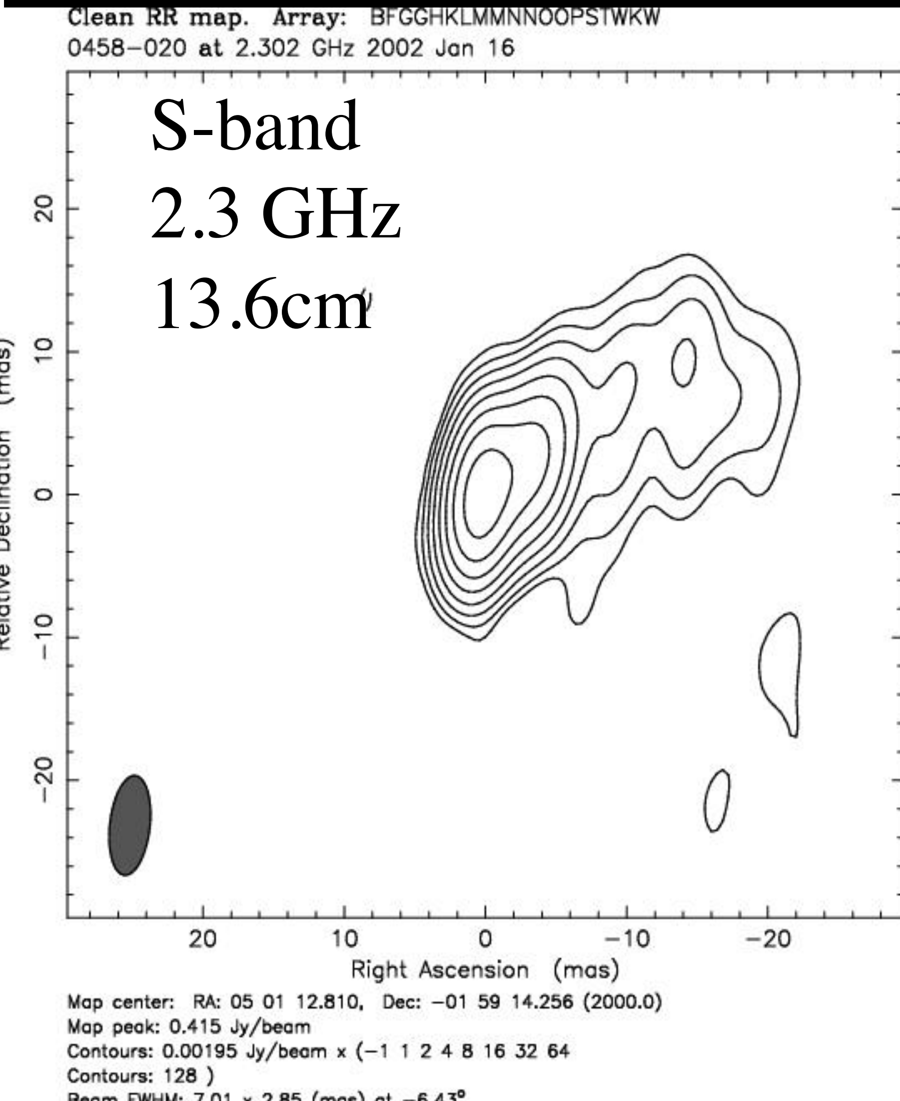
- Resolution of diffraction-limited telescope:
  Wavelength / Diameter
  example: Gaia 1.5 m mirrors
  Wavelength 0.5 microns
  Resolution or order 50 mas

- Resolution for an interferometer
  Wavelength / Baseline
  Wavelengths for Celestial Frames 0.9 to 3.6 cm
  Baselines up to 10,000 km
  Resolution = 1 to 4 nanoradians = 0.2 to 0.8 mas

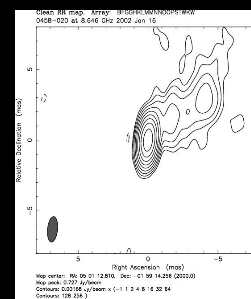
- Radio has 60 to 250 times better resolution.

Source Structure vs. Frequency (absolute scale)

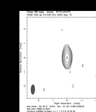
S-band
2.3 GHz
13.6cm



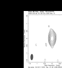
X-band
8.6 GHz
3.6cm



K-band
24 GHz
1.2cm



Q-band
43 GHz
0.7cm

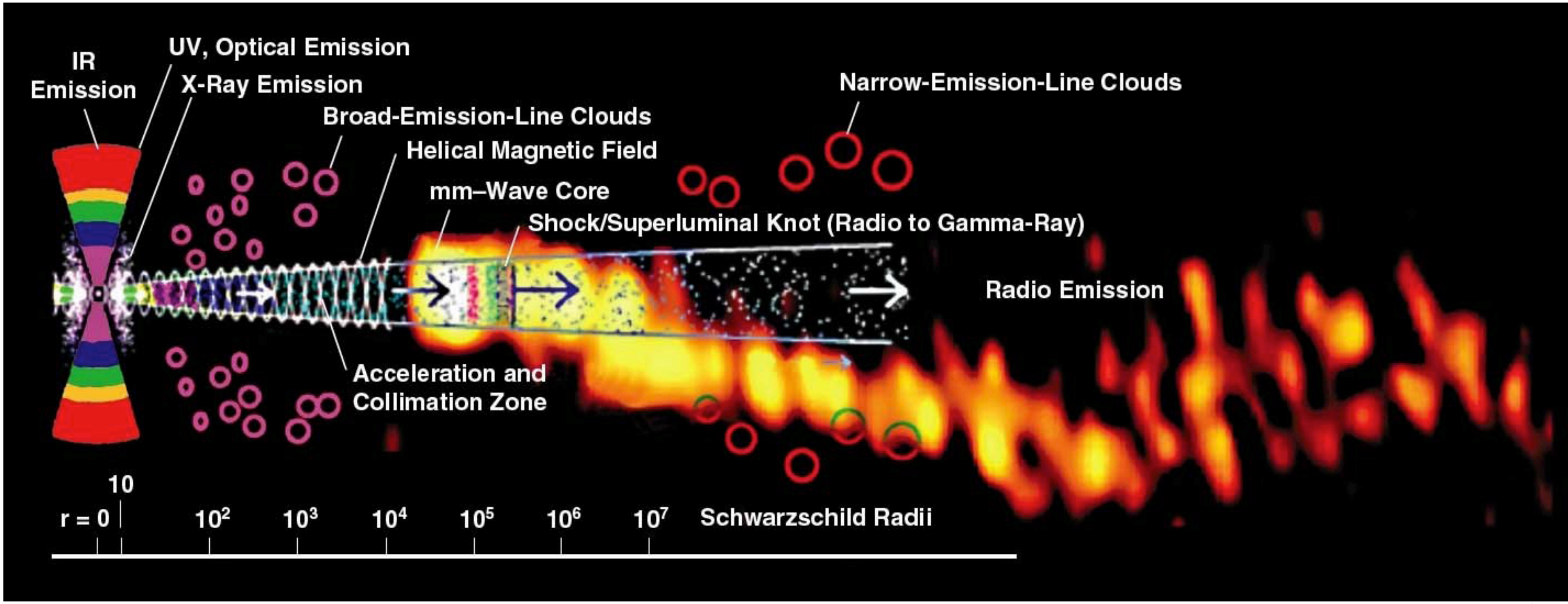


Ka-band
32 GHz
0.9cm

The sources become better →
smaller structure indexes
(Fey & Charlot 1997)

Images credit: P. Charlot et al, AJ, 139, 2010

9mm vs. 3.6cm? Core shift & structure



R~0.1-1 μas 1mas

Credit: A. Marscher, Proc. Sci., Italy, 2006.
Overlay image: Krichbaum, et al, IRAM, 1999.
Montage: Wehrle et al, ASTRO-2010, no. 310.

Positions differences from 'core shift'

- wavelength dependent shift in radio centroid.
- *3.6cm to 9mm core shift:*

  100 μas in phase delay centroid?

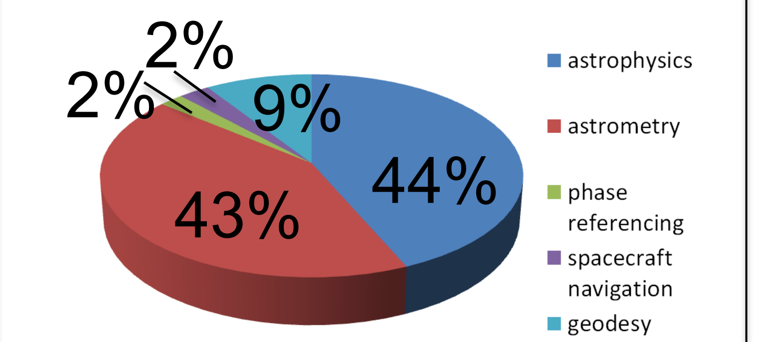
  <<100 μas in group delay centroid? (*Porcas, AA, 505, 1, 2009*)
- shorter wavelength closer to Black hole and Optical: 9mm X/Ka better

ICRF-3: needs and goals

3rd generation International Celestial Reference Frame

Assessment of needs for ICRF-3

1. VLBA Cal Survey is most (2/3) of ICRF-2
   but positions are 5X worse than rest of ICRF-2
2. ICRF-2 is weak in the south
3. High frequency frames
   Fewer sources, weak in the south



ICRF-1 users: Distribution of ~400 citations

Figure Credit: Heinkelmann, EVGA, 2013

Goals:

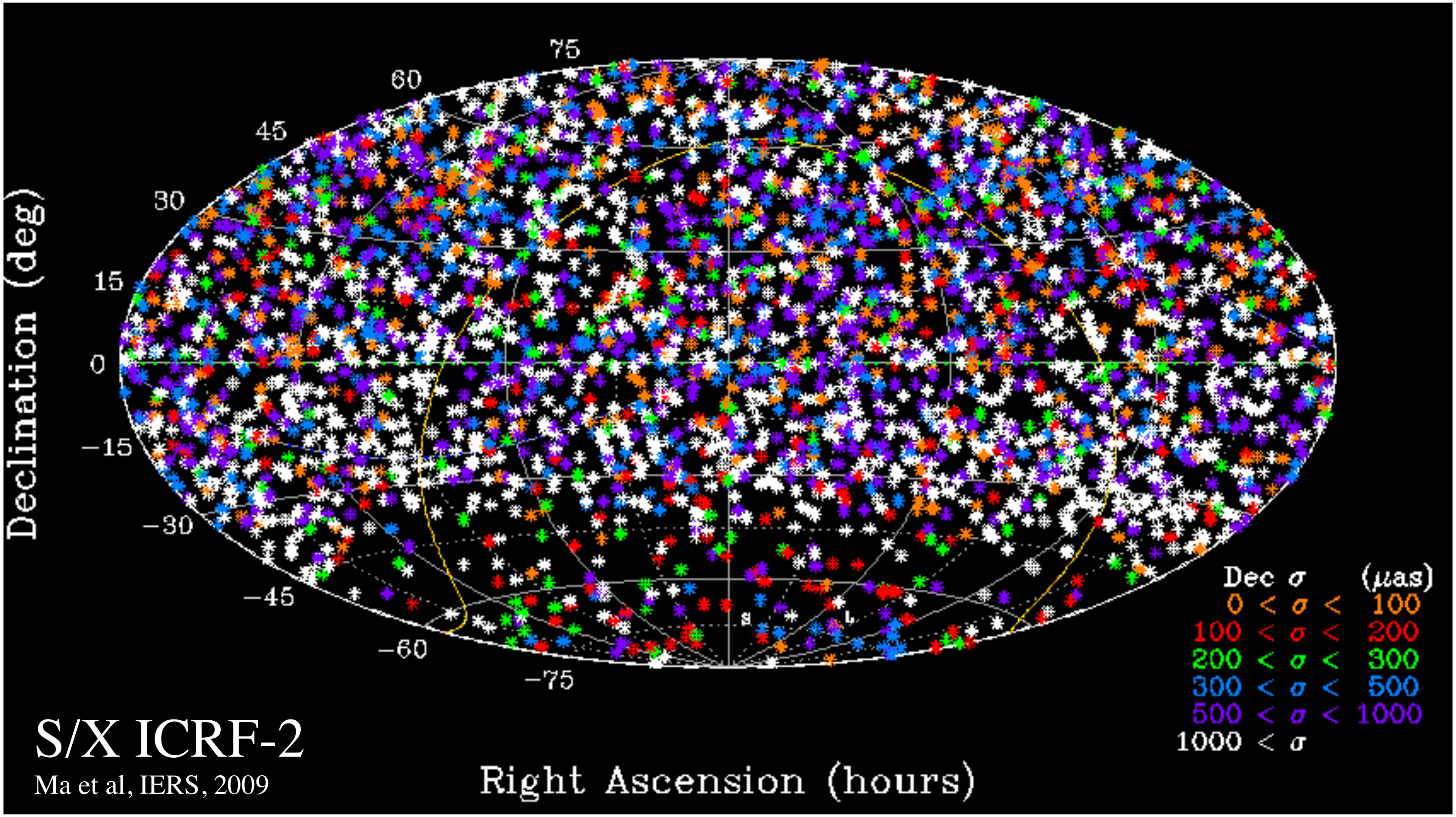
1. Complete ICRF-3 by 2018
   in time for comparisons with Gaia optical frame
2. Competitive precision with Gaia ~ 70 μas (1-sigma RA, Dec)
3. Uniform precision for all sources. Implies improving VCS positions.
4. High frequency frames (K, XKa, Q?)
   Improve number, accuracy, and southern coverage
5. Maximize high quality optical-radio tie sources

ICRF-2 reference: Ma et al, IERS, 2009. http://adsabs.harvard.edu/abs/2009ITN....35....1M

Current Status of
Celestial Reference Frames
at radio wavelengths:

S/X ICRF2: 3.6cm, 8 GHz
K-band: 1.2cm, 24 GHz
X/Ka-band: 9mm, 32 GHz

ICRF2 can be improved



Southern Hemisphere:

VLBI generally & ICRF-2 specifically lacks southern observations (Dec < -35 deg)

AuScope, Hobart, HartRAO exploring additional S/X observations

S/X-band Plan for Southern Improvements

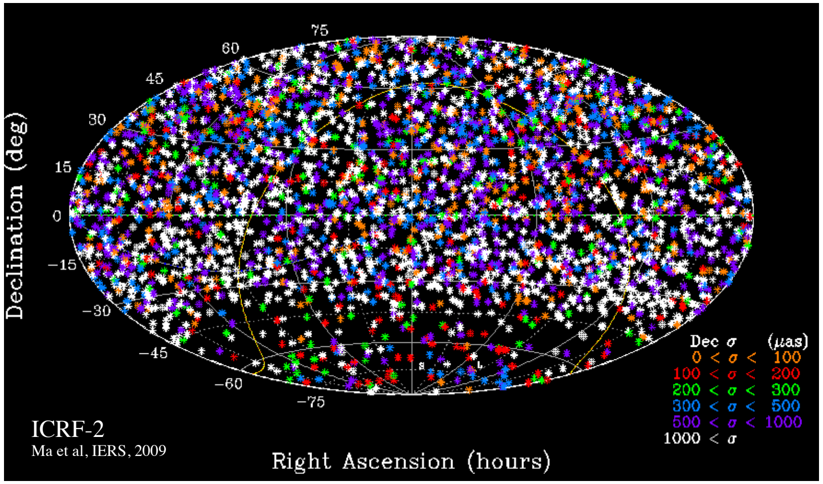
- Plans from Titov et al, IAG, 2013

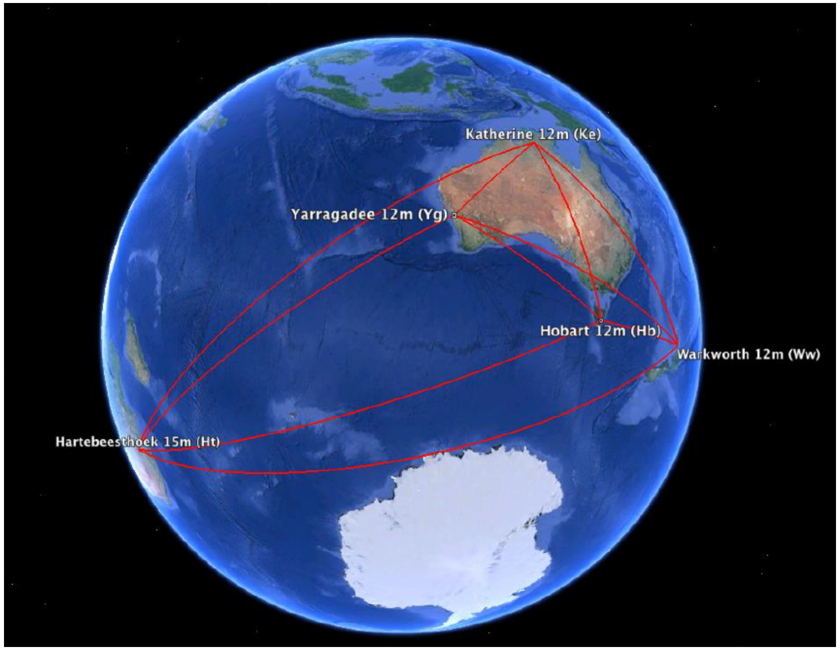
- 2013-15: Observing underway for 100-200 **strong** (> 400 mJy) sources using the small, fast stations of the southern CRF Network at S/X-bands.

- Goal > 100 scans per source, 50 μas precision

- **Weaker sources** observed with large telescopes: Parkes, DSS45, Hobart26, HartRAO 100-200 sources over 2 years (2015-2017)

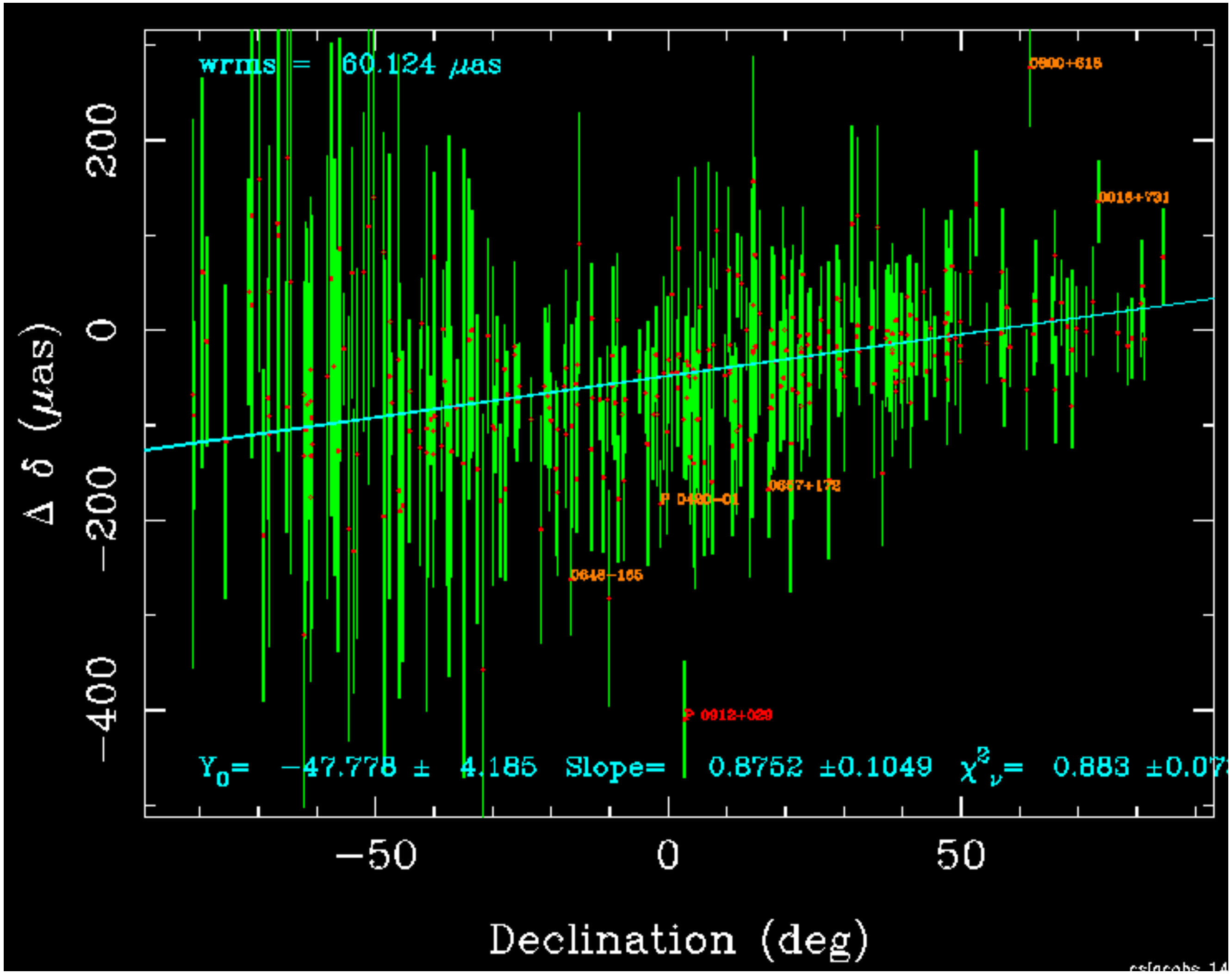
- Goal 20 scans/source, 100-150 μas precision





Southern Hemisphere CRF stations
Credit: Titov el al, IAG, 2013

S/X zonal errors: ICRF2-Def vs. Recent S/X



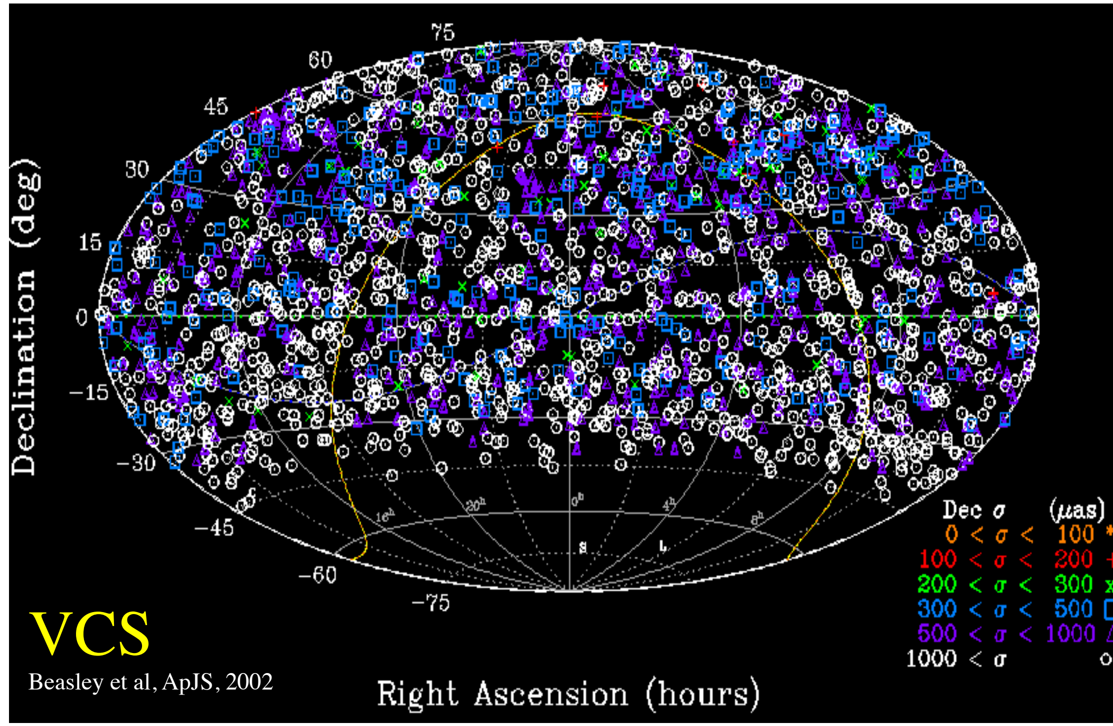
Credit:
Gordon et al, GSFC, private .comm., 2014

Jacobs, et al, REFAG-2014

GSFC-2014bp3 – ICRF2 Definings: 0.5 ppb zonal error in Declination

ICRF-3 Needs

- Uneven precision of current ICRF-2 VCS's 2200 sources (2/3 of the ICRF-2)
- VCS precision is typically 1000 μas
  5 times worse than the rest of ICRF2!



Beasley et al, ApJS, 2002

Good news:

- VLBA Cal Survey-II
  VLBA approved 8 x 24-hour sessions
  to re-observe VCS sources.

  PI: David Gordon, GSFC
  8 of 8 passes completed .

ICRF2: VCS vs. Non

Item	VCS	non-VCS	factor
N_src	2197	1217	VCS 1.8X better
median sessions	1	13	VCS 13X worse
median observations	45	249	VCS 5.5X worse
median time span	0	13 years	VCS arbitrarily worse
median RA sigma	621	130 μas	VCS 4.8X worse
median Dec sigma	1136	194 μas	VCS 5.9X worse

VLBA Observing Networks

VLBA

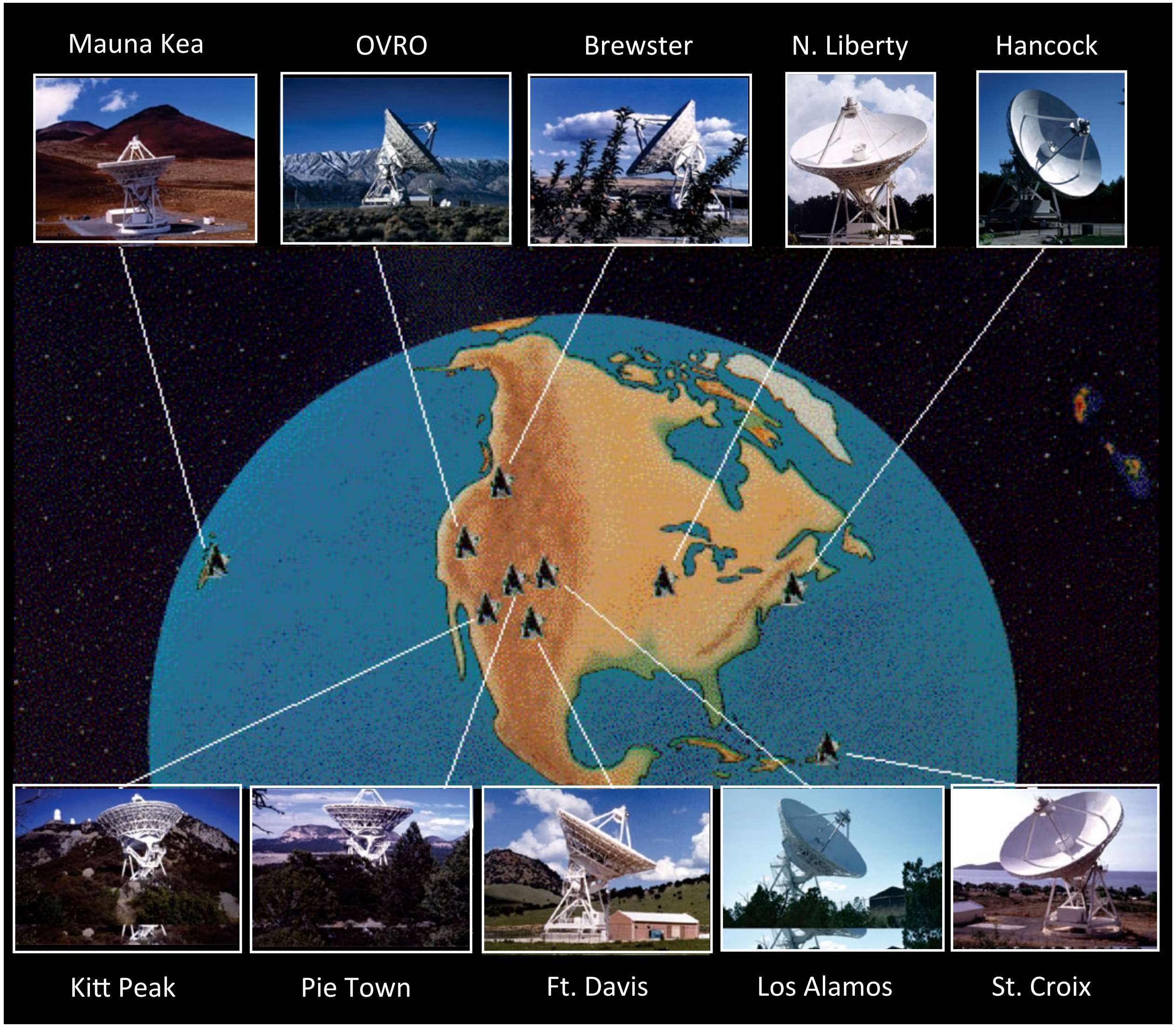
S/X VCS catalog
K, Q catalogs

25-meter dishes

10 stations

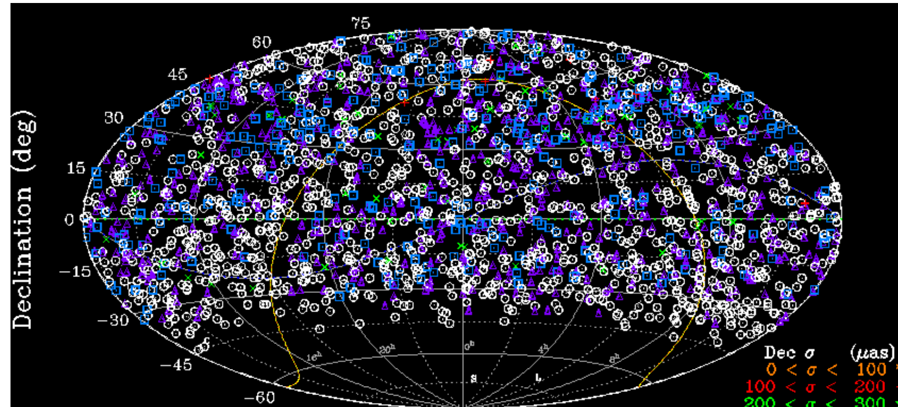
Baselines up to
8000 km

No southern
stations

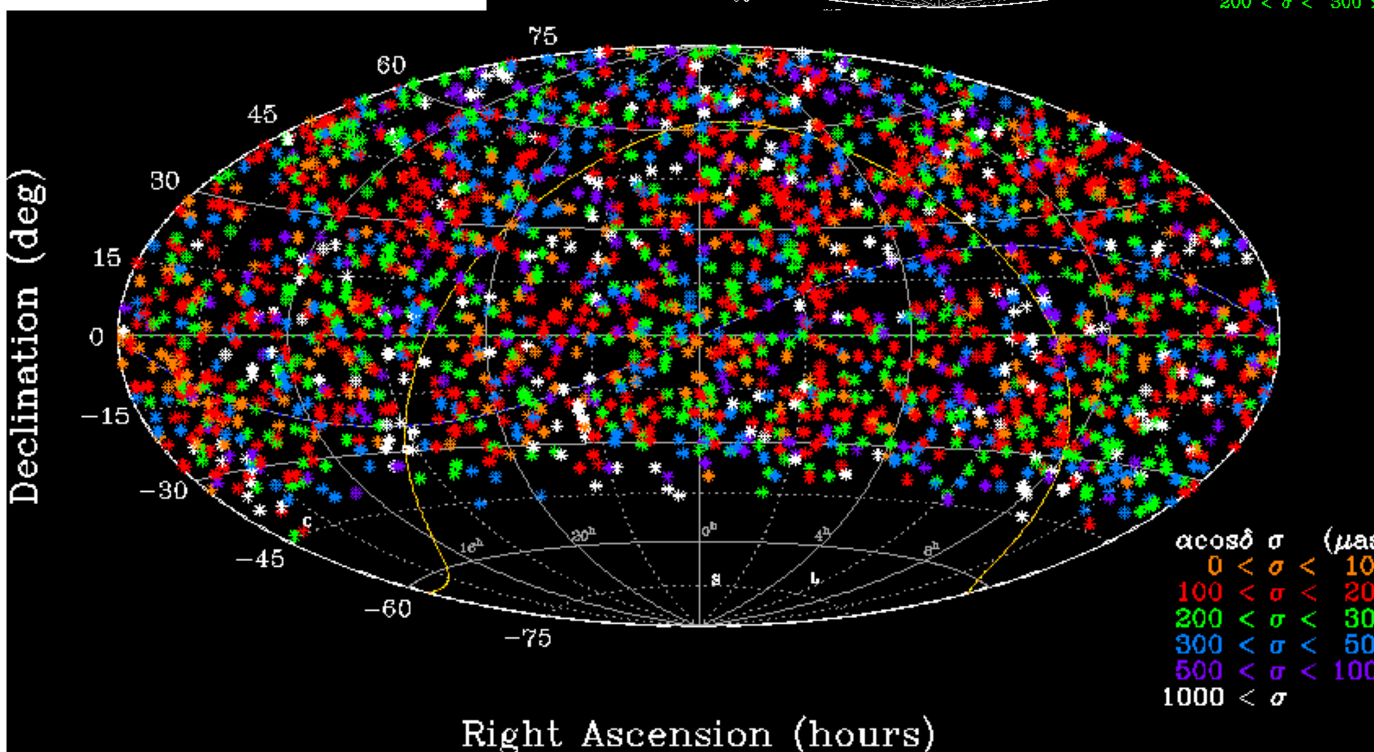


Very Large Baseline Array http://www.vlba.nrao.edu/

VLBA Calibrator Survey improvement



VCS-I: ~1 mas precision
for 2200 sources
credit: Beasley et al, AJ, 2002

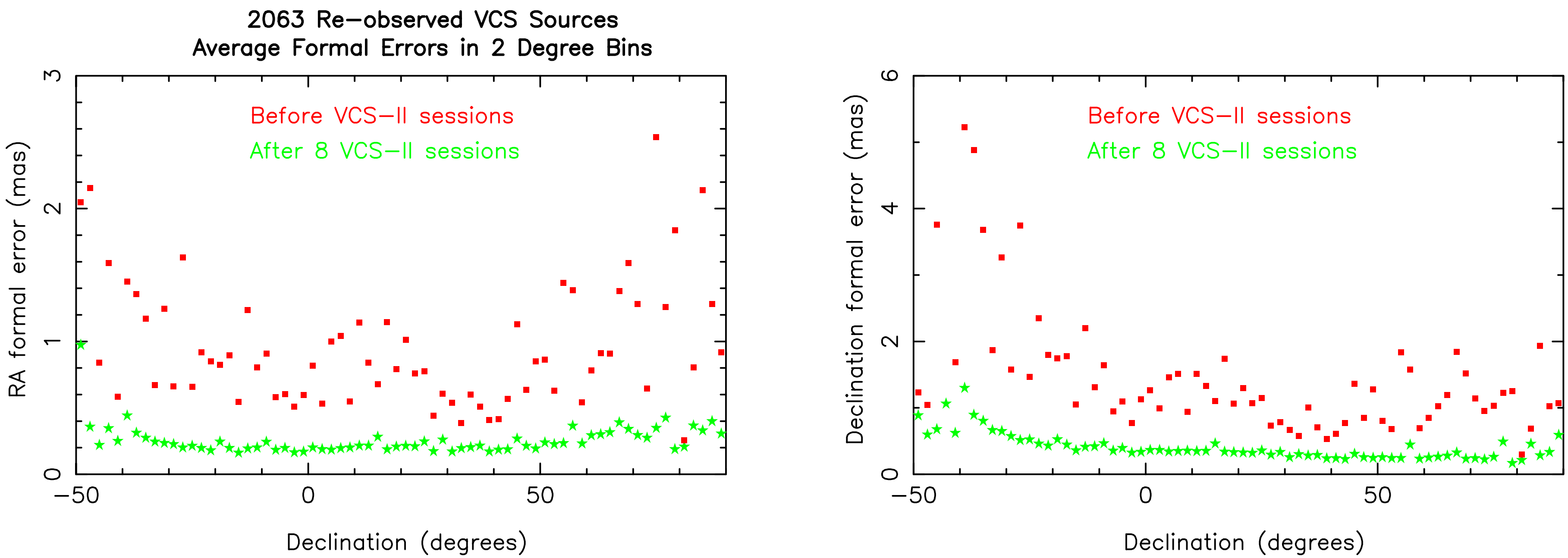


VCS-II:
RA 0.23 mas
Dec 0.39 mas

Improvement
~3.7 times

Credit: Gordon et al, EVGA, Azores, Portugal, May 2015

VLBA Calibrator Survey improvement

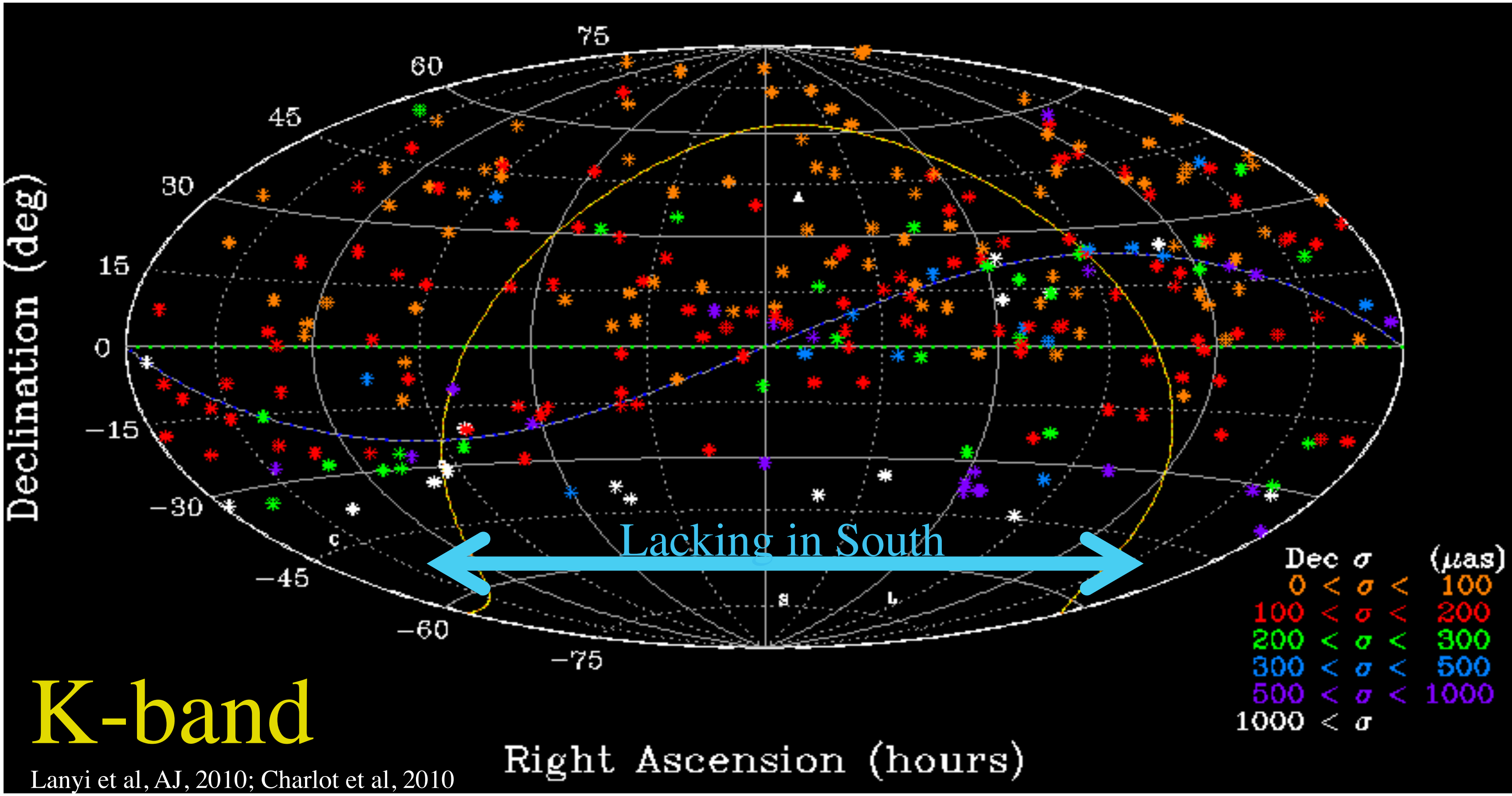


~3.7 times X improvement in precision

much more uniform distribution of the position uncertainties vs. declination.

Credit: Gordon et al, EVGA, Azores, Portugal, May, 2015.,

K-band (24 GHz) CRF: 275 sources



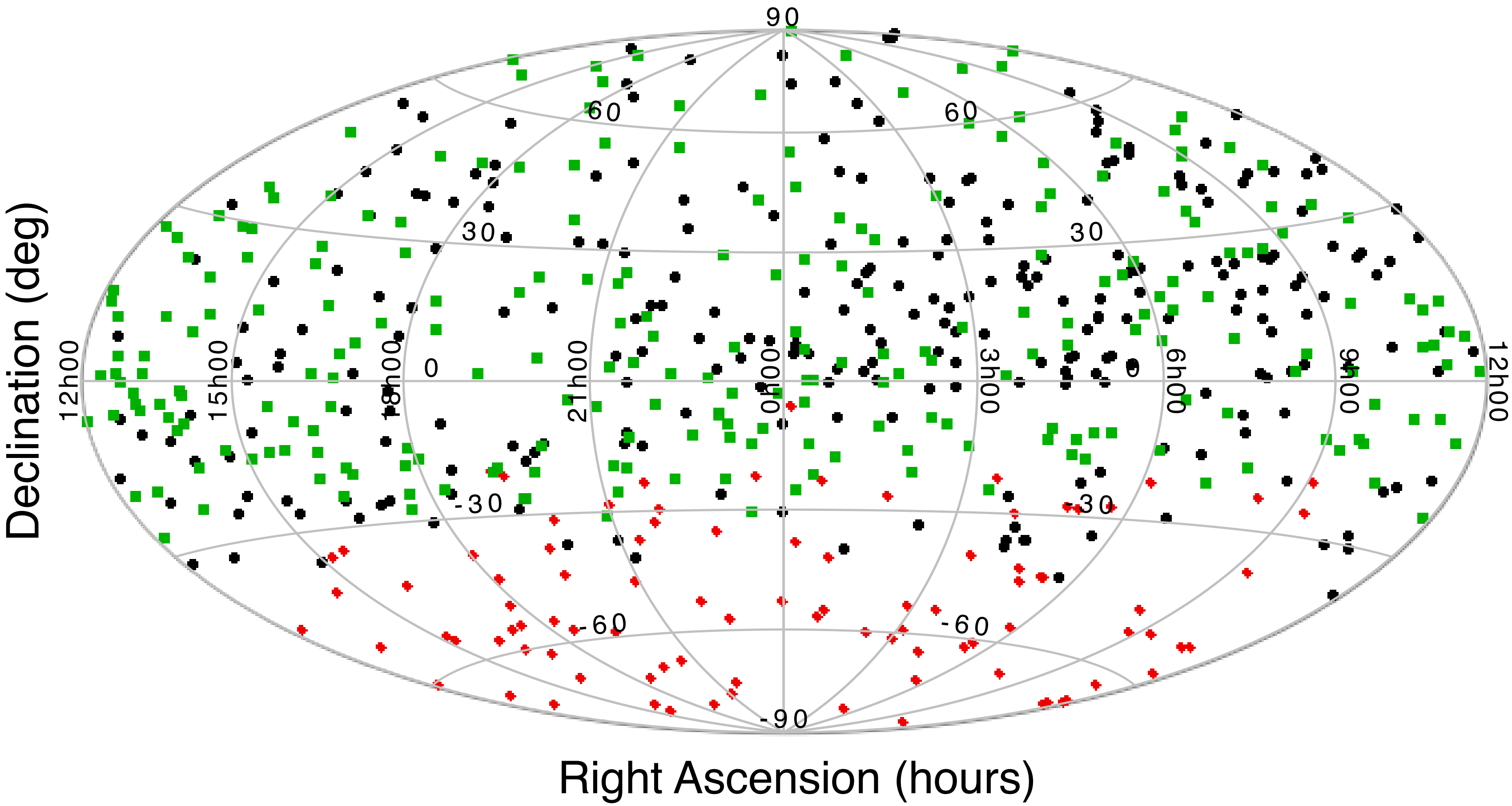
K-band full sky coverage collaboration: De Witt+, EVGA, May 2015

First southern K-band fringes: Hobart-HartRAO (23 Aug 2013)

Data completing full sky coverage being processed.

VLBA approved time to densify the north -> expect 500+ sources total

K-band (24 GHz) CRF: > 500 sources



- K-band existing (Lany+, Charlot+).
- New K-band data fron Bertarini et al collaboration (De Witt+, EVGA, 2015)

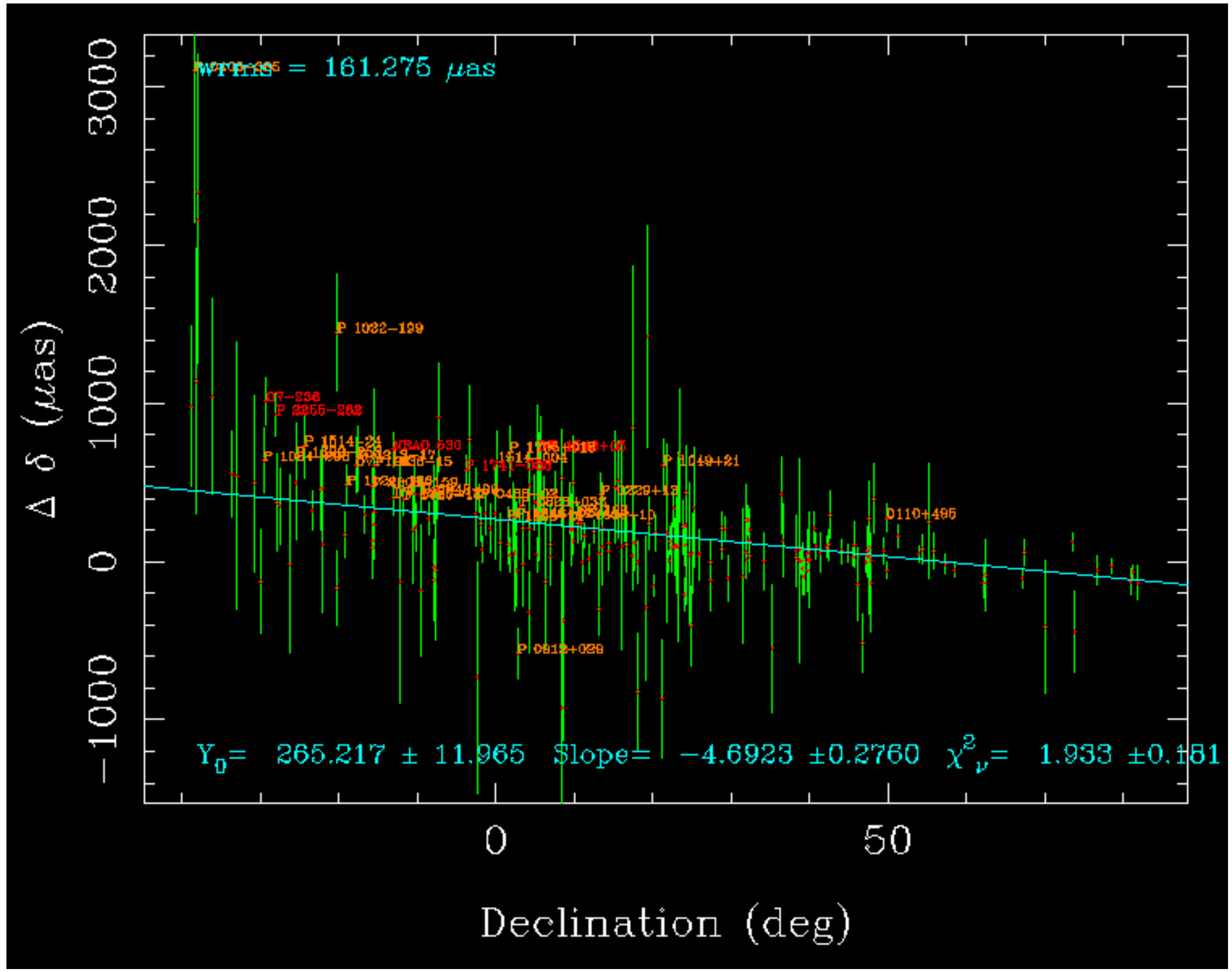
Data completing full sky from (Australia –South Africa) being processed.

VLBA approved time to densify the north. Expecting > 500 sources total

K-band 1.2cm *vs.* ICRF2 at 3.6cm (S/X)

Lack of direct
Dual-band ion
Calibrations
and
Lack of any
Station in south

Leads to poor
ΔDec vs. Dec
Zonal stability:
500 μas tilt



K(1.2cm) Declinations vs. S/X ICRF2 (current IAU standard)

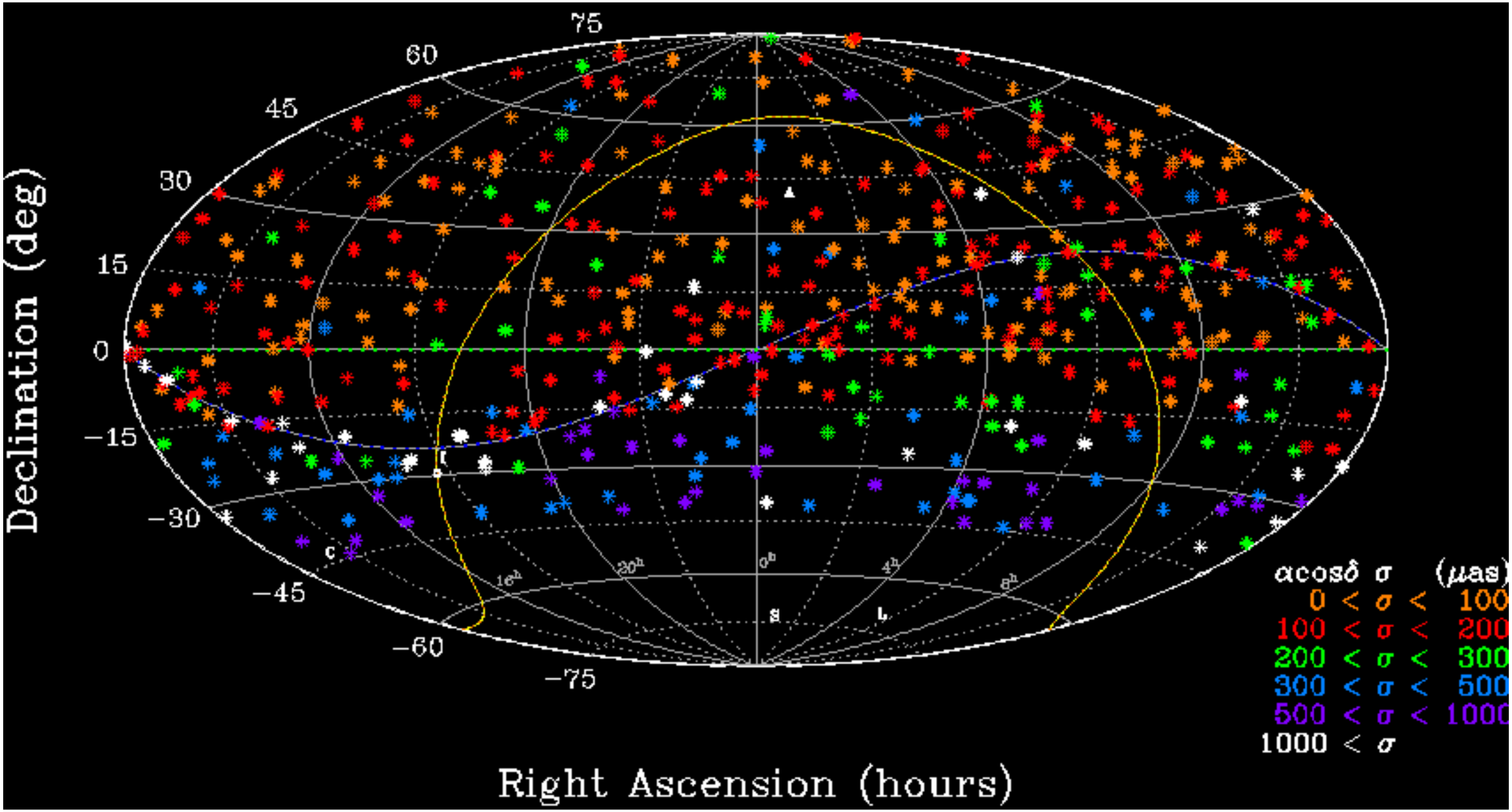
Credit: K(1.2cm): Lanyi et al, AJ, 139,5, 2010
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs,IERS, Germany, 2009

X/Ka Celestial Reference Frame

ESA's Argentina 35-meter antenna **adds 3 baselines** to DSN's 2 baselines

- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina

Status 2012: X/Ka had 482 Sources

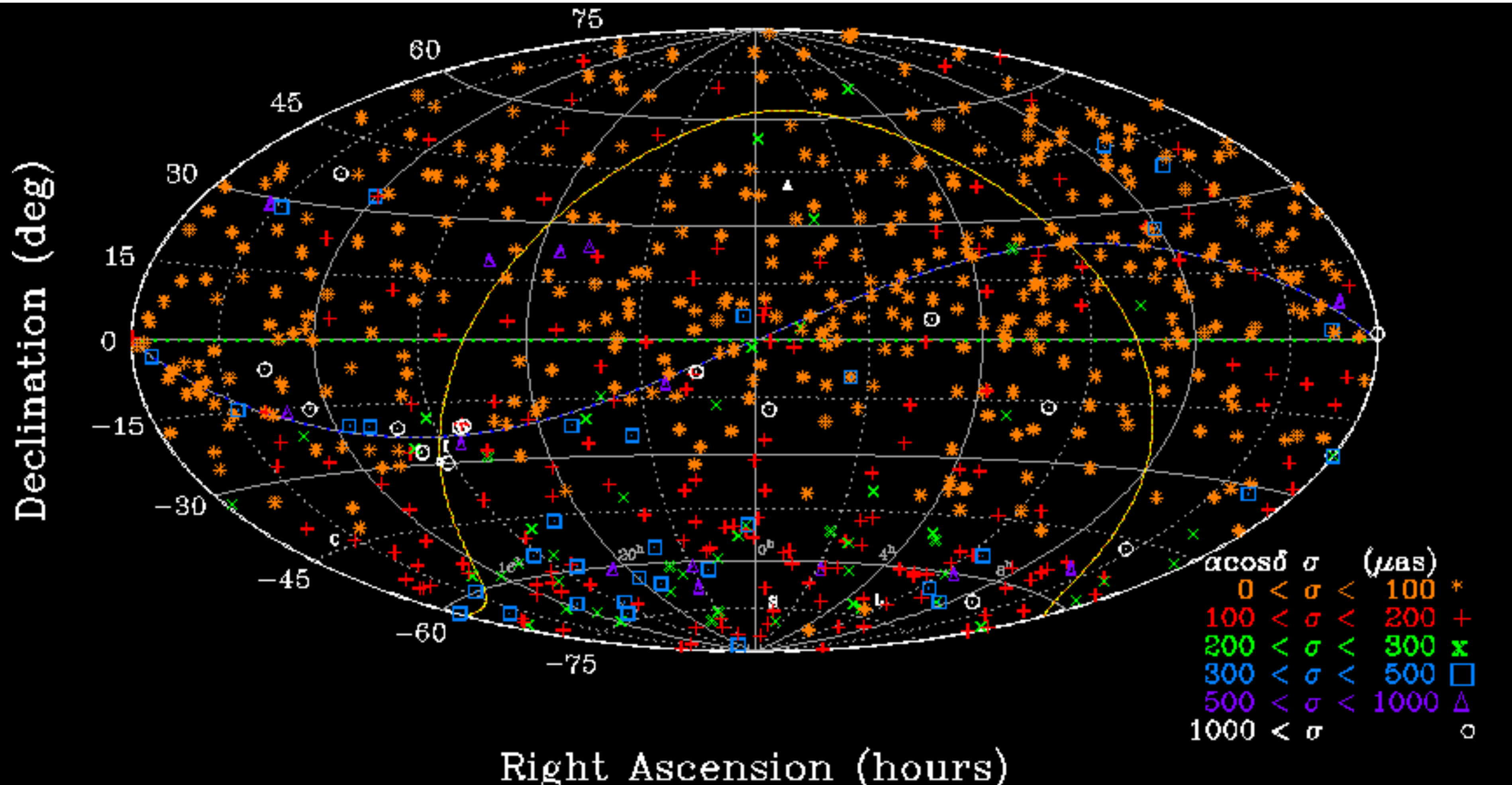


400 µas precision Dec 0 to -45 deg. No sources in south polar cap

Cal. to Madrid, Cal. to Australia. Weakens south of Dec = -15deg

Credit: Jacobs et al, ISSFD, Pasadena, 2012

NASA-ESA 32GHz RA results: 660 sources

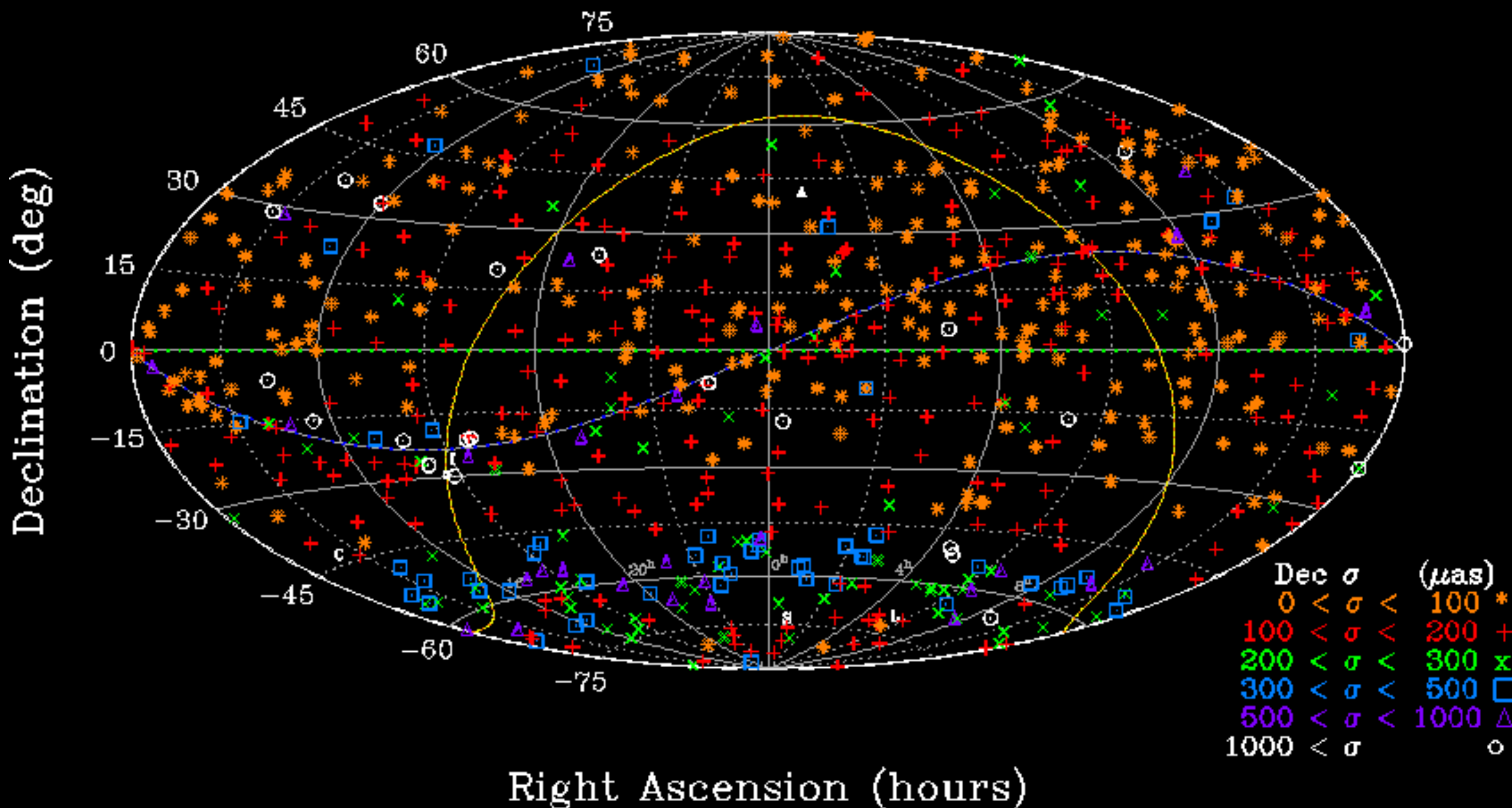


DSN: Goldstone to Madrid & Canberra

+ ESA baselines: Malargüe to Canberra, Goldstone, Madrid

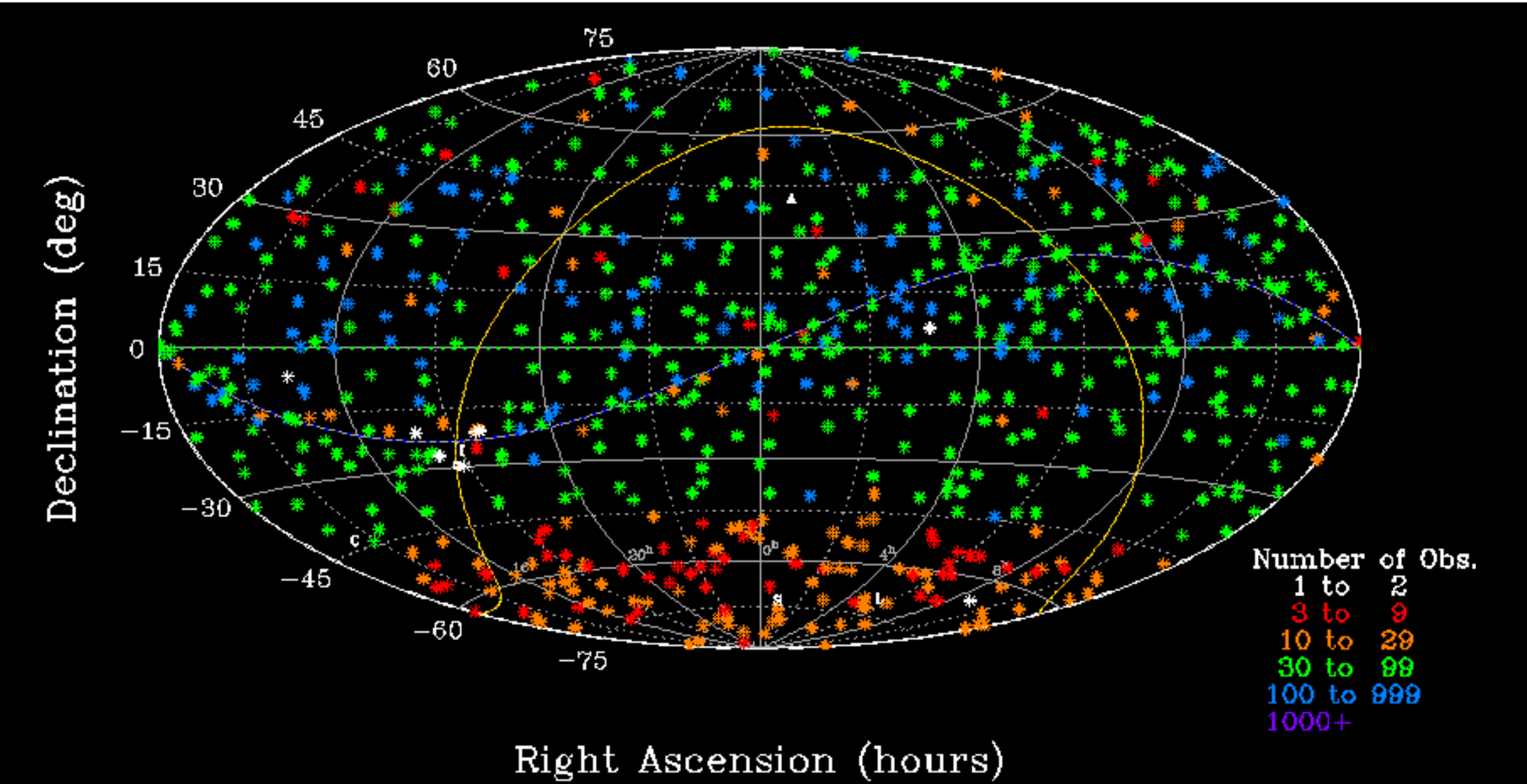
Full sky: 110 sessions, 40K group delay/phase rate observations

NASA-ESA 32GHz
Dec results: 660 sources



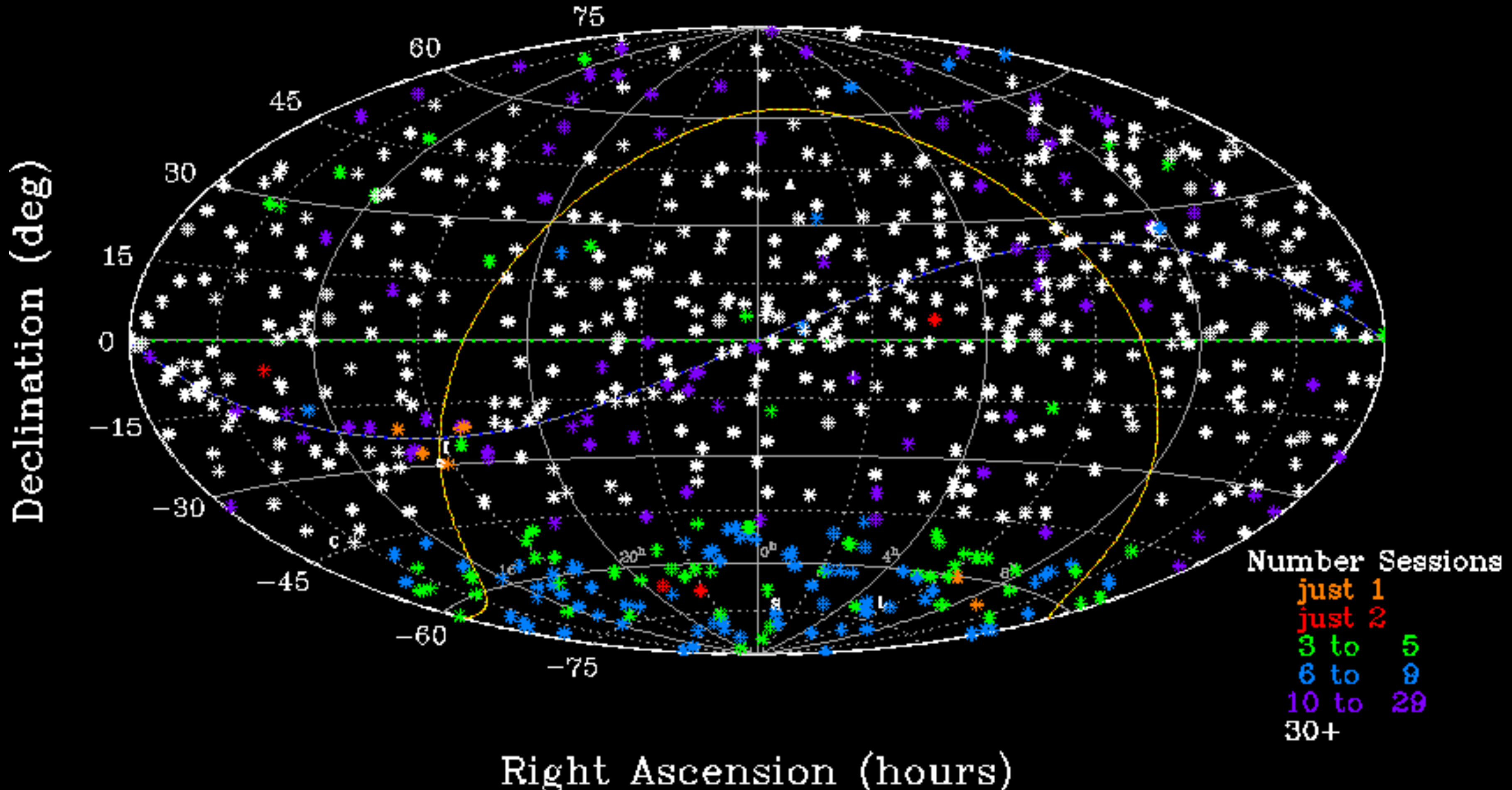
Goldstone to Madrid & Australia **+ Malargüe to Canberra,Goldstone, Madrid**.
South cap: 144 candidates, detected 138 sources (96% for Dec < -45 deg)

NASA-ESA 32GHz Number of observations



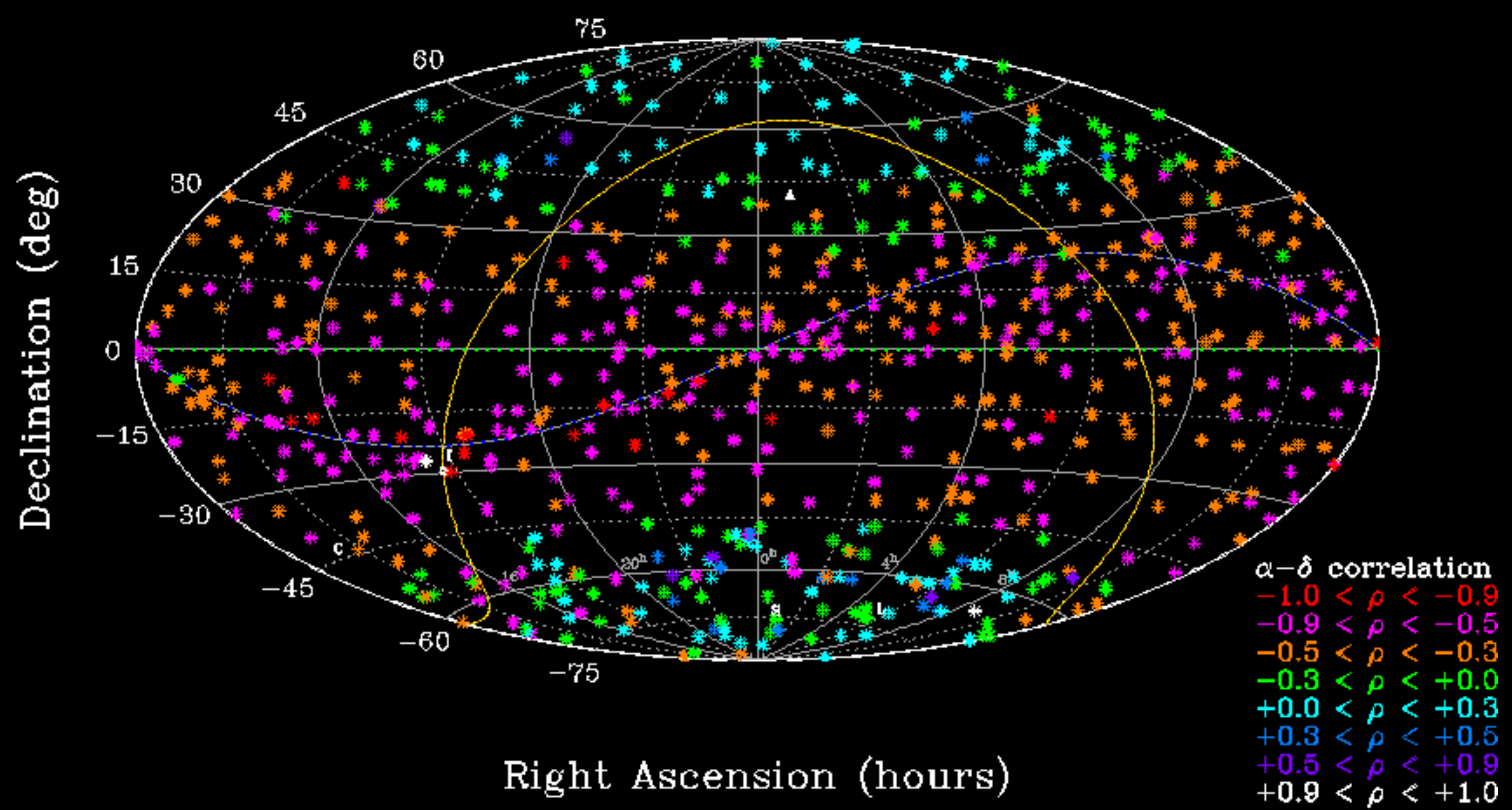
Need Argentina- Australia observations to balance frame for Dec < -45 deg

NASA-ESA 32GHz Number of Sessions



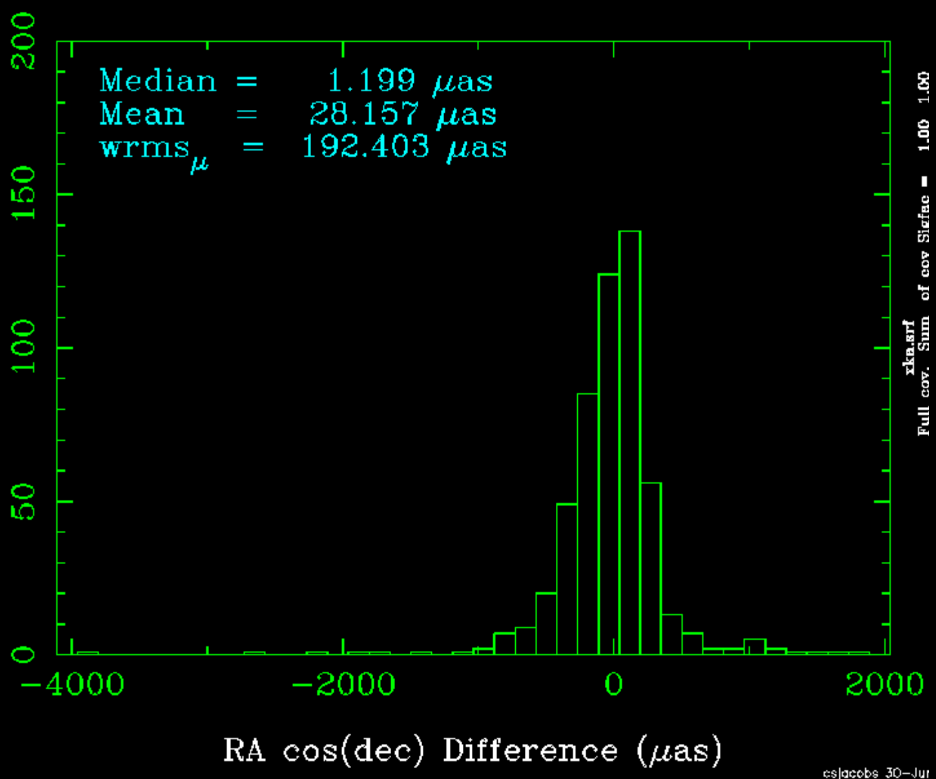
Need Argentina- Australia sessions to balance frame for Dec < -45 deg

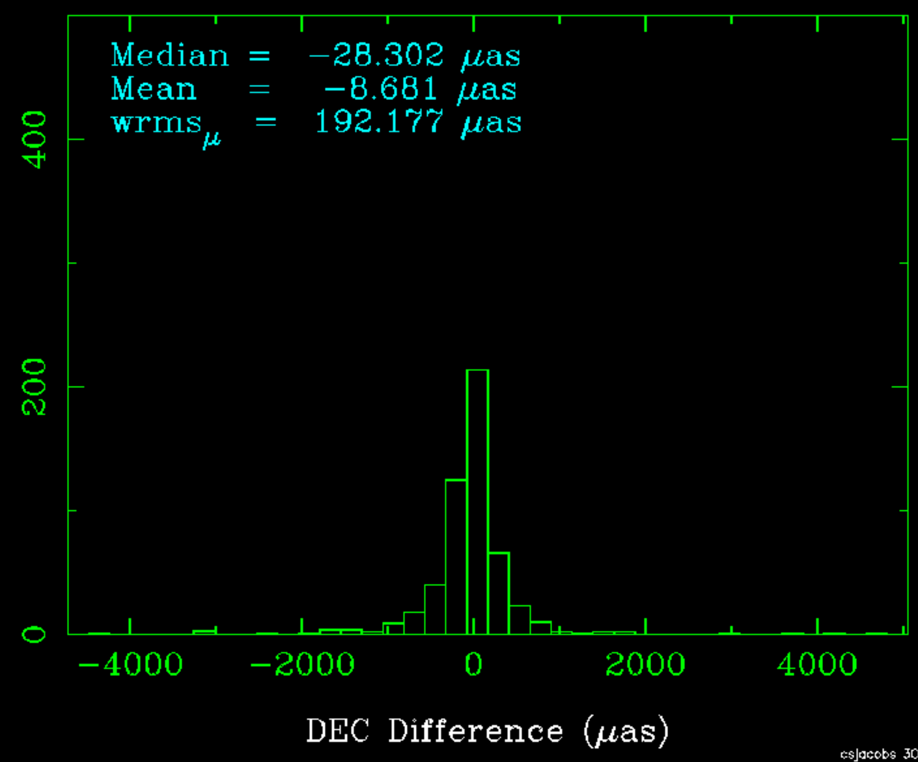
NASA-ESA 32GHz RA-Dec correlation



Need Argentina-California sessions to balance frame for Dec within +-45 deg

XKa vs. SX ICRF2: 532 sources





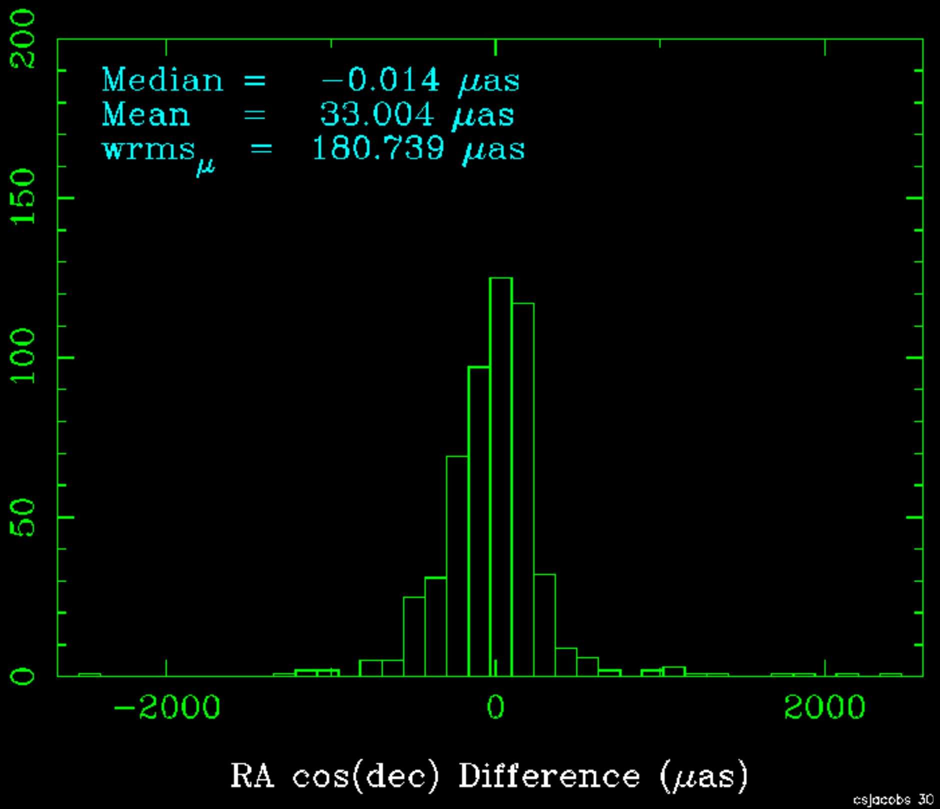
wRMS(α cosδ) = 0.93 nrad

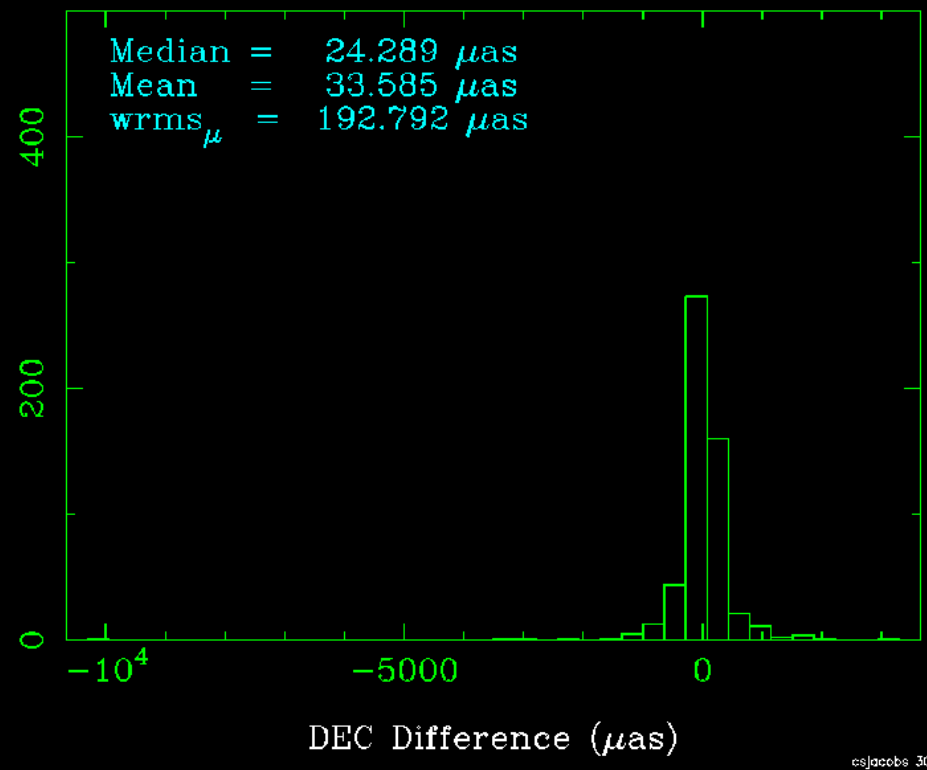
No bias, but zonals errors ~200 μas

wRMS(δ) = 0.93 nrad

Dec bias “cured” by recent data!

XKa vs. recent SX: 540 sources





wRMS(α cosδ) = 0.88 nrad

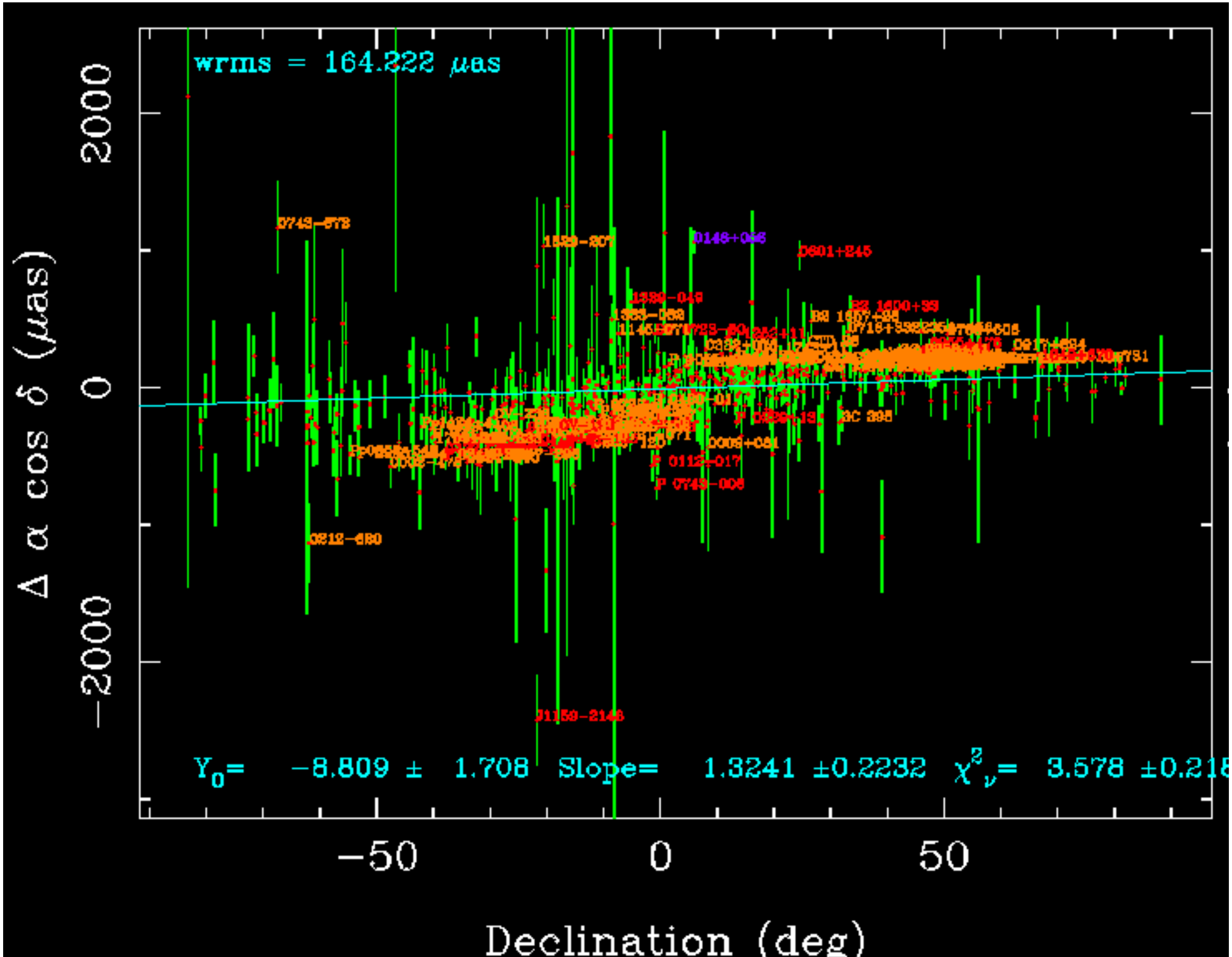
wRMS(δ) = 0.94 nrad

δ Mean offset negligible

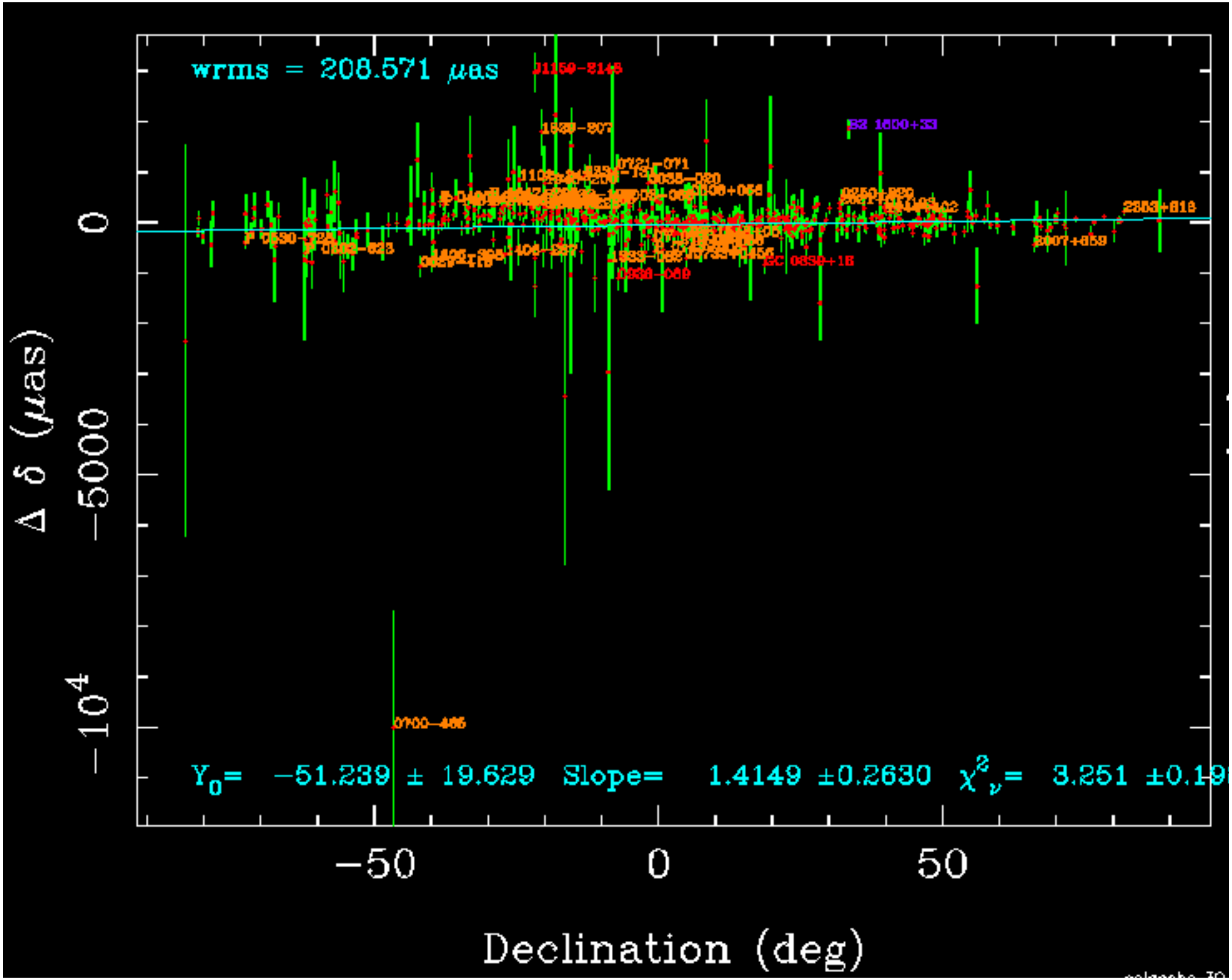
δ zonal error dominates

GSFC-2104bp3: credit Gordon et al, private communication, NASA Goddard, 2014

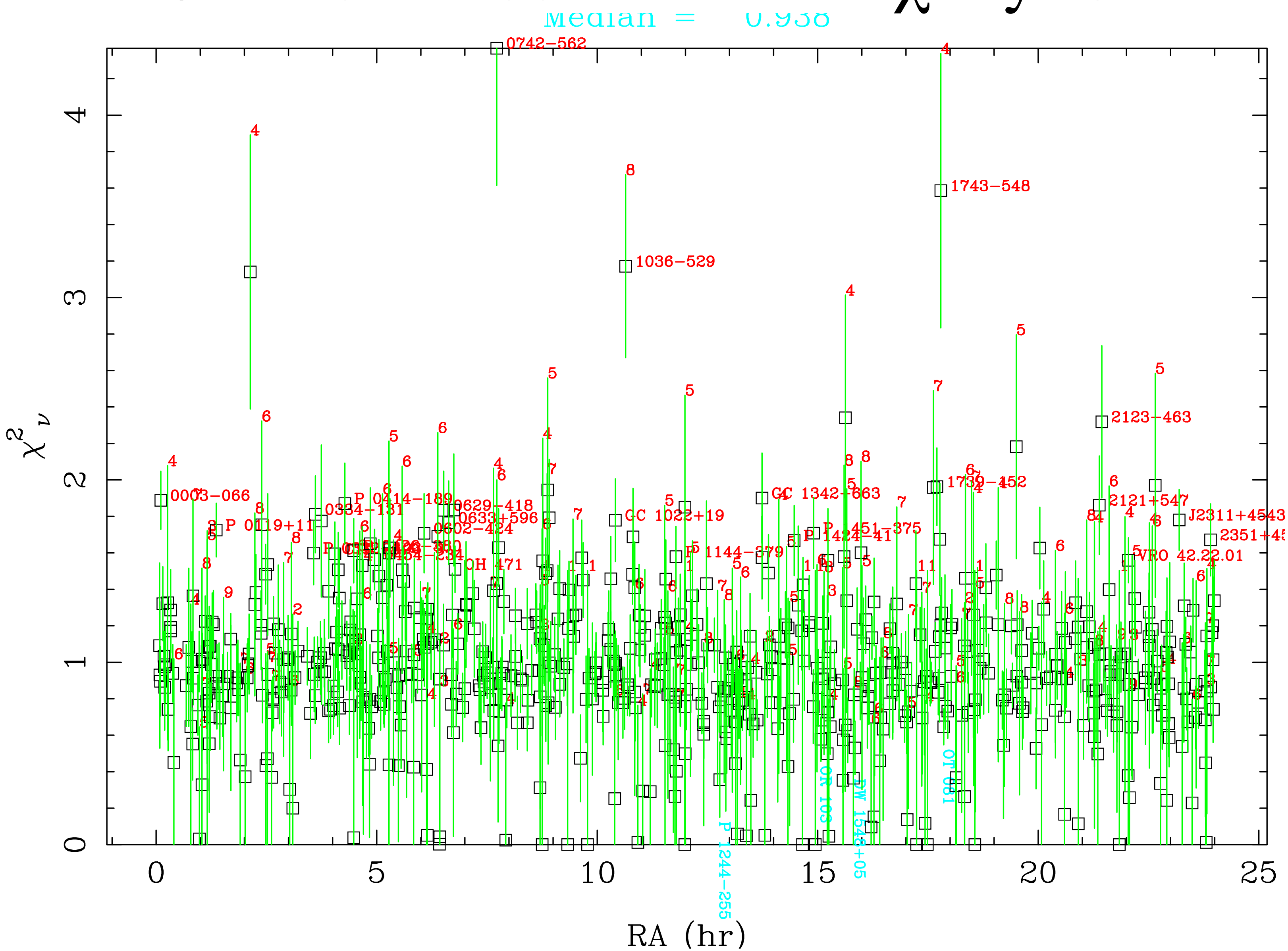
XKa vs. SX: Zonal errors



XKa vs. SX: Zonal errors



X/Ka noise floor: internal χ^2 by source



No sign of dominant systematics. Median number of sessions = 40, over 10 years

XKa accuracy goal 100 μas

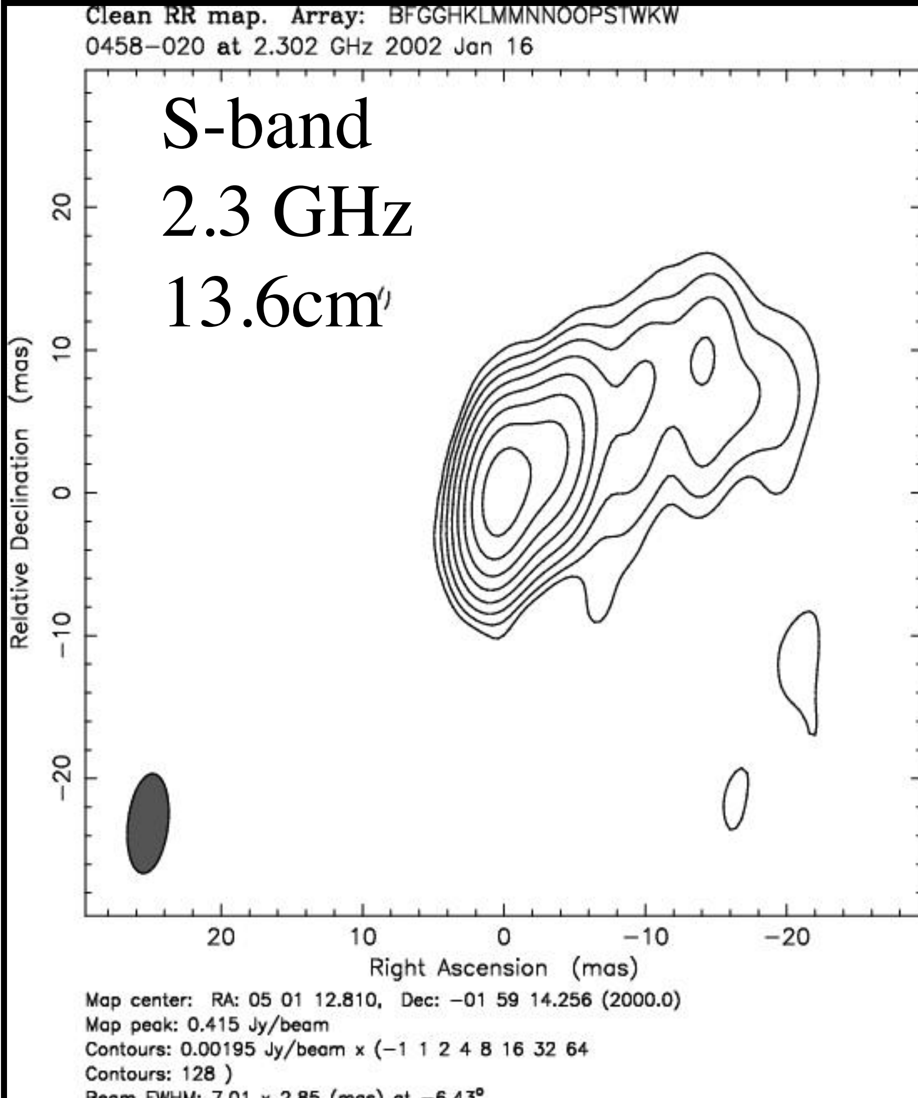
- Goal of 100 μas or ~ 5mm
- Largest celestial frame error:
  Zonal errors vs. Declination of ~ 200 μas

- **Issues**
  - Ion cals from GPS not yet applied to Malargüe passes
    ~100 μas per session. Does it average down over sessions?
  - DSA03 meteo data not yet applied.
  - Nutation has stochasticaly varying 430 day free mode
    which can be as large as 500 μas

  - Terrestrial Frame corrupted at 1cm level?
    DSA03 has 7mm/year velocity shift relative to a priori
    DSS 54/DSS 55 have relative 2mm/year velocity? Real?

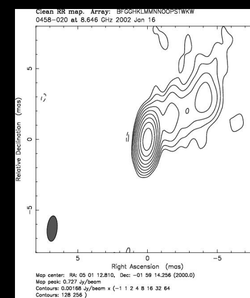
  - Malargüe is 60% of baselines, only 10% of data

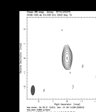
Source Structure vs. Frequency (absolute scale)

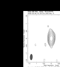


Images credit: P. Charlot et al, AJ, 139, 2010

X-band	K-band	Q-band
8.6 GHz	24 GHz	43 GHz
3.6cm	1.2cm	0.7cm



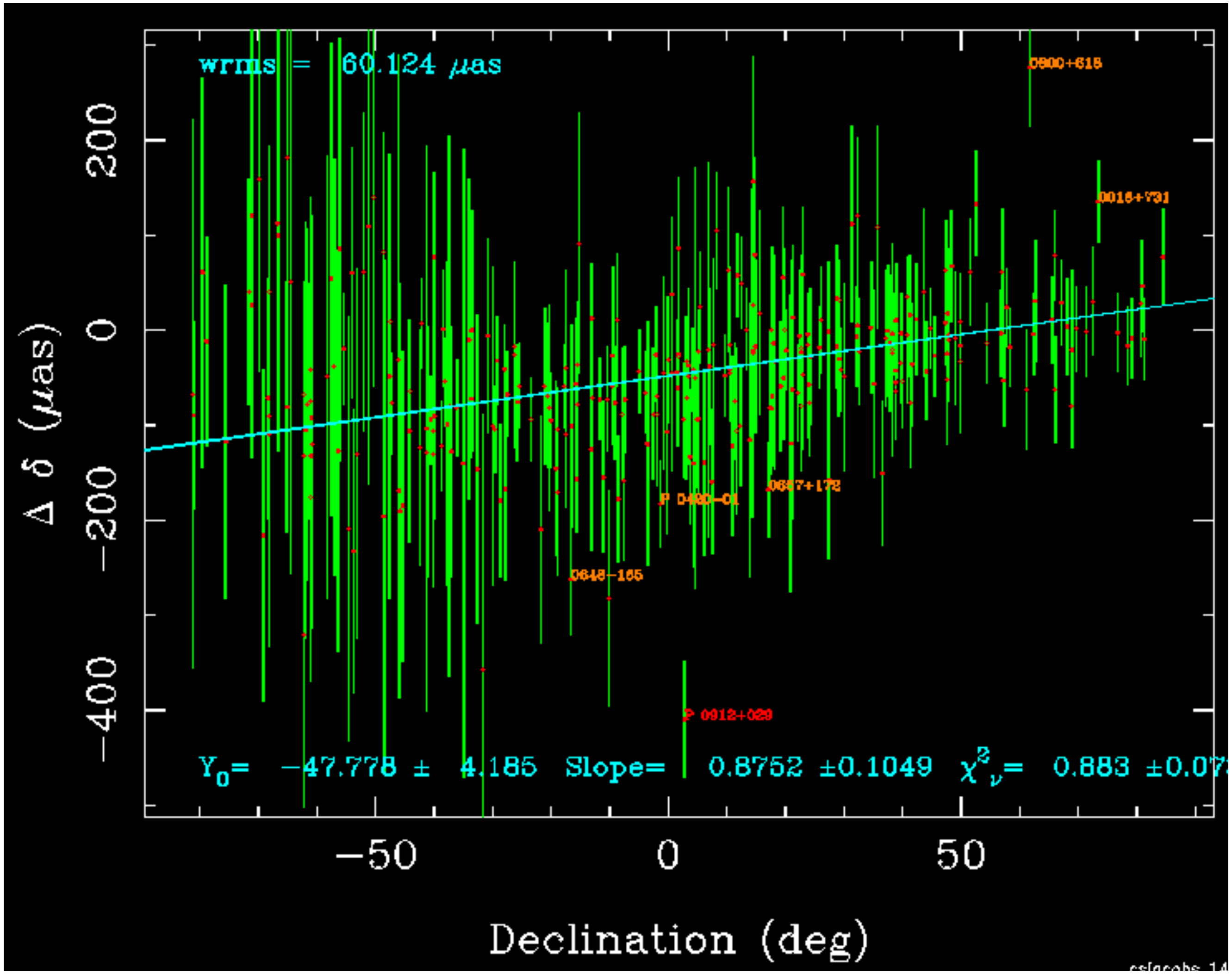




The sources become better → smaller structure indexes (Fey & Charlot 1997)

Ka-band
32 GHz
0.9cm

S/X zonal errors: ICRF2 vs. Recent S/X



Credit:
Gordon et al, GSFC,
private .comm., 2014

GSFC-2014bp3 – ICRF2 Definings: 0.5 ppb zonal error in Declination

Gaia-Optical *vs.* VLBI-radio:

Celestial Frame tie
and
Accuracy Verification

Gaia frame tie and accuracy verification

<u>Gaia: 10^9 stars</u>

- 500,000 quasars V< 20
  20,000 quasars V< 18
- radio loud 30-300+ mJy
  and optically bright: V<18
  ~2000 quasars
- Accuracy
  100 μas @ V=18
  25 μas @ V=16

Gaia References:

Lindegren et al, IAU 248, 2008
http://adsabs.harvard.edu/abs/2008IAUS..248..217L

Mignard, IAU, JD-7, 2012
http://referencesystems.info/uploads/3/0/3/0/3030024/fmignard_iau_jd7_s3.pdf
http://adsabs.harvard.edu/abs/2012IAUJD...7E..27M

- S/X Frame Tie Strategy:
  Bring new optically bright quasars
  into the S/X radio frame
  use sources with S/X fluxes 30-100 mJy
  (Bourda et al, EVN, Bordeaux, 2012)

Launched Fall 2013

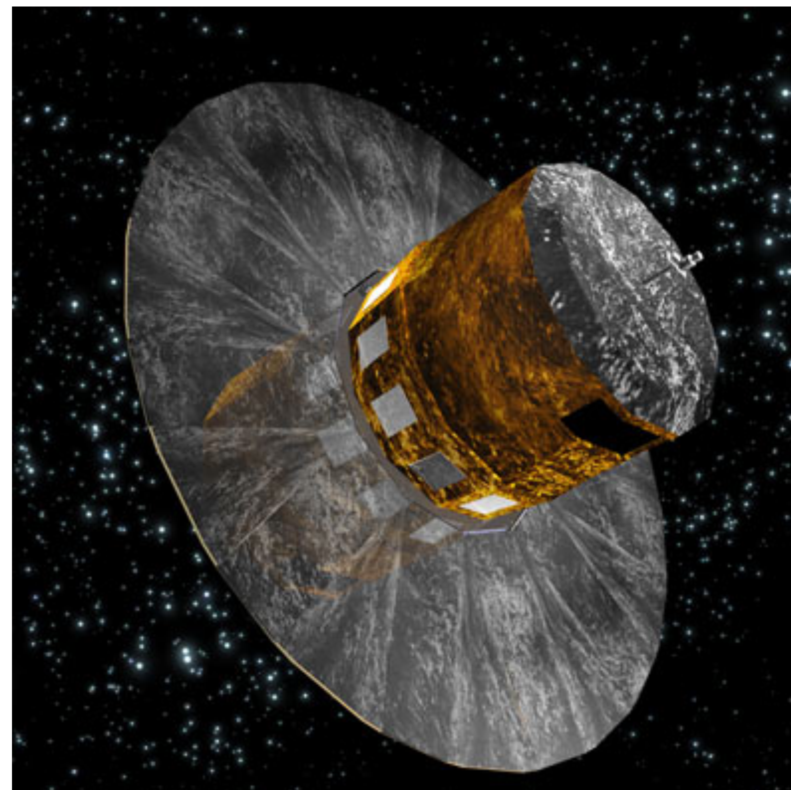


Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7

Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids

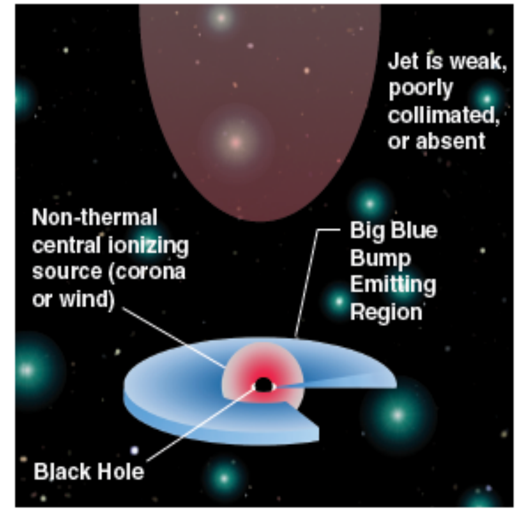
  - radio: synchrotron from jet

  - optical: synchrotron from jet?
    non-thermal ionization from corona?
    big blue bump from accretion disk?
  -host galaxy effects

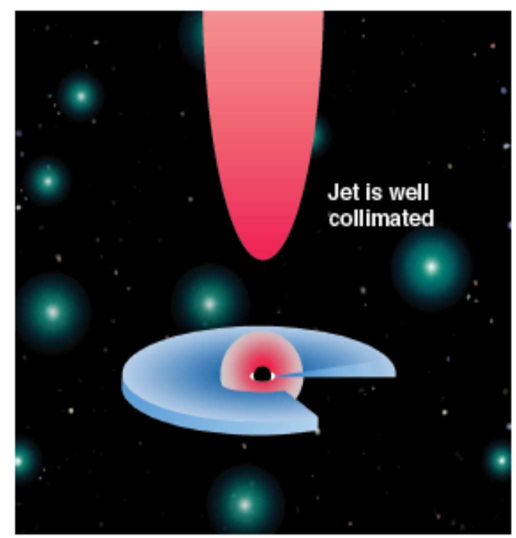
- Instrumental errors both radio & optical

- Analysis errors

Radio-quiet Quasar



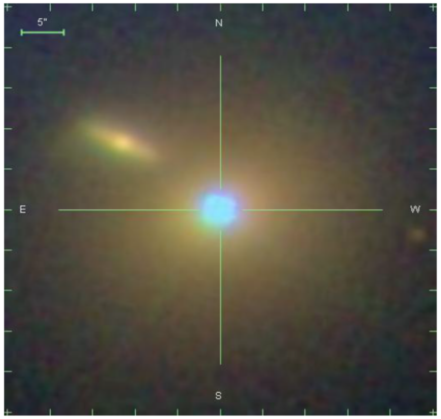
Radio-loud Quasar



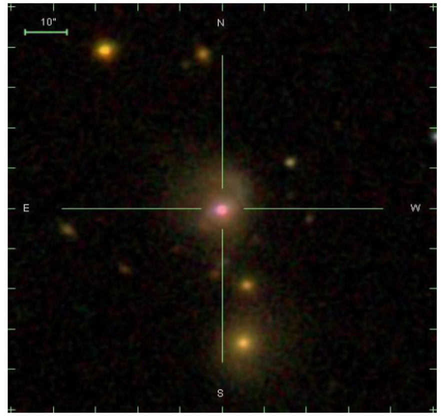
Credit: Wehrle et al, μas Science, Socorro, 2009
http://adsabs.harvard.edu/abs/2009astro2010S.310W

Optical vs. Radio systematics offsets

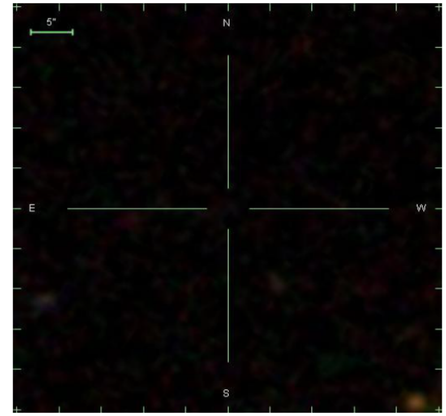
Credit: SDSS



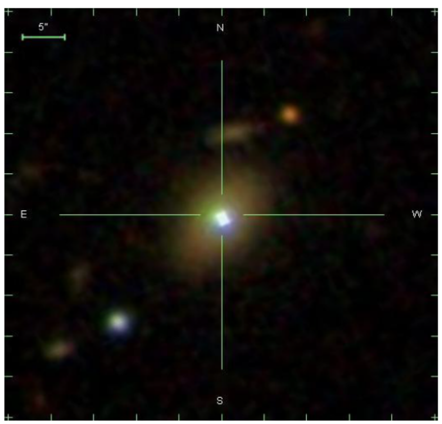
1101+384



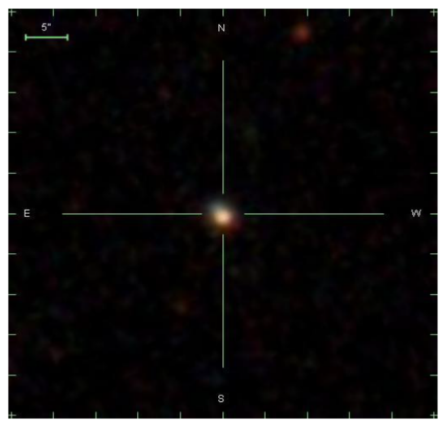
0007+106



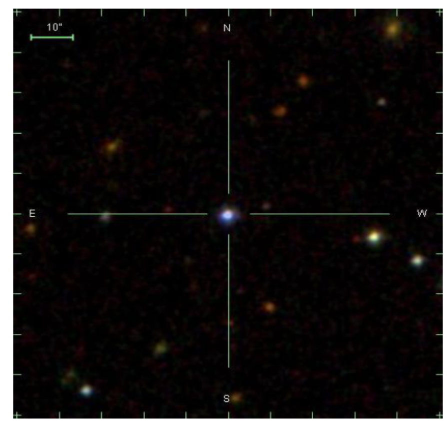
0920+390



1418+546



1514+192



1546+027

- Optical structure: The host galaxy may not be centered on the AGN or may be asymmetric. Zacharias & Zacharias (2014) see evidence for many milli-arsecs of optical centroid offset. This could dominate the error budget.
- Optical systematics unknown, perhaps as large as 10 mas optical centroid offset? (Zacharias & Zacharias, AJ, 2014)

Optical brightness of X/Ka sources

Allows for 7 μas precision in radio-optical frame tie. Systematics expected to dominate.

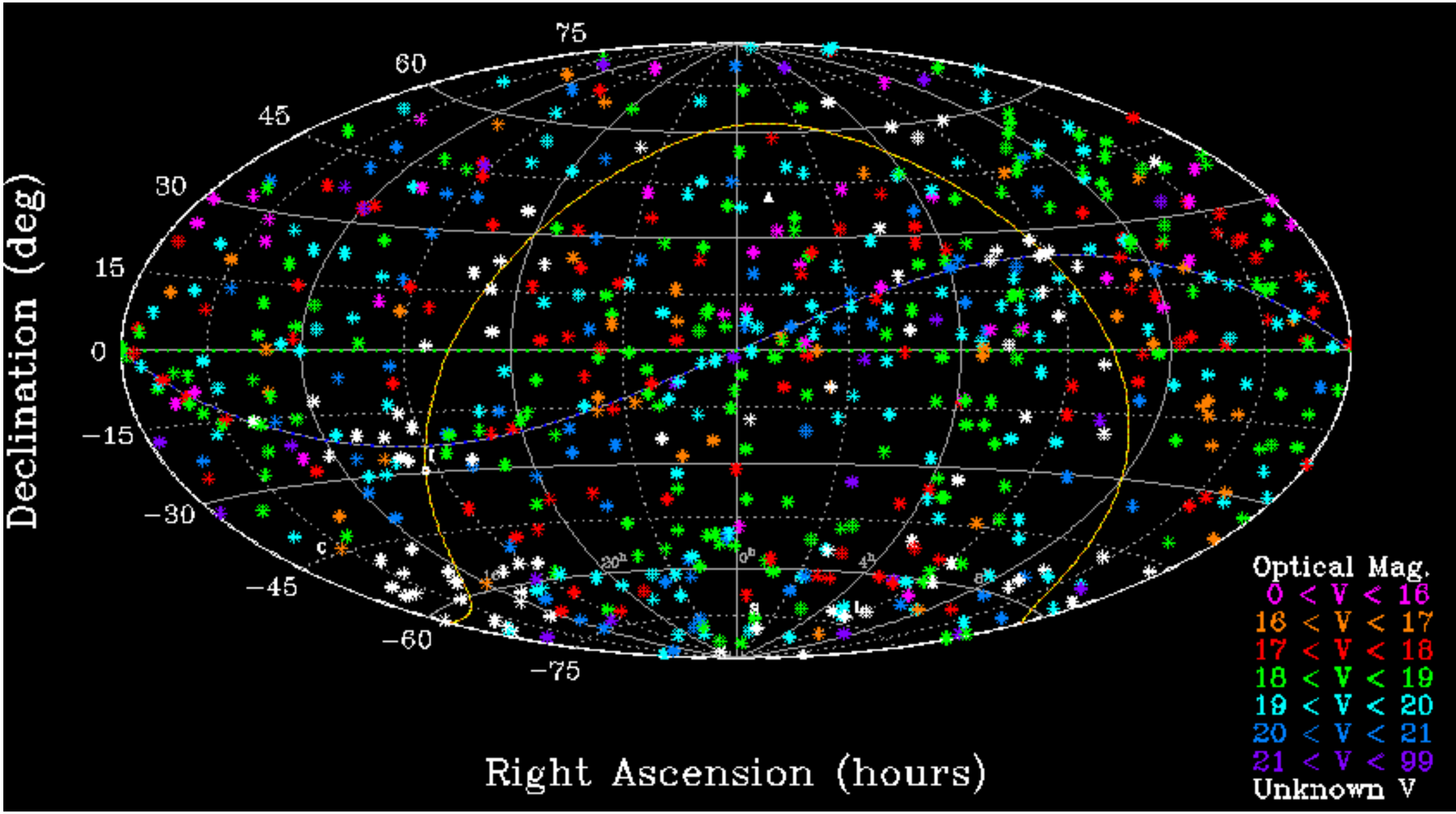


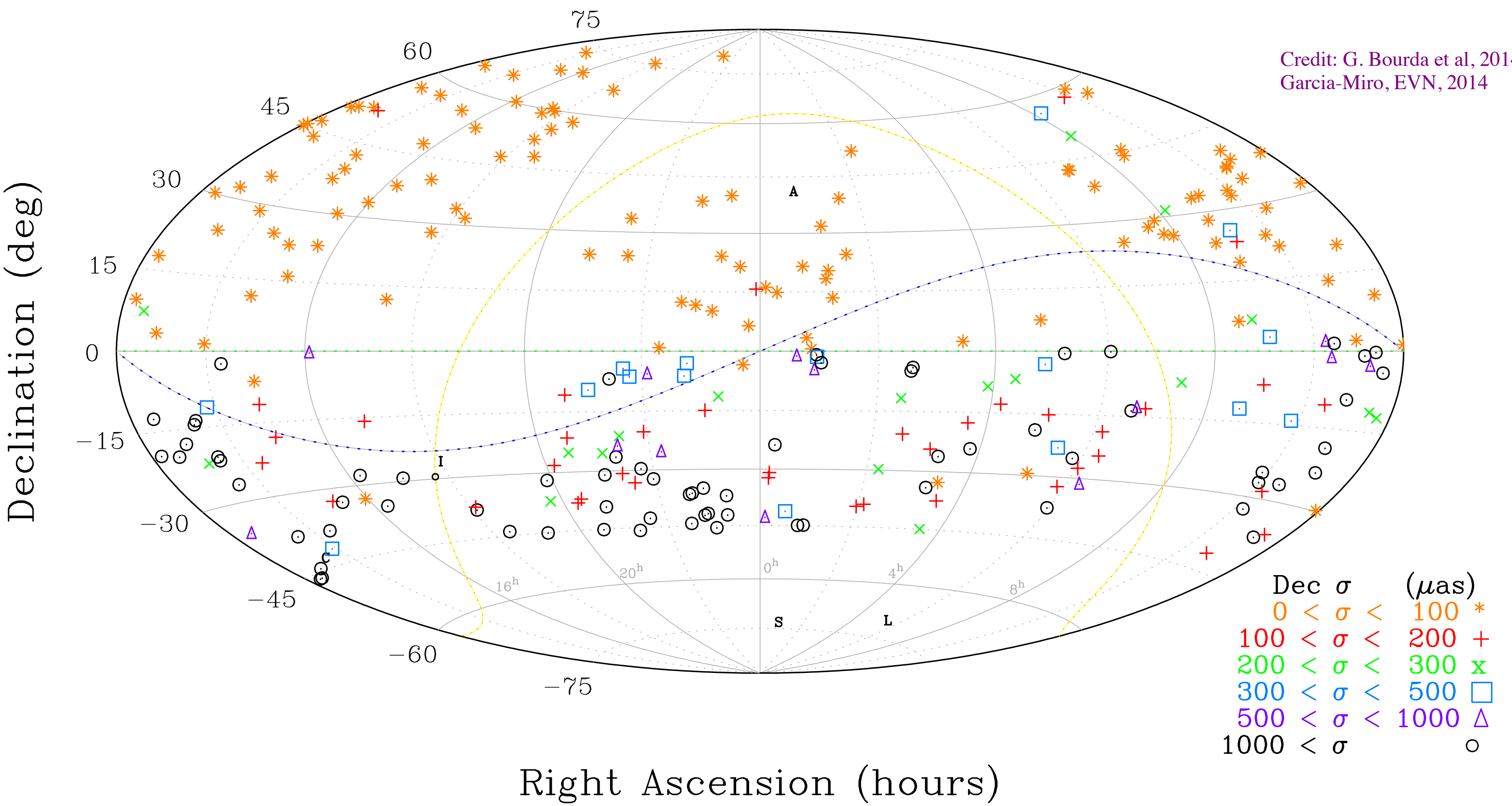
Figure credit: Garcia-Miro et al, EVN, 2014

Median optical magnitude V_{med} = 18.6 magnitude *(some obj. no data)*

> 175 of 660 objects optically bright by Gaia standard (V<18)

Credit for optical magnitude compilation: Véron-Cetty & Véron, 2010 http://adsabs.harvard.edu/abs/2010A%26A...518A..10V

Adding optically bright sources to radio



- S/X (3.6cm): Detected ~275 optically bright sources on long baselines
- Southern hemisphere additions just starting.
- XKa (9mm) is detecting only 10-20% of these due to sensitivity limits

Conclusions

3rd generation International Celestial Reference Frame

Assessment of needs for ICRF-3

1. Survey sources are most (2/3) of ICRF-2
   but positions were 5X worse than rest of ICRF-2 -> Now reduced to 1.3X worse,
2. ICRF-2 is weak in the south -> Adding new Australia/Africa data
3. High frequency frames should have more point-like sources
   but at present have fewer sources, weak in the south
   -> Added Argentina at Ka-band. Added Australia-Africa at K-band

Goals:

1. Complete ICRF-3 by 2018
   in time for comparisons with Gaia optical frame
2. Competitive precision with Gaia ~ 70 μas (1-sigma RA, Dec)
3. Uniform precision for all sources. Implies improving VCS positions.
4. High frequency frames (K, XKa, Q?)
   Improve number, accuracy, and southern coverage
5. Maximize high quality optical-radio tie sources

Backup slides

Optical vs. Radio positions

Positions differences from:

• Astrophysics of emission centroids

- radio: synchrotron from jet

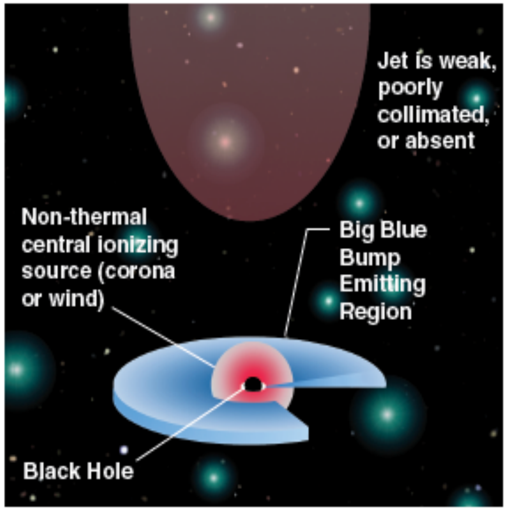
- optical: synchrotron from jet?
non-thermal ionization from corona?
"big blue bump" from accretion disk?

- optical centroid biased by host galaxy?

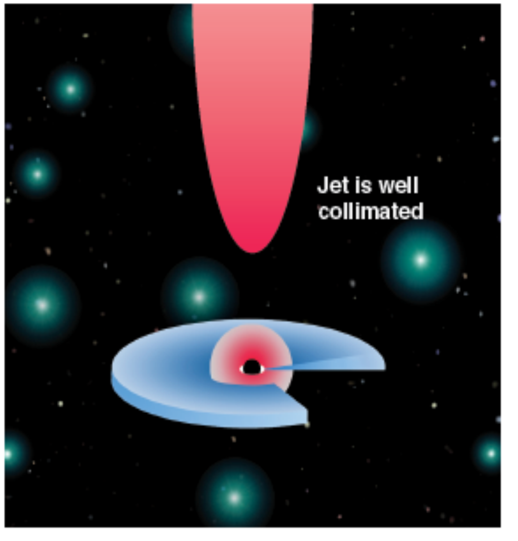
• Instrumental errors both radio & optical

• Analysis errors

Radio-quiet Quasar

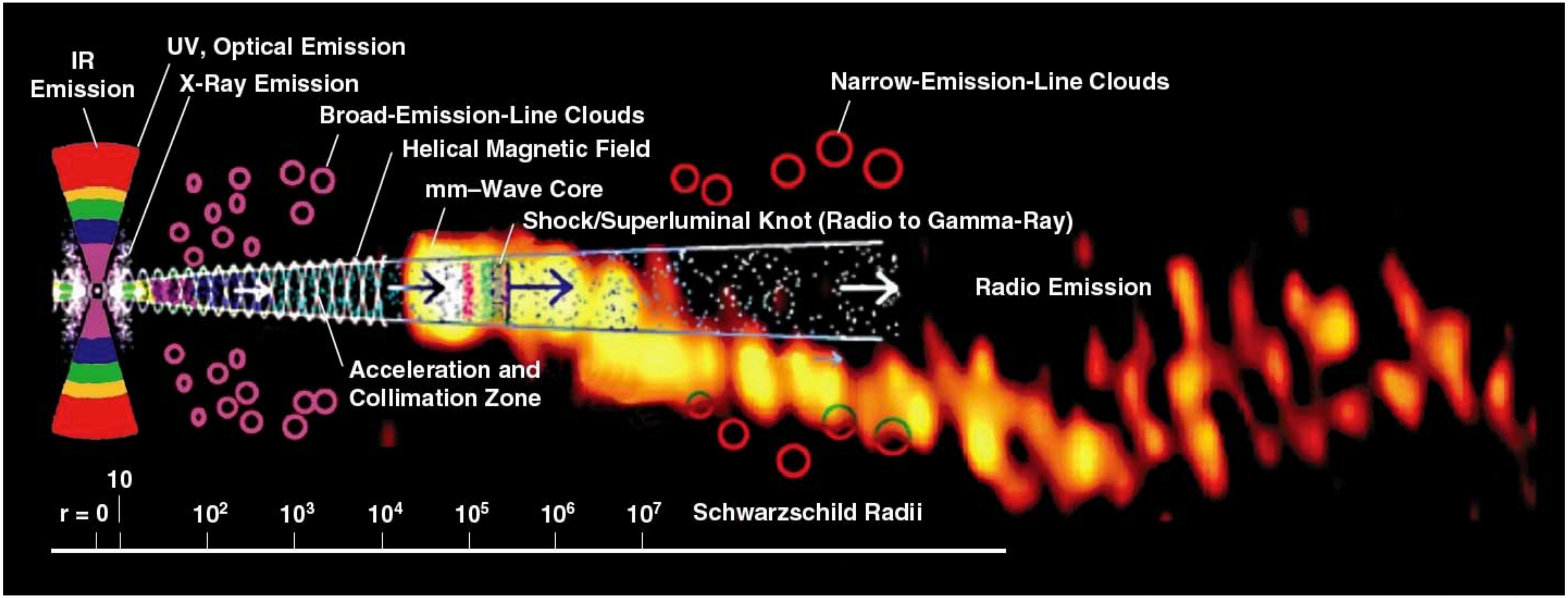


Radio-loud Quasar



Credit: Wehrle et al, μas Science, Socorro, 2009

9mm vs. 3.6cm? Core shift & structure



R~0.1-1 μas 1mas

Credit: A. Marscher, Proc. Sci., Italy, 2006.
Overlay image: Krichbaum, et al, IRAM, 1999.
Montage: Wehrle et al, ASTRO-2010, no. 310.

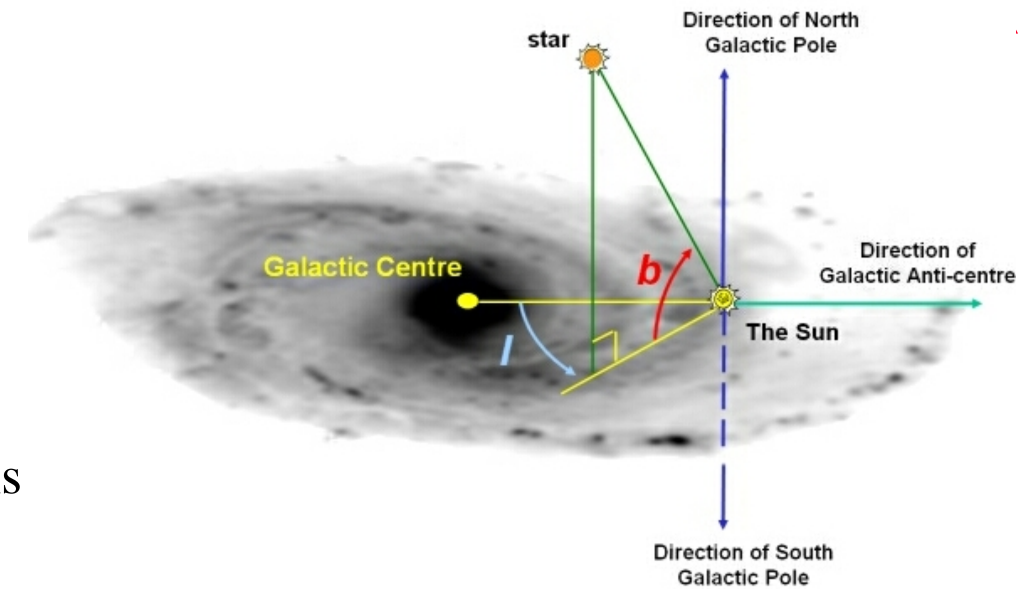
Positions differences from ‘core shift’

- wavelength dependent shift in radio centroid.
- *3.6cm to 9mm core shift:*

  100 μas in phase delay centroid?

  <<100 μas in group delay centroid? (*Porcas, AA, 505, 1, 2009*)
- shorter wavelength closer to Black hole and Optical: 9mm X/Ka better

Galactic Acceleration



http://astronomy.swin.edu.au/cosmos/N/North+Galactic+Pole

- ICRF-2 is in the Frame of the Solar System Barycenter (SSB)

- SSB has unmodelled accelerations in direction of galactic center (200 Myr period around SgrA*) plus other smaller accelerations

- SSB orbit *velocity* around Galactic center causes a large aberration which is mostly constant on decade scales
  This is currently absorbed as ~constant distortion in reported positions.

- SSB orbit *acceleration* causes changes of 5 μas/yr (times projection factor)

- IAU's ICRS working group (not ICRF-3 wg) is charged with setting standard
- We anticipate the need for a default model in the Gaia era to account for motion between mean epochs of sources in Gaia & VLBI frames

Charter for IAU Division A Working Group on the Third Realization of the International Celestial Reference Frame

The purpose of the IAU Division A Working Group on the Third Realization of the International Celestial Reference Frame (ICRF) is to produce a detailed implementation and execution plan for formulation of the third realization of the ICRF and to begin the process of executing that plan.

The implementation plan along with execution progress will be reported to IAU Division A at the XXIX General Assembly of the IAU in 2015.

Targeted completion of the third realization of the ICRF will be the XXX General Assembly of the IAU in 2018.

Derived from VLBI observations of extragalactic radio sources, the third realization of the ICRF will apply state-of-the-art astronomical and geophysical models and analysis strategies, and utilize the entire relevant astrometric and geodetic data set. The Working Group will examine and discuss new processes and procedures for formulating the frame along with the potential incorporation of new global VLBI arrays, and new observing frequencies offering the potential for an improvement over ICRF2. The Working Group will provide oversight and guidance for improving the relevant data sets.