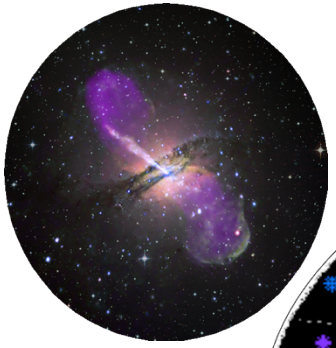
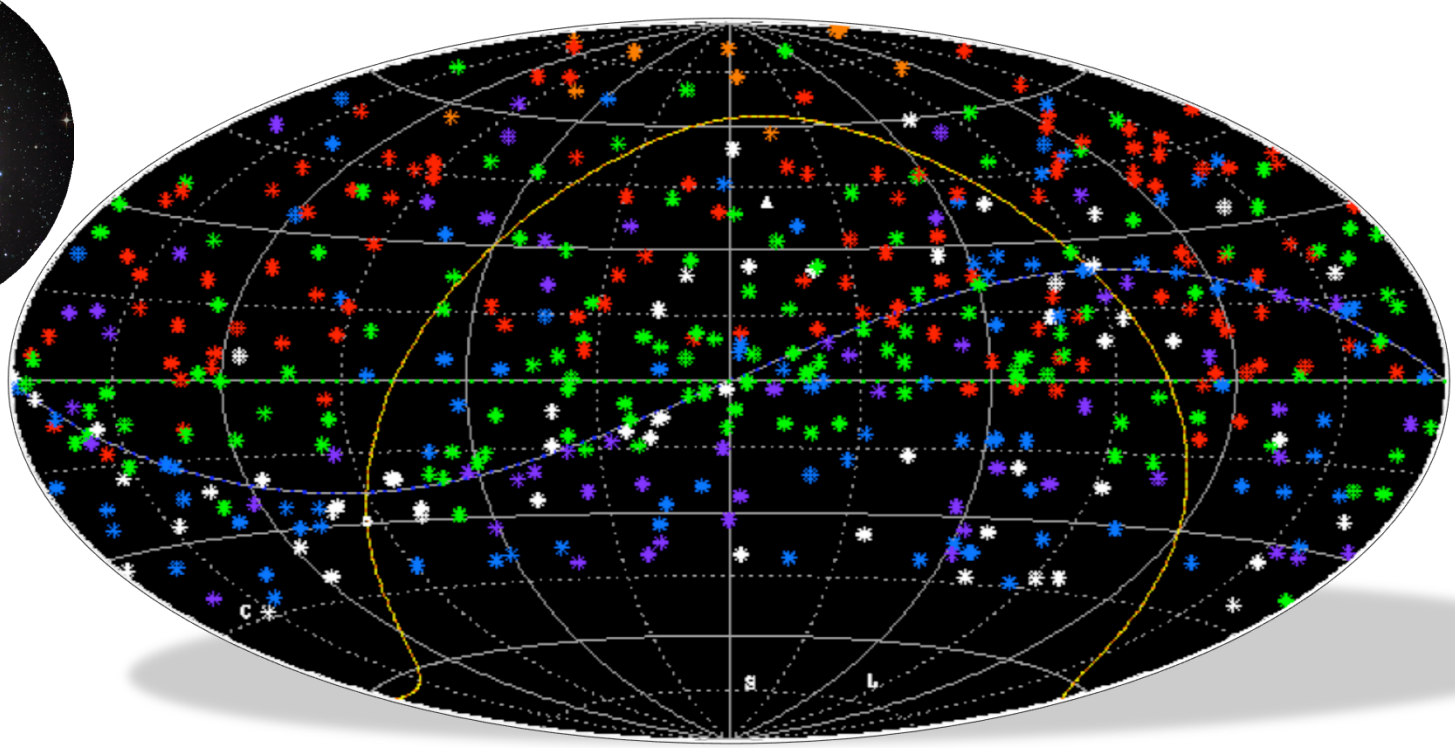
The Celestial Reference Frame at Multiple Radio Wavelengths





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28 August 2012

Overview

- How do sources change with wavelength?
- Overview of Celestial Frames

S/X ICRF-2	>40 μas	3414 sources
K-band	~100 μas	268 sources
Q-band	~300 μas	131 sources
X/Ka-band	~220 μas	482 sources

Neil Armstrong
(1930-2012)

- Future Prospects for Improvements:

  SNR: higher data rates 2-32 Gbps

  Instrumentation: Digital Back Ends, better clocks??

  Troposphere: Faster sweeps of sky, WVR cals

  Geometry: increase Southern hemisphere observations

  Optical frames: tieing to ESA's Gaia mission c. 2021

Collaborators

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

  C.S. Jacobs, P.I.,

  J. Clark, C. García-Miró, S. Horiuchi, A. Romero-Wolf, I. Sotuela, L.G. Snedeker, O.J. Sovers

- 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

- 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. Böckmann, A. Collioud, J.M. Gipson, D. Gordon, S.O. Lytvyn , D.S. MacMillan, R. Ojha

VLBI wavelength dependence?

- **Sensitivity worsens** at shorter wavelength/high frequency

  Higher system temperature: atmosphere H_20 (22 GHz), O_2 60 GHz

  Antenna pointing more difficult

  Antenna surface shape control more difficult

  Atmospheric absorption

  Resolved sources

- **Quasar astrophysics gets better**

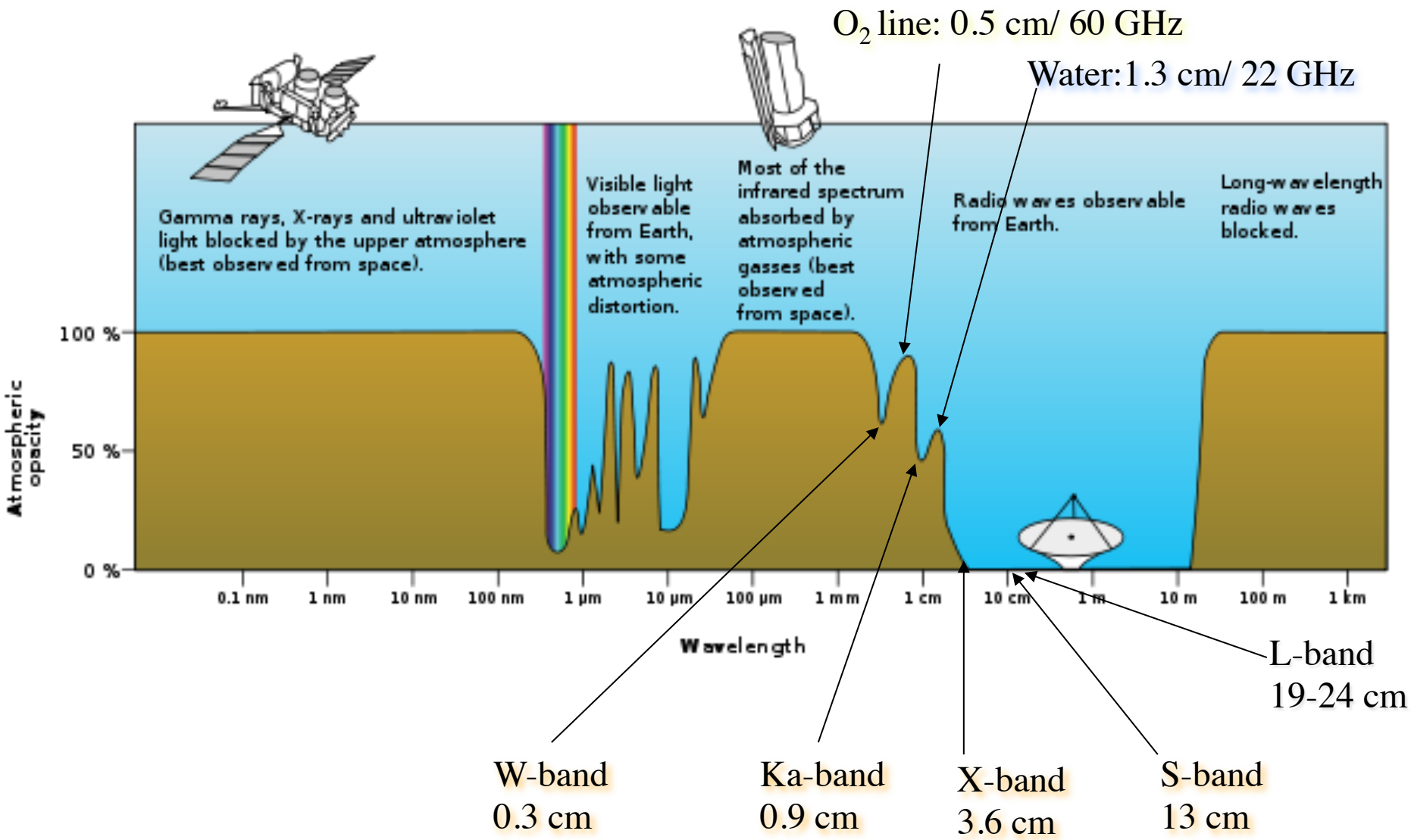
  Sources more compact at shorter wavelength (higher frequency)

  More sources resolved at higher frequency-> less sources

  Less extended structure: plume is steep spectrum

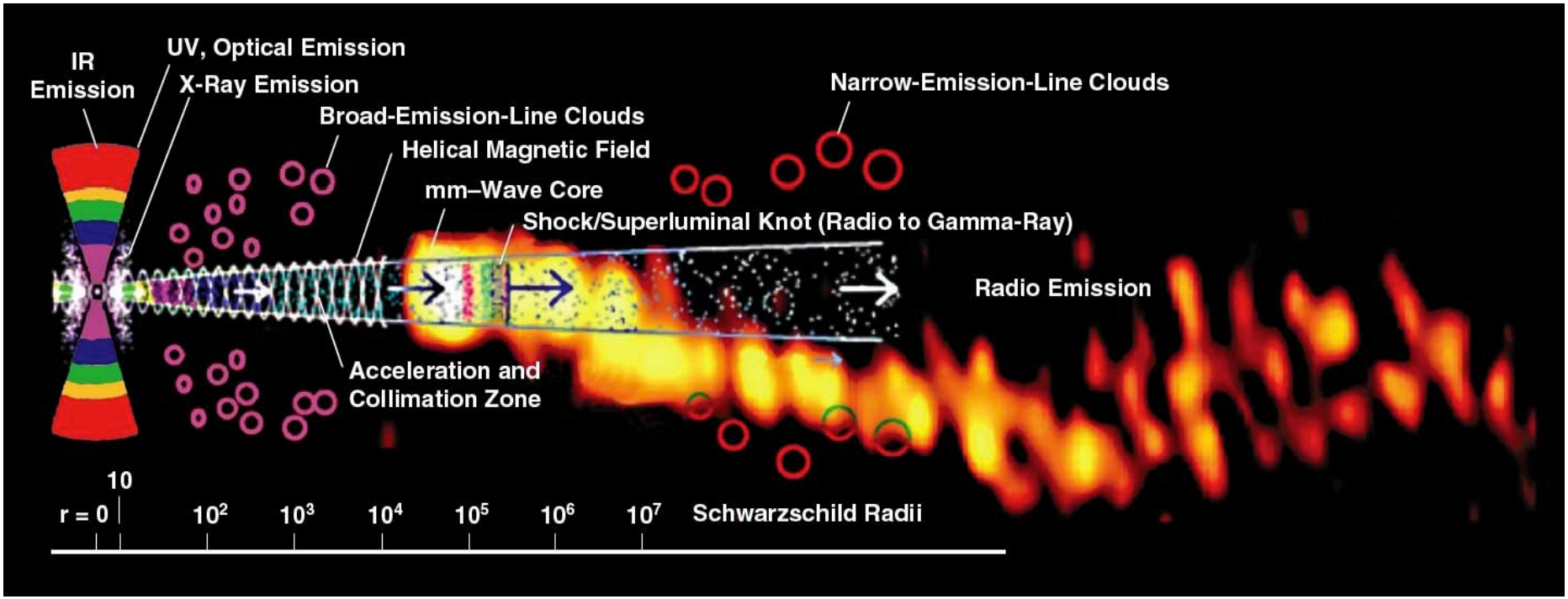
  Core shift reduced at short wavelength/high frequency

Why observe in Radio? The 'Window'



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

Active Galactic Nuclei (*Marscher*)



R~0.1-1 μas 1mas

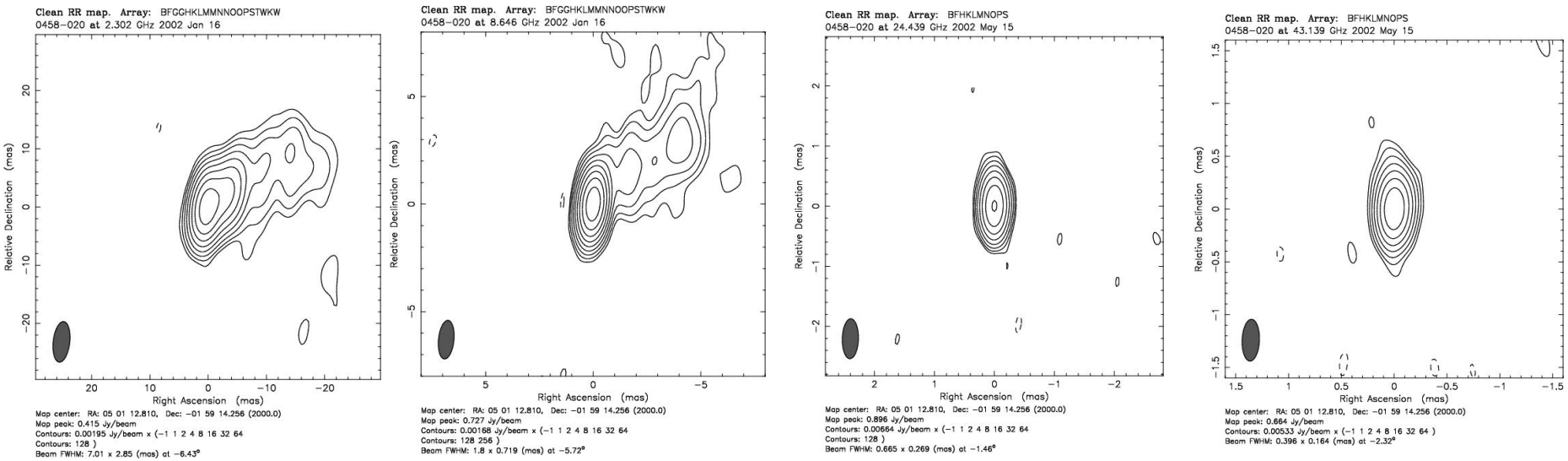
Credit: A. Marscher, Proc. Sci., 2006. T. Krichbuam et al, IRAM, 1999. Wehrle et al, ASTRO-2010

Features of AGN: *Note the Logarithmic length scale*.

- Frequency dependent Core shift: 8 GHz -> 32 GHz (3.6cm->9mm)
  ~100 μas in phase delay (e.g. Sokolovsky *et al*, 2011; Kovalev *et al*, 2008)
  << 100 μas in group delay (Porcas, A&A, 505, 2009)

- Higher frequencies closer to blackhole origin. And perhaps closer to optical position.

Source Structure vs. Wavelength



S-band	X-band	K-band	Q-band
2.3 GHz	8.6 GHz	24 GHz	43 GHz
13.6cm	3.6cm	1.2cm	0.7cm

The sources become better ----->

Ka-band
32 GHz
0.9cm

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

Celestial Reference Frames

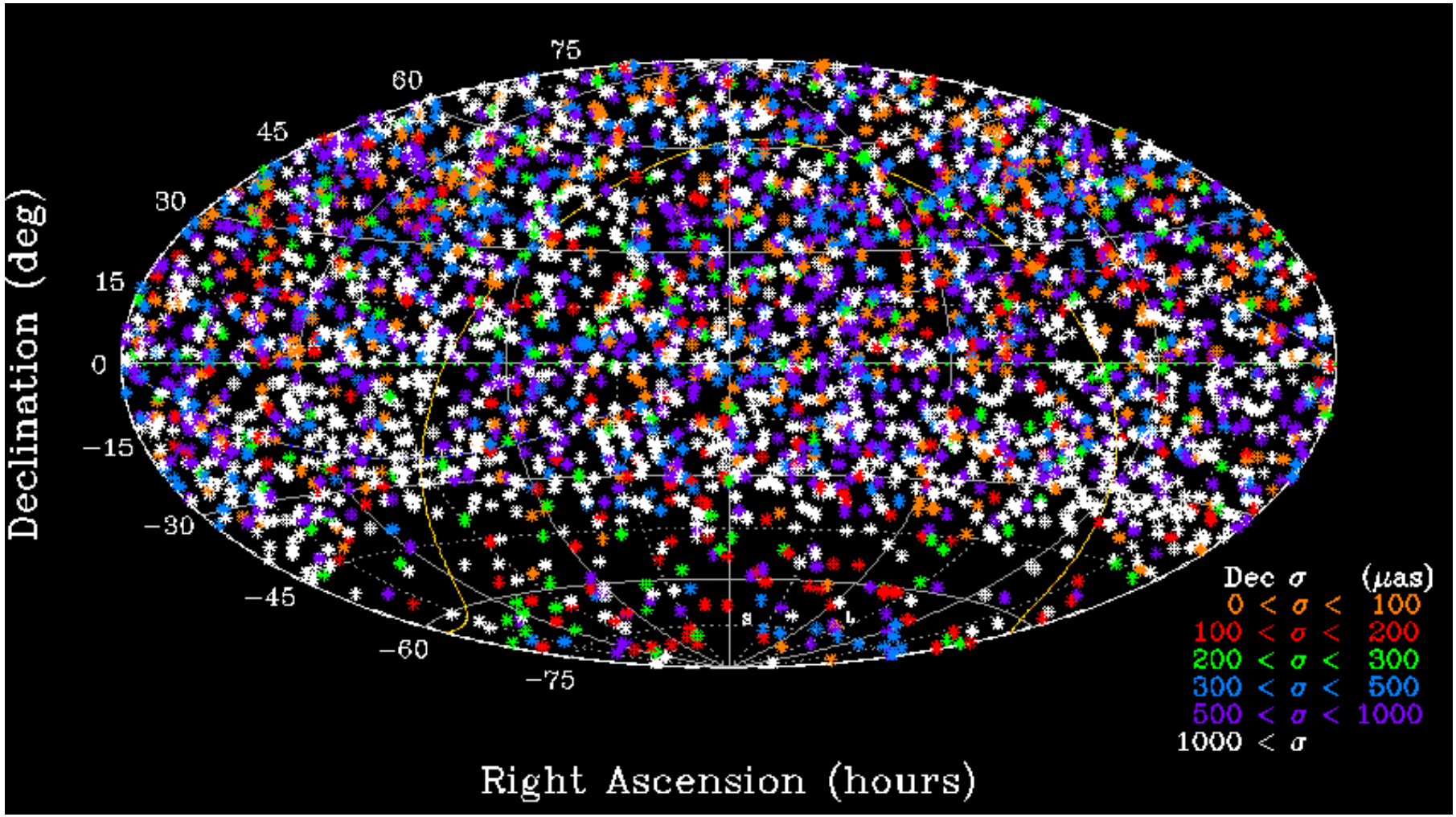
Current Status of CRF at radio wavelengths:

S/X ICRF2: 3.6cm, 8 GHz (Ma et al, IERS, 2009)

K-band: 1.2cm, 24 GHz (Lanyi et al, AJ, 2010)
(Charlot et al, AJ, 2010)

X/Ka-band: 9mm, 32 GHz (García-Miró et al, IVS, 2012)

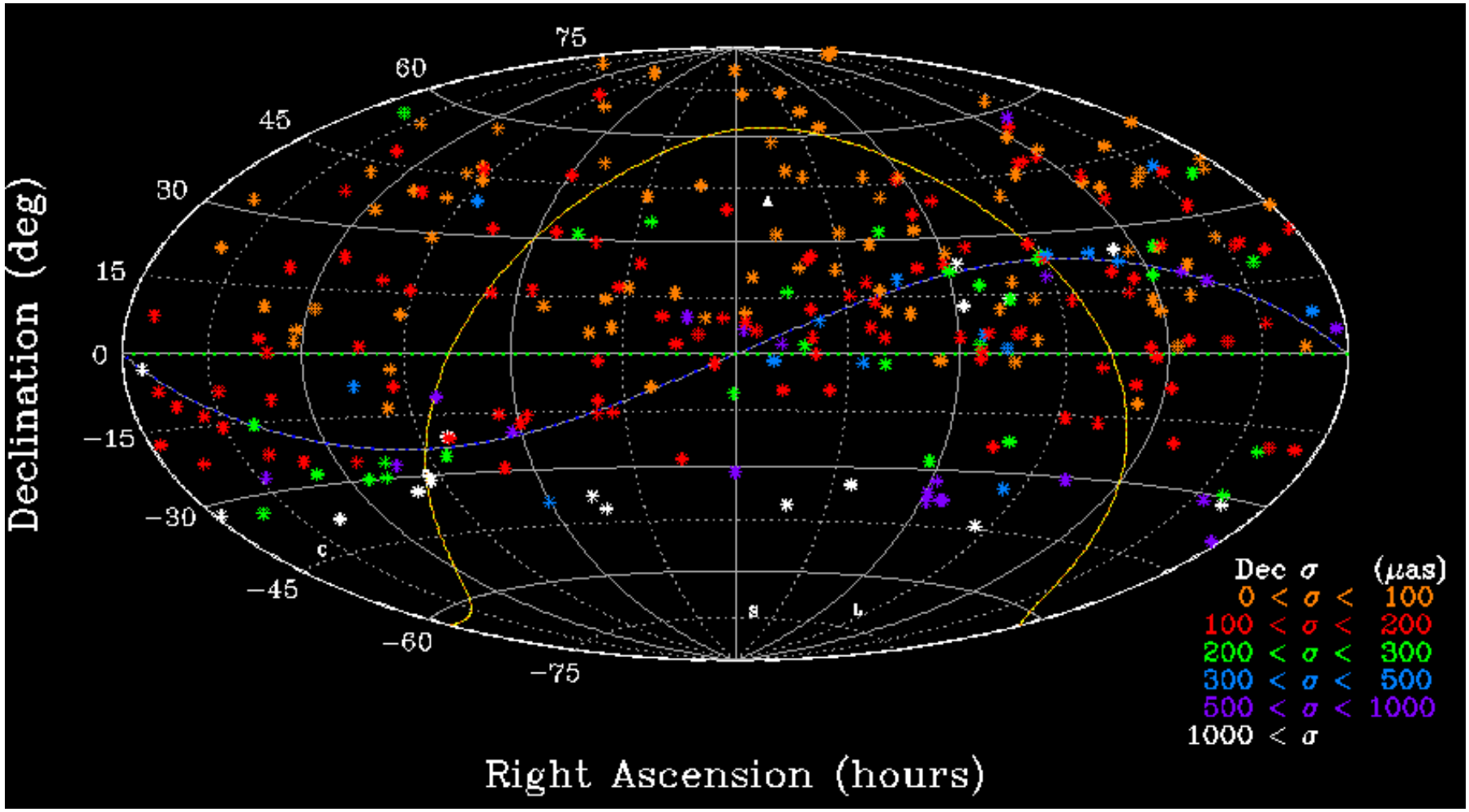
ICRF2 S/X: 8.4 GHz, 3.6cm: 3414 sources



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

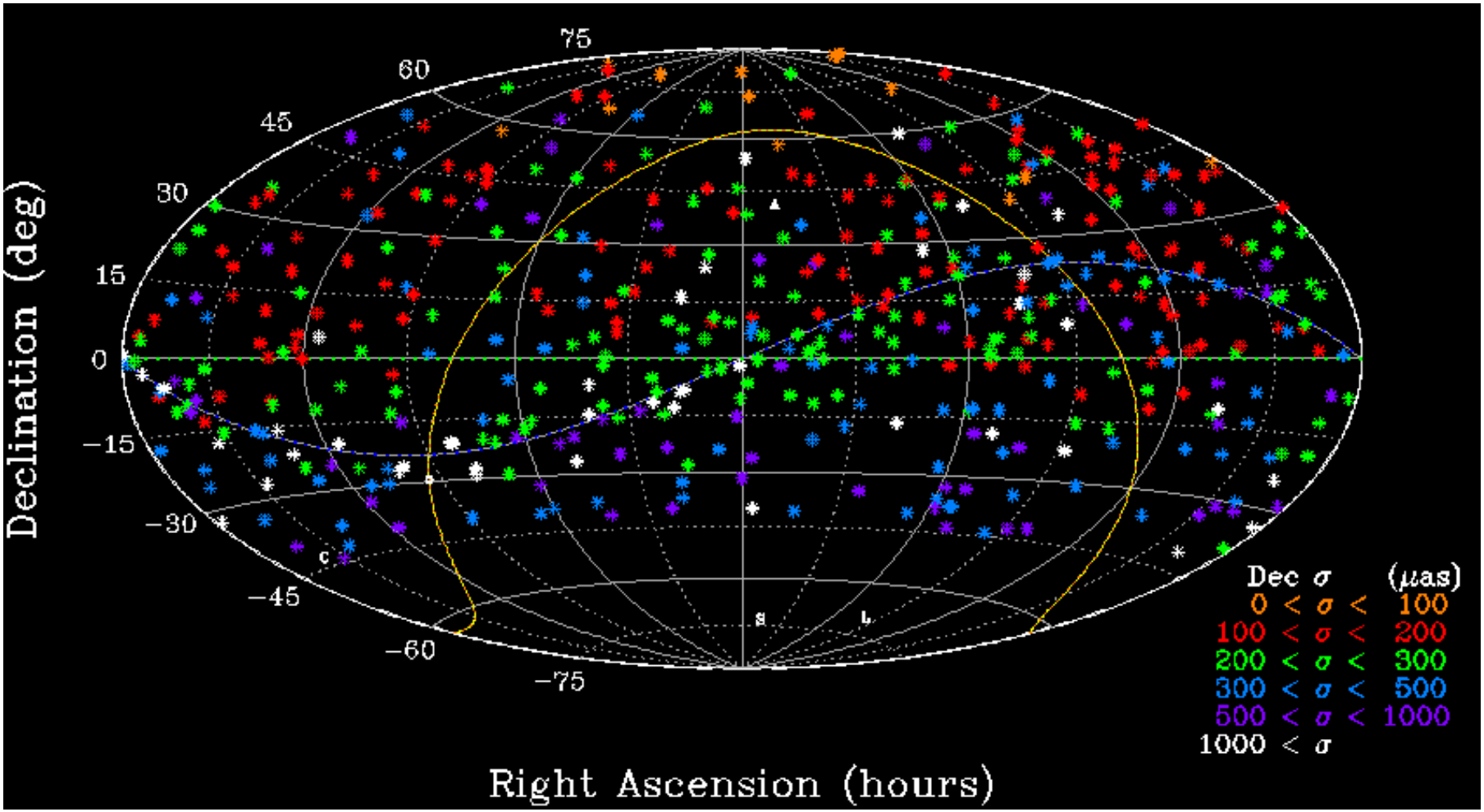
K-band 24GHz, 1.2cm: 278 Sources



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

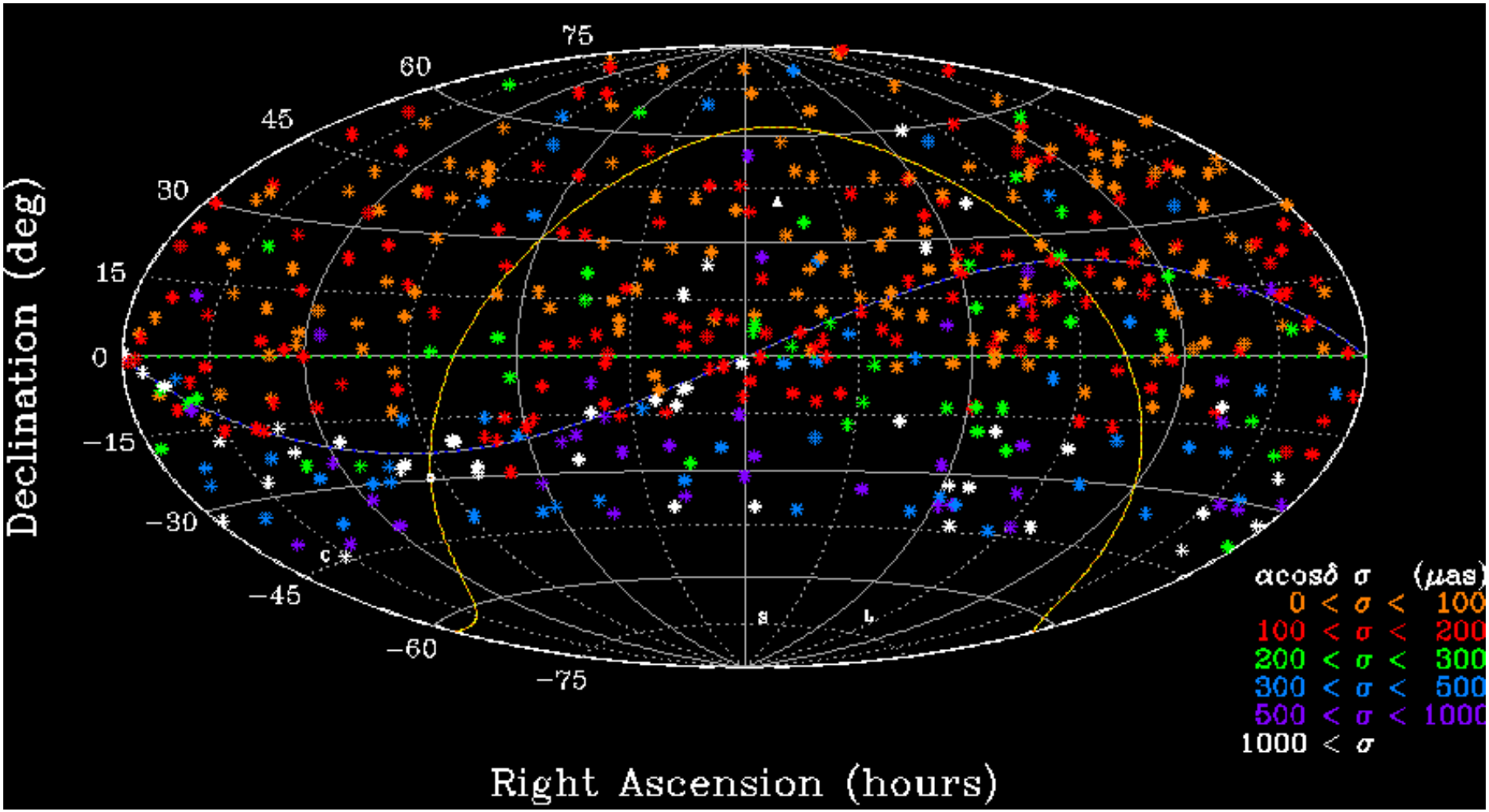
X/Ka 32GHz, 9mm Dec results: 469 Sources



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

Credit: García-Miró et al, IVS, Madrid Spain, 2012

X/Ka current RA results: 469 Sources

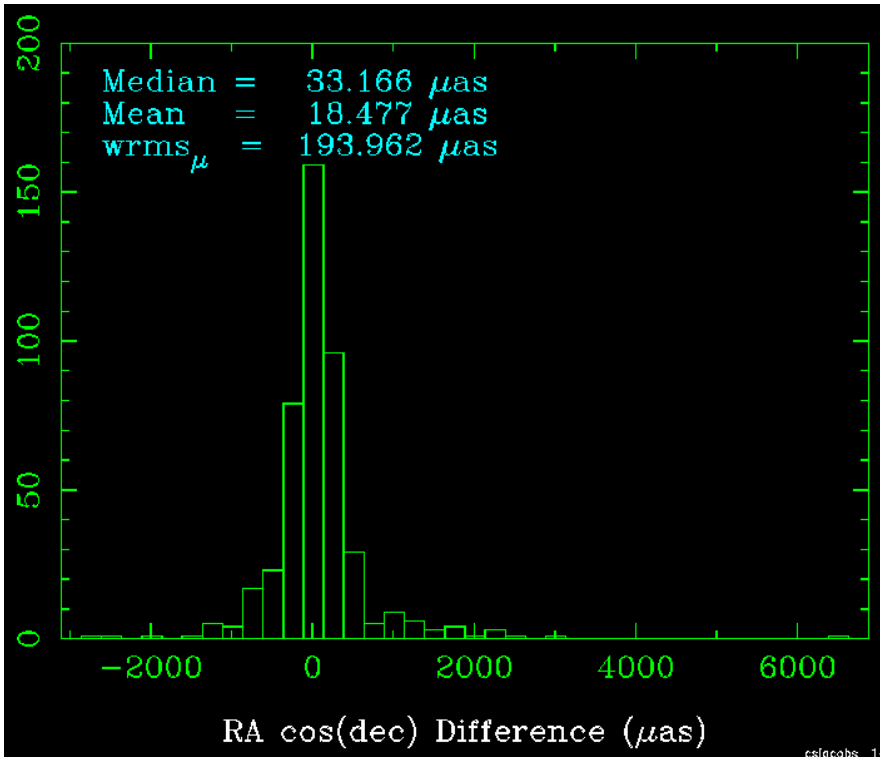


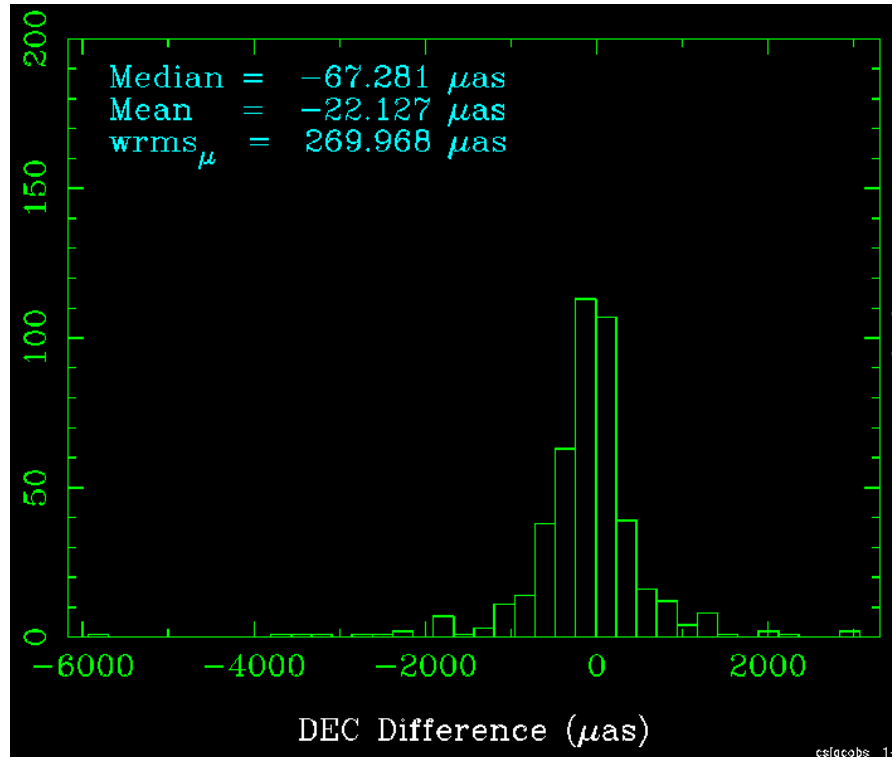
Cal. to Madrid, Cal. to Australia. Weakens south of Dec = -15deg

Credit: García-Miró et al, IVS, Madrid Spain, 2012

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

Accuracy of 450 X/Ka sources vs. S/X ICRF2 (current IAU standard)





RA: 194 µas = 0.9 nano-rad

Dec: 270 µas = 1.3 nano-rad

X/Ka: García-Miró et al, IVS, 2012. S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, IERS, Germany, 2009

Attacking the Error budget

- **SNR:** low cost disk drives -> more bits!
- **Instrumentation:** IVS: Ruszczyk et al, 2012; Tuccari, 2012

  DBE: Digital Baseband Conversion, Filters García-Miró et al, 2012

  Phase calibration for X/Ka-band Hamell, Tucker, Calhoun, 2003
- **Troposphere cals:**

  Faster coverage of sky: VLBI-2010

  Calibrations: WVR Tanner et al, R.Sci, 2003; Bar-Sever et al, IEEE, 2007
- **Southern Geometry**

  S/X: HARTRAO. Auscope+: Hobart, Katherine, Yaragadee, Warwick

  K: HARTRAO, S. Africa? Tidbinbilla, Australia?

  Q: ??

  X/Ka: Malargue, Argentina, Hobart? New Norcia?

Attacking the Error budget: SNR

- Current data

S/X RDVs	256 Mbps	
K/Q	128 Mbps	(*program dormant at present*)
X/Ka	448 Mbps	

- Mark-5C

2048 Mbps (within next year or so?)

-> 4 to 16X in data rate

-> 2 to 4 in sensitivity, delay precision

4096 Mbps (later)

- Mark-6 (Whitney, Capallo, Lapsley, IVS, 2012)

16 Gbps sustained

Summary of Instrumental Improvements

Instrument	MkIV	DBE/Mk5-C	Comment
Filters	Analog 7-pole Butterworth	Digital FIR phase linear	removes phase ripple, chans identical
Spanned bandwidth	360 MHz	500-1000 MHz	Mk4 limit 1.4-3X improvement
Mk4 rate @ start	112 Mbps		SNR limited
@ max.	896 Mbps		trop/inst. limited
Mk5 rate @ start		2048 Mbps	trop/inst. limited
@ max.		4096 Mbps	6X sensitivity
Phase Cal: S/X, K, Q	Yes	Yes	
X/Ka	No	Yes	removes 100s of psec

Calibrating Troposphere Turbulence

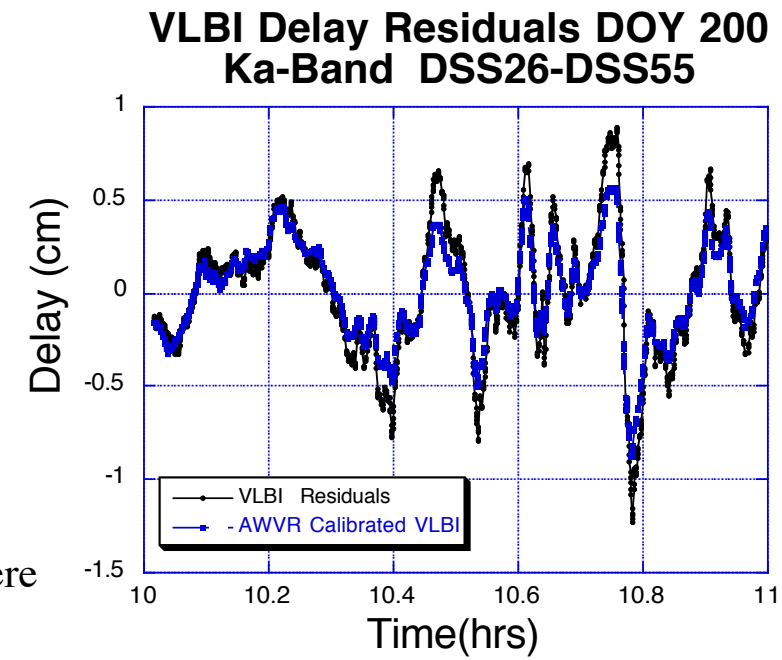
- Monitor 22 GHz/1.3cm water (rotational) line brightness temperature along line-of-sight

- JPL Advanced Water Vapor Radiometer
  - ~ 1 deg beam better matches VLBI
  - improved gain stability
  - improved conversion of brightness temperature to path delay (Tanner & Riley, R.Sci, 2003)

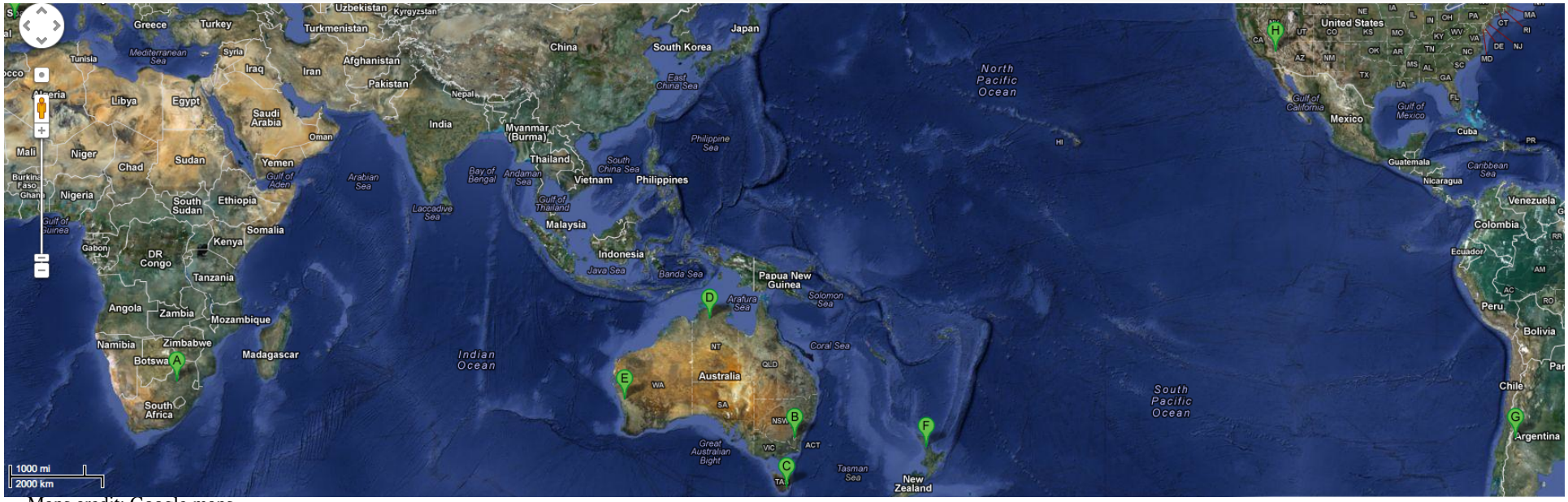
- Demonstrated ~20 μas calibration accuracy Goldstone-Madrid 8000 km baseline using X/Ka phase delays
  - *Jacobs et al, AAS Winter 2005.*
  - *Bar Sever et al , IEEE, 2007.*

- A-WVRs deployed at Goldstone/Madrid Seeking funding for Tidbinbilla, Aus not used yet for Operations

- VLBI-2010: Fast slewing (~5 deg/sec) to allow better estimation from covering full geometry before troposphere can change



Southern Hemisphere Stations for CRF



Maps credit: Google maps

A	Hartebeesthoek RAO, South Africa	26-m S/X now, K-band now, but little used
B	Tidbinbilla, Australia	34-m S/X, 70-m K-band, 34-m X/Ka
C	Hobart, Tasmania, Australia	12-m S/X, 2-14 GHz? S/X/Ka???
D	Katherine, Northern Territory, Australia	" "
E	Yaragadee, Western Australia, Australia	
F	Auckland, New Zealand	" "
G	Malargüe, Mendoza, Argentina	34-m X/Ka operational Fall 2012

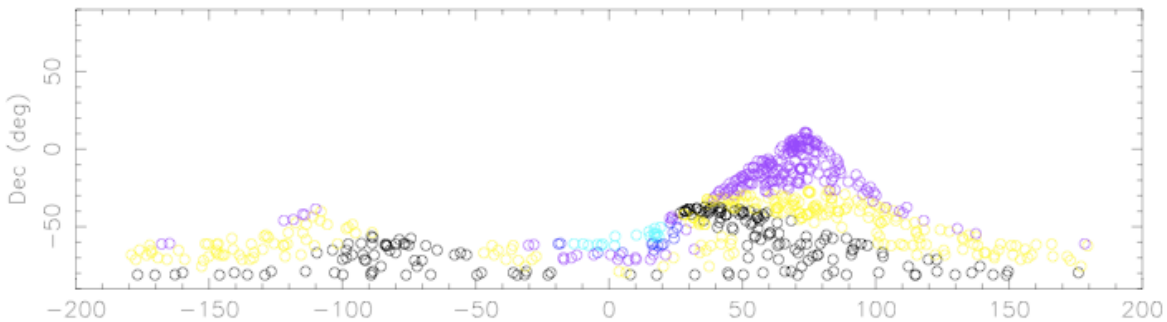
Potential Southern VLBI Stations?

- X/Ka: ESA Deep Space Antenna DSA-03

  Malargue, Argentina:

  Fall-2012 NASA/ESA collaboration

  - 35-m, X/Ka-band, 9,500 km baseline
  - Dry desert site is good for Ka-band



Credit:www.esa.int/esaMI/Operations/SEME9C19Y8G_0.ht

Malargue 35-meter as of 25 May 2012

ESA Deep Space Antenna
X/Ka-band capable

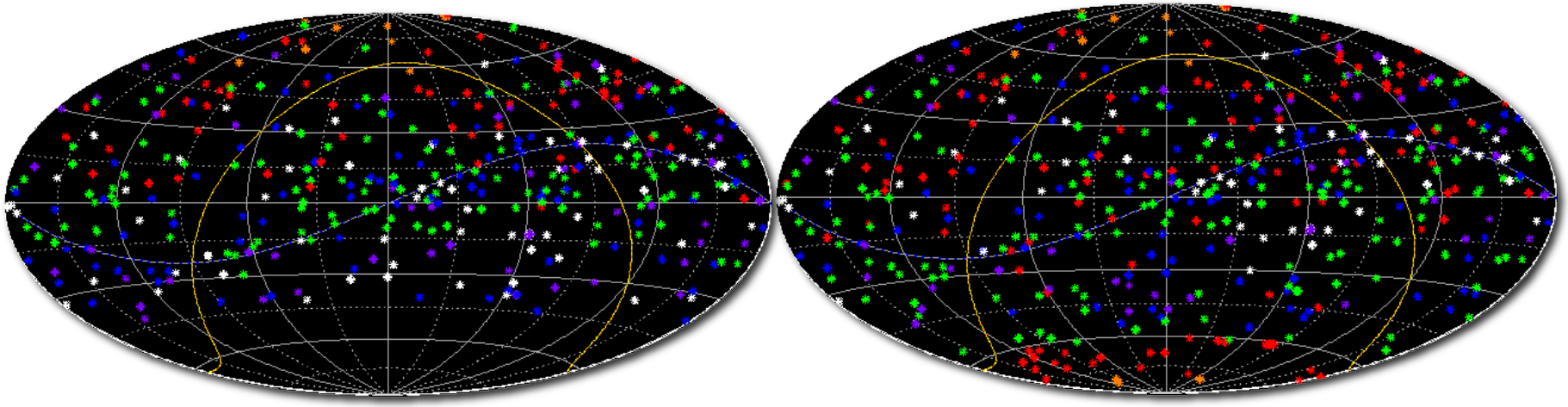
- K-band: Hart, South Africa
  - 26-m, surface good to K-band

    Was broken ~2yr, Now repaired

    Resurfaced in 2005 (0.5mm RMS) efficient to 22 GHz

- S/X: Auscope, Warwick, NZ; HARTRAO, S. Africa

Simulation: 9000km all-Southern baseline



50 sessions, No Sim. Southern Data *Adding Simulated data*

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.

Gaia/VLBI frame tie and accuracy verification

Gaia: 10^9 stars

- 500,000 quasars V< 20 mag
  20,000 quasars V< 18 mag
- radio loud 30-300+ mJy
  and optically bright: V<18 mag
  ~2000 quasars
  (*Mignard, next talk: 4.03*)

- X/Ka:
  130 sources optically bright (V> 18)
  Frame tie simulated precision ~ 10 μas
  Improving with more data arriving.
  (*García-Miró et al, IVS, 2012*)

- S/X: Strategy: Bring new quasars which are optically bright into the radio frame
  (*Charlot & Bourda, this session: 4.10*)

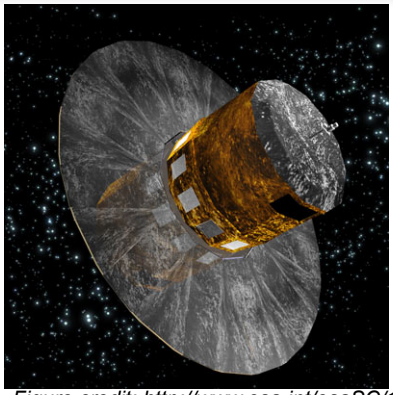
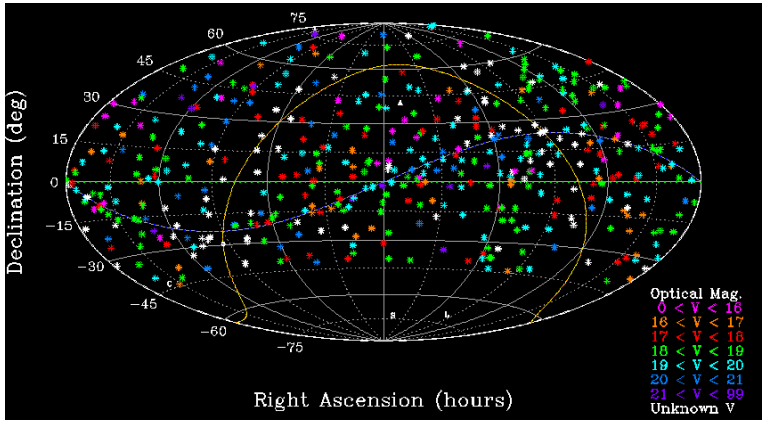


Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7

- Quasar Precision
  70 μas @ V=18
  25 μas @ V=16



(V magnitudes: Veron-Cetty & Veron, 2010)

Conclusions

- **Increasing frequency -> lower sensitivity, but more compact**

- **Celestial Frame Overview:**

S/X ICRF-2	$> 40\ \mu$as	3414 sources
K-band	$\sim 100\ \mu$as	268 sources
Q-band	$\sim 300\ \mu$as	131 sources
X/Ka-band	$\sim 220\ \mu$as	482 sources

- **Future Prospects for Improvements:**

  SNR: higher bit rates 2 to 16 Gbps

  Instrumentation: Digital Back Ends, better clocks?

  Troposphere: faster sweeps of sky, WVR calibrations

  Improving Southern geometry: Auscope+, HART, Malargue

- **Frame tie** ~2021 VLBI/Gaia optical tie precision $\sim 10\ \mu$as.