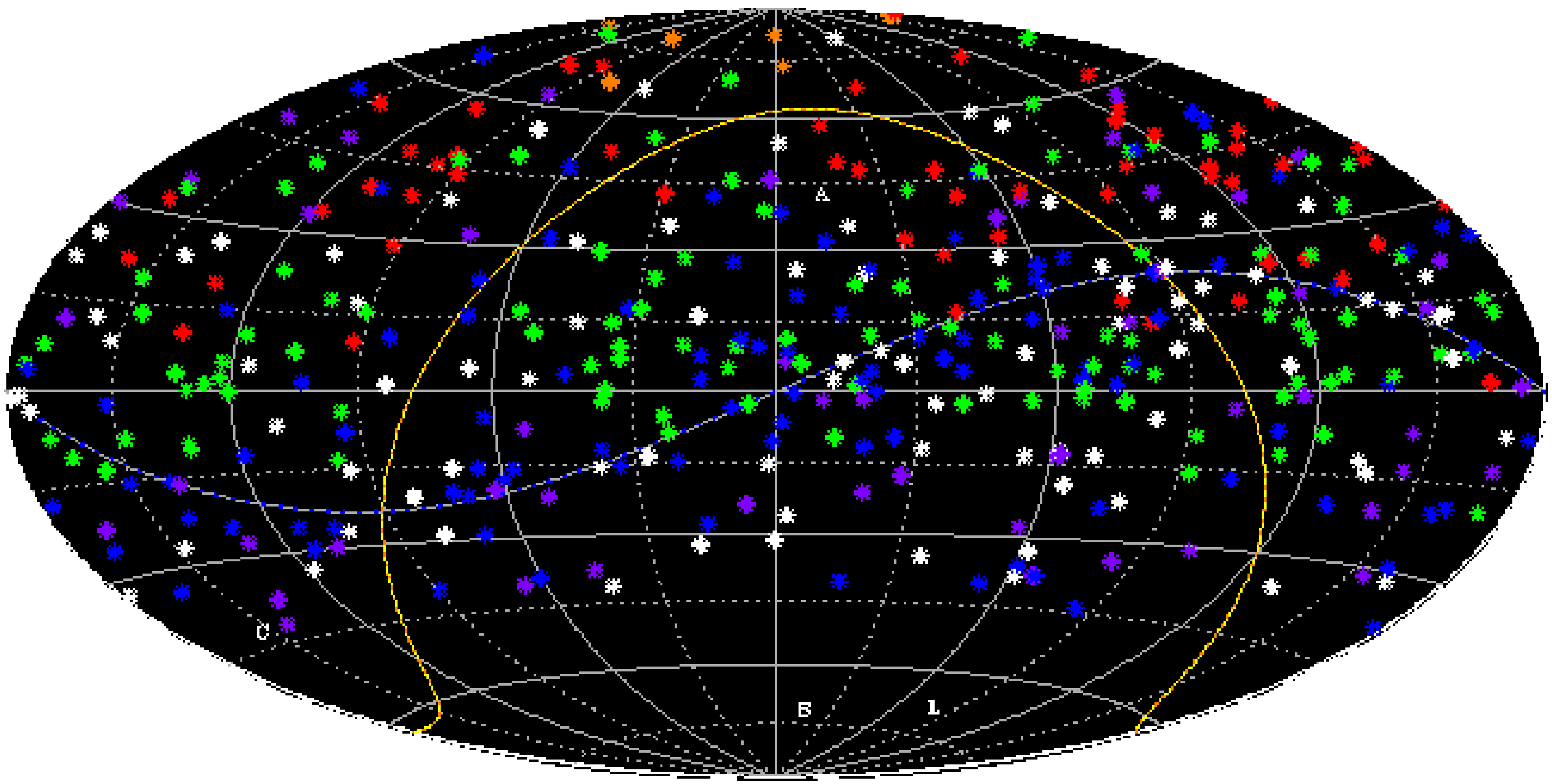
The Celestial Frame at X/Ka-band (8.4/32 GHz)



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30 March 2011

Overview

- Status of current radio-based celestial frames
  - ICRF2: wavelength 3.6cm, 3.4K objects, 40-100 µas
  - K-band: wavelength 1.2cm, 0.3K objects, 100-250 µas
  - X/Ka: wavelength 9mm, 0.5K objects, 200-300 µas

- Need southern stations: complementary geometry
  - Benefits southern cap, Declination accuracy

- Gaia/optical to VLBI/radio frame tie

  70-100 µas independent accuracy verification per source

  5- 15 µas potential precision in 3-D frame tie

Celestial Frame Collaborators

- ICRF2 Working Group (S/X-band, 3.6cm)

  C. Ma chair

  E.F. Arias, G. Bianco, D.A. Boboltz, S.L. Bolotin, P. Charlot, G. Engelhardt, A.L. Fey, R.A. Gaume, A.-M. Gontier, R. Heinkelmann, C.S. Jacobs, S. Kurdubov, S.B. Lambert, Z.M. Malkin, A. Nothnagel, L. Petrov, E. Skurikhina, J.R. Sokolova, J. Souchay, O.J. Sovers, V. Tesmer, O.A. Titov, G. Wang, V.E. Zharov, C. Barache, S. Bockmann, A. Collioud, J.M. Gipson, D. Gordon, S.O. Lytvyn , D.S. MacMillan, R. Ojha

- KQ Collaboration (1.2cm,7mm or 24, 43 GHz)

  G.E. Lanyi, P.I.

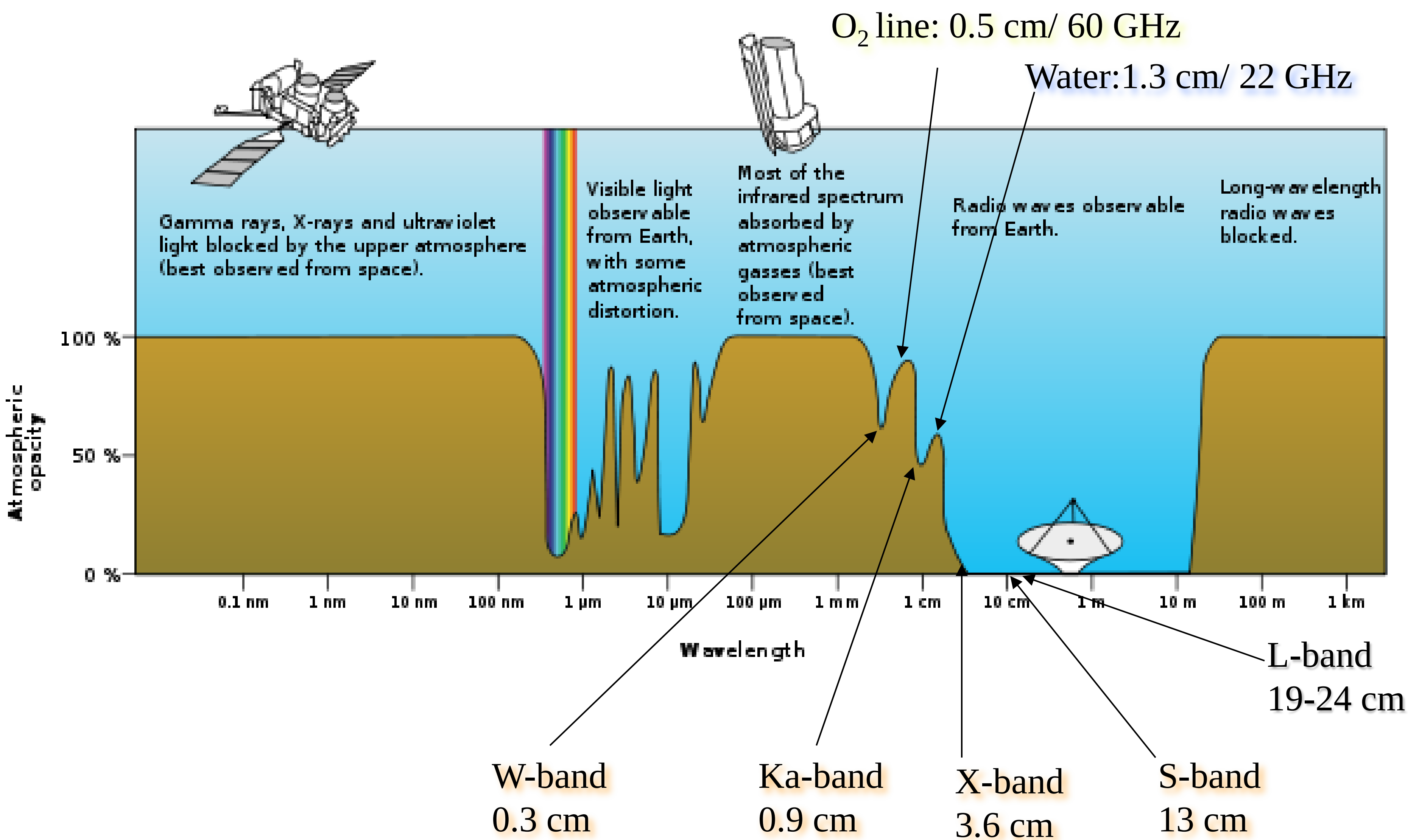
  D.A. Boboltz, P. Charlot, A.L. Fey, E. B. Fomalont, B.J. Geldzahler, D. Gordon, C.S. Jacobs, C. Ma, C.J. Naudet, J.D. Romney, O.J. Sovers, L.D. Zhang

- X/Ka-band Collaboration (9mm, 32 GHz)

  C.S. Jacobs, P.I.

  J. Clark, C. Garcia-Miro, S. Horiuchi, V.E. Moll, L.J. Skjerve, O.J. Sovers

Why observe in Radio? The 'Window'

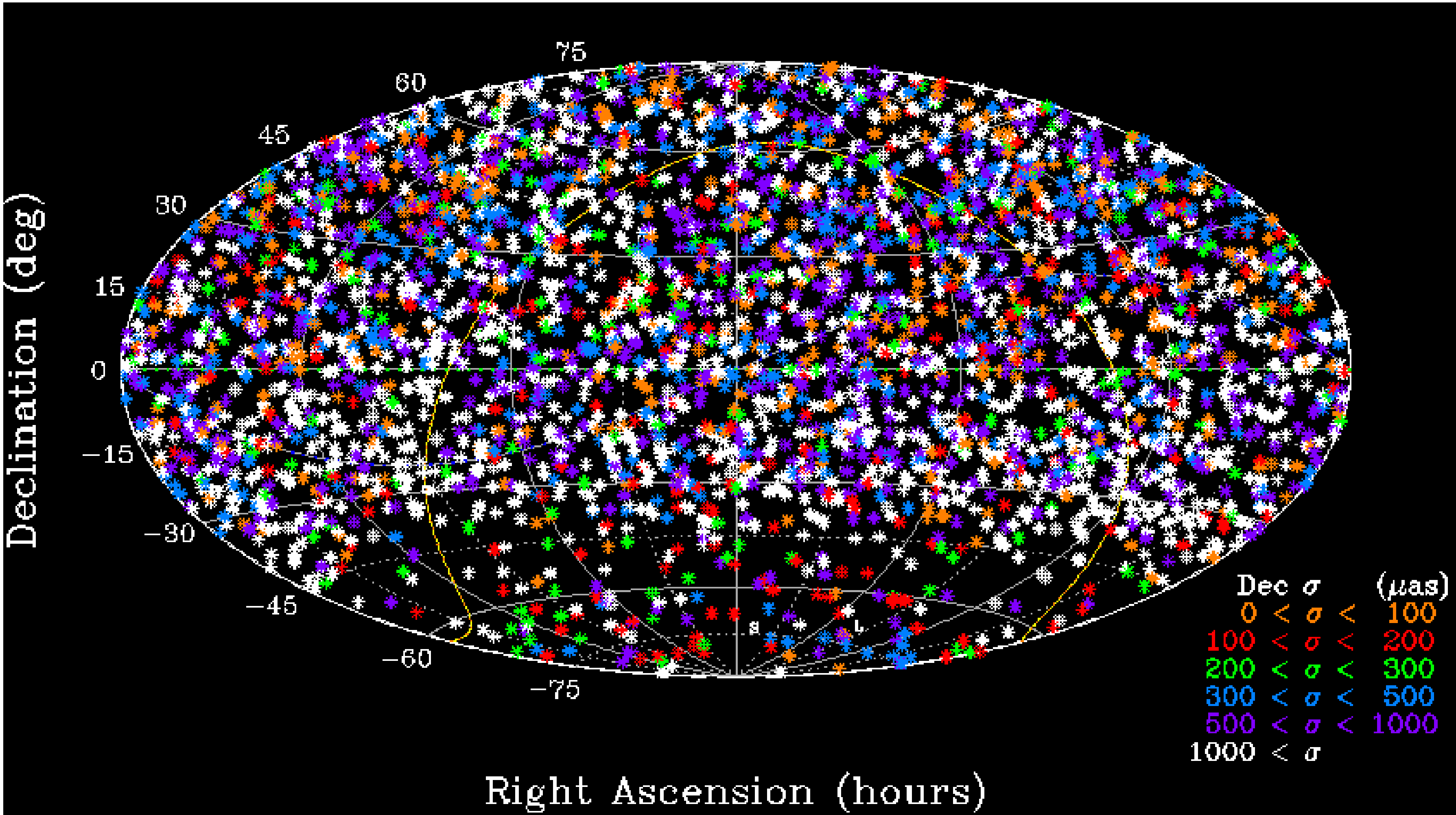


Credit: NASA; http://en.wikipedia.org/wiki/Radio_window

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

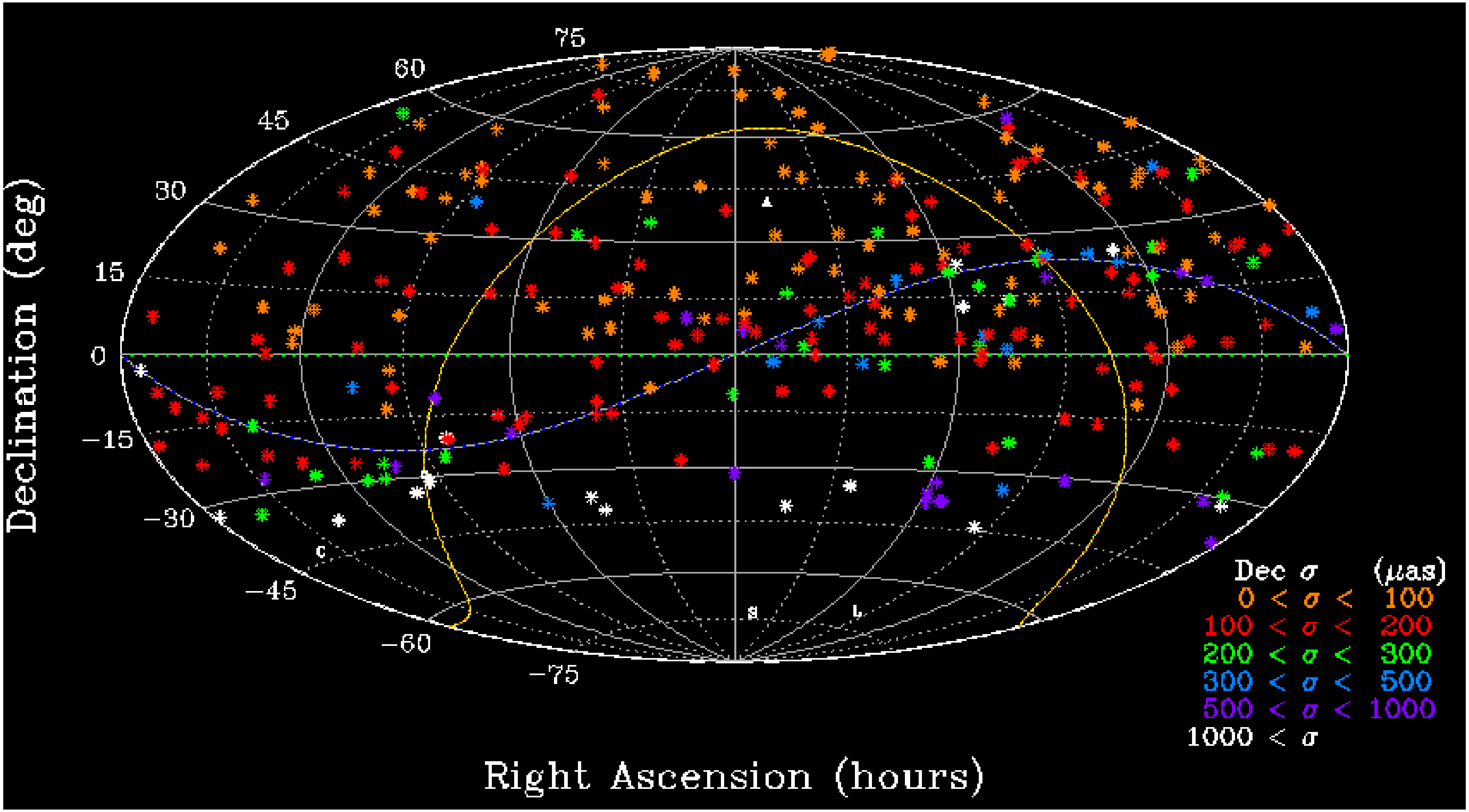
ICRF2 S/X 3.6cm: 3414 sources



40 μas floor. ~1200 obj. well observed, ~2000 survey session only

Credit: Ma et al, eds. Fey, Gordon, Jacobs, IERS Tech. Note 35, Germany, 2009

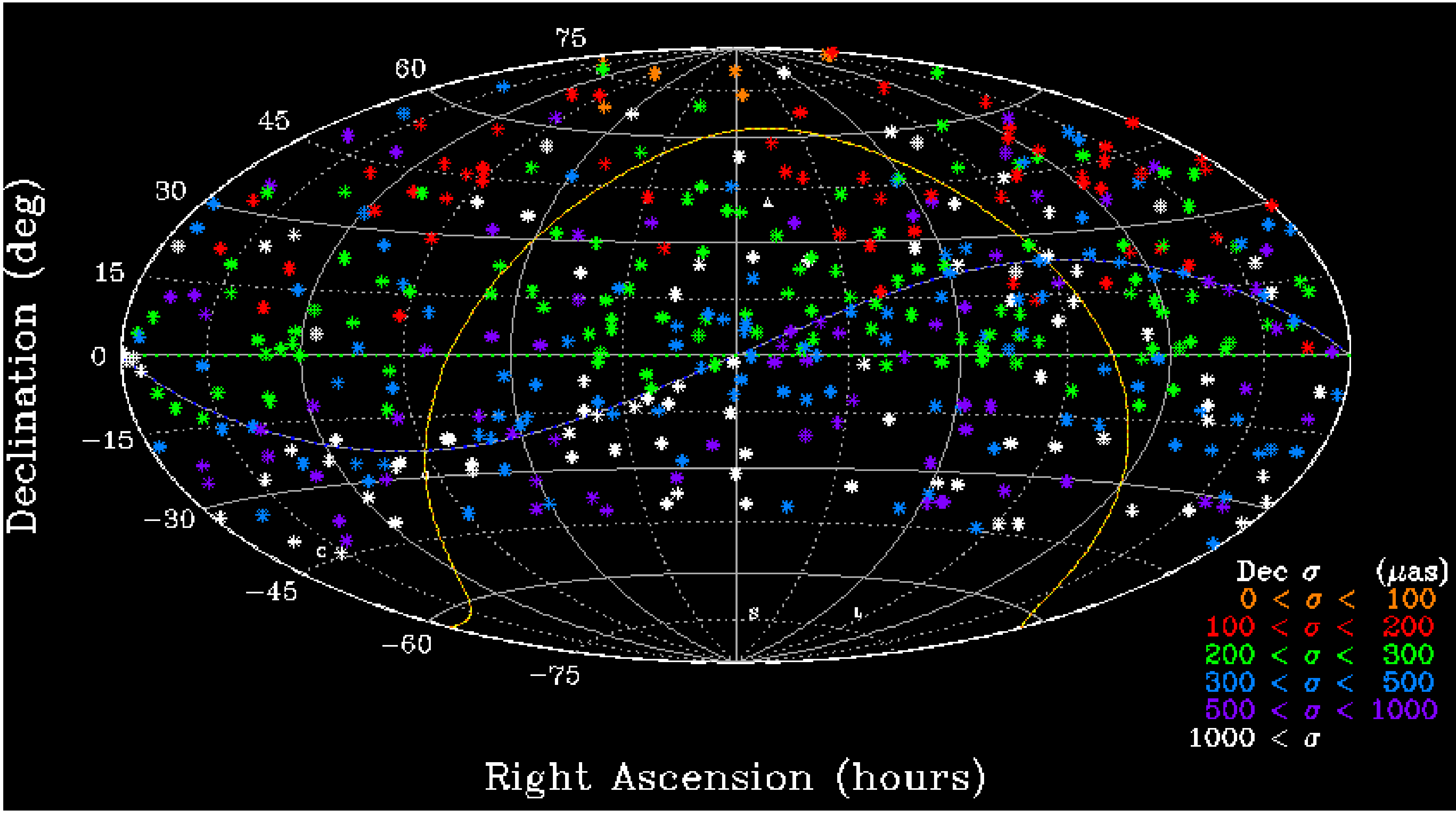
K-band 1.2cm: 278 Sources



VLBA all northern, poor below Dec. -30˚. ΔDec vs. Dec tilt= 500 μas

Credit: Lanyi et al, AJ, 139, 5, 2010; Charlot et al, AJ, 139, 5, 2010

X/Ka current results: 455 Sources

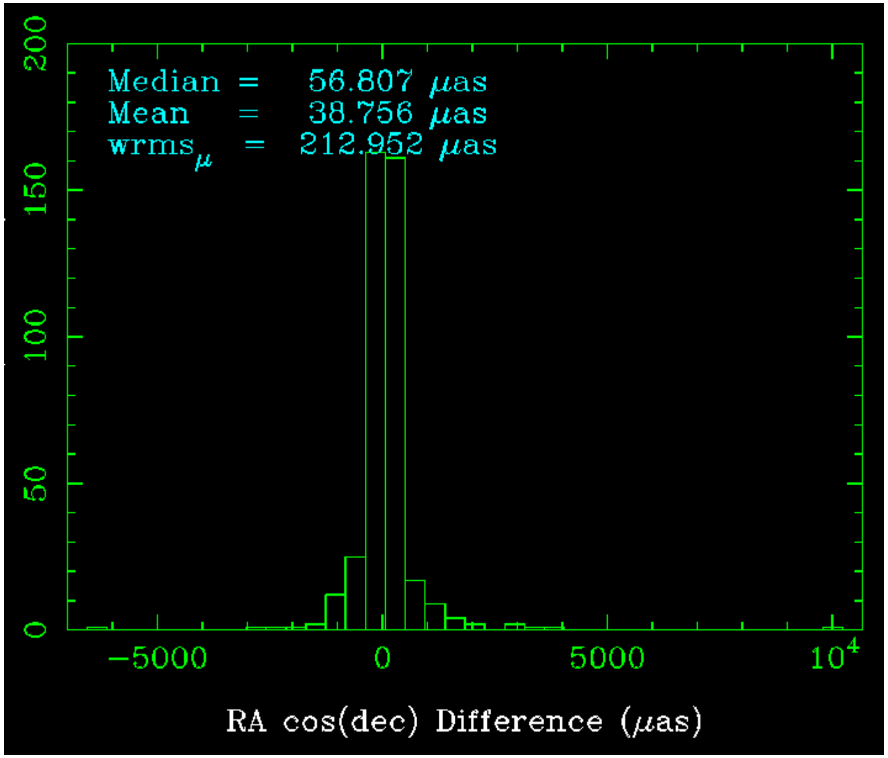


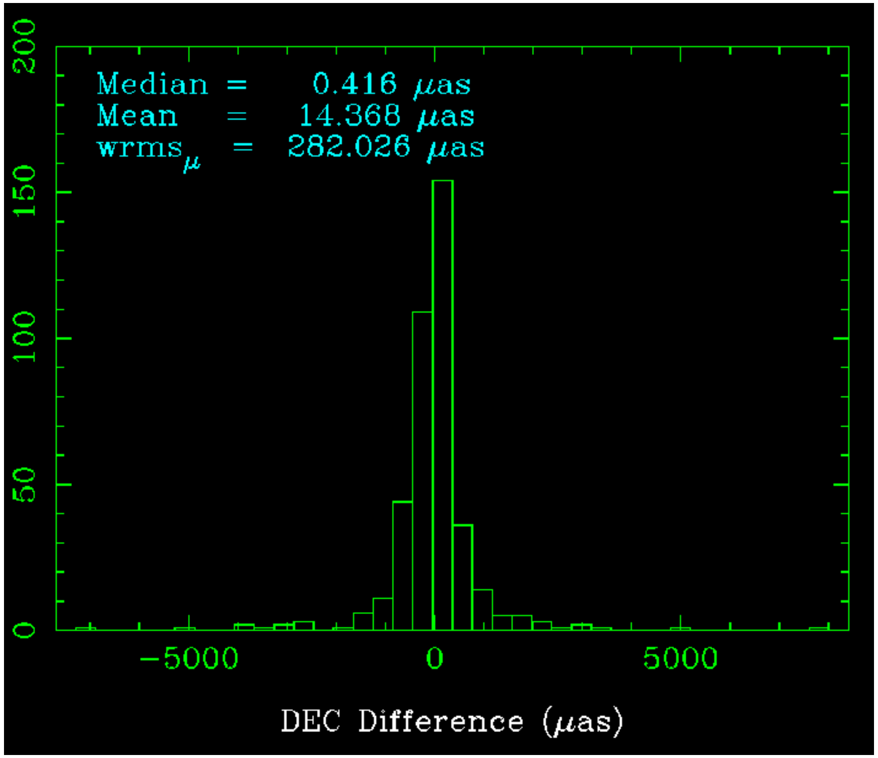
Cal. to Madrid, Cal. to Australia. Weakens southward. No ΔDec tilt

Credit: Jacobs et al, EVGA, Bonn, Germany, 2011

9mm (X/Ka) *vs.* ICRF2 at 3.6cm (S/X)

Accuracy of 404 X/Ka sources vs. S/X ICRF2 (current IAU standard)





RA: 213 μas = 1.0 nrad

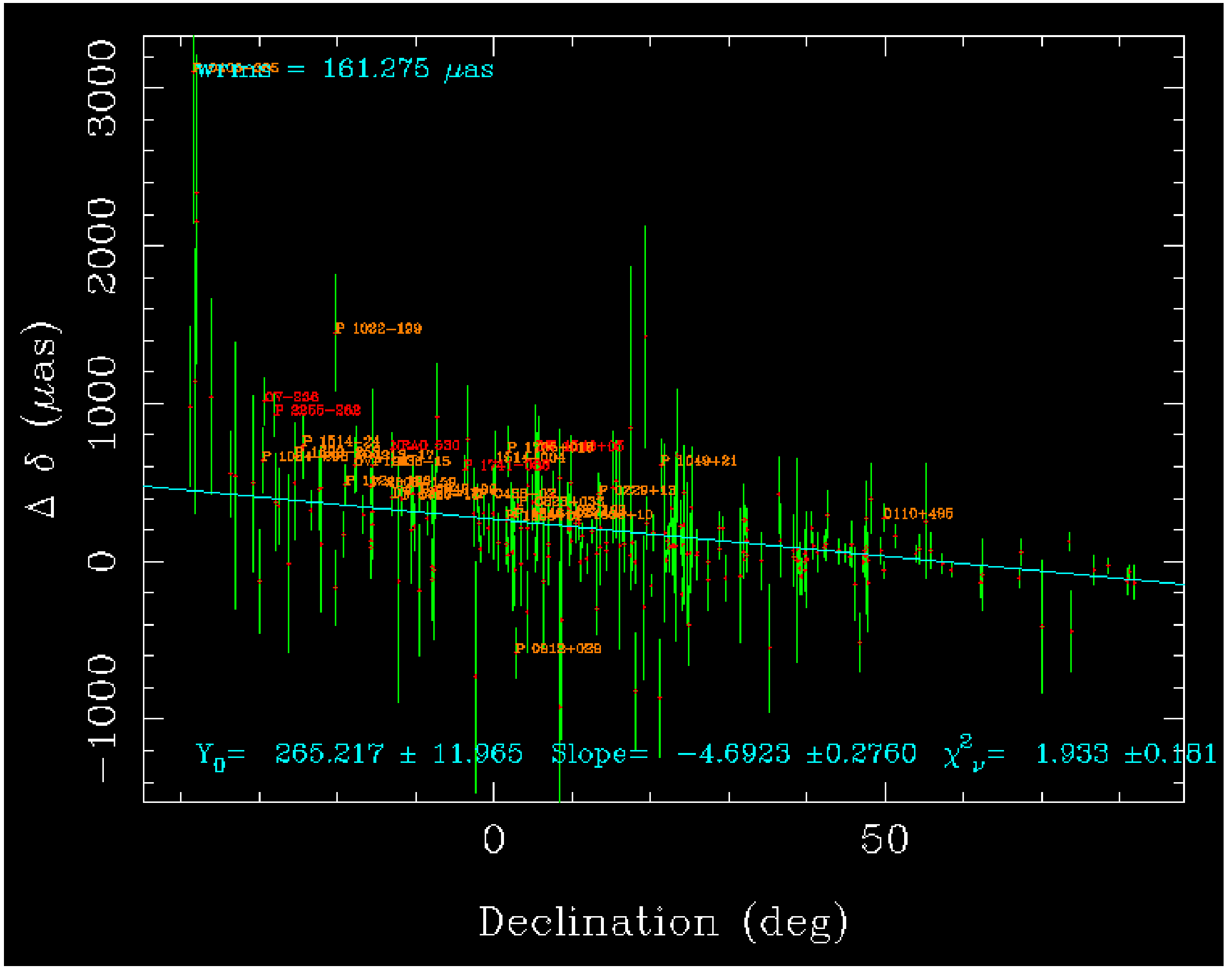
Dec: 282 μas = 1.4 nrad

Credit: X/Ka: Jacobs et al, EVGA, Bonn, Germany, 2011
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009

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)

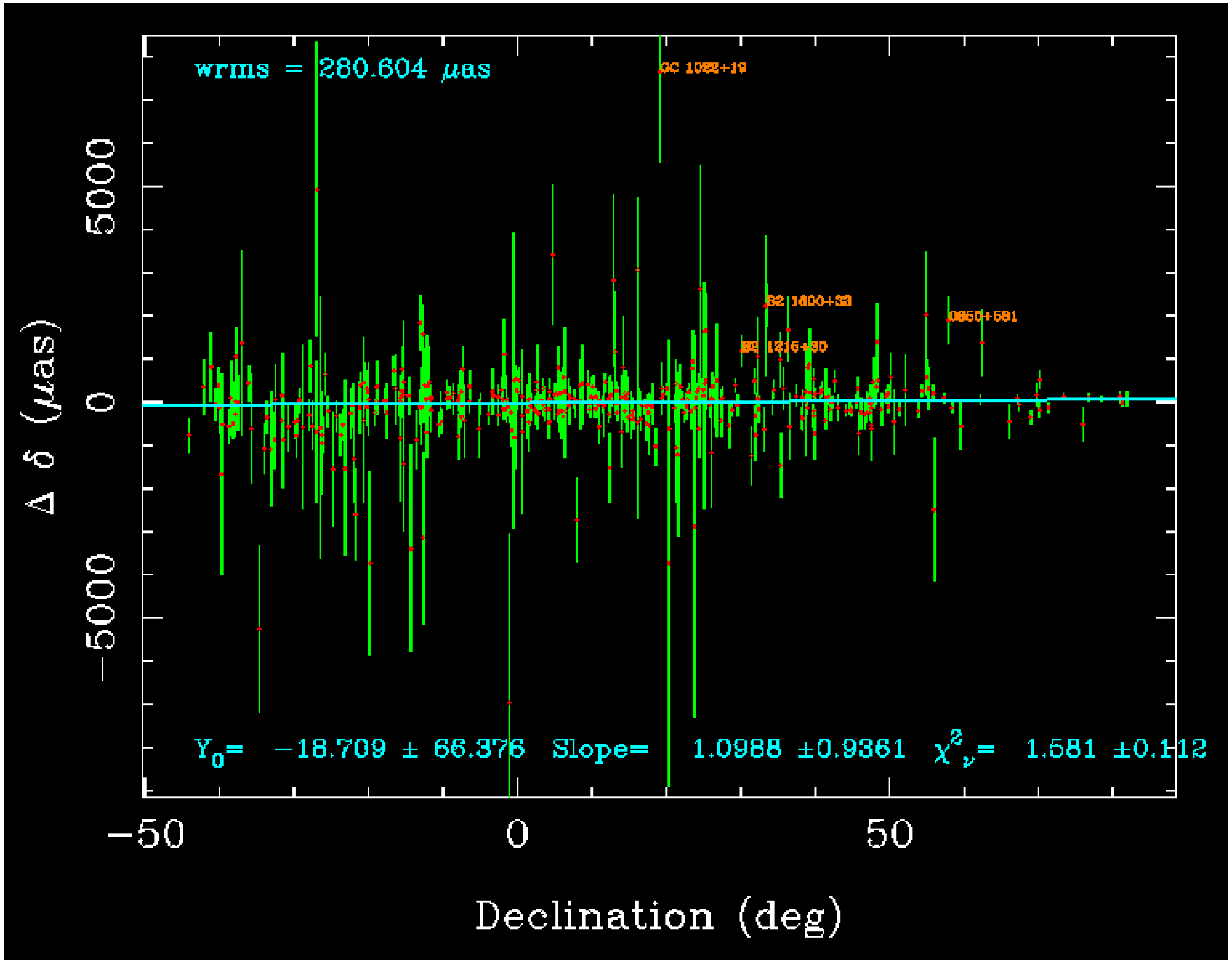
Credit: K(1.2cm): Lanyi et al, AJ, 139,5, 2010
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009

9mm (X/Ka) *vs.* ICRF2 at 3.6cm (S/X)

Dual-band ion
Calibrations
and
Station in south

Leads to better
ΔDec vs. Dec
Zonal stability:

100+-100 µas tilt



X/Ka(9mm) Dec. vs. S/X ICRF2 (current IAU standard)

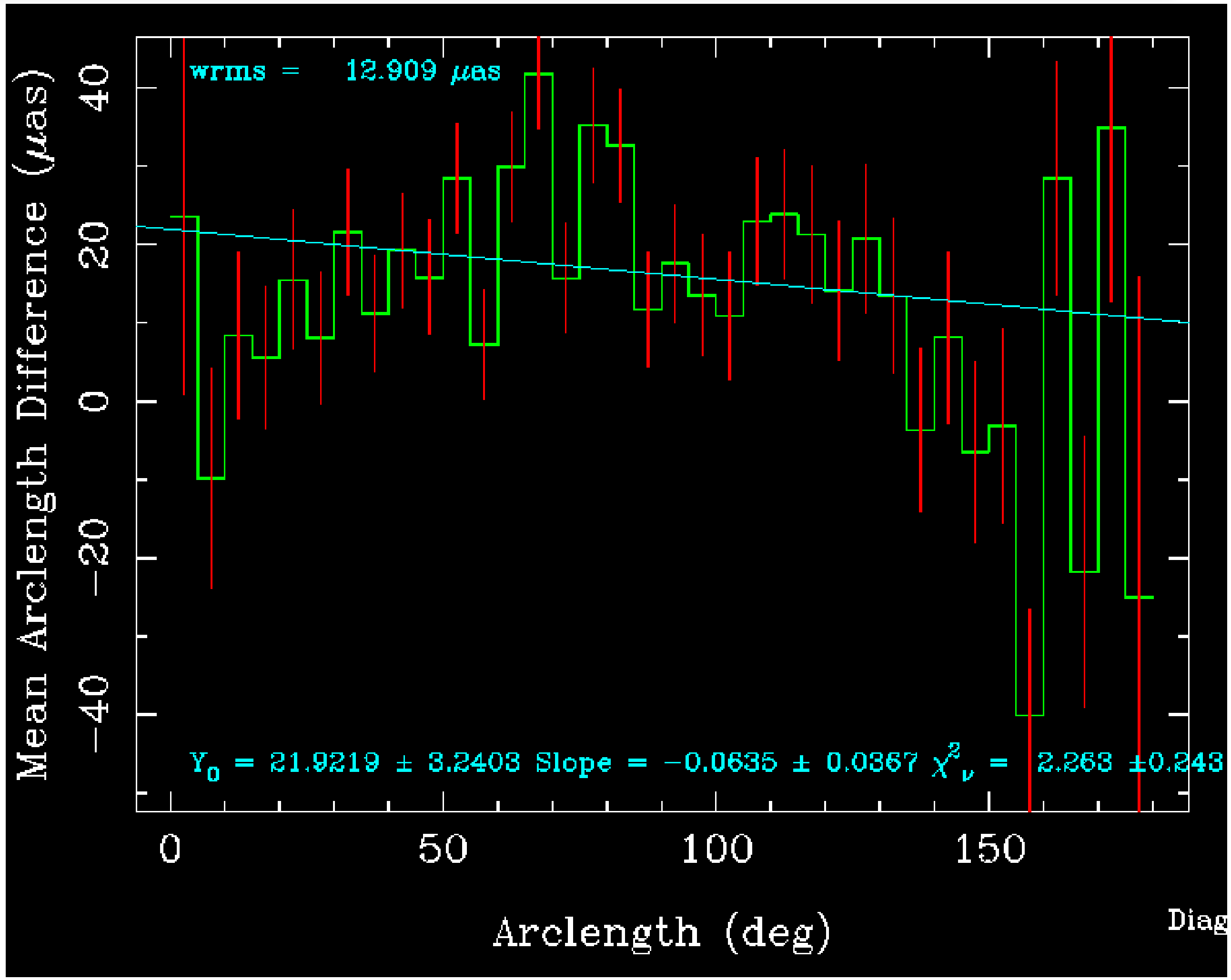
Credit: X/Ka(9mm): Jacobs et al, EVGA, Bonn, Germany, 2011
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009

9mm (X/Ka) *vs.* ICRF2 at 3.6cm (S/X)

Mean zonal error as shown by Δarc vs. arc ~20 µas (0.1 nrad)

When southern Station XYZ is fixed to S/X data estimate +-1cm.

Weaker constraint leads to 150 µas Zonal errors.



X/Ka(9mm) vs. S/X ICRF2 (current IAU standard)

Credit: X/Ka(9mm): Jacobs et al, EVGA, Bonn, Germany, 2011
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009

Improving X/Ka VLBI

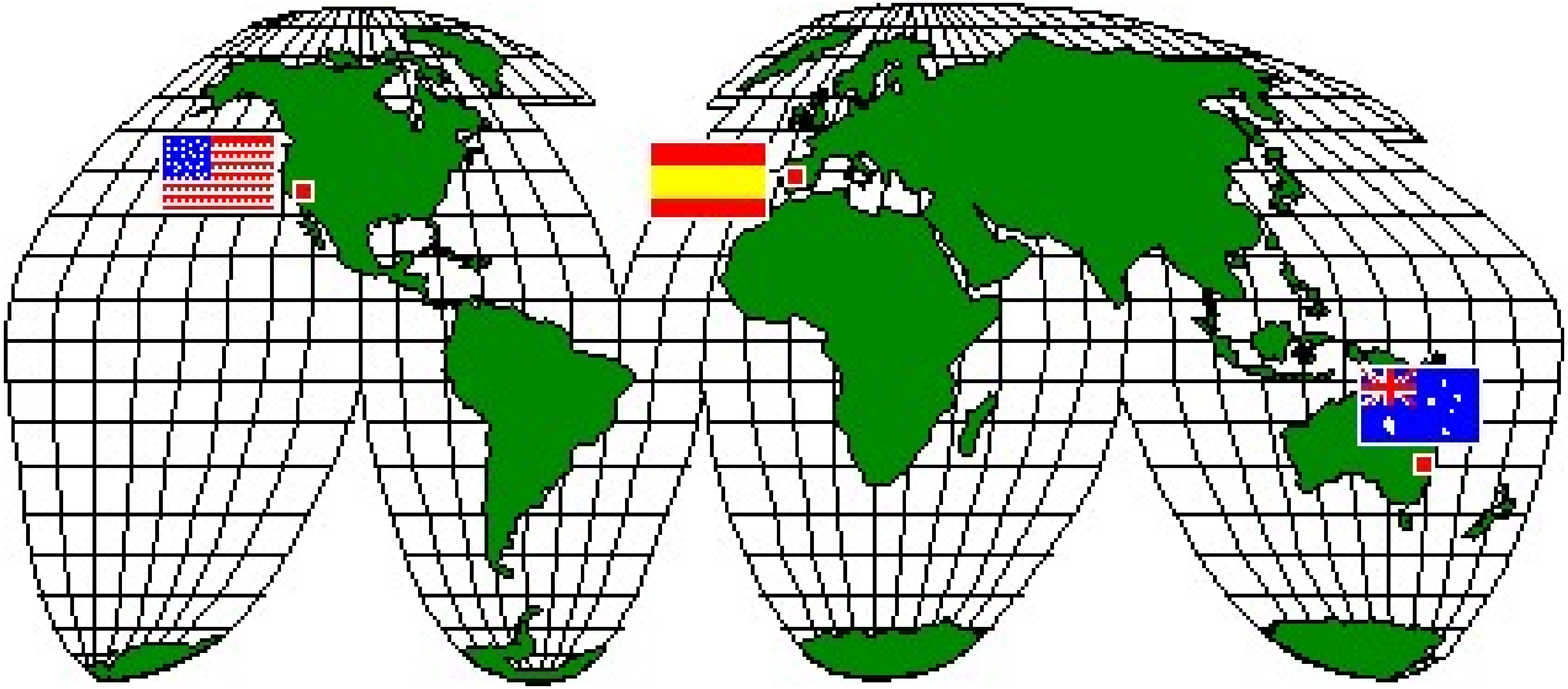
Systems Analysis shows dominant Errors are

- Limited SNR/sensitivity
  - already increasing bit rates: 112 to 448 Mbps. Soon to 896?
- Instrumentation: already building better hardware
  - Ka-band phase calibrators, Digital Back Ends (filters)
- Troposphere: better calibrations being explored for turbulent variations in signal delay

- **Weak geometry in Southern hemisphere**
  - Limits accuracy to about 1 nrad (200 μas) level in Declination
  - No observations below Declination of -45 Deg!
  - DSN has only one southern site: Canberra, Australia (DSS 34)
  - Need 2nd site in the Southern hemisphere

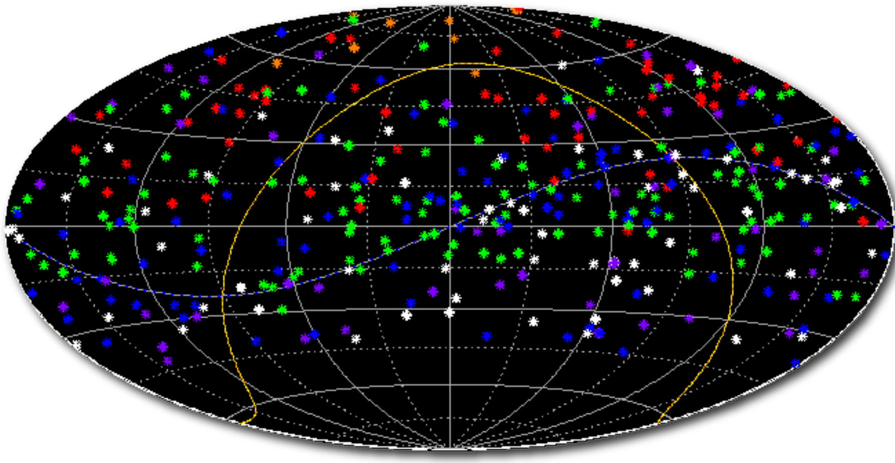
Attacking the Error budget

DSN lack of Southern Geometry

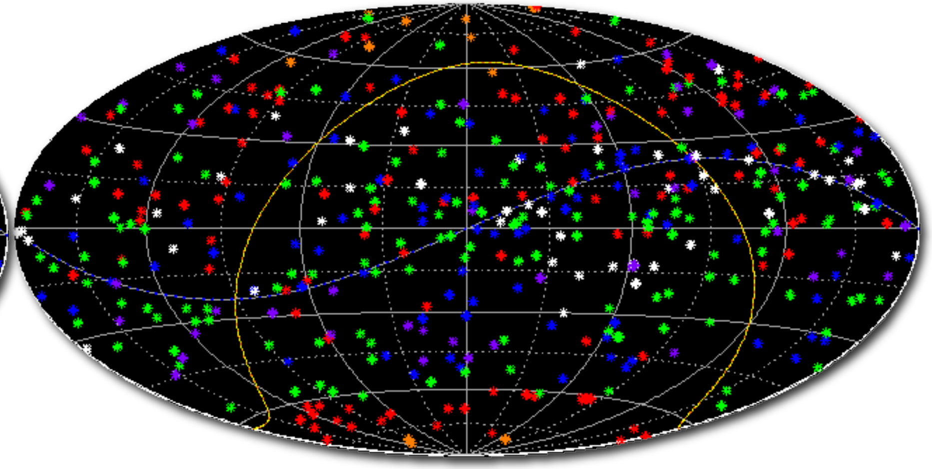


www.spacetoday.org/images/SolSys/DeepSpaceNetwork/NASA_DSN_WorldMap.gif

Simulation of Added Southern Station



Before Southern Data



After

Declination Sigma

Orange: < 100 μas
Red: < 200
Green: < 300
Blue: < 500
Purple: < 1000
White: > 1000

- 50 real X/Ka sessions augmented by simulated data
  simulate 1000 group delays, SNR = 50
  ~9000 km baseline: Australia to S. America or S. Africa

- Completes Declination coverage: cap region -45 to -90 deg
  200 μas (1 nrad) precision in south polar cap,
  mid south 200-1000 μas, all with just a few days observing.

<u>Gaia-Optical *vs*. VLBI-radio</u>:

Celestial Frame tie
and
Accuracy Verification

Optical vs. Radio positions

Positions differences from:

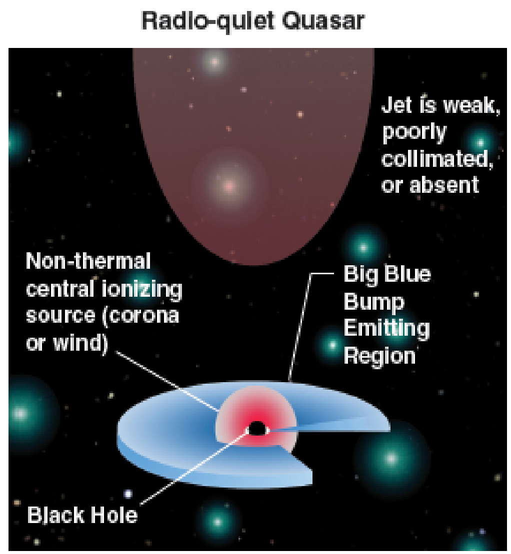
• Astrophysics of emission centroids

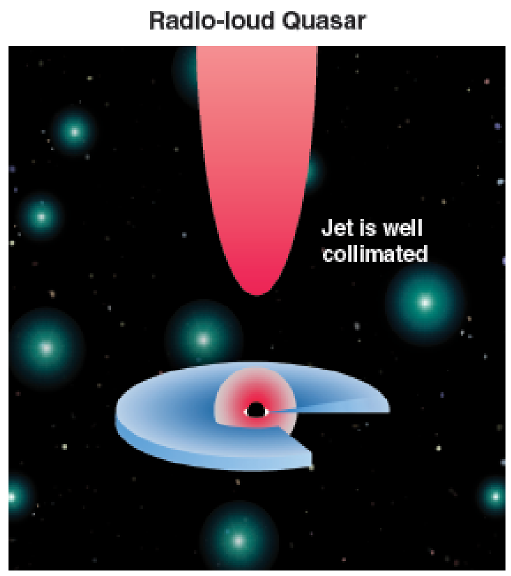
- radio: synchrotron from jet

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

• Instrumental errors both radio & optical

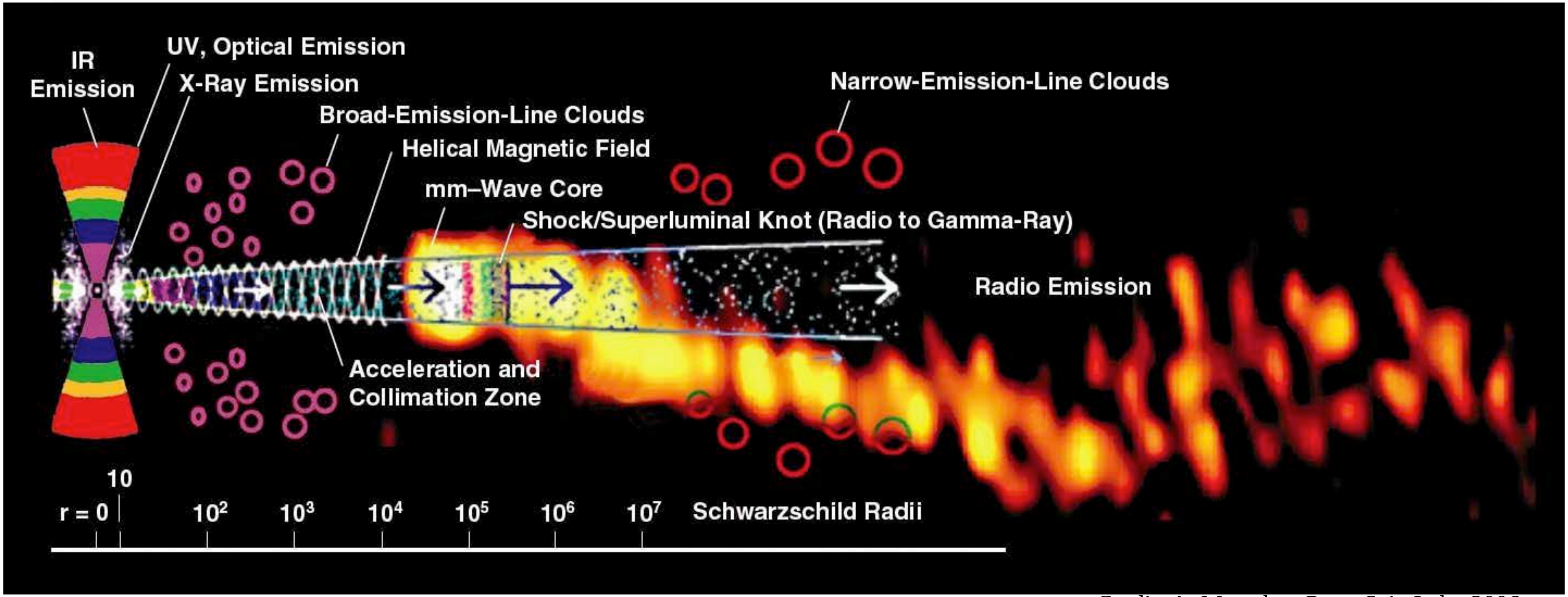
• Analysis errors





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

9mm vs. 3.6cm? Core shift & structure



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

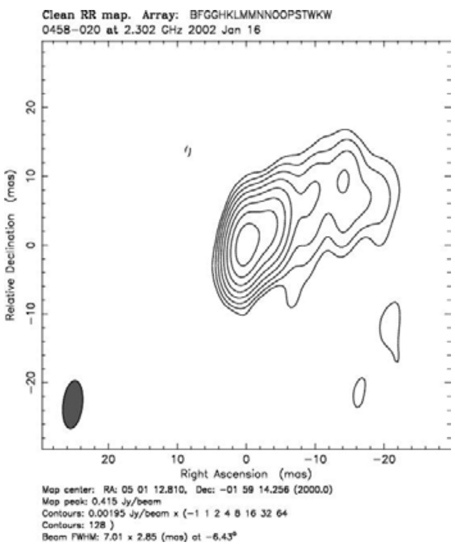
Positions differences from 'core shift'

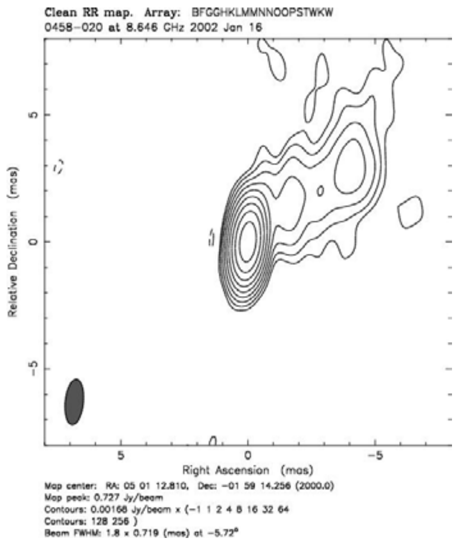
- wavelength dependent shift in radio centroid.
- *3.6cm to 9mm core shift:*

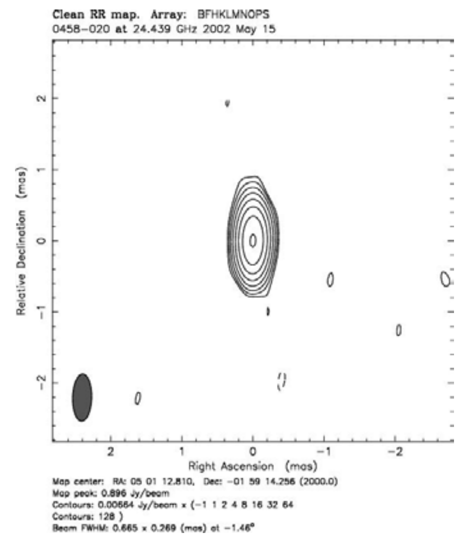
  100 μas in phase delay centroid?

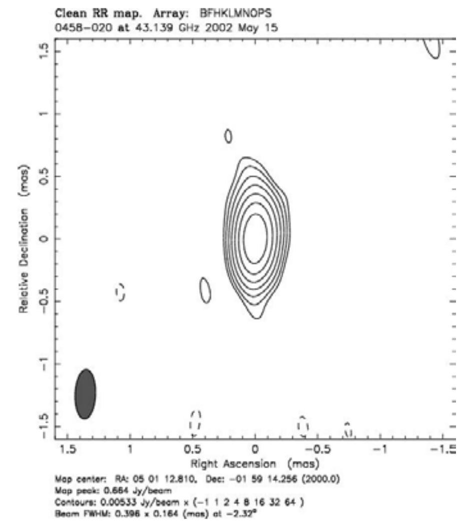
  <<100 μas in group delay centroid? (*Porcas, AA, 505, 1, 2009*)
- shorter wavelength closer to Black hole and Optical: 9mm X/Ka better

Source Structure vs. Wavelength









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 ----->

Image credit: P. Charlot et al, AJ, 139, 5, 2010

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
  70 μas @ V=18
  25 μas @ V=16

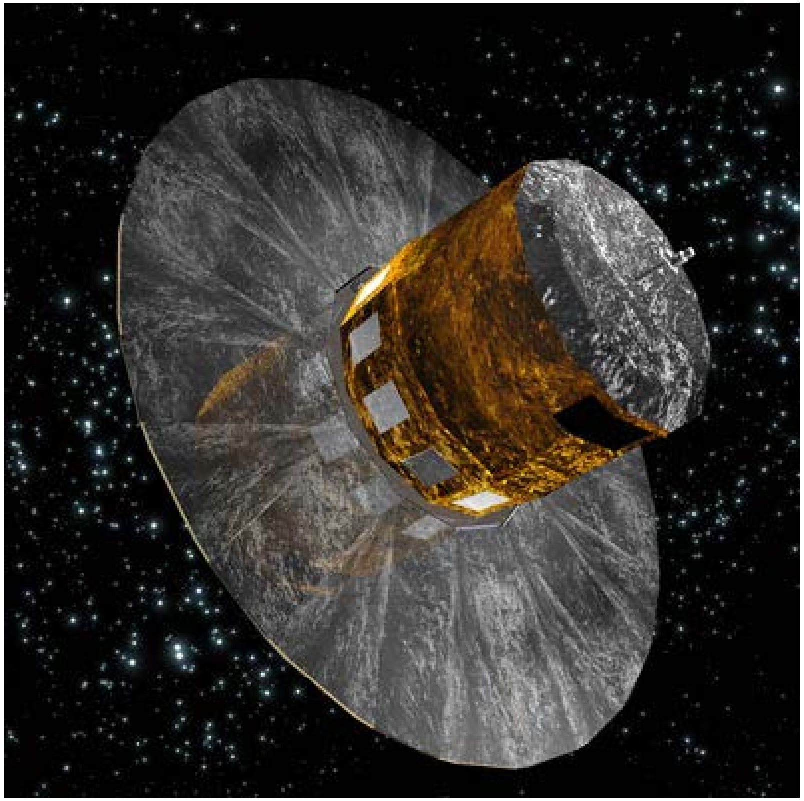
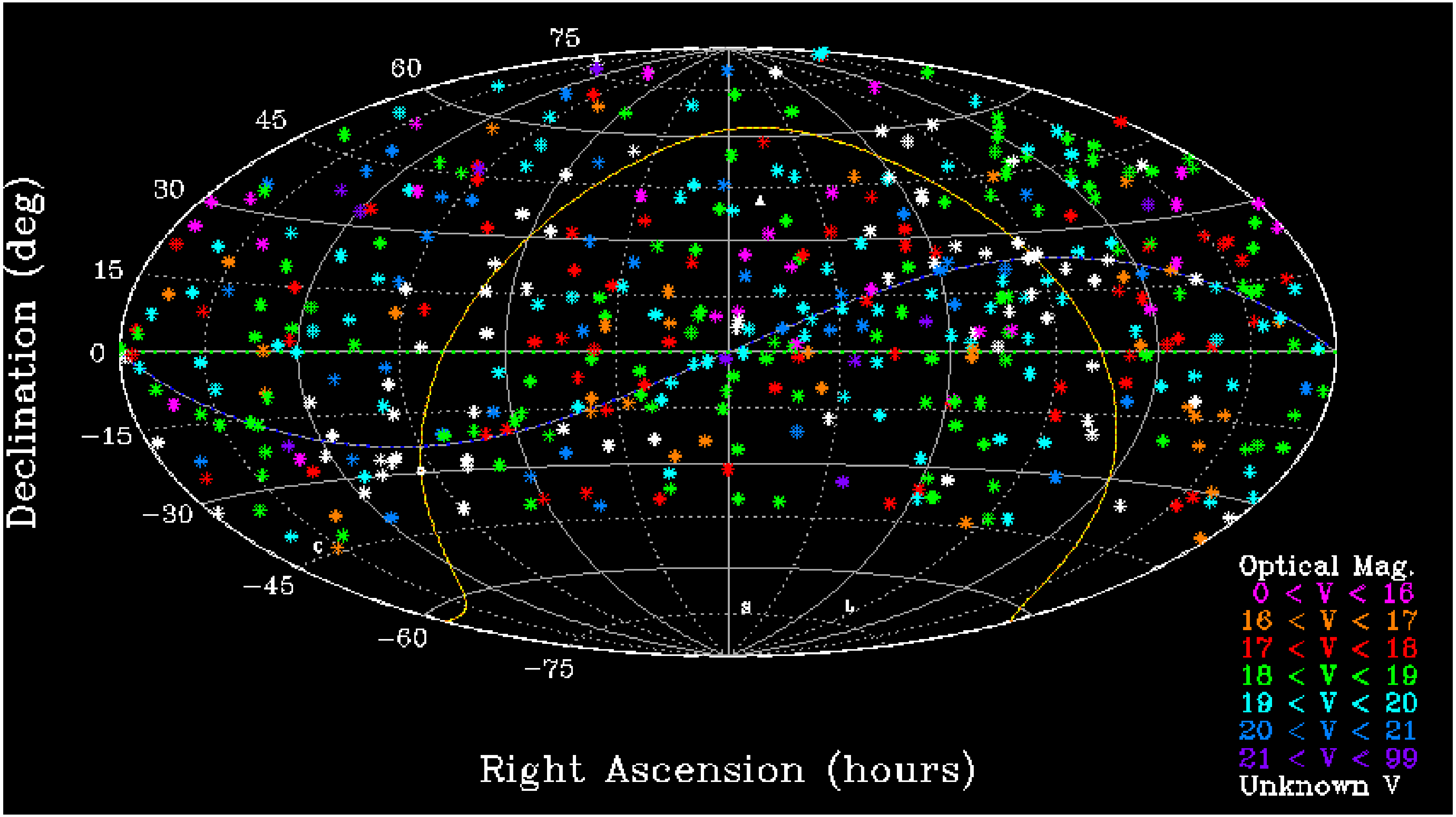


Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7

Optical brightness of X/Ka 9mm sources



Median optical magnitude V_{med} = 18.6 magnitude *(68 obj. no data)*

> 130 objects optically bright by Gaia standard (V<18)

Gaia Optical vs. X/Ka 9mm frame tie

- 387 of 455 X/Ka 9mm objects with known optical V magnitudes
  130 objects optically bright (V< 18)
  206 objects optically weak (18 < V< 20)
  51 objects optically undetectable (V > 20)
  68 objects *no optical info yet* (*V = ??)*
- Simulated Gaia measurement errors (sigma RA, Dec)
  for 336 objects: median sigmas ~ 100 µas per component
- VLBI 9mm radio sigmas ~200 µas per component and improving
- Covariance calculation of 3-D rotational tie
  using current 9mm radio sigmas and simulated Gaia sigmas
  Rx +- 16 µas <- Weak. Needs south polar VLBI (Dec < -45)
  Ry +- 13 µas
  Rz +- 11 µas
- Now limited by radio sigmas for which 2-3X improvement possible.
  Potential for rotation sigmas ~5 µas per frame tie component

Conclusions

- Astrometry using VLBI at 9mm (32 GHz)
  455 objects: RA, Dec accuracy 200, 280 μas

- Quasar astrophysics: 9mm position closer to optical position than S/X-based ICRF2, less extended structure expected

- Need southern *complementary* geometry for
  Full sky radio coverage, 70-100 μas accuracy at X/Ka 9mm

- Gaia tie:
  >130 objects radio loud @9mm *and* optically bright V<18
  Ties Gaia optical to VLBI radio frame
  Study astrophysics: core shift, jet vs. accretion disk
  Independent check on Gaia accuracy at 70-100 μas level
  5-15 μas potential precision for 3-D frame tie