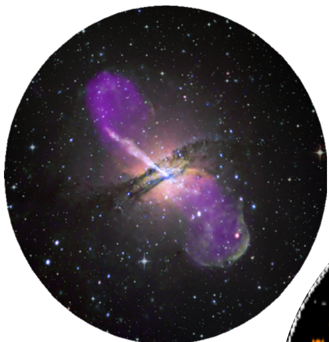
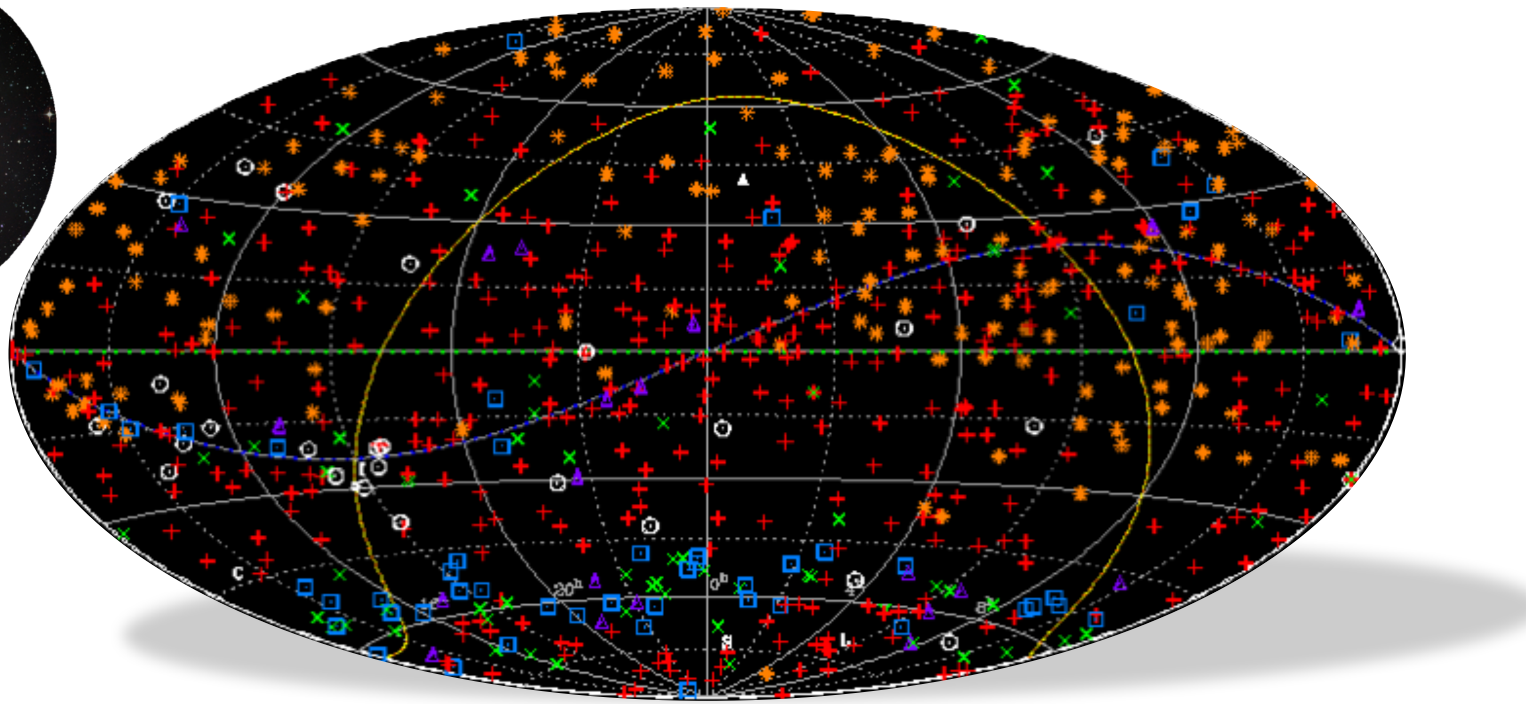
IVS General Meeting 2016

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





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2016 March 17, Ekudeni, Gauteng, South Africa

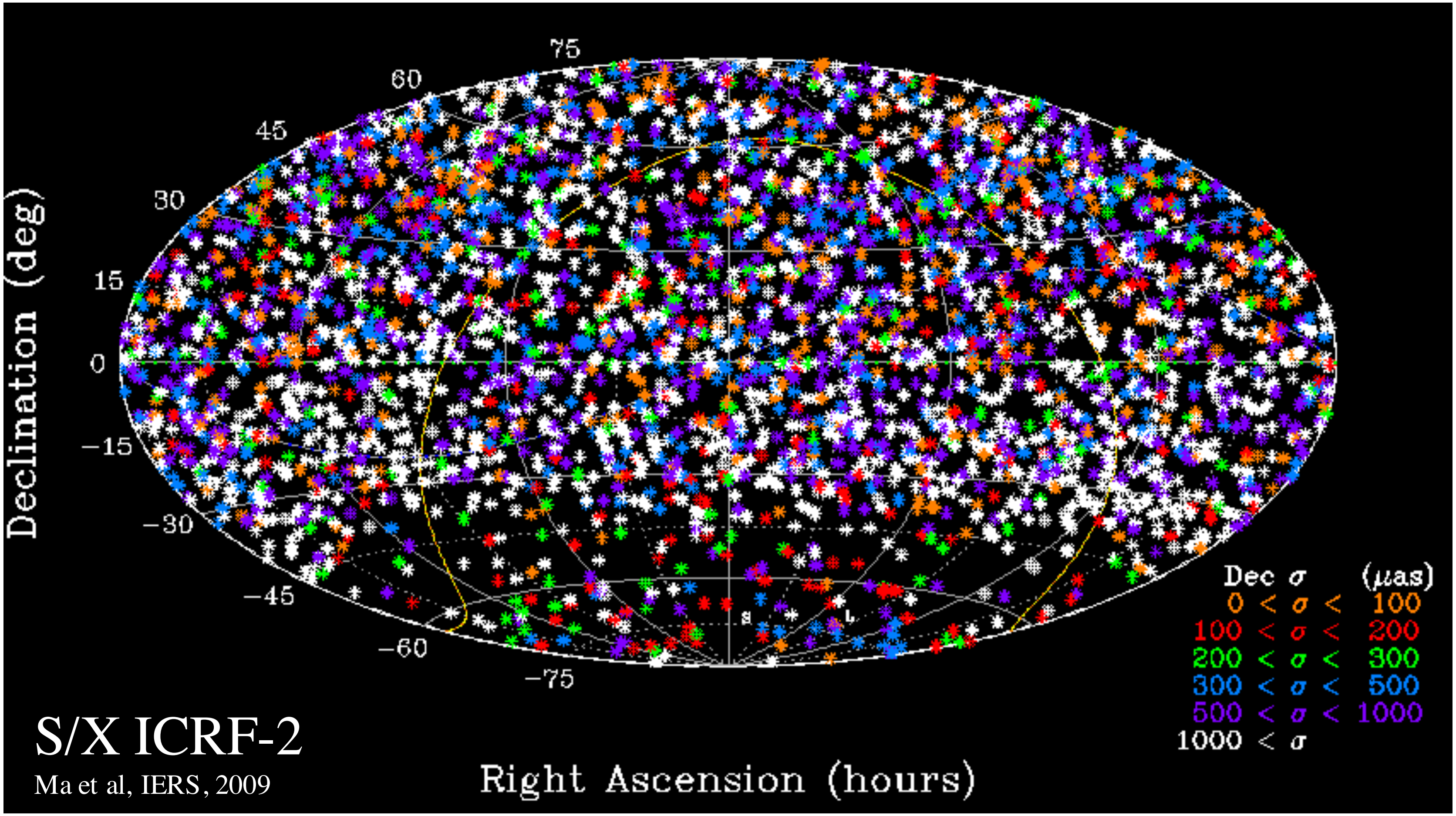
Overview:

- 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

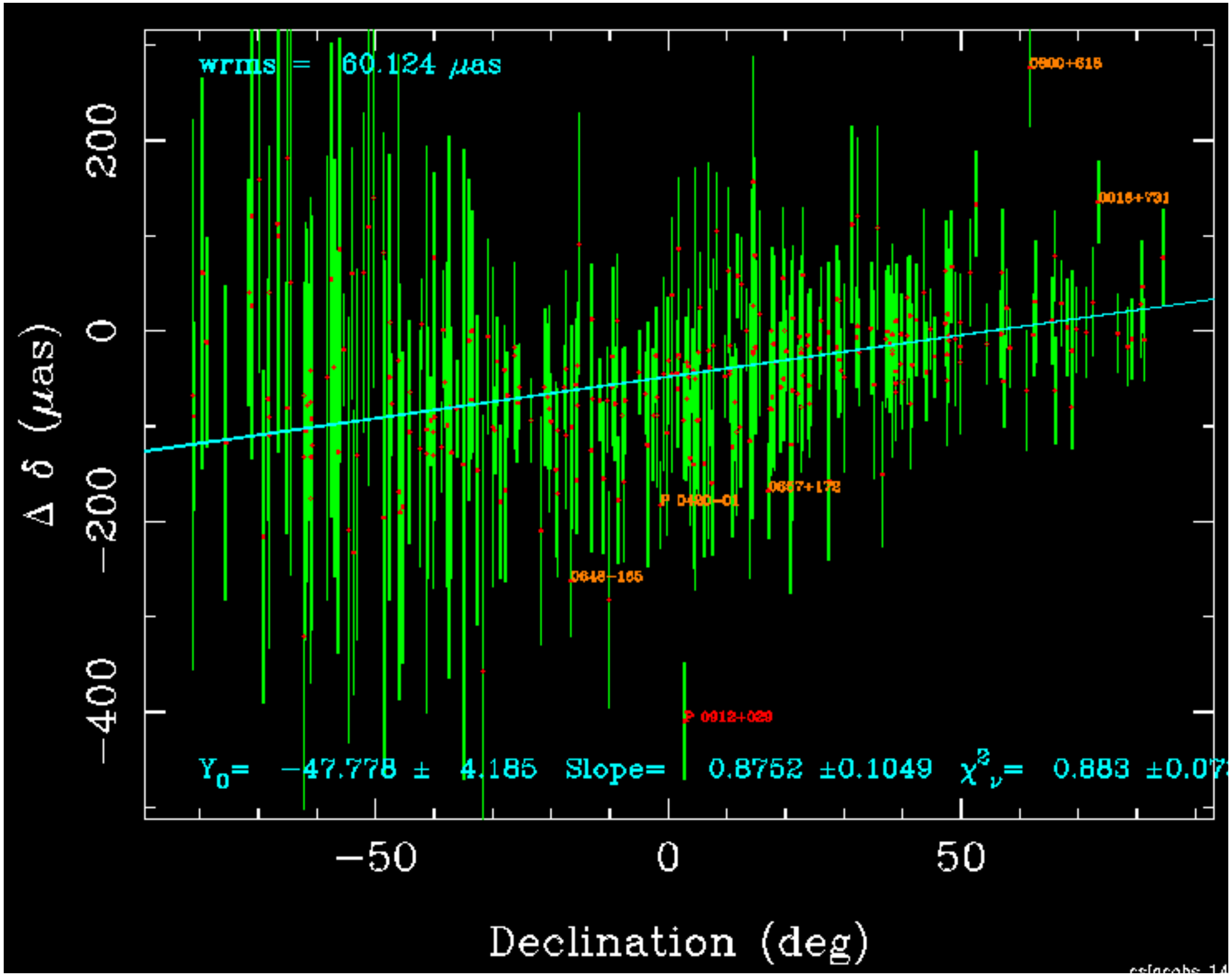


VLBI generally & ICRF-2 specifically lacks southern observations

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-160212)		
N_Common	512		552		
N_sessions	54	30	53	57	
N_obs	83	601	82	1297	
σ_α	77	82	78	27	μas
σ_δ	113	108	113	40	μas

Differences:

	XKa vs. ICRF-2	XKa vs. SX(GSFC-160212)	
wRMS α^*	197	181	μas
wRMS δ	199	192	μas
Mean α^*	29	31	μas
Mean δ	-148	-83	μas
$\Delta\alpha^*$ vs. δ	1.7+-0.3	1.2 +-0.2	μas/deg
$\Delta\delta$ vs. δ	0.7 +-0.4	0.7 +- 0.3	

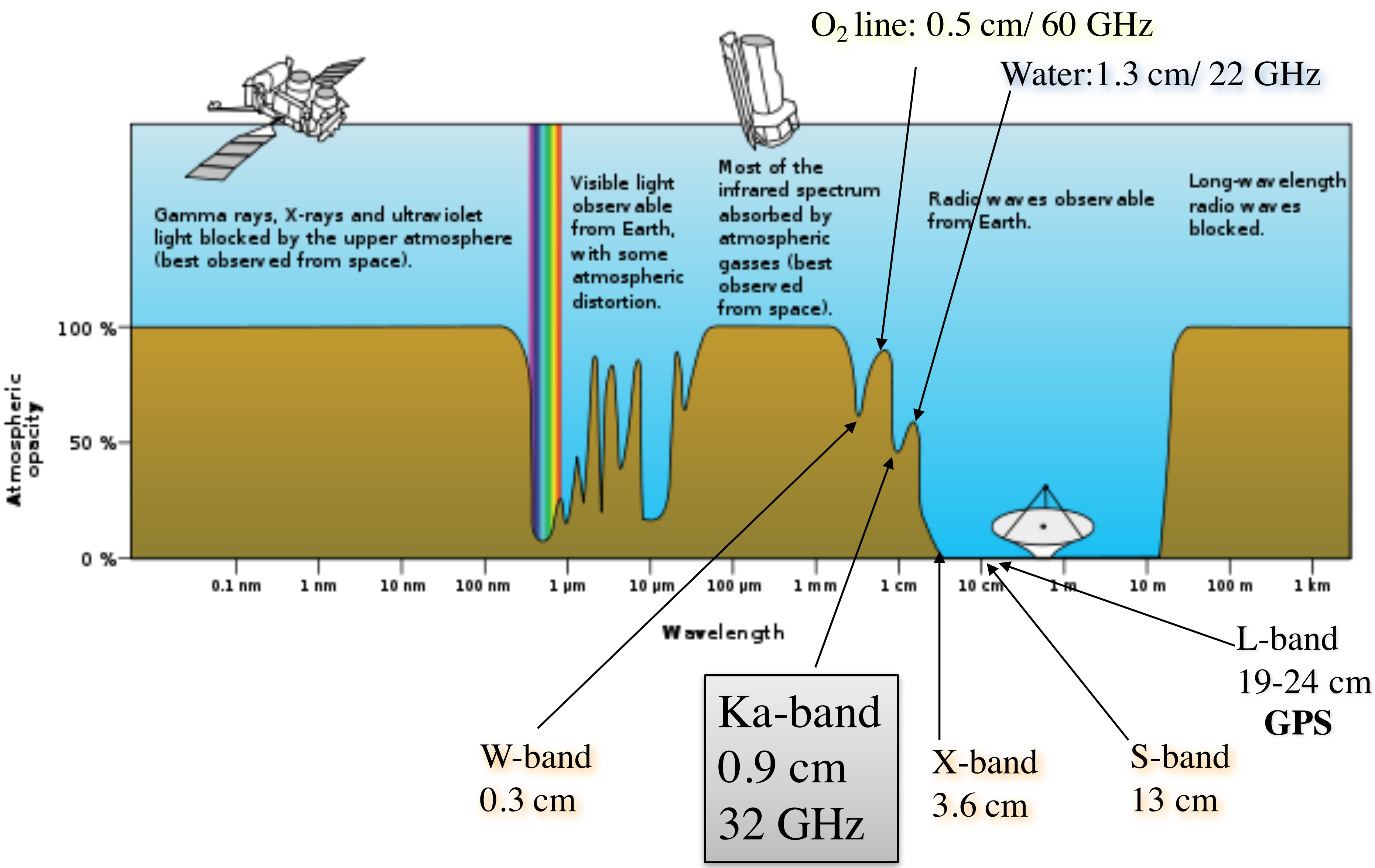
XKa (tcov) vs. S/X (preliminary)

	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.

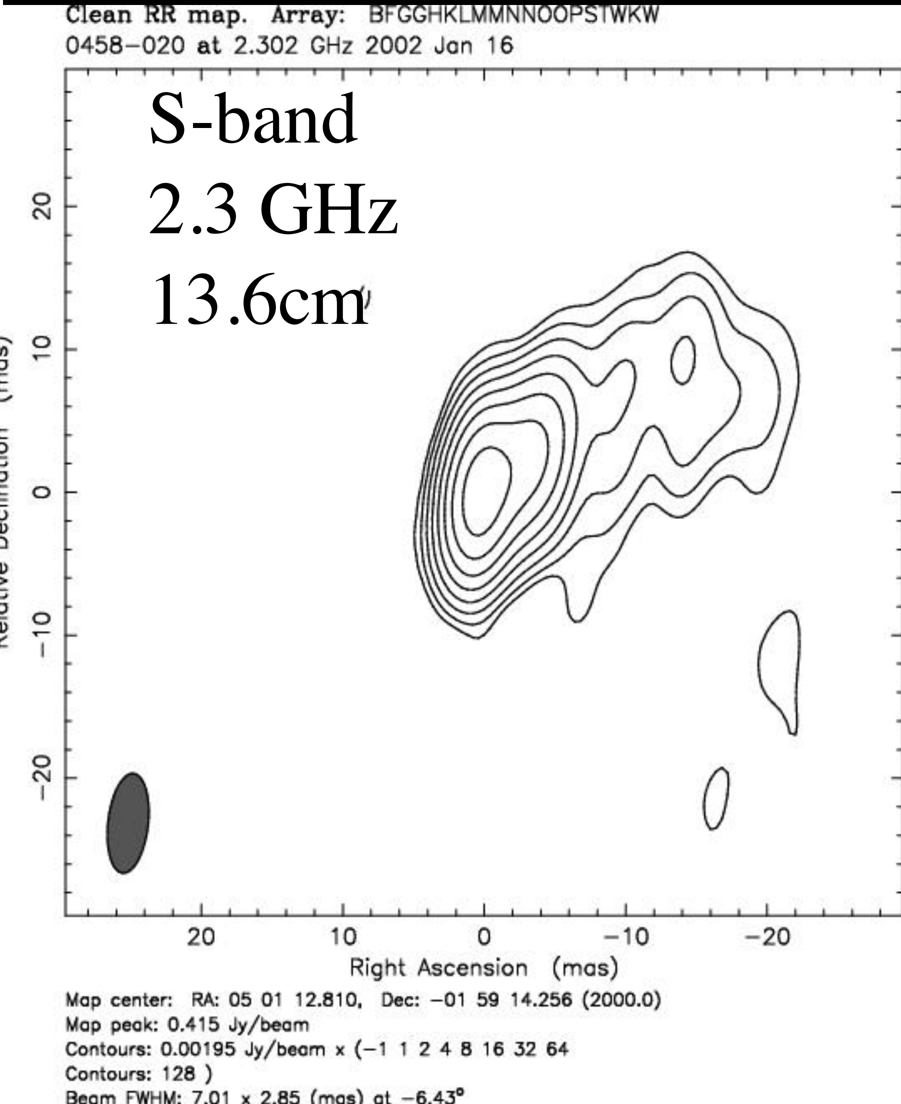
- **Results**

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

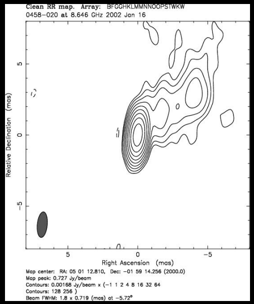
-> About 3 to 11 psec (1 to 4 mm) instrumental floor
or about 20 to 80 μas translated to long baselines

Source Structure vs. Frequency (absolute scale)

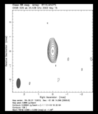
S-band
2.3 GHz
13.6cm



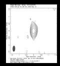
X-band
8.6 GHz
3.6cm



K-band
24 GHz
1.2cm



Q-band
43 GHz
0.7cm

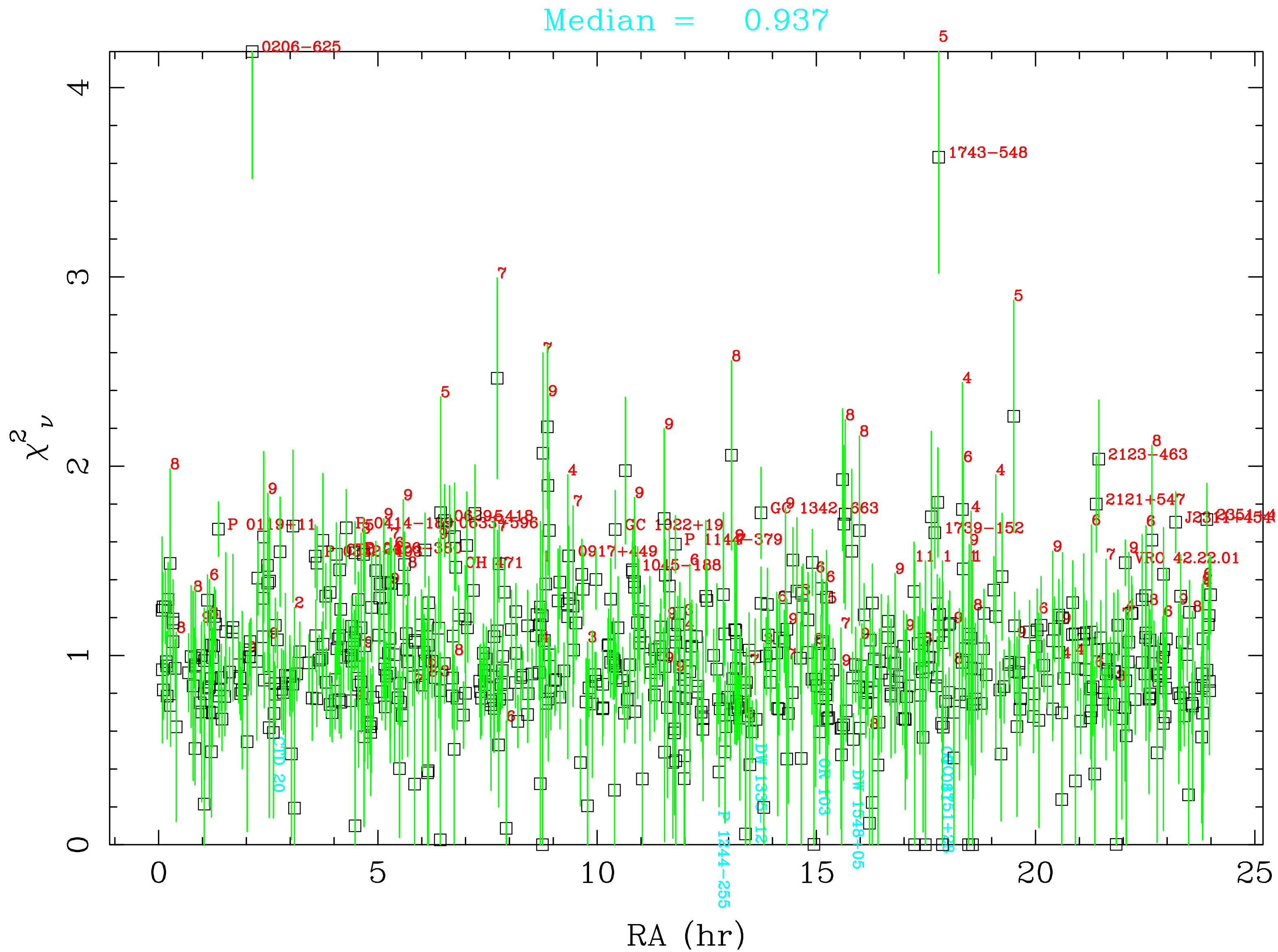


The sources become better →
smaller structure indexes
(Fey & Charlot 1997)

Ka-band
32 GHz
0.9cm

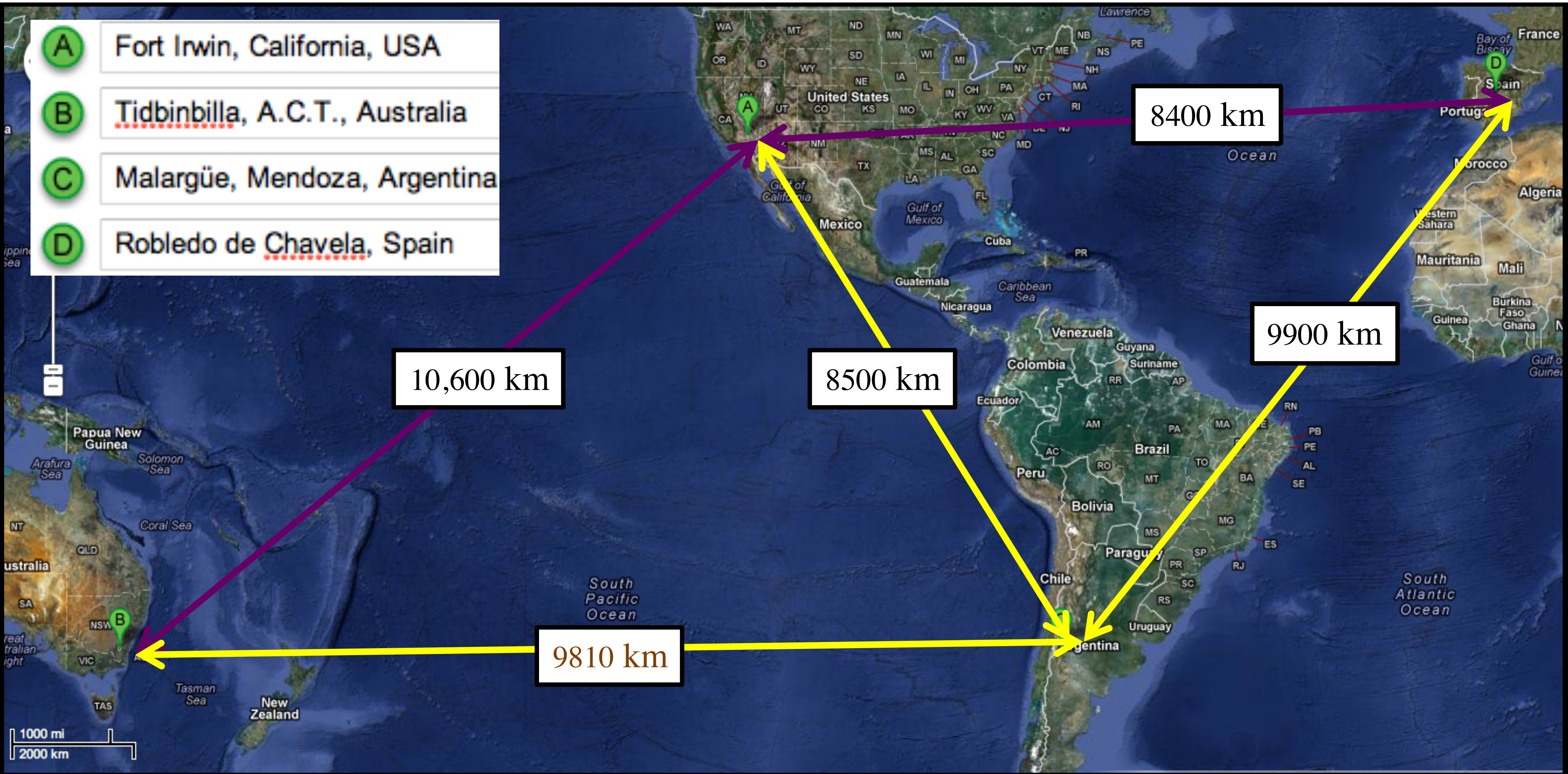
Images credit: P. Charlot et al, AJ, 139, 2010

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



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

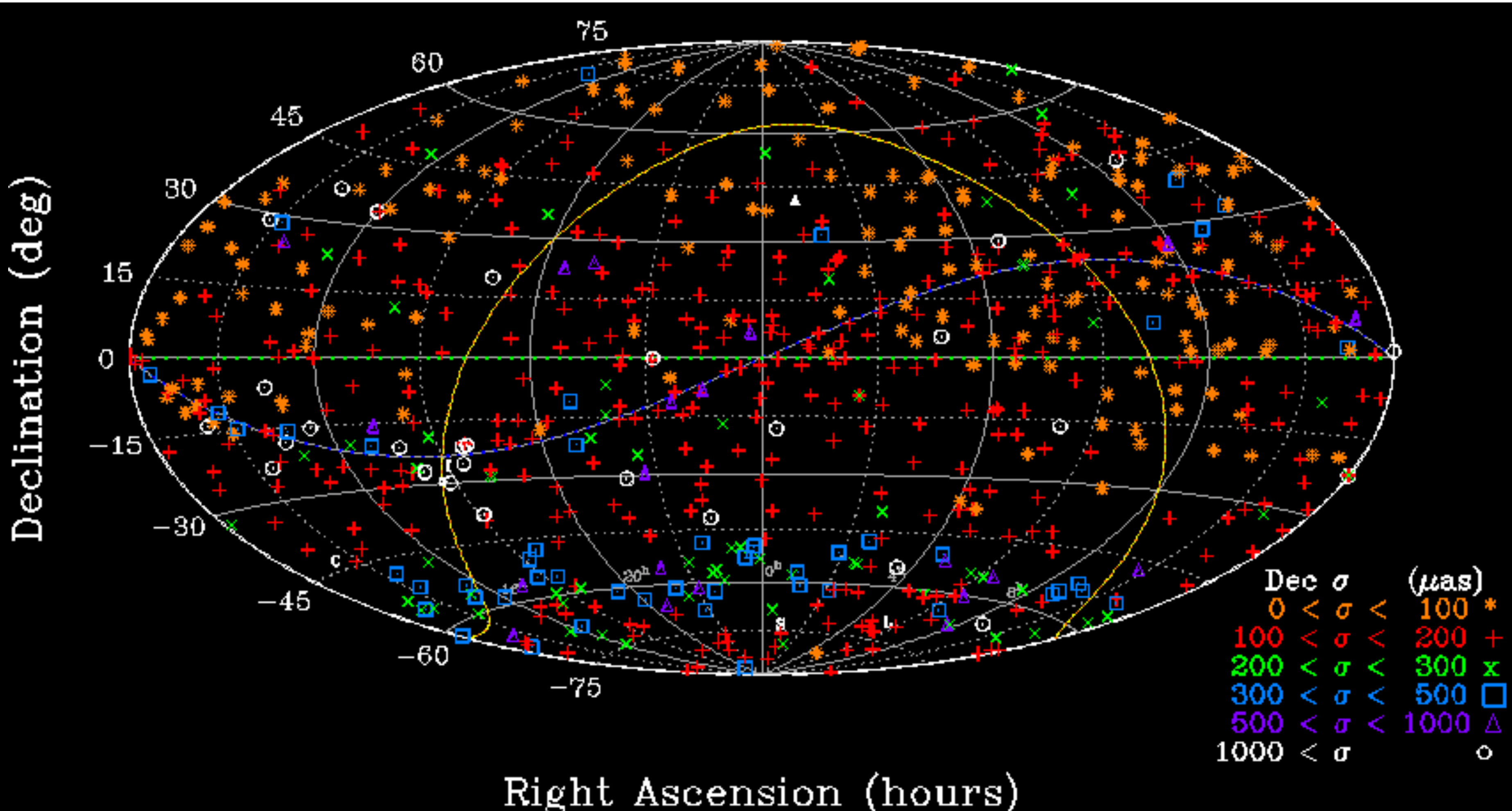
X/Ka Network Geometry



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 sources, 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

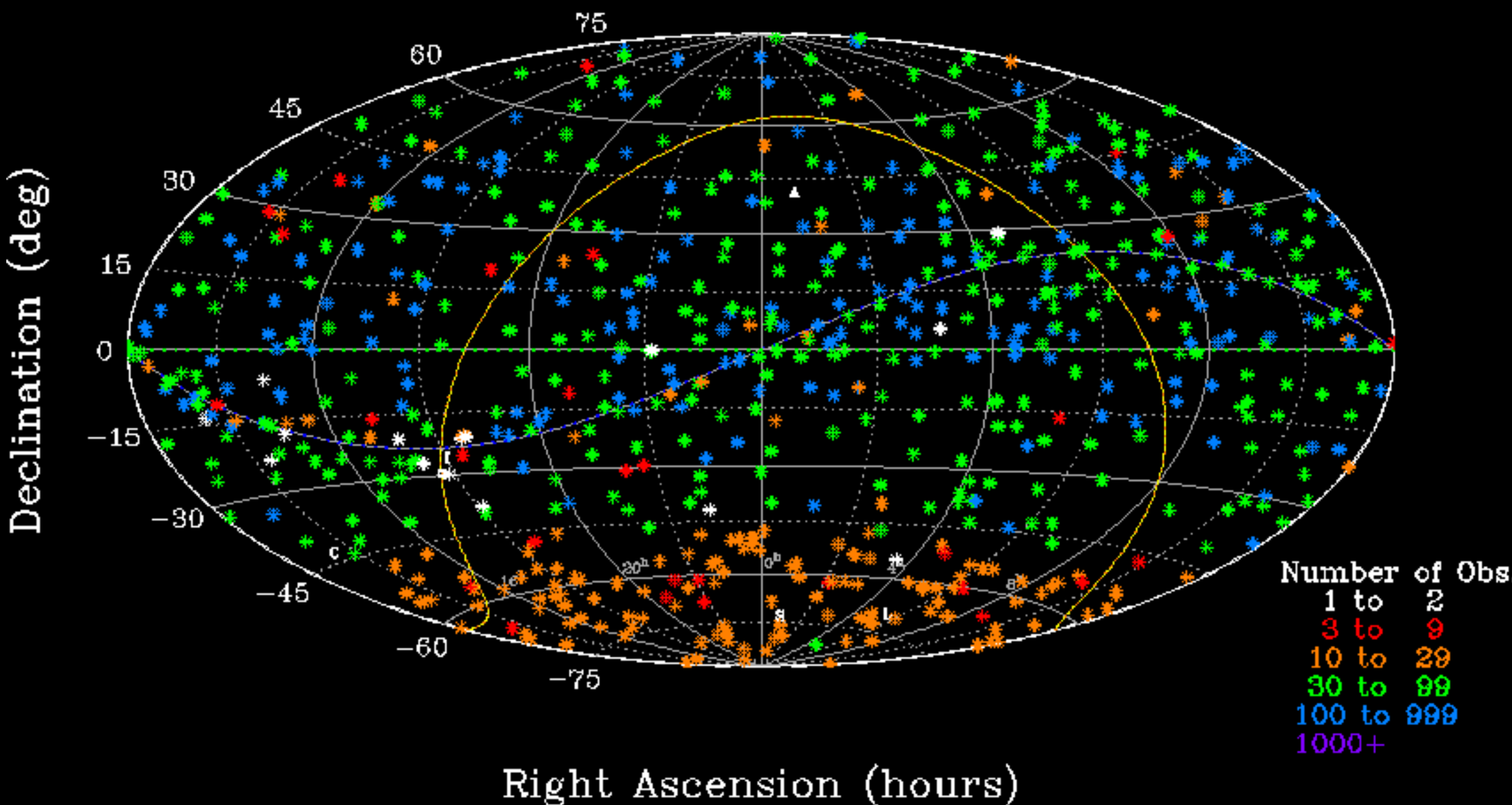
- Goal of < 100 μas (< 5mm)
- Largest celestial frame error:
  Zonal errors vs. Declination of ~ 200 μas

- **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



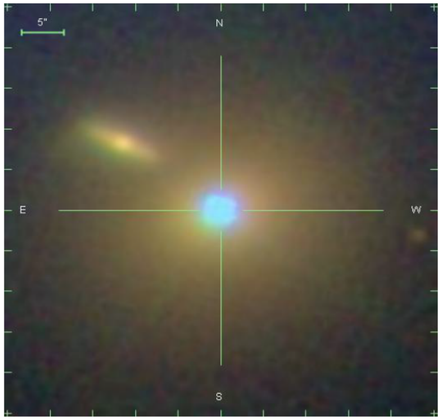
Need Argentina- Australia observations to balance frame for Dec < -45 deg

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

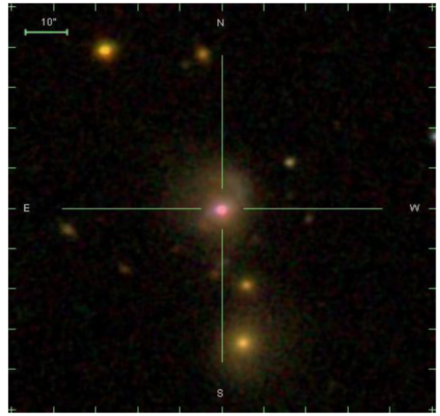
- Radio interferometry (VLBI) is the only independent technique capable of sub-milliarsec full sky verification of Gaia
- For Gaia a bright sources means V < 18th magnitude
- S/X (3.6cm): Expect about 400-500 optically bright sources
- Southern hemisphere additions underway
- XKa (9mm) may have ~200 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

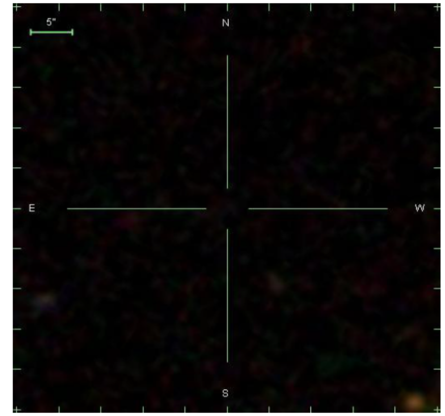
Credit: SDSS



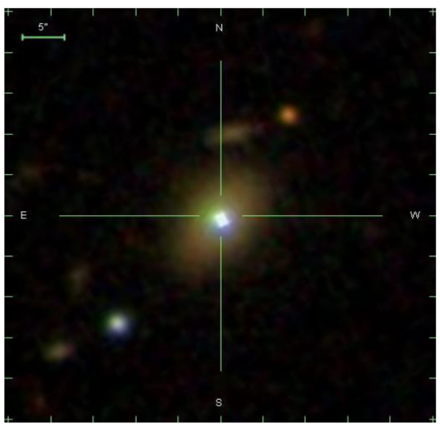
1101+384



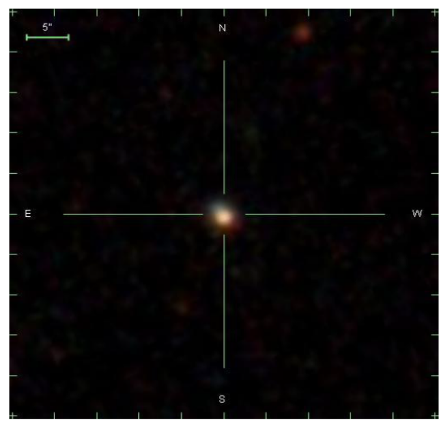
0007+106



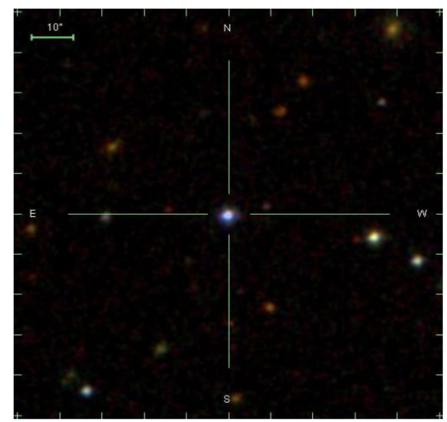
0920+390



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

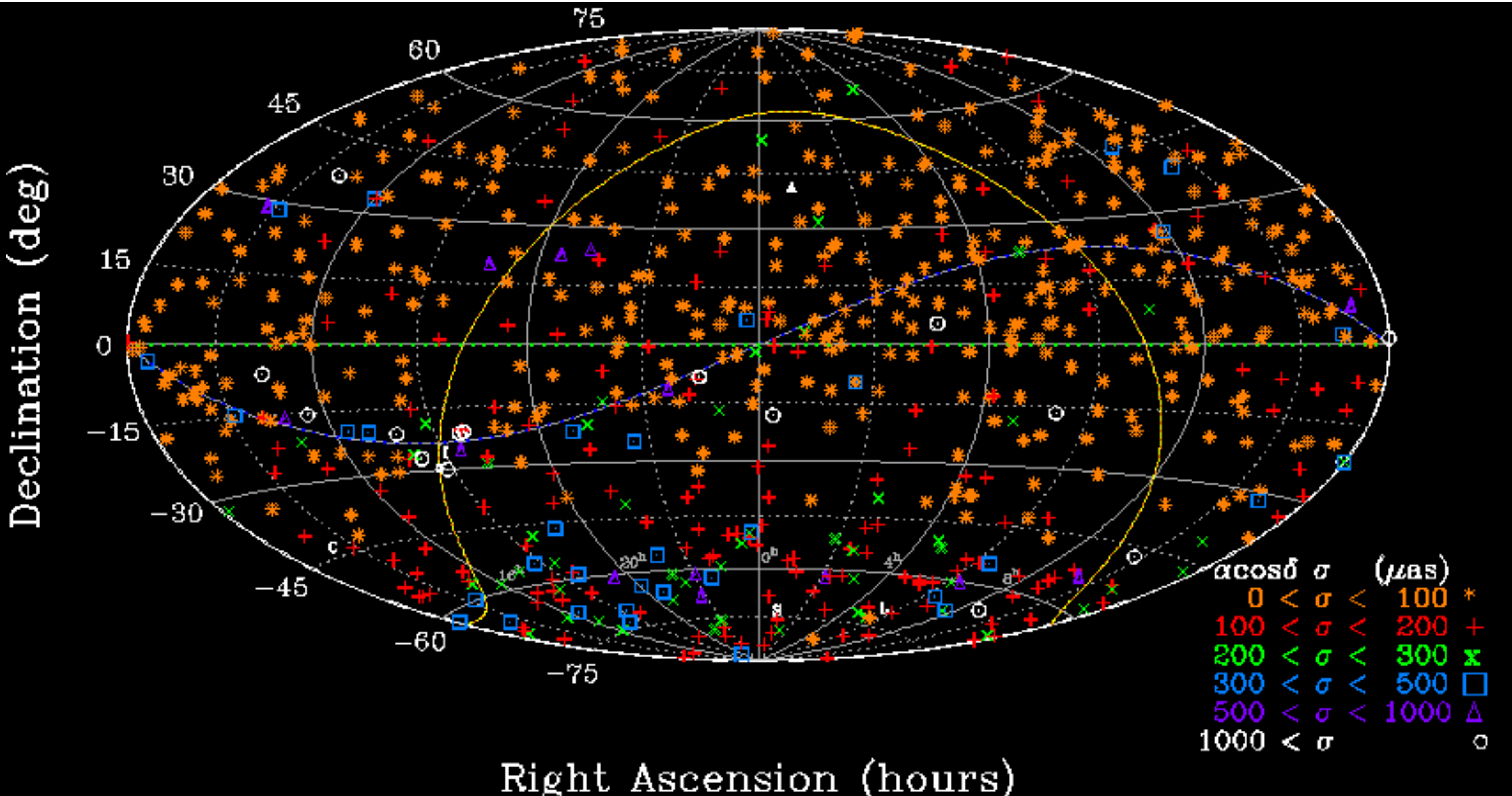
- Recent S/X solutions agree better with X/Ka than
  S/X based ICRF2 does.

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

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

Backup slides

NASA-ESA 32GHz RA results: 674 sources

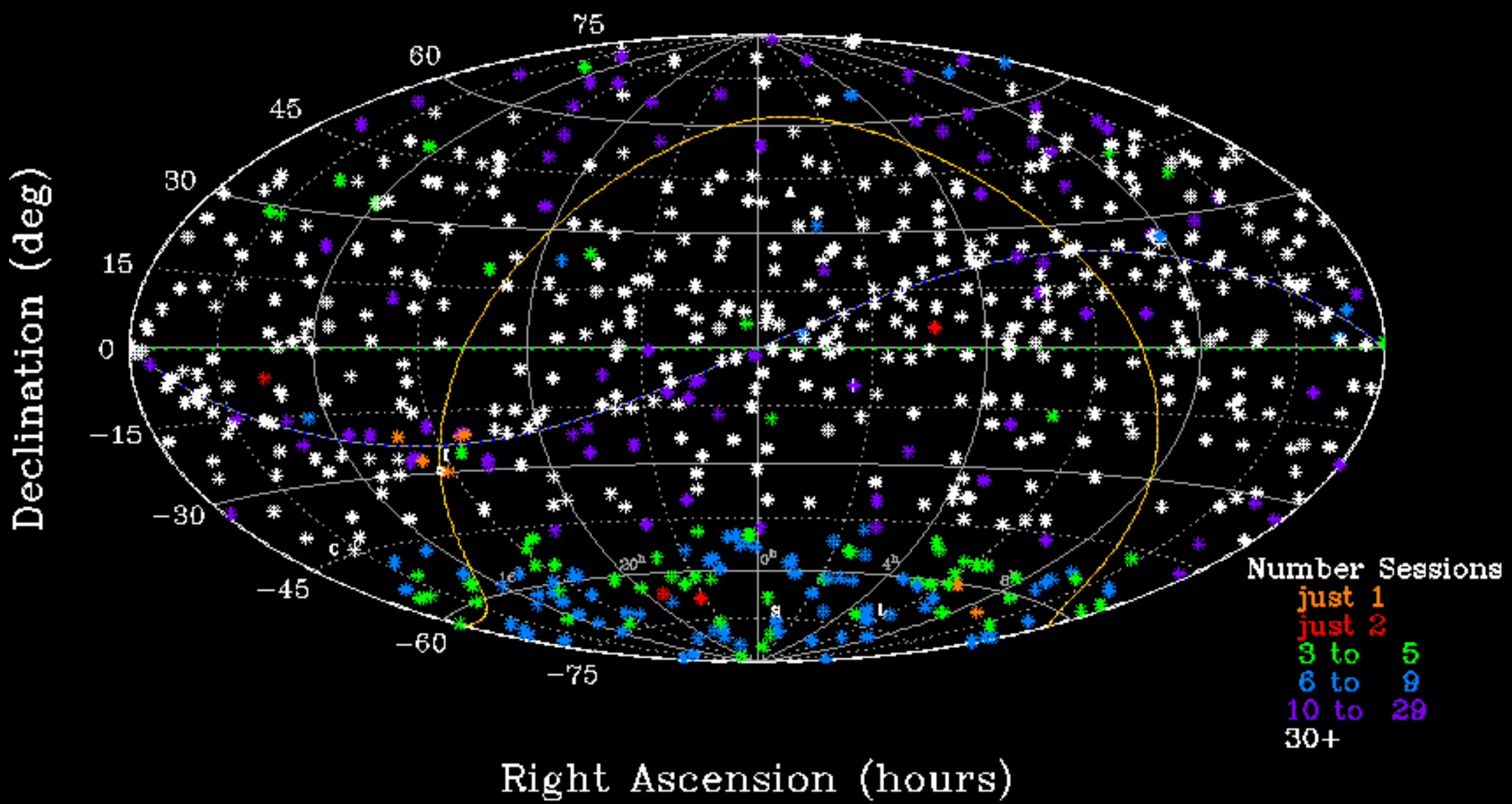


DSN: Goldstone to Madrid & Canberra

+ ESA baselines: Malargüe to Canberra, Goldstone, Madrid

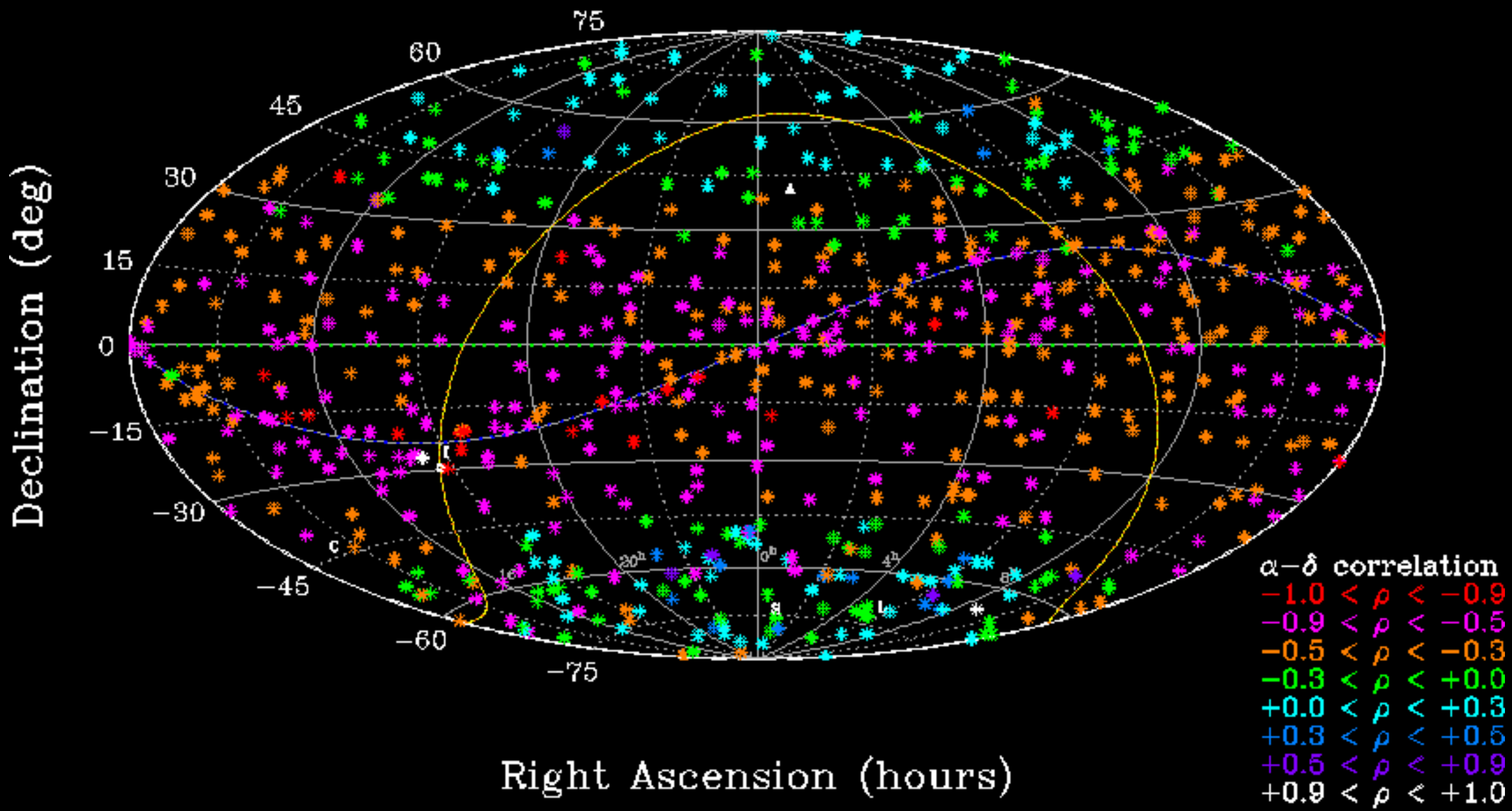
Full sky: 110 sessions, 40K group delay/phase rate observations

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