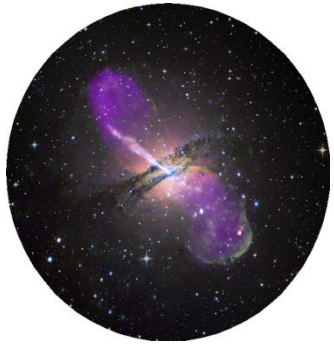
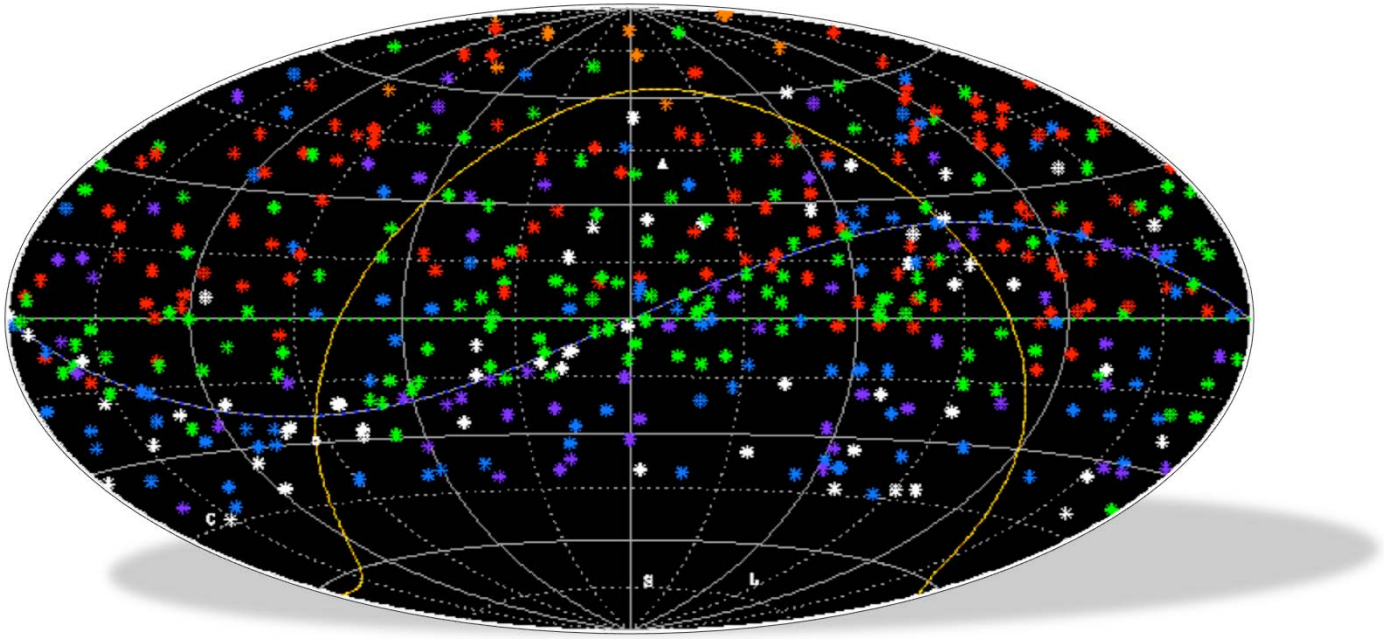
The Celestial Reference Frame at X/Ka-band: Status & Prospects for Improving the South





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J. Alonso, J.E. Clark, L. Gamborino, C. García-Miró, S. Horiuchi, J. Lobo, R. Madde, M. Mercolino, C.J. Naudet, L. Snedeker, I. Sotuela, L. White

9-12 October 2012

Overview

- How do sources change with wavelength? Why Ka-band?

- X/Ka in the context of other 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

- Prospects for Improvements:

  SNR, Instrumentation, Troposphere

- Improving Southern Geometry:

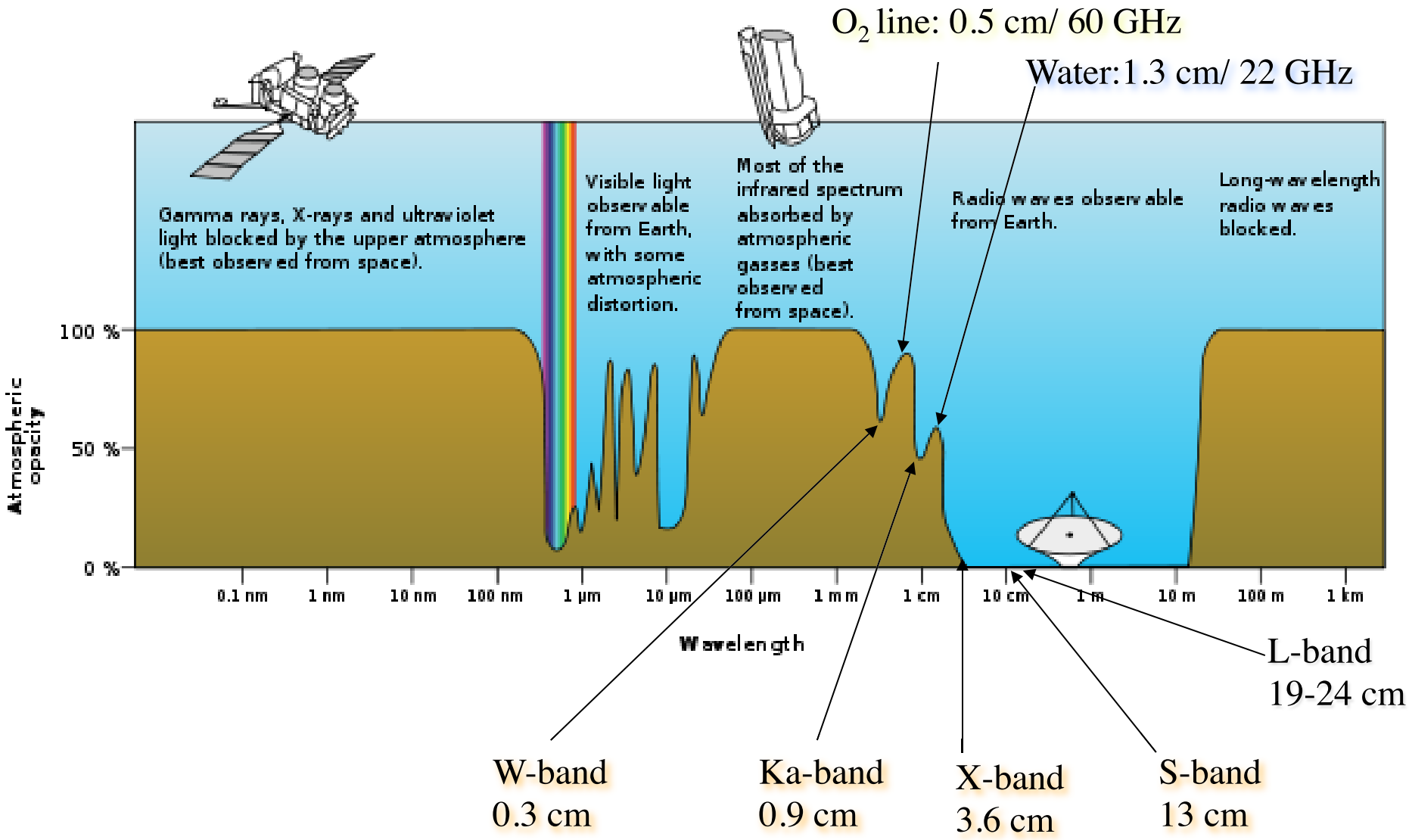
  ESA-DSN collaboration for X/Ka: Malargue, Argentina

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

VLBI wavelength dependence?

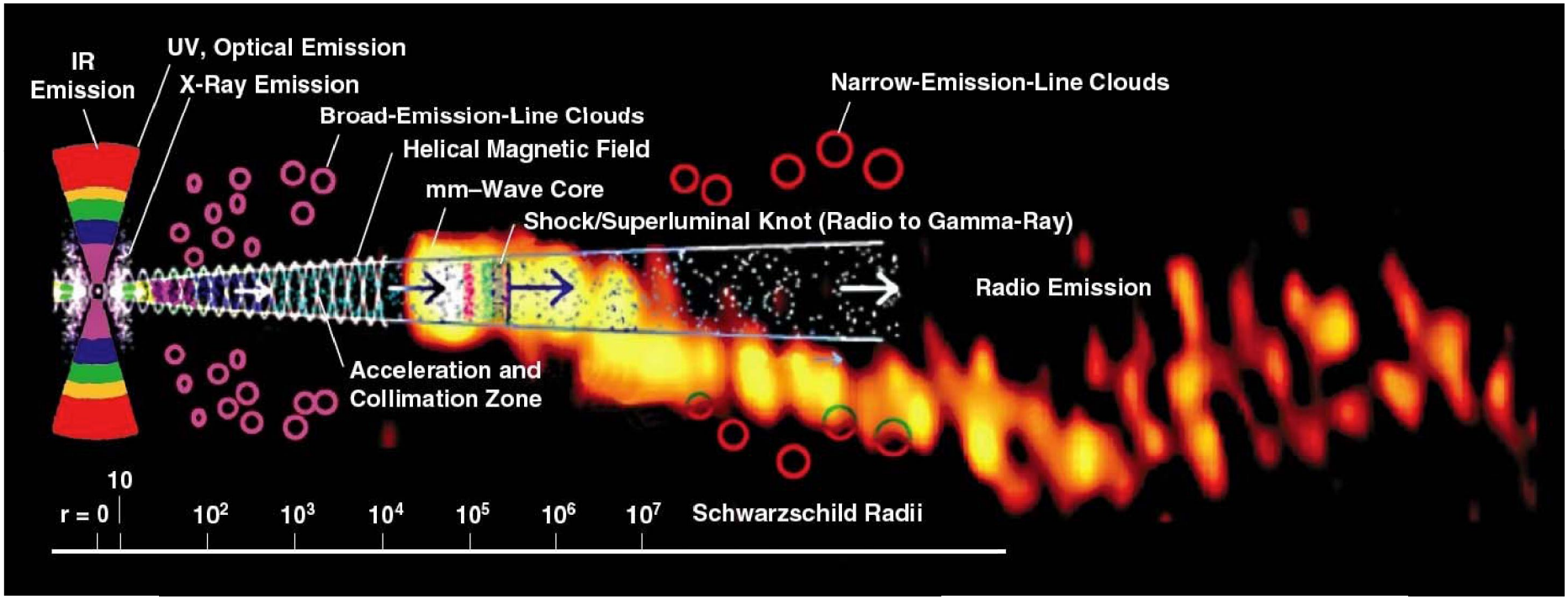
- **Sensitivity worsens** at shorter wavelength/high frequency
  - Higher system temperature: atmosphere H_20 (22 GHz), O_2 60 GHz
  - Antenna pointing more difficult
  - Antenna surface shape control more difficult
  - Atmospheric absorption
  - Resolved sources
- **Quasar astrophysics gets better**
  - 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

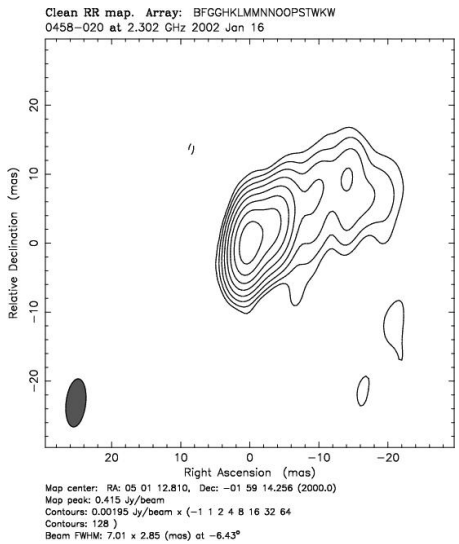
Credit: A. Marscher, Proc. Sci., 2006. T. Krichbuam et al, IRAM, 1999. Wehrle et al, ASTRO-2010

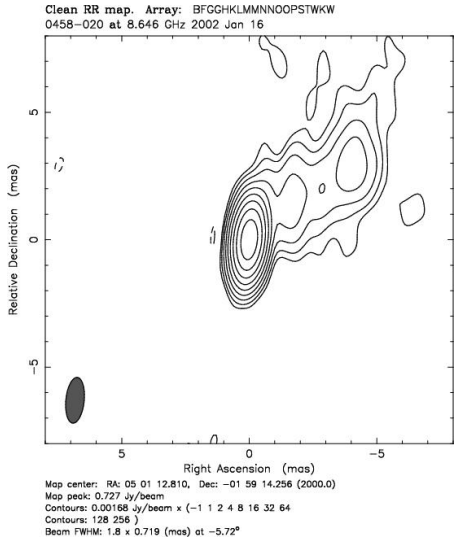
Features of AGN: *Note the Logarithmic length scale*.

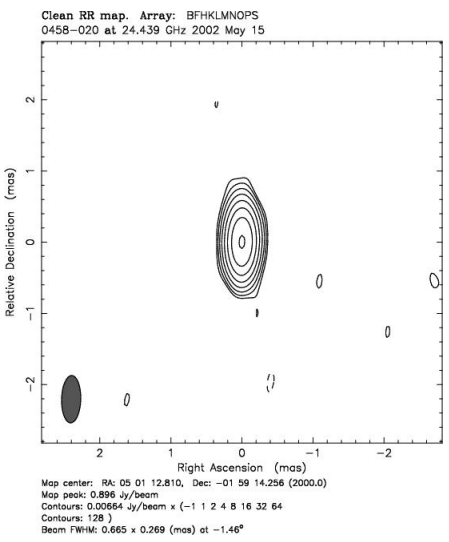
- Frequency dependent Core shift: 8 GHz -> 32 GHz (3.6cm->9mm)
  ~100 μas in phase delay (e.g. Sokolovsky *et al*, 2011; Kovalev *et al*, 2008)
  << 100 μas in group delay (Porcas, A&A, 505, 2009)

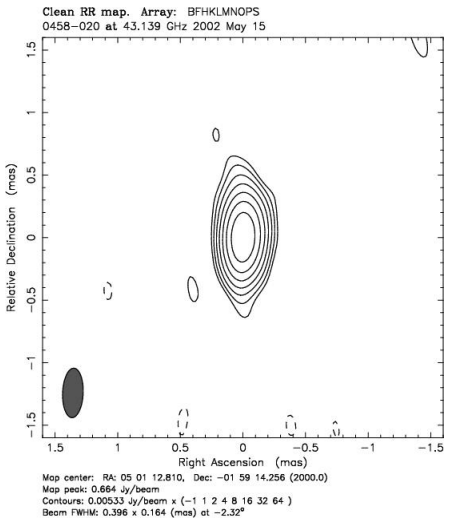
- Higher frequencies closer to blackhole origin. And perhaps closer to optical position.

Source Structure vs. Wavelength









S-band
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 ----->

Ka-band
32 GHz
0.9cm

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

Celestial Reference Frames

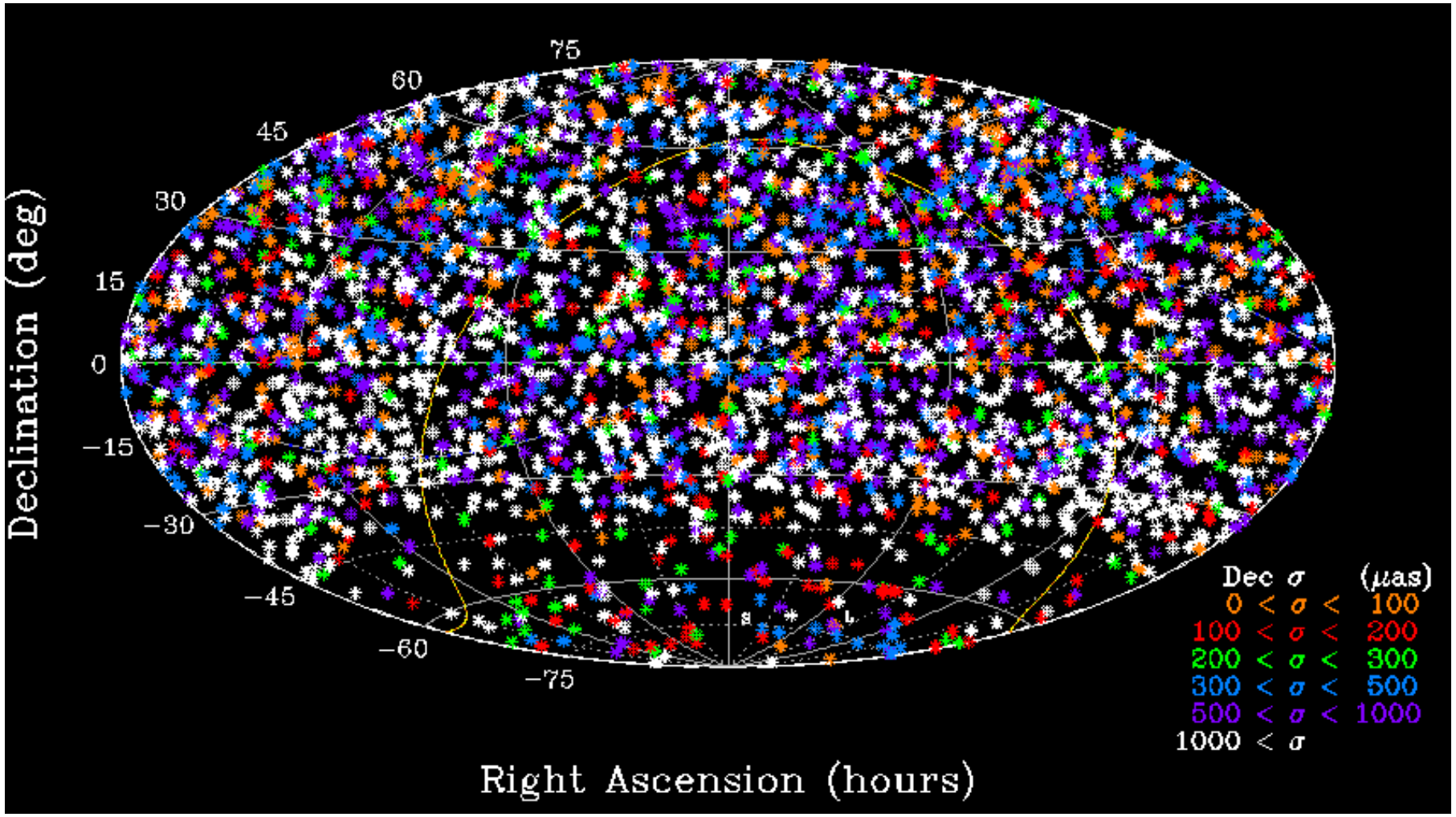
Current Status of CRF at radio wavelengths:

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)

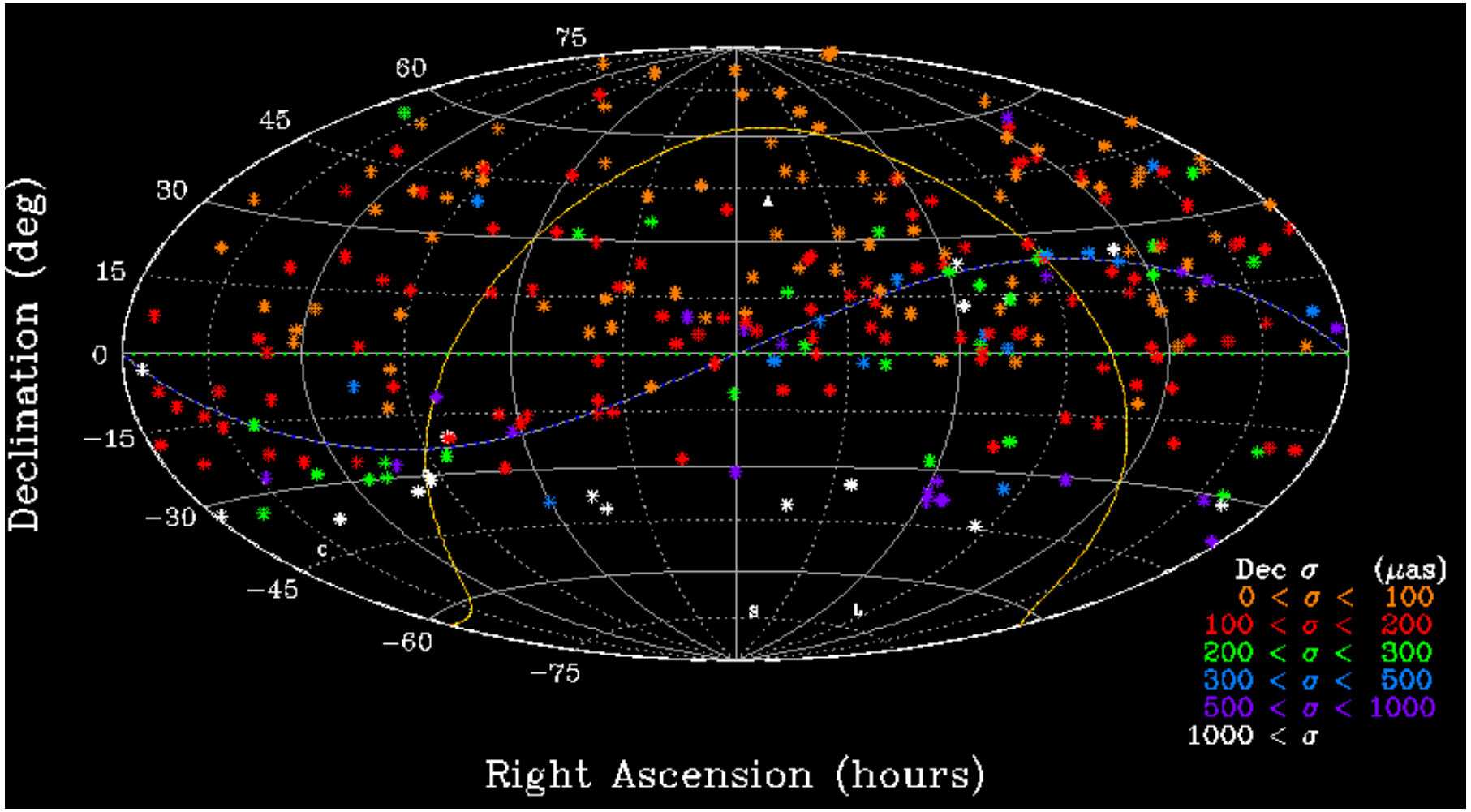
ICRF2 S/X: 8.4 GHz, 3.6cm: 3414 sources



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

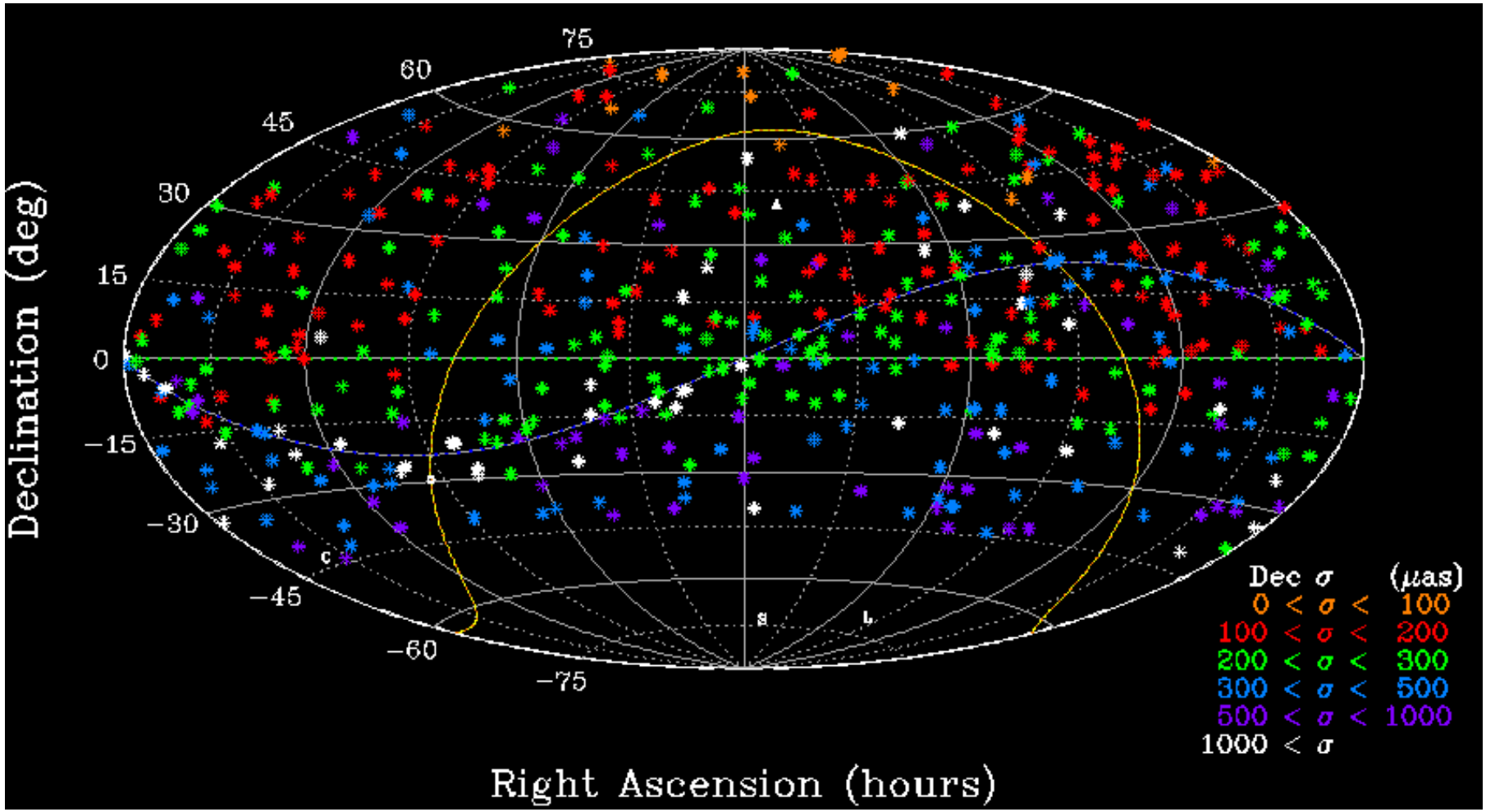
K-band 24GHz, 1.2cm: 278 Sources



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

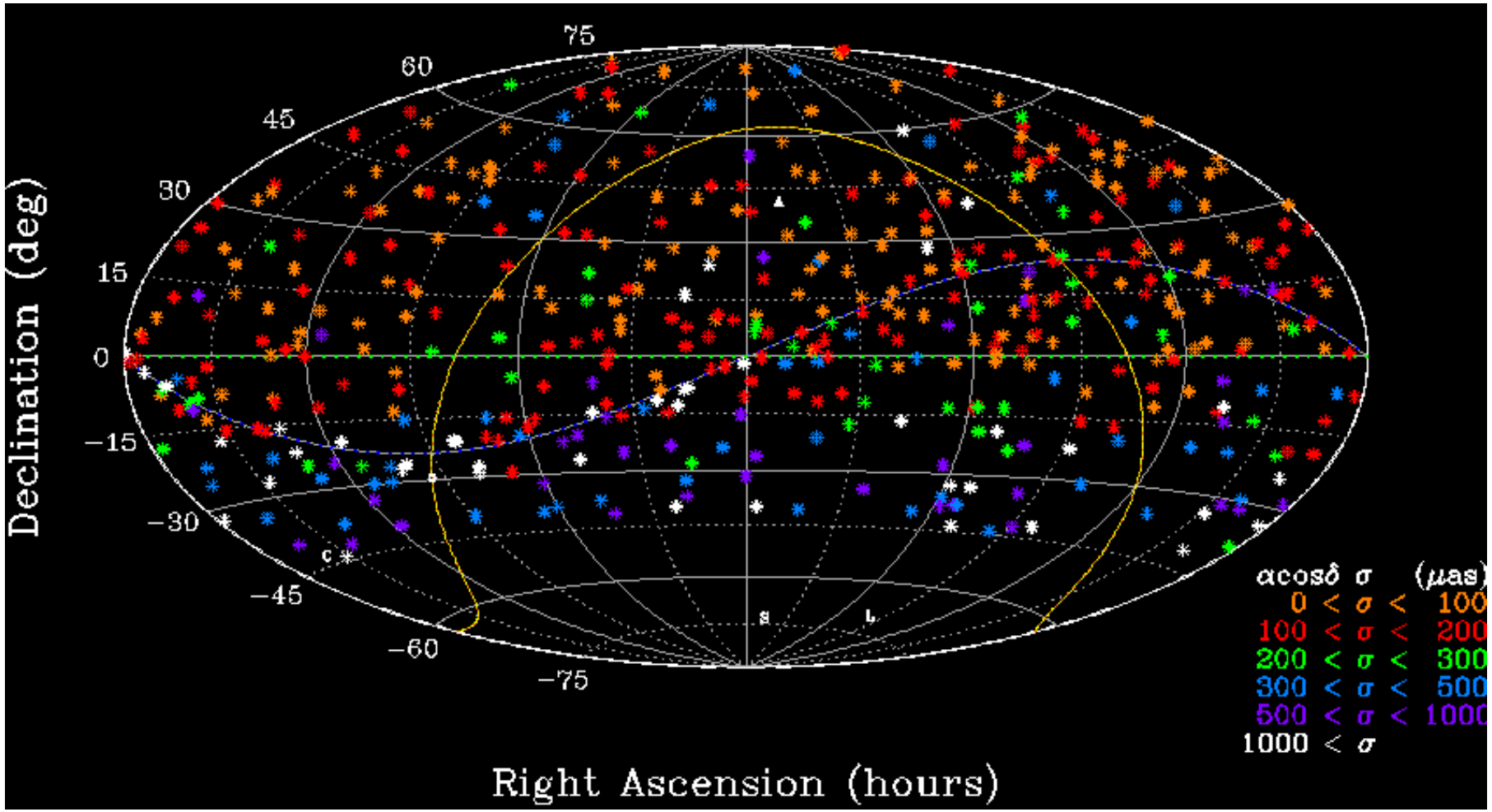
X/Ka 32GHz, 9mm Dec results: 469 Sources



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

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, IEER, 2007
- **Southern Geometry**

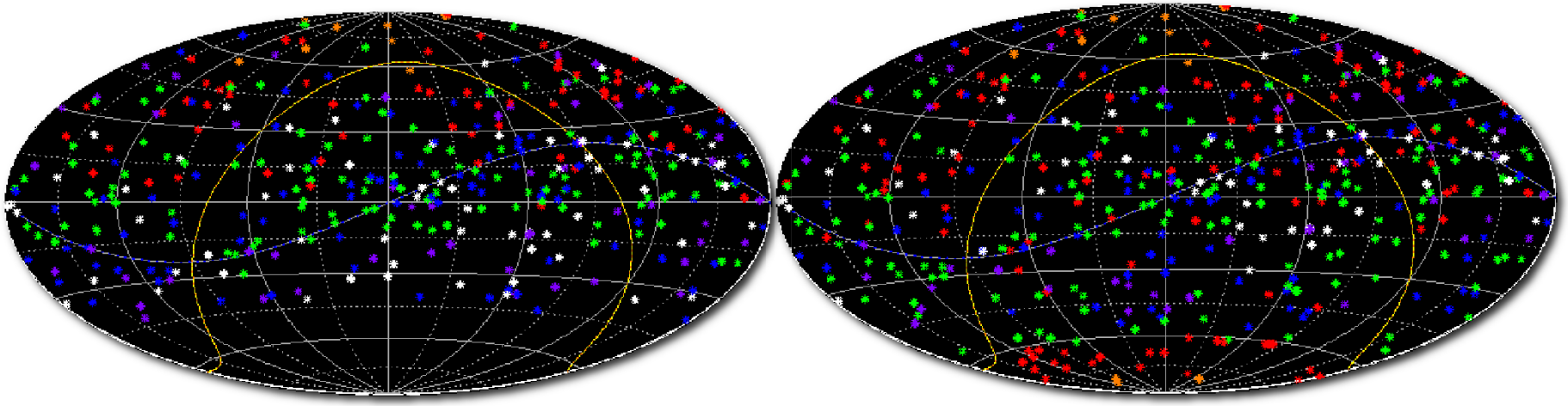
  S/X: HARTRAO. Auscope+: Hobart, Katherine, Yaragadee, Warwick

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

  Q: ??

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

Simulation: 9000km all-Southern baseline



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

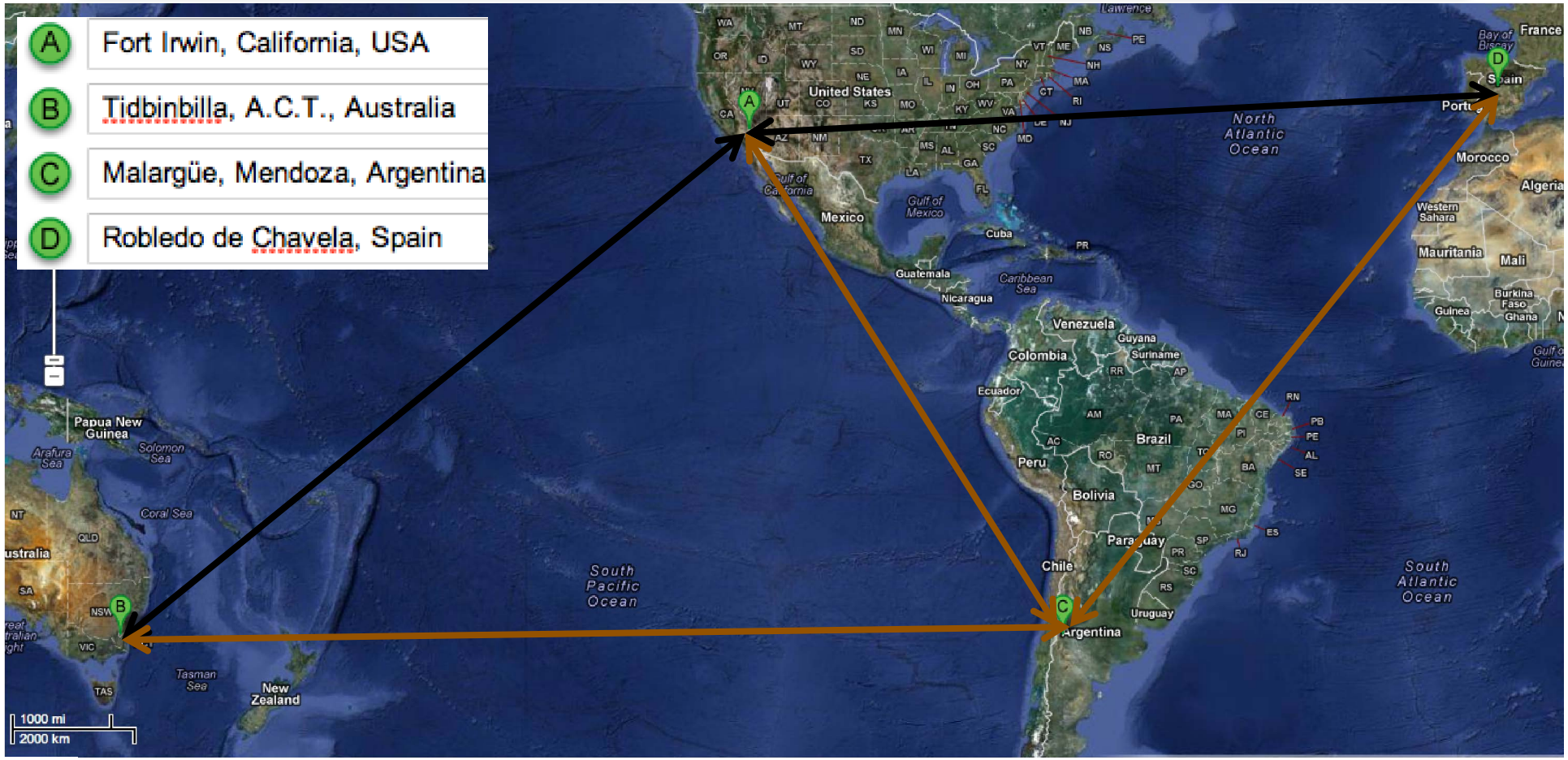
- 50 real X/Ka sessions augmented by simulated data
  simulate 1000 group delays, SNR = 50
  ~9000 km baseline: Australia to S. America or S. Africa

- Completes Declination coverage: cap region -45 to -90 deg
  144 south polar candidate sources (*Sotuela et al, Porto, 2011*)
  200 μas (1 nrad) precision in south polar cap,
  mid south 200-1000 μas, all with just a few days observing.

Declination Sigma

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

X/Ka stations for Celestial Reference Frame



Maps credit: Google maps

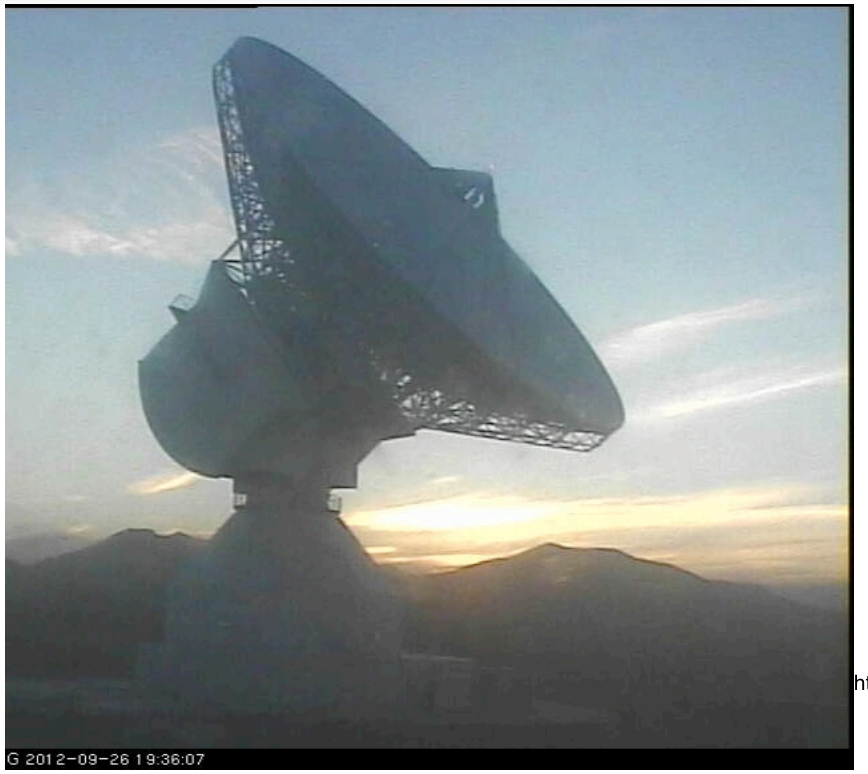
ESA's Argentina 35-meter antenna **adds 3 baselines** to DSN's 2 baselines

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

Malargue: The Next X/Ka VLBI Station

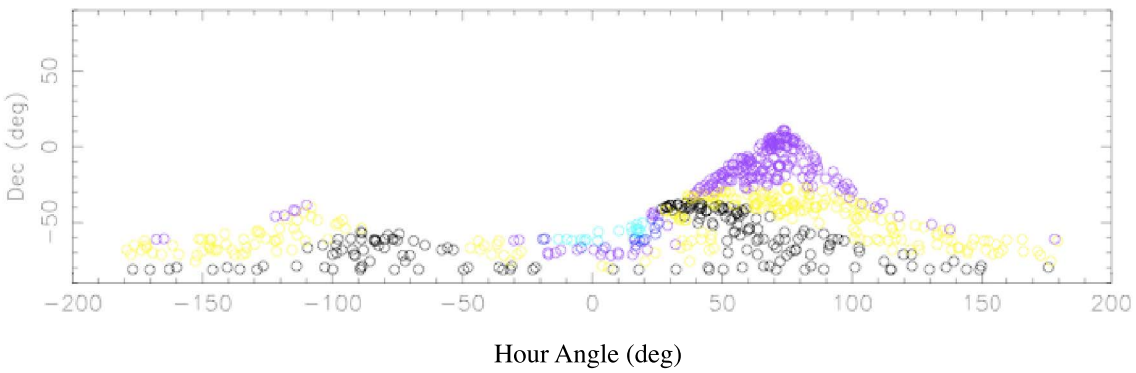
X/Ka: ESA Deep Space Antenna DSA 03

- **Malargue, Argentina**
- Fall-2012 NASA/ESA collaboration
- 35-m, X/Ka-band, 9,500 km baseline
  Argentina-Australia covers south polar cap
  Full sky coverage for X/Ka!!
- Argentina-California & Australia-California orthogonal baselines for mid-latitudes
- Dry desert site is good for Ka-band
- HA-Dec coverage: Tidbinbilla to Malargue:



Malargue, Argentina 35-meter as of 26 Sept .2012

ESA Deep Space Antenna
X/Ka-band capable



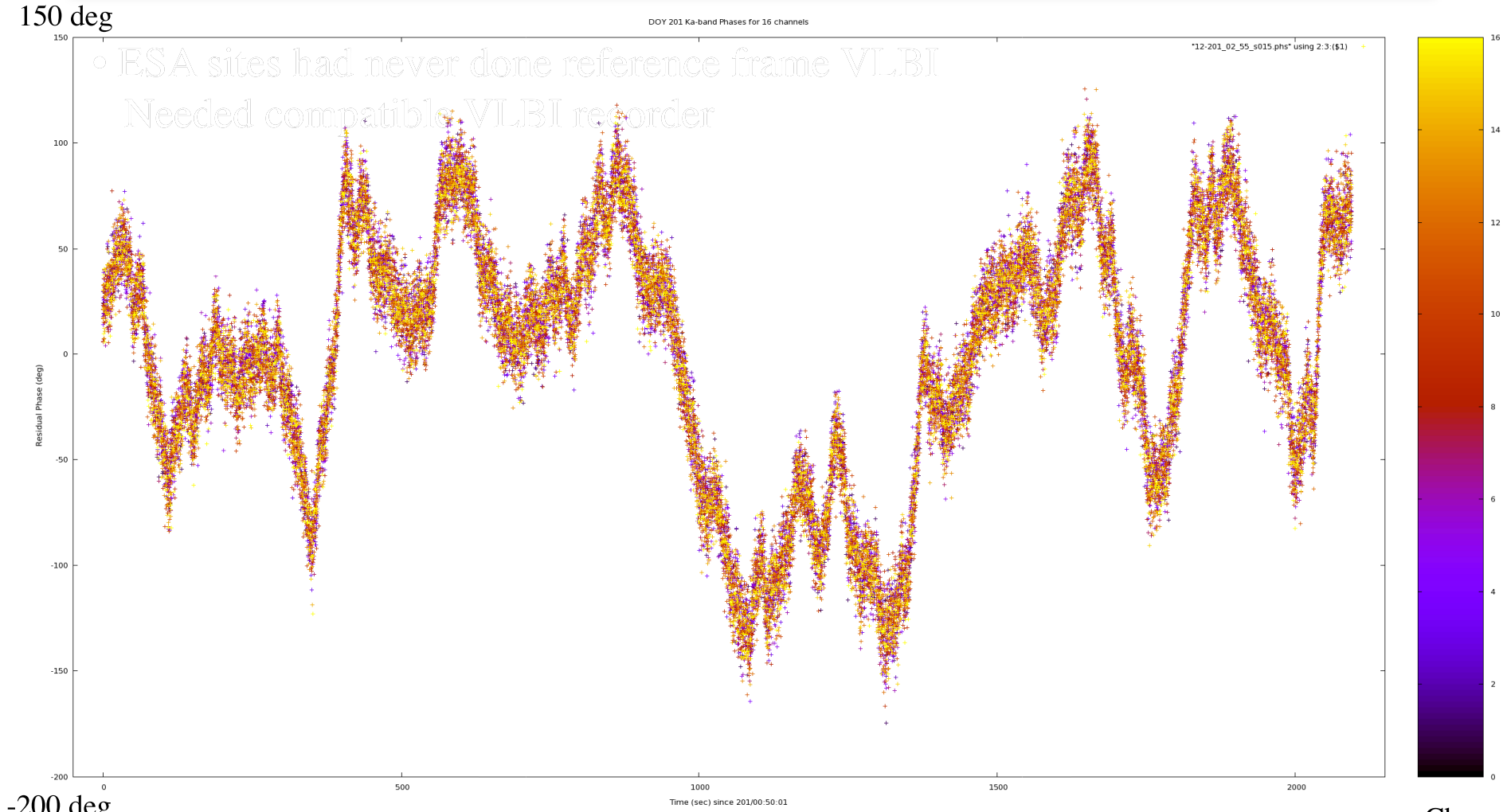
Validate Collaboration: Cebreros, Spain

- ESA sites first reference frame VLBI fringes
  Needed compatible VLBI recorder:
    Portable: laptop, USB 3.0 drives
    custom signal processing: 16 chan, 4 MHz, 2-bit, 256 Mbps
  Designed and validate pointing interfaces
  Validated instrumental stability
  Tied together ESA-NASA terrestrial frames

- Malargue Deep Space Antenna 03 to be ready in fall 2012
  Cebreros, Spain however was operational & close to DSN Robledo site

- Validation tests in July 2012
  Fringes X and Ka from ESA Cebreros DSA 02 to DSN Robledo DSS 55
  Initial Terrestrial frame tie to +- 2 cm
  Stability tested via 2000 sec phase delay on strong source
    Allan Standard deviation shows instrumentation stable
    to better than troposphere noise!

Ka-band Fringes! 16 chan x 4MHz x 2-bit=256 Mbps



Time (sec) since 201:00:50:01

RMS ~2mm/ 6psec (yscale: 360 deg = 9mm = ~30 psec)

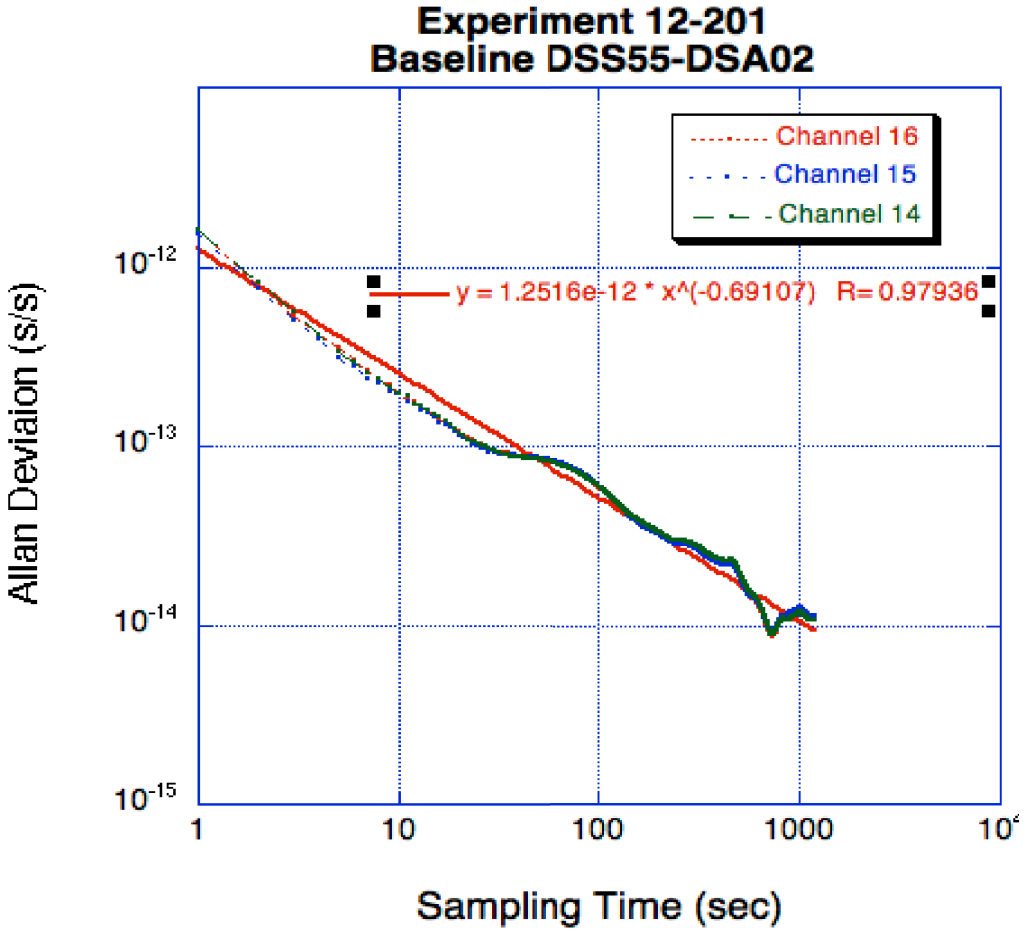
Interferometer Stability: Allan St. Dev.

- Cebreros-DSS 55
  Ka-band, 10km baseline,
  2000 sec

- Allan Deviation: 1 - 1000 sec
- Slope = -0.69
  consistent with 2-D
  Kolmogorov frozen flow
  trop noise (-2/3)
  (Treuhaft & Lanyi, Rsci,1987)

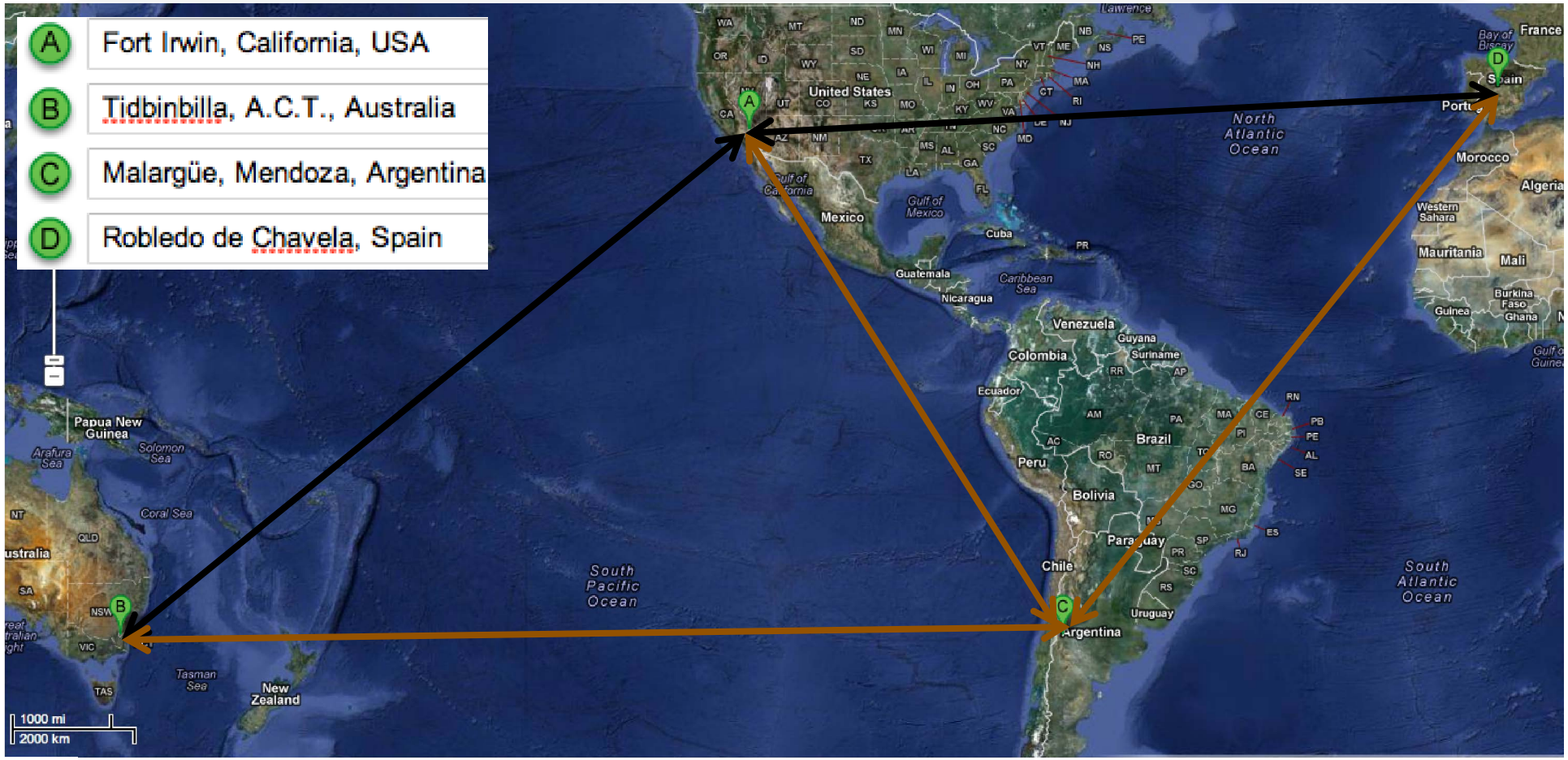
- Slope 1-20 sec shows some sign of white noise limitation (slope ~ -1)

- Slope plateaus around 25-75 sec
  3-D trop turbulence noise
  from small scale fluctuations?



Validates ESA-DSN baseline and interfaces. Malargue next. . .

X/Ka stations for Celestial Reference Frame



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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

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, this meeting*)

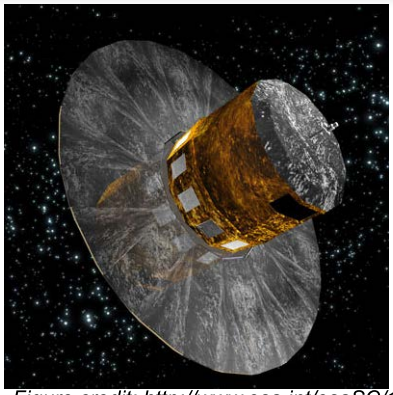
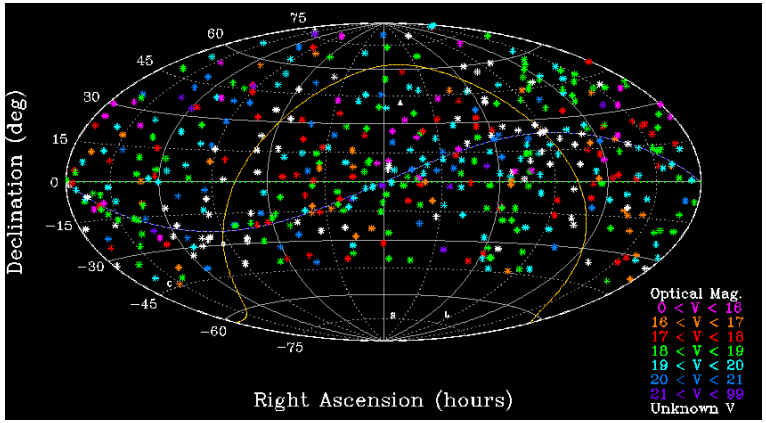


Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7

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

- X/Ka:
  130 sources optically bright (V> 18)
  Frame tie simulated precision ~ 10 μas per rotation angle (1-sigma).
  Improving with more data arriving.
  (*García-Miró et al, IVS, 2012*)



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

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

Conclusions

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

- **Celestial Frame Overview:**

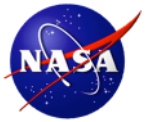
S/X ICRF-2	$> 40\ \mu$as	3414 sources
K-band	$\sim 100\ \mu$as	268 sources
Q-band	$\sim 300\ \mu$as	131 sources
X/Ka-band	$\sim 220\ \mu$as	482 sources

- **Future Prospects for Improvements:**
  SNR (2Gbps), Instrumentation: DBEs, PCGs, Trop.: WVRs

- **ESA-DSN collaboration: add Malargue, Argentina**
  Improve from 2 to 5 baselines, orthogonal mid-lat baselines
  Full sky coverage by accessing south polar cap!

- **Frame tie** ~2021 VLBI/Gaia optical tie precision ~10 μas.

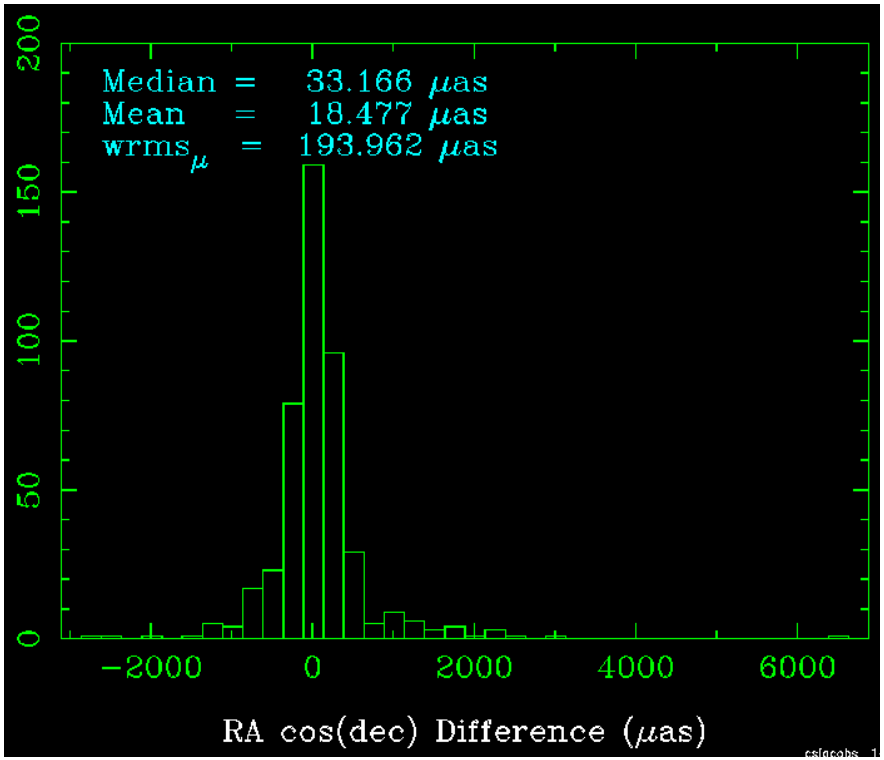
Research described herein done under contract with NASA. Copyright ©2012 California Institute of Technology. Government sponsorship acknowledged.

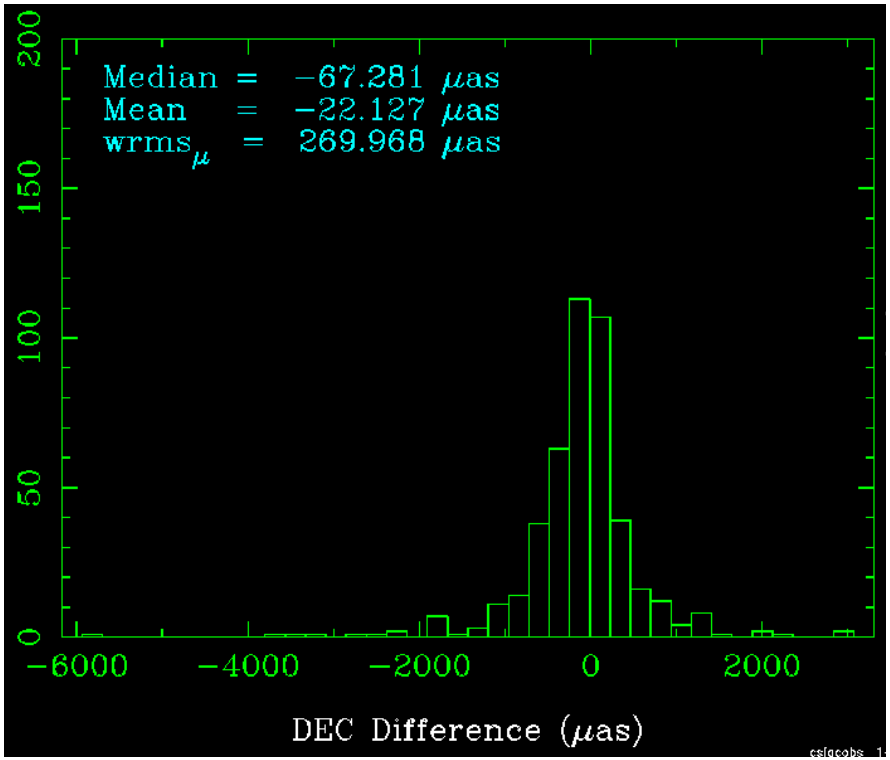


BACKUP SLIDES

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

- 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

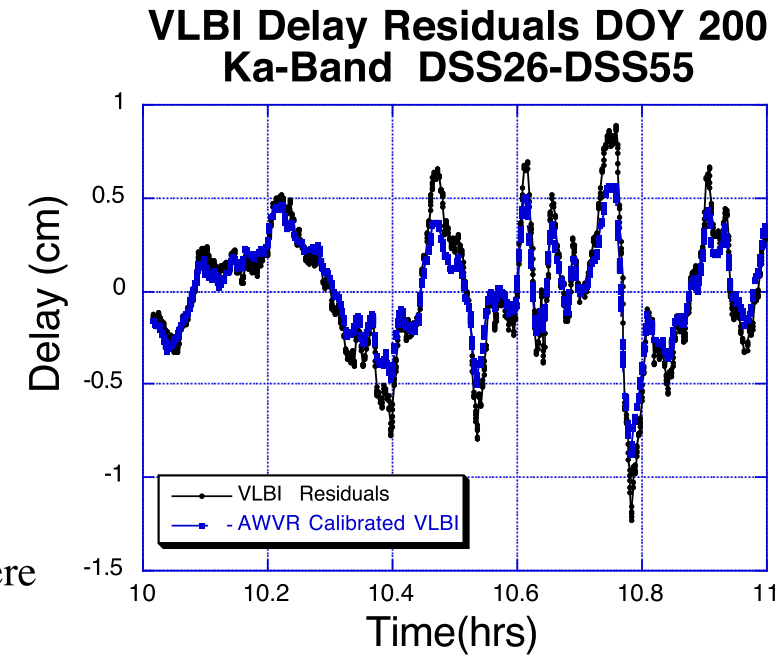
- Monitor 22 GHz/1.3cm water (rotational) line brightness temperature along line-of-sight

- 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



The Potential for a

Ka-band Worldwide VLBI Network

C. S. Jacobs[1],

U. Bach[6], F. Colomer[7], C. Garcia-Miro[2], J. Gomez-Gonzalez[7], S. Gulyaev[9], S. Horiuchi[3], R. Ichikawa[12], A. Kraus[6], G. Kronschnabl[5], J.A. Lopez-Fernandez[7], J. Lovell[8], W. Majid[1], T. Natusch[9], A. Neidhardt[4], C. Phillips[13], R. Porcas[6], A. Romero-Wolf[1], L. Saldana[14], U. Schreiber[5], I. Sotuela[2], H. Takeuchi[11], J. Trinh[1], A. Tzioumis[13], P. de Vicente[7], V. Zharov[10]

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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)

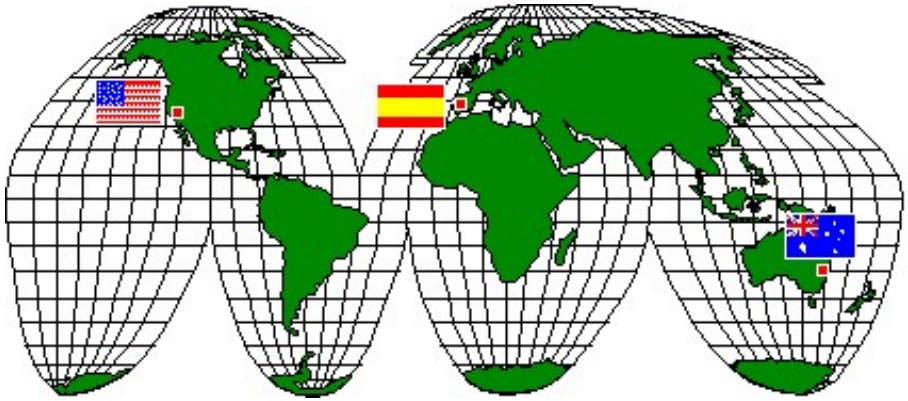
  G.E. Lanyi, P.I.,
  D.A. Boboltz, P. Charlot, A.L. Fey, E. B. Fomalont, B.J. Geldzahler, D. Gordon,
  C.S. Jacobs, C. Ma, C.J. Naudet, J.D. Romney, O.J. Sovers, L.D. Zhang

- 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

Attacking the Error budget

- SNR can be improved +8 dB!
- Instrumentation:
  - Phase calibration with test signals
  - Digital Baseband Conversion & Filtering
- Troposphere cals: WVR
- **Southern Geometry**



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

Gaia Optical vs. X/Ka 9mm frame tie

- 398 of 469 X/Ka 9mm objects with known optical V magnitudes
  132 objects optically bright (V< 18)
  213 objects optically weak (18 < V< 20)
  53 objects optically undetectable (V > 20)
  71 objects *no optical info yet* (*V = ??*)
- Simulated Gaia measurement errors (sigma RA, Dec)
  for 345 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 +- 14 μas <- Weak. Needs south polar VLBI (Dec < -45)
  Ry +- 11 μas
  Rz +- 10 μas
- Now limited by radio sigmas for which 2-3X improvement possible.
  Potential for rotation sigmas ~5 μas per frame tie component

Optical vs. Radio positions

Positions differences from:

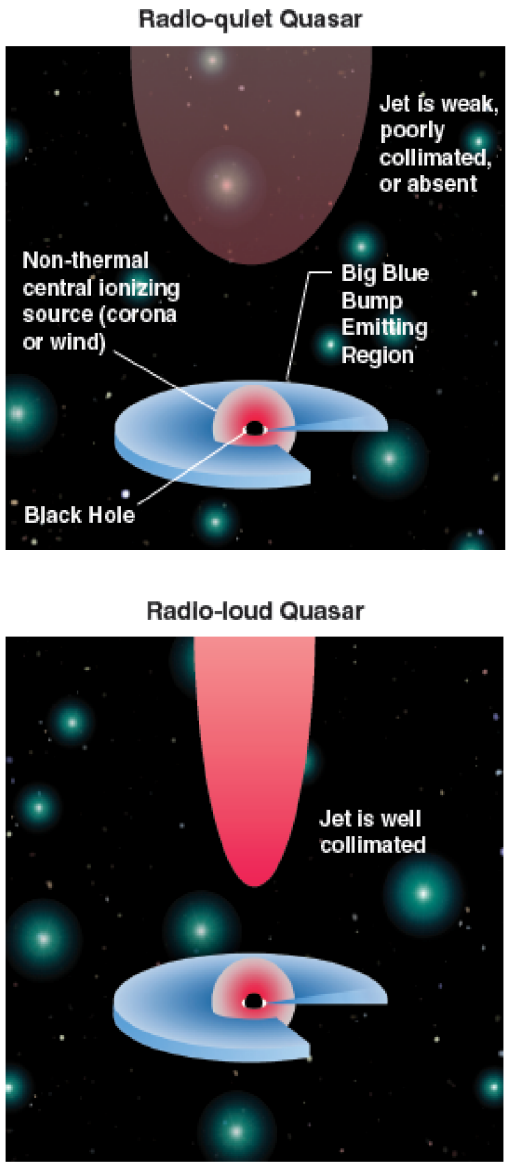
- Astrophysics of emission centroids

  - 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

Attacking the Error budget

- SNR can be improved +8 dB!
- **Instrumentation:**

  Phase calibration with test signals

  Digital Baseband Conversion & Filtering
- Troposphere cals: WVR
- Southern Geometry

Attacking the Error budget

- SNR can be improved +8 dB!
- Instrumentation:
  - Phase calibration with test signals
  - Digital Baseband Conversion & Filtering
- **Troposphere cals: WVR**
- Southern Geometry

History of Astrometry: Star positions

130 B.C.	Hipparchus	Precession	50 asec/yr
Telescope era:			
1718A.D.	Halley	proper motions	1 asec/yr
1727	Bradley	annual aberration	20 asec
1748	Bradley	18.6yr nutation	9 asec
1838	Bessel	parallax	~ asec
1930/40s	Jansky, Reber	Radio astronomy	
1960s	*several groups*	Very Long Baseline Interferometry (VLBI) invented	
1970s	"	VLBI	sub-asec
1980s	"	"	few 0.001 asec
1990s	"	"	< 0.001 asec
2000s	"	"	~0.0001 asec
2010s	Gaia	Optical astrometry	25-70 μas for V=16-18 quasar
2010s	ESA-DSN?	X/Ka 9mm VLBI	70 μas 0.3 Jansky quasar

24 & 43 GHz Observations

- VLBA ten 25m antennas

  12 sessions each 24 hours

  120K delay/rate obs. pairs

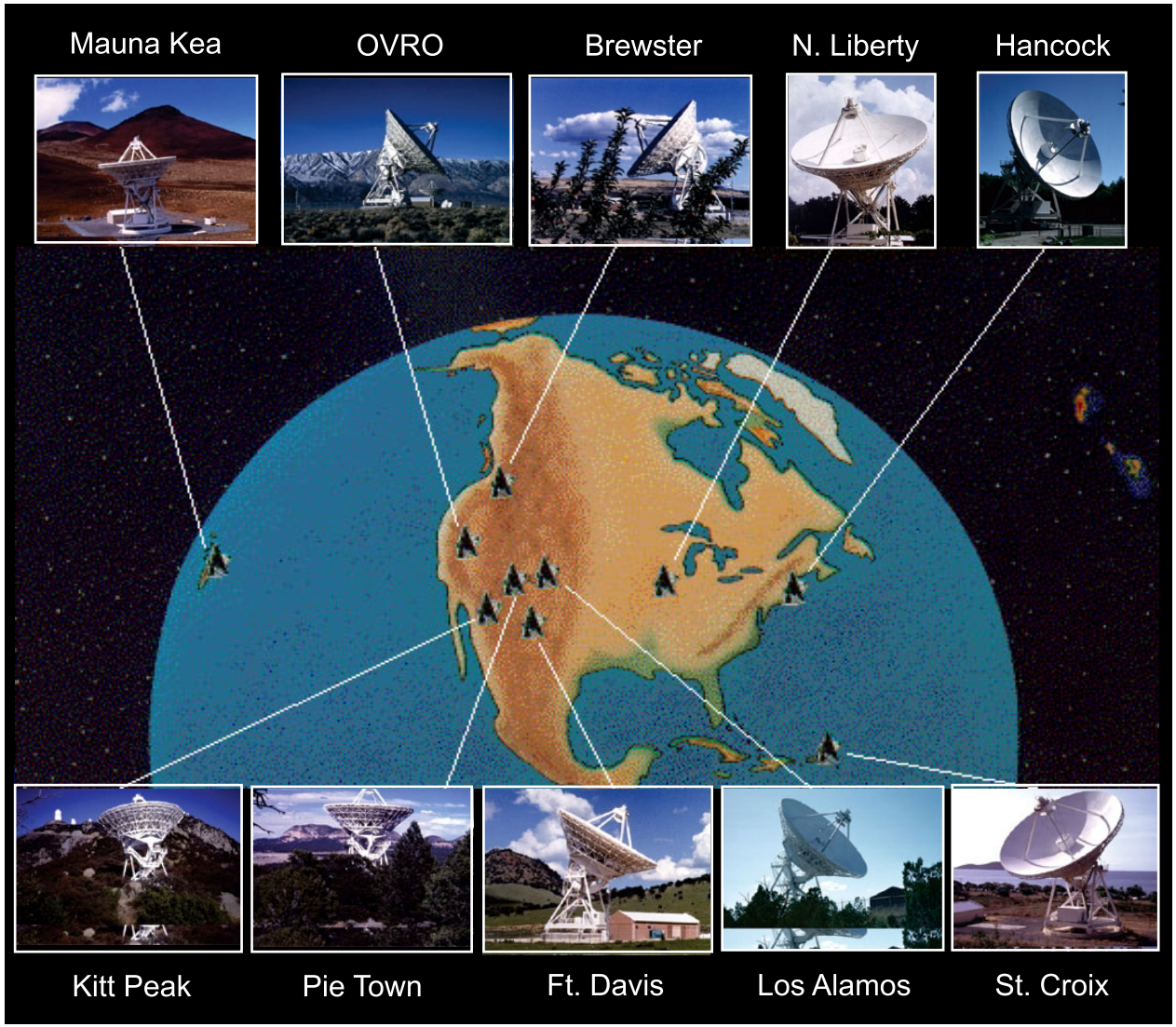
  ~65-180 sources /session

  3-5 snapshots, 2 min each

  400 MHz spanned band

  128 Mbps record rate

- Simultaneous astrometry and imaging



(photos credit NRAO/NSF/AUI http://www.aoc.nrao.edu/vlba/html/vlbahome/thesites.html)

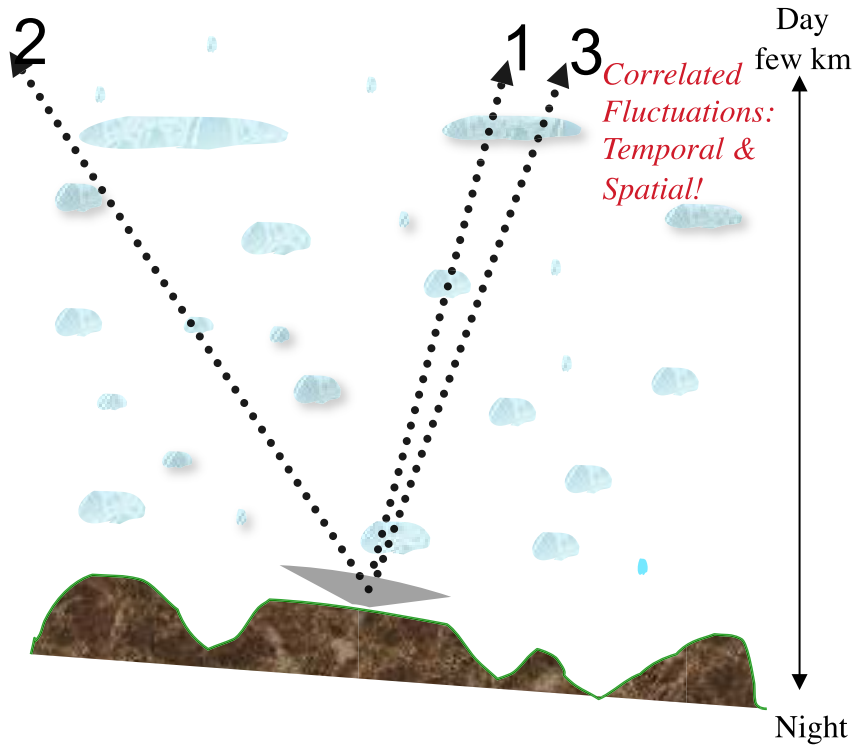
Troposphere Solution 1: Better Estimation

- Modified Least Squares to account for observation correlations -- both temporal and *spatial*

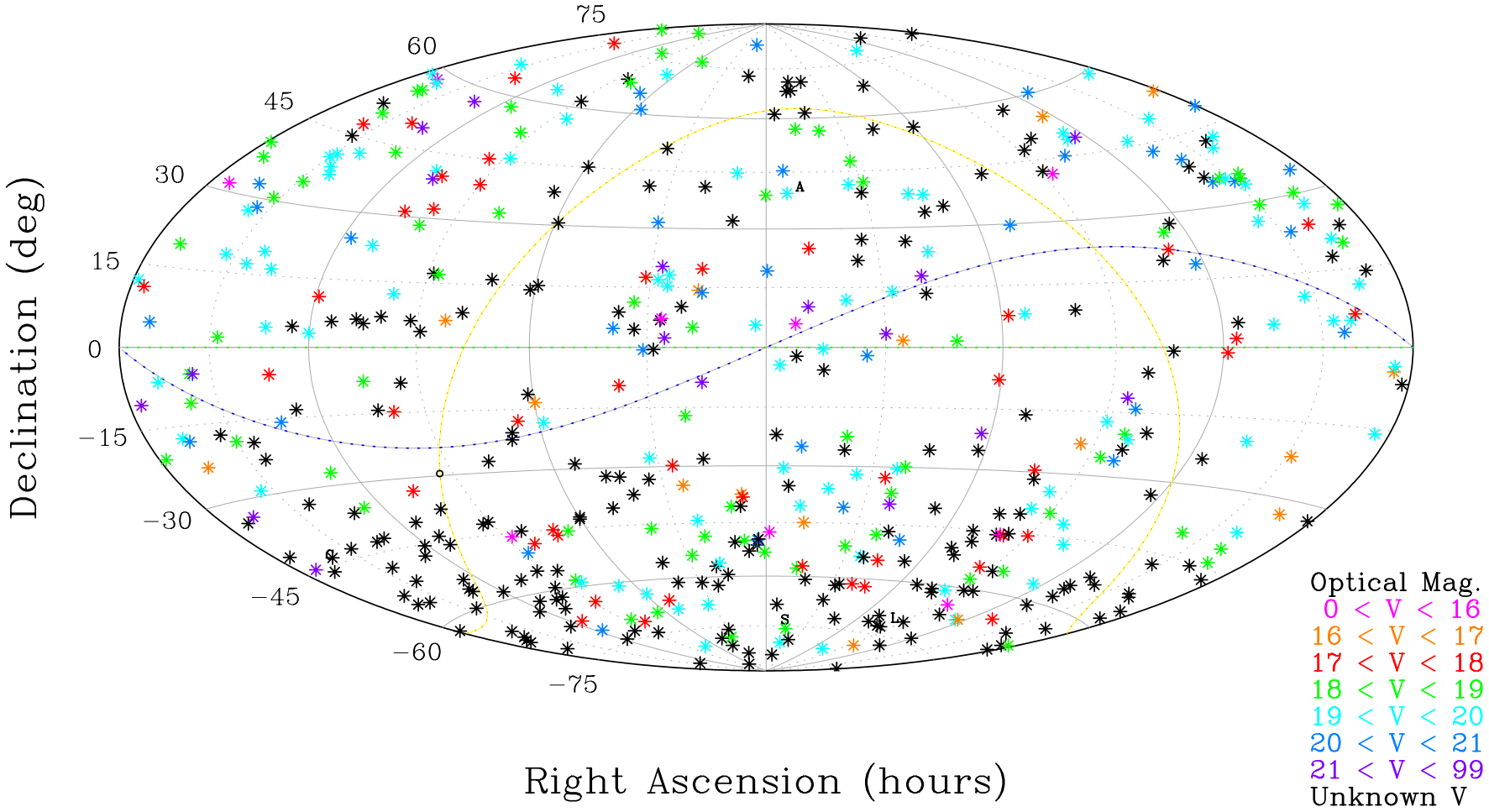
- Use Kolmogorov frozen flow model of Treuhaft & Lanyi (Radio Sci. 1987)

- Model increases information available to the estimation process
  1) Reduces parameter biases
  2) Reduces parameter sigmas

- Validation: Currently improves agreement X/Ka vs. S/X catalogs by about 10% in Declinations.
  Expect ~30% after SNR & phase cal errors peeled away to reveal troposphere errors.



Ka-band candidates: 498 sources identified

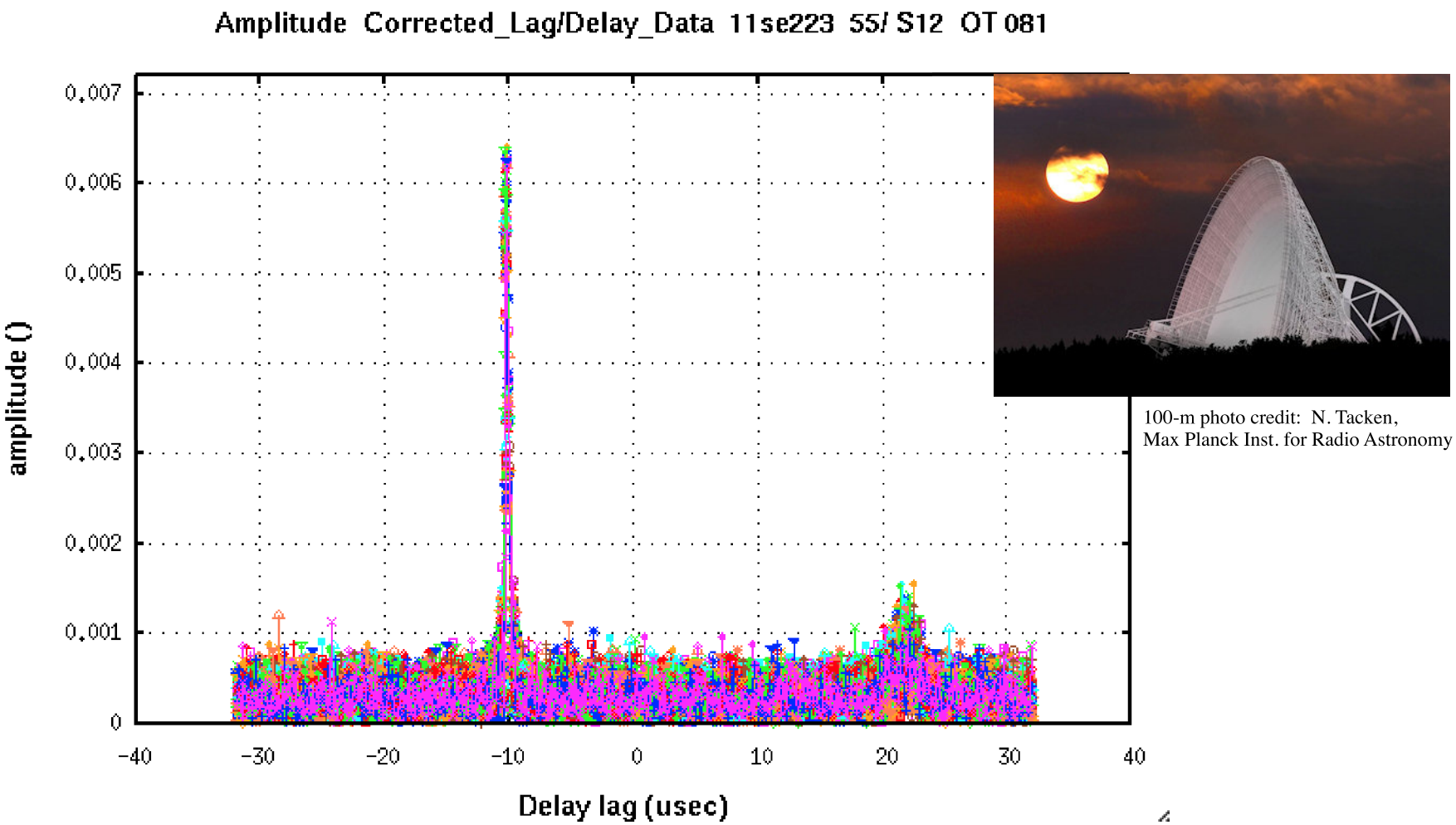


Ka candidate criteria: 200 mJy, 70% flux in unresolved X-band core

South polar cap is well covered, ready for observations.

Credit: Sotuela et al, GREAT-ESF Conf., Porto, Portugal, 2011 http://www.fc.up.pt/great-ws-porto/Ioana_Sotuela.pdf

“First Light”: 1st Ka-band Fringes outside DSN!



100-m photo credit: N. Tacken, Max Planck Inst. for Radio Astronomy

Effelsberg 100-meter to DSS 55 34-meter BWG

DOY 223, source OT 081, 28 x 4MHz chan @2-bit, 448 Mbps

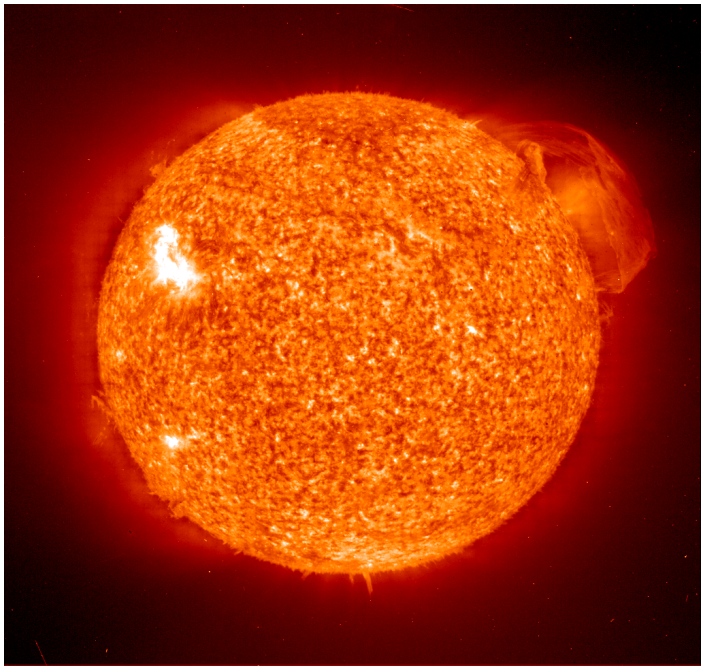
Credit: C. Jacobs, I. Sotuela, U. Bach, A. Kraus, R. Porcas, J. Trinh, L. Saldana

Motivation for Ka-band: 9mm/32 GHz

- Astrometry, Geodesy and Deep Space navigation, have been at 3.6cm/8.4 GHz (X-band) with 2.3 GHz (S-band) plasma cals

Ka-band (9mm/32 GHz) provides

- More *compact* sources which should lead to more *stable* positions!
- Higher Telemetry Rates: +5 to +8 dB
- Smaller, lighter RF spacecraft systems
- Avoid S-band *RFI* issues
- Ionosphere & solar plasma down 15X !! at 32 GHz (Ka-band) compared to 8 GHz thus observe closer to Sun & Galactic center



Picture credit: SOHO/ESA/NASA

Drawbacks of Higher radio frequencies:

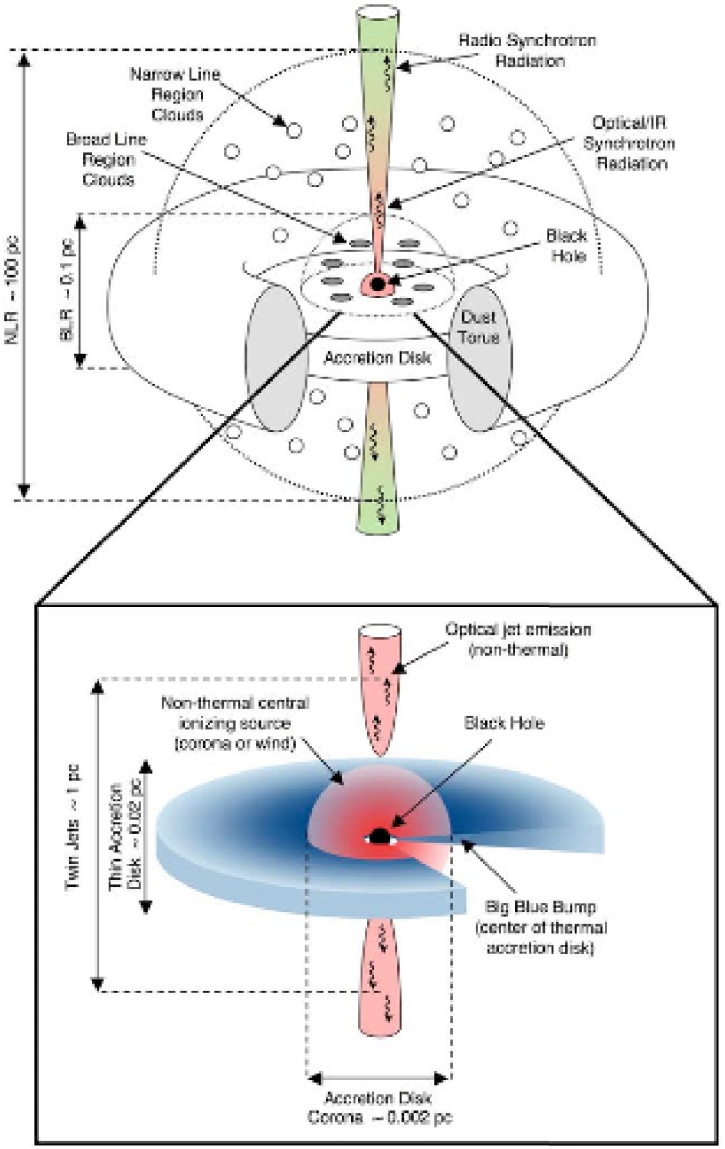
- More weather sensitive, higher system temp.
- Shorter coherence times
- Weaker sources, Many sources resolved
- Antenna Pointing more difficult

Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids
  - radio: synchrotron from jet
    frequency dependent structure
    frequency dependent core shift

  -optical: synchrotron in jet?
  non-thermal ionization in corona?
  big blue bump?

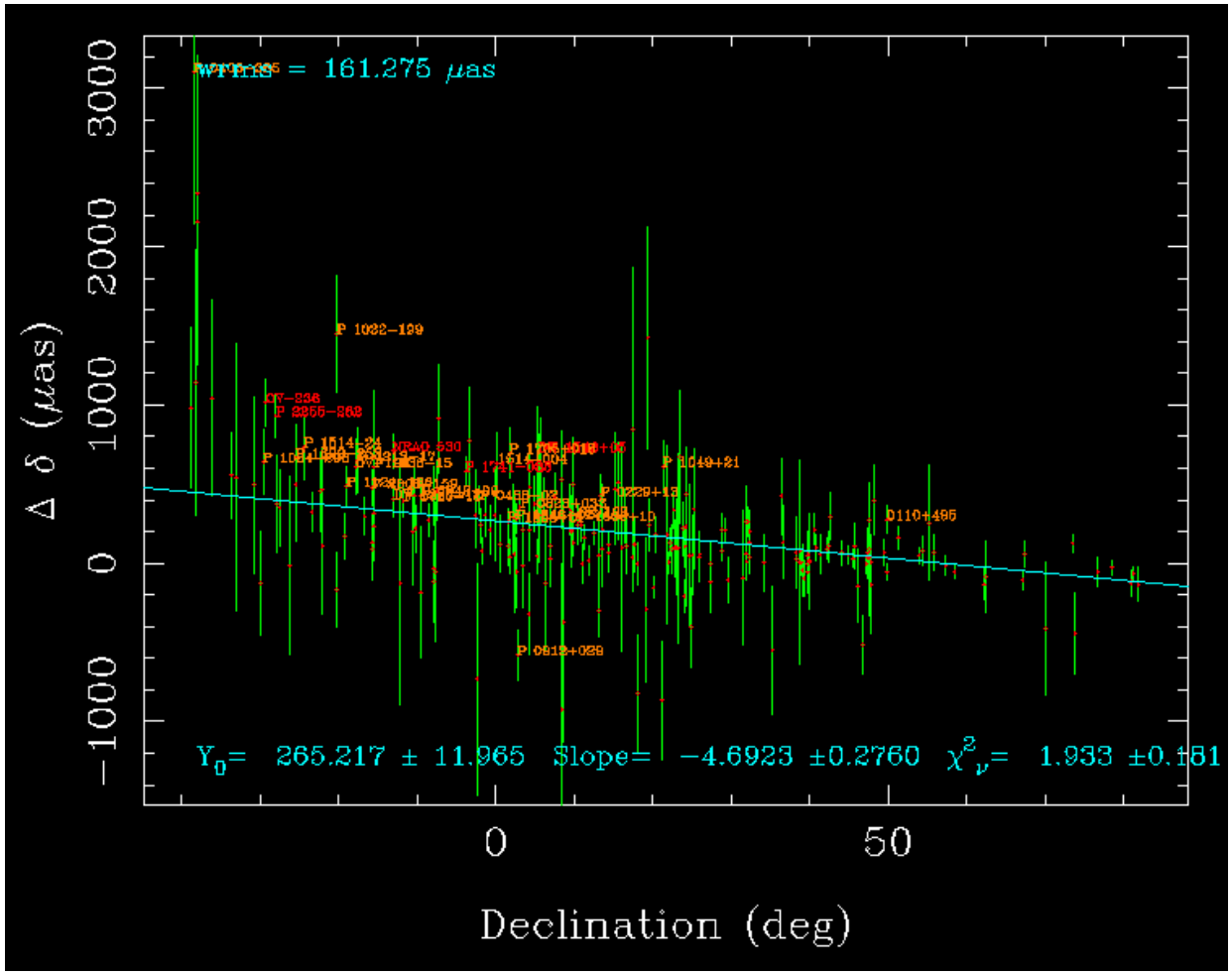


Credit: Elvis (2000) and Smith quoted in Unwin et al (2008)

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)

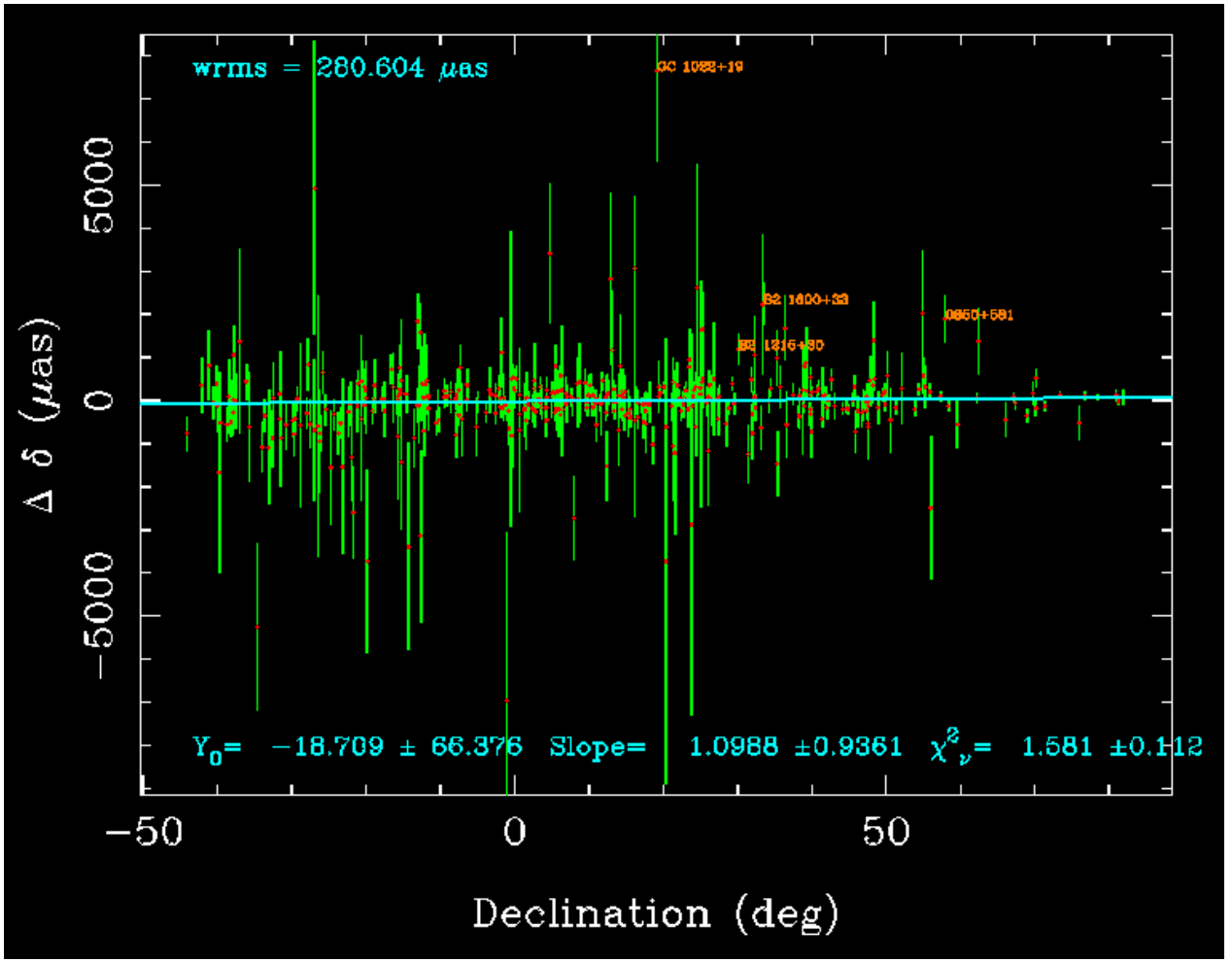
Dual-band ion Calibrations

and

Station in south

Leads to better ΔDec vs. Dec Zonal stability:

100 ± 100 μas tilt



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

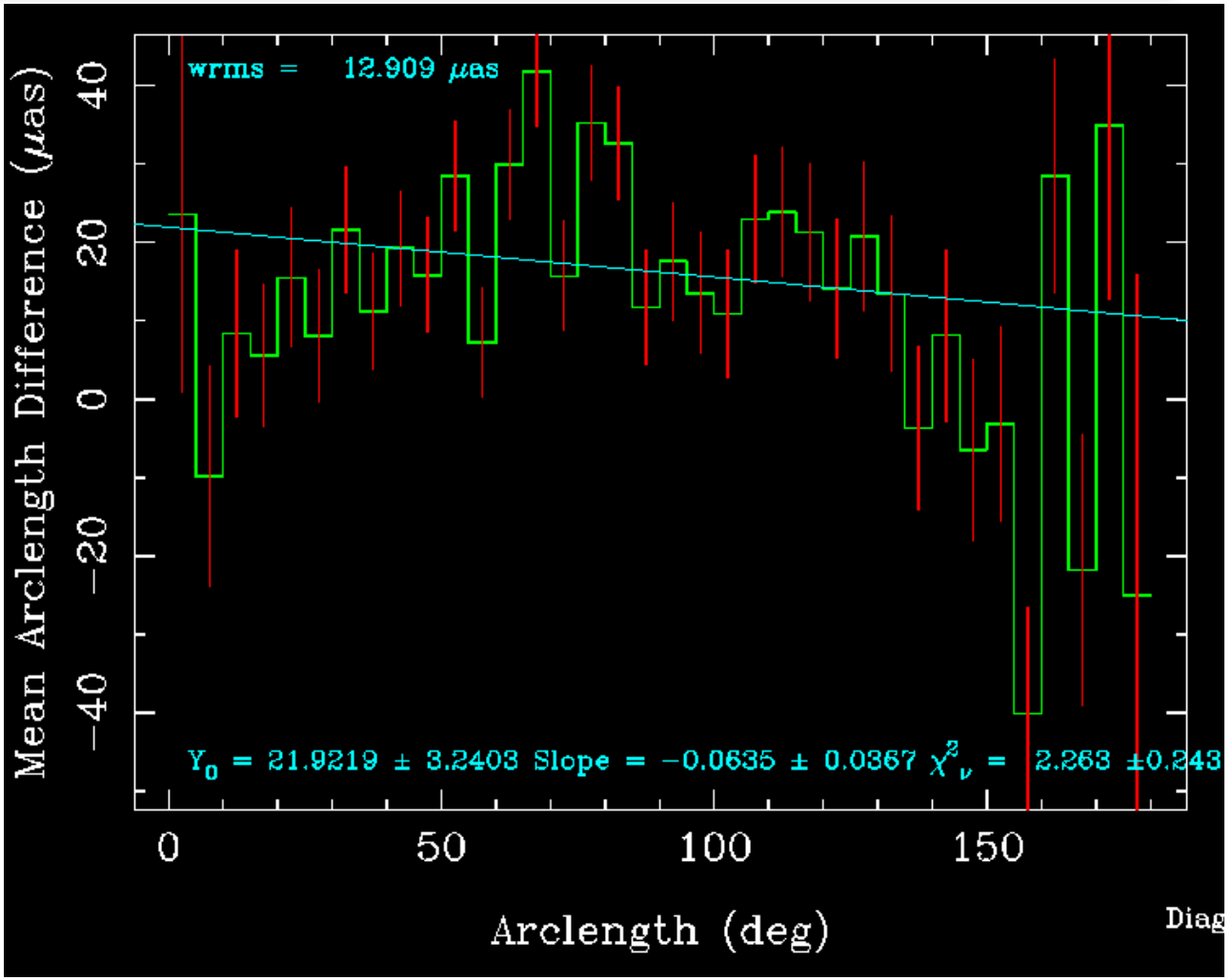
Credit: X/Ka(9mm): Jacobs et al, EVGA, Bonn, Germany, 2011
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009

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.



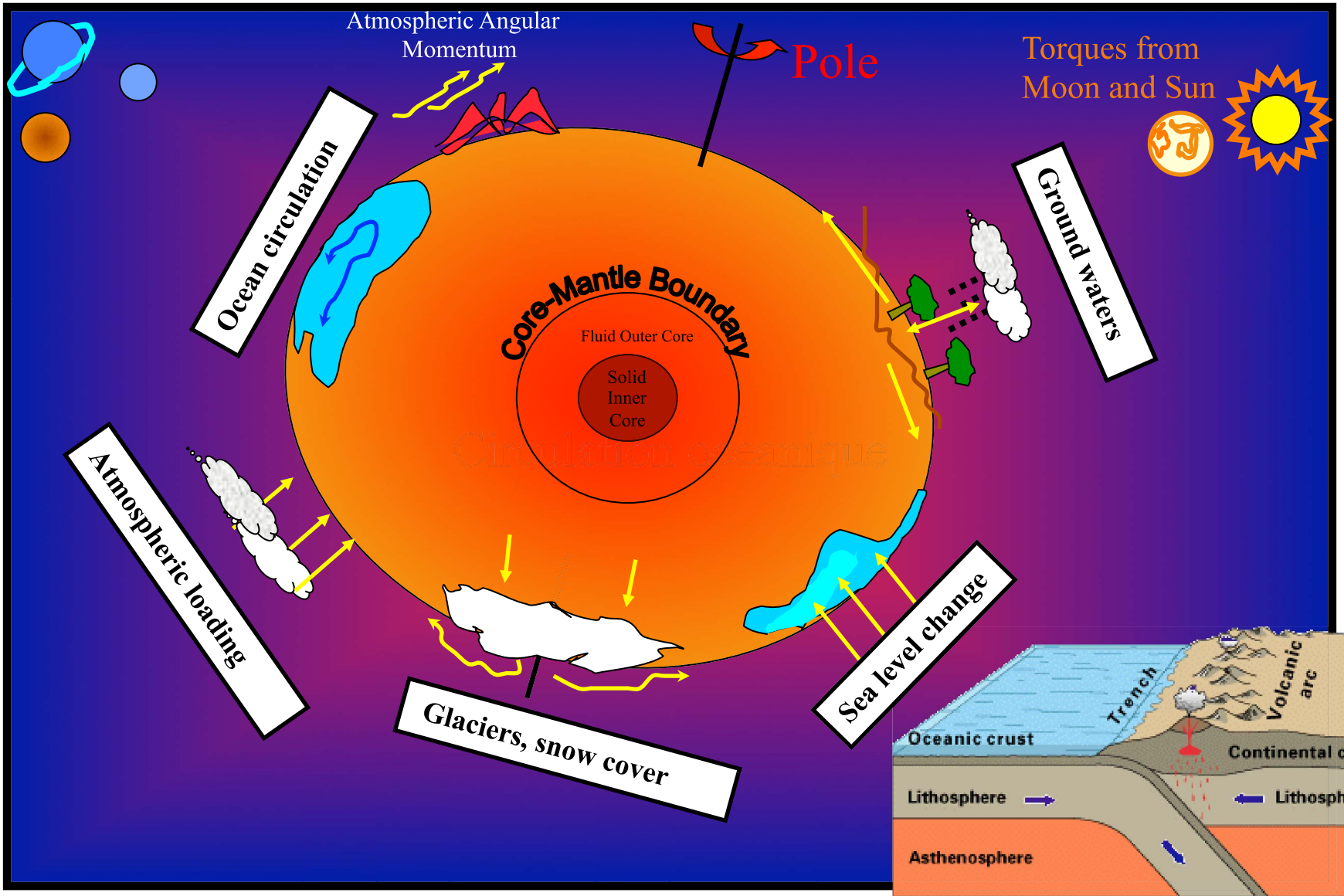
X/Ka(9mm) vs. S/X ICRF2 (current IAU standard)

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

How Does VLBI Work?

The Observing Platform

Moving Platform: UT1, Polar Motion, Nutation, Tectonics



http://pubs.usgs.gov/publications/text/understanding.html

Oceanic-continental convergence

 Credit:After Kurt Lambeck et al, The Earth's Variable Rotation, Cambridge, 1980

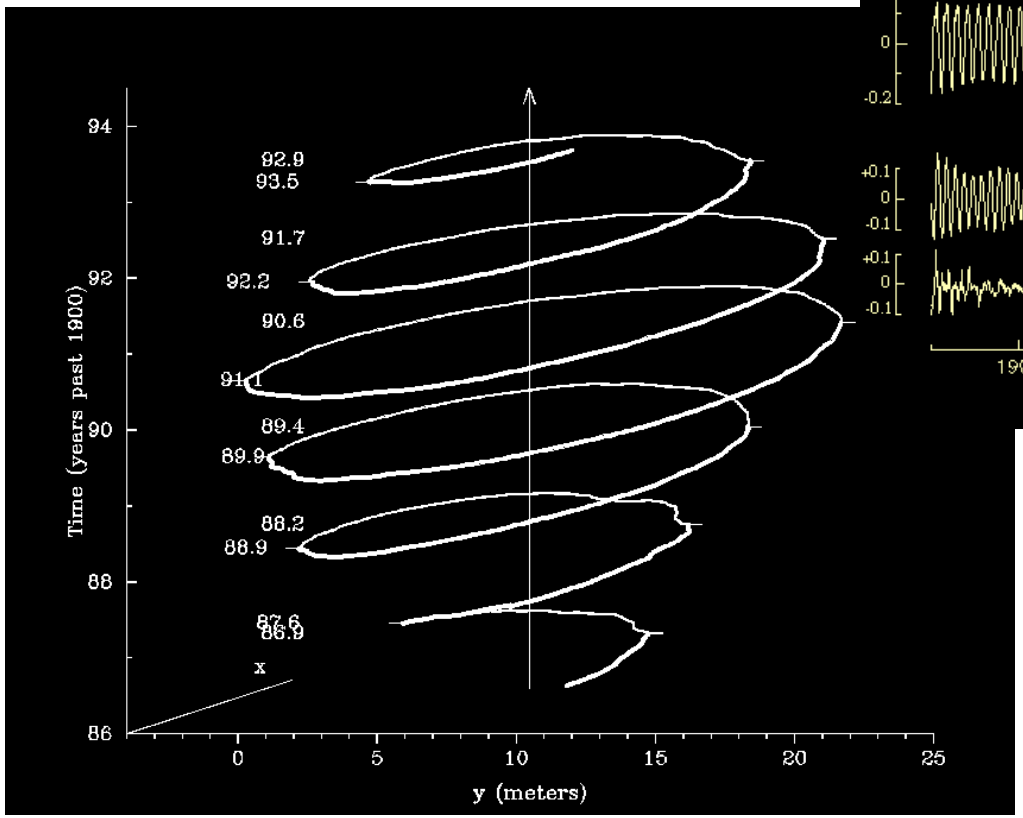
"Budget" of Effects contributing to Interpretation of Results

Term	Size	Uncertainty
Geometry	6,000,000,000 mm	... mm
Orbital aberration	600,000	1
General Relativity	2,000	2
Tectonic motion	2,000	2
Tidal motion	500	3
Non-tidal motion	50	5
Earth rotation/pole motion	20,000	2
Nutation/precession	300,000	3
Extended sources	50	3
Antenna structure	10,000	10
Electronics	300,000	5
Ionosphere	1000	1
Troposphere	**20,000**	**20**

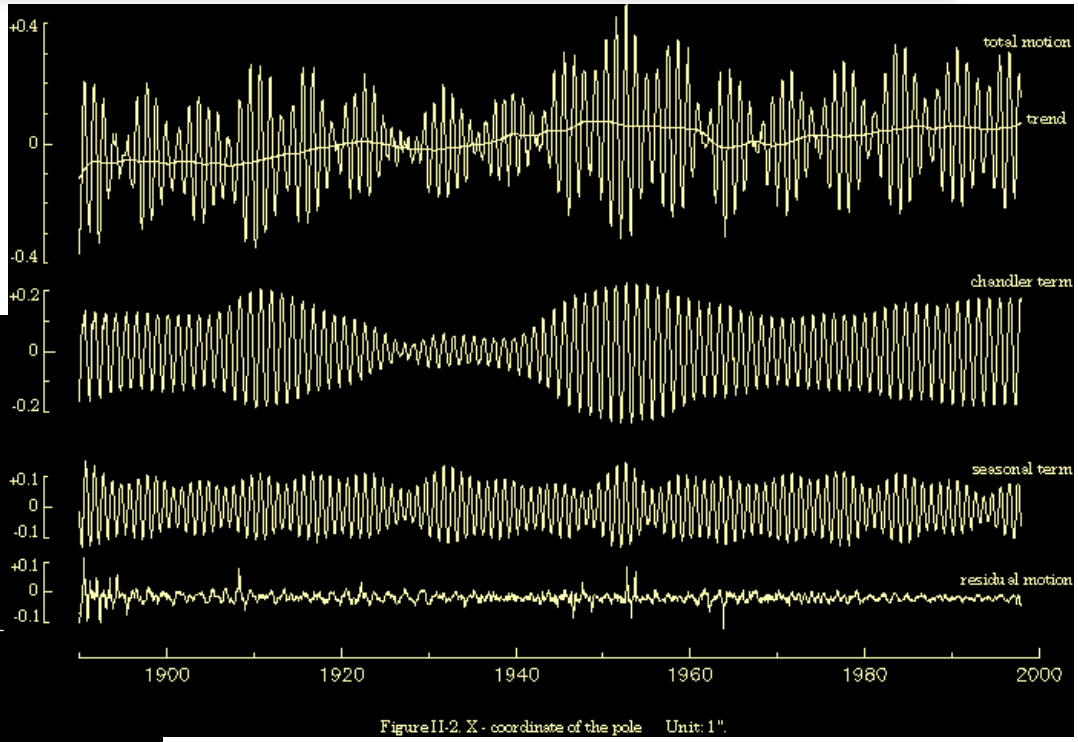
Credit: Sovers, Fanselow, & Jacobs, Rev Mod Phys 70, 4, 1998

Polar Motion Spiral

Polar Motion vs. Time



Credit Sovers, Fanselow, Jacobs, Rev Mod Phys 70,, 1998.



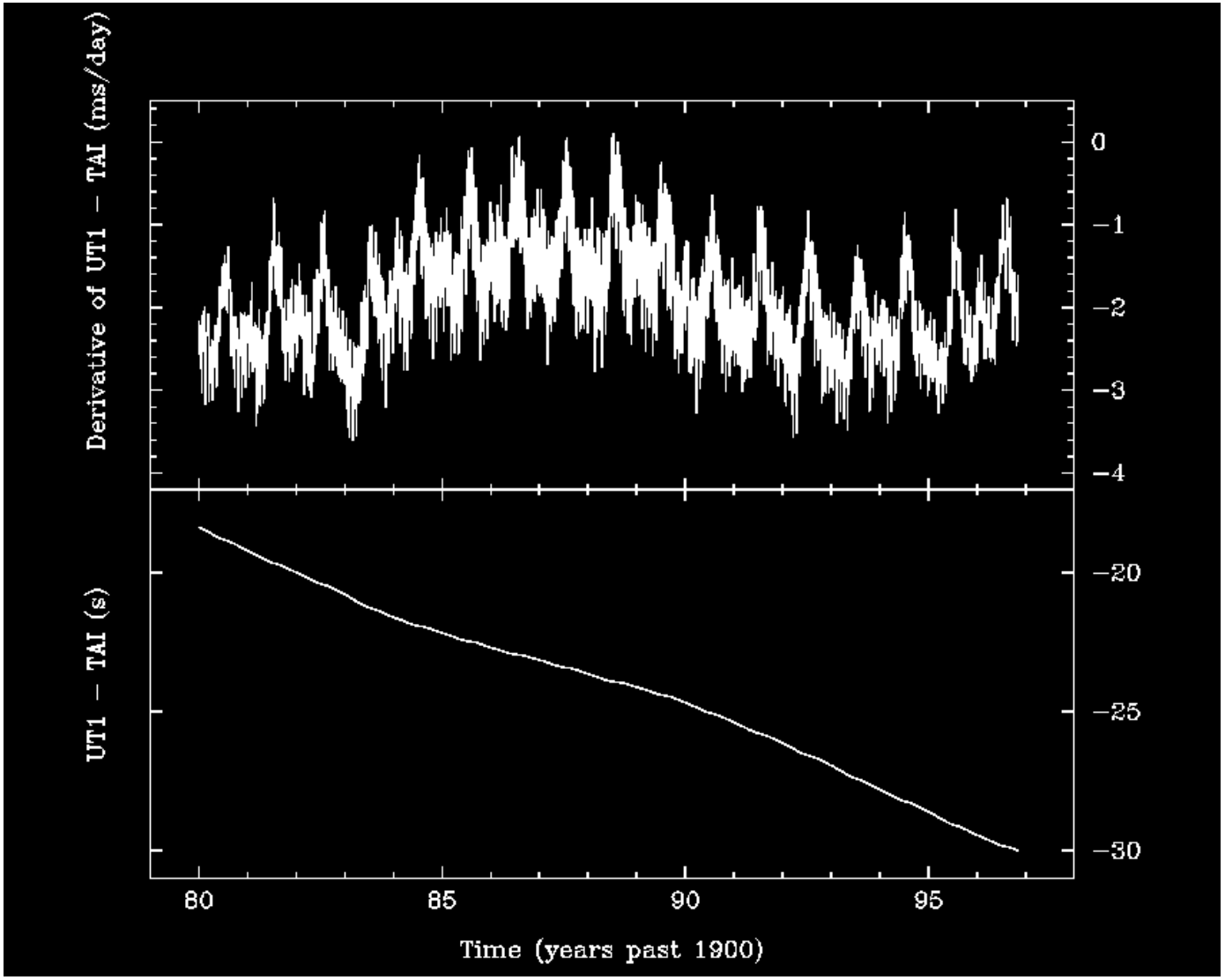
(credit http://www.iers.org/iers/earth/)

Effect ~ 10 m

Calibrated to ~1cm with

GPS + VLBI + …

Length Of Day Spectrum, UT1 vs. TAI



Length Of Day Spectrum

and

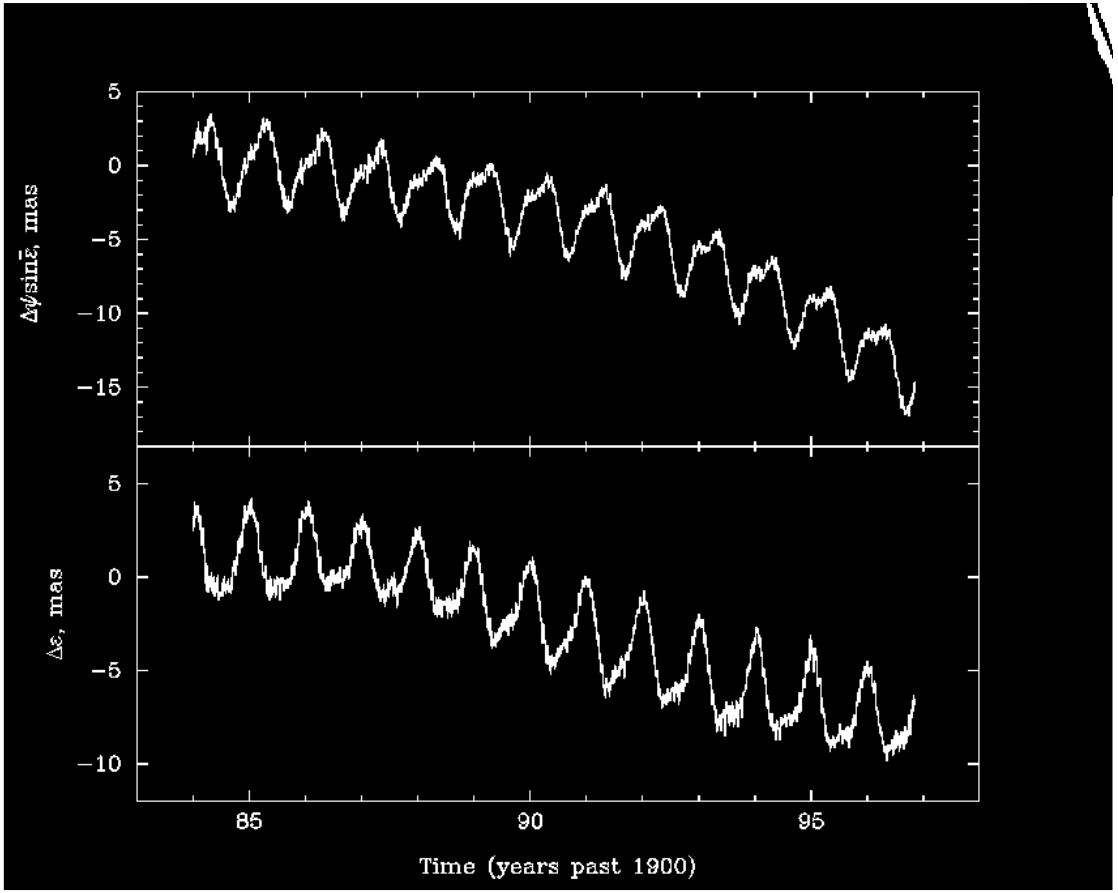
UT1 -- TAI

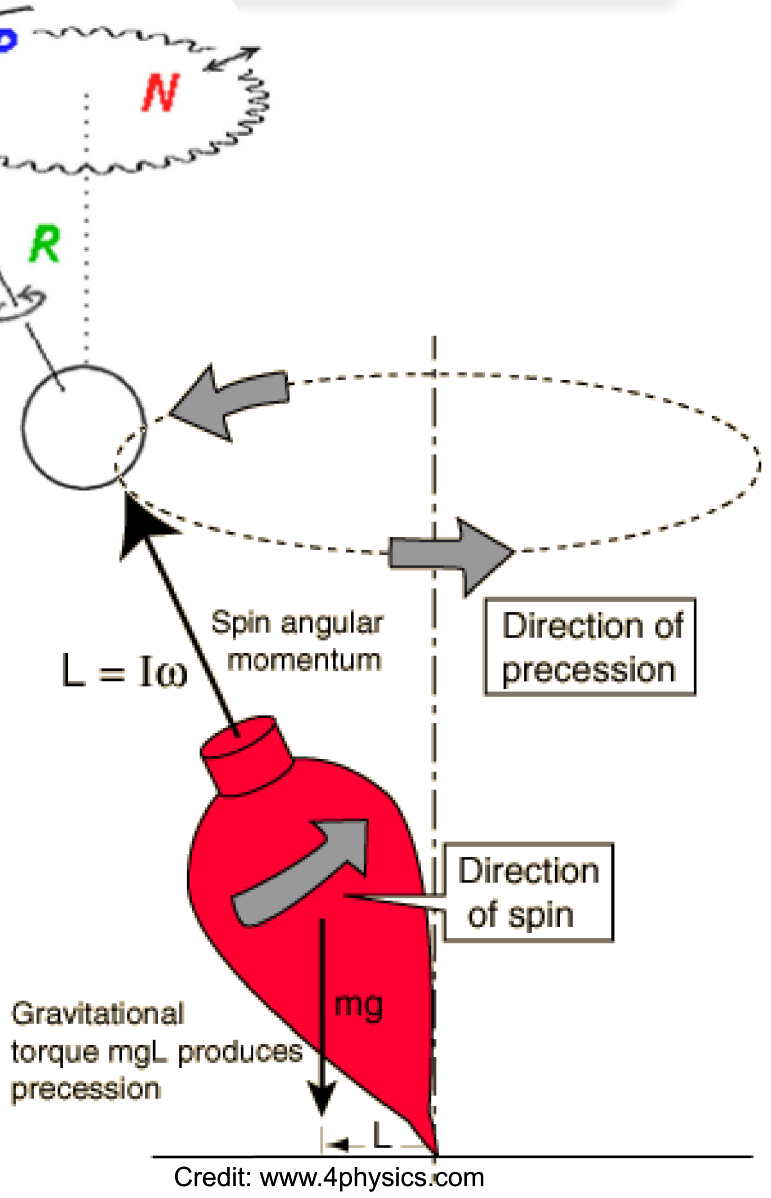
Credit Sovers, Fanselow, Jacobs, Rev Mod Phys 70, 4, Oct 1998.

Nutation: The Earth's axis is like a Top

From German Wikipedia, by User Herbye.

1980 IAU Model vs.
VLBI observed
Nutation





Credit: www.4physics.com

Credit Sovers, Fanselow, Jacobs, Rev Mod Phys 70, 4, Oct 1998.

Accuracy has been limited by SNR

Solution:

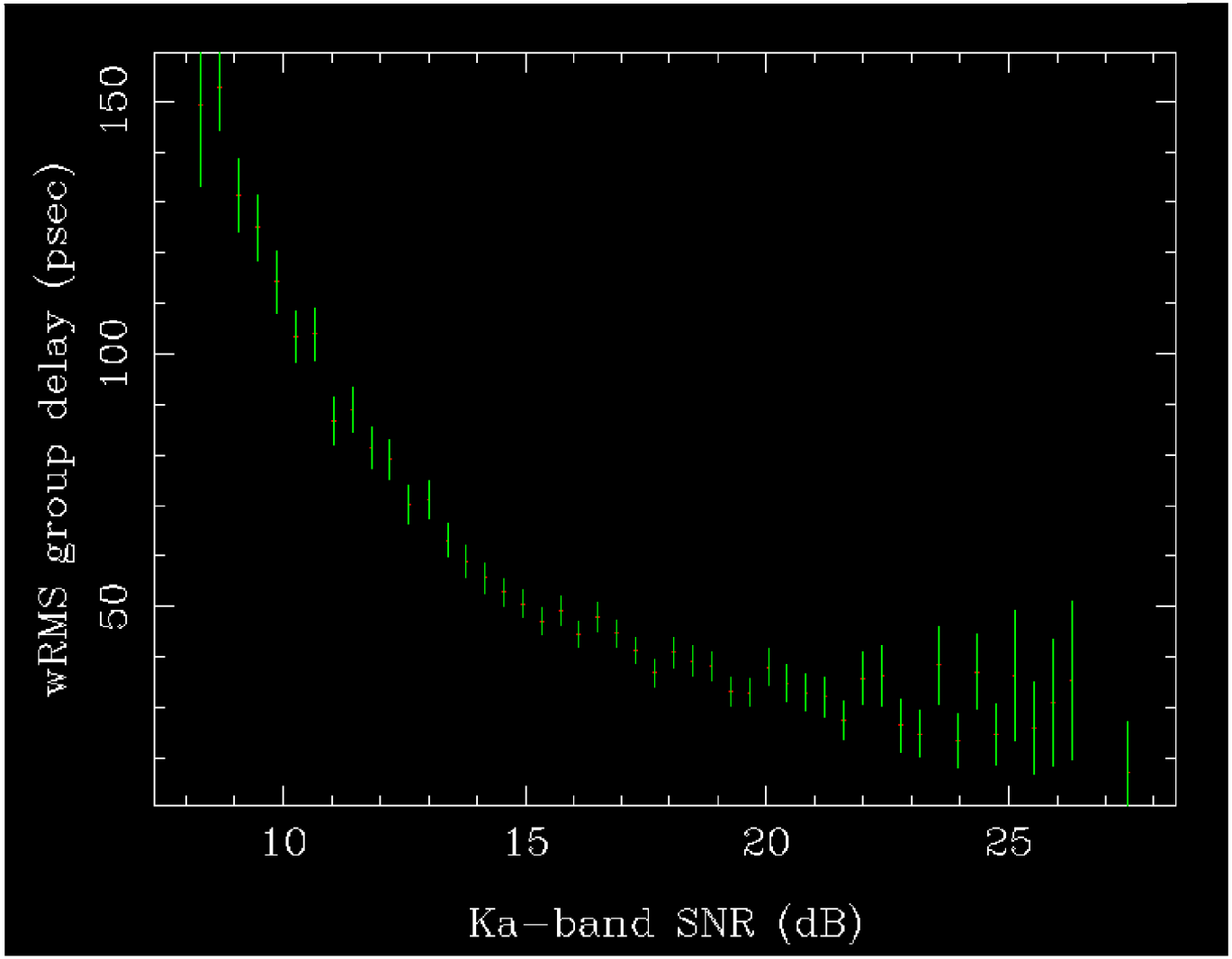
1) More bits:
4X operational
8X R&D
in ~6 months
yields +5 dB SNR

16X in 2-3 years
32X in 3-5 years

2) Ka pointing

Now with improved Pointing calibrations ~3 dB more SNR

Total vs. early passes +8 dB SNR increase!

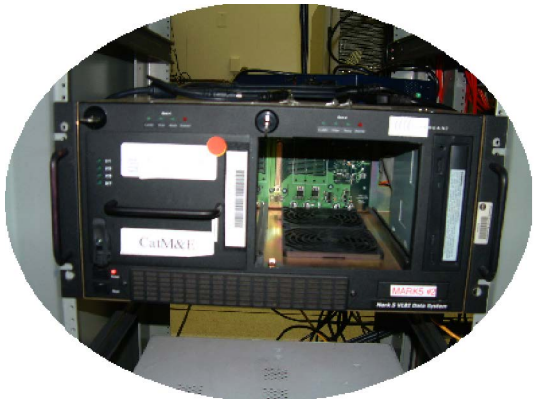


Data scatter has been SNR limited for SNR < 15 dB

Higher data rate hardware being developed

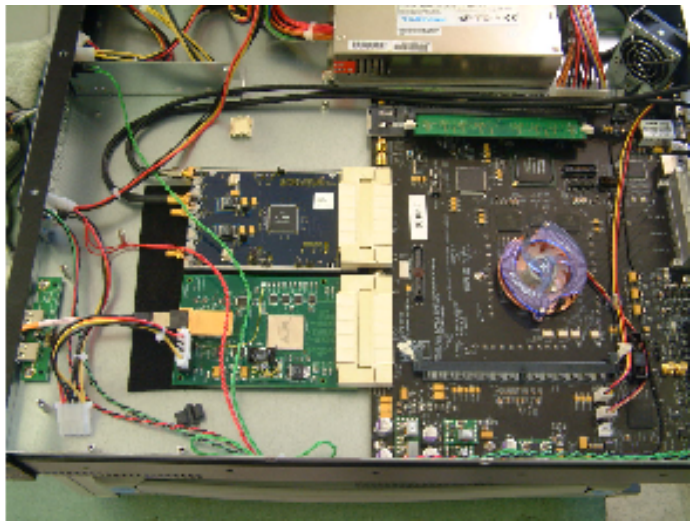
IF select switch:
12 inputs allows multiple bands, multiple antennas

Mark-5C recorder



Command & Control

Sampler: 1280 MHz, 8-bit/sample



Copper to fiber, **Digital filter**, Format

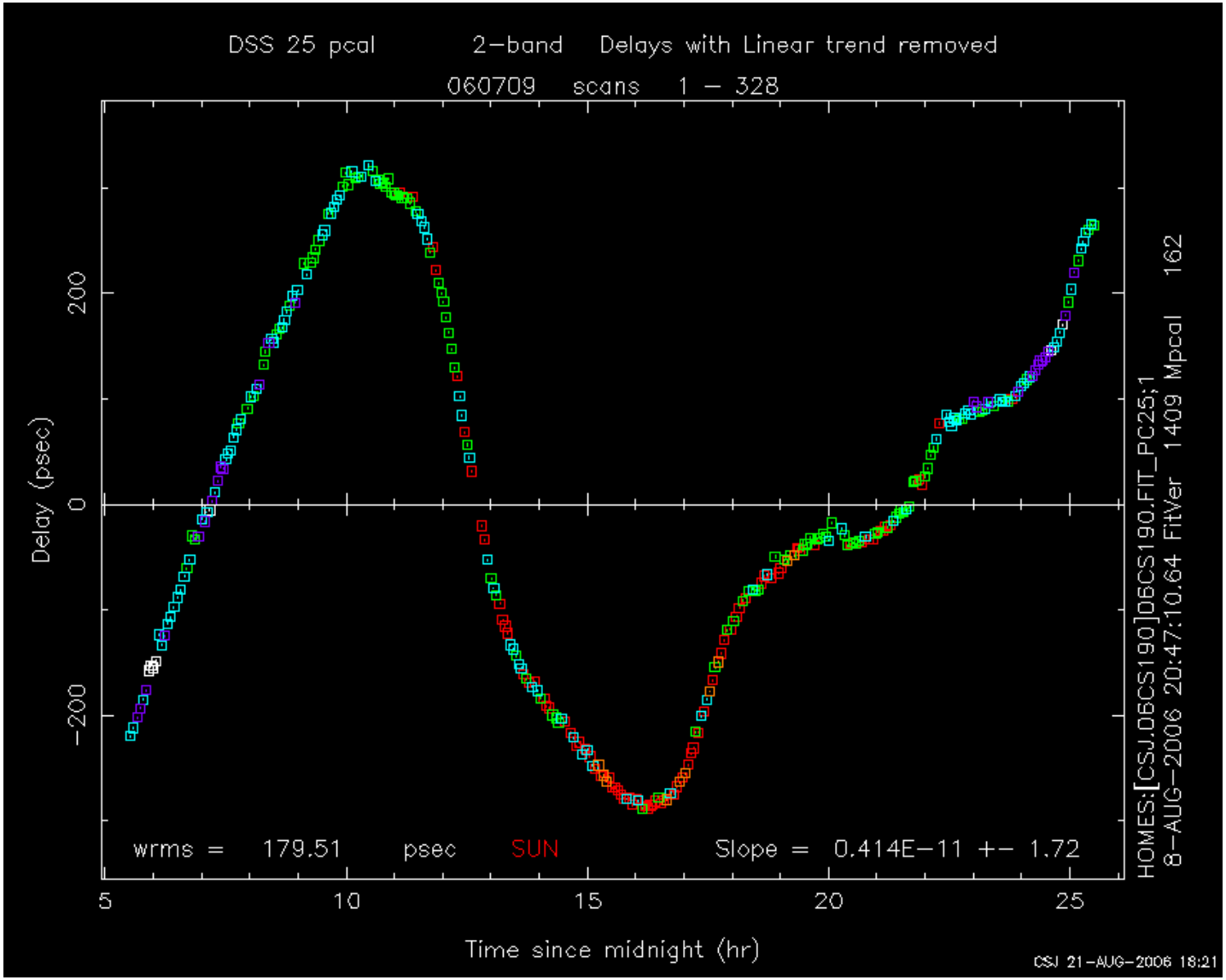
Design: Navarro et al., IVS, 2010. Photo credit: Les White

Need instrumental Phase calibrations

Problem:
180 psec ~diurnal effect

Solution:

Ka-band Phasecal Prototype Demo'd --- > Units being Built. Operations in ~1 year



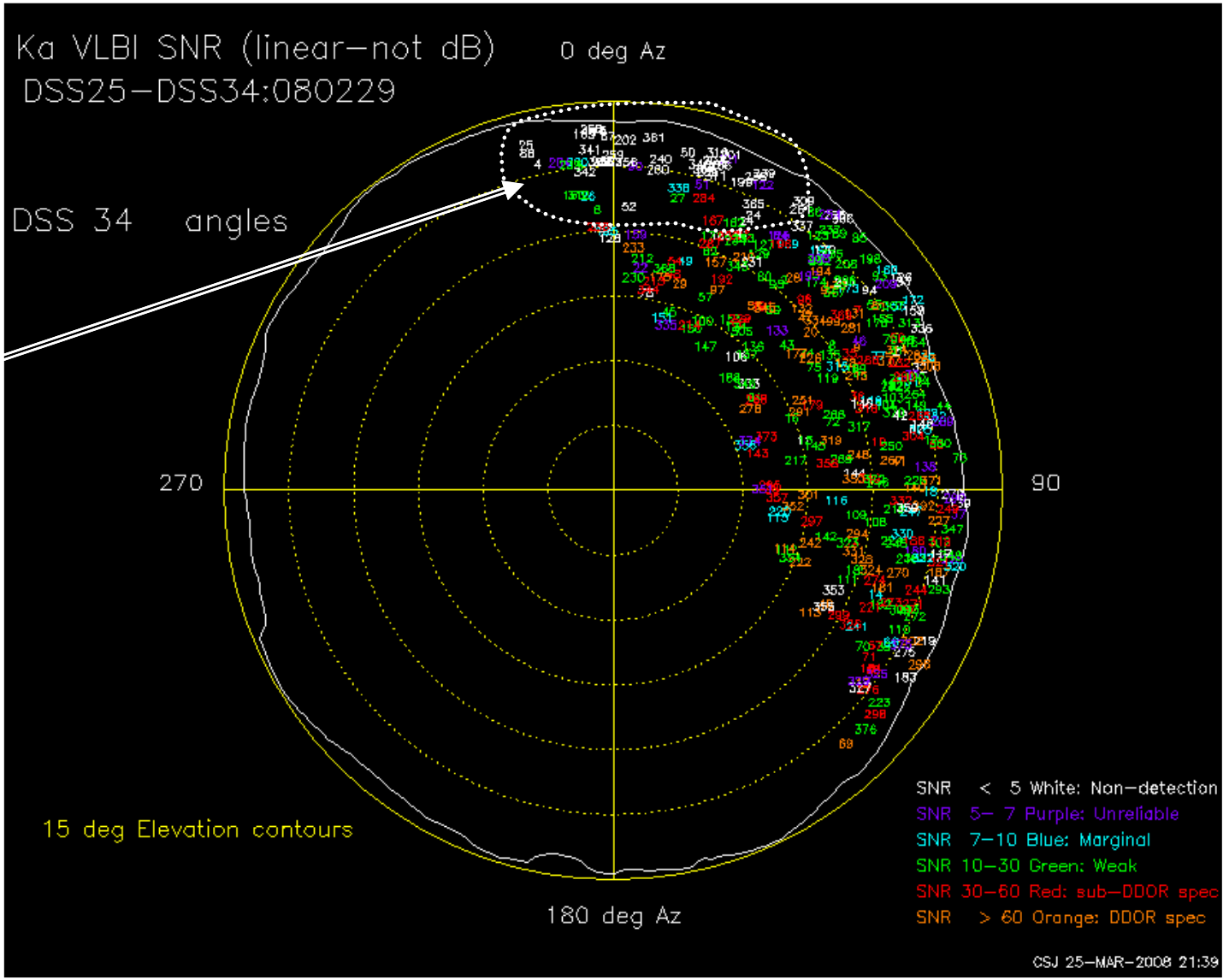
Proto-type shows need for calibrations. *Credit: C. Jacobs, B. Tucker, L. Skjerve*

Example: Ka-band Antenna Pointing

White pts. Represent Non-detection

Note Northern concentration of non-detects

Later, we got independent confirmation from ACME automated bore sight system of 18 mdeg errors



Credit: M. Vasquez, G. Baines, D. Rochblatt, C. Jacobs, C. Snedeker

How Does VLBI Work?

Figure credit: math.yorku.ca/infinity_old/NewMembers/NewMembers.html

Point Source at Infinity as Reference Beacon

How does VLBI work?

- **Point source at infinity as a direction reference**

  Extragalactic "nebulae" idea from

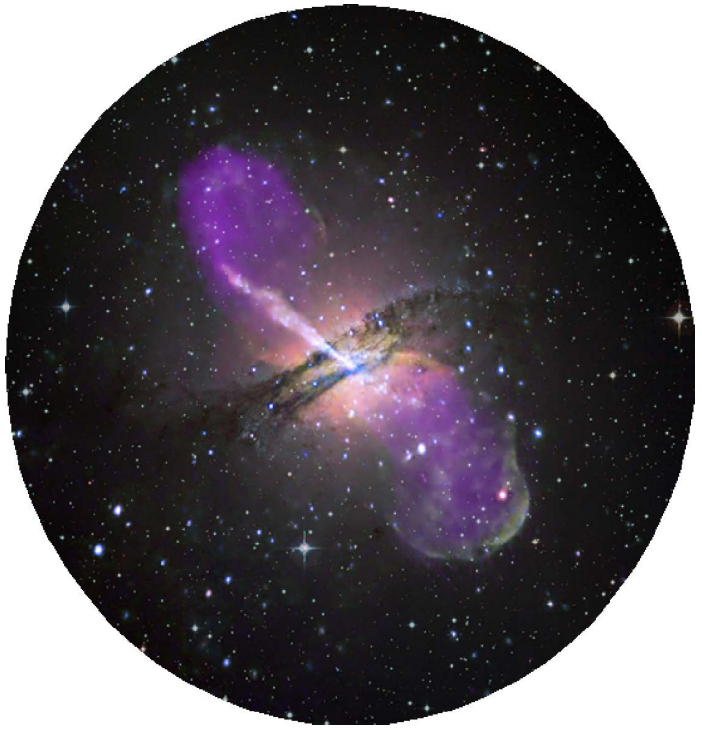
  Laplace (1749-1827) and

  Wm. Herschel (1738-1822): *in 1785*

  realized that "nebulae" likely very distant

  `On the Construction of the Heavens,' Ph.Trans.Roy.Soc., 1785, p. 213 ff.

- **Advantage: sources don't move**



Credit: chandra.harvard.edu/photo/2008/cena/cena_multi.jpg

BUT at a distance of a *billion* light years . . .

- **The price to be paid is**

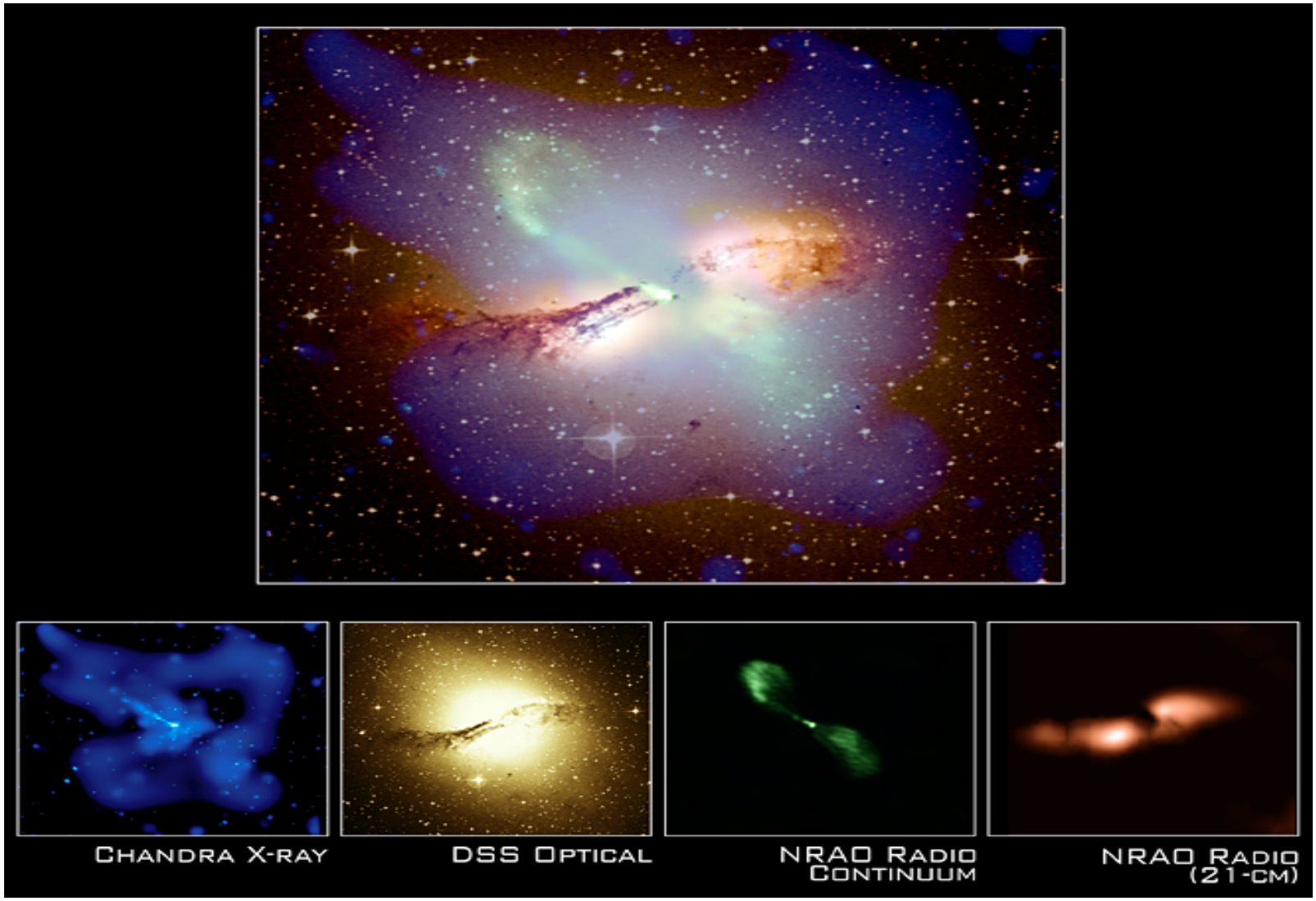
  Very weak sources **1 Jy = 1.0E-26 watt/m**2/Hz**

  need lots of square meters => 34 - 70m Antenna

  lots of Hz bandwidth => 0.1 to 4 Gbps

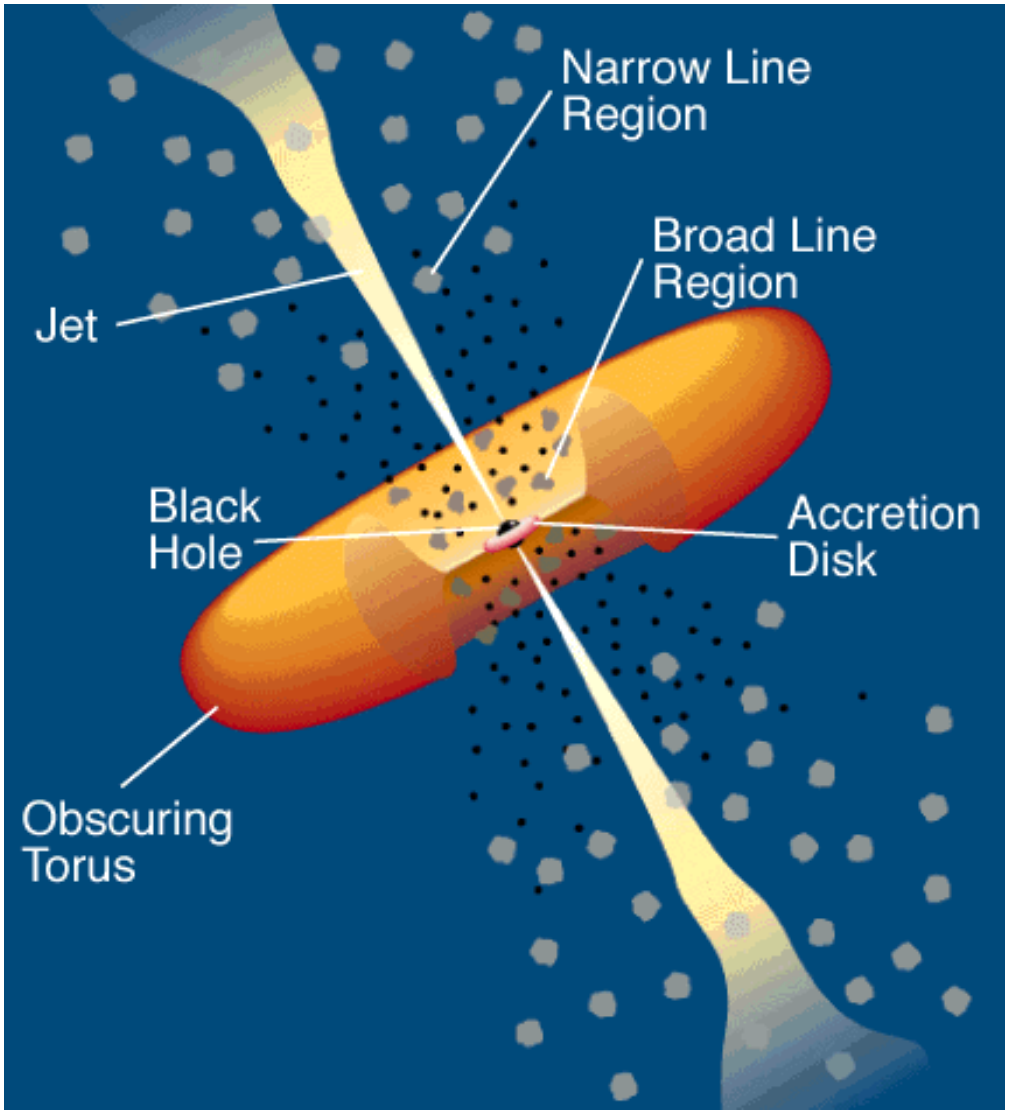
  low system temperature => Tsys = 20 - 40 Kelvin

AGN Centaurus-A in X-ray, Optical, Radio



Credits: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/Schiminovich, et al.),
Radio continuum image (NRAO/VLA/J.Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI)

Active Galatic Nuclei (AGN) schematic



http://heasarc.gsfc.nasa.gov/docs/objects/agn/agn_model.html

Credit: C.M. Urry and P. Padovani, PASP, 1995

Schematic of
Active Galactic Nuclei
Redshift z~ 0.1 to 5
Distance:
billions light years
Parallax = 0
Proper motion
< 0.1 nrad/yr

Centroid of radiation
Gets closer to central
engine (black hole)
As one goes to higher
frequencies, therefore,

Ka-band (9mm, 32 GHz)
is better than
X-band (3.6cm, 8.4 GHz)

Paradigm of "Sailing by the stars"

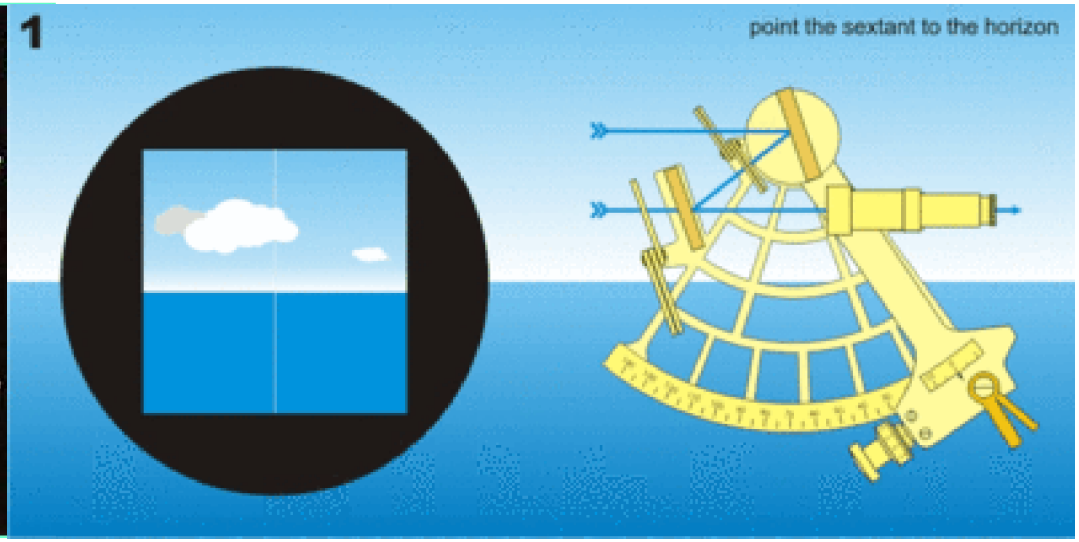


Photo Credit: Dimitry Bobroff, www.ludmillaalexander.com

Credit for sextent/octant: en.wikipedia.org/wiki/Sextant (GNU Free Doc license)

Navigation & Astrometry:
Historical Perspective

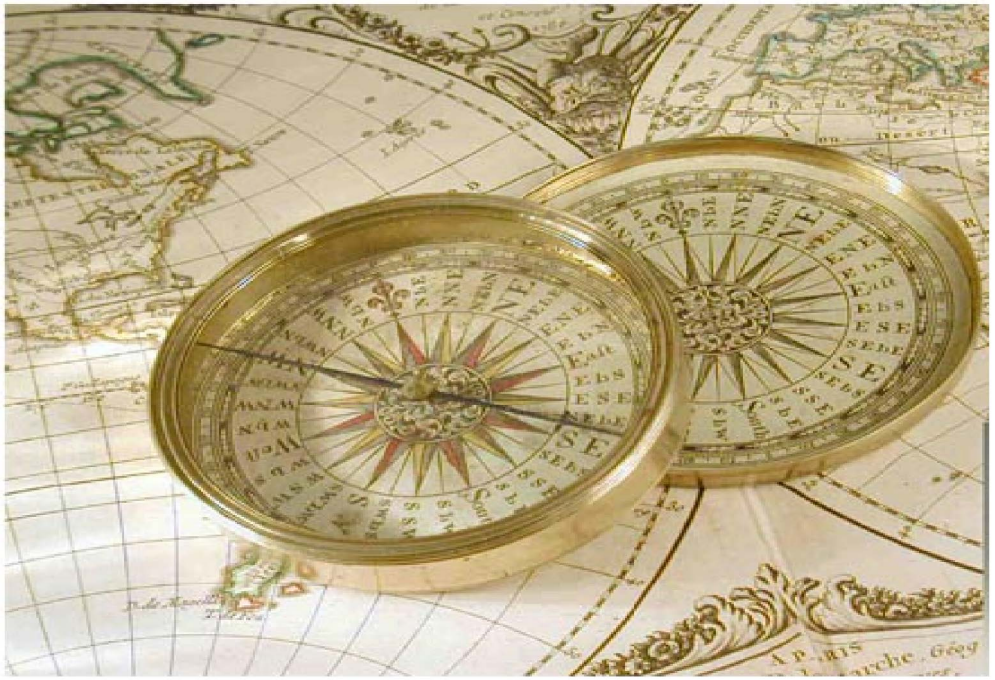
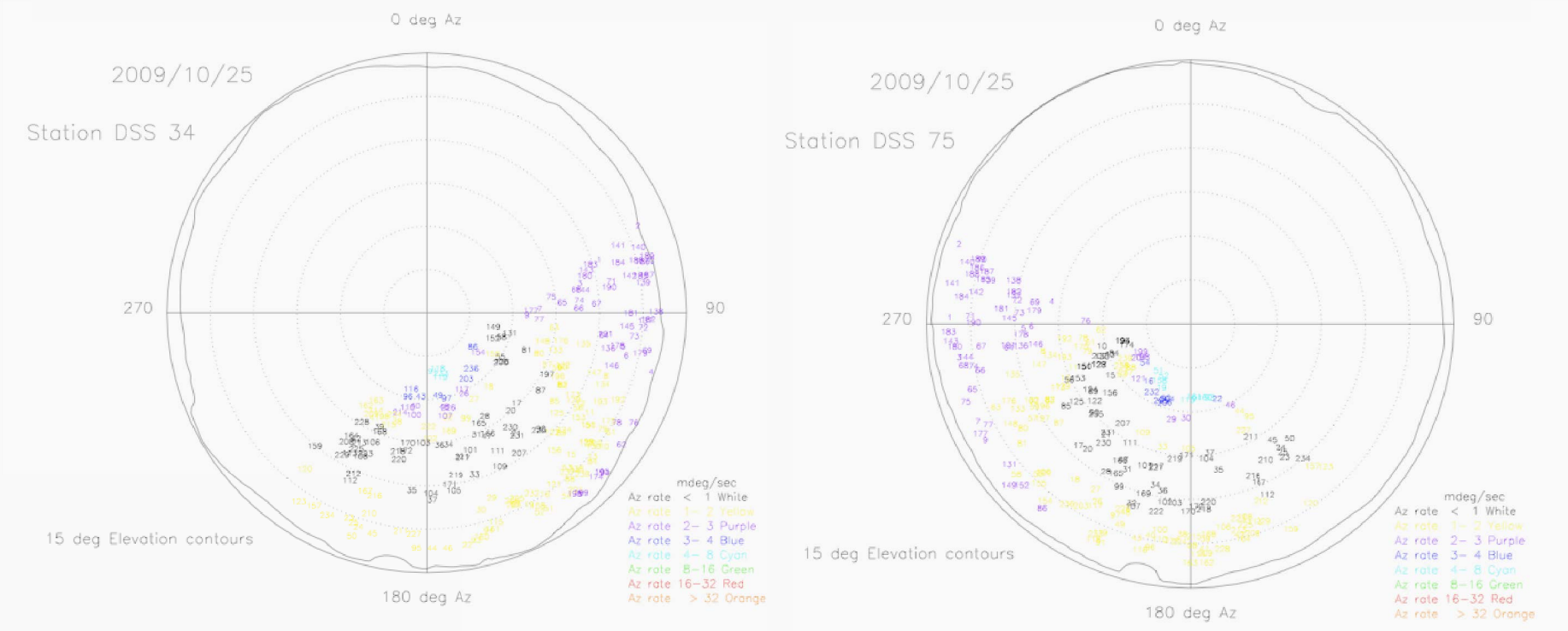
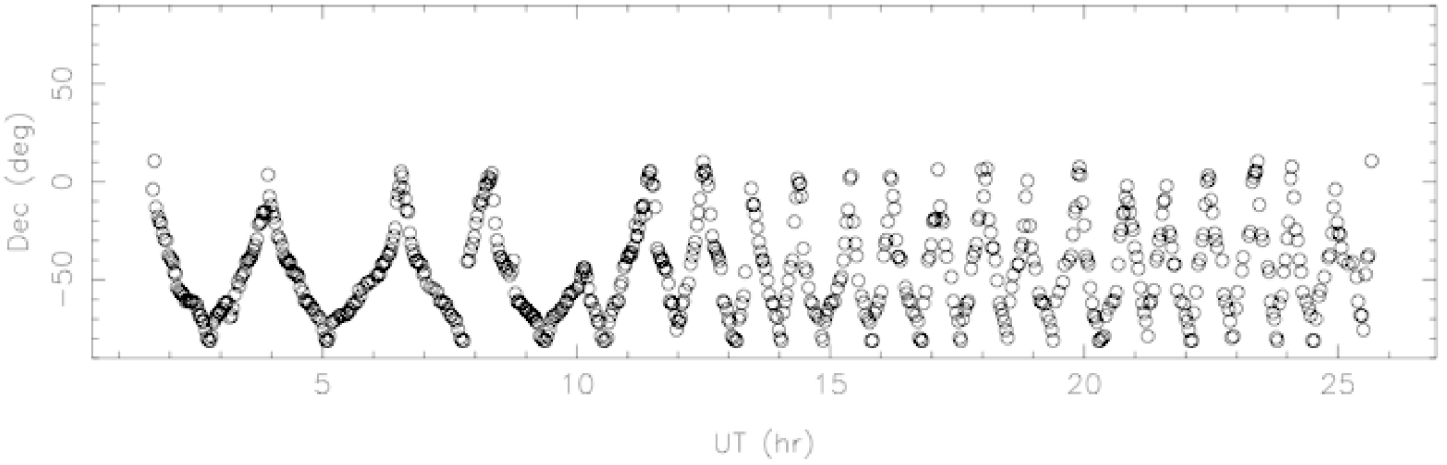


Photo credit: Tom Grill Images, tomgrill.com (www.arsmachina.com/images/compass7012-1.jpg)

DSS 34 to Malargue, Argentina (DSA-3)



Simulated Coverage:

Dec +10 deg to –90 deg