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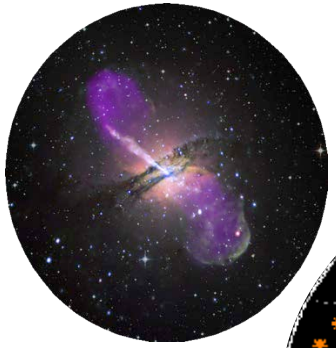
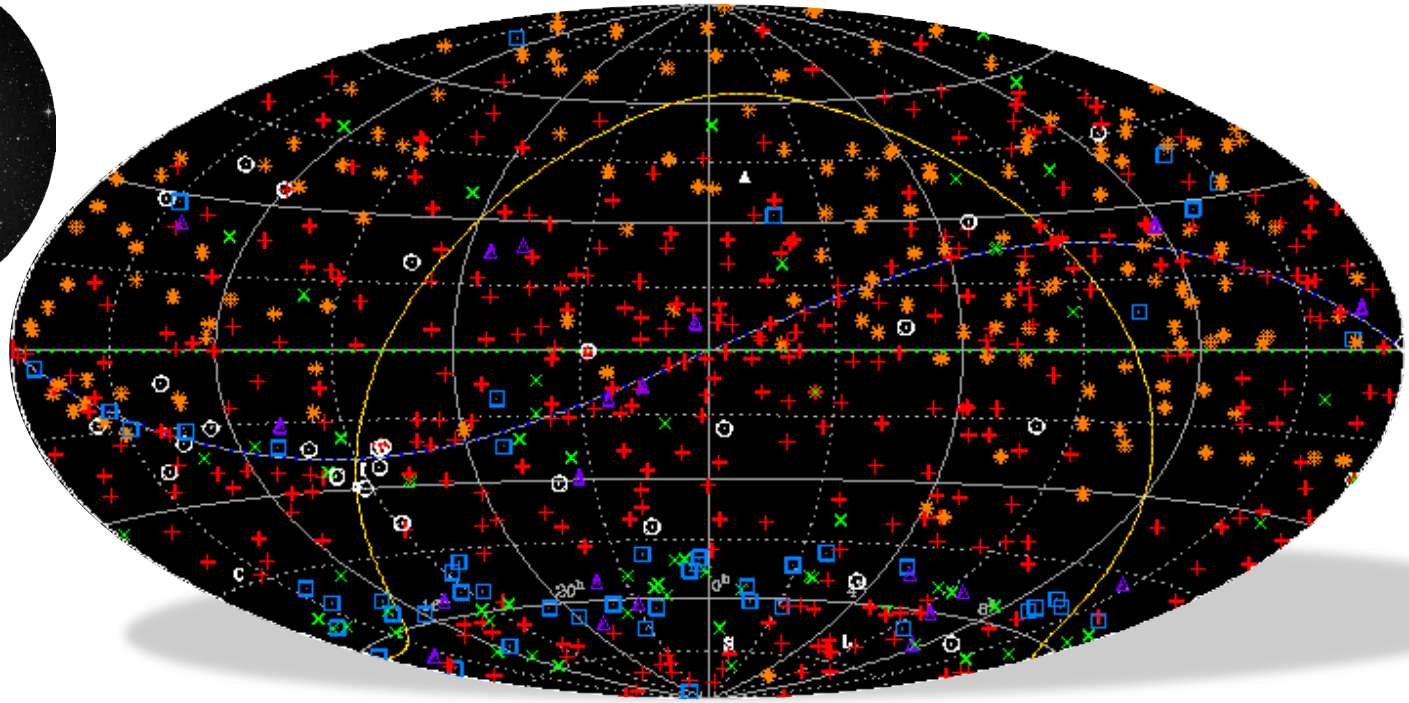
IVS General Meeting 2016

The X/Ka Celestial Reference Frame: Assessing Accuracy – Can it be more accurate than the ICRF2?





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2016 March 17, Ekudeni, South Africa

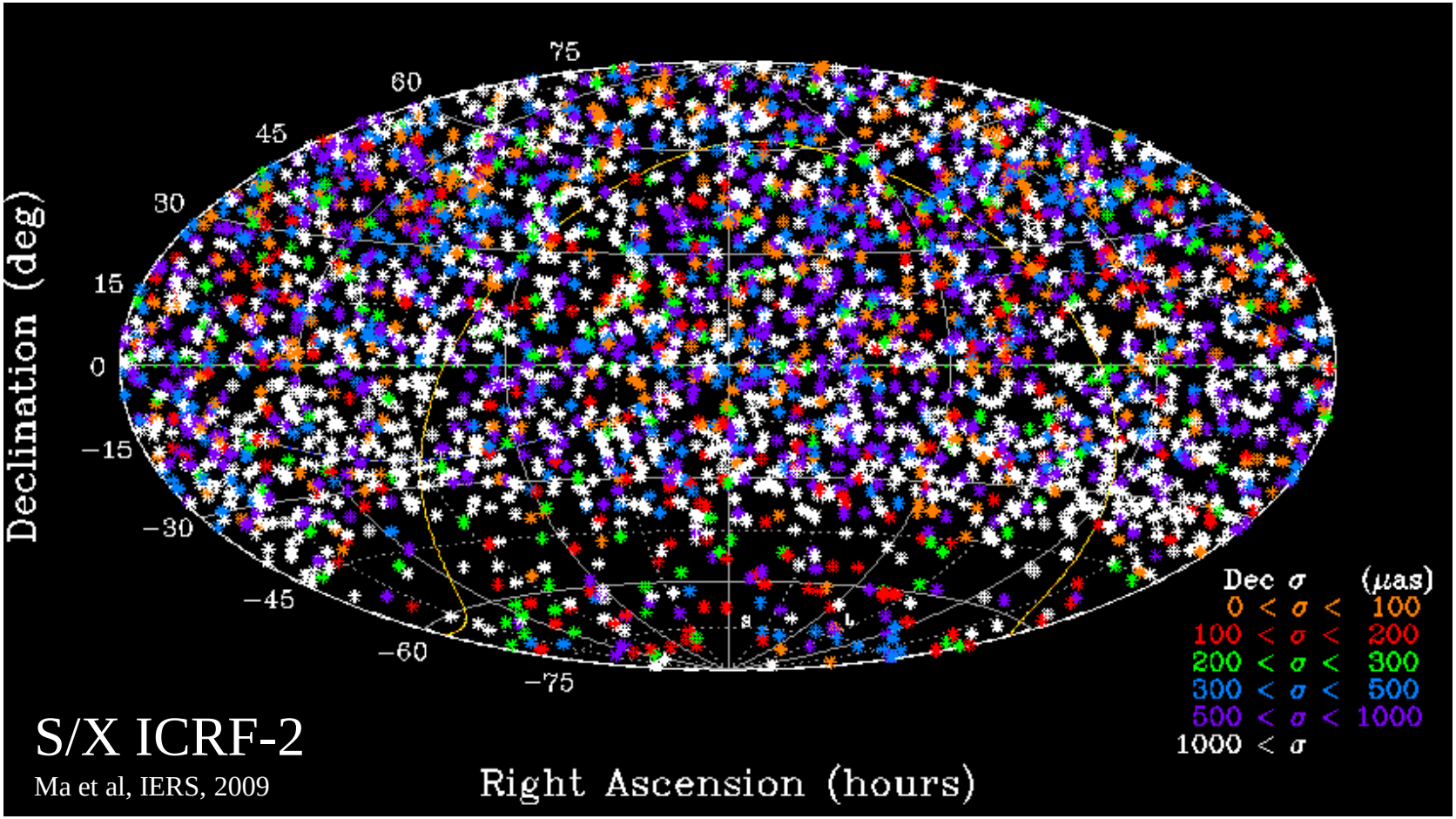
Overview:

- How does the XKa Celestial Frame compare to the ICRF-2?
  - Median precision, number of sources
  - wRMS differences, mean offsets, zonal differences

- Systematic Errors
  - Troposphere
  - Instrumentation: twin telescope tests
  - Source Structure

- **Optical-radio frame tie** for Gaia
  Gaia instrumental errors
  optical host galaxy
  Binary Black Holes

ICRF2 can be improved

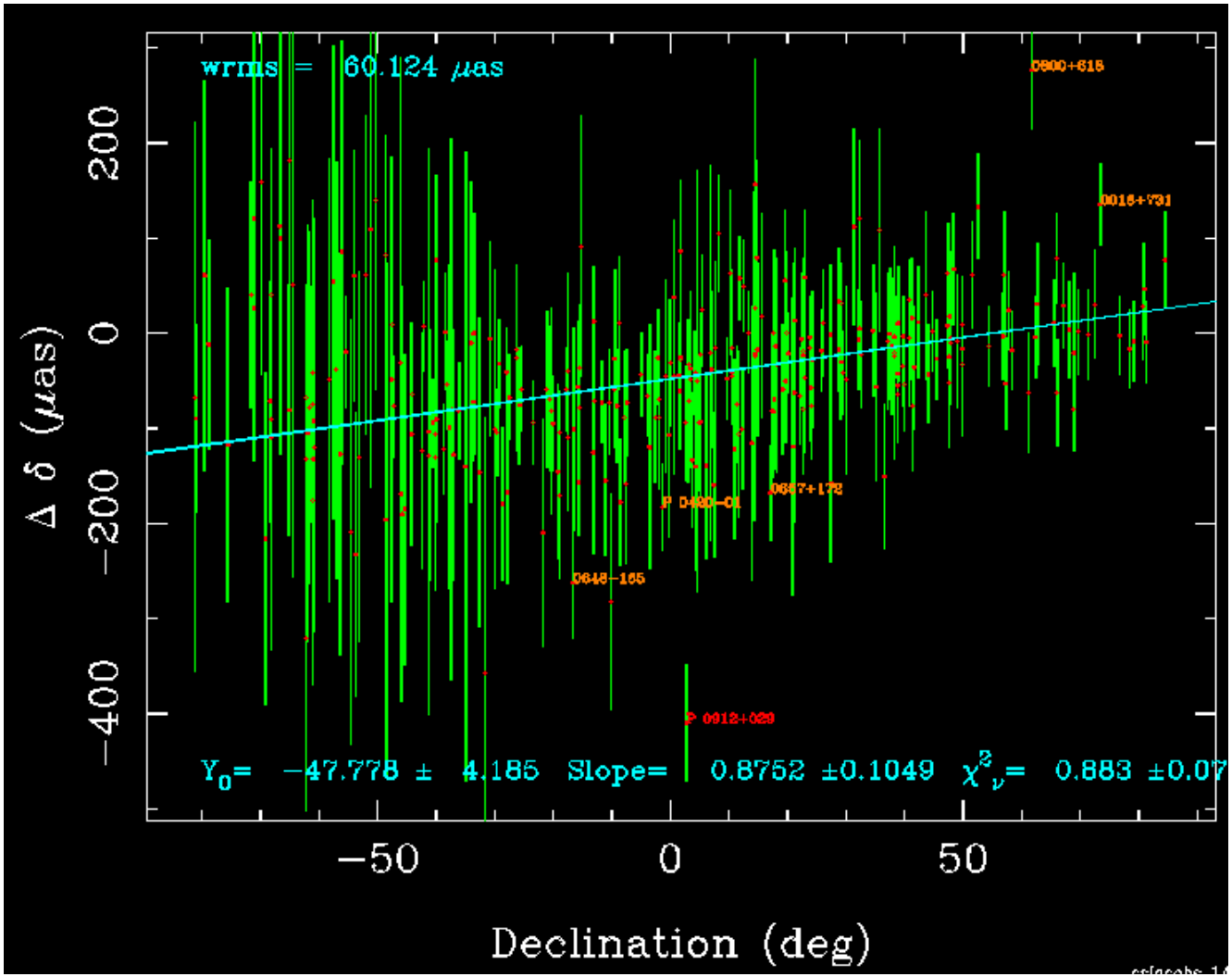


VLBI generally & ICRF-2 specifically lacks southern observations

Many low precision survey sources

Many sources have significant source structure

S/X zonal errors: ICRF2-Defining 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

XKa (diag) vs. S/X Celestial Frames

	XKa vs. ICRF-2		XKa vs. SX(GSFC-151218)		
N_Common	512		551		
N_sessions	54	30	52	57	
N_obs	83	601	80	1297	
σ_α	77	82	81	27	µas
σ_δ	113	108	116	41	µas

Differences:

wRMS α^*	197	181	µas
wRMS δ	199	198	µas
Mean α^*	29	31	µas
Mean δ	-148	-90	µas
$\Delta\alpha^*$ vs. δ	1.7+-0.3	1.1 +-0.2	µas/deg
$\Delta\delta$ vs. δ	0.7 +-0.4	0.5 +- 0.3	

XKa (tcov) vs. S/X Celestial Frames

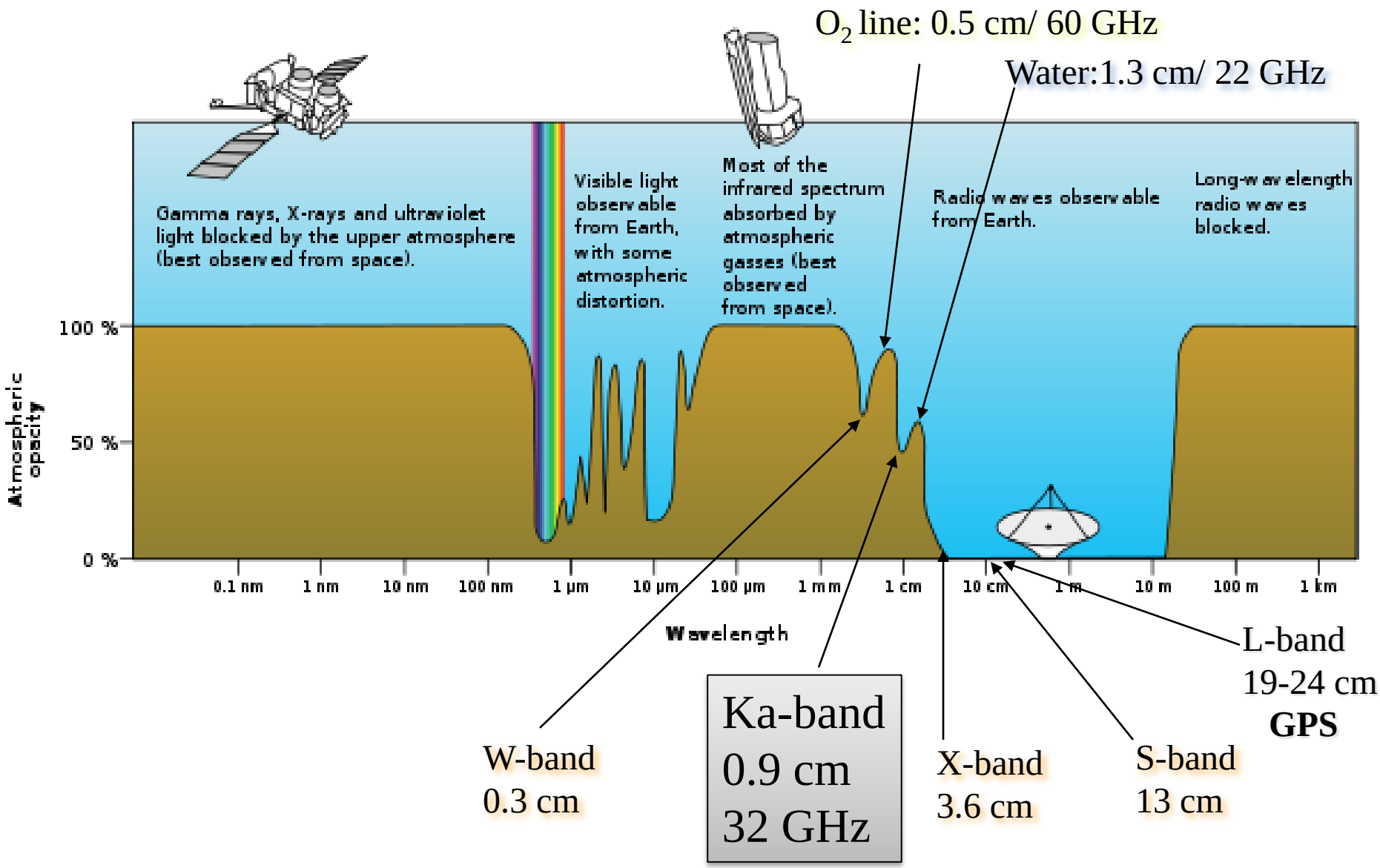
	XKa vs. ICRF-2		XKa vs. SX(GSFC-151218)		
N_Common	512		551		
N_sessions	54	30	52	57	
N_obs	83	601	80	1297	(takes 16X more obs)
σ_α	66	82	69	27	µas
σ_δ	97	109	100	41	µas

Differences:

wRMS α^*	194	177	µas
wRMS δ	216	199	µas
Mean α^*	29	34	µas
Mean δ	-243	-185	µas
$\Delta\alpha^*$ vs. δ	1.7+-0.3	1.1 +-0.2	µas/deg
$\Delta\delta$ vs. δ	1.8 +-0.3	1.6 +- 0.2	

S/X solutions are moving closer to X/Ka!

Why observe in Radio? Deep 'Window'



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

Why observe at Ka-band? Resolution

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

- Resolution for an interferometer
  Wavelength / Baseline example: Baseline of 10,000 km
  S/X (36mm) resolution ~0.8 mas
  X/Ka (9mm) resolution ~ 0.2 mas

- X/Ka resolution is 60-250X better than Gaia optical
  4X better than S/X VLBI

XKa Twin Telescope Tests of Instrumental Noise Floor

- NASA Deep Space Network has multiple 34-meters per site

- Short baselines (200-300 meters), same clock, nearly identical tropsophere, same mechanical structures, same geophysics (tides, plate tectonics).

  Expect that residuals are dominated by instrumental floor.

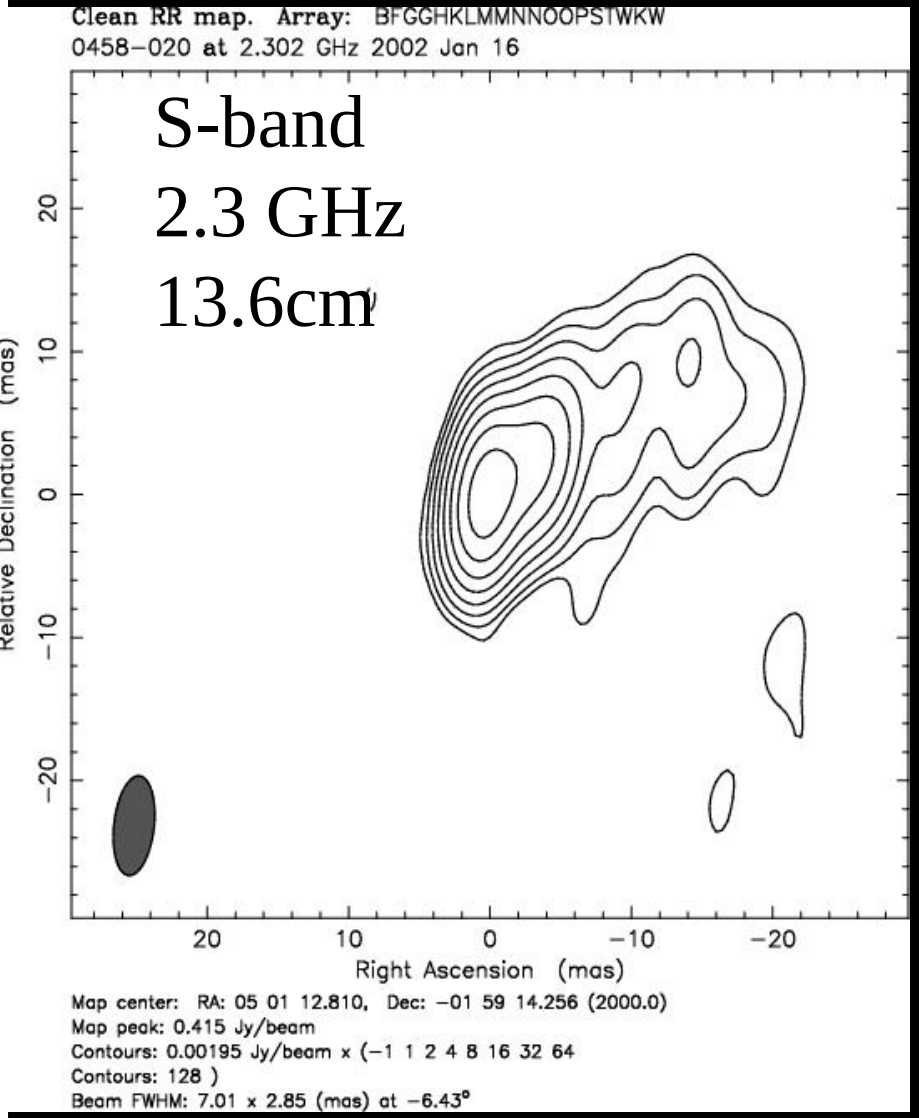
- **Results**

yymmdd	stations	Nobs	wRMS (psec)
140528	34-35	317	4.6
140712	34-35	132	6.3
140719	34-35	153	2.7
140725	34-35	261	11.1
151205	54-55	119	5.2
160118	25-26	265	6.8
160131	54-55	132	5.4

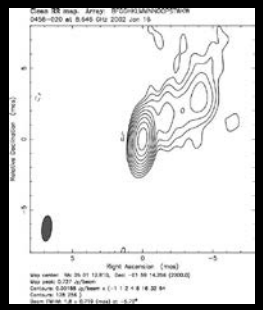
-> About 3 to 11 psec (1 to 4 mm) instrumental floor

or about 20 to 80 μas translated to long baselines

Source Structure vs. Frequency (absolute scale)



X-band
8.6 GHz
3.6cm



K-band
24 GHz
1.2cm

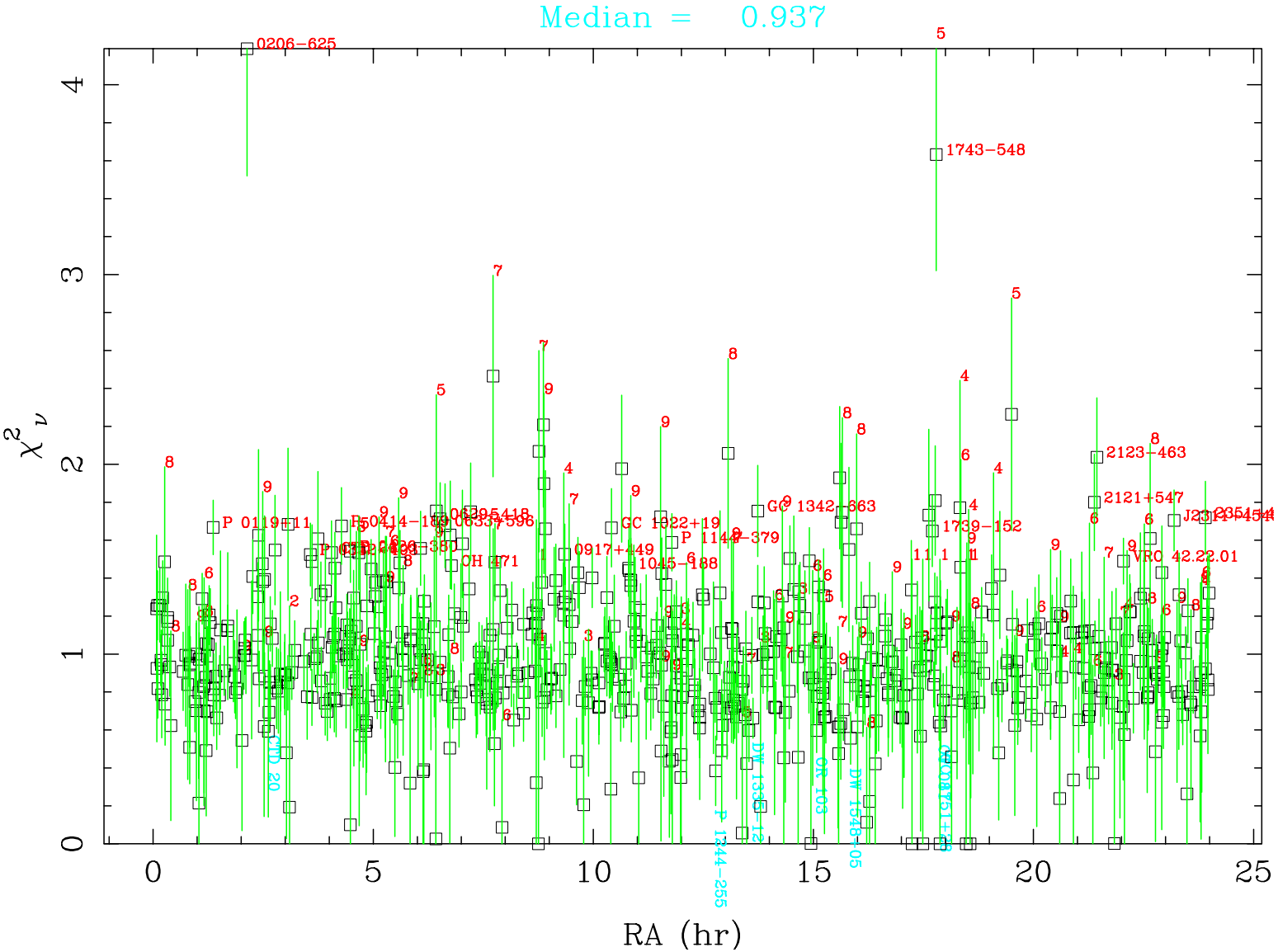
Q-band
43 GHz
0.7cm

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

Ka-band
32 GHz
0.9cm

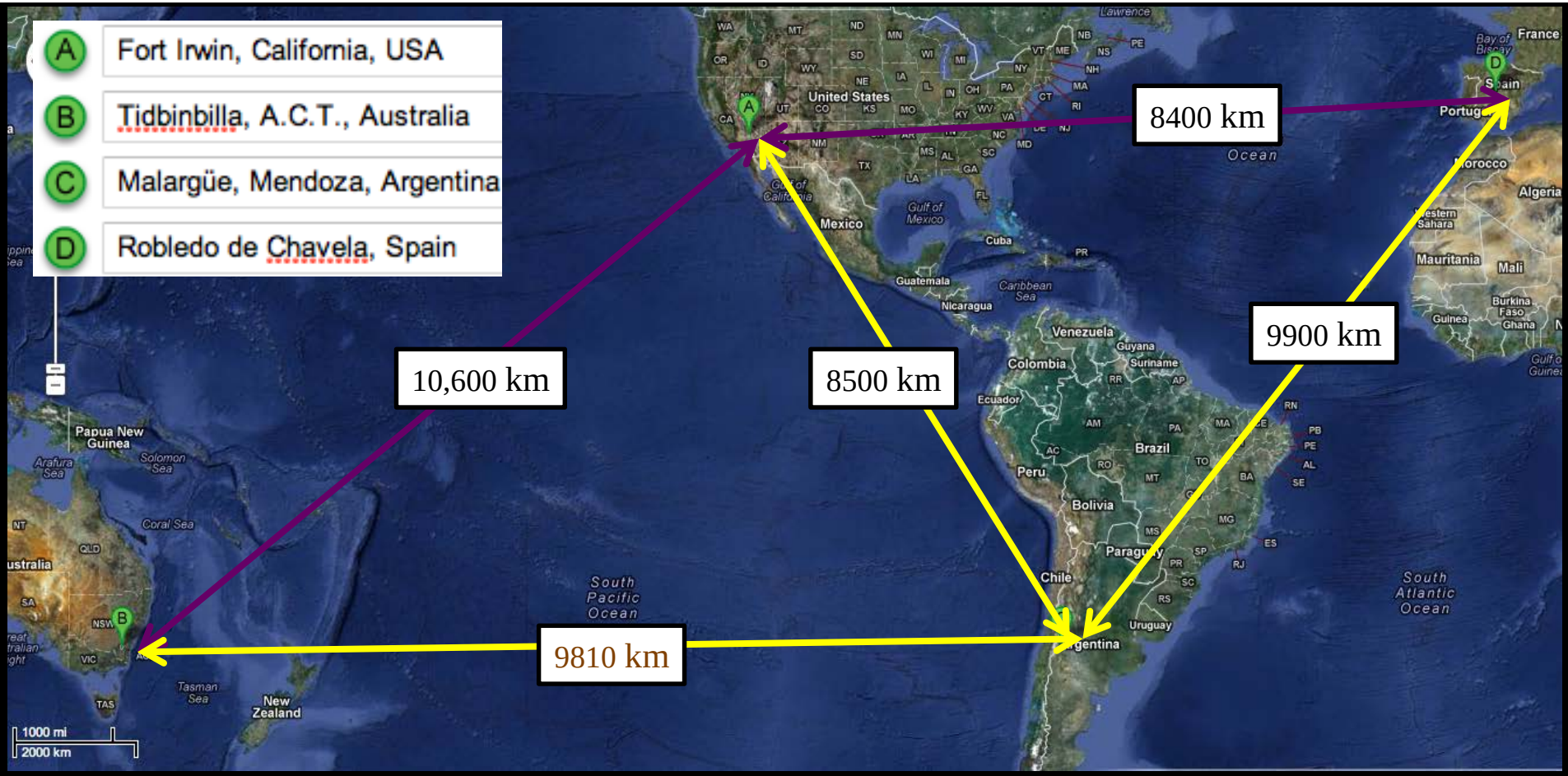
Images credit: P. Charlot et al, AJ, 139, 2010

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



No sign of dominant systematics. Median number of sessions = 52, over 10 years

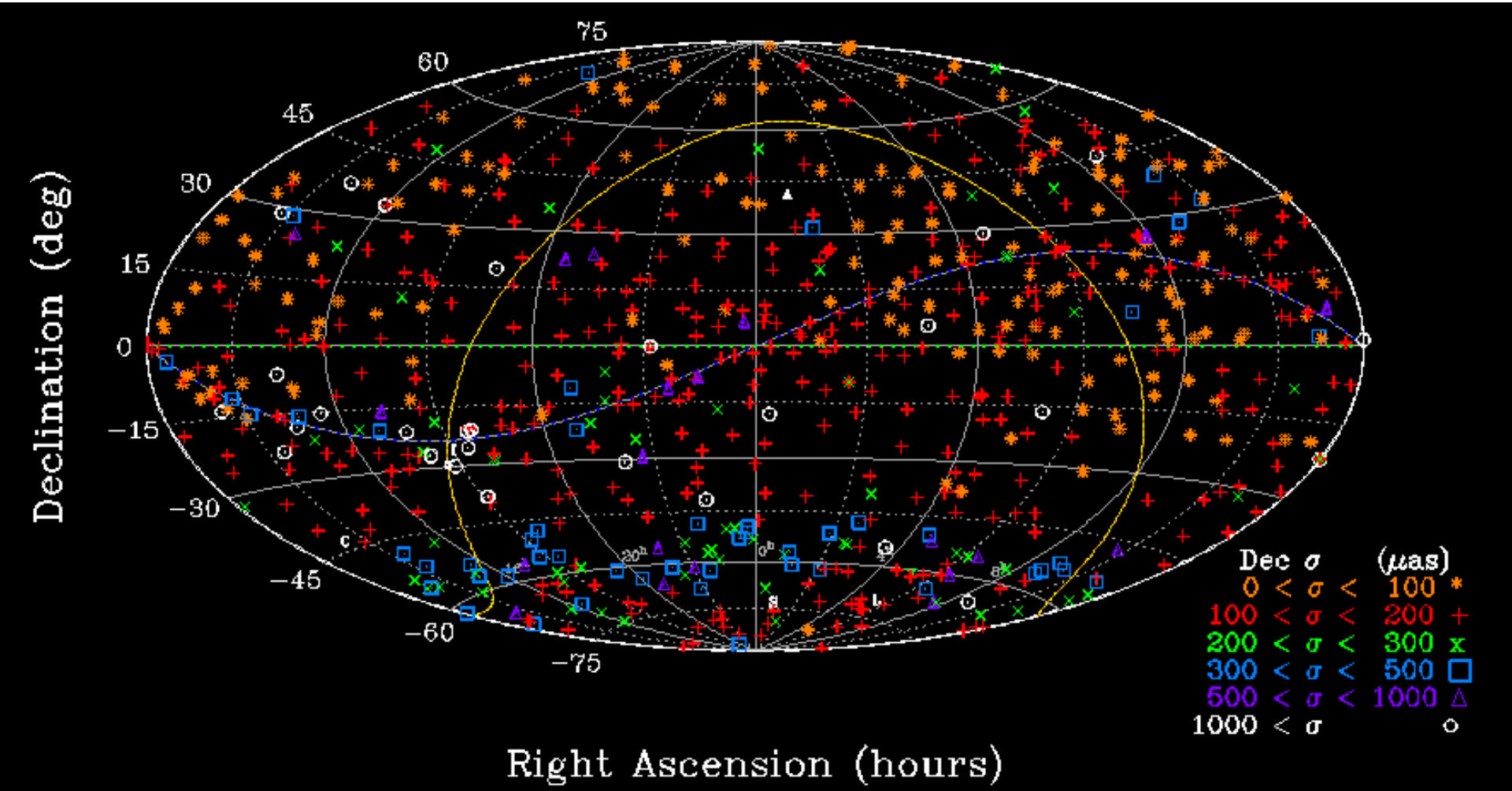
X/Ka Network Geometry



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

NASA-ESA 32GHz
674 source, median σ_δ ~100 µas



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

XKa accuracy goal sub-100 µas

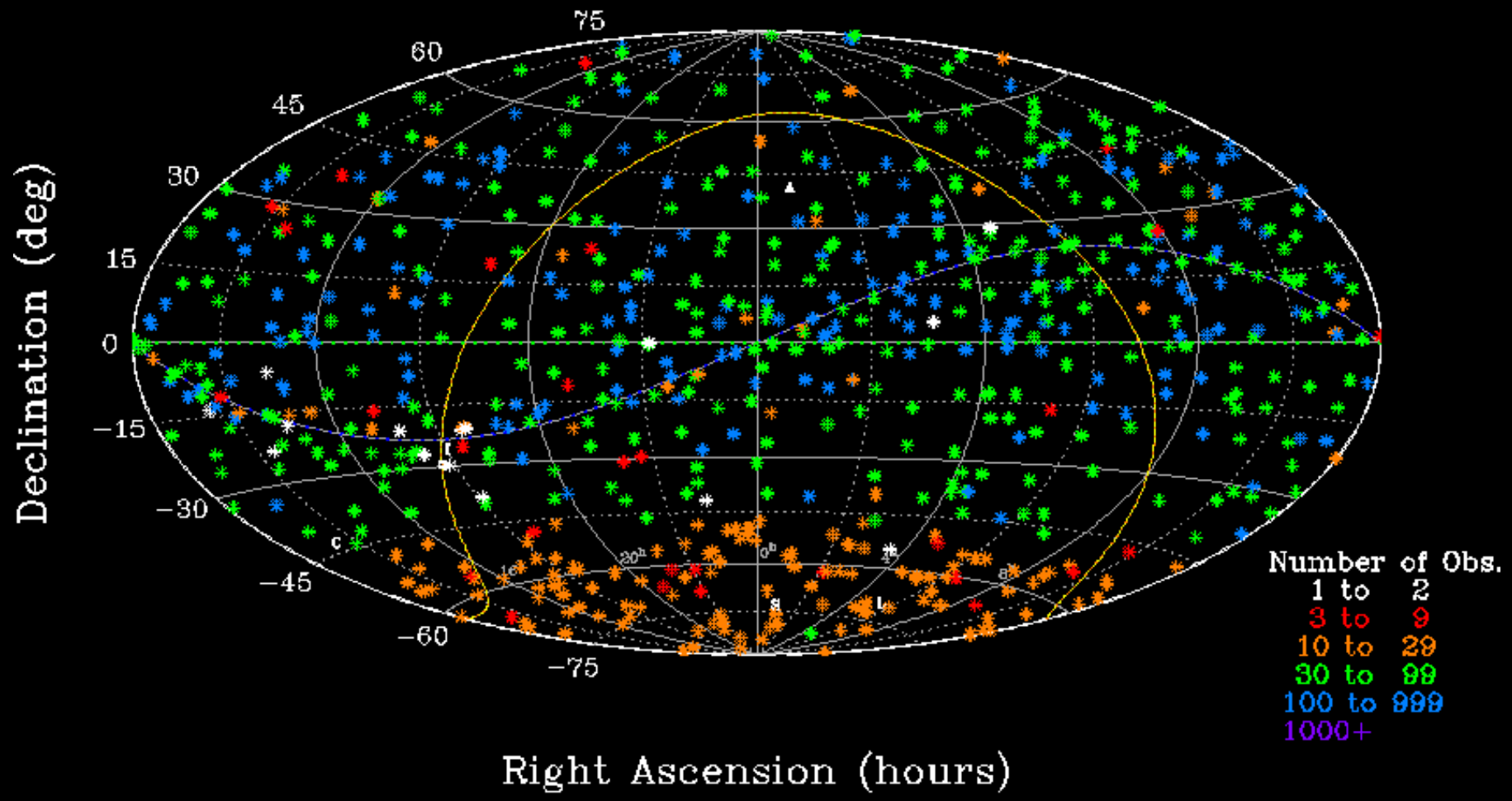
- Goal of < 100 µas (< 5mm)
- Largest celestial frame error:
  Zonal errors vs. Declination of ~ 200 µas

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

  - Terrestrial Frame corrupted at 5 mm level?
    DSA03 has velocity from only 3 years data
    Twin telescopes (DS25/26, 34/35, 54/55) have few mm issues

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

NASA-ESA 32GHz Number of observations



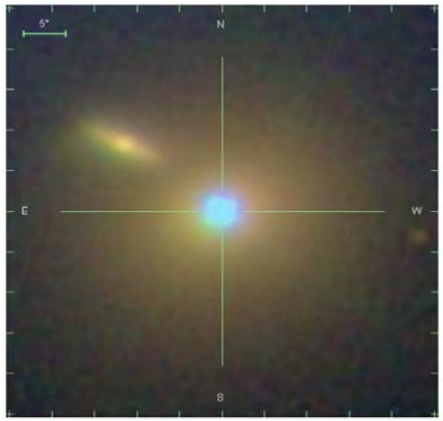
Need Argentina- Australia observations to balance frame for Dec < -45 deg

Tying VLBI to Gaia optical Frame:
Adding optically bright sources to radio frame

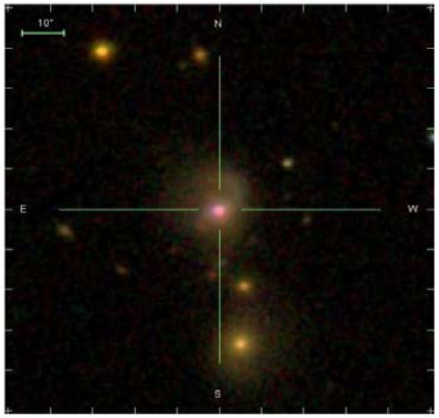
- Radio interferometry (VLBI) is the only independent technique capable of sub-milliarsec full sky verification of Gaia
- For Gaia a bright sources means V < 18th magnitude
- S/X (3.6cm): Expect about 400-500 optically bright sources
- Southern hemisphere additions underway
- XKa (9mm) may have ~200 optically bright sources.
- Formal precision of tie should be better than 10 µas
- True accuracy expected to be dominated by systematic errors.

Optical vs. Radio systematics offsets

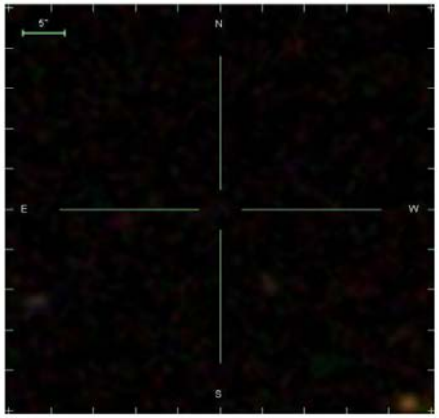
Credit: SDSS



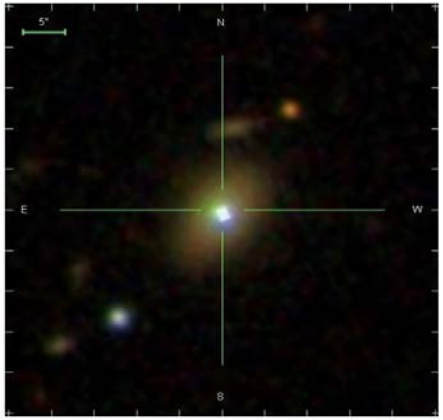
1101+384



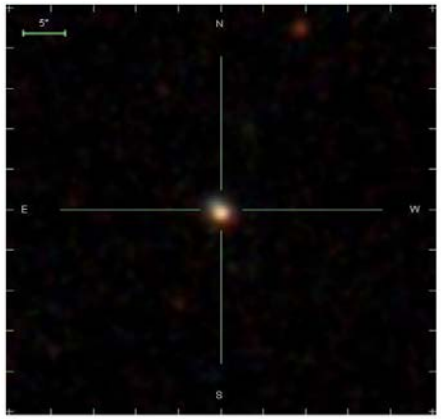
0007+106



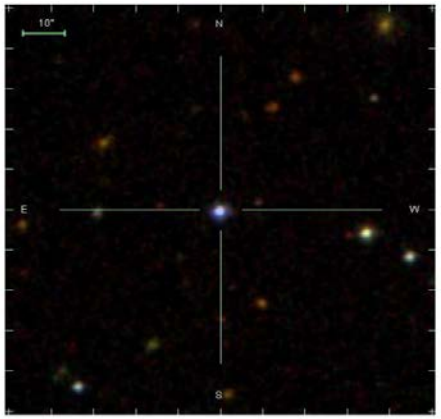
0920+390



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)

Conclusions

- XKa diagonal median precision comparable to ICRF2
  trop cov correlated noise precision better than ICRF2

- Recent S/X solutions agree better with X/Ka than
  S/X based ICRF2 does.

- Source structure is reduced at X/Ka (vs. S/X)

- If zonal errors can be addressed, XKa can be
  more accurate than the ICRF2.

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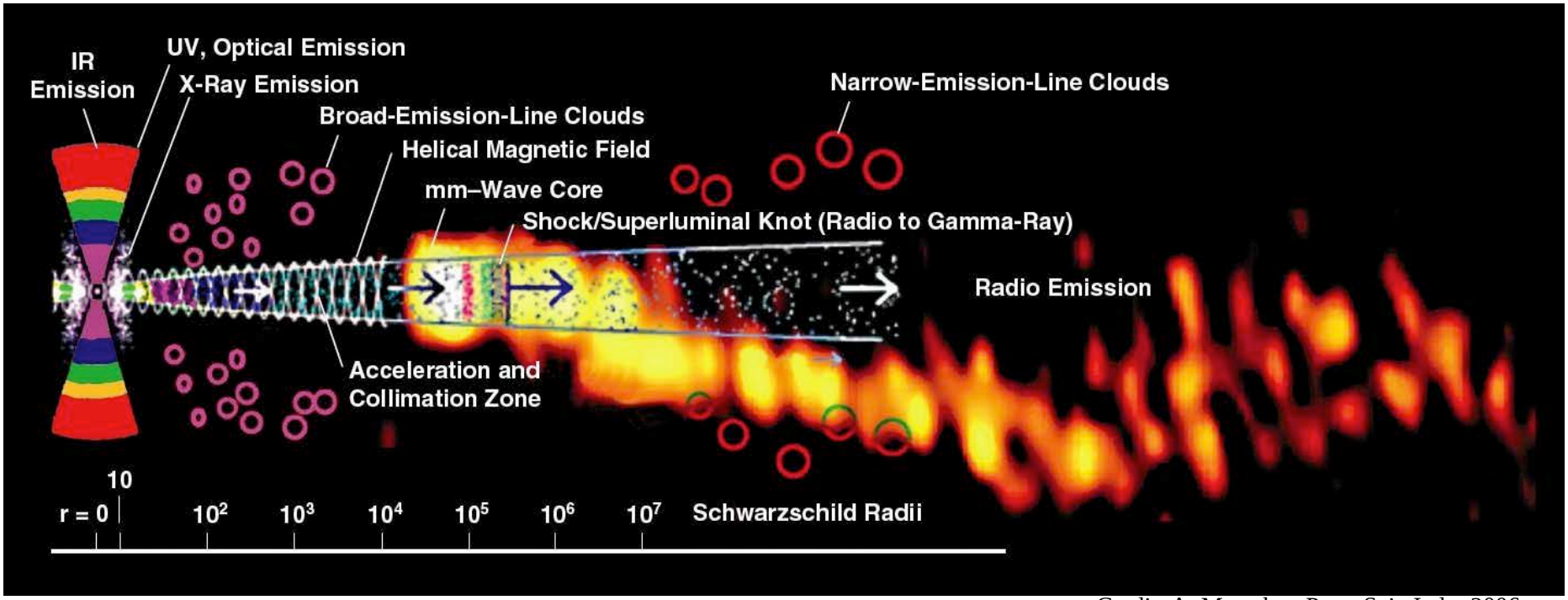
Backup slides

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.

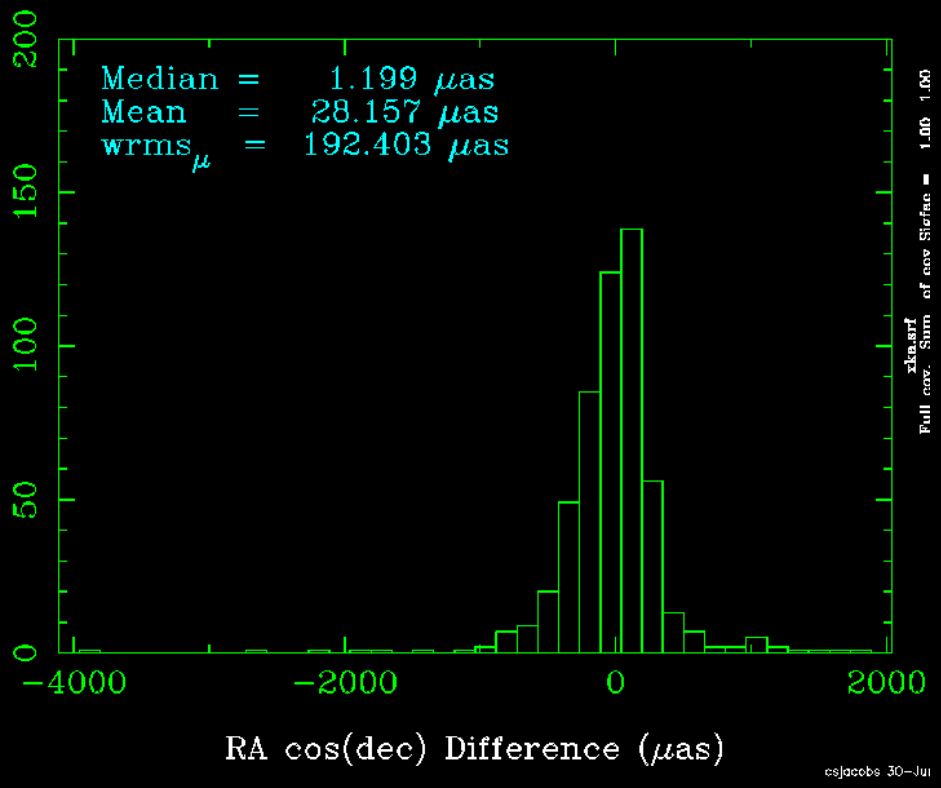
Positions differences from 'core shift'

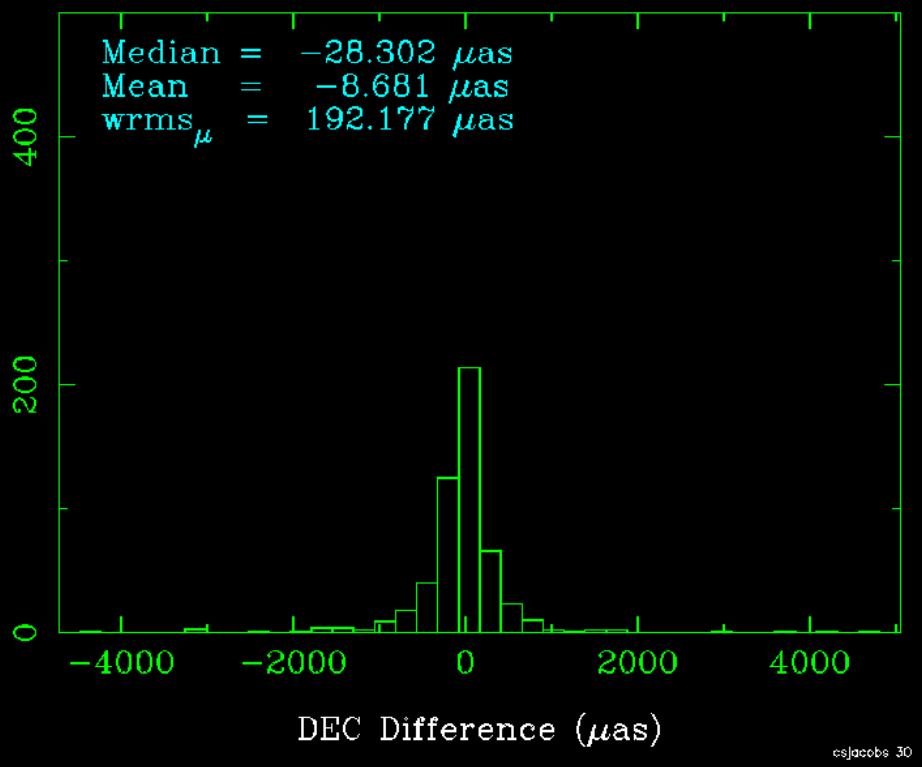
- wavelength dependent shift in radio centroid.
- *3.6cm to 9mm core shift:*

  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

XKa vs. SX ICRF2: 512 sources





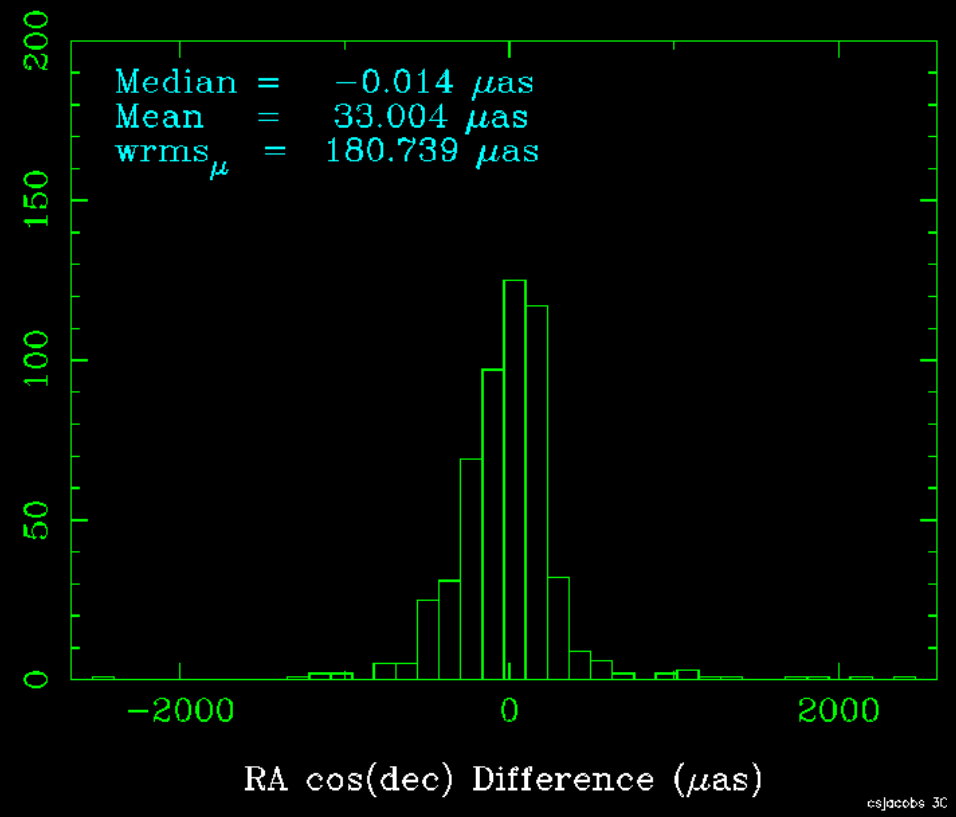
wRMS(α cosδ) = 0.93 nrad

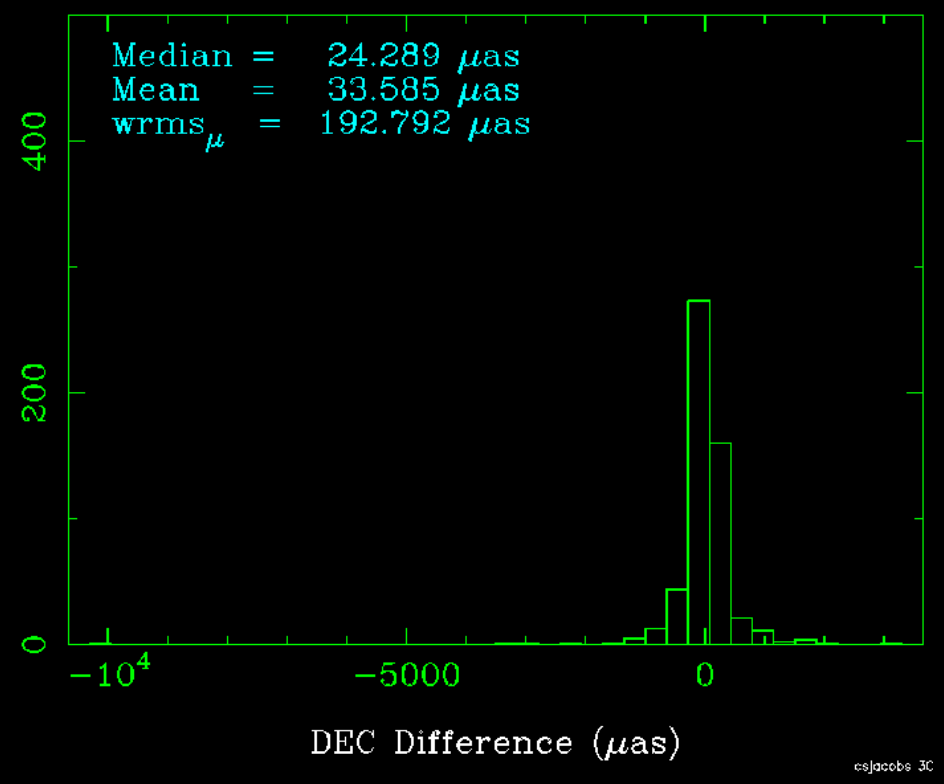
No bias, but zonals errors ~200 μas

wRMS(δ) = 0.93 nrad

Dec bias "cured" by recent data!

XKa vs. recent SX: 551 sources





wRMS(α cosδ) = 0.88 nrad

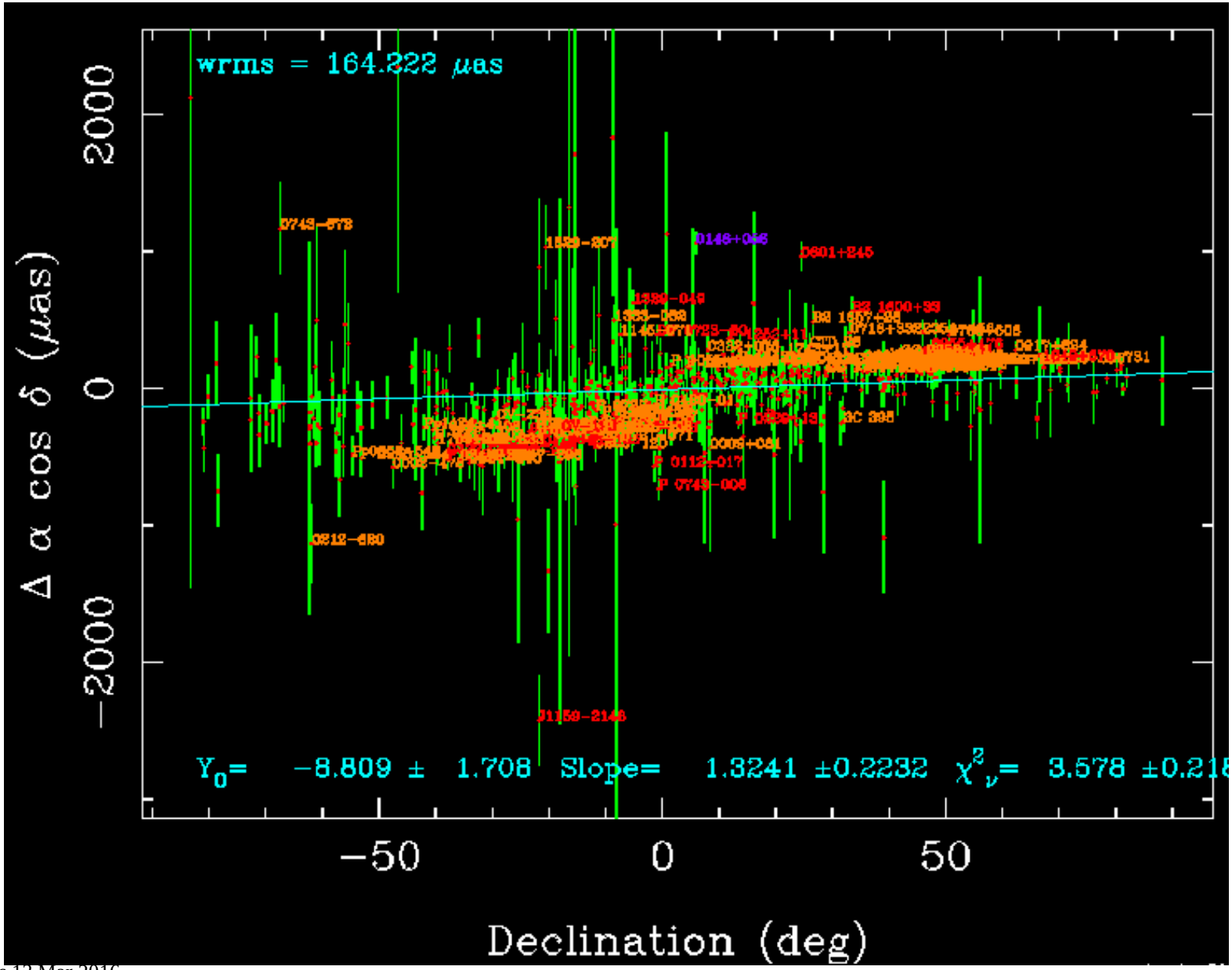
wRMS(δ) = 0.94 nrad

δ Mean offset negligible

δ zonal error dominates

GSFC-151218: credit Gordon et al, private communication, NASA Goddard, 2015

XKa vs. SX: Zonal errors

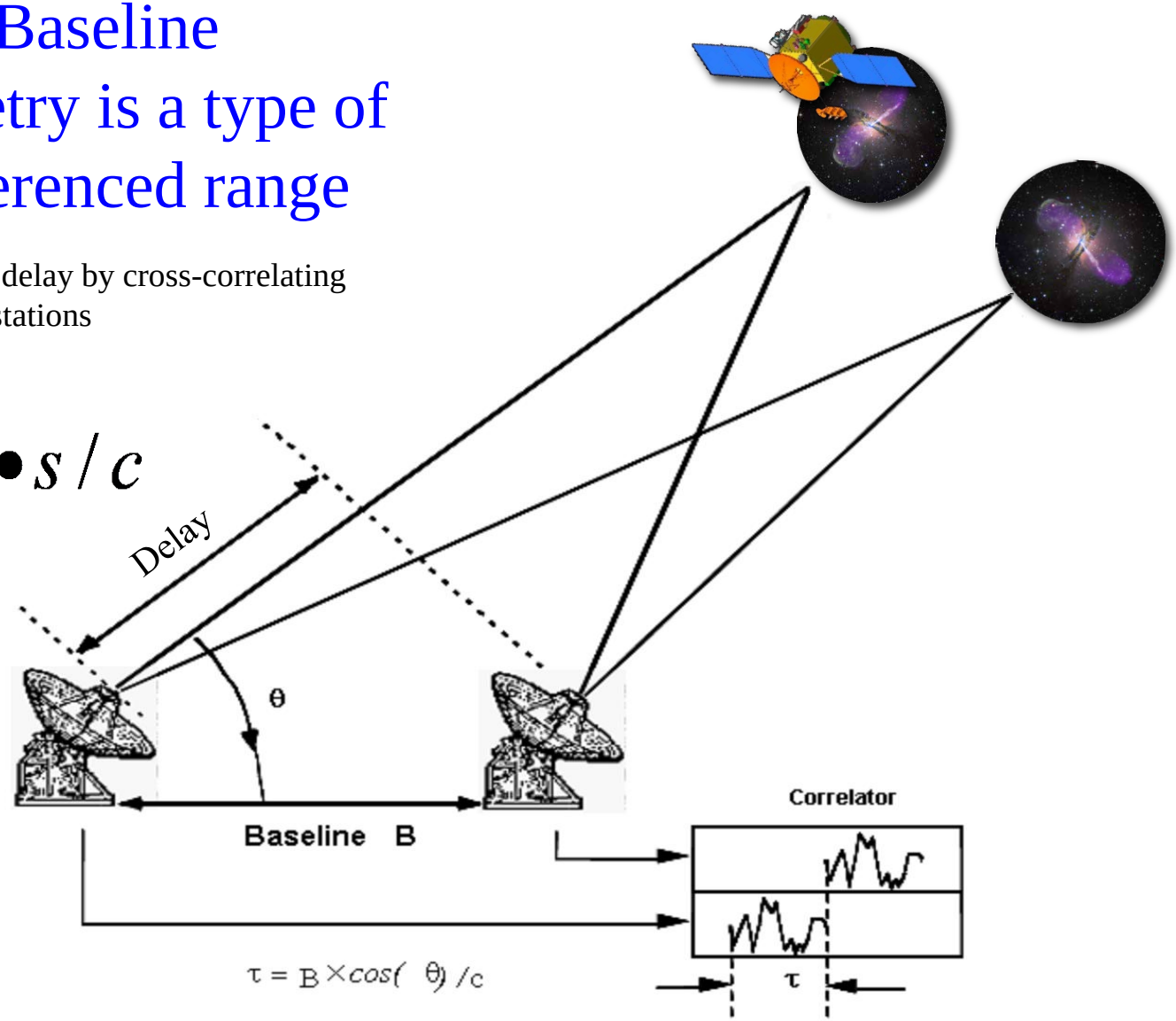


VLBI Delay: $\tau = B \bullet s / c$

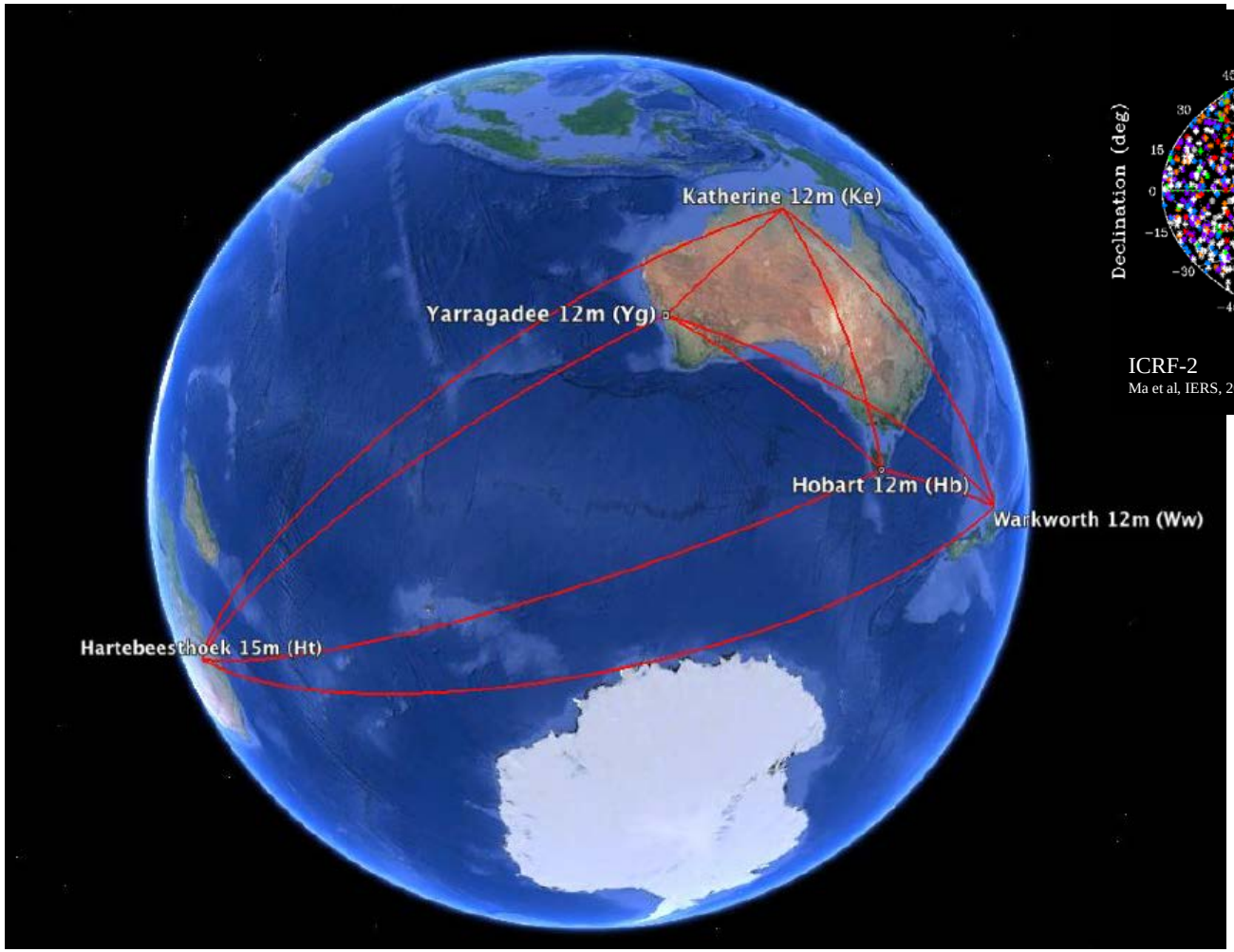
Very Long Baseline Interferometry is a type of station differenced range

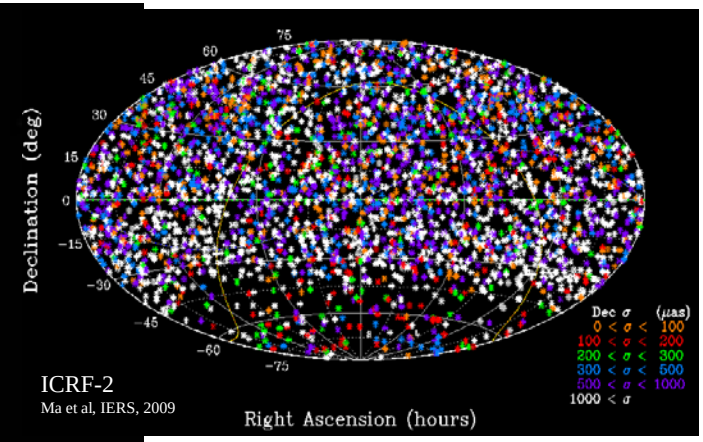
- Measures geometric delay by cross-correlating signal from two (2) stations

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



S/X-band Plan for Southern Improvements



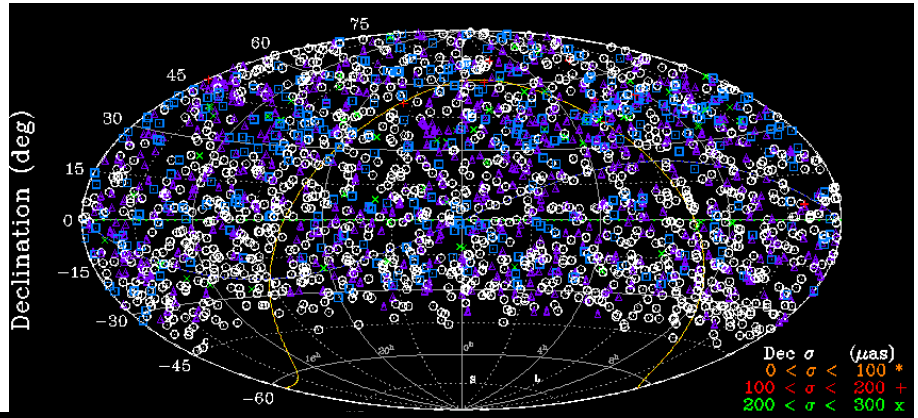


ICRF-2
Ma et al, IERS, 2009

Observe southern sources with South Africa to Australia/New Zealand baselines

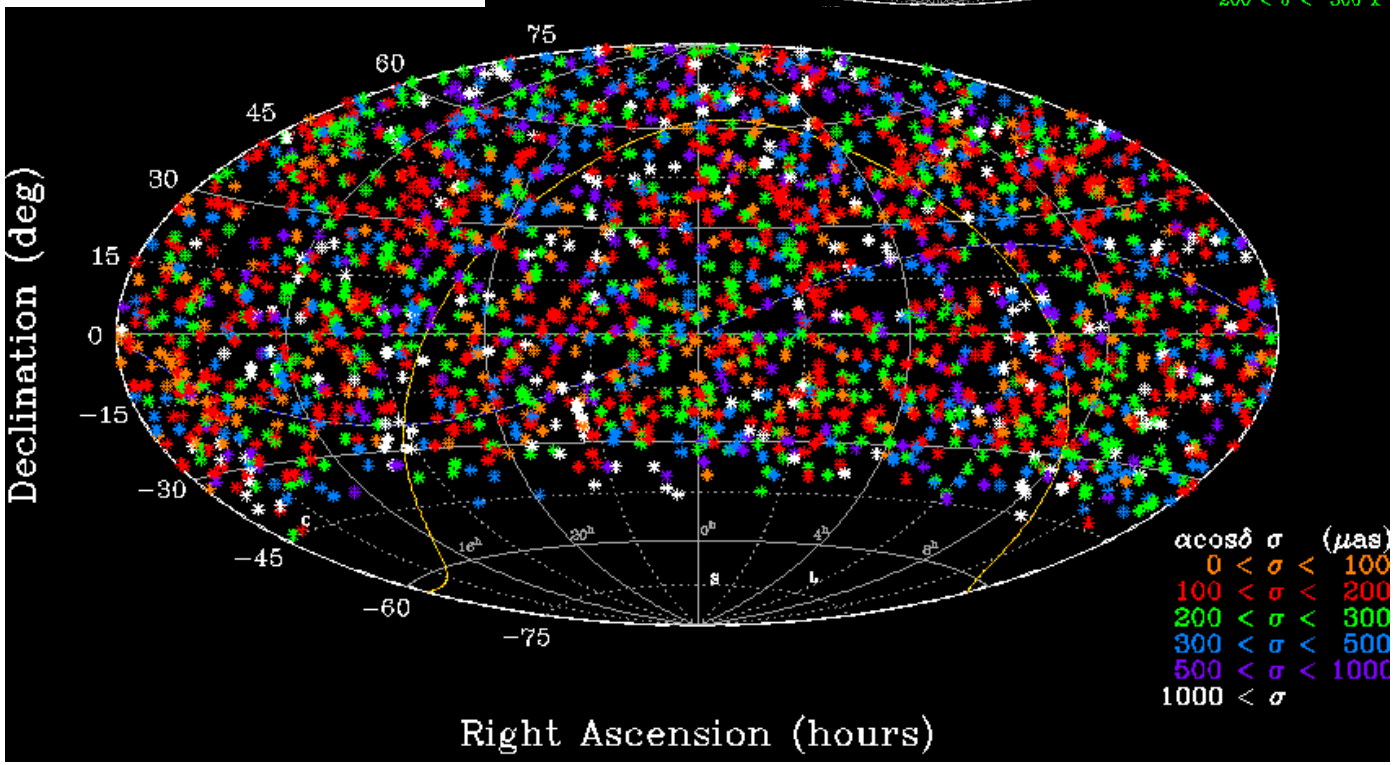
VLBA Calibrator Survey improvement

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



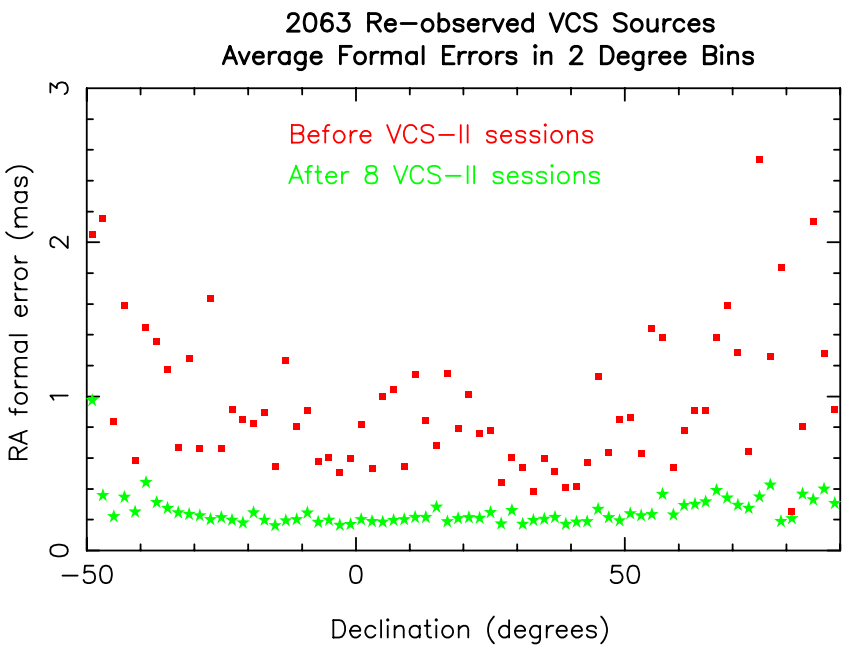
VCS-II:
RA 0.23 mas
Dec 0.39 mas

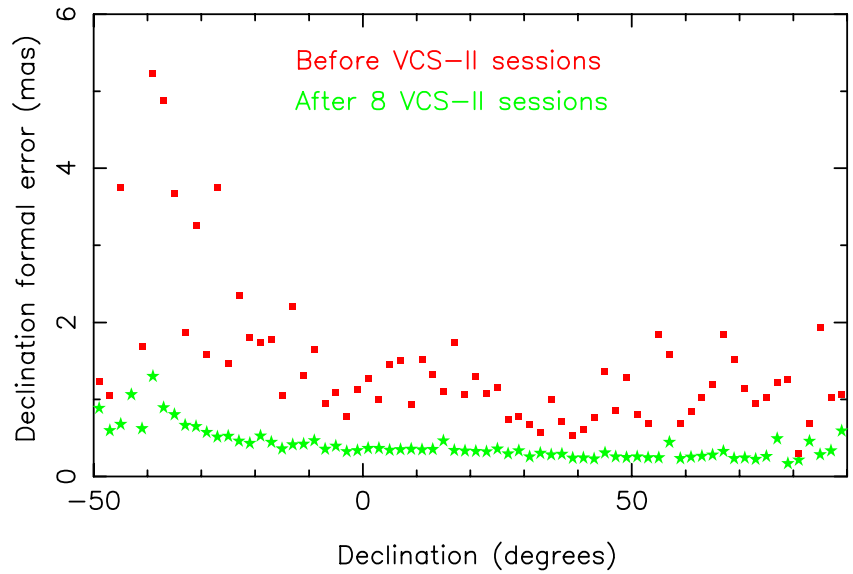
Improvement
~3.7 times



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

VLBA Calibrator Survey improvement



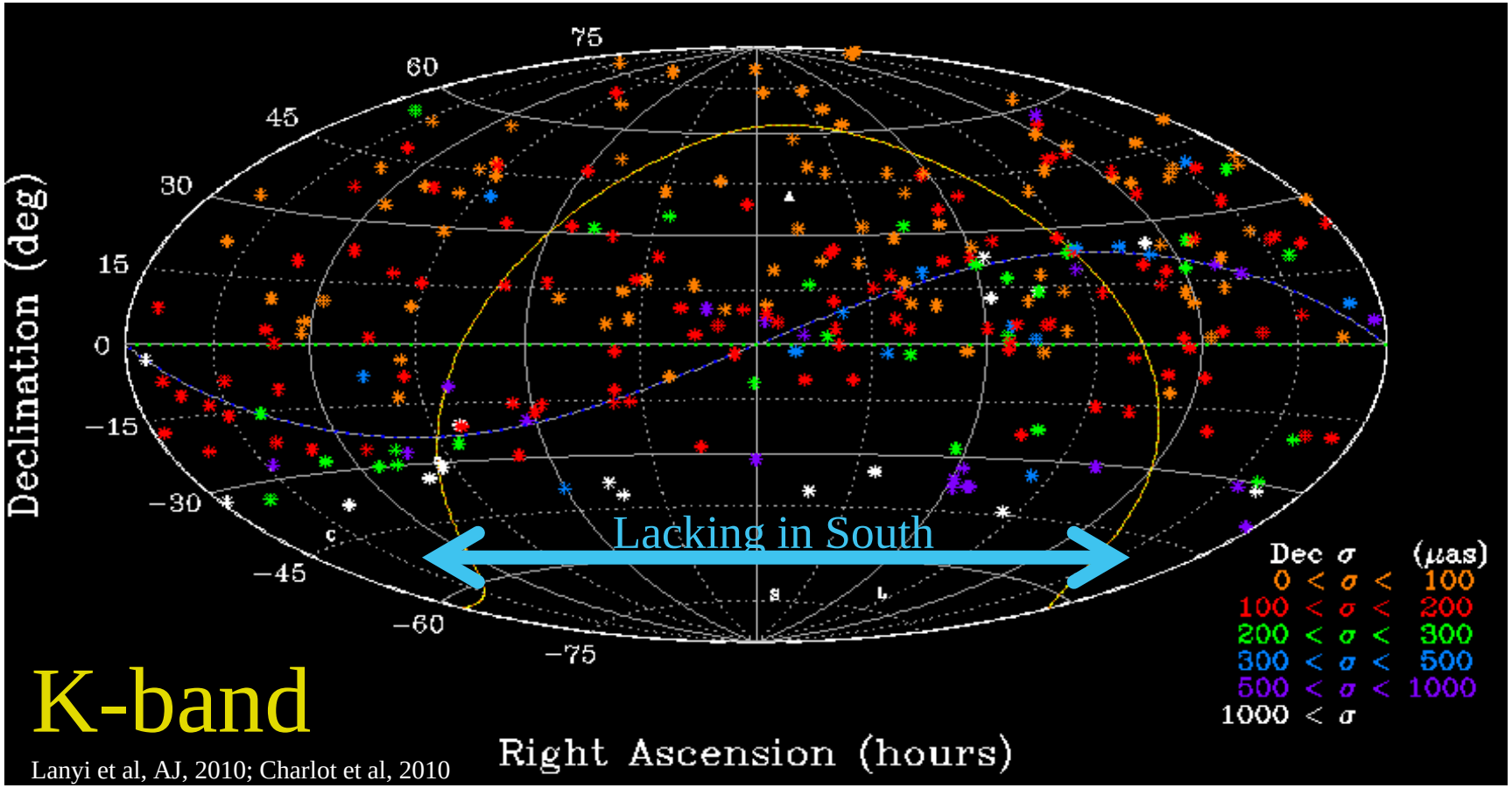


~3.7 times X improvement in precision

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



Lanyi et al, AJ, 2010; Charlot et al, 2010

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.

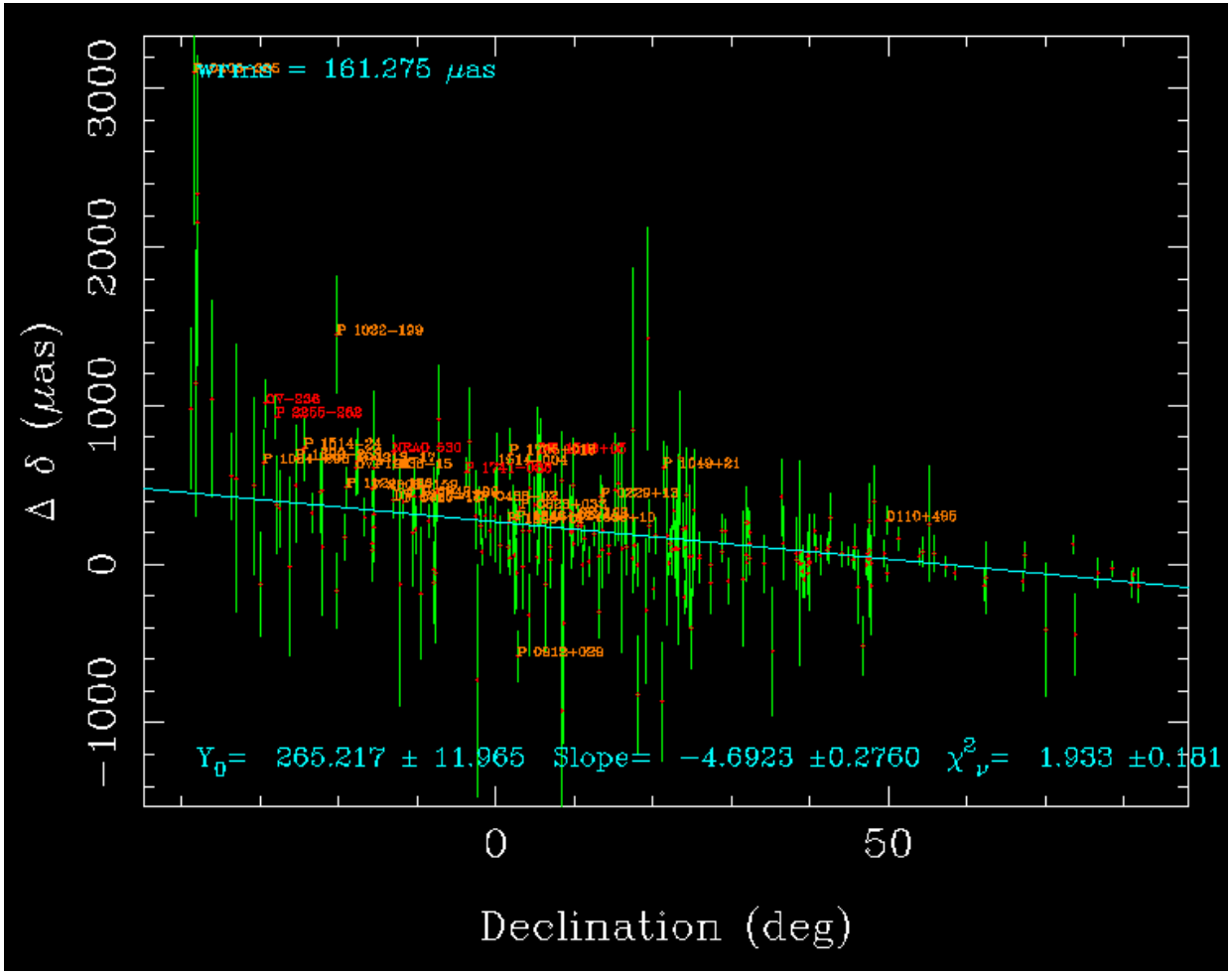
VLBA 4 sessions approved to densify the north. Data from one session in hand

-> expect 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

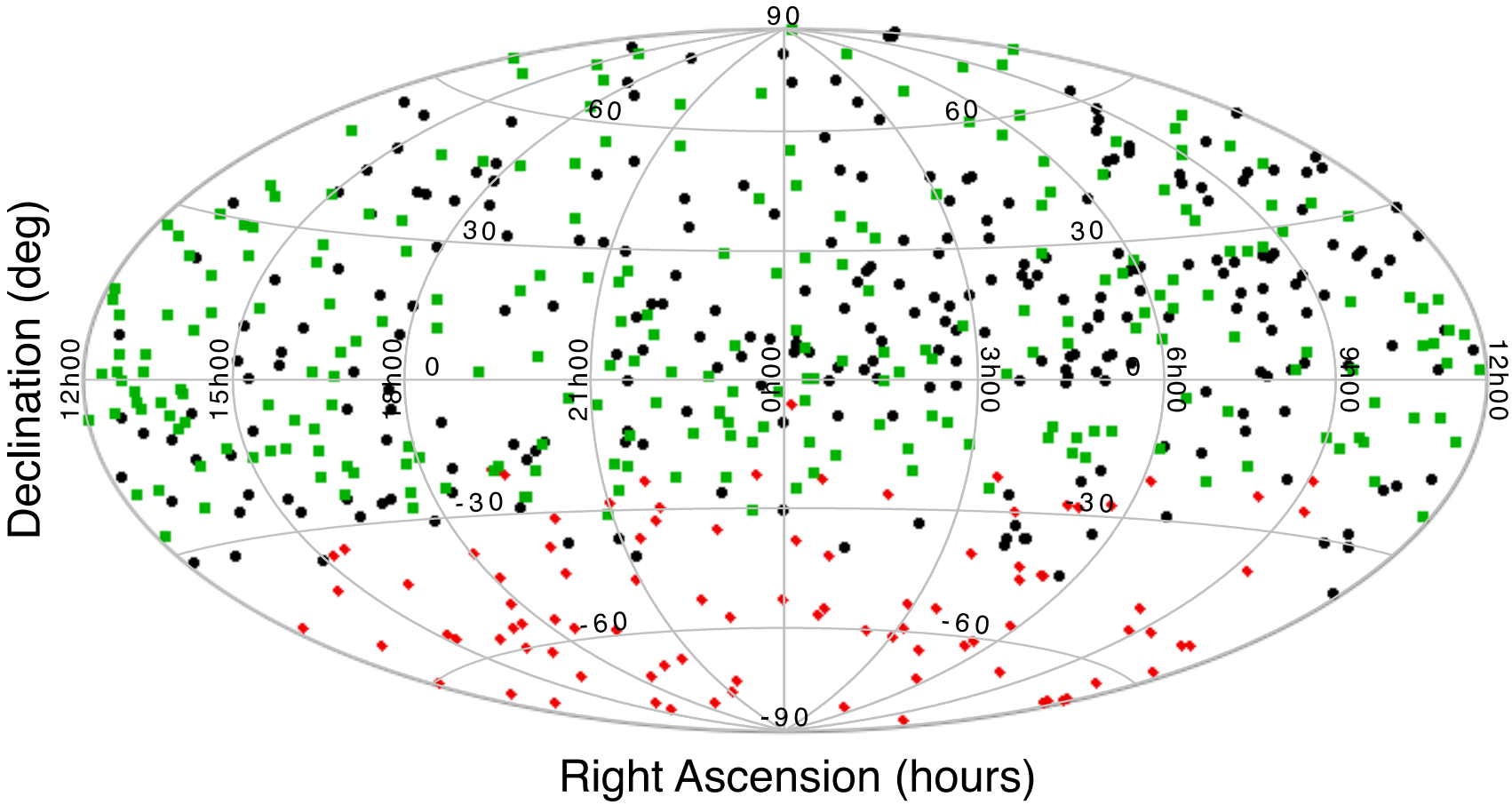
Leads to poor
ΔDec vs. Dec
Zonal stability:
500 µas tilt



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

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



- K-band existing (*Lanyi+, Charlot+, AJ, 2010*).
- New K-band data fron Bertarini et al collaboration (De Witt+, EVGA, 2015)

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

VLBA 4 sessions approved to densify the north. One session in hand.

Expecting > 500 sources total

Fundamental Astrometric Sources

- Fundamental Astrometric Sources:
  Common sources observable at all wavelengths used for reference frames.

- Desire agreement in centroids to better than 100 µas at
  3.6 cm (S/X-band)
  1.2 cm (K-band)
  0.9 cm (X/Ka-band)
  Gaia optical

- Would allow direct access to frame defining sources by both radio and optical techniques

- How many objects meet these criteria?

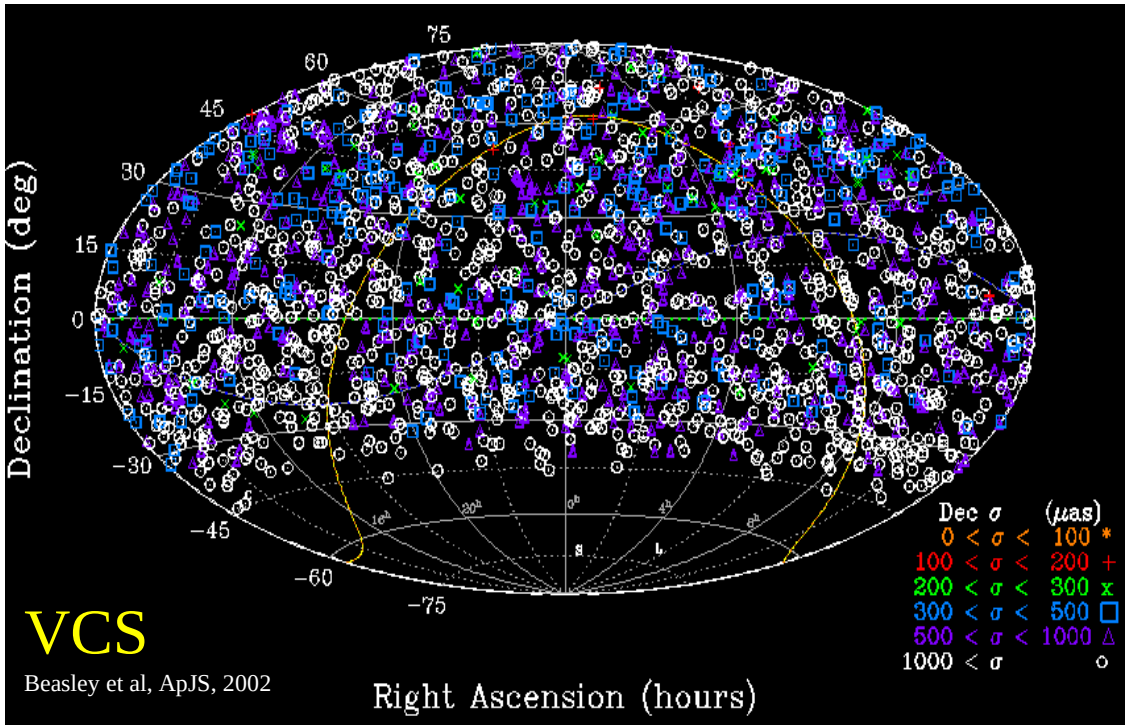
ICRF-3 Needs

- 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!

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

Current Status of Celestial Reference Frames at multiple radio wavelengths:

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

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

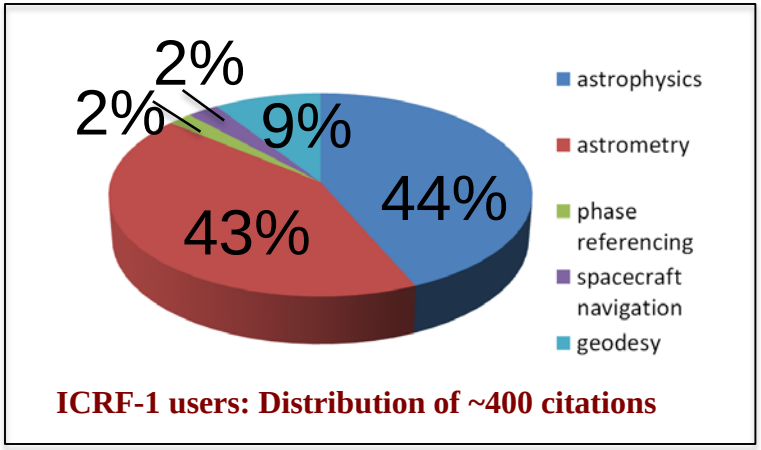


Figure Credit: Heinkelmann, EVGA, 2013

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

VLBA Observing Networks

VLBA

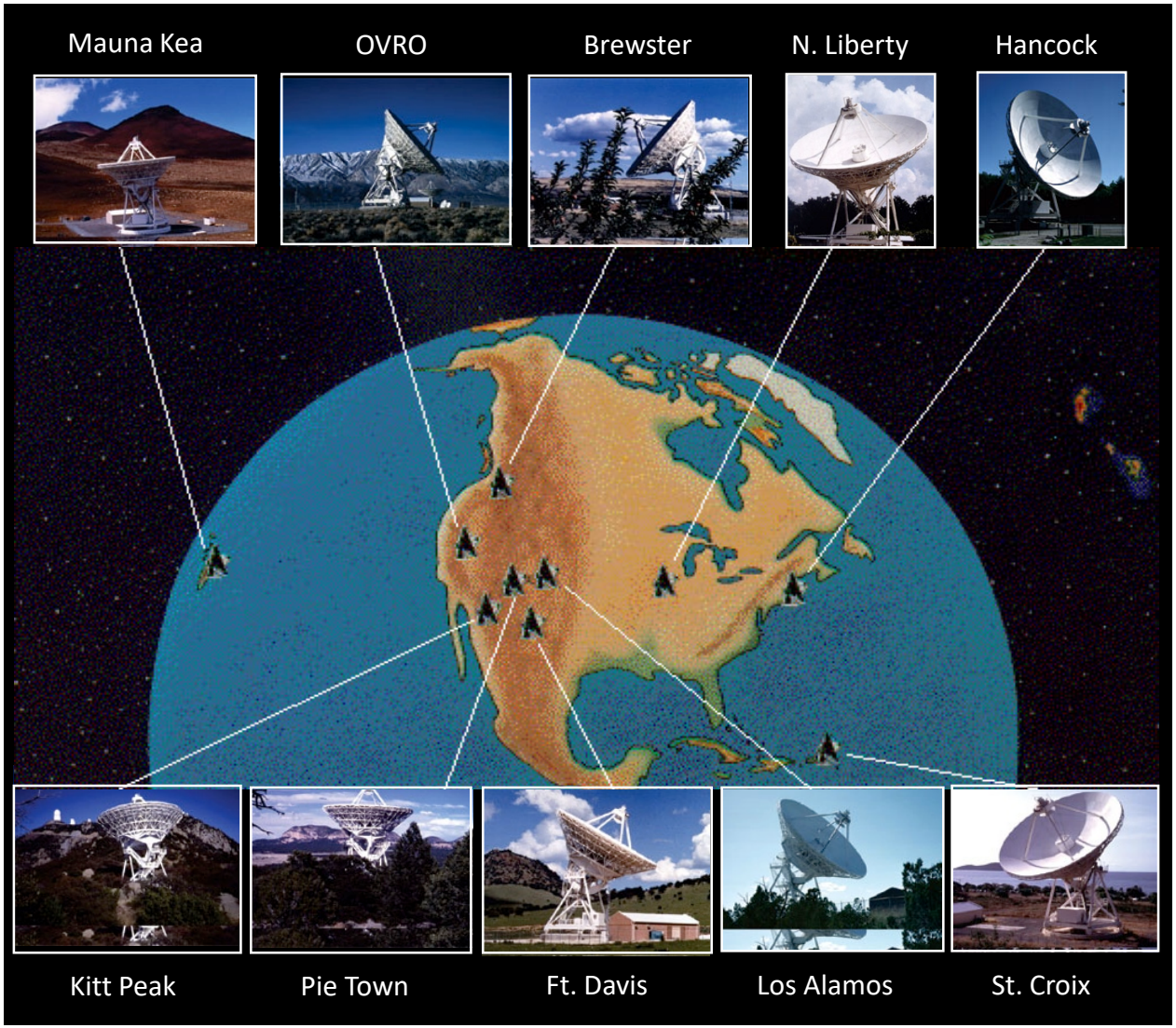
S/X VCS catalog
K, Q catalogs

25-meter dishes

10 stations

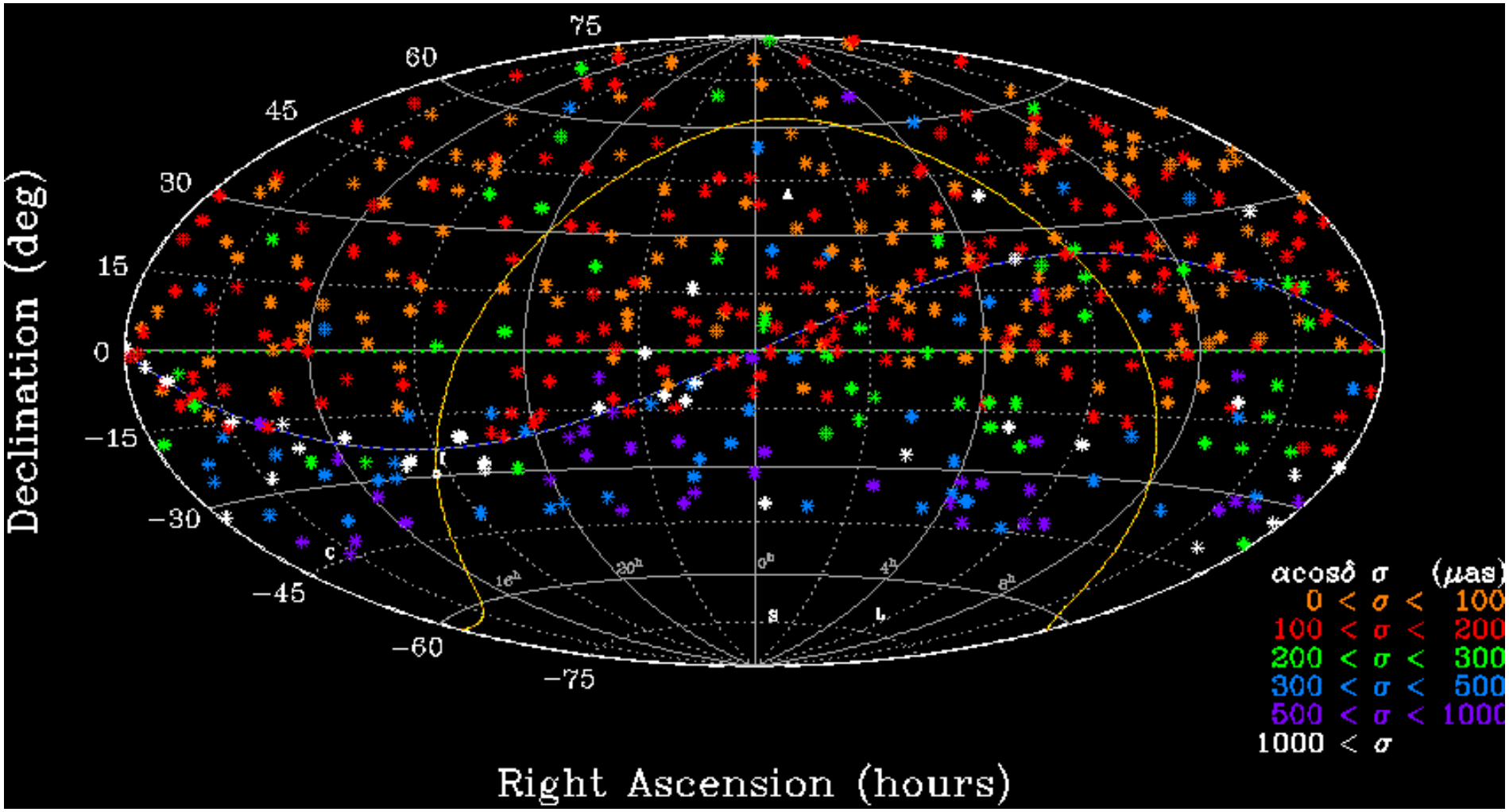
Baselines up to 8000 km

No southern stations



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

Status 2012: X/Ka had 482 Sources

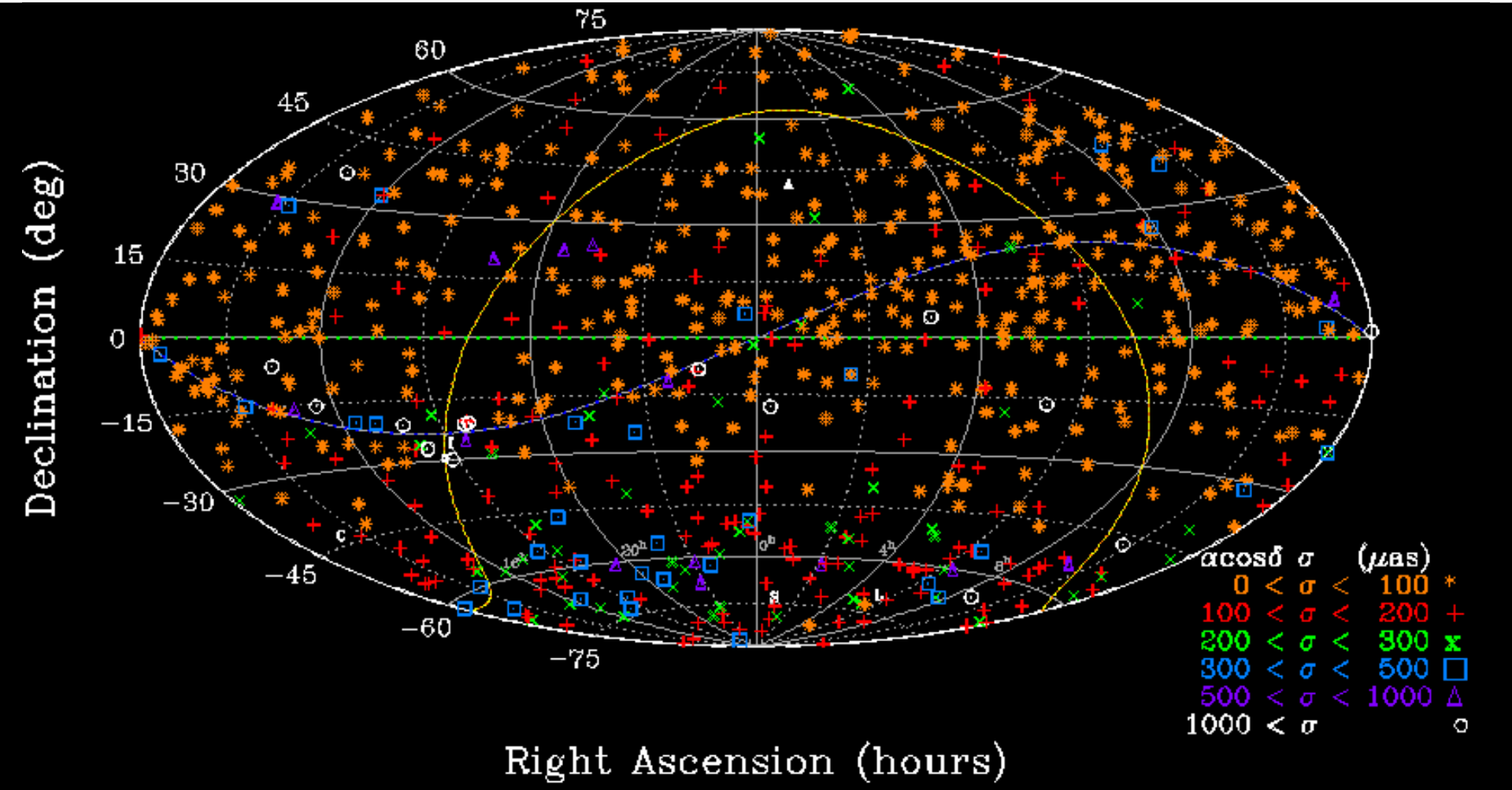


400 μas precision Dec 0 to -45 deg. No sources in south polar cap

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

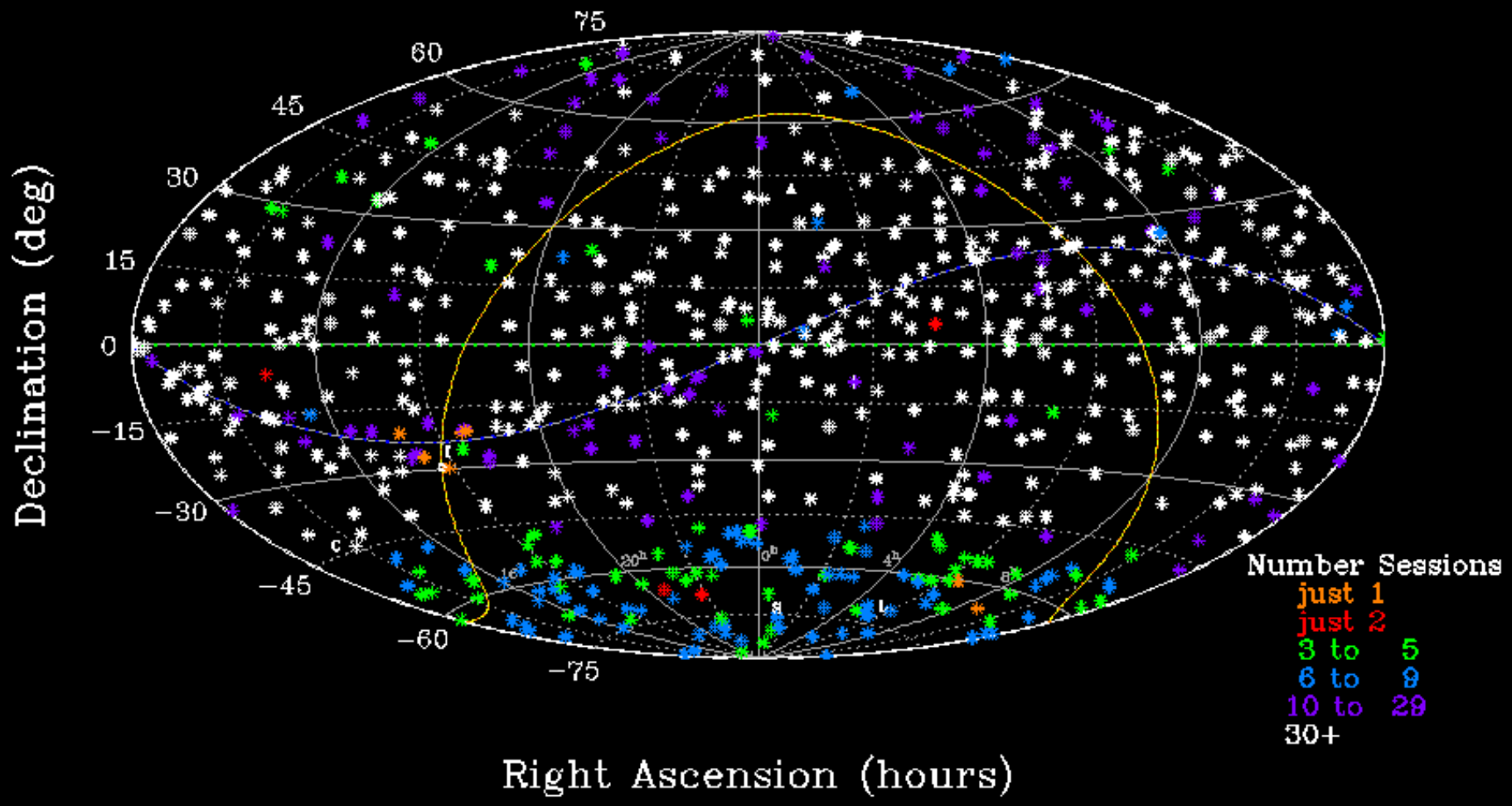


DSN: Goldstone to Madrid & Canberra

+ ESA baselines: Malargüe to Canberra, Goldstone, Madrid

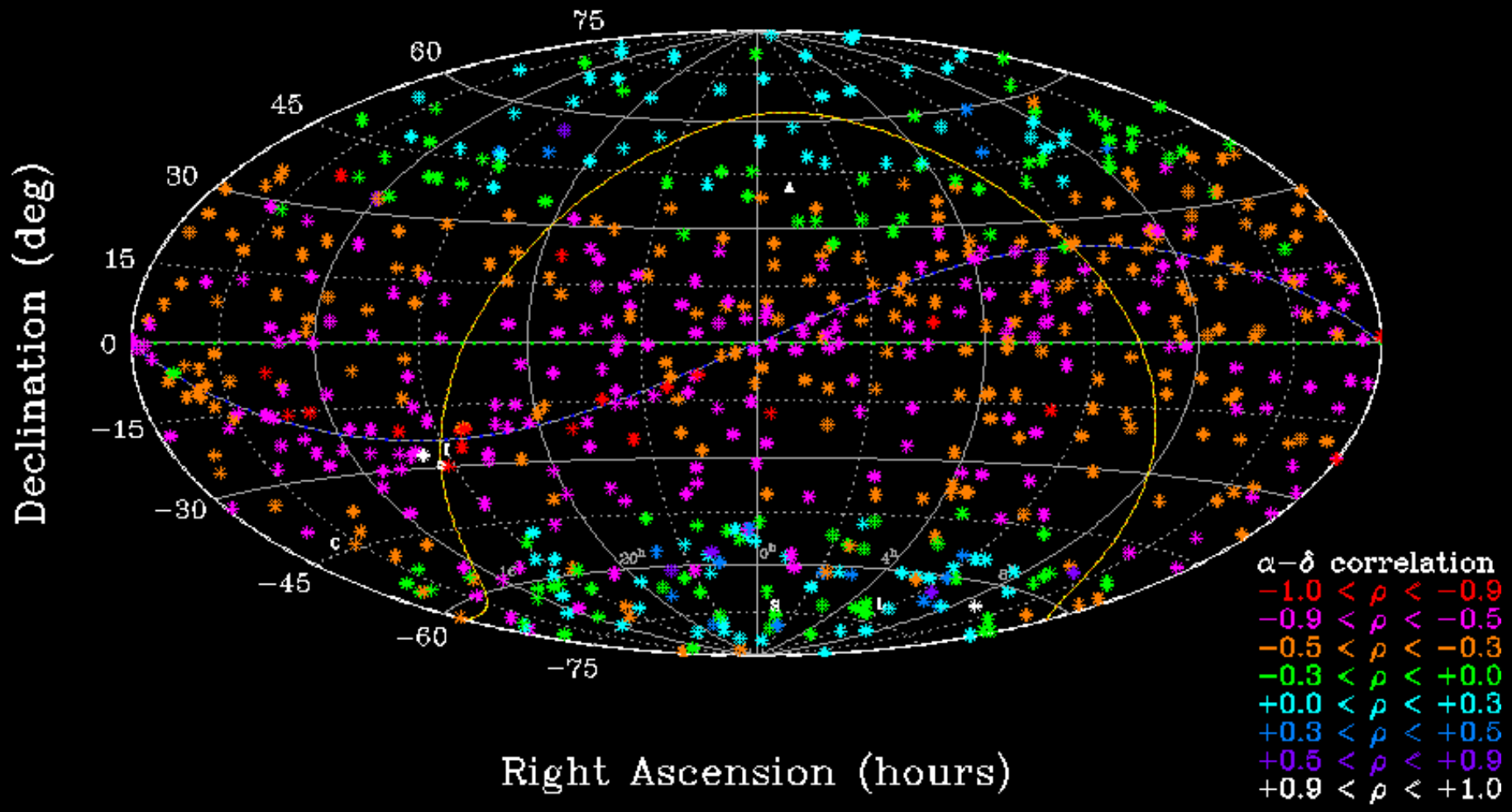
Full sky: 110 sessions, 40K group delay/phase rate observations

NASA-ESA 32GHz Number of Sessions



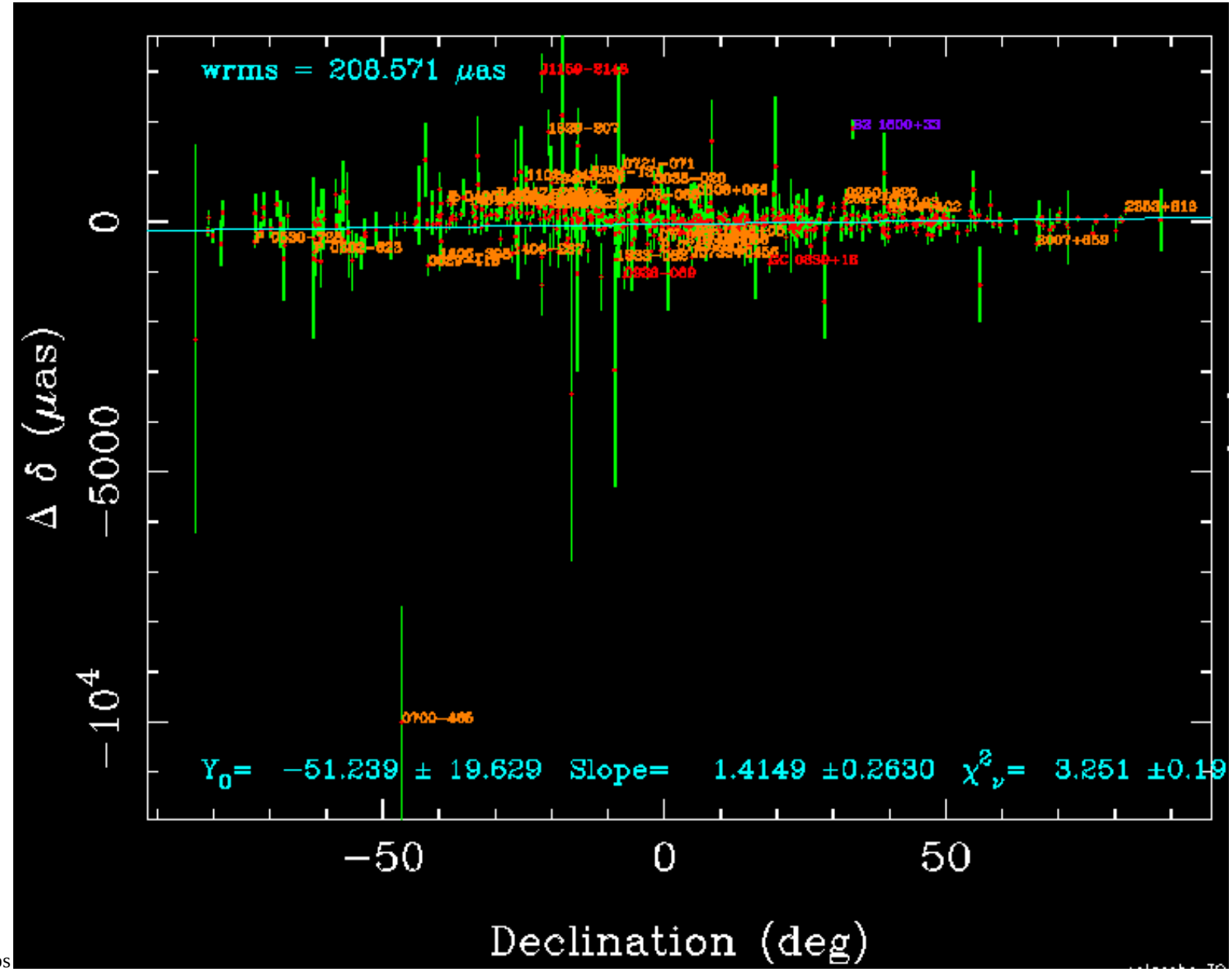
Need Argentina- Australia sessions to balance frame for Dec < -45 deg

NASA-ESA 32GHz RA-Dec correlation



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

XKa vs. SX: Zonal errors



Gaia frame tie and accuracy verification

Gaia: 10^9 stars

- 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

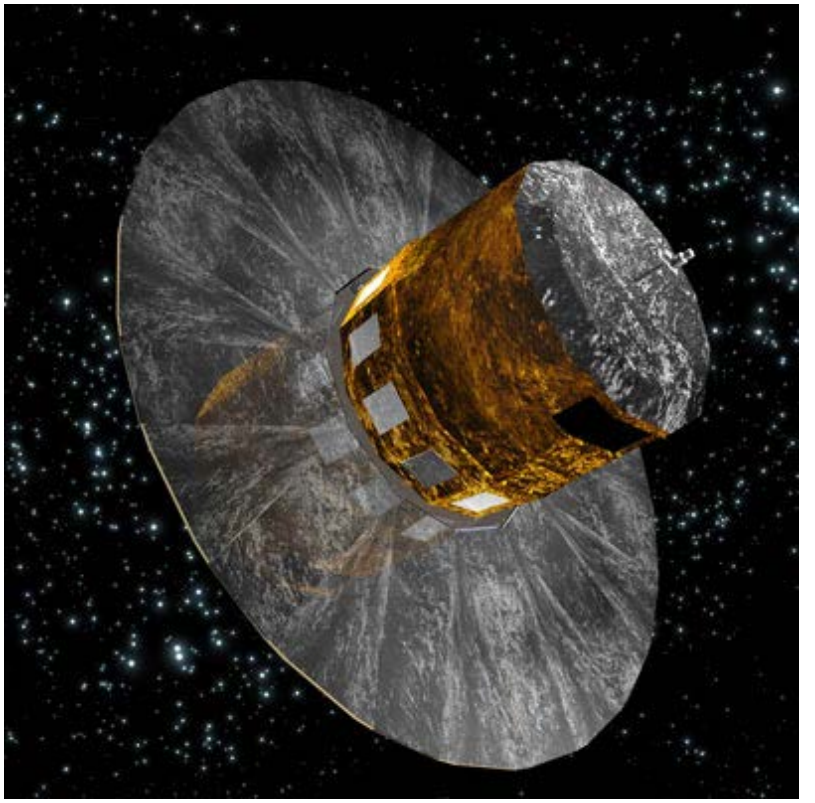


Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7

Optical vs. Radio positions

Positions differences from:

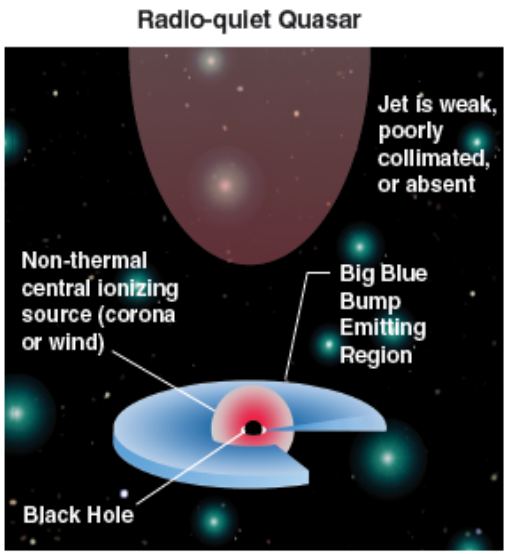
- Astrophysics of emission centroids

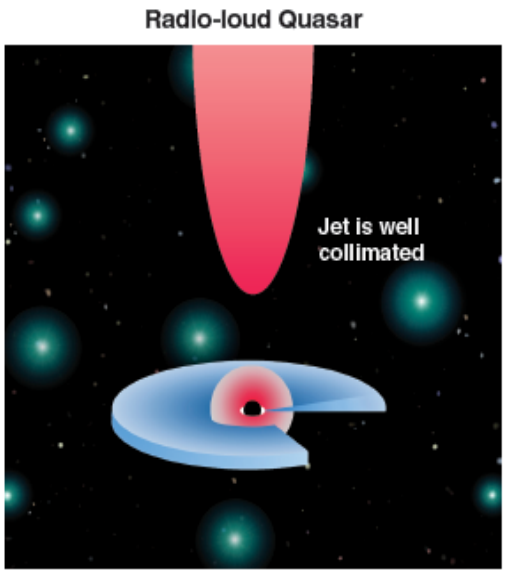
  - radio: synchrotron from jet

  - 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





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

Optical brightness of X/Ka sources

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

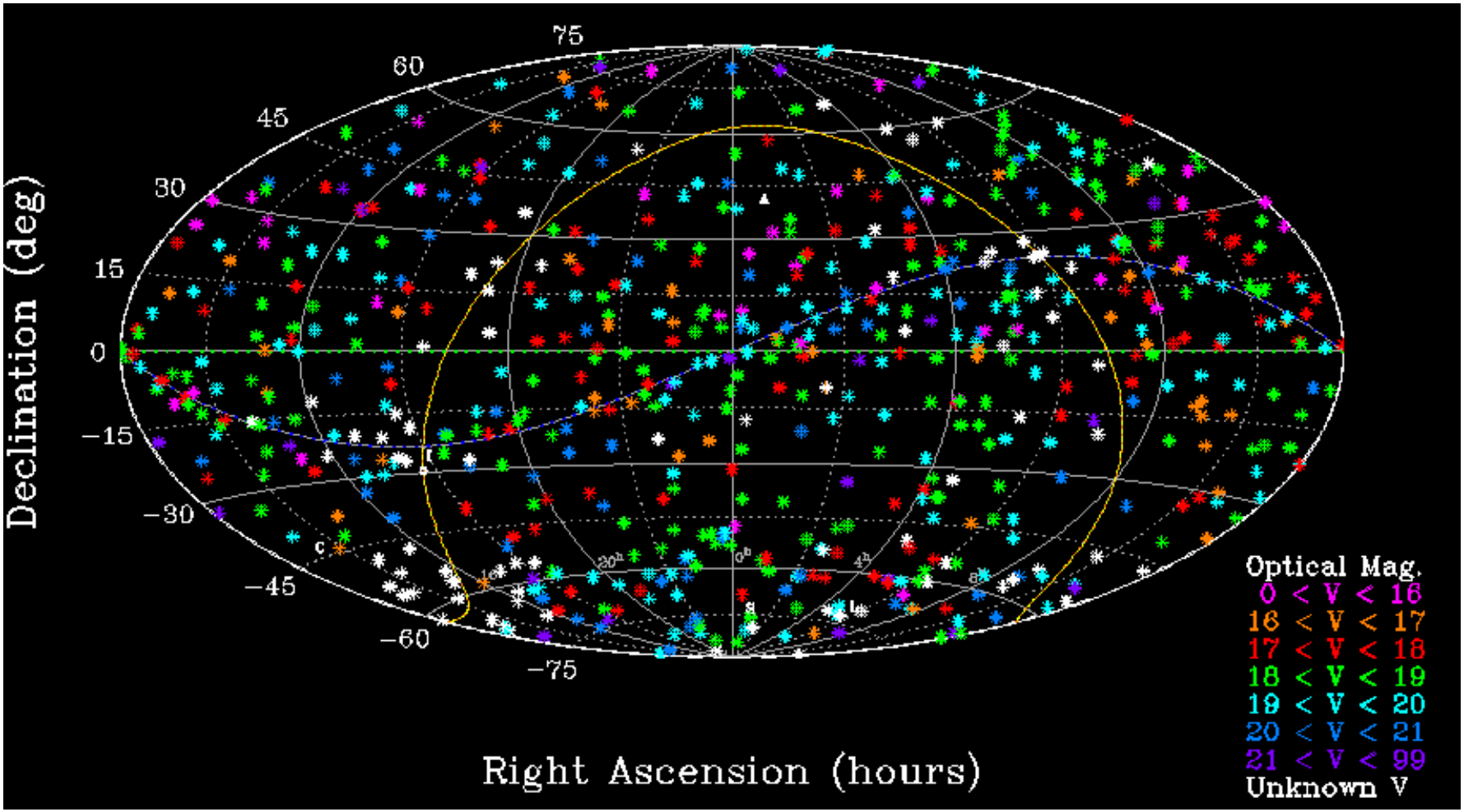


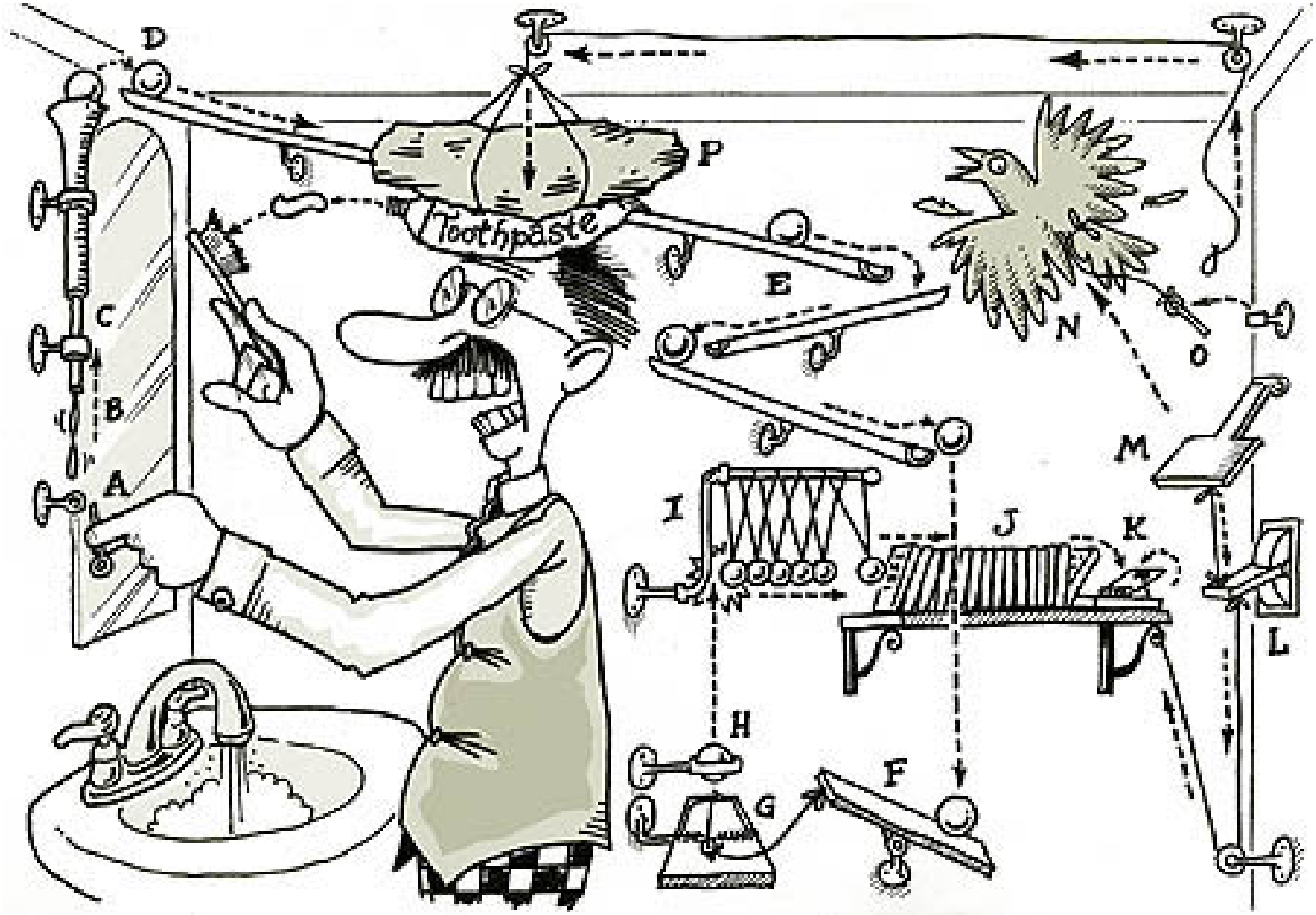
Figure credit: Garcia-Miro et al, EVN, 2014

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

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

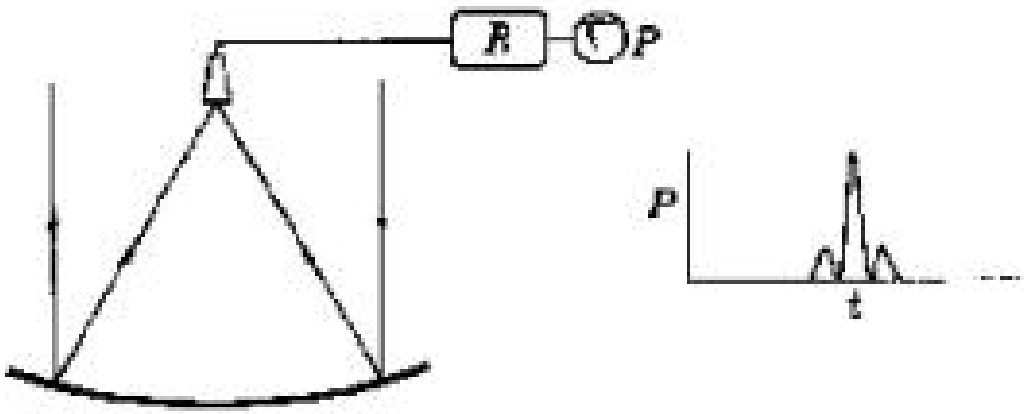


Cartoon credit: Rube Goldberg

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

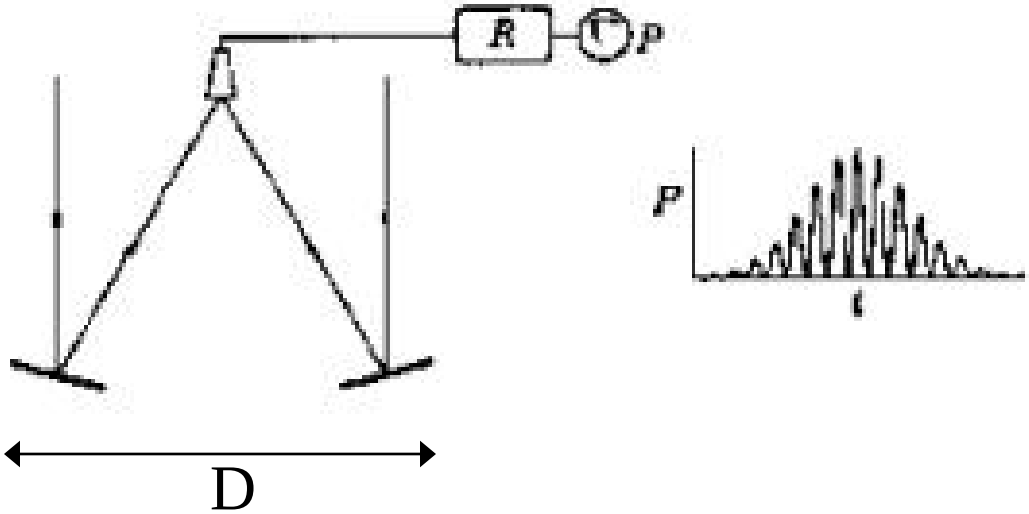
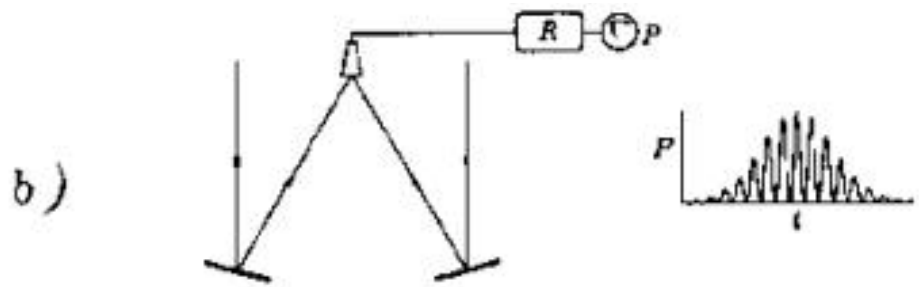


Figure credit: H. Gush

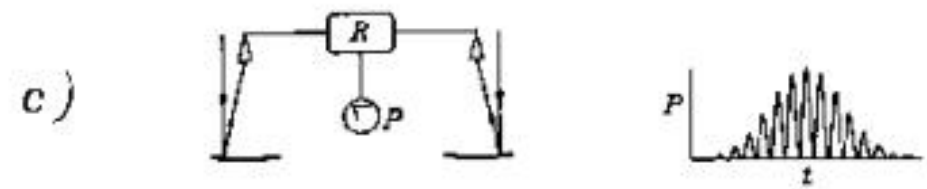
Mechanical → electrical alignment → VLBI

Two segments of antenna



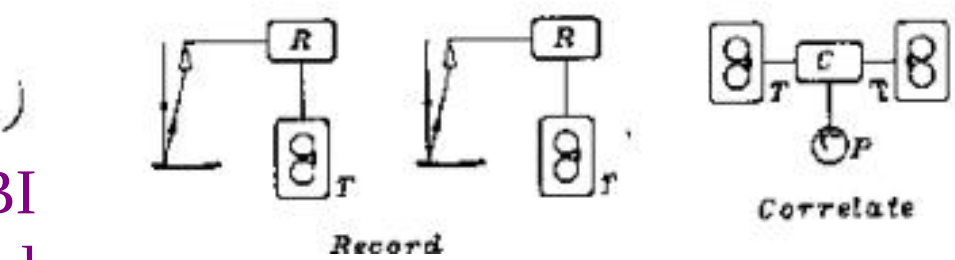
"Fringes"

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

Optical vs. Radio positions

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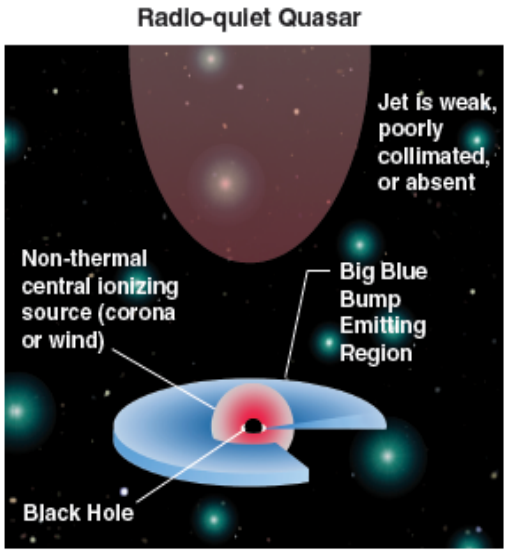
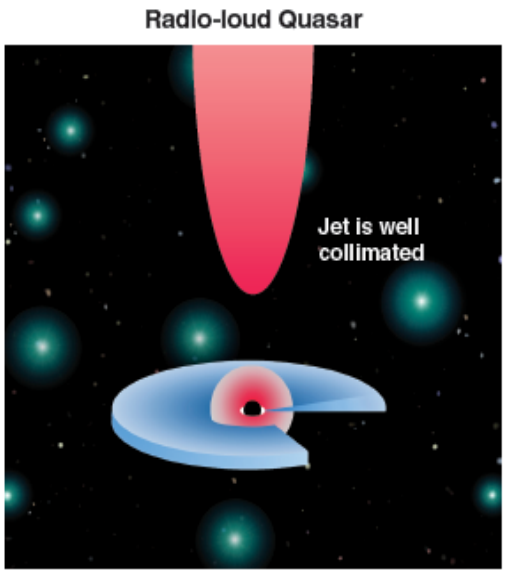
    "big blue bump" from accretion disk?

  - optical centroid biased by host galaxy?

- Instrumental errors both radio & optical

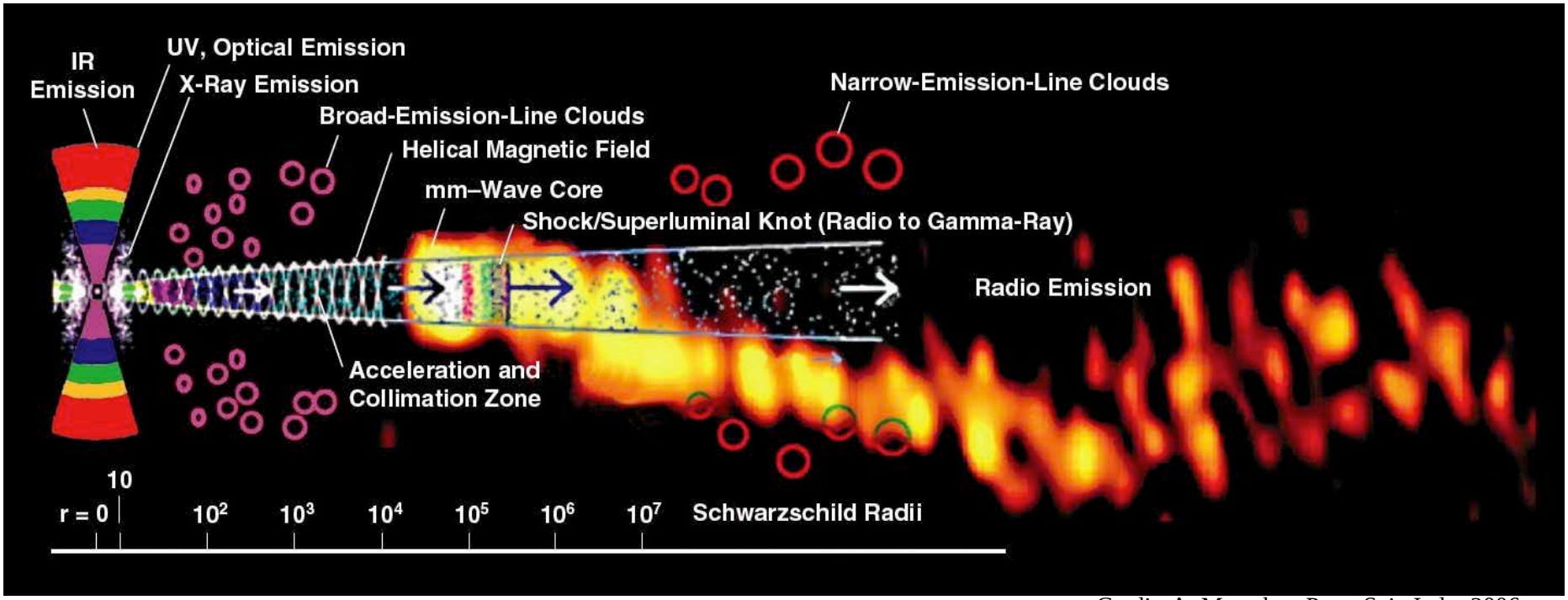
- Analysis errors





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.

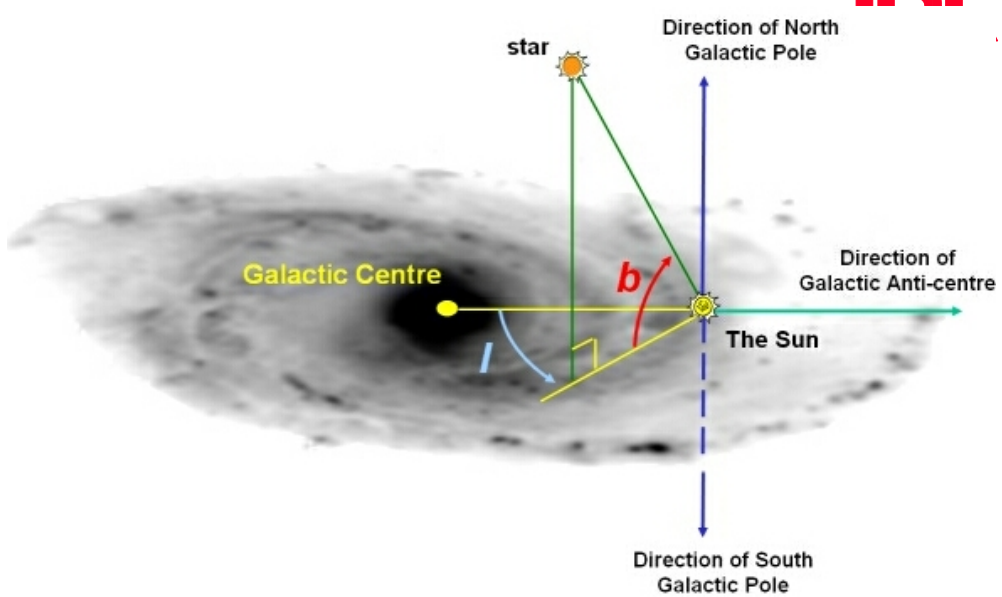
Positions differences from 'core shift'

- 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 ICR**S** working group (not ICR**F**-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