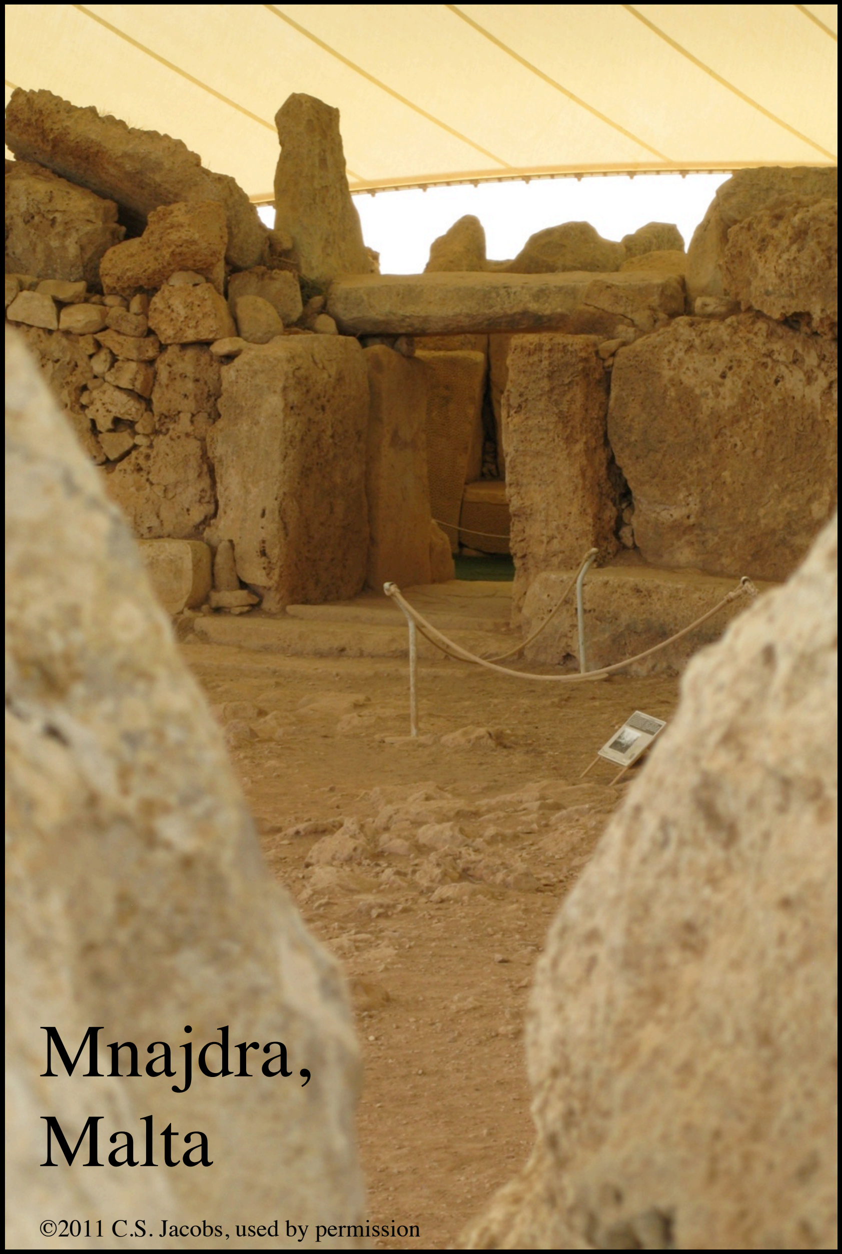

WallyPacholka / AstroPics.com

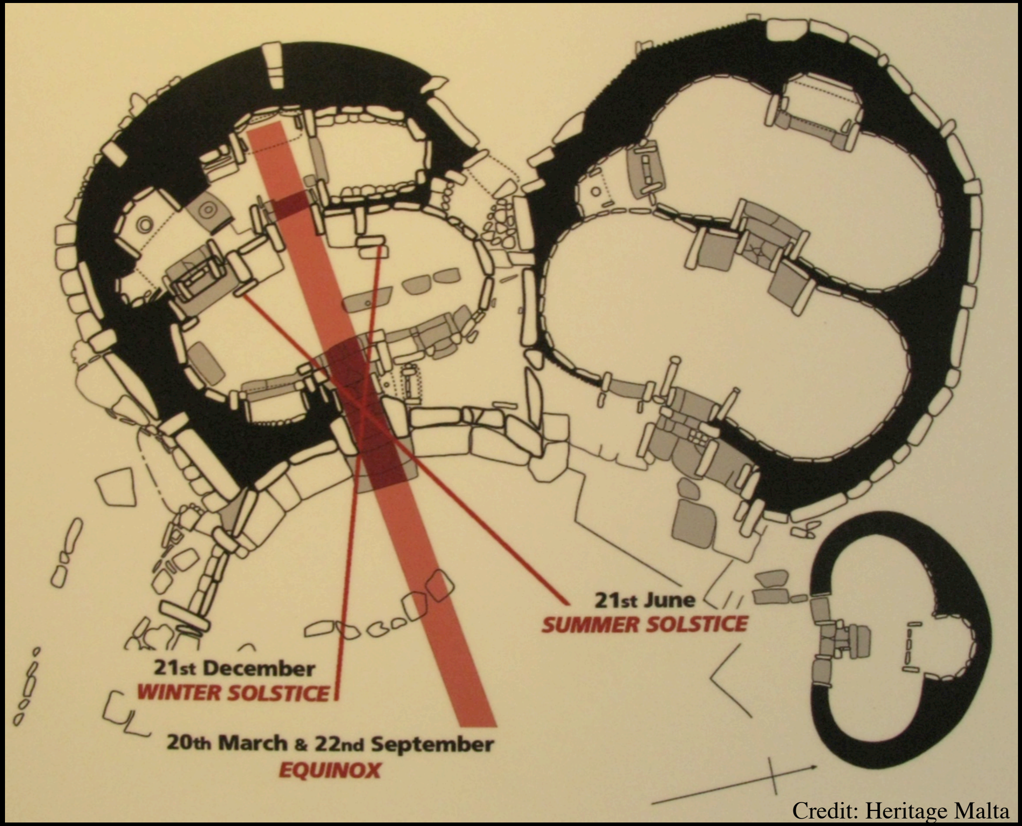
Astrometry goes back over 5000 years!

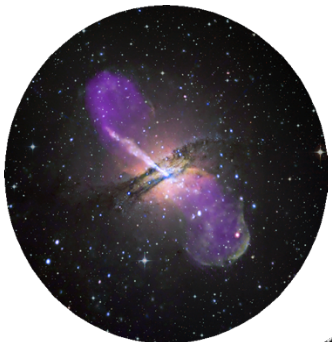


Island of Malta
Ggantija ~3500 B.C.
Mnajdra ~3200 B.C.

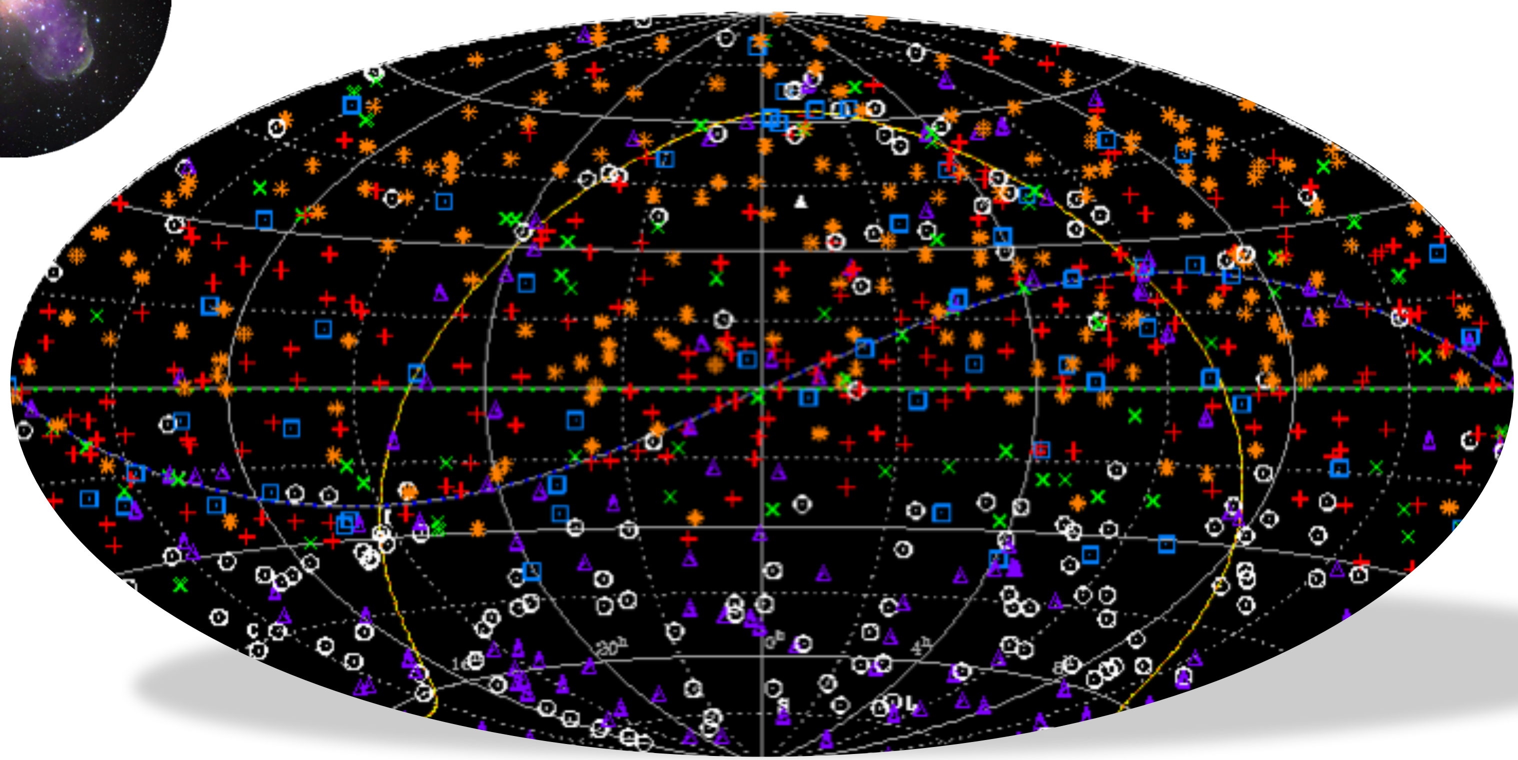
Credit: Heritage Malta

Mnajdra solar alignments





Celestial Reference Frames



Christopher S. Jacobs

Jet Propulsion Laboratory, California Institute of Technology

2018 March 21

Outline

I. Concepts and Background:

A. What is a Reference frame? Concepts, uses, desired properties

B. Networks: The instruments used to build the frame

ad hoc, VLBA, EVN, Global, NASA-ESA DSN, LBA, AuScope, etc.

C. Brief history of Astrometry: The ‘fixed’ stars aren’t so fixed.

1. Precession, proper motion, nutation, parallax
2. Invention of radio astronomy. VLBI’s pursuit of (sub)milli-arsecond accuracy.

II. Celestial Frames built using *Very Long Baseline Interferometry* (VLBI)

A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS

B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)

C. Higher frequency radio frames: K&Q (24 & 43GHz), X/Ka (32 GHz)

III. The Path to the Future:

A. Error Budgets: a tool for allocating resources for improvement

B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame

C. ICRF-3: the next standard radio frame

D. Gaia: an optical frame with high accuracy, billion sources

I. A. Concepts for Celestial Frames

1. **Questions:**
   Why do we need reference frames? Celestial Frames?
   Time, positions, velocities

2. **The Celestial Frames**
   Terrestrial: Azimuth, Elevation
   Equatorial plane: Right Ascension & Declination
   Ecliptic Plane: Ecliptic Longitude & Latitude
   Galactic Plane: Galactic Longitude & Latitude

3. **Inertial Frames**
   approximate point sources at infinity
   No rotation
   No acceleration
   Quasi-inertial

I. A.1 Why a Celestial Frame?

Questions:
Why do we need reference frames? Celestial Frames?

To measure Time, positions, and velocities

Time: The rotation of the earth

Positions & velocities:
Angular positions and distances of
Quasars, galaxies, stars, planets, spacecraft

I. A.2 The Celestial Sphere

Preferred Frame changes with scale and application

- Local terrestrial: Elevation, Azimuth
  Local gravity or normal to horizon gives preferred direction
  Useful for antenna pointing

- Equatorial plane: Right Ascension & Declination
  Earth's spin gives preferred direction

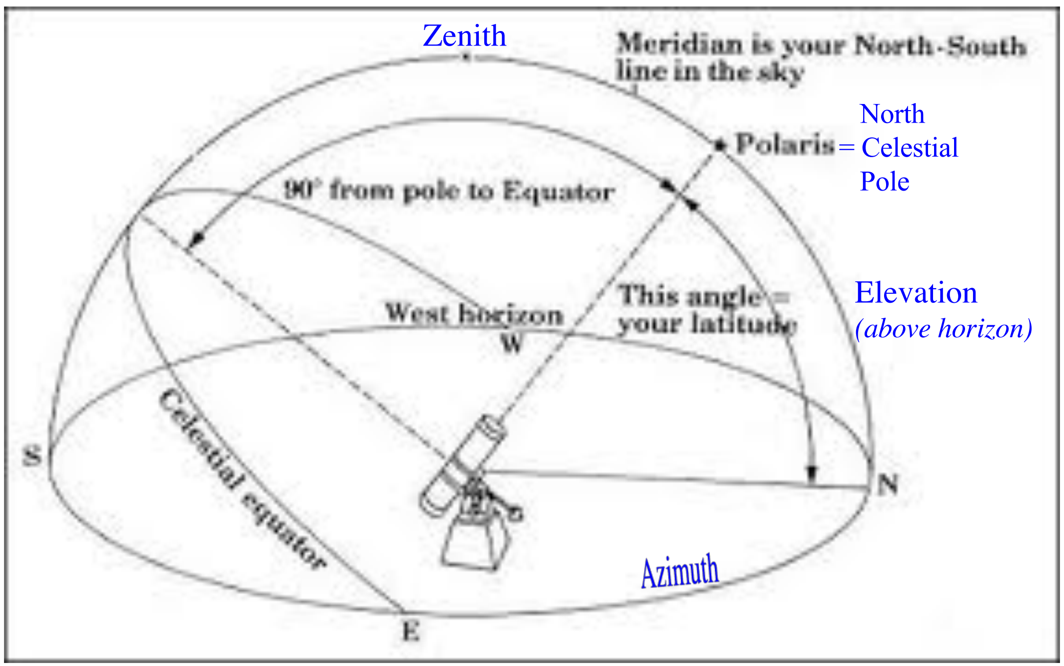
- Ecliptic Plane: Ecliptic longitude & latitude
  plane of solar system, planetary orbits
  useful for studying the solar system and
  inter-planetary navigation

- Galactic Plane: Galactic Longitude & latitude
  plane of Milky Way galaxy
  Useful for pulsars, masers, rotation curves…

- Even larger structure: local group of galaxies, Virgo cluster, …

I. A.2 Local Horizon: Azimuth, Elevation

- Local terrestrial: Elevation, Azimuth
  Local gravity or normal to horizon gives preferred direction
  Useful for antenna pointing

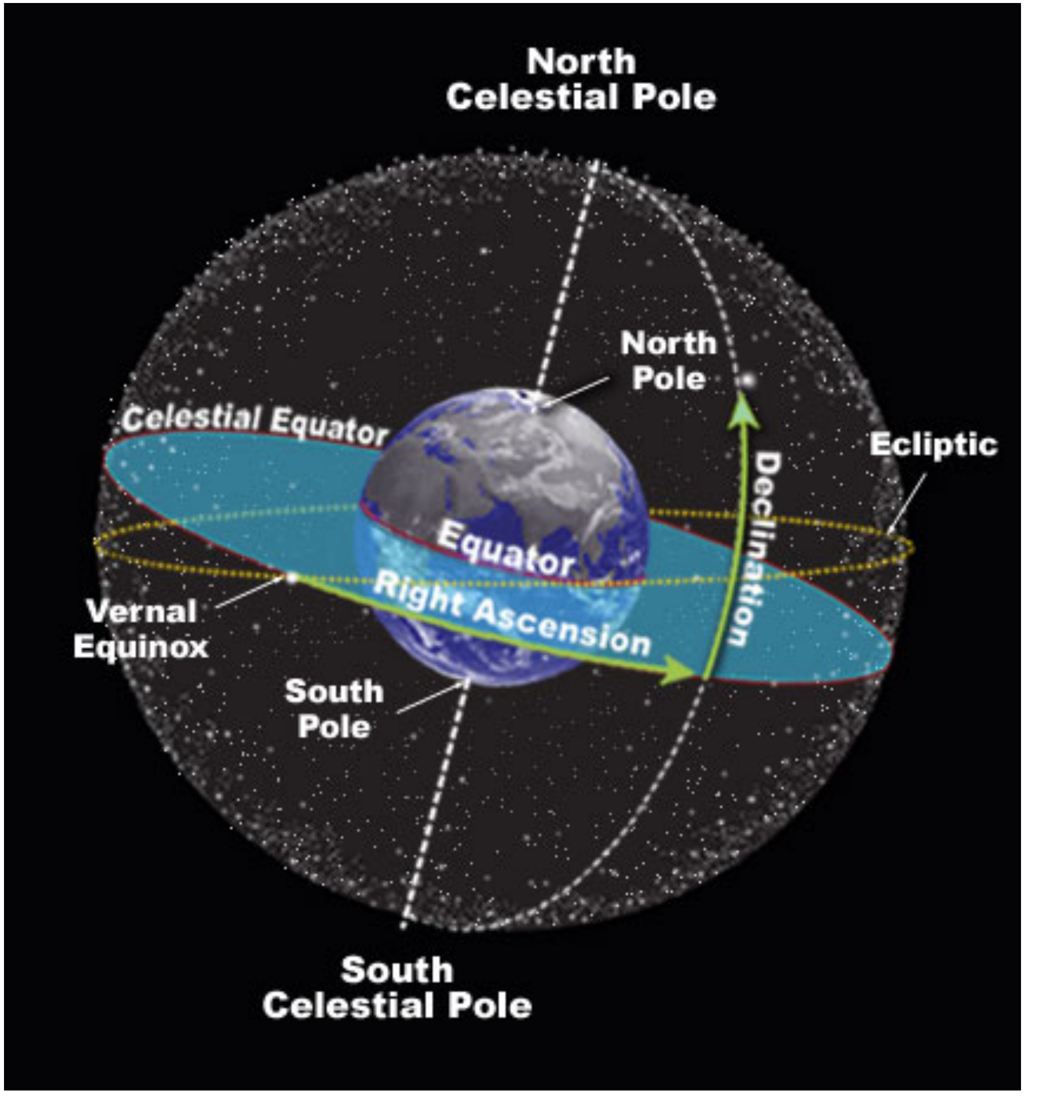


I. A.2 The Celestial Sphere

Equatorial System:
Earth's spin axis gives preferred direction, the celestial pole

Coordinates on the sky:
Right Ascension ("longitude")
Declination ("latitude")

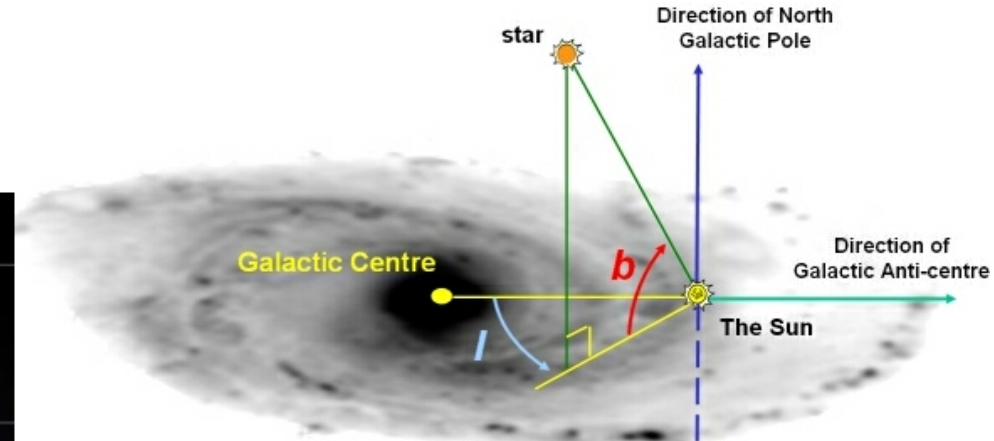
Ecliptic Plane:
Ecliptic Longitude &
Ecliptic Latitude
plane of solar system
useful for studying the solar system and inter-planetary navigation



Credit: http://www.daviddarling.info/encyclopedia/C/celsphere.html

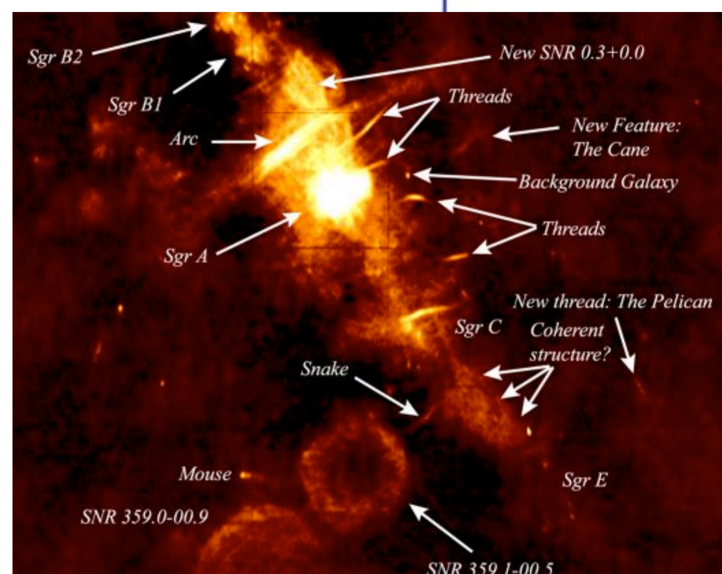
I. A.2 The Celestial Sphere

- Galactic Plane: Galactic Longitude, l, & Galactic latitude, b
  Useful for pulsars,
  masers, rotation curves…



http://astronomy.swin.edu.au/cosmos/N/North+Galactic+Pole

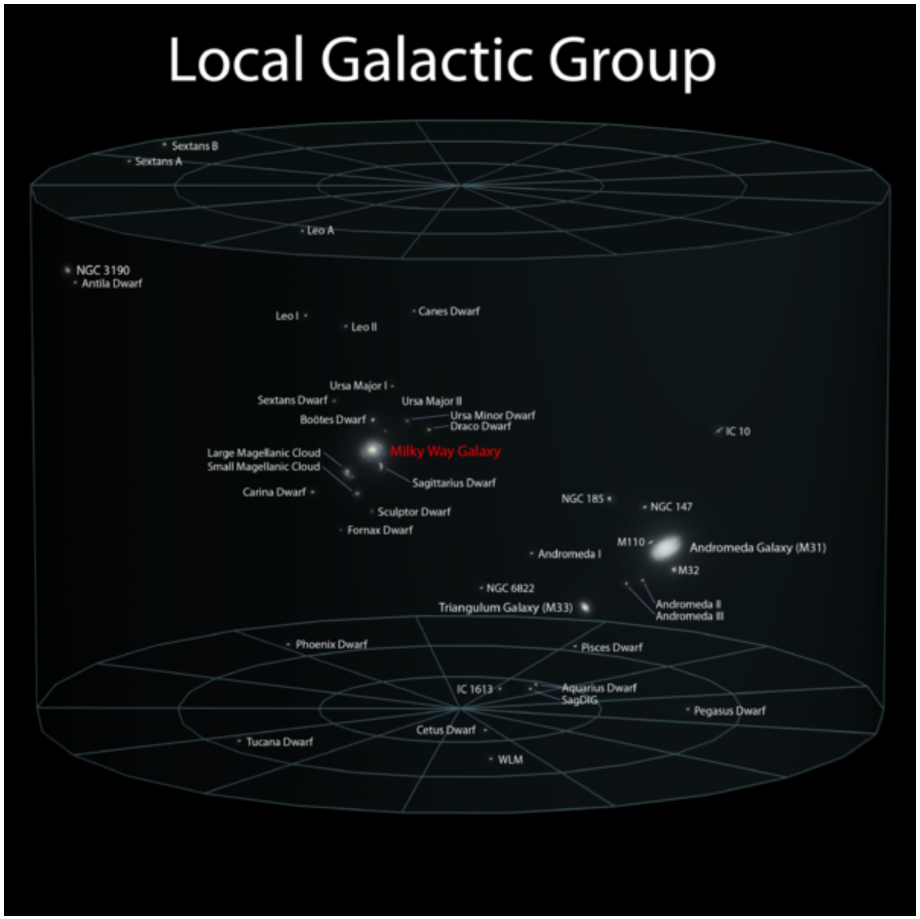
Credit: Robert Hurt & NASA
http://tracingknowledge.wordpress.com/tag/milky-way/

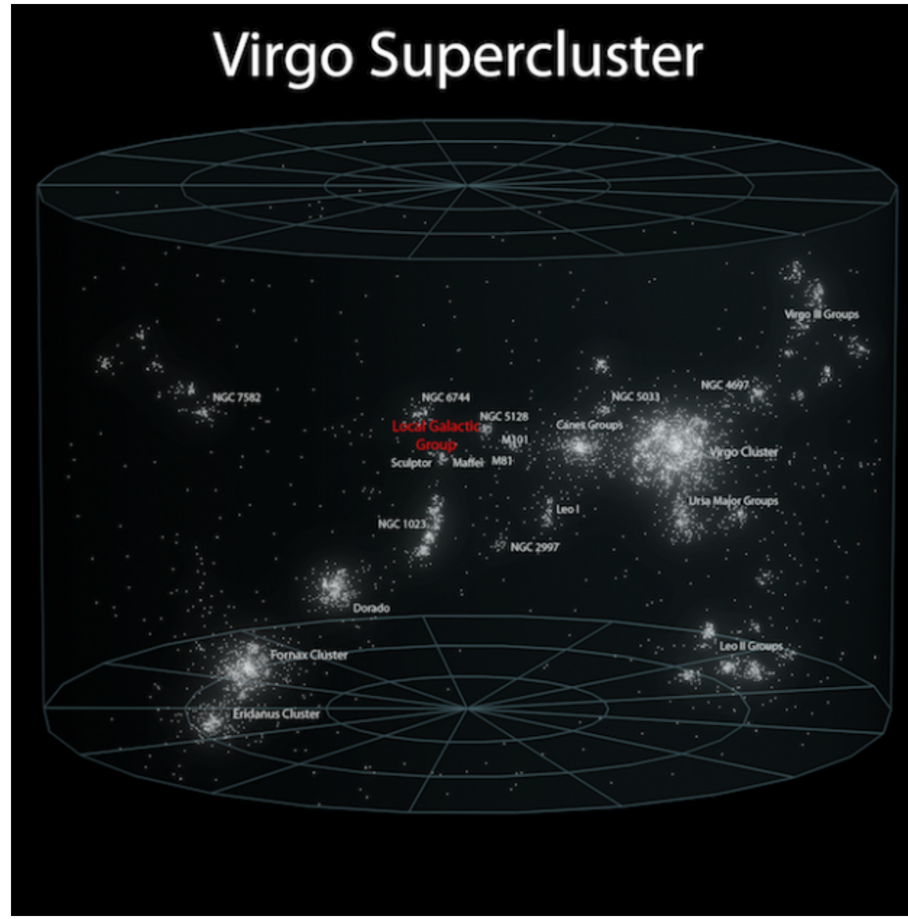


Galactic center: VLA radio image
Kassim, NRAO. http://images.nrao.edu/326

I. A.2 The Celestial Sphere

- How far before we get to the quasars? Even larger structures: local group of galaxies, Virgo cluster, Virgo super cluster…



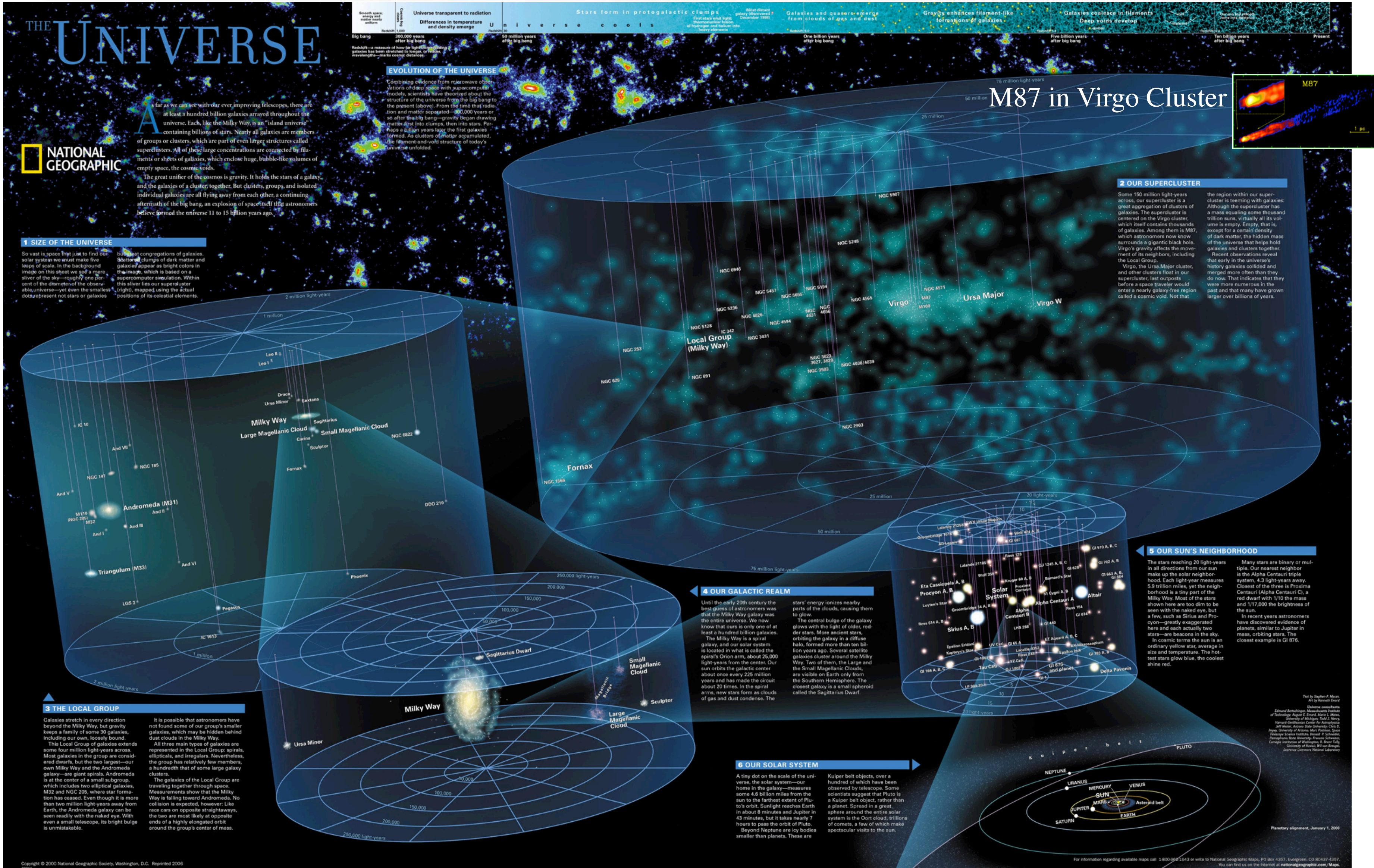


~3 Million light years

~100 Million light years

Credit: Andrew Z. Colvin
http://commons.wikimedia.org/wiki/File%3AEarth's_Location_in_the_Universe_(JPEG).jpg

Quasars ~ Giga-parsec; Virgo cluster distance (50 Mpcs)



M87 in Virgo Cluster

Diagram credit: National Geographic

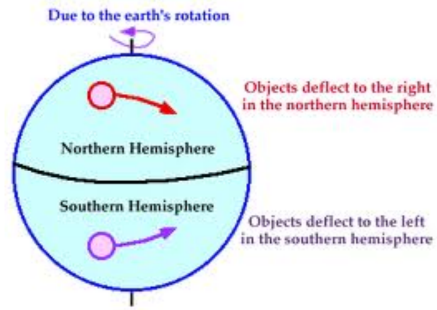
I. A.3 Inertial Frames

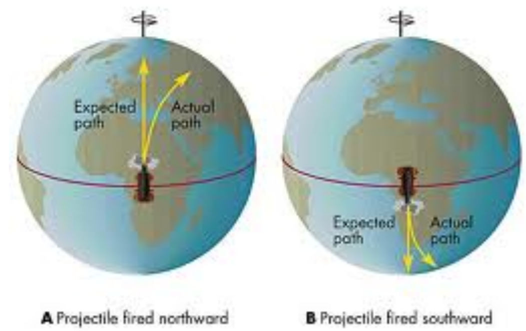
- Why an Inertial Frame?

  Make the calculations easy! Avoid Coriolis forces etc.

  No rotation

  No acceleration





Univ. Illinois WW2010 Project
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/fw/crls.rxml

- Quasi-inertial

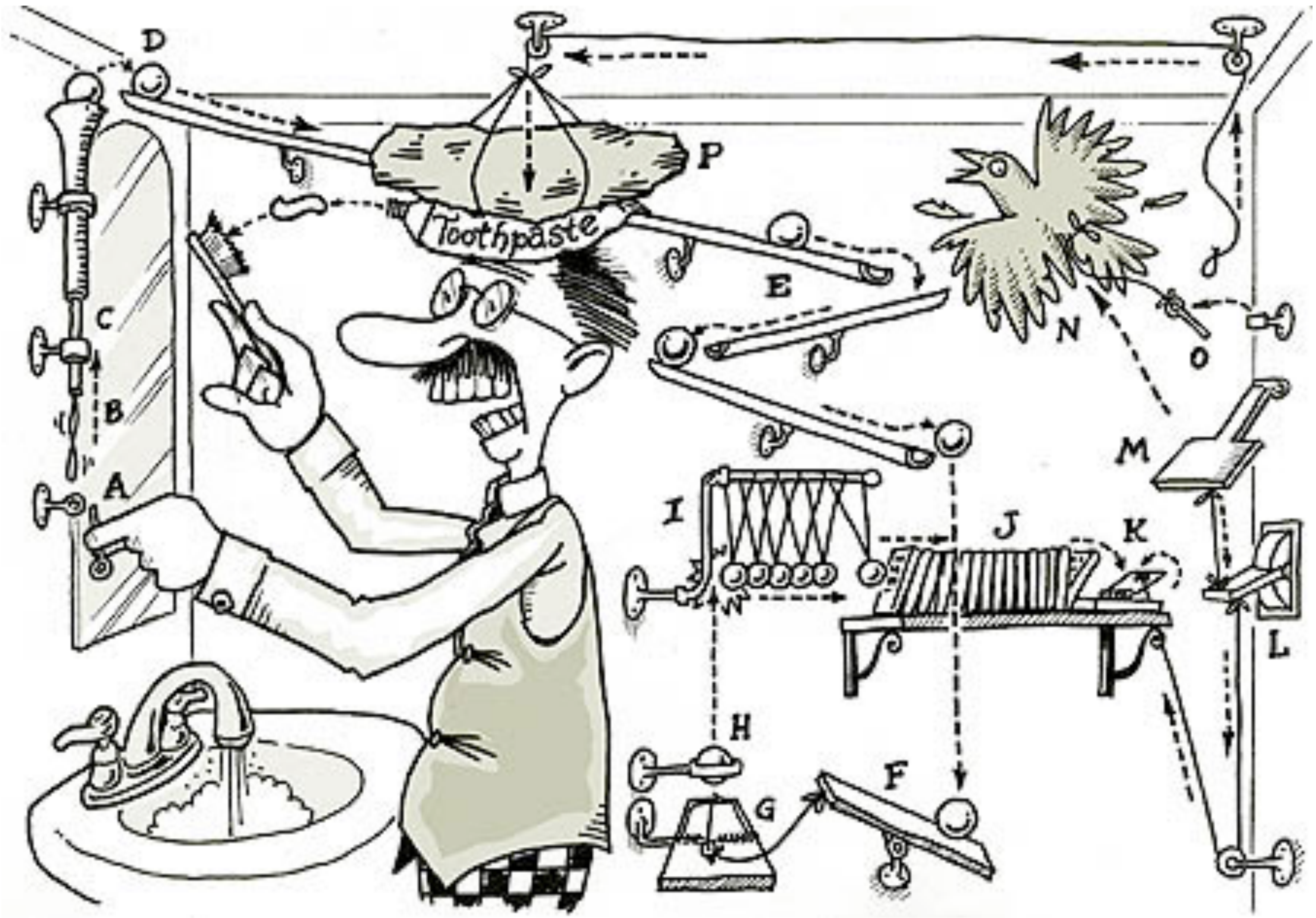
  In real systems we have some unmodeled accelerations

  At present, VLBI doesn't yet model acceleration toward the Galactic center, but this is being studied

  e.g. Titov et al http://arxiv.org/pdf/1301.0364v1.pdf

- VLBI uses quasi-inertial frame with origin at the Solar System Barycenter (center of mass)

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



Cartoon credit: Rube Goldberg

Figure: www.vedicsciences.net/intelligent/rube-goldberg.jpg

How Does VLBI Work?

Combine signals
from a
Phased Array

Antennas are Mechanical Arrays

Single Large Dish is an “array” of panels aligned mechanically. Note side lobes.

Imagine removing inner panels, then beam pattern changes, sidelobes rise, but center lobe still has high resolution ~ wavelength / D

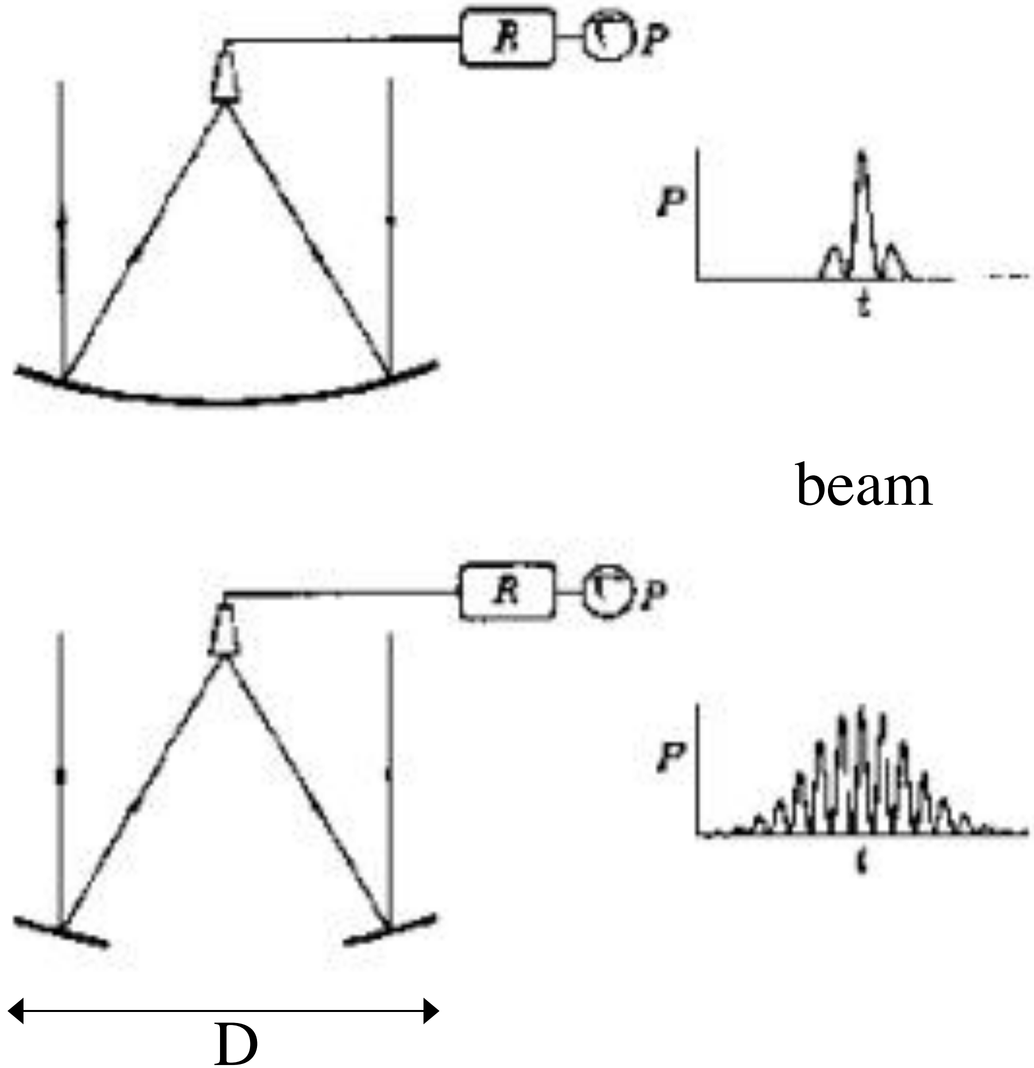
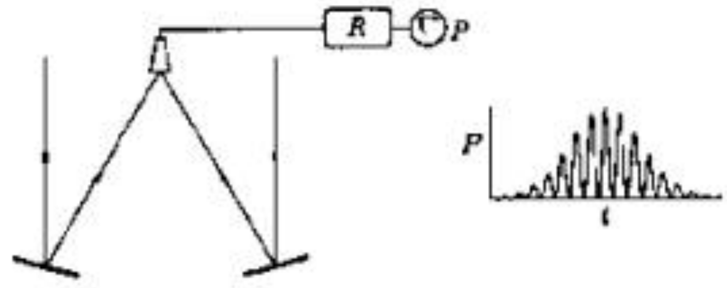


Figure credit: H. Gush

Mechanical → electrical alignment → VLBI

Two segments of antenna

b)



"Fringes"

Two separate antennas with Electrical Connection

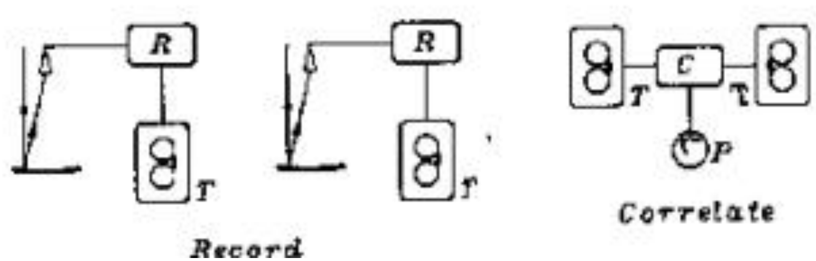
c)

Same fringes as b).

Unconnected Antennas = VLBI

Time tag data and combine signals later at correlator

d)



Same fringes as b).

Figure credit: H. Gush

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

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

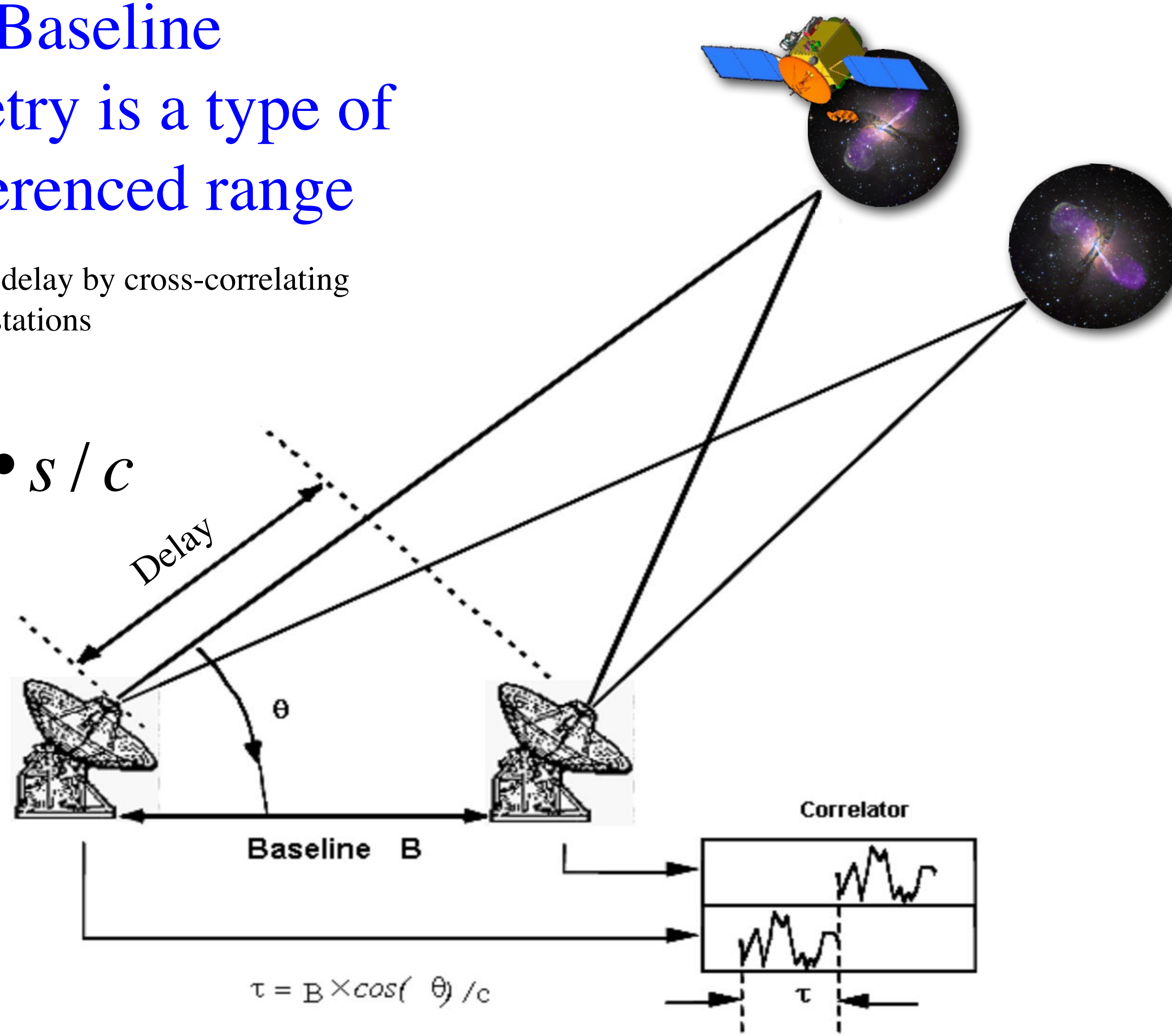


Fig. credit: J.S. Border, J. Patterson

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I.B. Observing Networks

VLBA

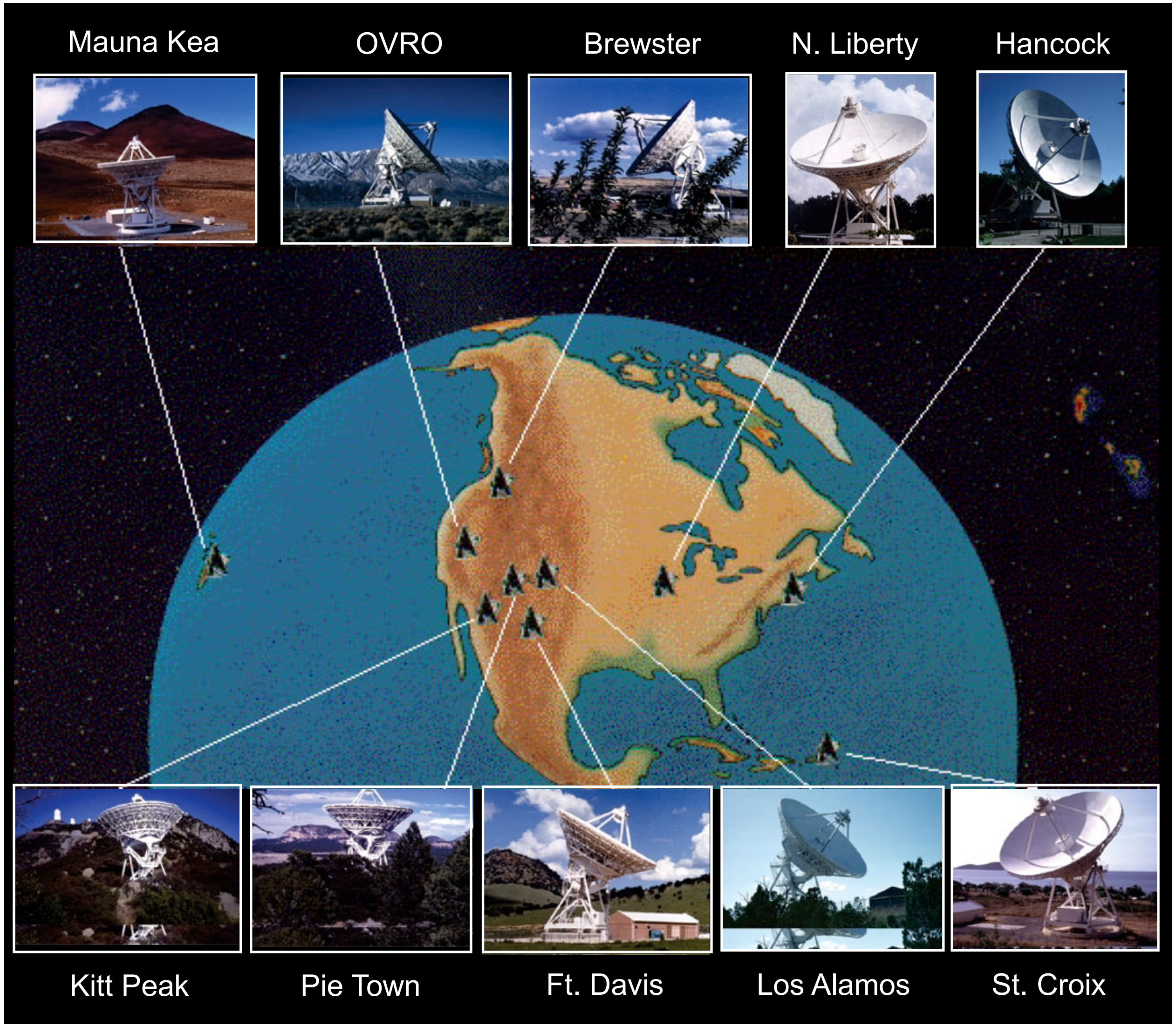
S/X VCS catalog
K, Q catalogs

25-meter dishes

10 stations

Baselines up to 8000 km

No southern stations



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

I.B. Observing Networks: EVN

EVN

S/X-band
K-band

Inhomogeneous
set of antennas

+ HartRAO,
South Africa

European VLBI Network http://www.evlbi.org/

I.B. Observing Networks: Global

Map credit: Tae-Hyun, Jung (MPIfR, 2004)
http://www3.mpifr-bonn.mpg.de/staff/tkrichbaum/Global-VLBI.html

Ka-band combined NASA/ESA Deep Space Net

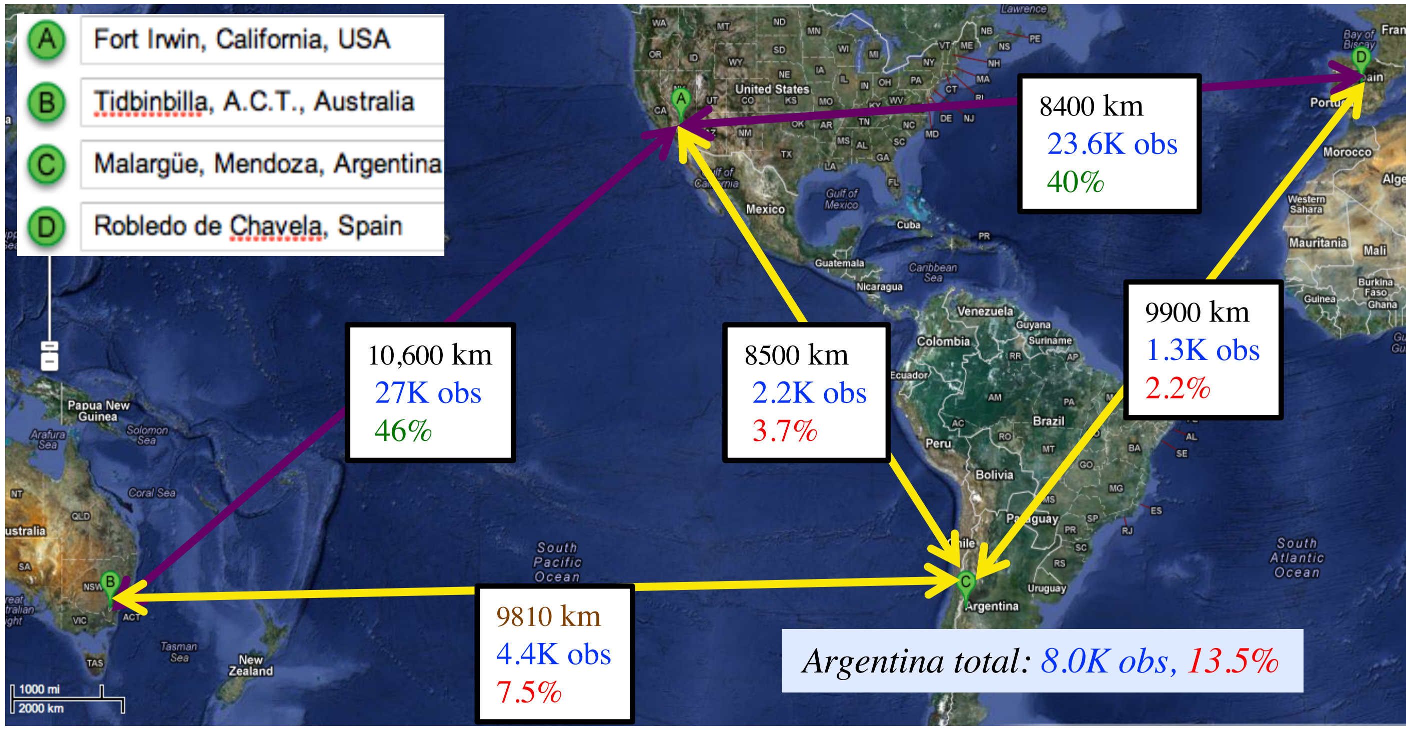
ESA Argentina to NASA-California under-observed by order of magnitude!

Baseline percentages

- Argentina is part of 3/5 baselines or 60% but only 13% of obs
- Aust- Argentina 7.5%
- Spain-Argentina 2.2%
- Calif- Argentina 3.7%

This baseline is under-observed by a factor of ~ 12.

More time on ESA's Argentina station would have a huge, immediate impact!!



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

I.C. History of Astrometry

130 B.C.	Hipparchus	Precession		50 asec/yr
Telescope era:				
1718 A.D.	Halley	proper motions		1 asec/yr
1729	Bradley	annual aberration		20 asec
1730	Bradley	18.6yr nutation		9 asec
1838	Bessell	parallax		~ asec
1930s	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		70 μas for Vmag=18 quasar
2010s	ICRF-3, ESA-DSN XKa			20-70 μas? 0.3 Jy quasar

Paradigm of "Sailing by the stars"

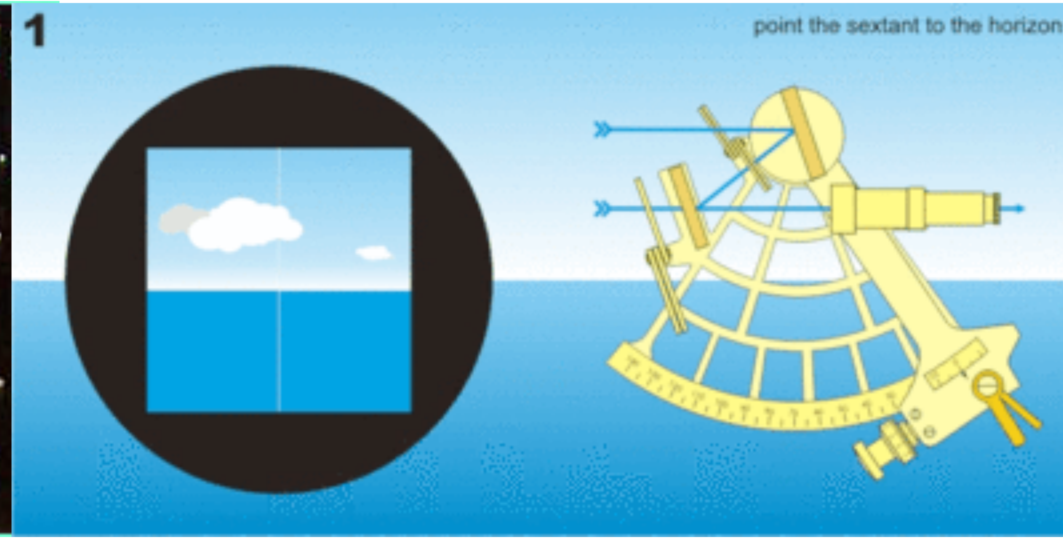


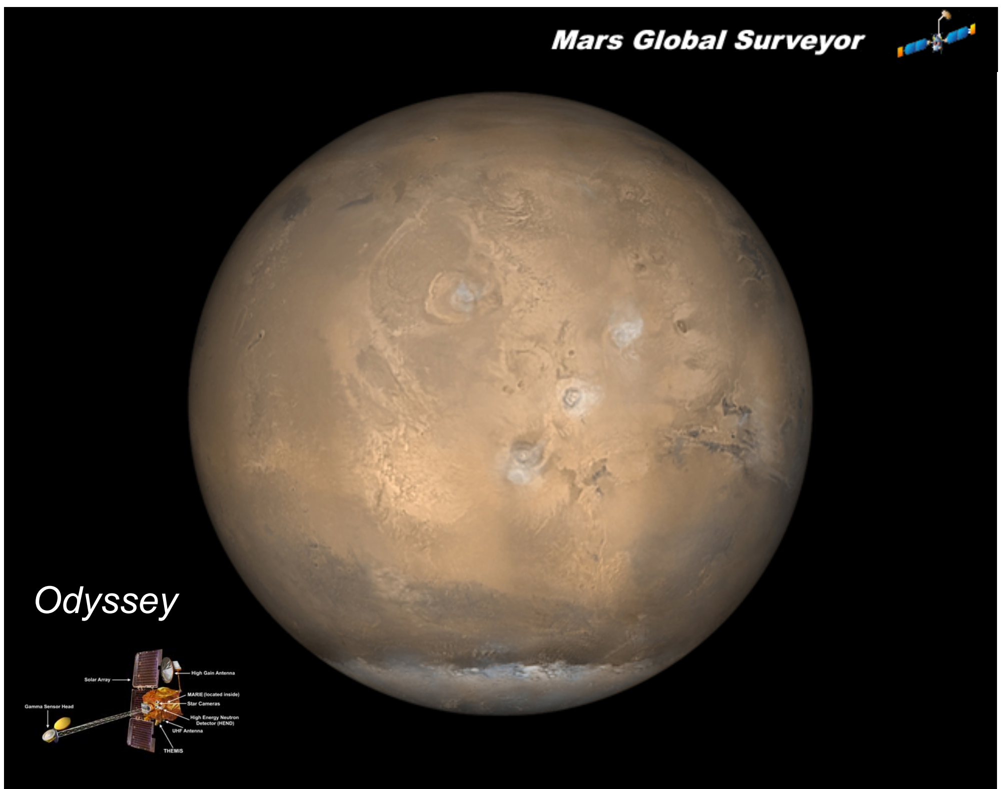
Photo Credit: Dimitry Bobroff, www.ludmillaalexander.com

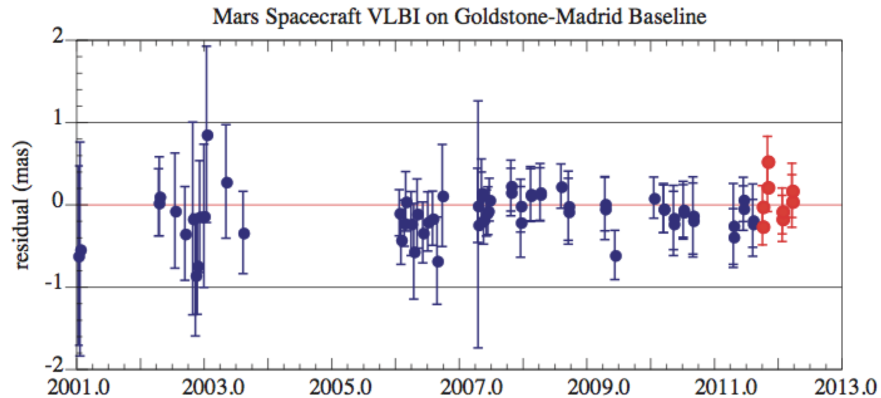
Credit for sextent/octant: en.wikipedia.org/wiki/Sextant (GNU Free Doc license)

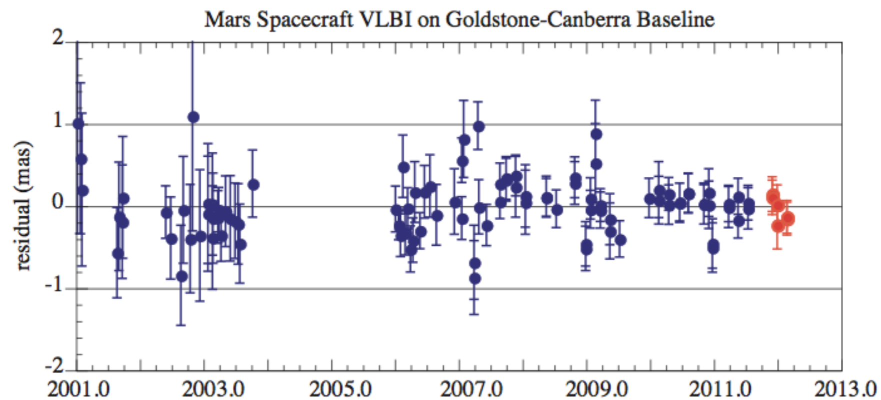
Planetary Ephemeris to ICRF Frame Tie

- ΔVLBI measurements of spacecraft around a planet obtains position in the ICRF frame

- Doppler and range measures spacecraft in planet center Frame.





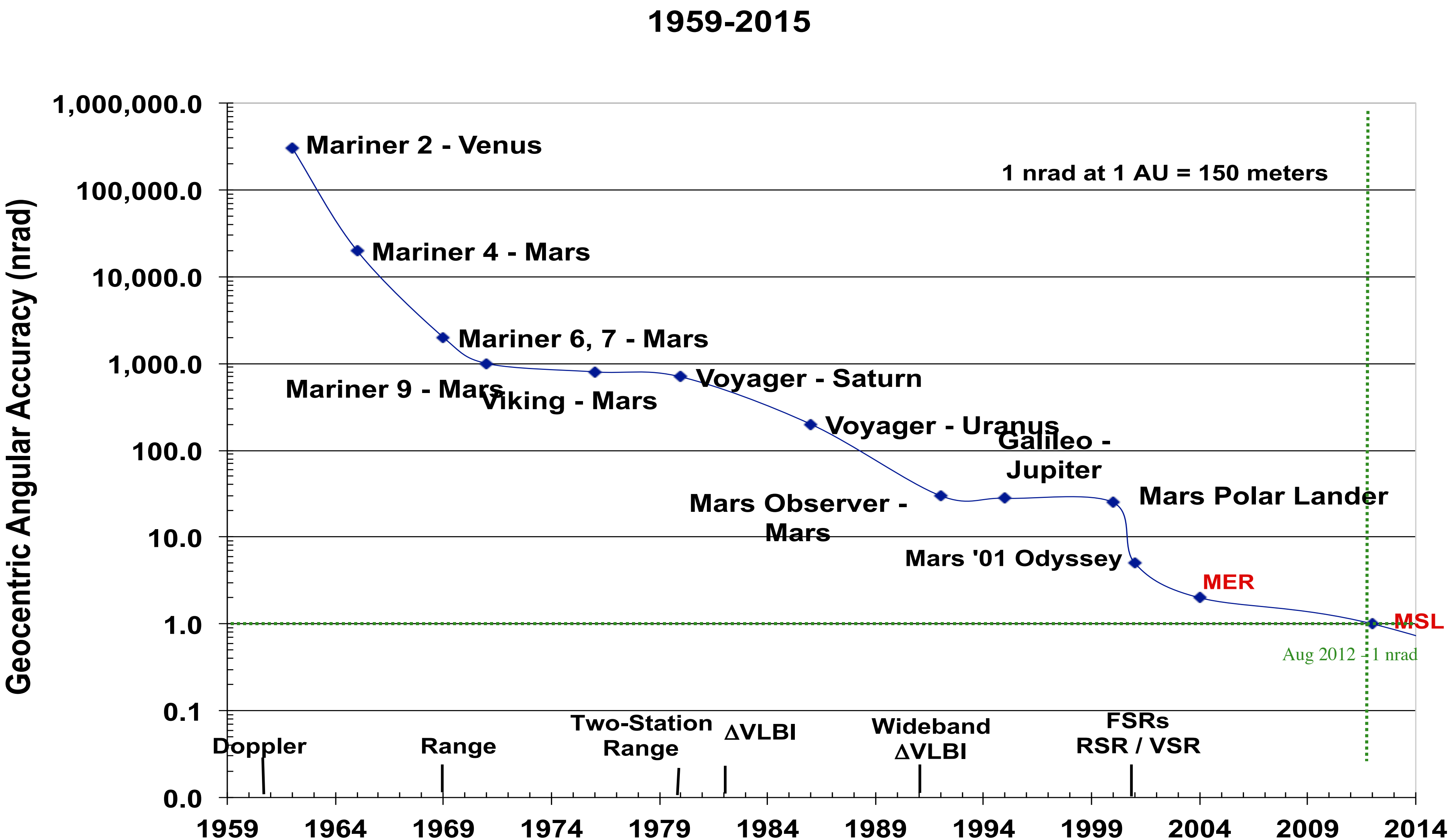


Folkner et al, IAU, Aug. 2012
200 μas (1. nrad) residuals

http://referencesystems.info/uploads/3/0/3/0/3030024/folkner.pdf
http://adsabs.harvard.edu/abs/2012IAUJD...7E..36F

Credit: NASA, JPL/Caltech: www.jpl.nasa.gov

NASA Navigation System Accuracy



Credit: J.E. Patterson, J.S. Border, C.S. Jacobs

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

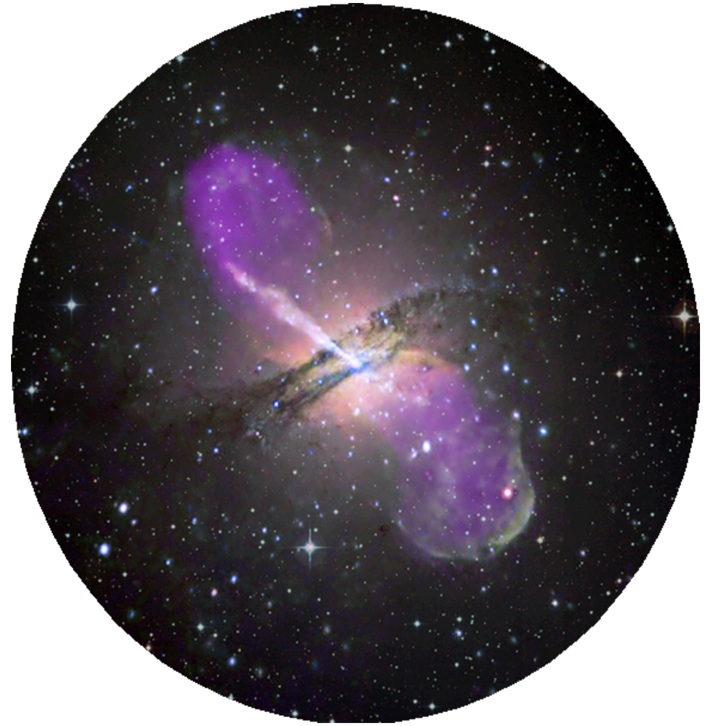
  Laplace (1749-1827) and

  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**

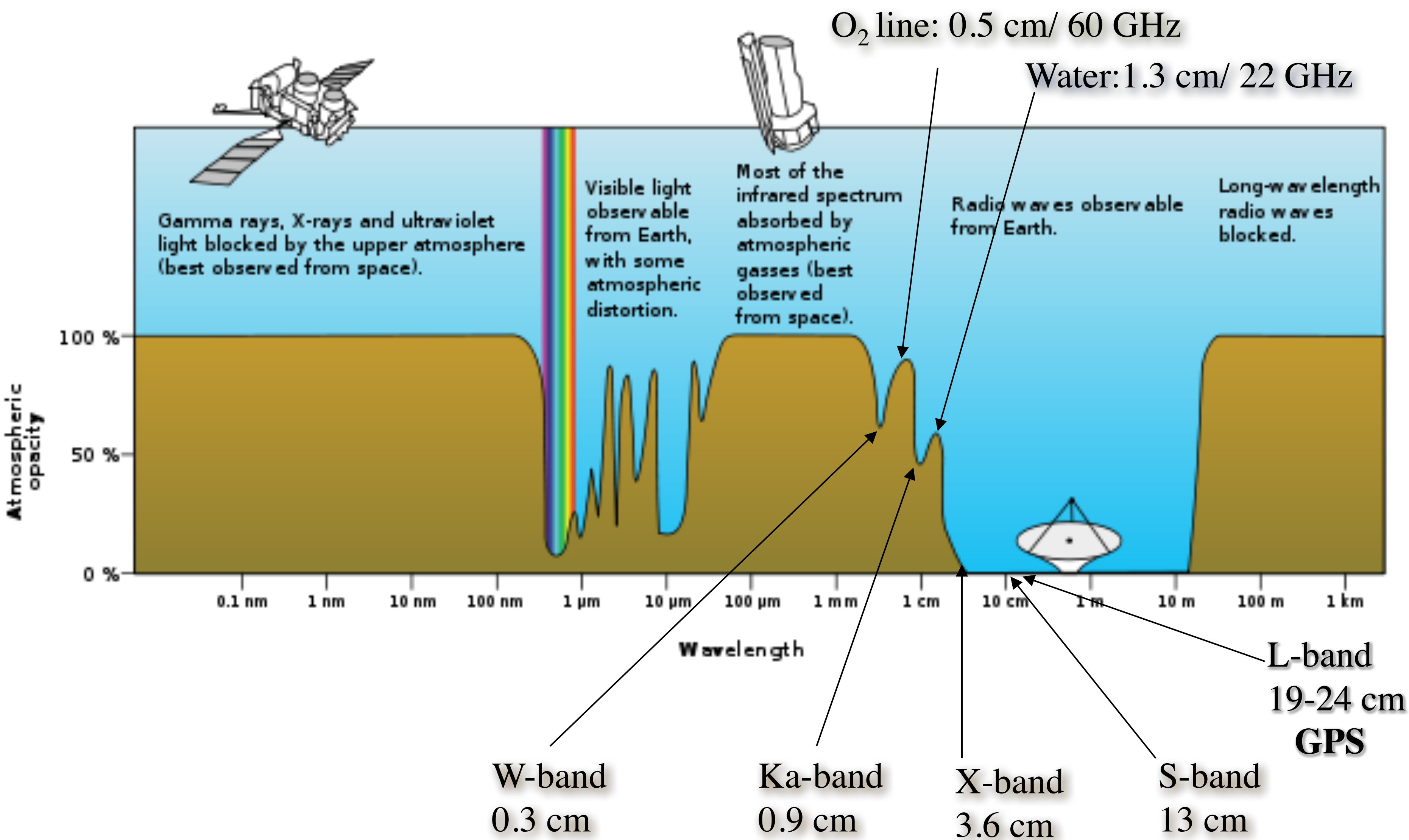
  Very weak sources **1 Jy = 1.0E-26 watt/m**2/Hz**

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

  lots of Hz bandwidth => 0.1 to 4 Gbps

  low system temperature => Tsys = 20 - 40 Kelvin

Why observe in Radio? The 'Window'



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

Why observe in Radio? Resolution

- Resolution of diffraction-limited telescope:
  Wavelength / Diameter
  example: Hubble Space Telescope
  Wavelength 0.1 to 2.5 microns
  Diameter 2.4 meters
  Resolution = 10 to 250 mas

- Resolution for an interferometer
  Wavelength / Baseline
  Wavelengths for Celestial Frames 0.9 to 3.6 cm
  Baselines up to 10,000 km
  Resolution = 1 to 4 nanoradians = 0.2 to 0.8 mas

- Radio has 50 times better resolution than Hubble.

Why observe in Radio? Resolution

THE QUEST FOR RESOLUTION

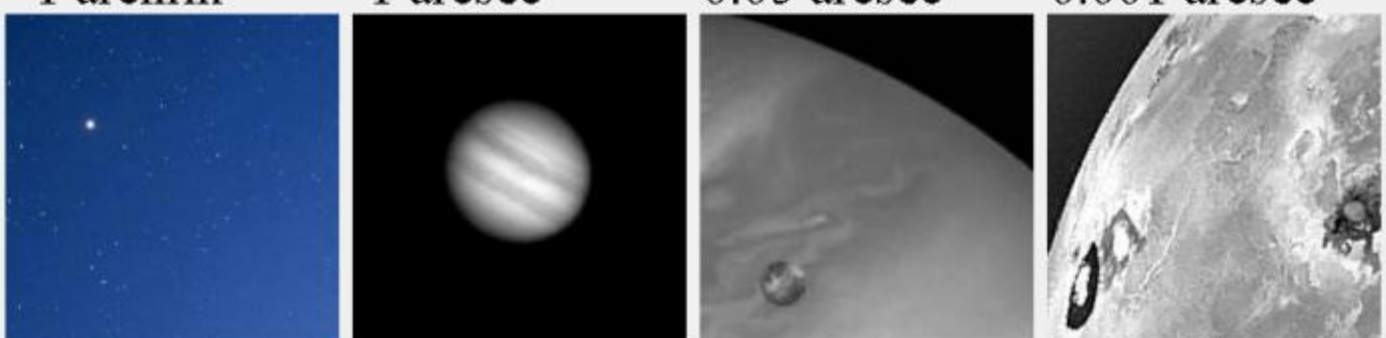
Resolution = Observing wavelength / Telescope diameter

Angular	Optical (5000A)		Radio (4cm)	
Resolution	Diameter	Instrument	Diameter	Instrument
1′	2mm	Eye	140m	GBT+
1″	10cm	Amateur Telescope	8km	VLA-B
0.″05	2m	HST	160km	MERLIN
0.″001	100m	Interferometer	8200km	VLBI

Atmosphere gives 1″ limit without corrections which are easiest in radio

Jupiter and Io as seen from Earth

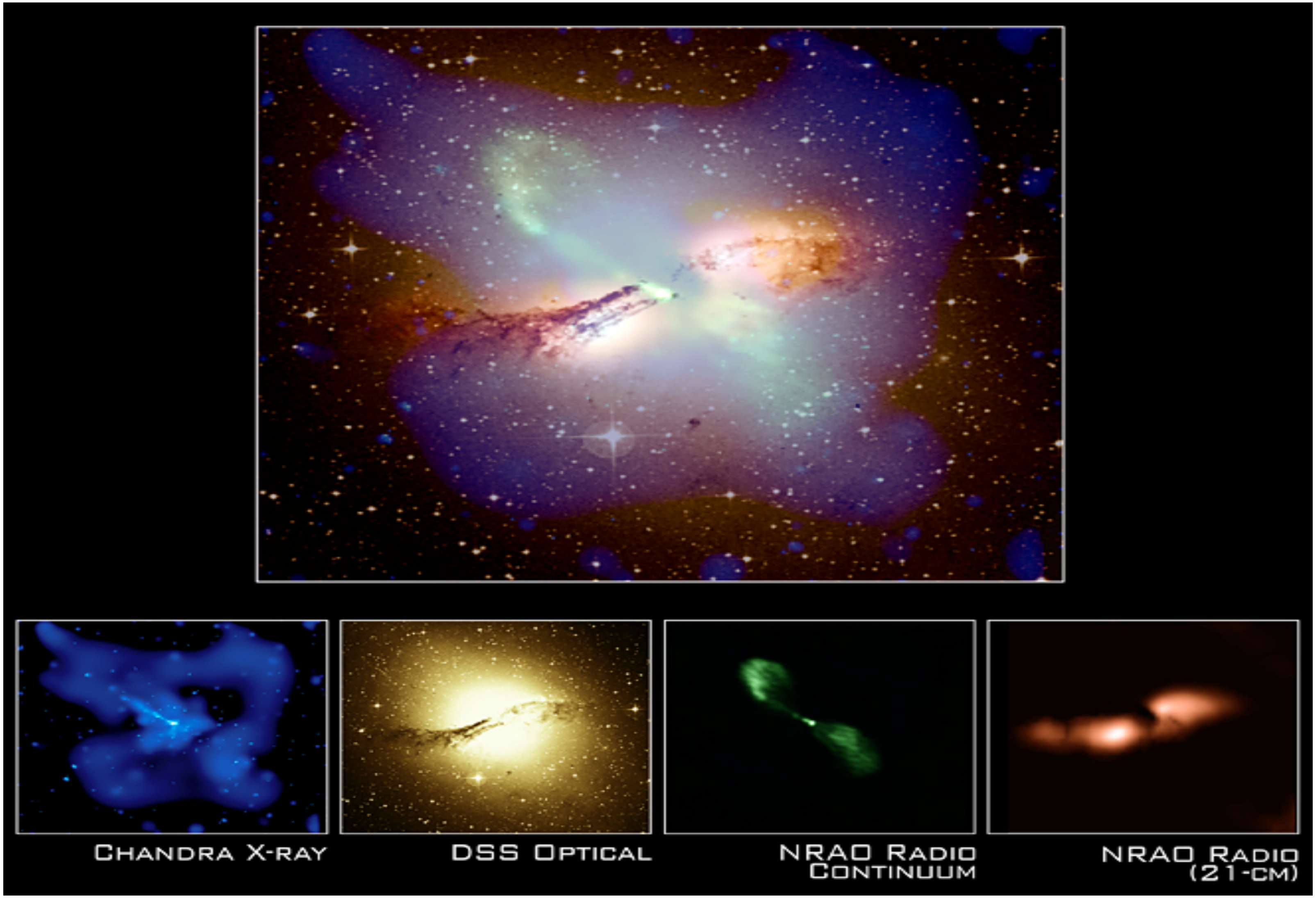
1 arcmin | 1 arcsec | 0.05 arcsec | 0.001 arcsec



Simulated with Galileo photo

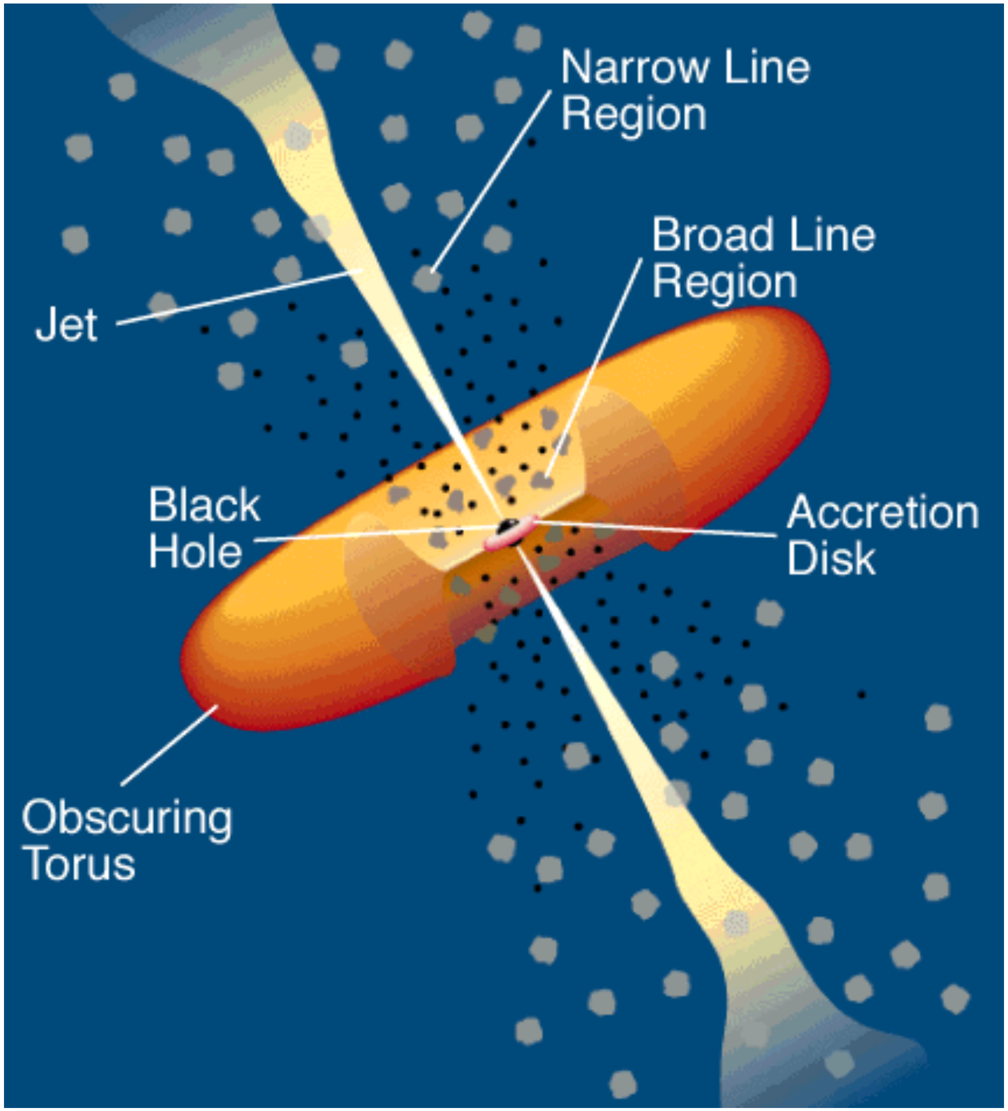
Credit: R. Craig Walker, NRAO, AAAS, 2001, http://www.aoc.nrao.edu/~cwalker/talks/aaas_2001/sld002.htm

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

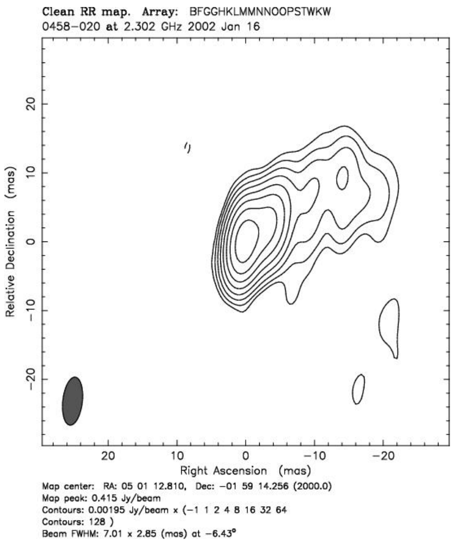
Credit: C.M. Urry and P. Padovani, 1995

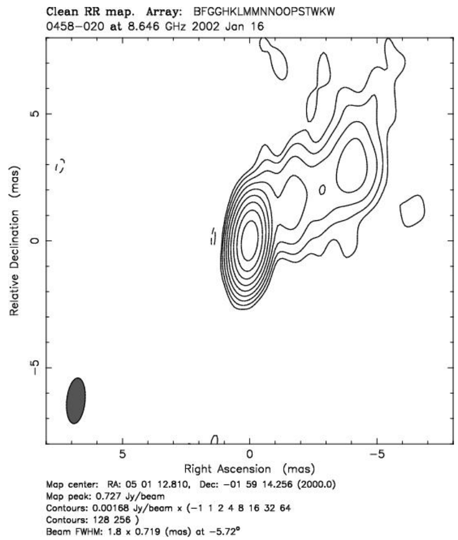
Schematic of
Active Galactic Nuclei
Redshift z~ 0.1 to 5
Distance:
billions light years
Parallax = 0
Proper motion
< 0.1 nrad/yr

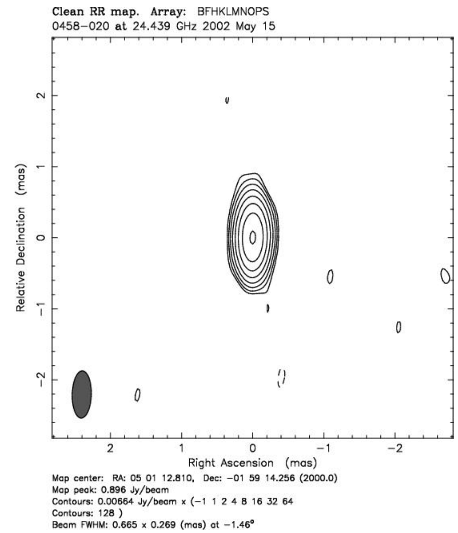
Centroid of radiation
Gets closer to central
engine (black hole)
As one goes to higher
frequencies, therefore,

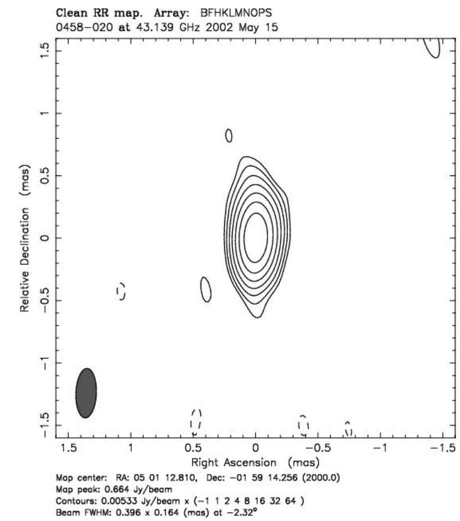
Ka-band (32 GHz)
is better than
X-band (8.4 GHz)

Source Structure vs. Frequency (scaled to beam)









S-band
2.3 GHz
13.6cm

X-band
8.6 GHz
3.6cm

K-band
24 GHz
1.2cm

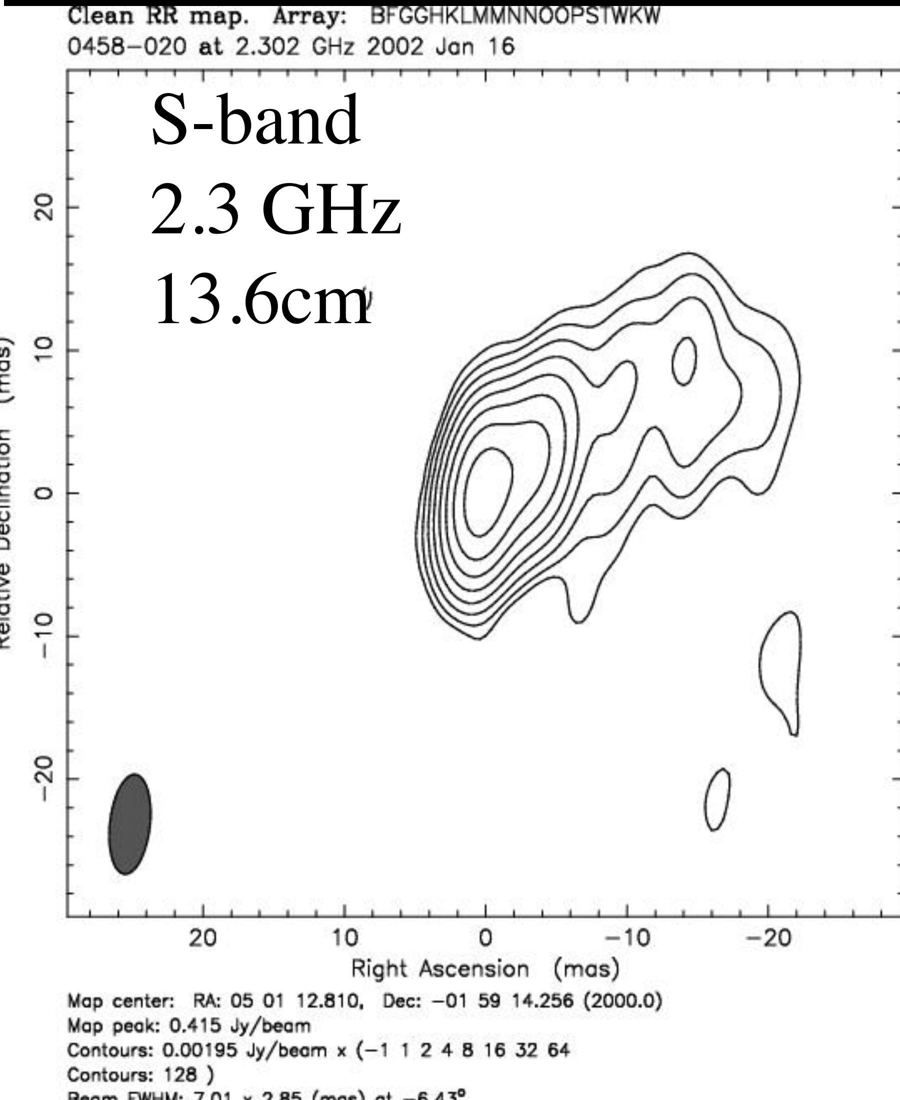
Q-band
43 GHz
0.7cm

Ka-band
32 GHz
0.9cm

The sources become better ----->

Image credits: Pushkarev & Kovalev A&A, 544, 2012 (SX); P. Charlot et al, AJ, 139, 5, 2010

Source Structure vs. Frequency (absolute scale)



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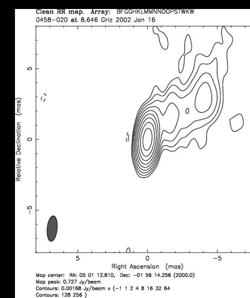
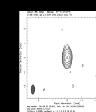
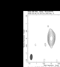






The sources become better →
smaller structure indexes
(Fey & Charlot 1997)

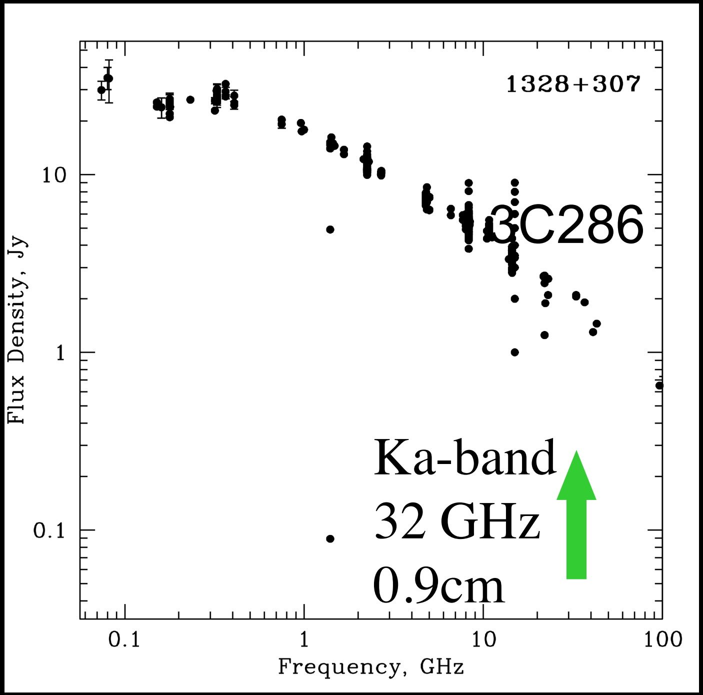
Ka-band
32 GHz
0.9cm

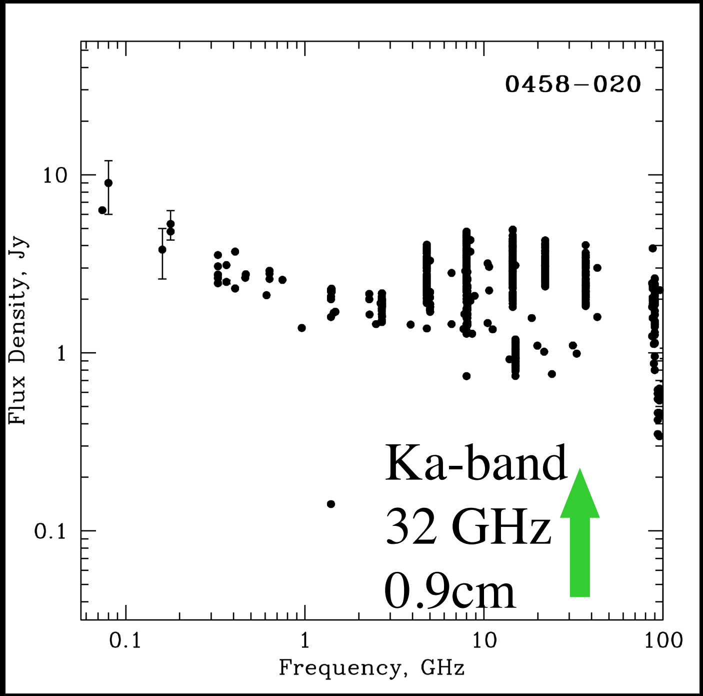
Images credit: Pushkarev & Kovalev A&A, 544, 2012 (SX); P. Charlot et al, AJ, 139, 2010

Source Flux Density vs. Frequency

Typical source emission:

Generally emission decreases with frequency (steep spectrum), but not for all sources!
and variable with time, but not for all sources!

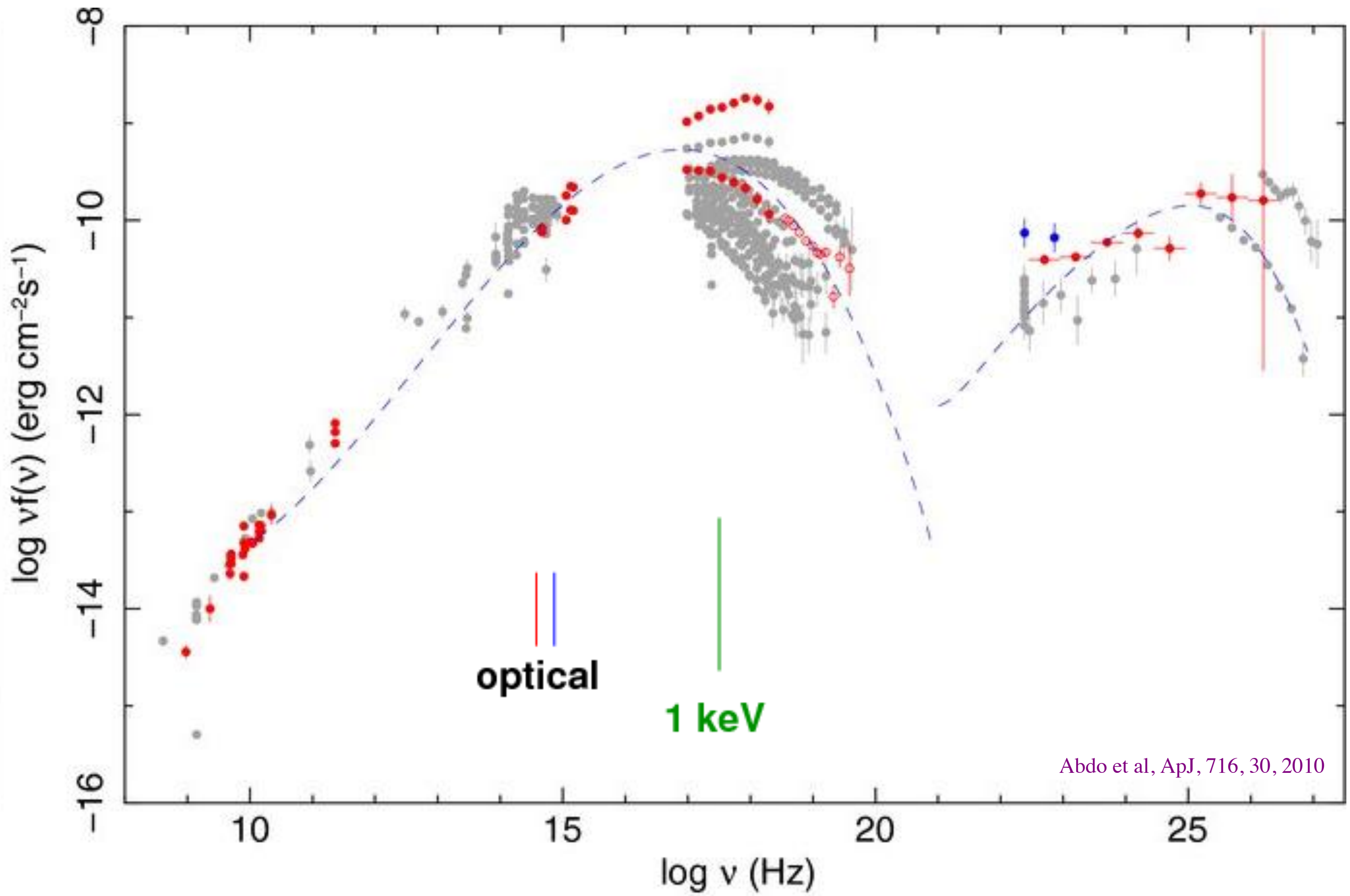




Images credit: MOJAVE project, Lister et al, AJ, 137, 2009

Credit: Garcia-Miro et al, EVN, 2014

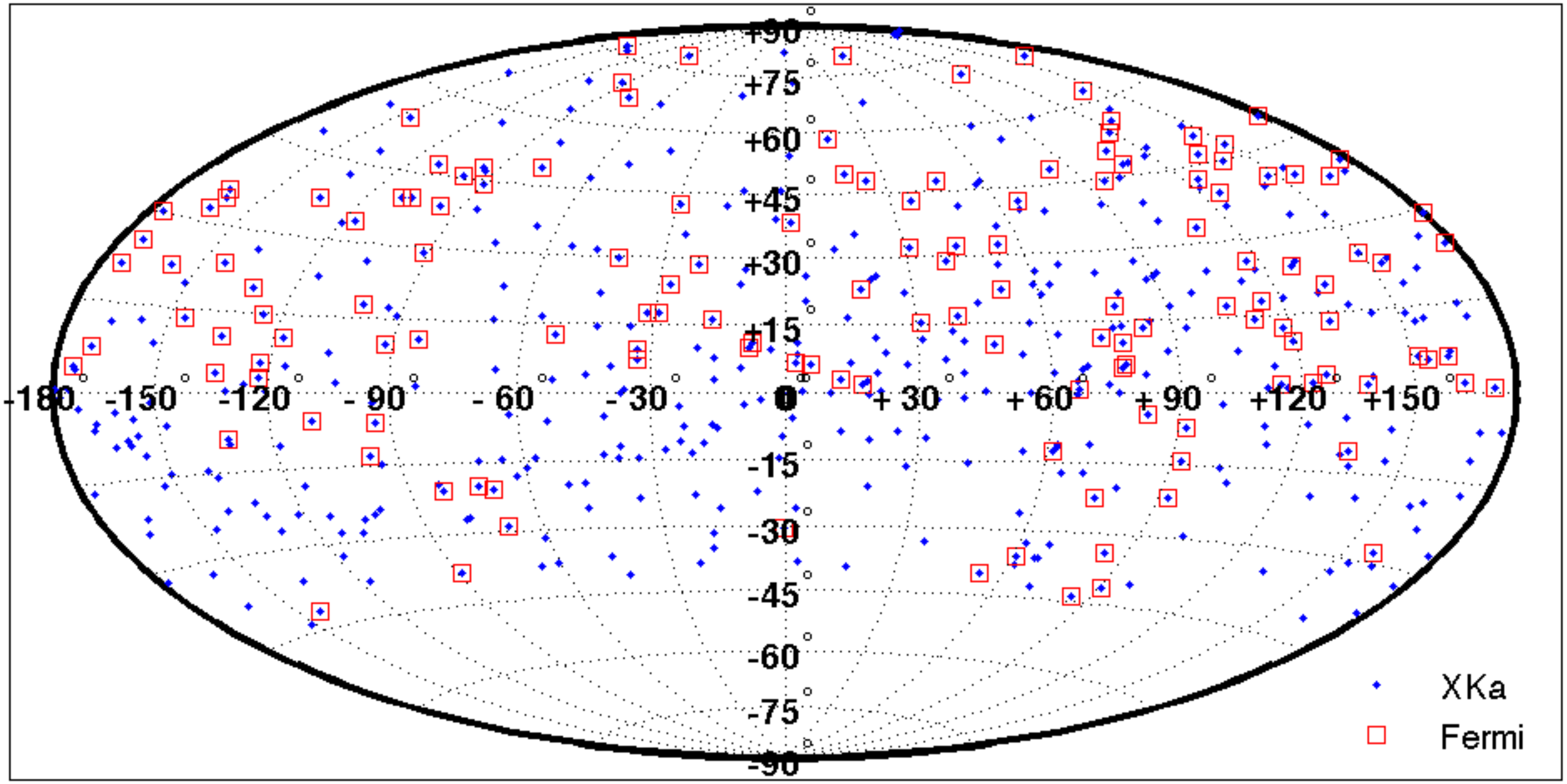
Spectral Energy Distribution: Mkn 421



radio synchrotron | optical | X-ray acc. disk. thermal | gamma inverse Compton

Credit: http://spiff.rit.edu/classes/phys443/lectures/agn_1/agn_1.html

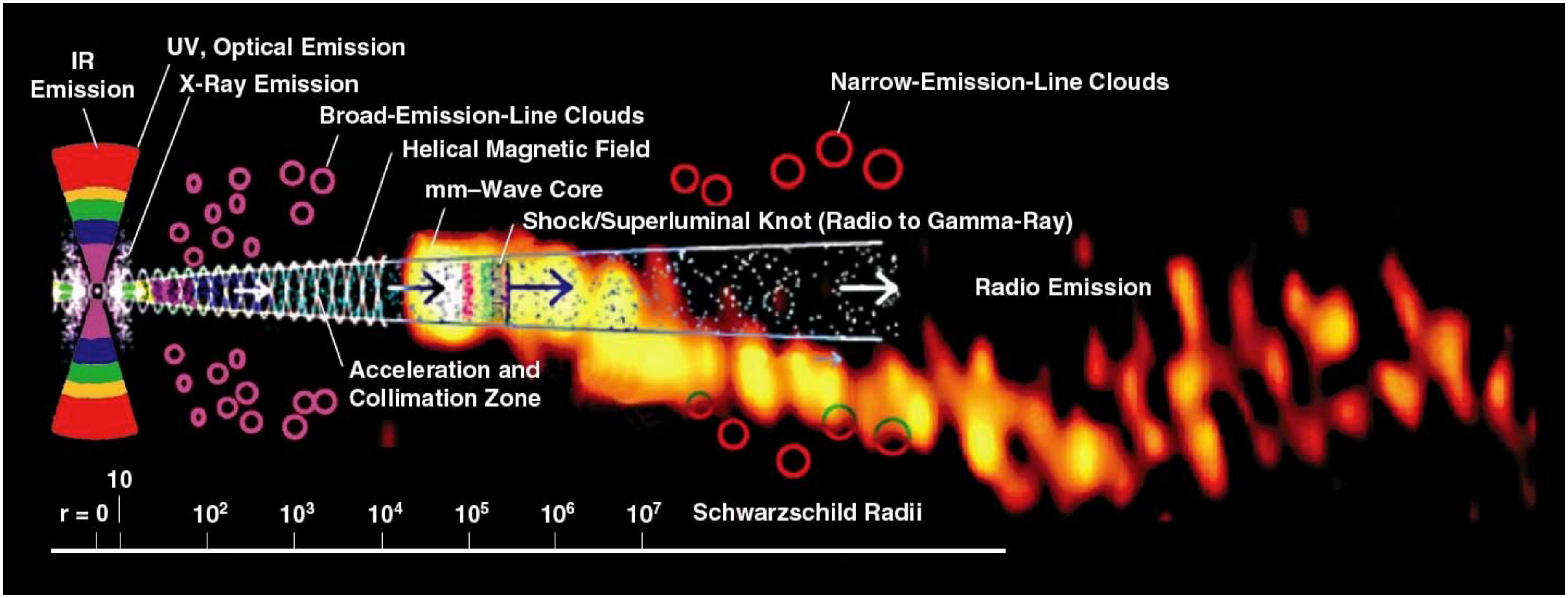
X/Ka / FERMI gamma-ray correspondance



X/Ka sources (blue) which are surrounded by Red squares are also in the Fermi 2FGL gamma-ray point source catalog. Over 1/3 of X/Ka sources (~175) have gamma-ray detections.

Credit: Majid et al, IVS, Madrid Spain, 2012

Active Galactic Nuclei (*Marscher*)



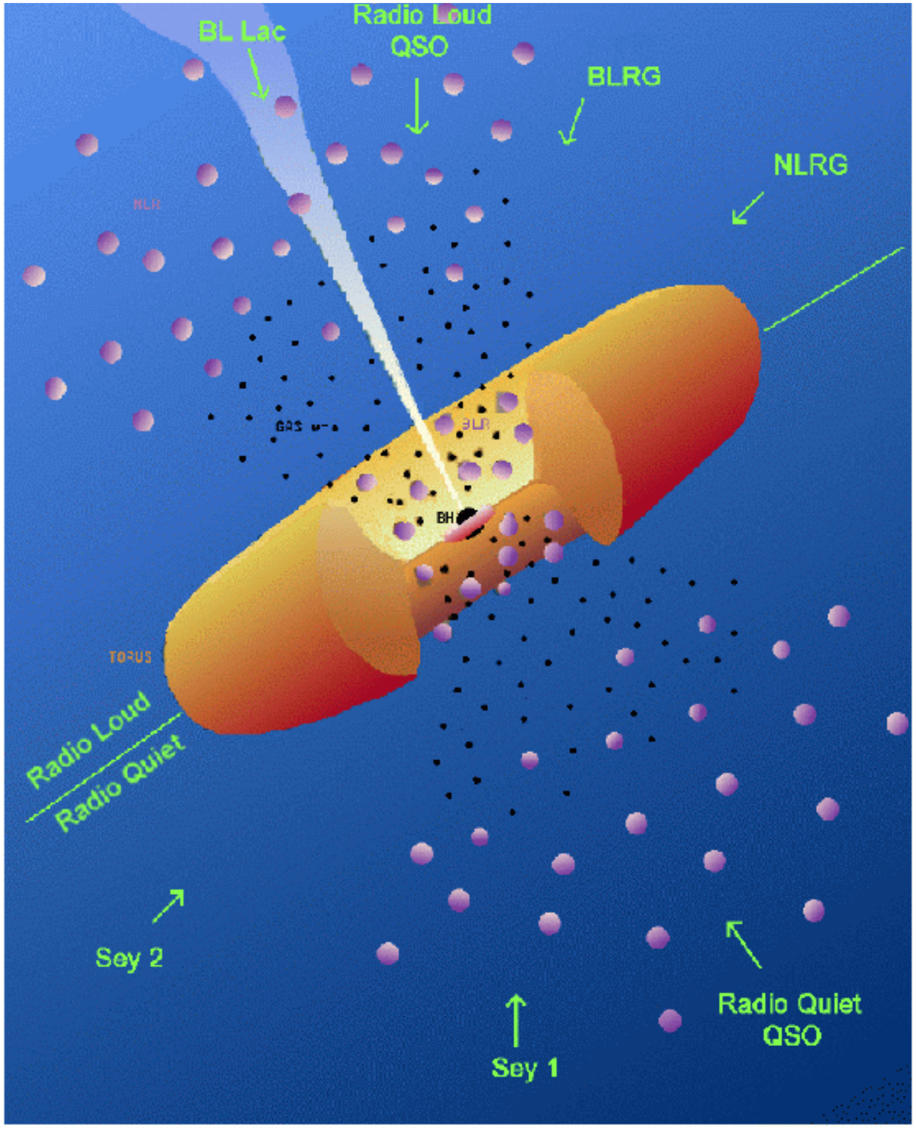
R~0.1-1 μas 1mas

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

"Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core."

Credits: Alan Marscher, `Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,' Proc. of Science,VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006. Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)

AGN: Viewing Angle Effect



Courtesy of M. Polletta, ITESRE/CNR, Bologna, Italy
from BeppoSax Calendar 1999; http://www.sdc.asi.it/calendar/

Schematic of AGN Viewing Angle

1. Down jet:
   BL Lac, Blazar
2. Small angle
   Radio loud
3. Mid-angle:
   Broad line region
4. Side view
   Narrow Line Region

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

Celestial Reference Frame: Long term stability

GPS is not sufficient for a long term inertial frame

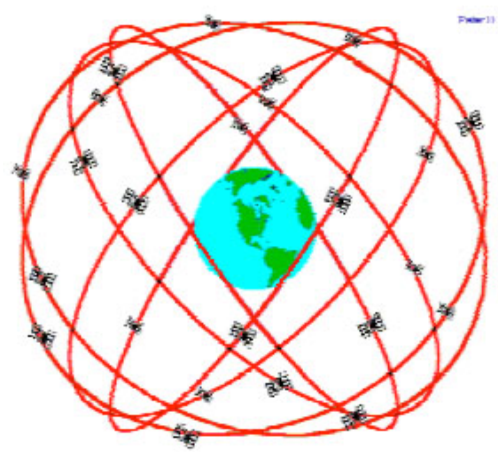
Orientation: Relative to what?

One must define stable (ppb) reference directions

- GPS orbits are well modelled (ppb) over ~day time periods.

But . . .

- GPS constellation node drifts over weeks. . .



1.e18 increase in range

Solution: Change sources from range of GPS's nano-Light year to VLBI's Giga-Light Years ~eighteen (18) orders of magnitude!

Credit: www.international.gc.ca/arms-armes/assets/images/bourbonniere_img6.jpg

Celestial Pole & Alignment of Axes

- VLBI determines angles *between* sources
- Absolute positions only weakly determined at 10-100 mas level by tidal effects (RA, dec of Sun &Moon) and atmospheric effects (elevation)
- Orientation of axes is defined at sub-mas level by convention
- Enforced by No-Net-Rotation constraint:

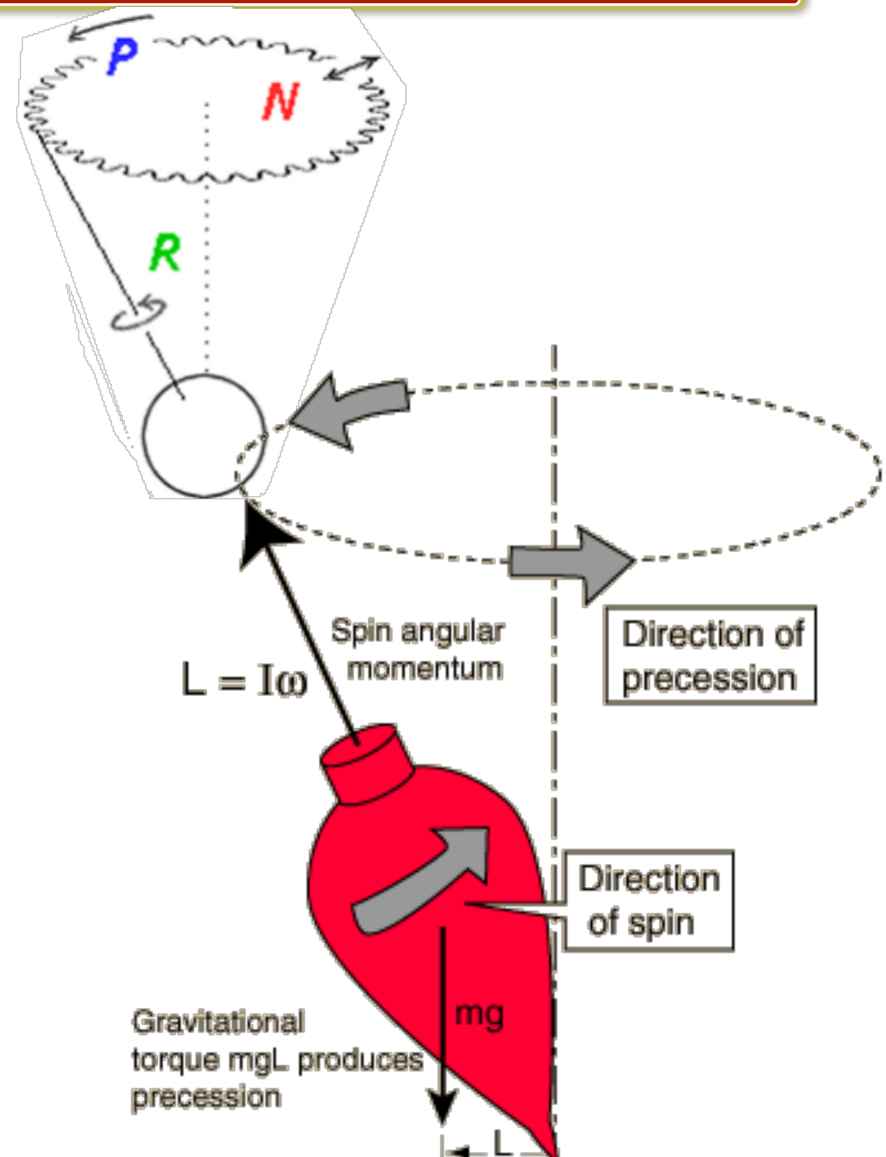
$$\sum_{i=1}^{N} s \times \Delta s = 0$$

where s direction is source unit vector

cf. Jacobs et al, IVS, 2010.

http://ivscc.gsfc.nasa.gov/publications/gm2010/jacobs2.pdf

From German Wikipedia, by User Herbye.



Credit: www.4physics.com

Outline

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ad hoc, VLBA, EVN, Global, NASA-ESA DSN, LBA, AuScope, etc.

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C. ICRF-3: the next standard radio frame

D. Gaia: an optical frame with high accuracy

II.B. The Transition from Optical to Radio

- Optical to Radio transition era documented in
  Hans Walter & Ojars Sovers, Astrometry of Fundamental Catalogues: The Evolution from Optical to Radio Reference Frames, 2000
  http://adsabs.harvard.edu/abs/2000afce.conf.....W
- Fundamental Katalog FK5 (Fricke, 1988)
  http://adsabs.harvard.edu/abs/1988VeARI..32....1F
  1535 stars limited by proper motions of stars
  ~150 mas regional differences from ICRF1 http://adsabs.harvard.edu/abs/1997IAUJD...7E..24M
- IAU called for a move to Active Galactic Nuclei (AGN)
  obtain very distant sources (redshift ~1, ~5 billion light years)
  No parallax, no proper motion
- IAU formed in 1990s a working group on International Celestial Reference Frame (ICRF)
- ICRF-1 adopted by the IAU as on 1998 Jan 01.
  Ma et al, AJ, 116, 516, 1998 http://adsabs.harvard.edu/abs/1998AJ....116..516M

II.A. Surveys: How are sources found? Positions?

1. Single dish surveys: A single radio telescope sweeps the sky to search for point-like sources. Example: Parkes-MIT-NRAO 4.8 GHz (Griffith & Wright, 1993) ~10 arcsec positions.
http://www.parkes.atnf.csiro.au/observing/databases/pmn/pmnpubs.html 1993AJ....105.1666G

2. Connected element array surveys:
   - next step is interferometric connected arrays such as the Very Large Array or ATCA
   - Positions improved to 10s of milli-arcsec

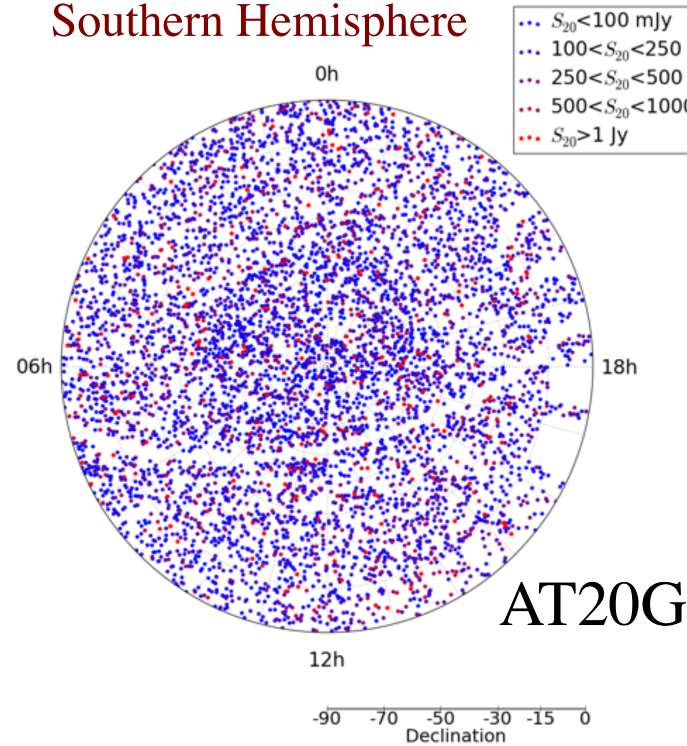
   - North: Jodrell Bank VLA Survey (JVAS) (Patnaik et al, MNRAS, 1992)
     http://adsabs.harvard.edu/abs/1992MNRAS.254..655P

http://www.vla.nrao.edu/

   - South: ATCA 20-GHz (AT20G), 5890 sources, Southern hemisphere (Murphy et al, MRAS, 2010)
     http://www.atnf.csiro.au/research/AT20G http://adsabs.harvard.edu/abs/2010MNRAS.402.2403M

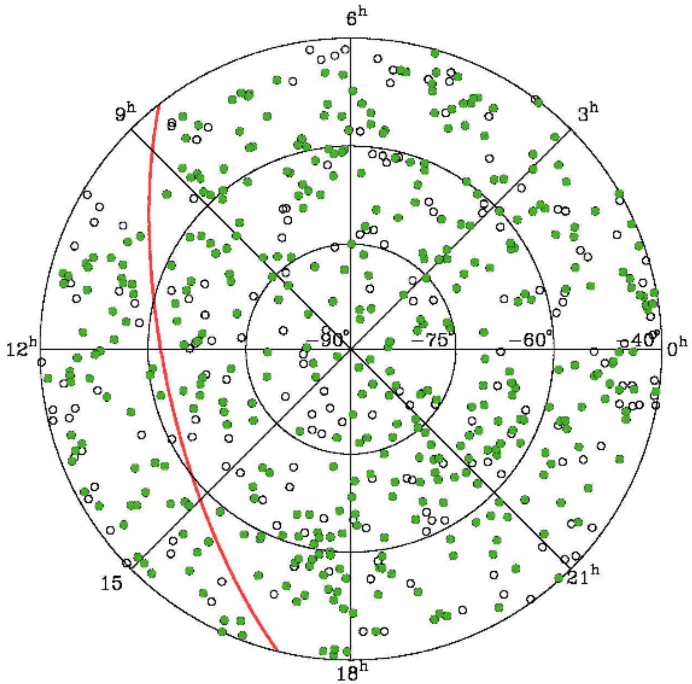
3. Final Survey stage: VLBI gets ~milli-arcsec positions e.g
   - North: VLBA Calibrator Survey (Beasley et al, ApJS, 2002)
     http://adsabs.harvard.edu/abs/2002ApJS..141...13B
   - South: LBA Calibrator Survey, (Petrov et al, MNRAS, 2011)
     http://arxiv.org/abs/1012.2607 http://adsabs.harvard.edu/abs/2011MNRAS.414.2528P

Southern Hemisphere



http://www.narrabri.atnf.csiro.au/public/

II.A. Surveys: milli-arcsec VLBI surveys



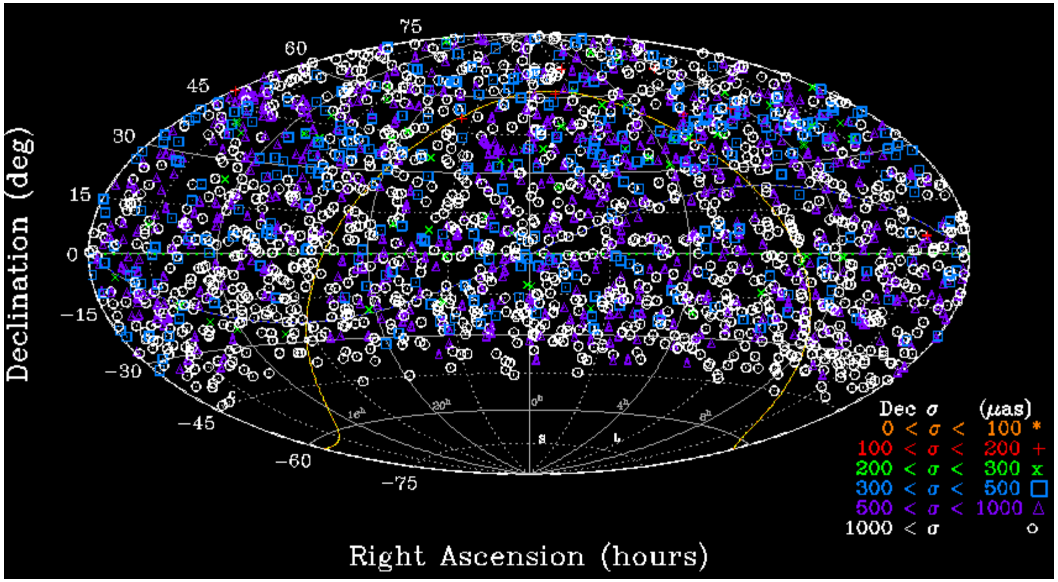


Figure credit: C.S. Jacobs

South:

LBA Cal Survey1:

~1 mas accuracy

view from south pole

http://arxiv.org/pdf/1012.2607v2.pdf

North:

VLBA Calibrator Survey

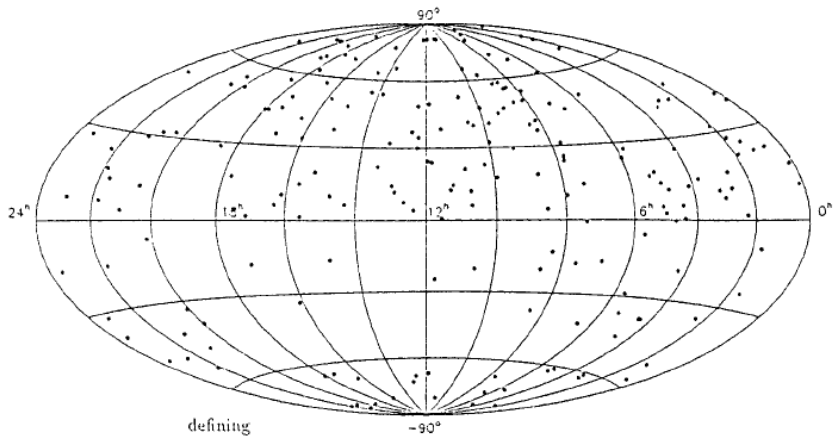
~2200 sources, ~1 mas

Hammer-Aitoff Projection

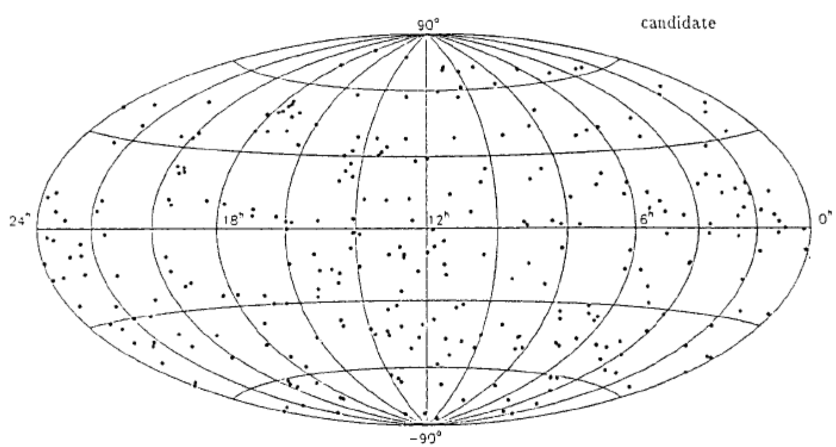
http://adsabs.harvard.edu/abs/2002ApJS..141...13B

1st International Celestial Reference Frame

- ICRF-1 adopted by the IAU as on 1998 Jan 01.
  Ma et al, AJ, 116, 516, 1998 http://adsabs.harvard.edu/abs/1998AJ....116..516M



212 "Defining" sources which define the orientation of the frame's axes.
Weak in the south.

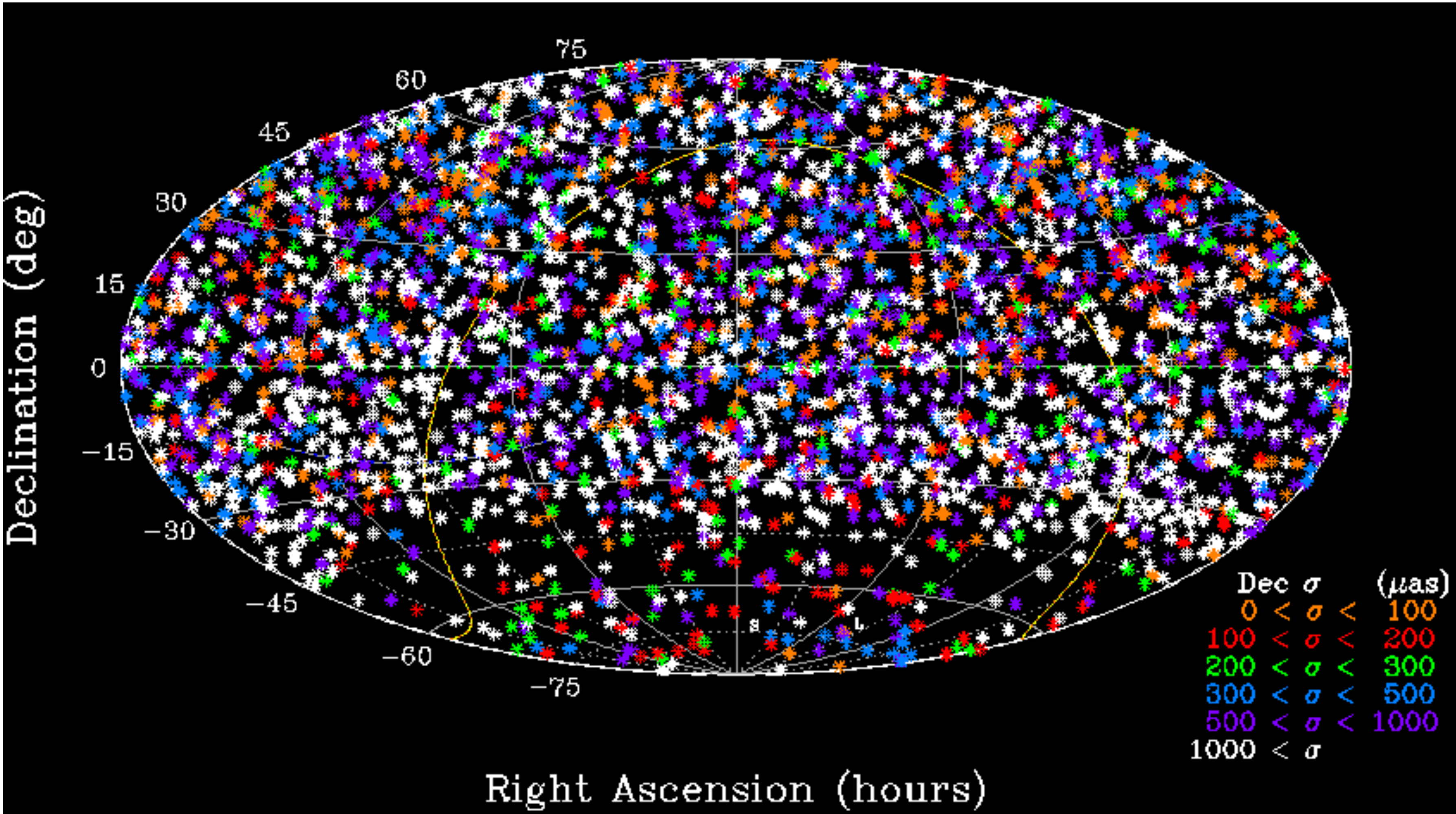


"Candidate" sources (left)
Plus a few "other" sources
For a total of 608 sources.

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

ICRF-2 S/X 3.6cm: 3414 sources

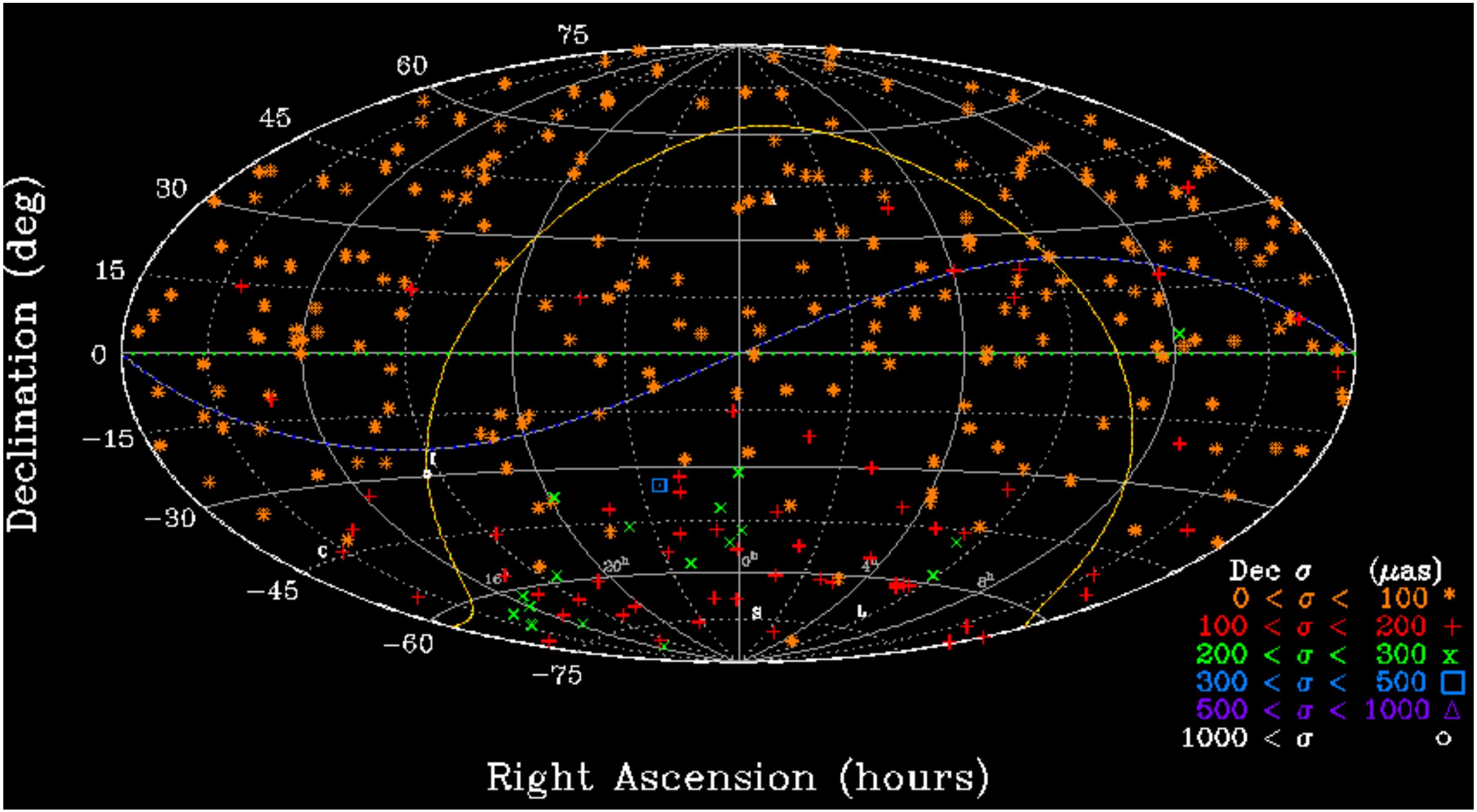


40 μas floor. ~1200 obj. well observed, ~2000 survey session only

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

http://adsabs.harvard.edu/abs/2009ITN....35....1M

ICRF2 S/X 3.6cm: 295 Defining sources

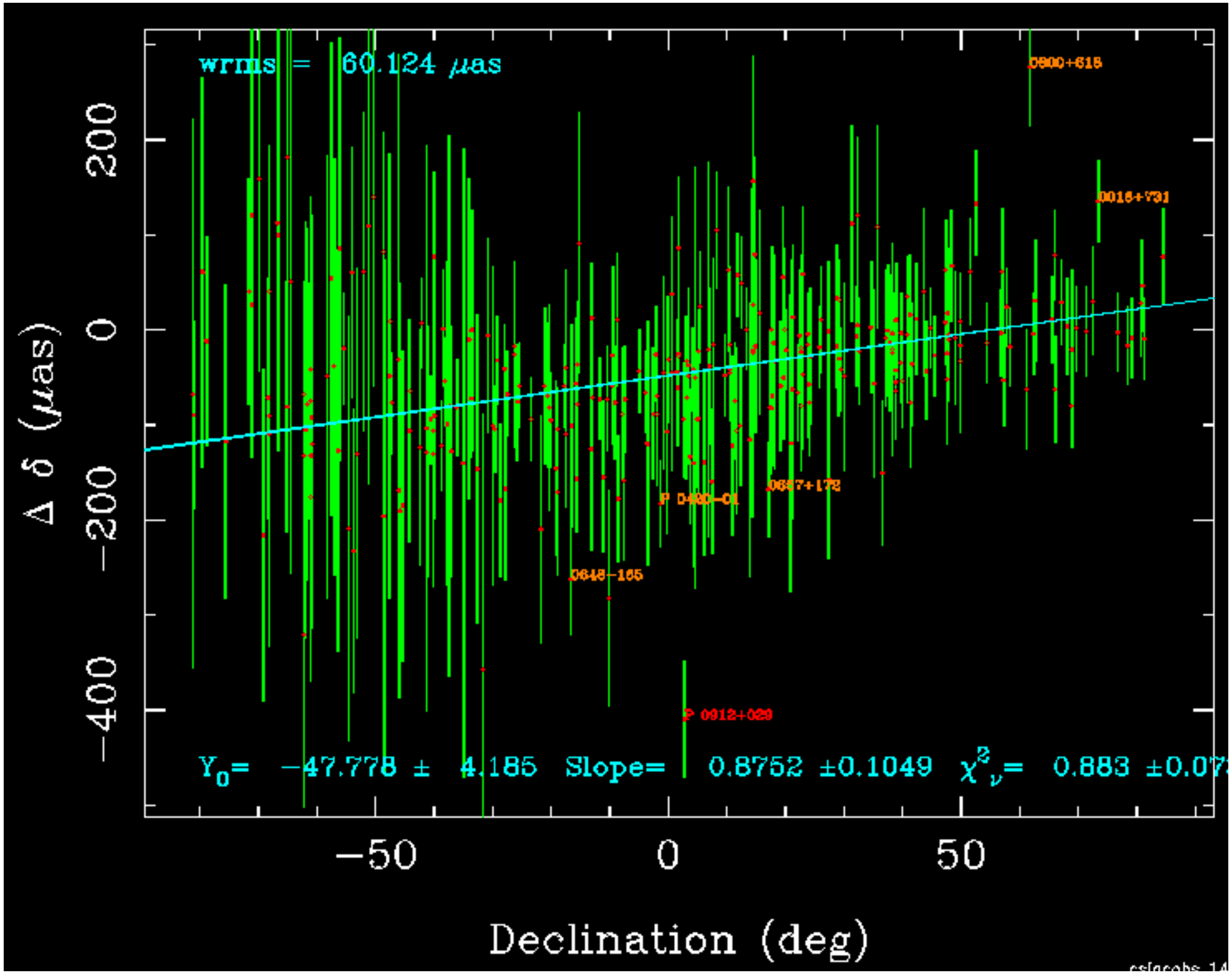


295 "best" sources Define the orientation of the axes. Weak in the South

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

http://adsabs.harvard.edu/abs/2009ITN....35....1M

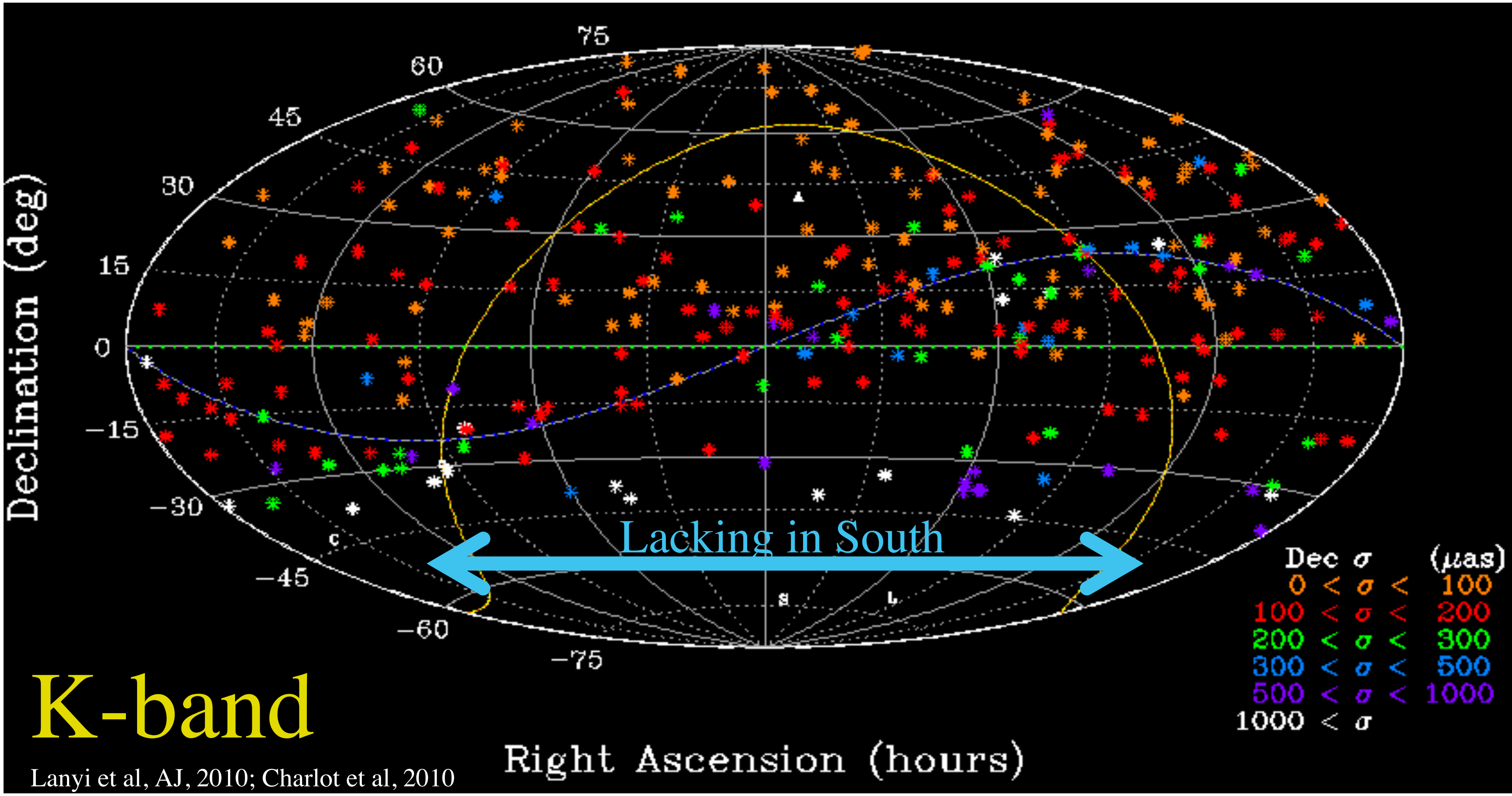
S/X zonal errors: ICRF2 vs. Recent S/X



Credit:
Gordon et al, GSFC,
private .comm., 2014

GSFC-2014bp3 – ICRF2 Definings: 0.5 ppb zonal error in Declination

K-band (24 GHz) CRF: 275 sources



Work stopped c. 2010.

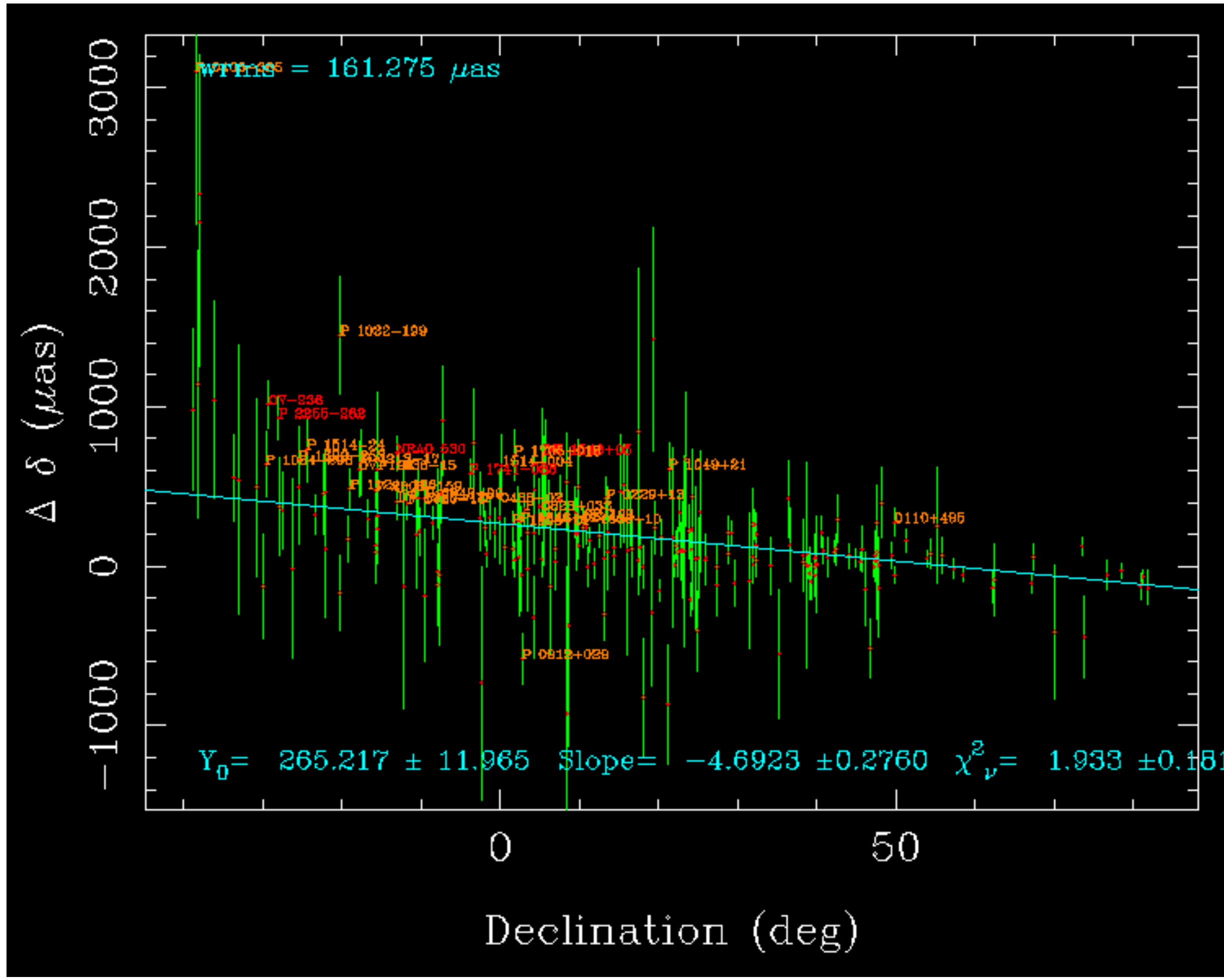
Resumed 2013. First southern K-band fringes: Hobart-HartRAO (23 Aug 2013)

VLBA work resumed 2016 (project BJ083). Extended in 2017 (UD001)

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

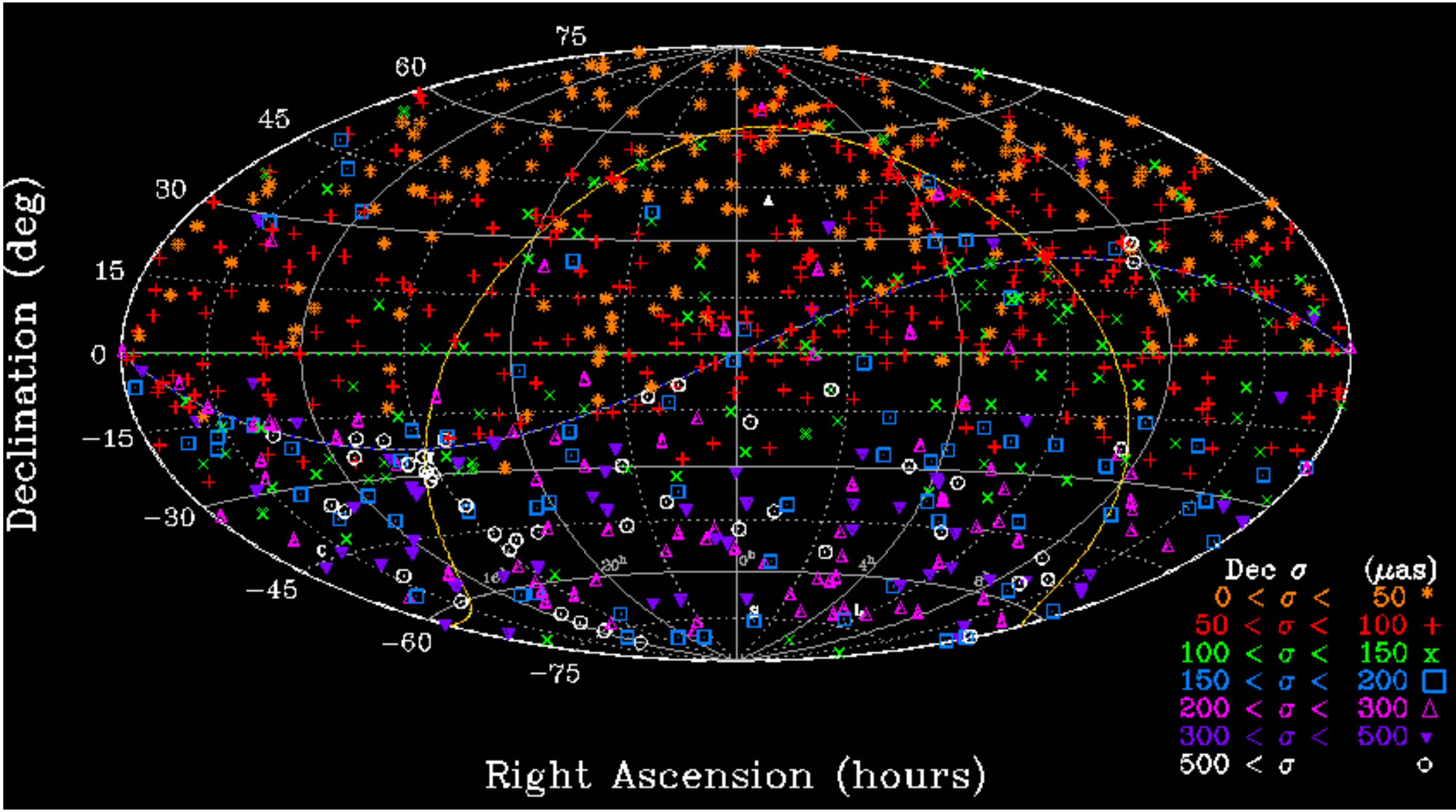
Leads to poor
ΔDec vs. Dec
Zonal stability:
500 μas tilt



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

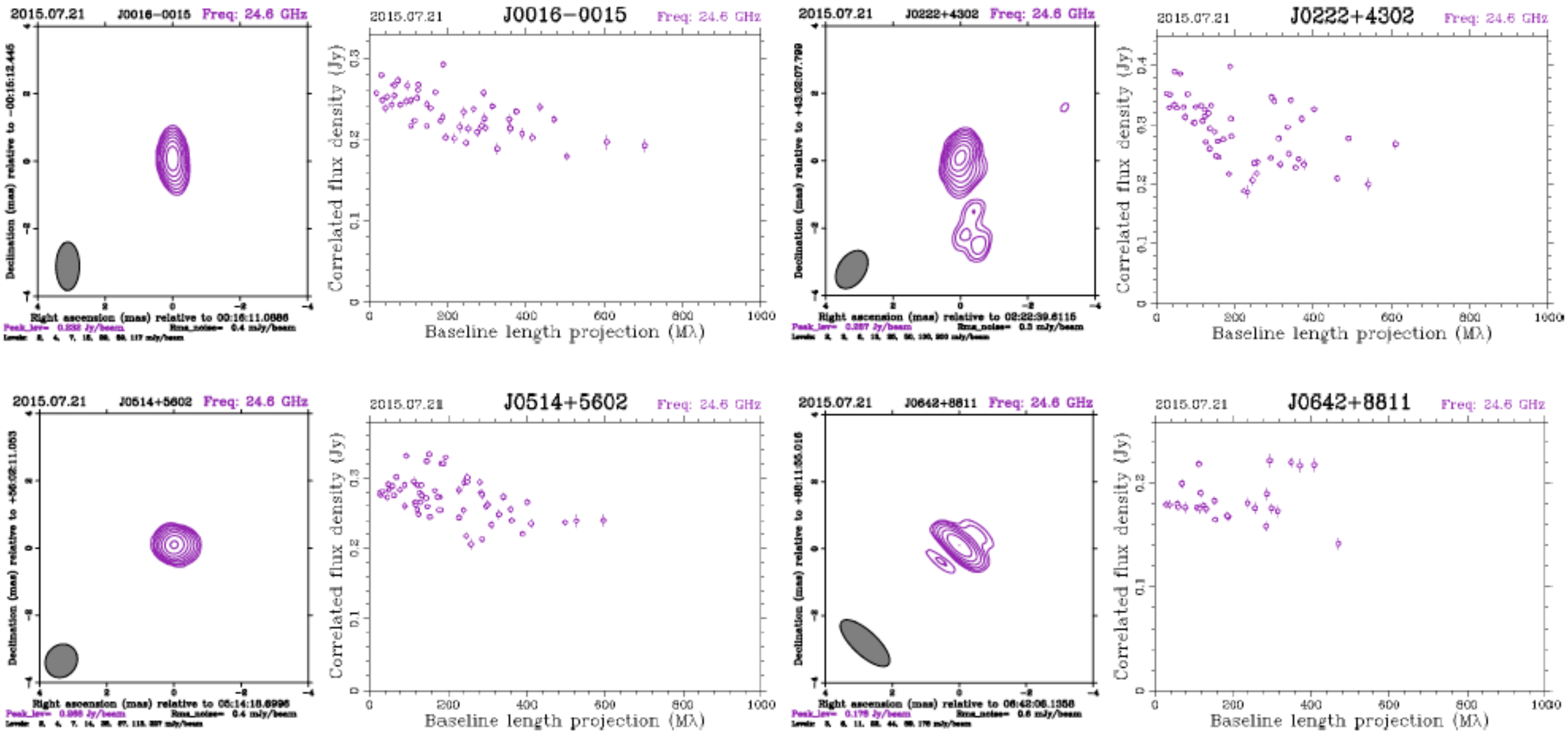
K-band (24 GHz) CRF: 826 sources



VLBA 35 sessions @2Gbps to densify the north *(de Witt et al, EVGA, 2017)*

Hart-Hobart (Tianma): 15 sessions. Archive (Lanyi et al, 2010, Petrov et al, 2006).

Imaging: VLBA at 24 GHz (1.2cm) (de Witt et al, 2016)



K-band (24 GHz) imaging shows VLBI sources are compact on millarcsec scales.

Data for 5000+ sources acquired. Processing limited by available analyst resources.

Imaging will be prioritized as comparison outliers pinpoint sources of interest

The authors gratefully acknowledge use of the Very Long Baseline Array under the US Naval Observatory's time allocation. This work supports USNO's ongoing research into the celestial reference frame and geodesy.

I.B. Observing Networks

VLBA

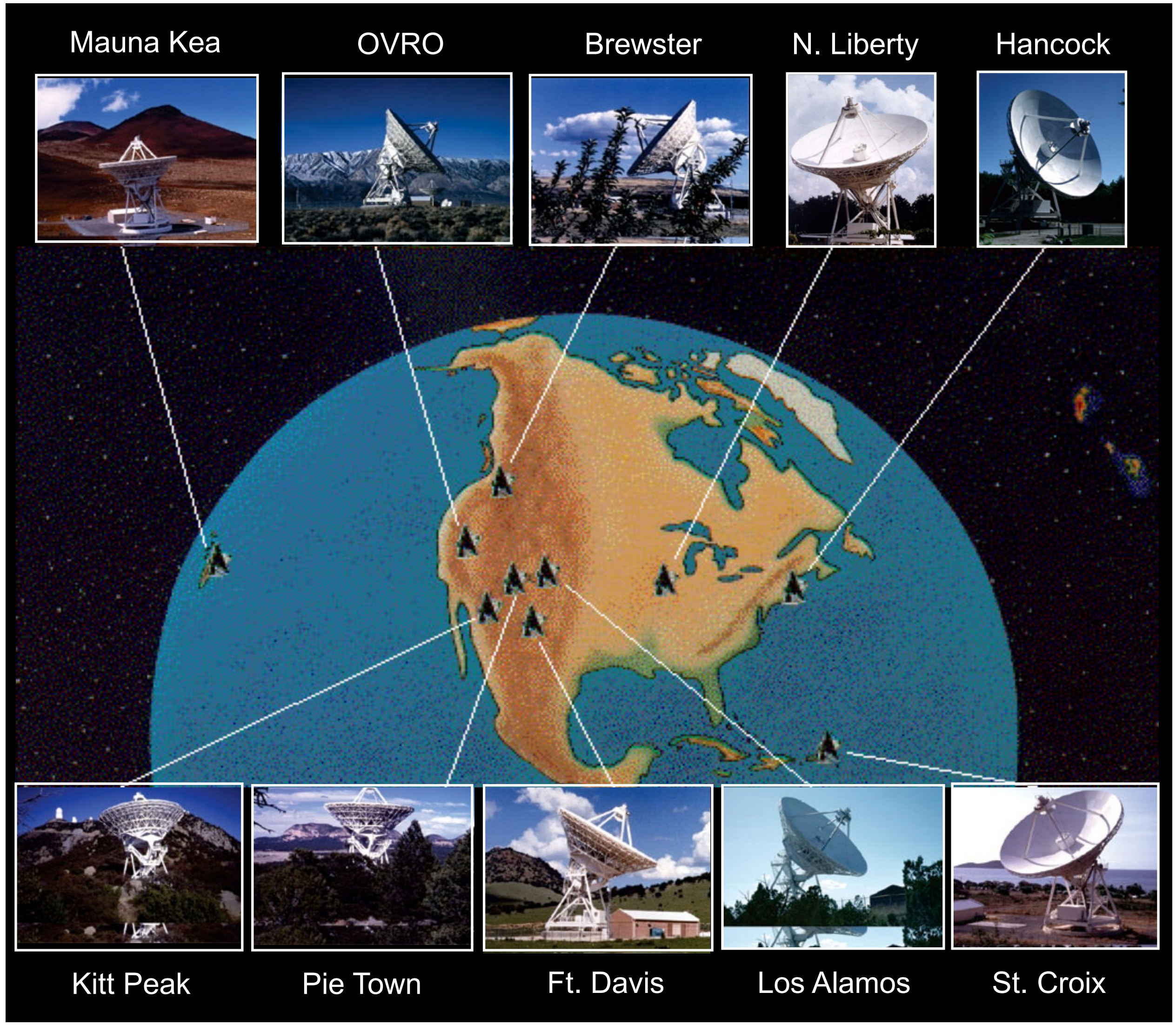
S/X VCS catalog
K, Q catalogs

25-meter dishes

10 stations

Baselines up to
8000 km

No southern
stations



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

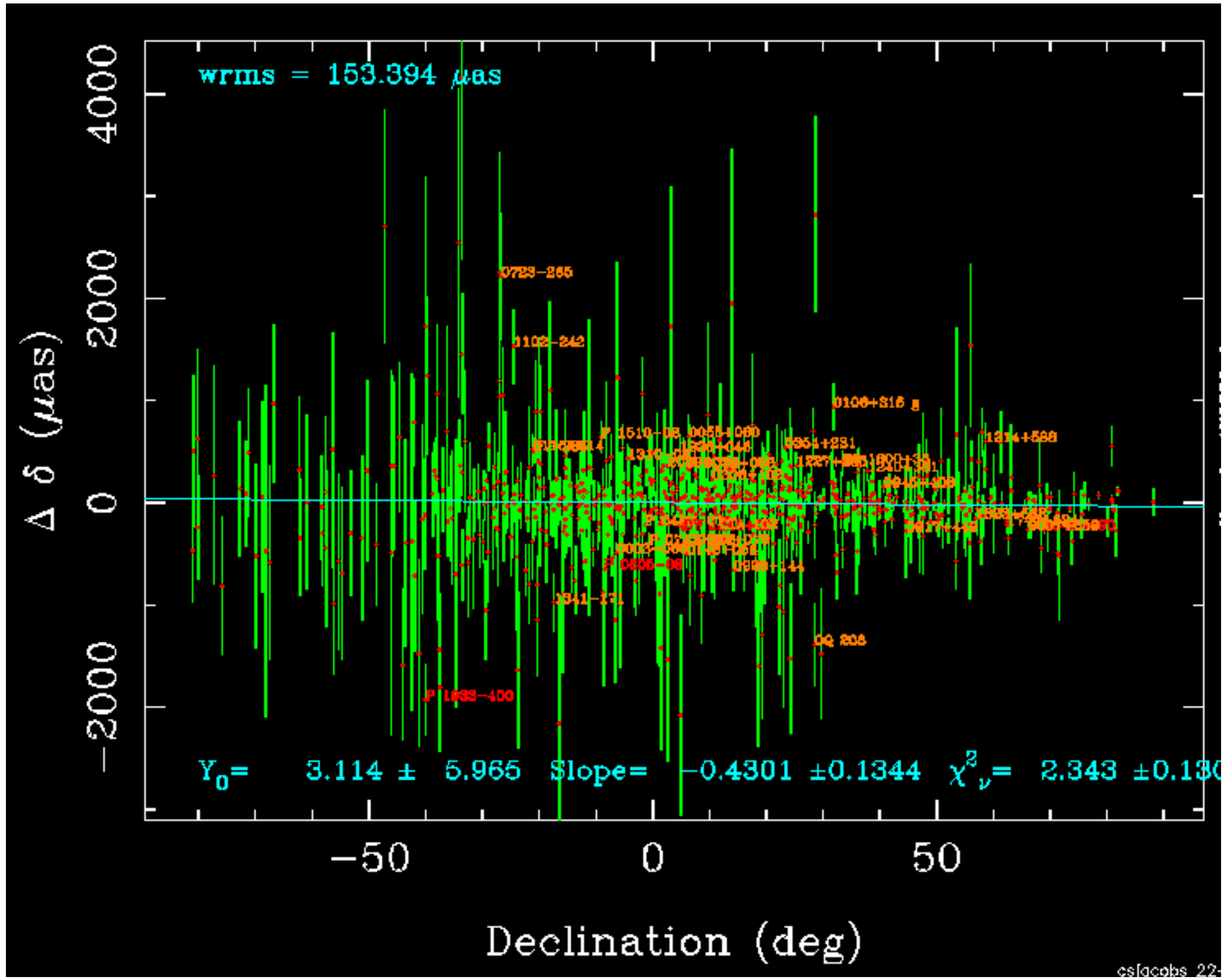
New K-band 1.2cm *vs.* S/X-band 3.6cm

GPS ion cals

***Added baseline Hart-Hobart* in south**

ΔDec vs. Dec
Tilt now an order of magnitude
Improved!!!

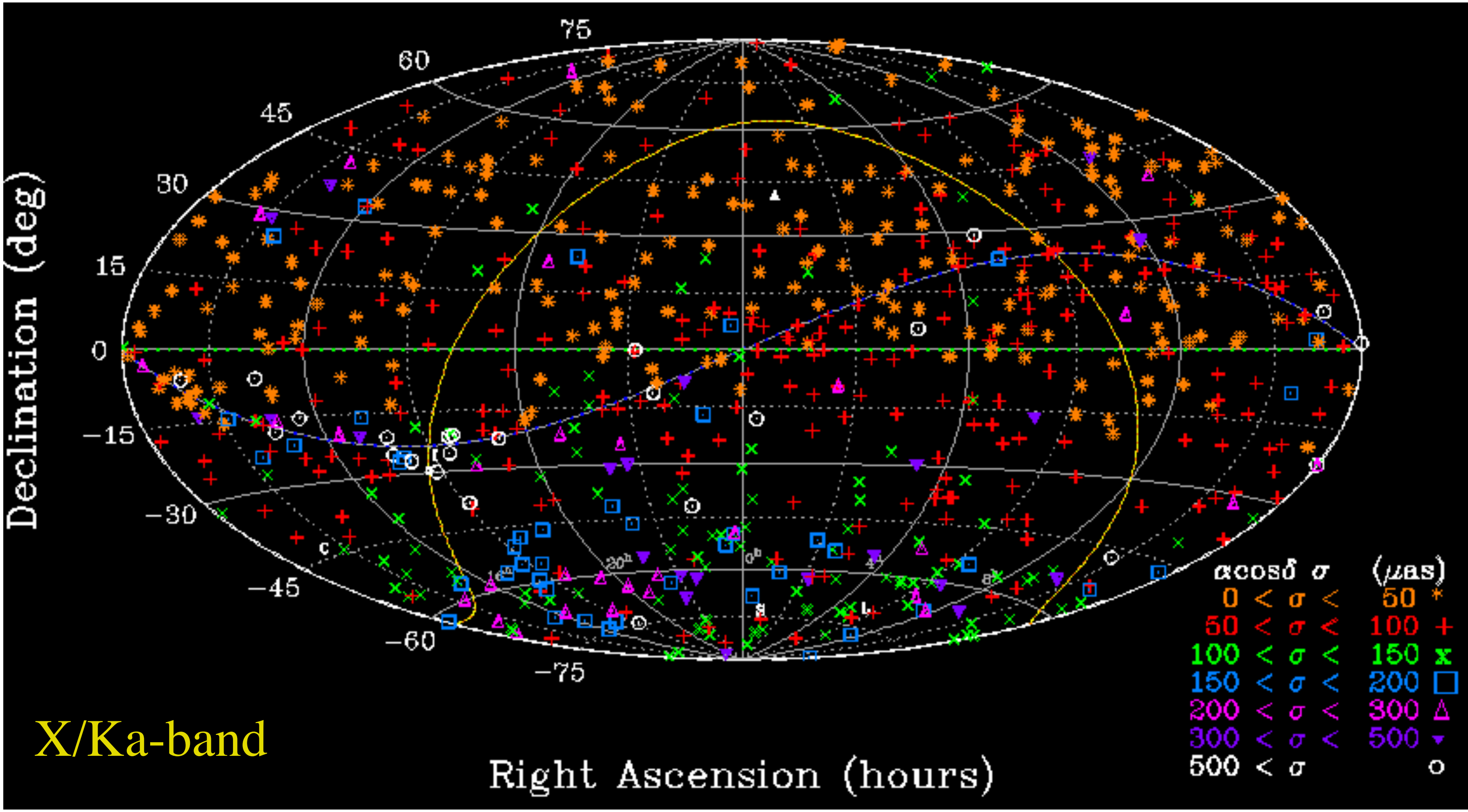
Tilt of
-43 μas over
100 deg span



K (*2017 Mar 20*) Declinations vs. S/X (2016 Dec 20)

Credit: K(1.2cm): Gordon, priv. comm 20 Mar 2017
S/X :Gordon 2016 Dec 20

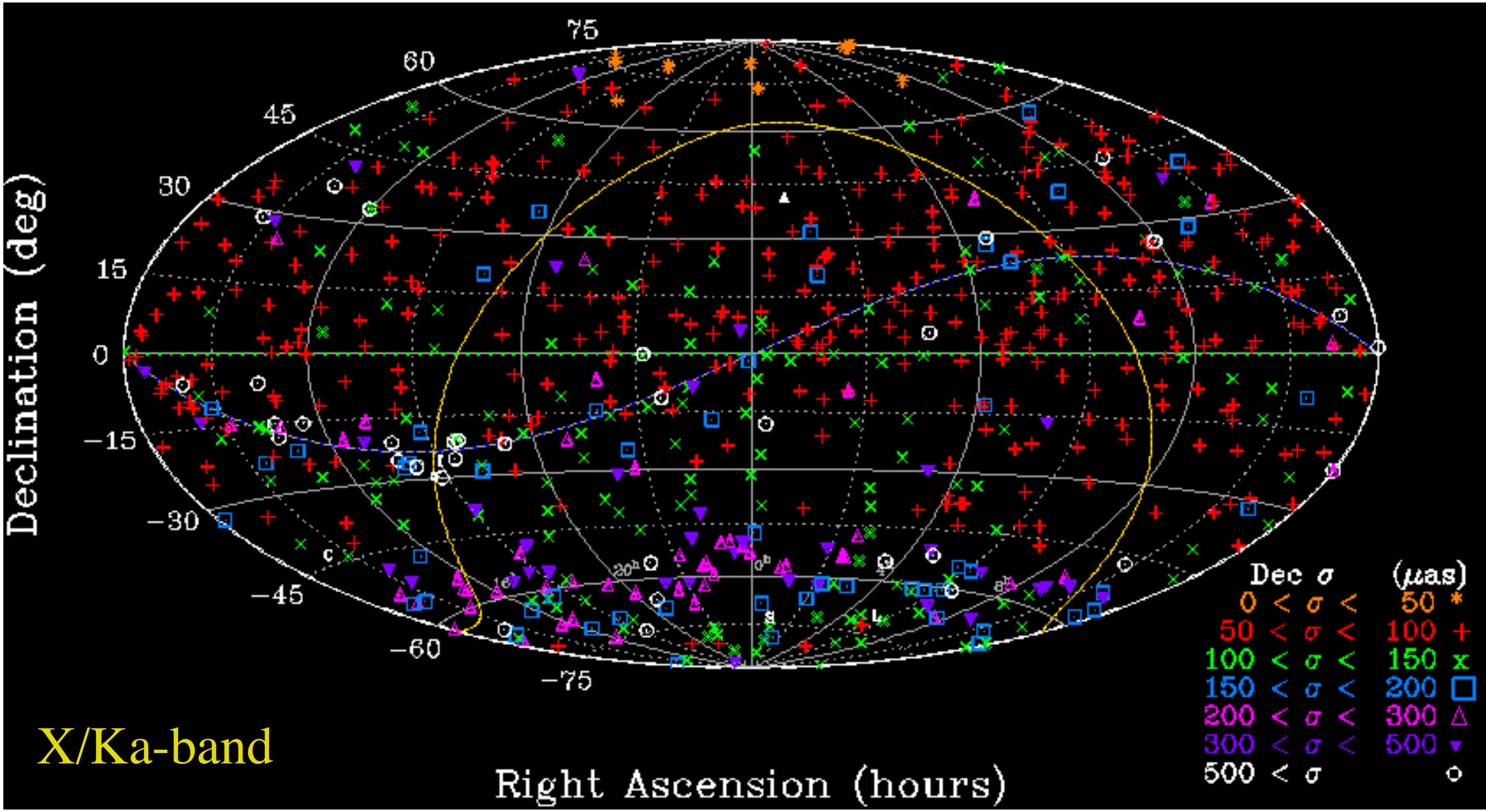
X/Ka RA results (*NASA-ESA*): 681 Sources



Goldstone, CA to Madrid & Australia **+ Malargüe to Canberra, Goldstone, Madrid**.
134 sources in south cap (dec<-45); 27 ICRF2 Defining; 2/3 of south cap non-ICRF2

Credit: Jacobs et al, IAU330, 2017; Garcia-Miro et al, EVN, 2014
Jacobs et al, ISSFD, Pasadena, 2012 http://adsabs.harvard.edu/abs/2012sfd..confE...1J

X/Ka Dec results (*NASA-ESA*): 674 Sources



DSN: Goldstone, CA to Madrid & Canberra

+ ESA baselines: Malargüe to Canberra, Goldstone, Madrid

Credit: Jacobs et a, IAU 330, 2017; Garcia-Miro et al, EVN Symposium, 2014

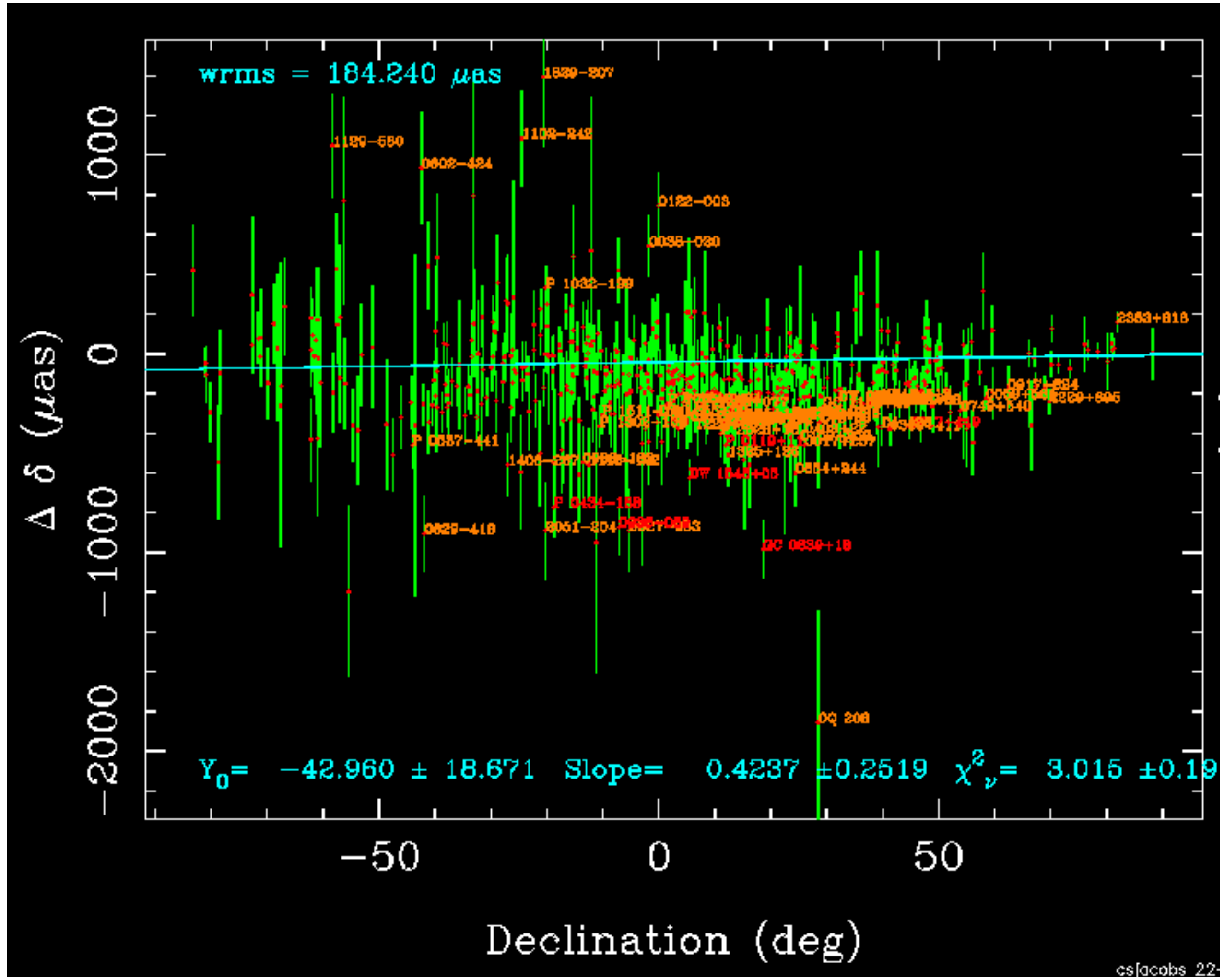
Jacobs et al, ISSFD, Pasadena, 2012 http://adsabs.harvard.edu/abs/2012sfd..confE...1J

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

Dual-band ion Calibrations
and
Station in south

Leads to better ΔDec vs. Dec Zonal stability:

42 +- 25 μas tilt over 100 degrees



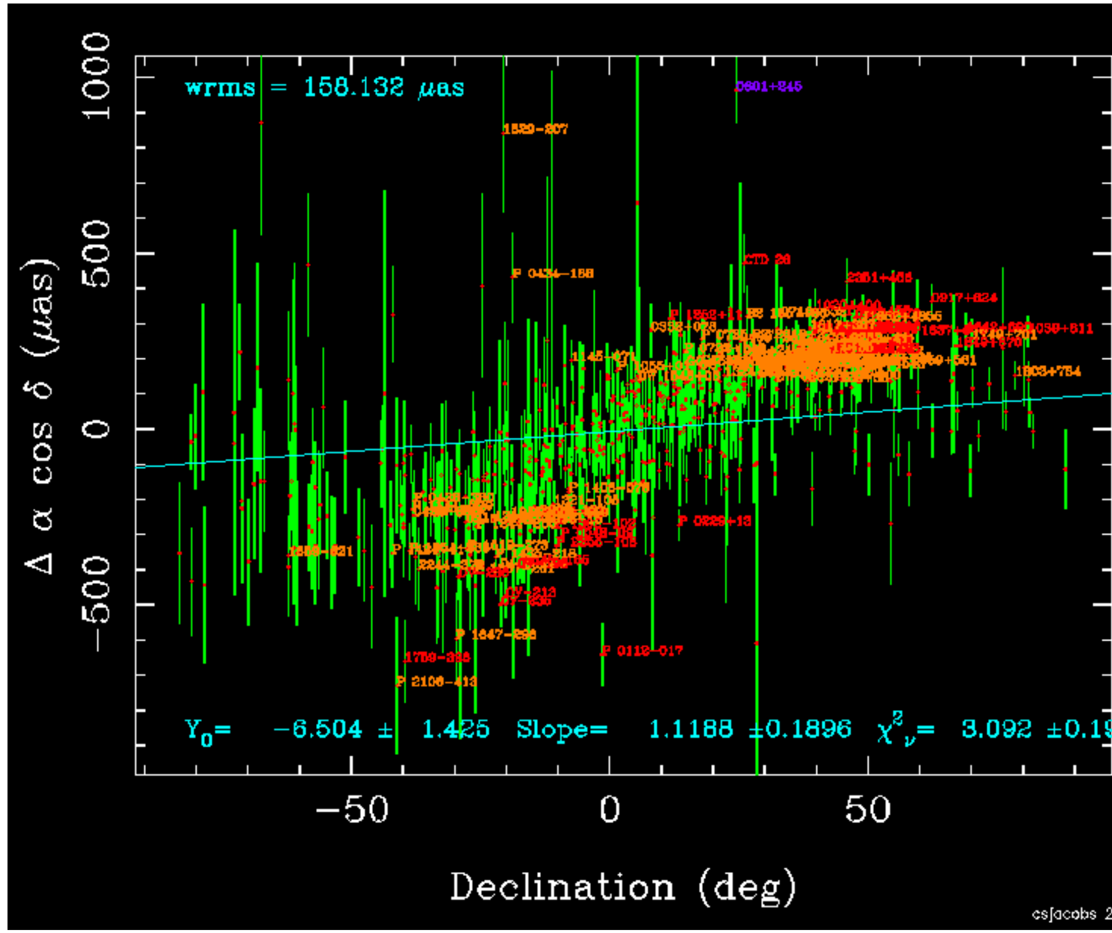
X/Ka(9mm) Dec. vs. S/X (3.6cm)

X/Ka, Garcia-Miro et al, EVN, 2014, Jacobs et al, 2016,
S/X: Gordon et al, private comm., GSFC, 20 Dec 2016

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

ΔRA vs. Dec
Zonal Differences
Are dominant error
In XKa vs SX.

Not well understood.



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

X/Ka, Garcia-Miro et al, EVN, 2014, Jacobs et al, 2016,
S/X: Gordon et al, private comm., GSFC, Dec 2016

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- A. What is a Reference frame? Concepts, uses, desired properties
- B. Networks: The instruments used to build the frame
  - ad hoc, VLBA, EVN, Global, NASA-ESA DSN, LBA, AuScope, etc.
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  - 2. Invention of radio astronomy. VLBI’s pursuit of (sub)milli-arsecond accuracy.

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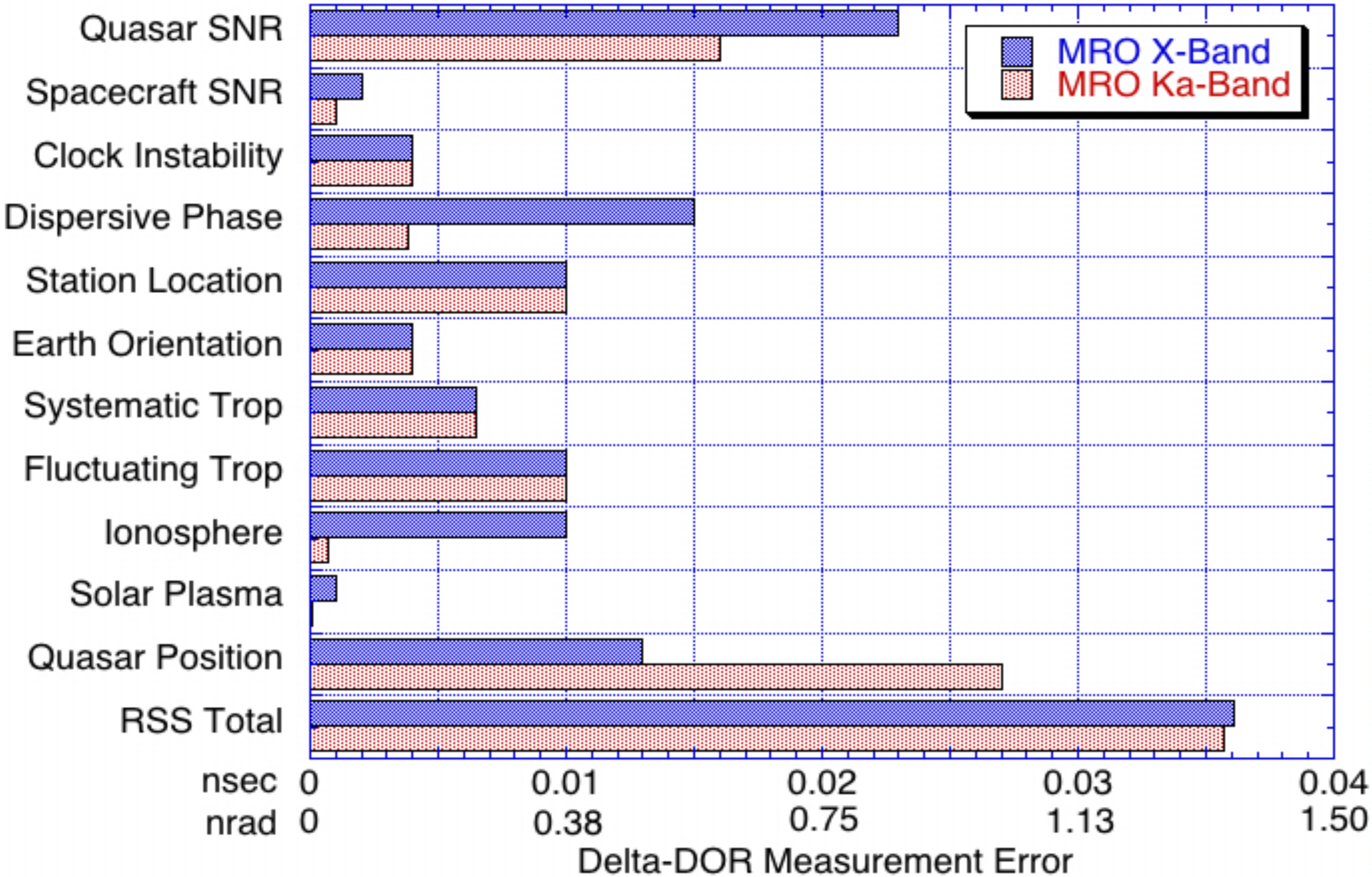
- **A. Error Budgets: a tool for allocating resources for improvement**
- **B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame**
- **C. ICRF-3: the next standard radio frame**
- **D. Gaia: an optical frame with high accuracy**

Error Budget for Reference Frame VLBI

The Tall Tent Poles

Figure credit: S. Myneni ssrl.slac.stanford.edu/research/highlights_archive/organo-cl_compounds.html

ΔVLBI Error Budget



Credit: ΔVLBI budget from J.S. Border

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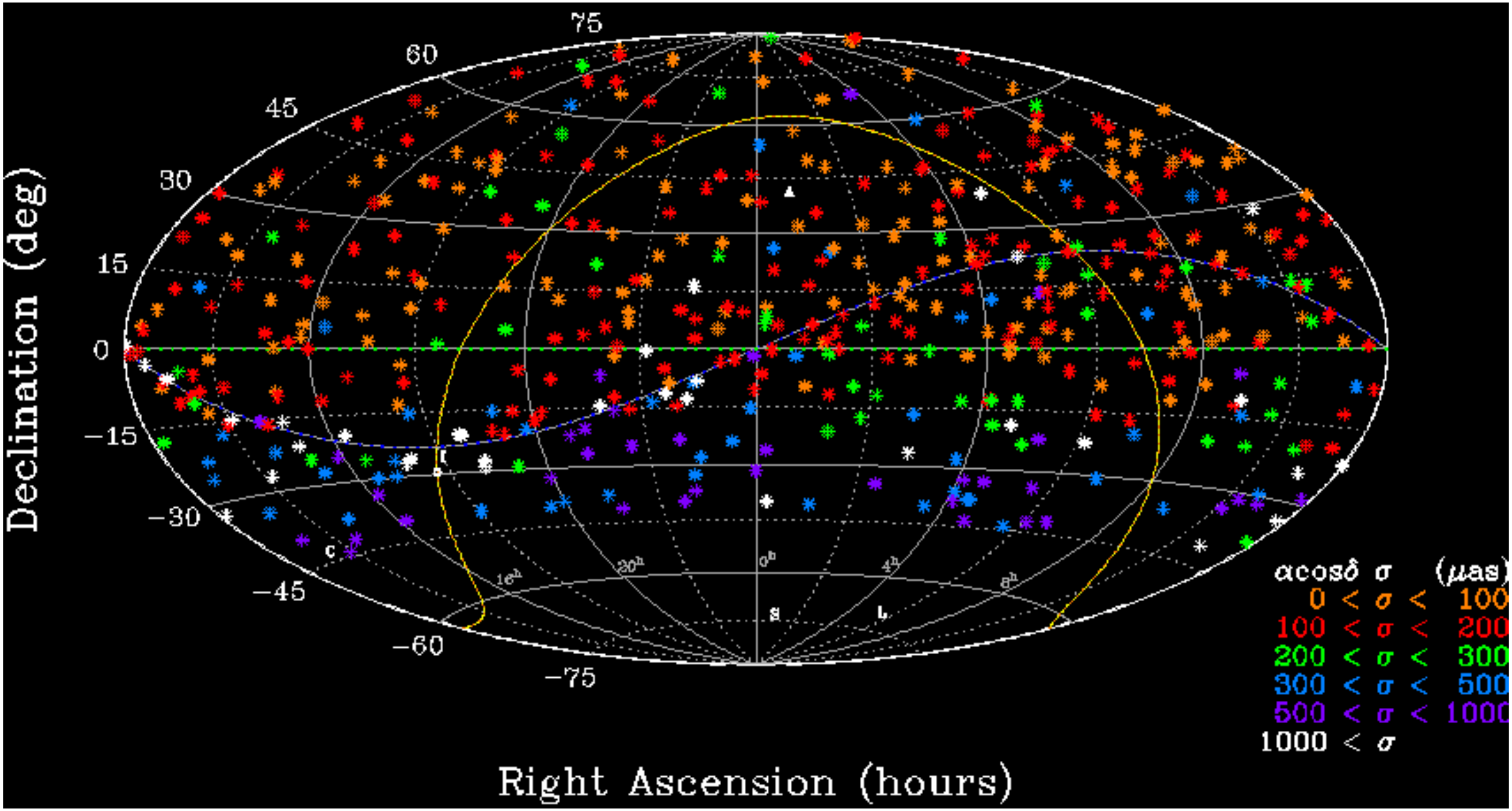
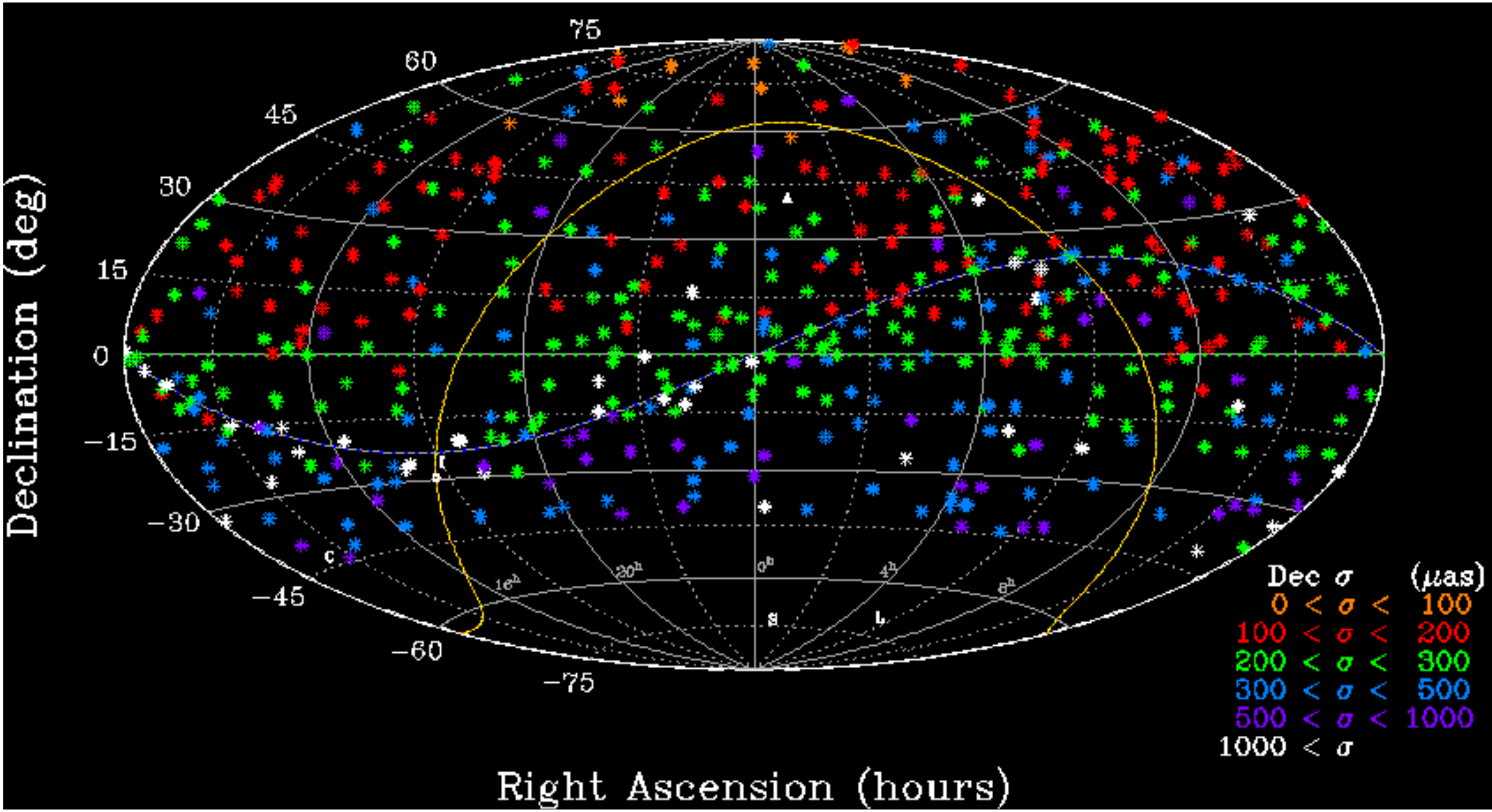
Status 2012: X/Ka RA results 482 Sources



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

Credit: Jacobs et al, ISSFD, Pasadena, 2012

Status 2012: X/Ka Dec results 482 Sources



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

Credit: Jacobs et al, ISSFD, Pasadena, 2012

Focus Work on the Tall Tent Poles

Systems Analysis shows dominant Errors are

- **Limited SNR/sensitivity**
  - already increased bit rates in 2009: 112 to 448 Mbps.
  - 2048 Mbps fringes May 2013. 1-2 Gbps operational in 2014
- **Instrumentation:** already building better hardware
  - BWG phase calibrators, Digital baseband conversion & filters
- **Troposphere:** better calibrations being explored
- **Weak geometry in Southern hemisphere**
  - Limits accuracy to about 1 nrad (200 μas) level
  - Need observations below Declination of -45 Deg!
  - DSN at X/Ka had only Canberra, Australia (DSS 34)
  - Needed 2nd site in the Southern hemisphere
    especially for upcoming southern ecliptic missions:
    Maven (2014), Exo-Mars (2016), InSight (2018).

Attacking the Error budget

- **SNR can be improved +6 to 9 dB!**
- Instrumentation:
  Phase calibration with test signals
  Digital Baseband Conversion & Filtering
- Troposphere cals: WVR
- Southern Geometry

Results have been limited by SNR

Solution:

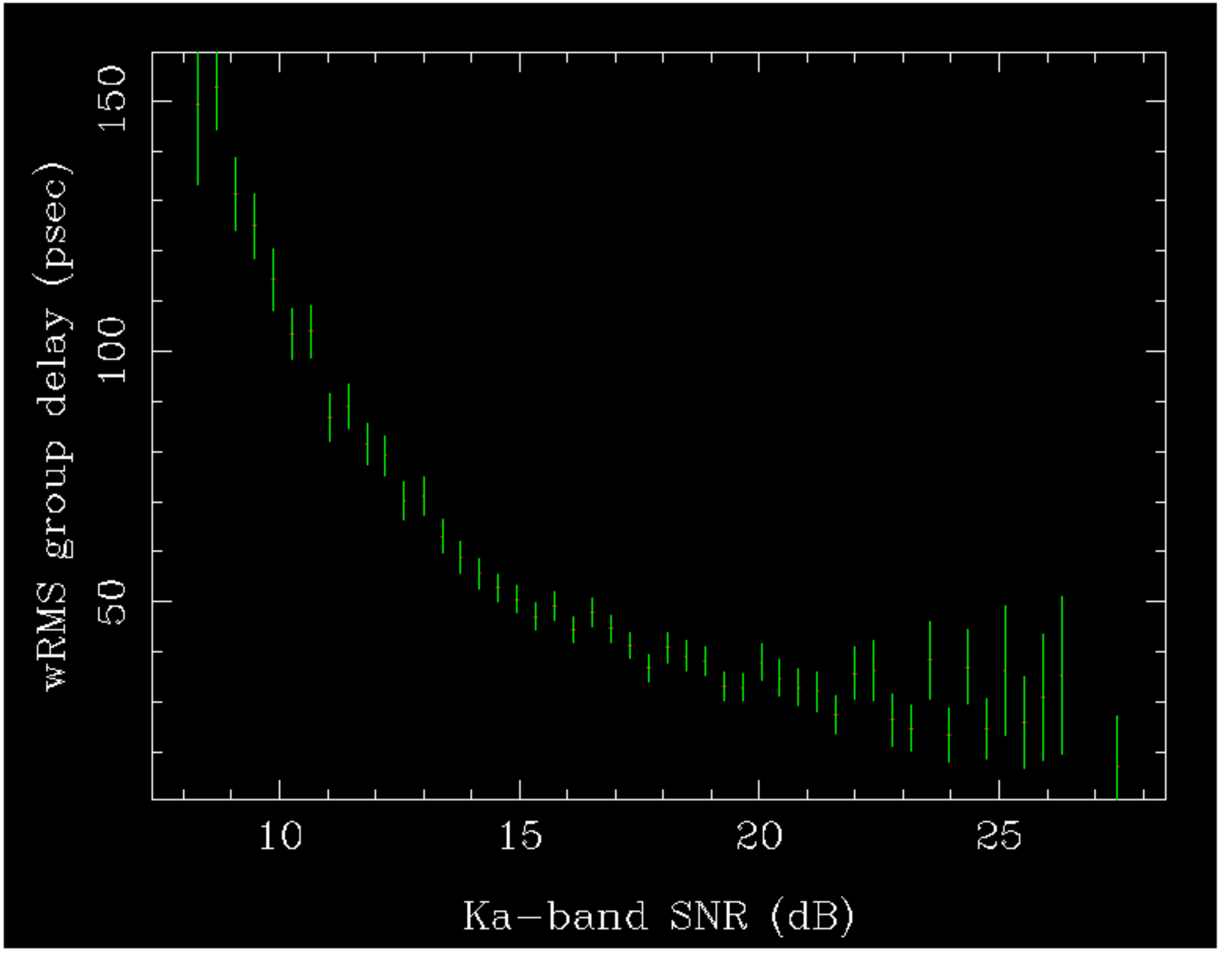
1) More bits:
112 Mbps 2005
448 Mbps 2010
2014 Mbps 2013

4.3 increase sensitivity
+6.3 dB SNR

2) Ka pointing

Now with improved
Pointing calibrations
~3 dB more SNR

Total vs. early passes
+9 dB SNR increase!



Results have been SNR limited for SNR < 30 (15 dB)

Phased implementation, testing

- **Data rate:** **43 passes @ 112 Mbps (X/Ka 56/ 56 Mbps)**

  3 passes @ 224 Mbps (X/Ka 80/144) ~ 3X

  30 passes @ 448 Mbps (X/Ka 160/288) ~ 5X

  current @ 2048 Mbps (X/Ka 640/1408) ~25X

Total Ka improvement 56 to 1408 Mbps => 5-10 psec del. precision

Reduces SNR below troposphere with increased Ka sensitivity!
Thus SNR will longer be the tallest tent pole.

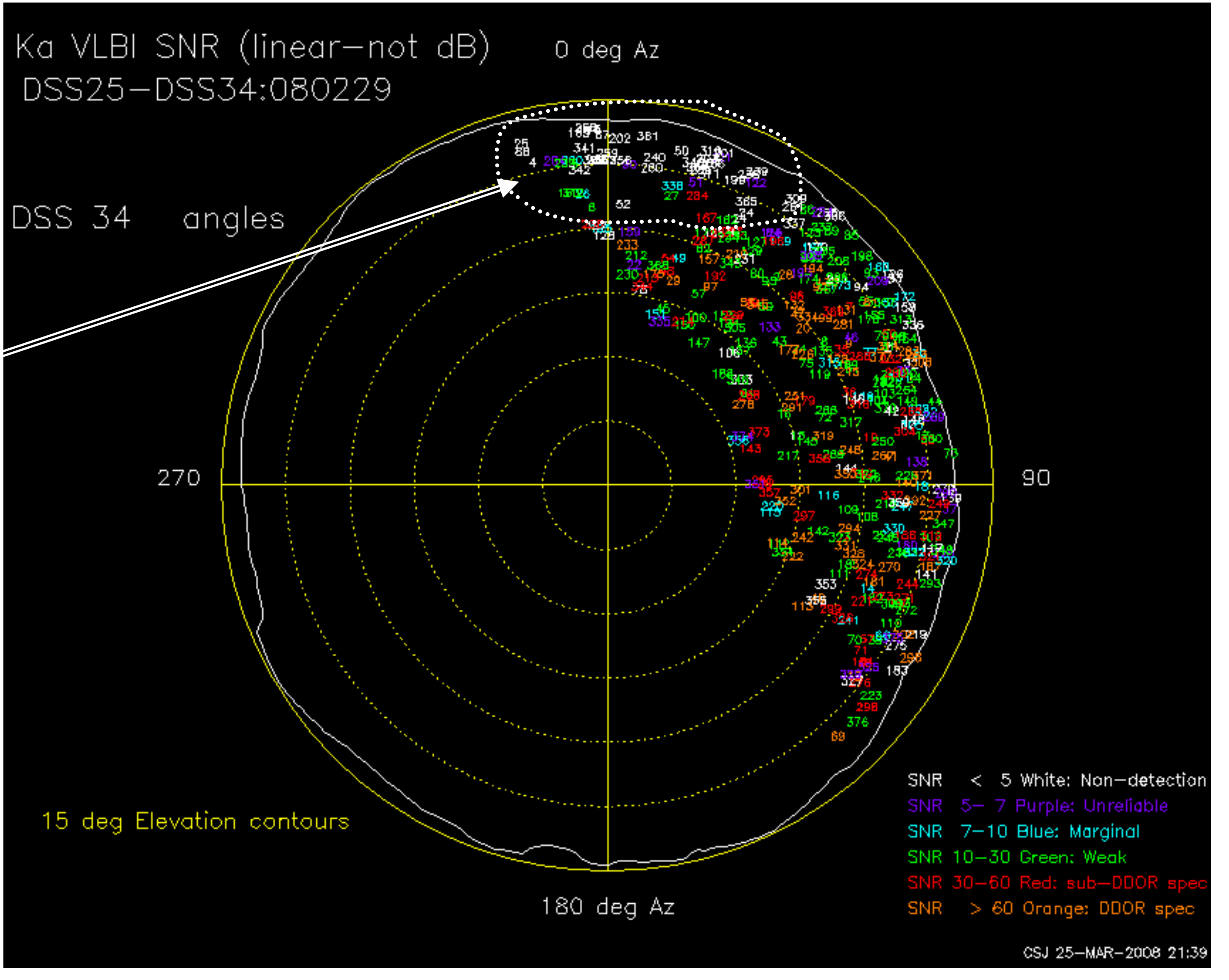
Credit: NASA: C. Jacobs, D. Bagri, E. Clark, C. Garcia-Miro, C. Goodhart, S. Horiuchi, S. Lowe, E. Moll, L. Skjerve, L White

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

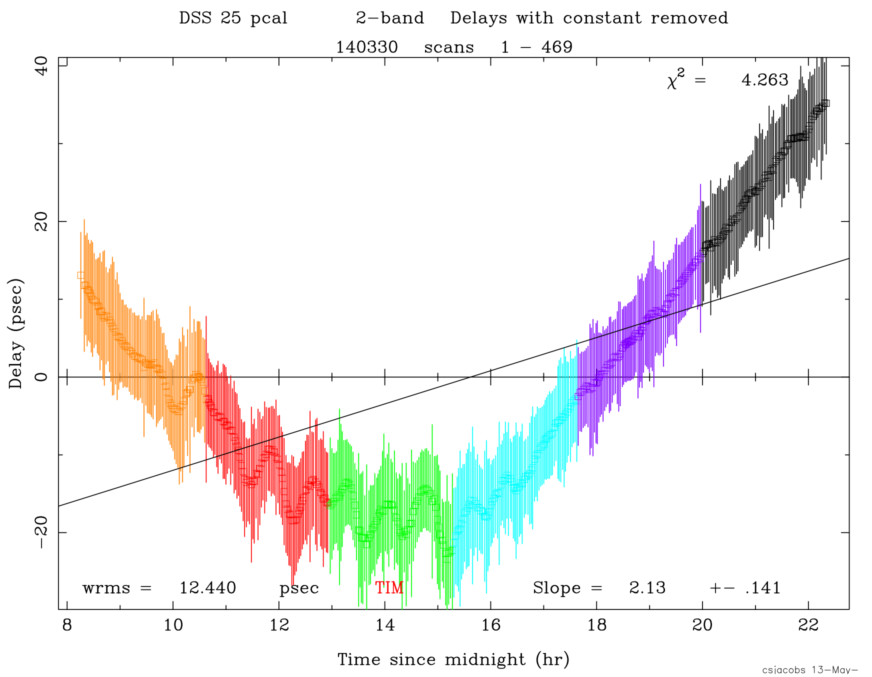
Attacking the Error budget

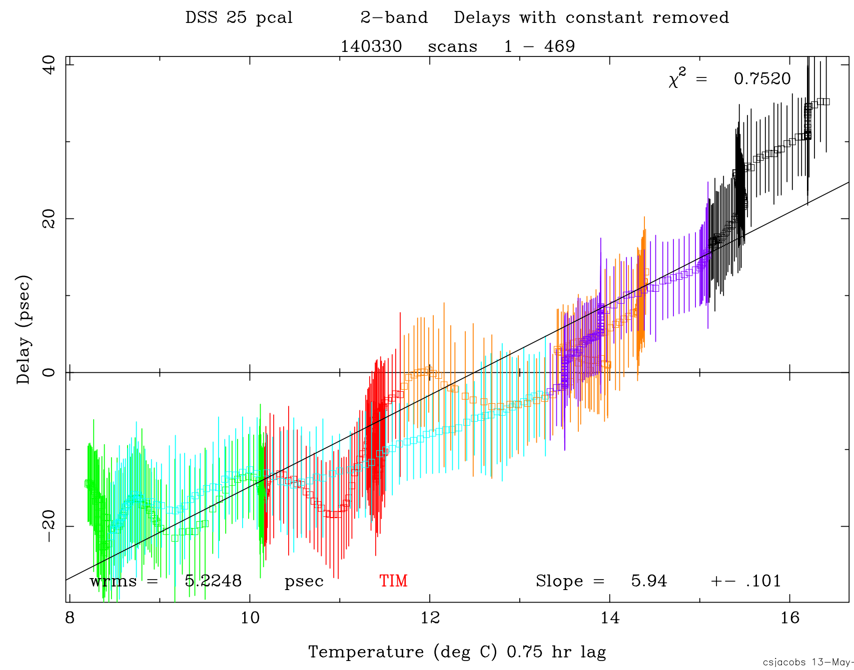
- SNR can be improved +8 dB!
- **Instrumentation:**

  Phase calibration with test signals

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

Results limited by instrumental delays



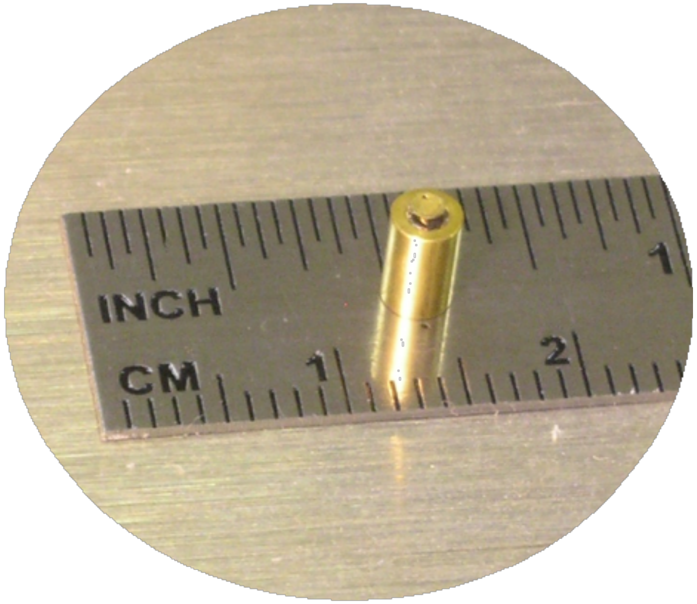


- **Problem: diurnal thermal effect on cables, time lag ¾ hour**
- **Solution: Ka-band Phase calibrator, uses test tones to measure delay**
- **Unit is now operational in California**
  Spain and Australia expected to have units in 1-2 years

Credit: Prototype: C. Jacobs, B. Tucker, L. Skjerve Operational: L. White, D. Bagri, D. Shin, N. Baker

BWG Phase Calibrator

- Concept: Tunnel diode
  Alan Rogers et al (Haystack)



Tunnel Diode Chip
0.055" diameter by
0.020" thick
Mounted on
0.119" diameter carrier
for solid grounding

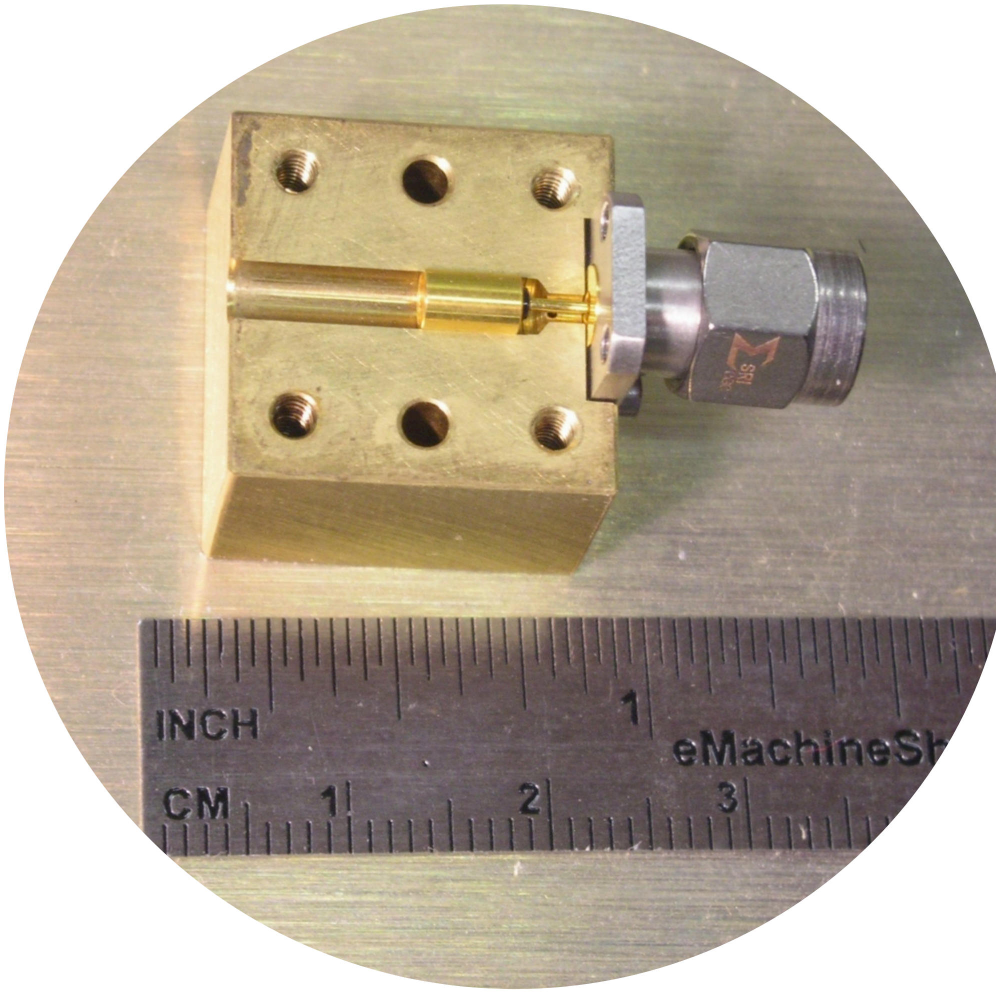
- JPL prototype BWG phase cal:
  Hammel, Tucker, & Calhoun,
  JPL Progress Report, 2003

http://tmo.jpl.nasa.gov/progress_report/42-154/154H.pdf

http://adsabs.harvard.edu/abs/2003IPNPR.154....1H

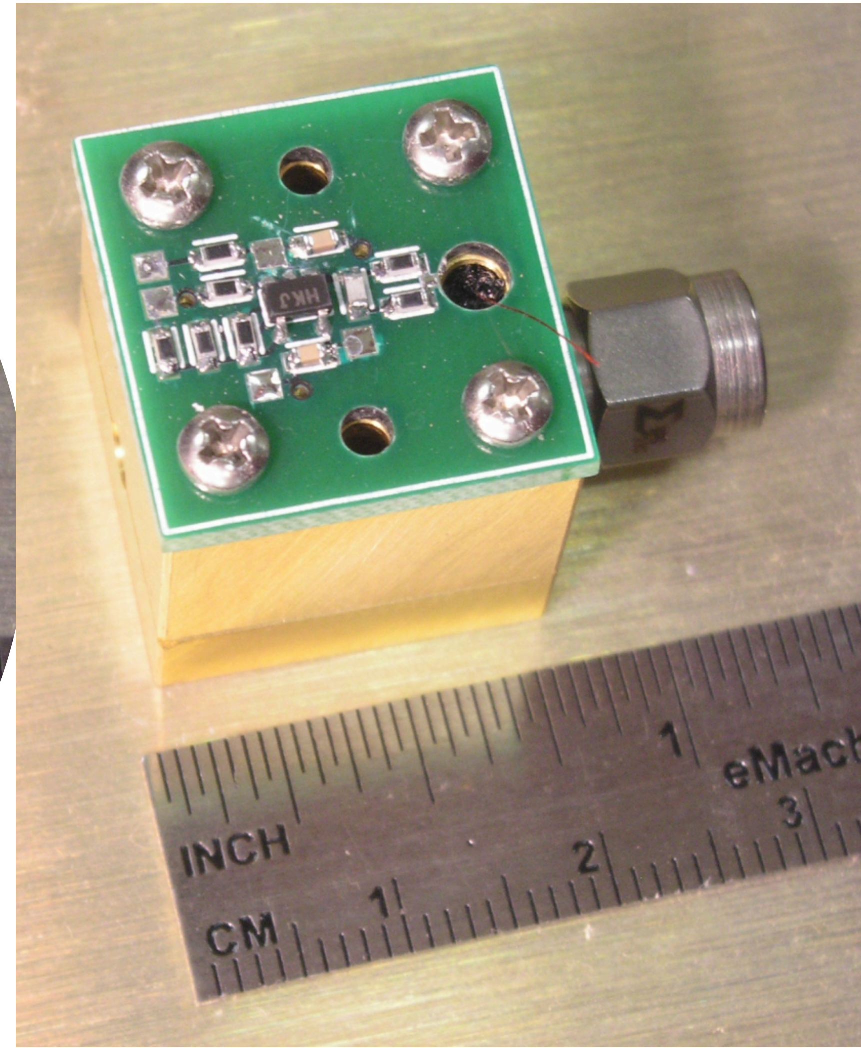
- Production units: Blake Tucker

Beam Wave Guide phase calibrator



Direct interface to K connector
inside coaxial structure.

Credit: Blake Tucker

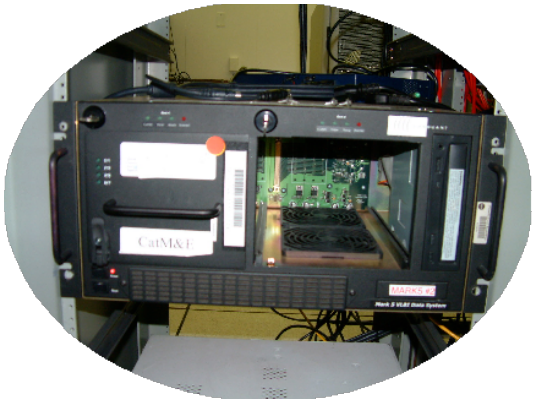


Pulse driver mounted as close as possible
and fed through coaxial structure
to minimize rise time and ringing

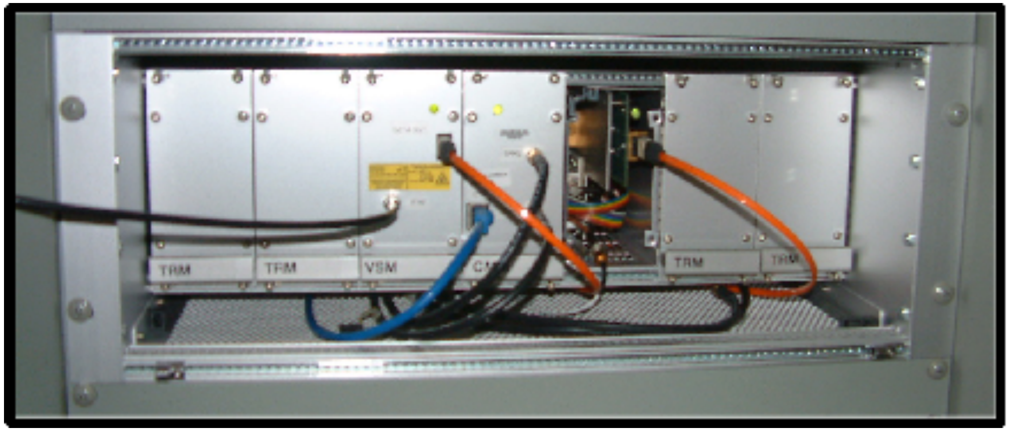
Sample, Baseband convert, Filter, Record

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

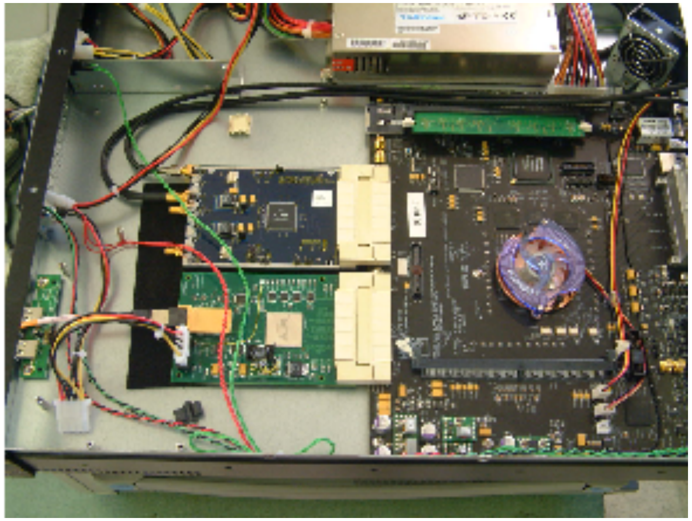
Mark-5C recorder



Command & Control



Sampler: 1280 MHz, 8-bit/sample



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

Design: Navarro et al. Photo credit: Les White

Summary of Instrumental Improvements

Instrument		MkIV	DBE/Mk5-C	Comment
Filters		Analog 7-pole Butterworth	Digital FIR phase linear	removes phase ripple in channel
Spanned bandwidth		360 MHz		Mk4 limit
			500 MHz	1.4X improvement
Data rate	@ start	112 Mbps		DSN SNR limited
	@ max.	896 Mbps		trop/inst. limited
	@ start		2048 Mbps	trop/inst. limited
	@ max.		4096 Mbps	6X sensitivity
Phase Cal:	HEF/70m	Yes	Yes	
	BWG	No	Yes	removes 100s of psec

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

Troposphere Solution 1: Better Estimation

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

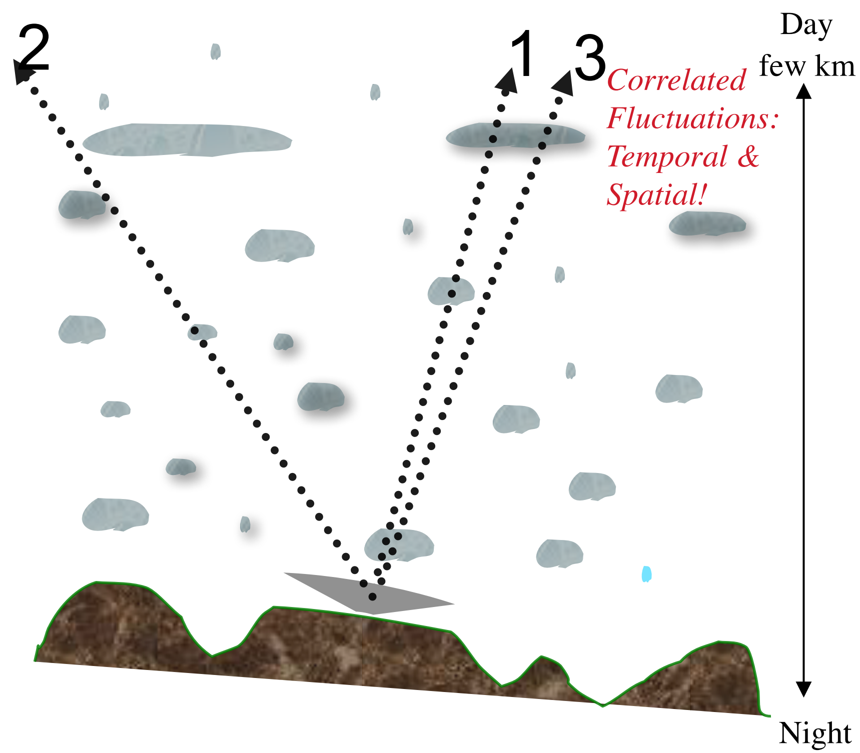
- Use Kolmogorov frozen flow model of Treuhaft & Lanyi (Radio Sci. 1987)

http://adsabs.harvard.edu/abs/1941DoSSR..32...16K
http://adsabs.harvard.edu/abs/1987RaSc...22..251T

- 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.

Romero-Wolf & Jacobs, IVS, 2012 http://www.oan.es/gm2012/pdf/oral_id_119.pdf



Calibrating Troposphere Turbulence

- JPL Advanced Water Vapor Radiometer

  ~ 1 deg beam better matches VLBI
  improved gain stability
  improved conversion of brightness
  temperature to path delay

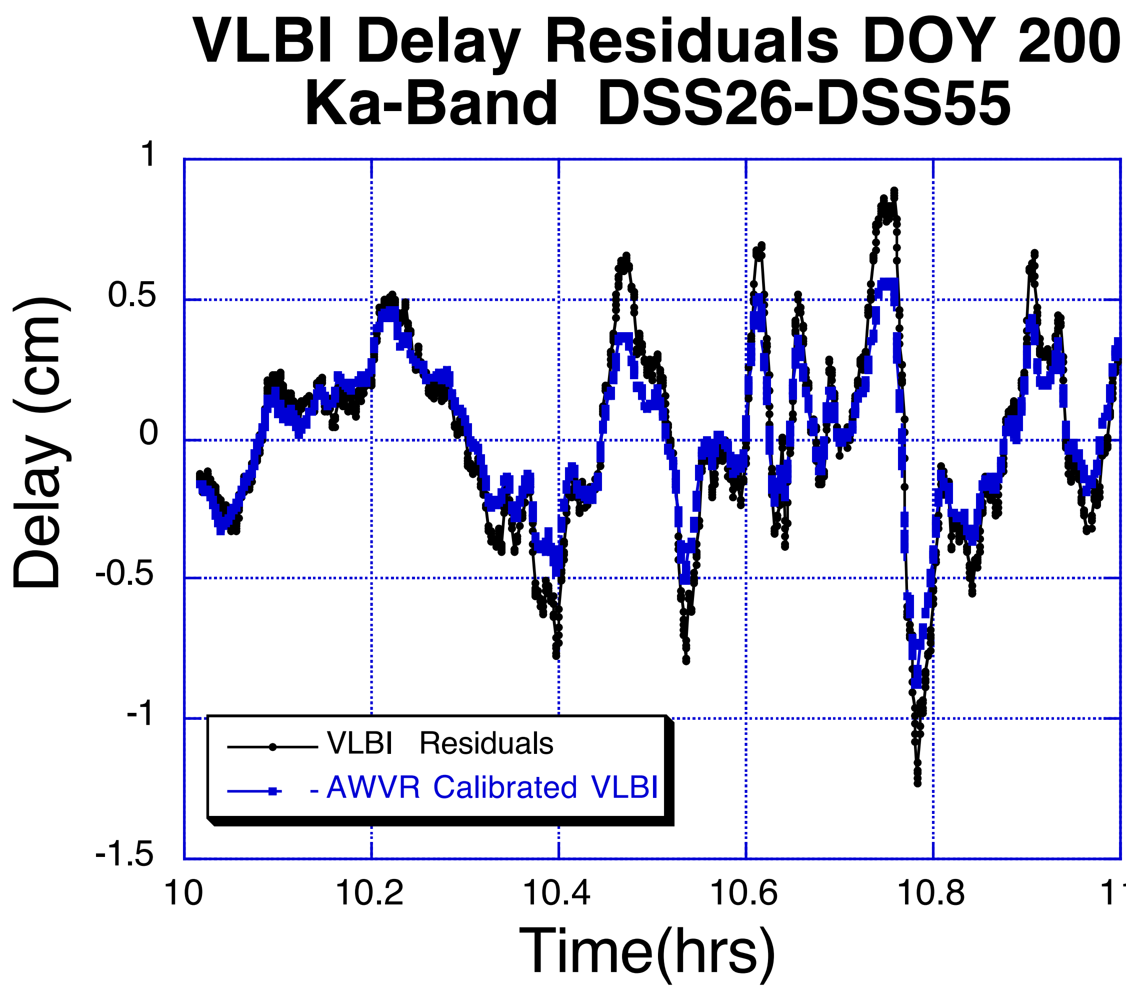
  Tanner & Riley, Radio Sci., 38, 2003
  http://adsabs.harvard.edu/abs/2003RaSc...38.8050T

- Initial demos show 1mm accuracy
  Goldstone-Madrid 8000 km baseline
  using X/Ka phase delays

  Jacobs et al, AAS Winter 2005.
  Bar Sever et al , IEEE, 2007.
  http://adsabs.harvard.edu/abs/2007IEEEP..95.2180B

- A-WVRs deployed at Goldstone/Madrid
  Seeking funding for Tidbinbilla, Aus

- A-WVR not used yet for Operations



Attacking the Error budget

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

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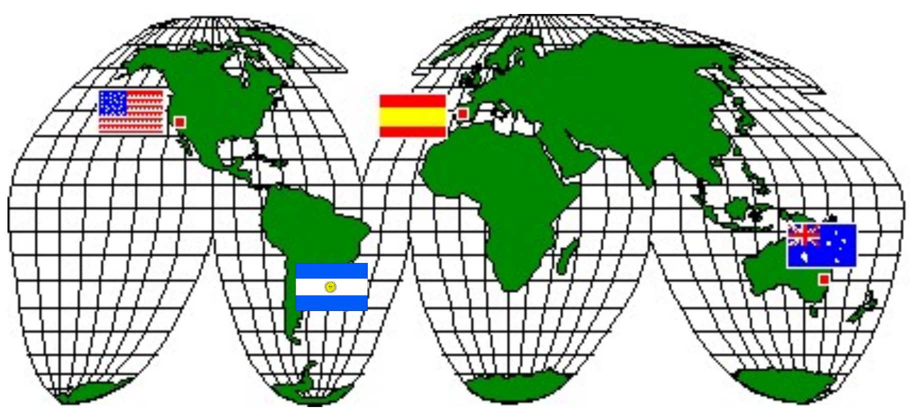
  Digital Baseband Conversion & Filtering
- Troposphere cals: WVR

- **Southern Geometry**

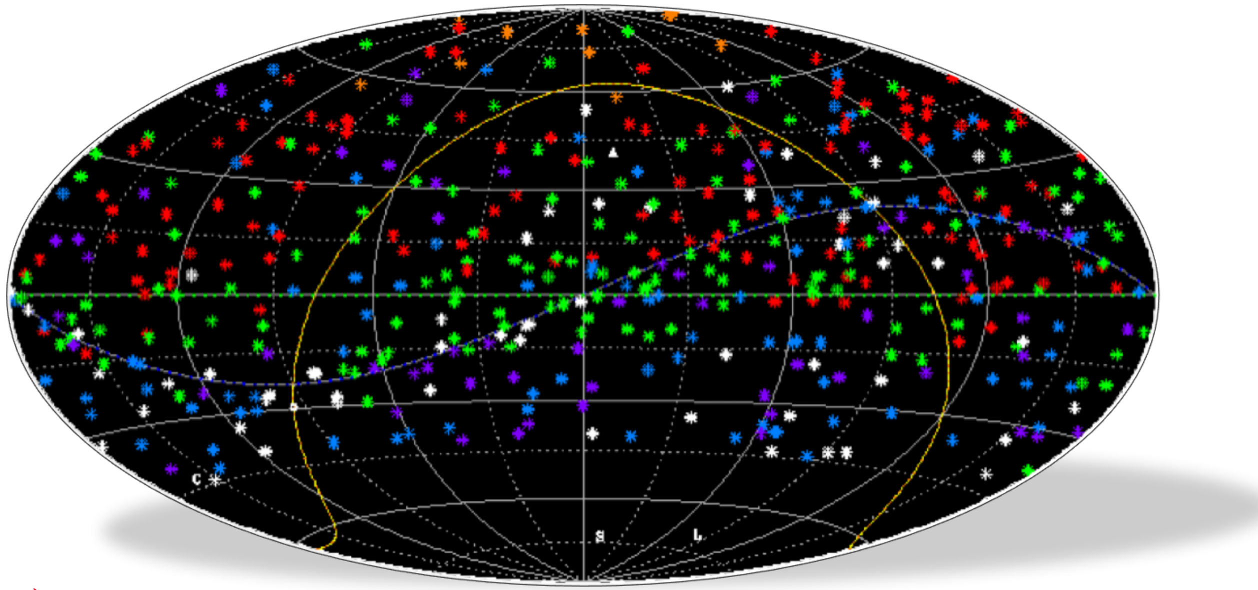


www.spacetoday.org/images/SolSys/DeepSpaceNetwork/NASA_DSN_WorldMap.gif

Need 2nd Station in South

- Almost no Ka sources meet the accuracy goal south of equator!

DSN X/Ka Frame after 50 sessions



- No coverage of South polar cap (-45 to -90 Dec)

- DSN weakly covers southern Ecliptic: only one strong baseline as California-Spain is weak in south

<u>Declination 1-sigma</u>

Orange	0-0.5 nrad meets future ΔDOR spec	
Red	0.5-1.0	current ΔDOR spec
Green	1.0-1.5	
Blue	1.5-2.5	
Purple	2.5-5.0	
White	5.0	

Southern VLBI Stations?

- ESA Deep Space Antennas (DSA-1, 2, 3)
  - New Norcia, Australia S/X (DSN Canberra, 3000km)
  - **Malargue, Argentina:** Ideal,

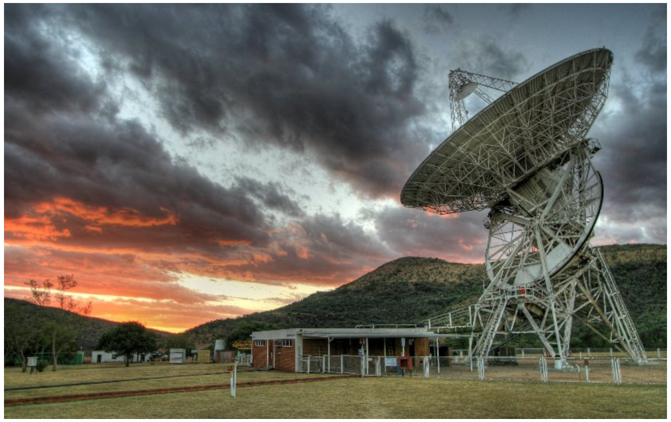
Operational Jan 2013, NASA-ESA collaboration
  - 35m, X/Ka-band, 9,500 km baseline
  - Dry desert site is good for Ka-band
  - HA-Dec coverage: Tidbinbilla to Malargue:

Malargüe 35-m X/Ka, photo credit: L.A. White, Dec. 2012

- HartRAO, South Africa

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

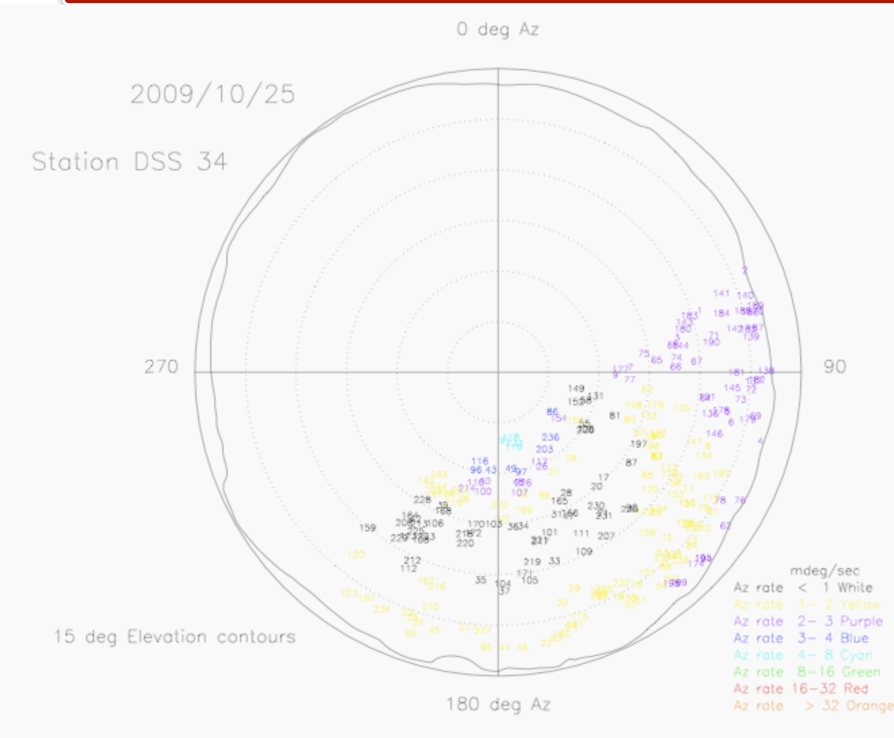
  K-band CRF: *DeWitt et al, and Bertarini et al, Journees 2013.*

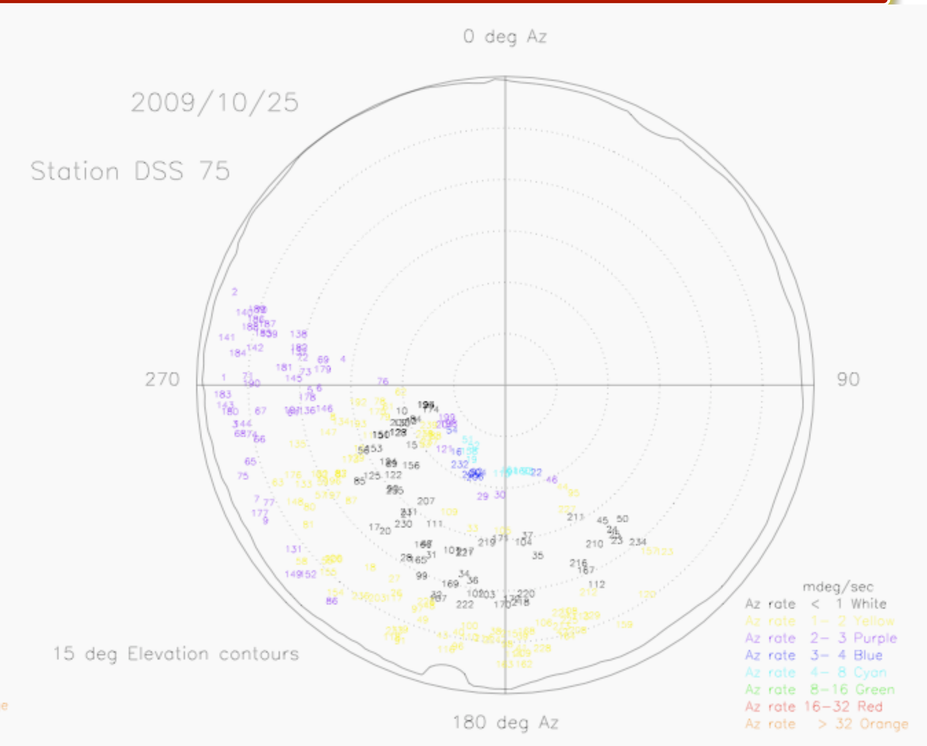


HartRAO 26-meter Photo credit: Thomas Abbott

- Hobart, Tasmania, 12-m (S/X) and 26-m S/X, K-band
- Warkworth, New Zealand, 12-m S/X
- Tidbinbilla, Australia: S/X (34m), X/Ka (34m), K (70m)

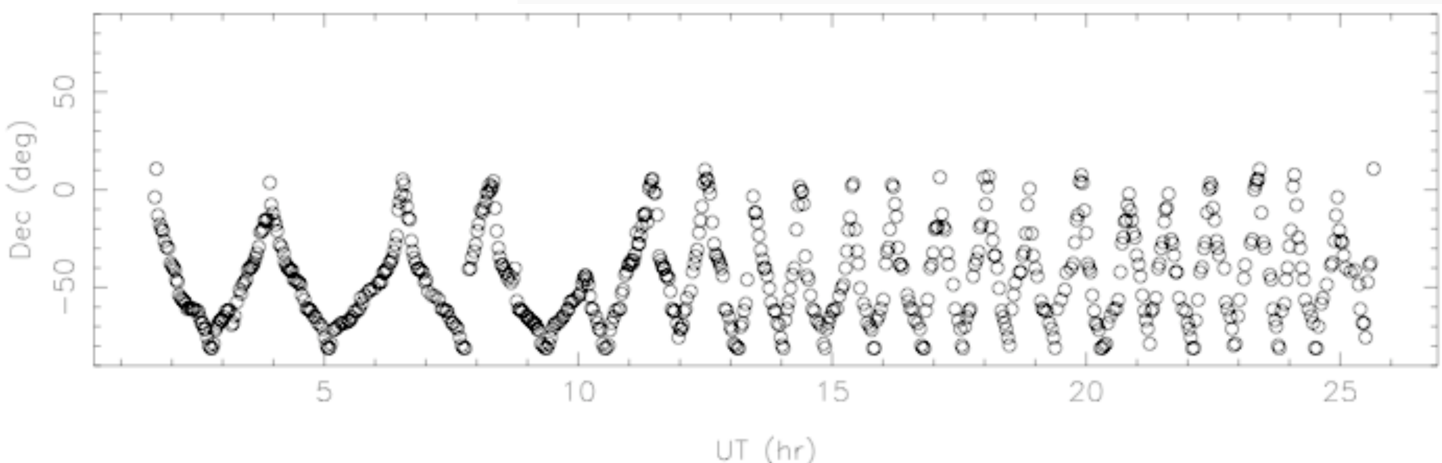
DSS 34 to Malargue, Argentina (DSA-3)



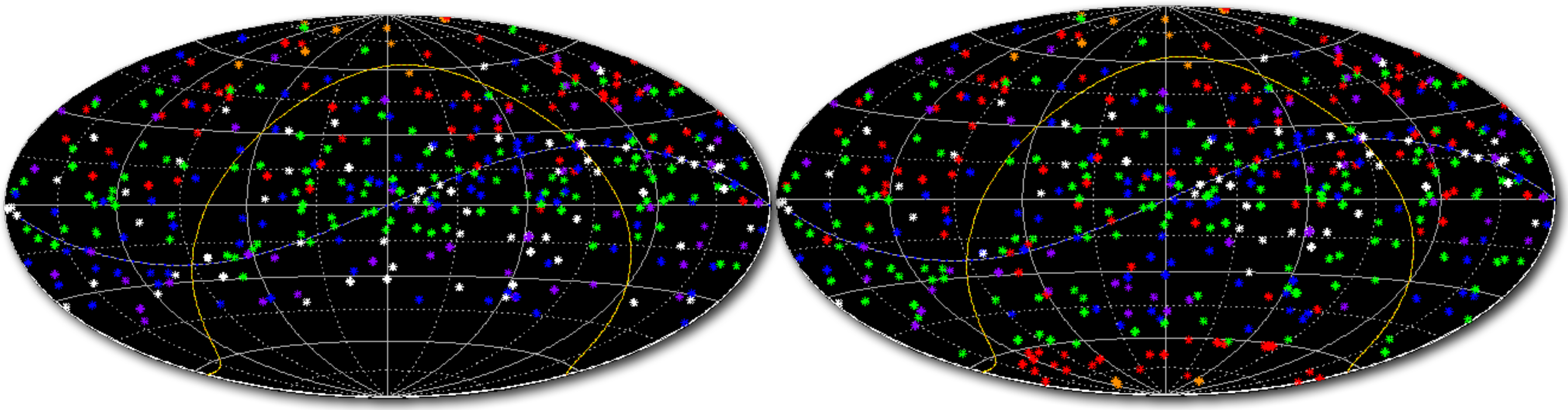


Simulated Coverage:

Dec +10 deg to –90 deg



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

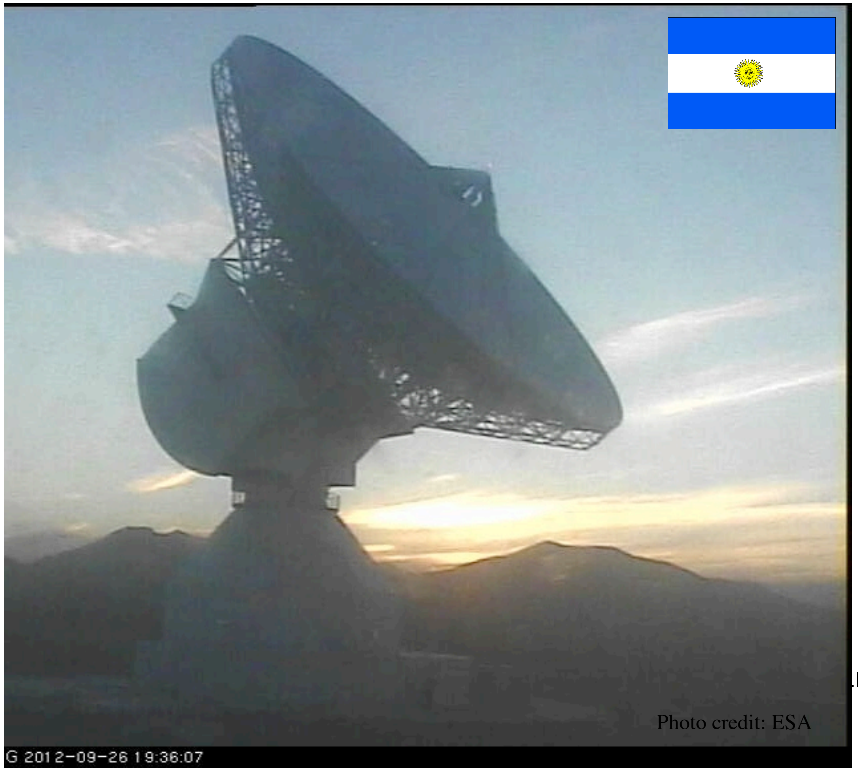
- Completes Declination coverage: cap region -45 to -90 deg
  200 μas (1 nrad) precision in south polar cap,
  mid south 200-1000 μas, all with just a few days observing.

Bourda, Charlot, Jacobs, 2011 http://adsabs.harvard.edu/abs/2011EAS....45..377B

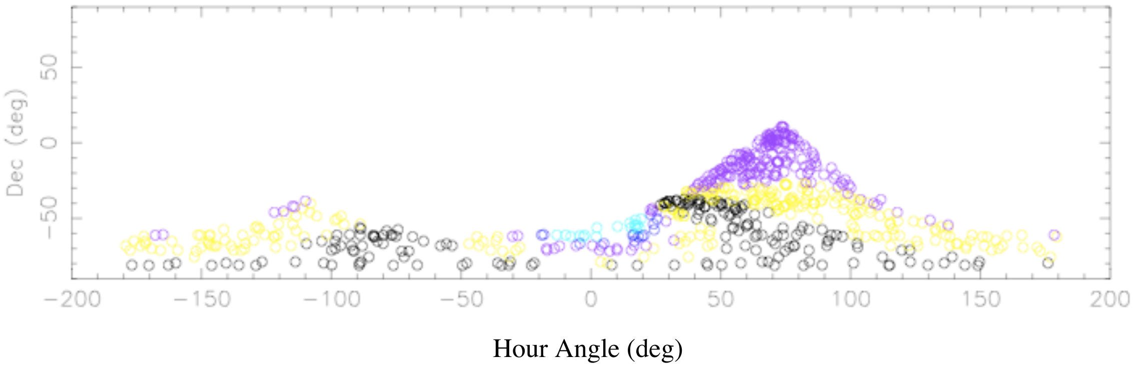
Malargüe: The Next X/Ka VLBI Station

X/Ka: ESA Deep Space Antenna DSA 03

- **Malargüe, 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
- High (1.5km), dry desert site: good for Ka-band
- HA-Dec coverage: Tidbinbilla to Malargüe:

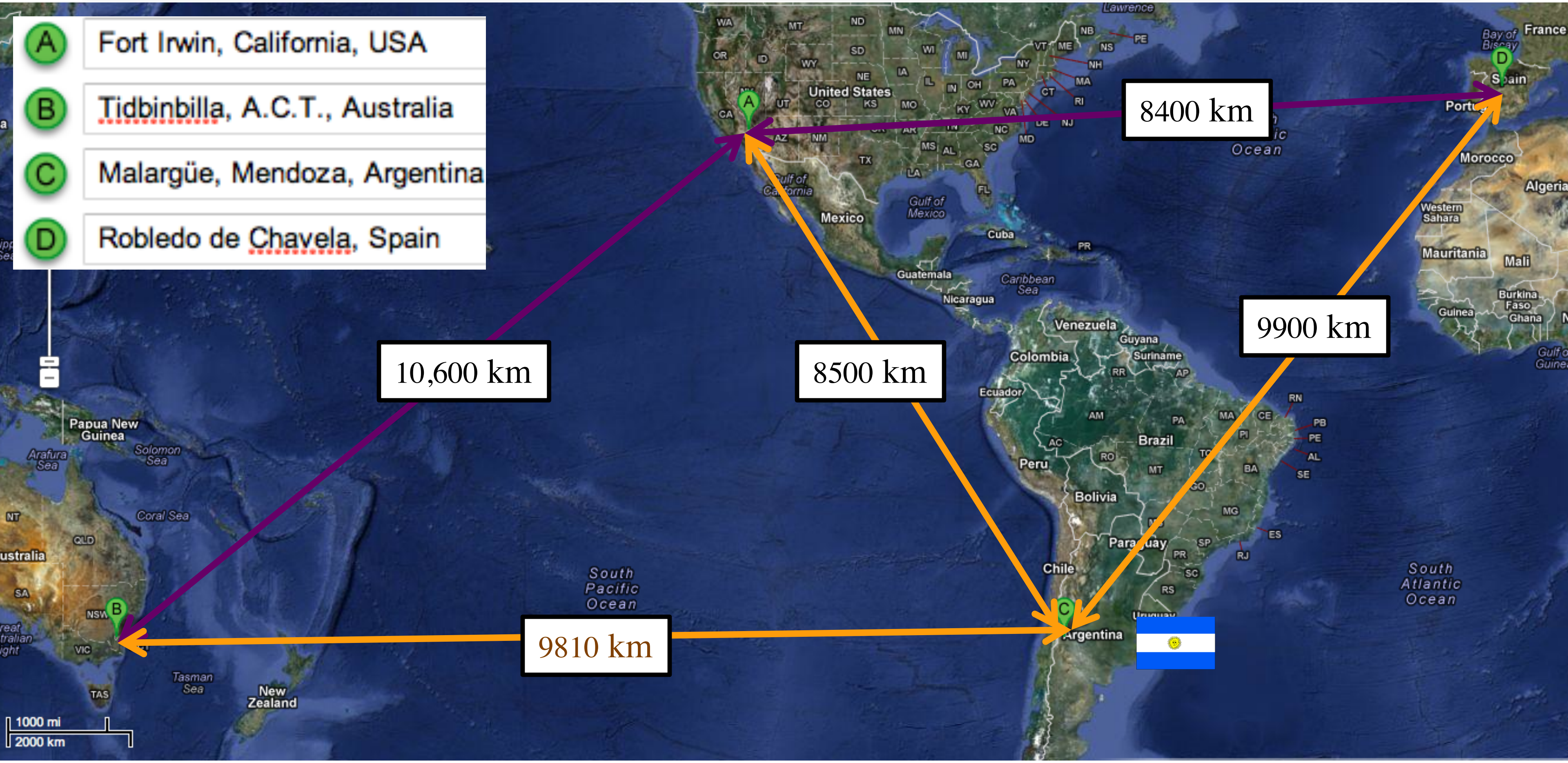


Malargüe, Argentina 35-meter as of 26 Sept .2012



ESA Deep Space Antenna
X/Ka-band capable

X/Ka stations for Celestial Frame



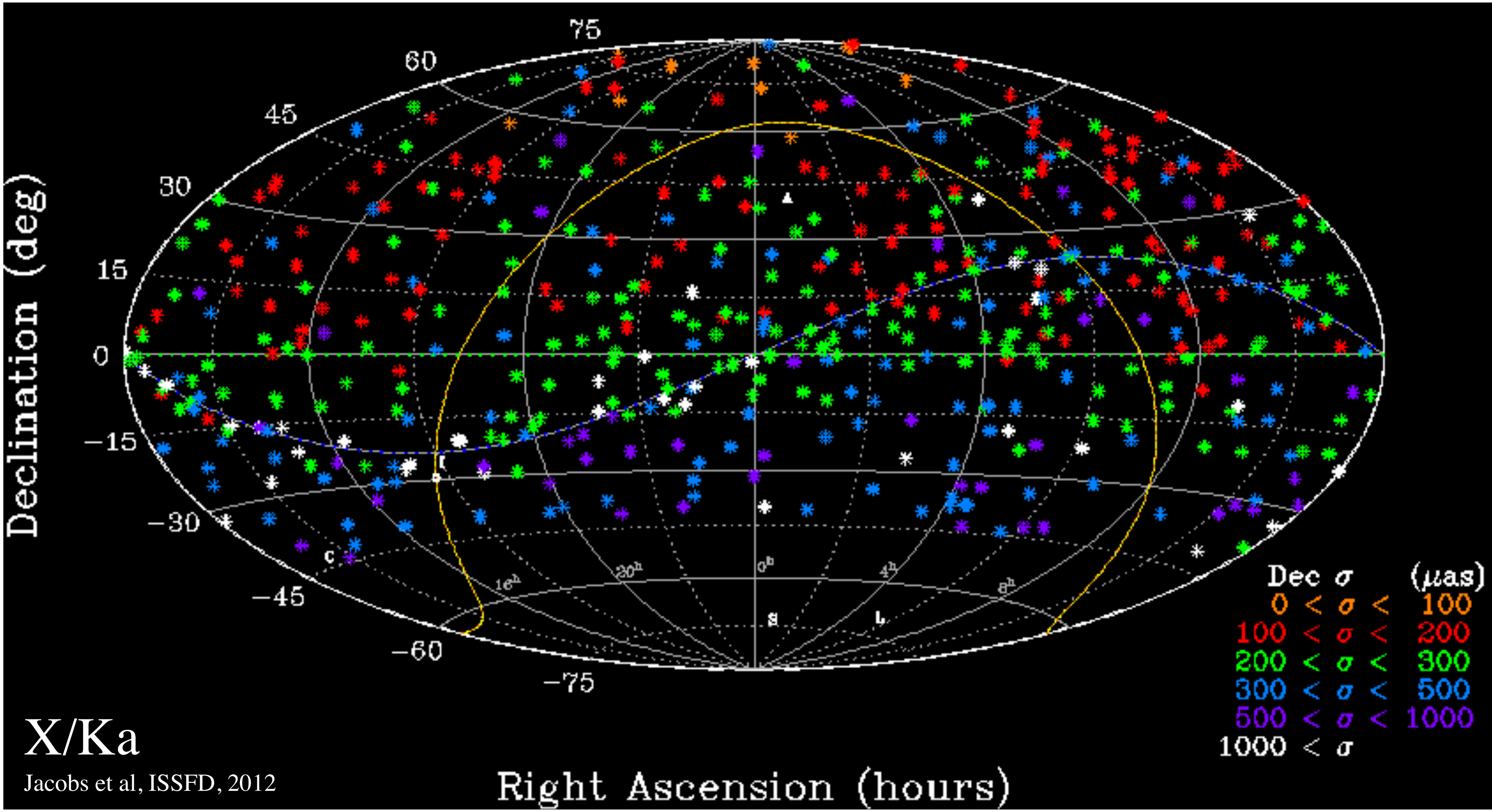
Maps credit: Google maps

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

Jacobs et al, EVGA, 2013 http://adsabs.harvard.edu/abs/2013evga.confE...1J

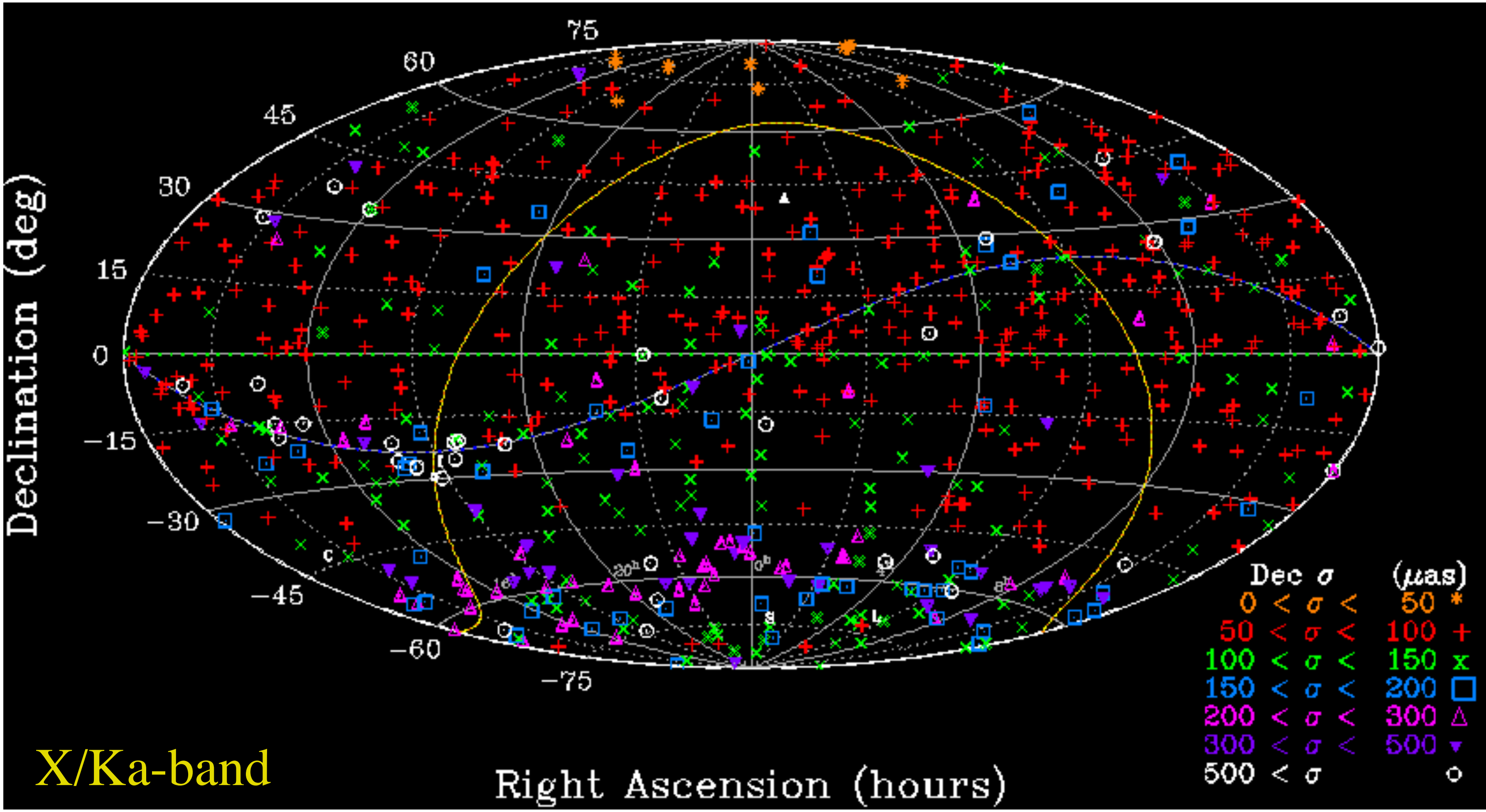
NASA-only 32GHz Dec results: 482 sources



DSN only data before Oct 2012: Goldstone, CA to Madrid, Australia.

Weak in the mid-south (Dec 0 to -45), no south Polar Cap (-45 to -90)

NASA-ESA 32GHz Dec results: 681 sources



DSN: Goldstone, CA to Madrid & Canberra

+ ESA baselines: Malargüe to Canberra, Goldstone, Madrid

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      ad hoc, VLBA, EVN, Global, NASA-ESA DSN, LBA, AuScope, etc.

   C. Brief history of Astrometry: The 'fixed' stars aren't so fixed.

      1. Precession, proper motion, nutation, parallax

      2. Invention of radio astronomy. VLBI's pursuit of (sub)milli-arsecond accuracy.

II. Celestial Frames built using VLBI

   A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS

   B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)

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III. The Path to the Future:

   A. Error Budgets: a tool for allocating resources for improvement

   B. Next-generation geodetic VLBI: Ultra-wide 2-14 GHz

   B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame

   C. ICRF-3: the next standard radio frame

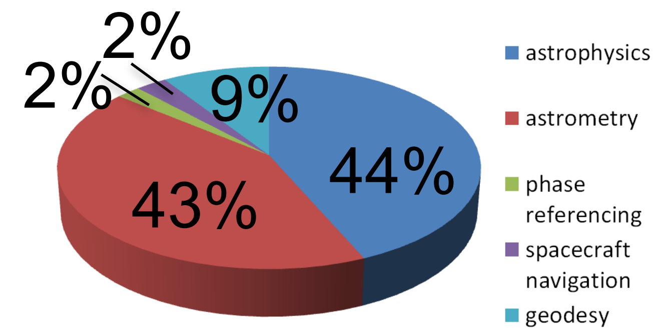
   D. Gaia: the return of optical

III.C. ICRF-3

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



ICRF-1 users: Distribution of ~400 citations

Figure Credit: Heinkelmann, EVGA, 2013

Goals:

1. Complete ICRF-3 by 2018
   in time for comparisons with Gaia optical frame
2. Competitive accuracy 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

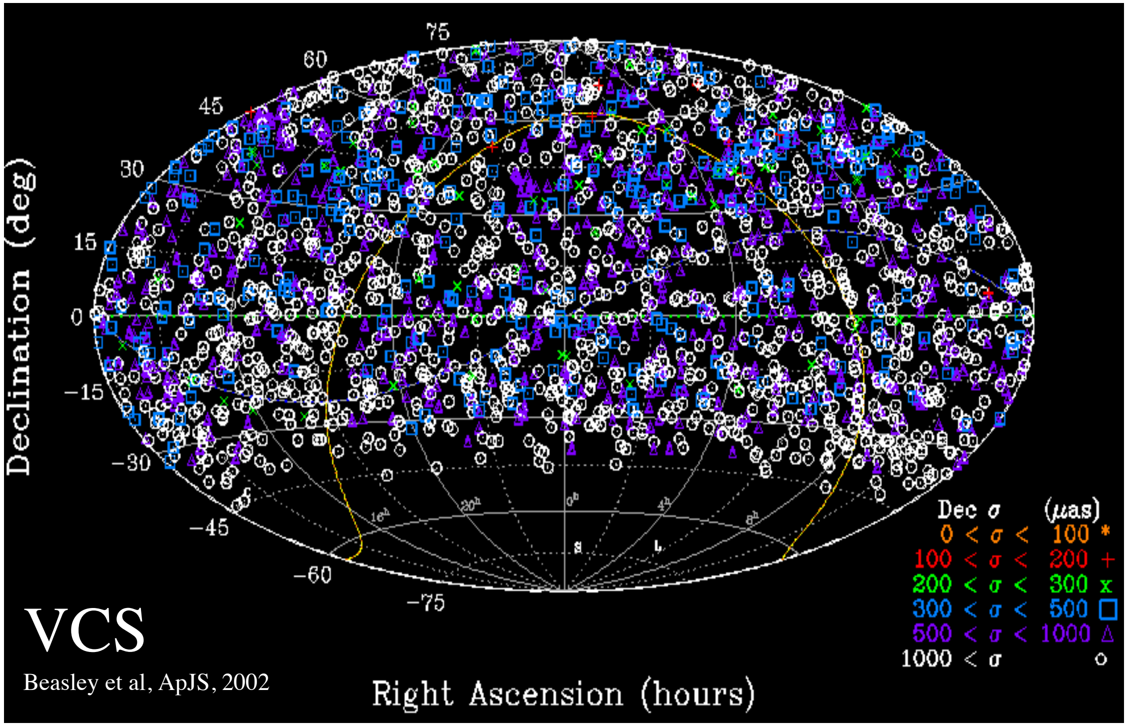
III.C. ICRF-3 Needs

- 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!

<u>Good news:</u>

- VLBA Cal Survey-II
  VLBA approved 8 x 24-hour sessions
  to re-observe VCS sources.

  PI: David Gordon, GSFC
  8 passes completed
  paper submitted to AJ Feb 2016

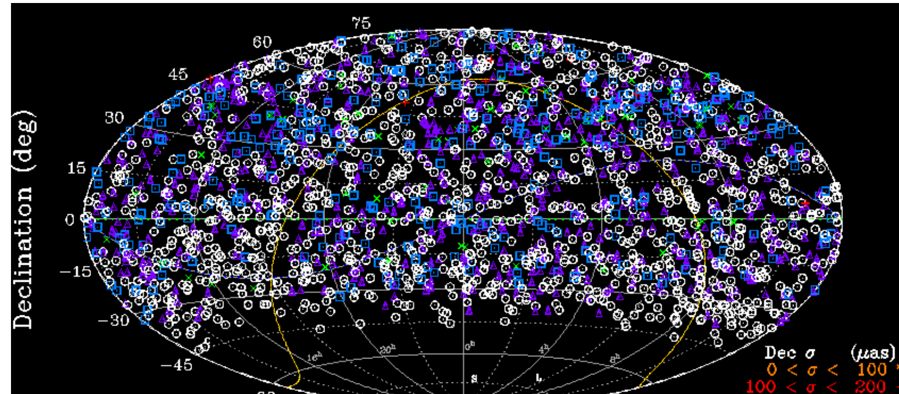


<u>ICRF2: VCS vs. Non</u>

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

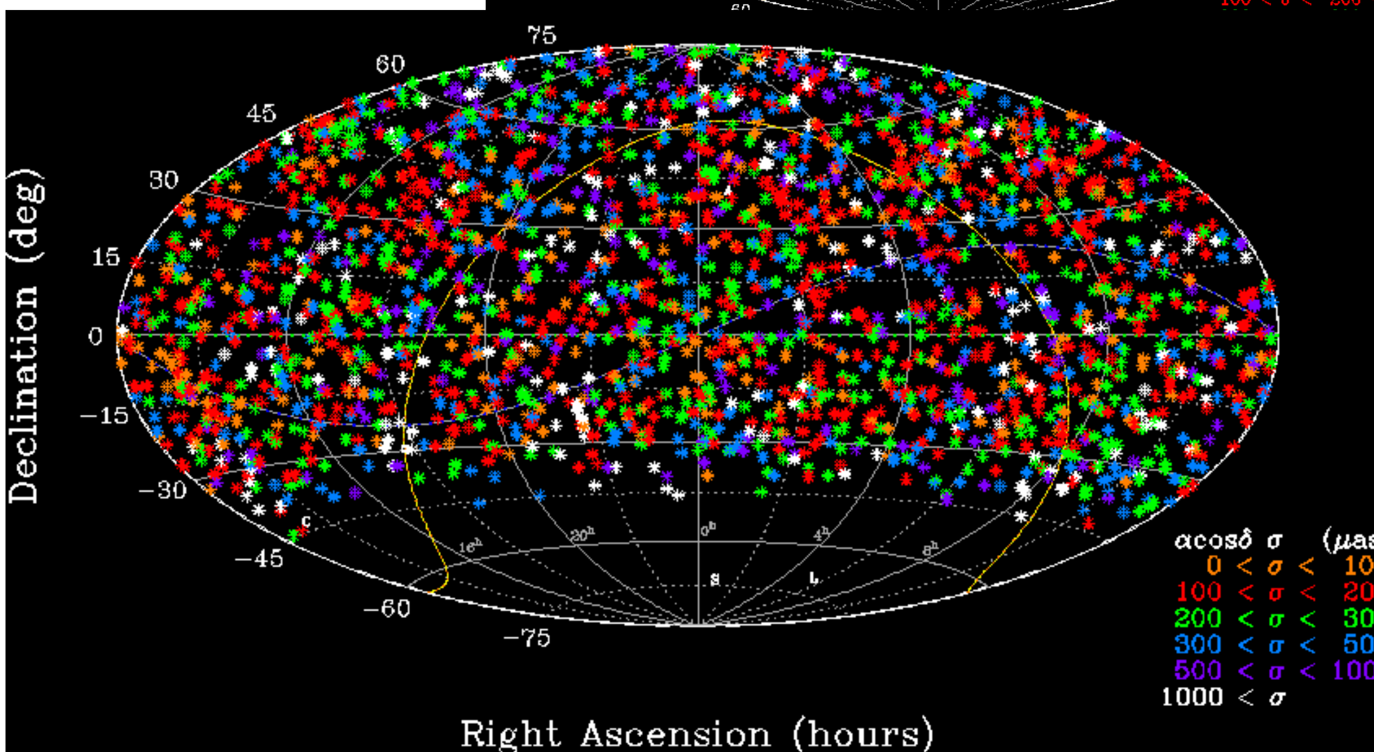
VLBA Calibrator Survey improvement

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



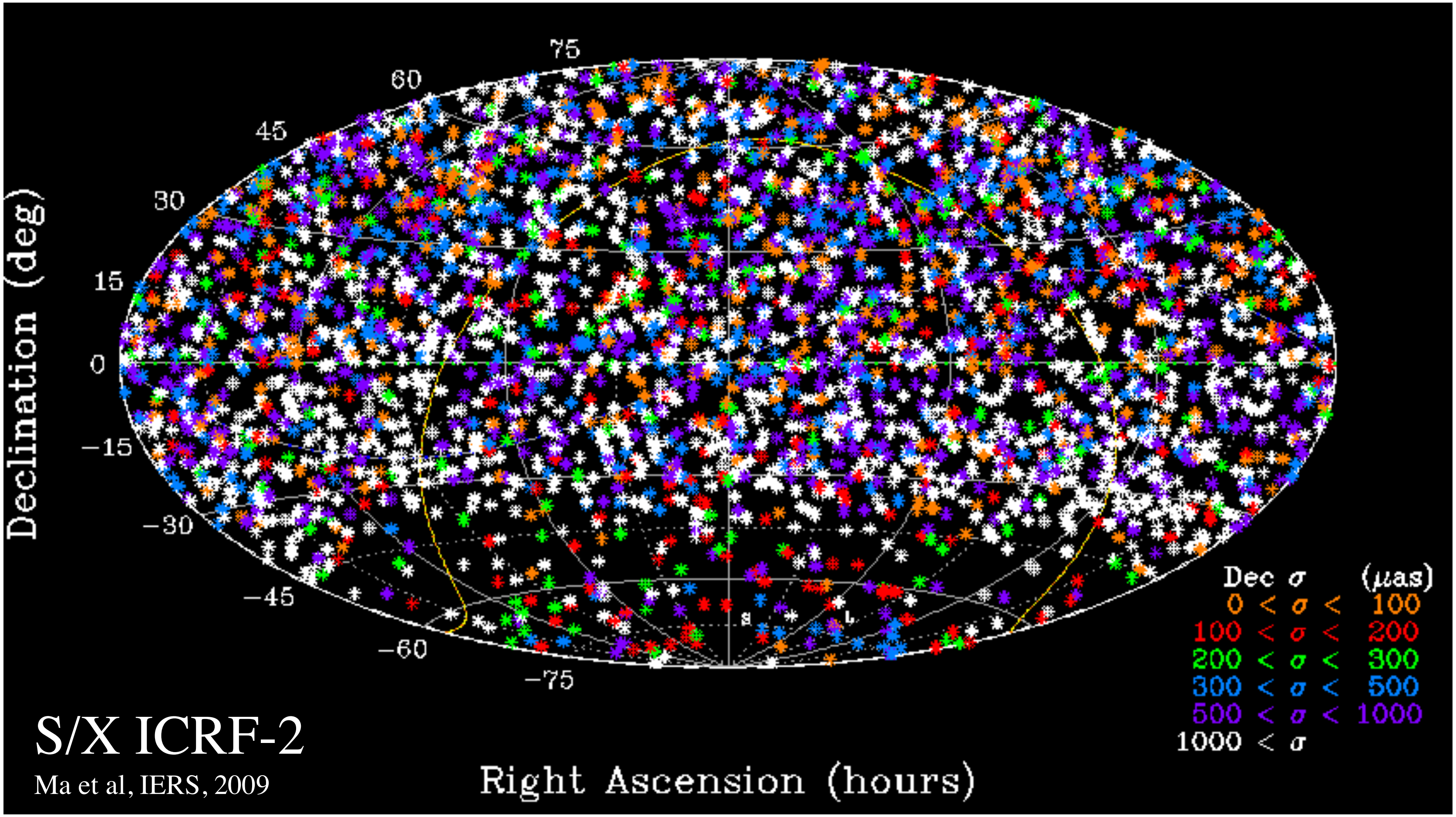
VCS-II:
RA 0.23 mas
Dec 0.39 mas

Improvement
~ 5 times



Credit: Gordon et al, AJ, submitted Feb 2016.

III.C. ICRF-3 Needs

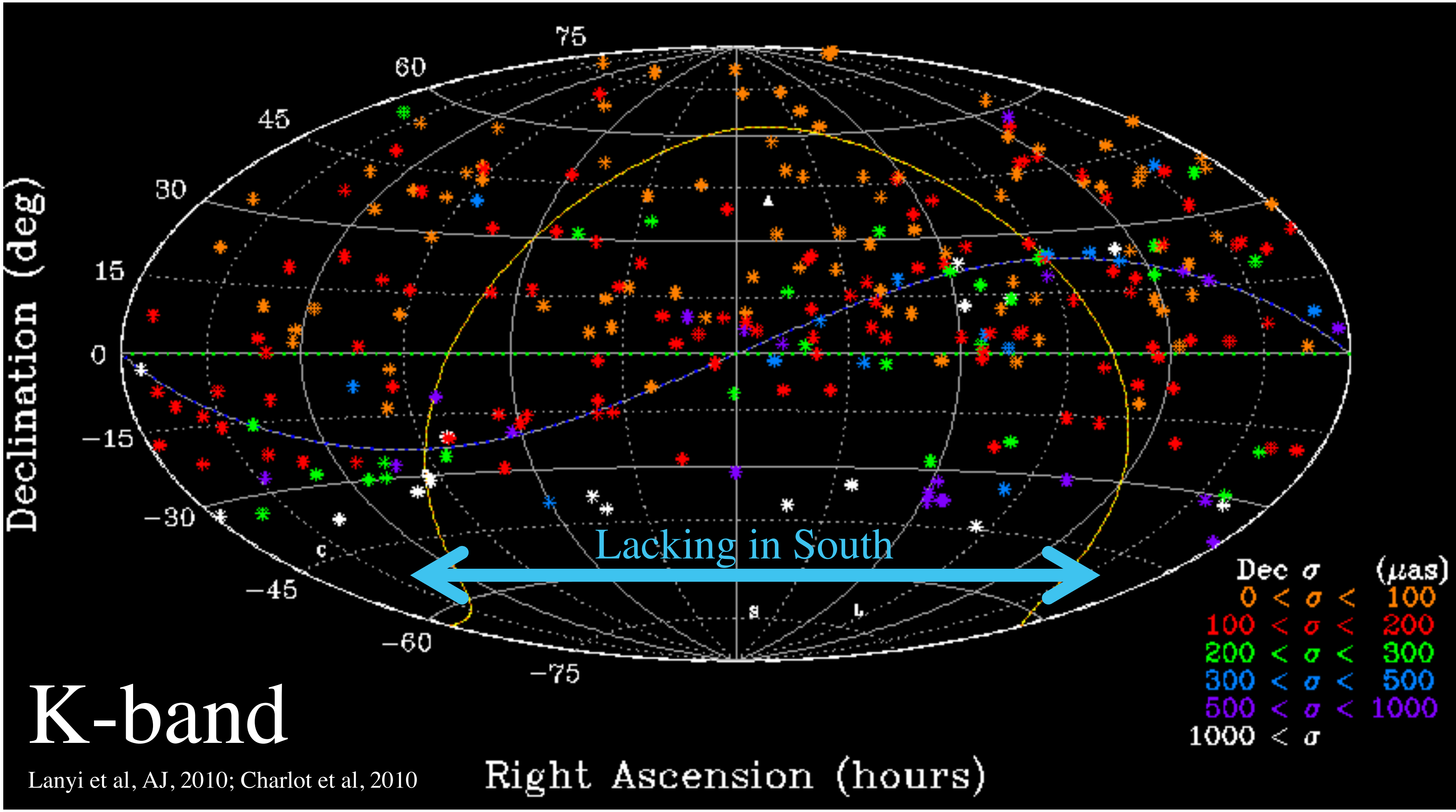


Southern Hemisphere:

VLBI generally & ICRF-2 specifically lacks southern observations (Dec < -35 deg)

AuScope, Hobart, HartRAO exploring additional S/X observations

III.C. ICRF-3 Needs

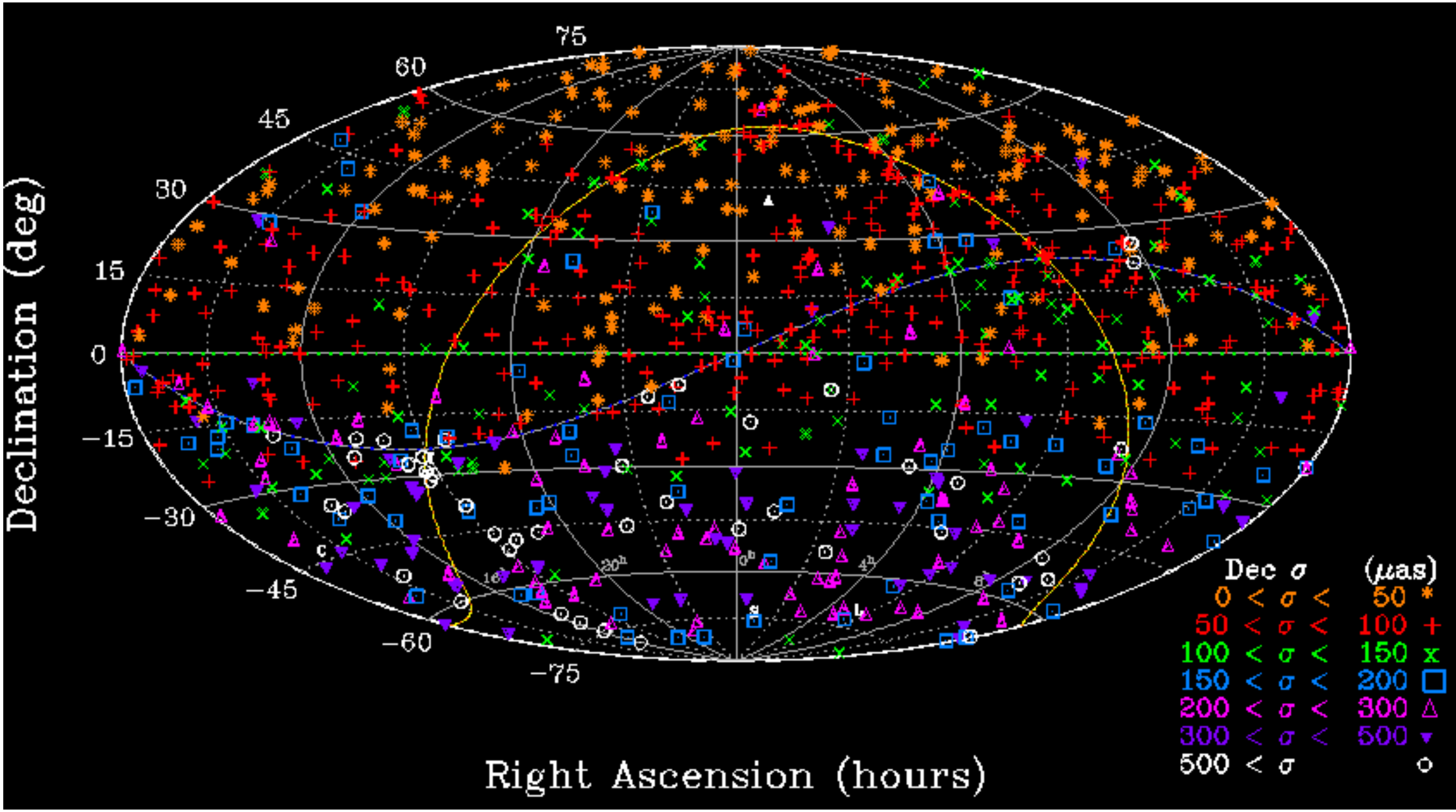


K-band frame (24 GHz) lacking in the south for Dec < -30 deg (limit of VLBA work)

K-band: HartRAO to Hobart, Tasmania

New K-band CRF collaboration: *cf. Bertarini et al* & *de Witt et al, Journees 2013*

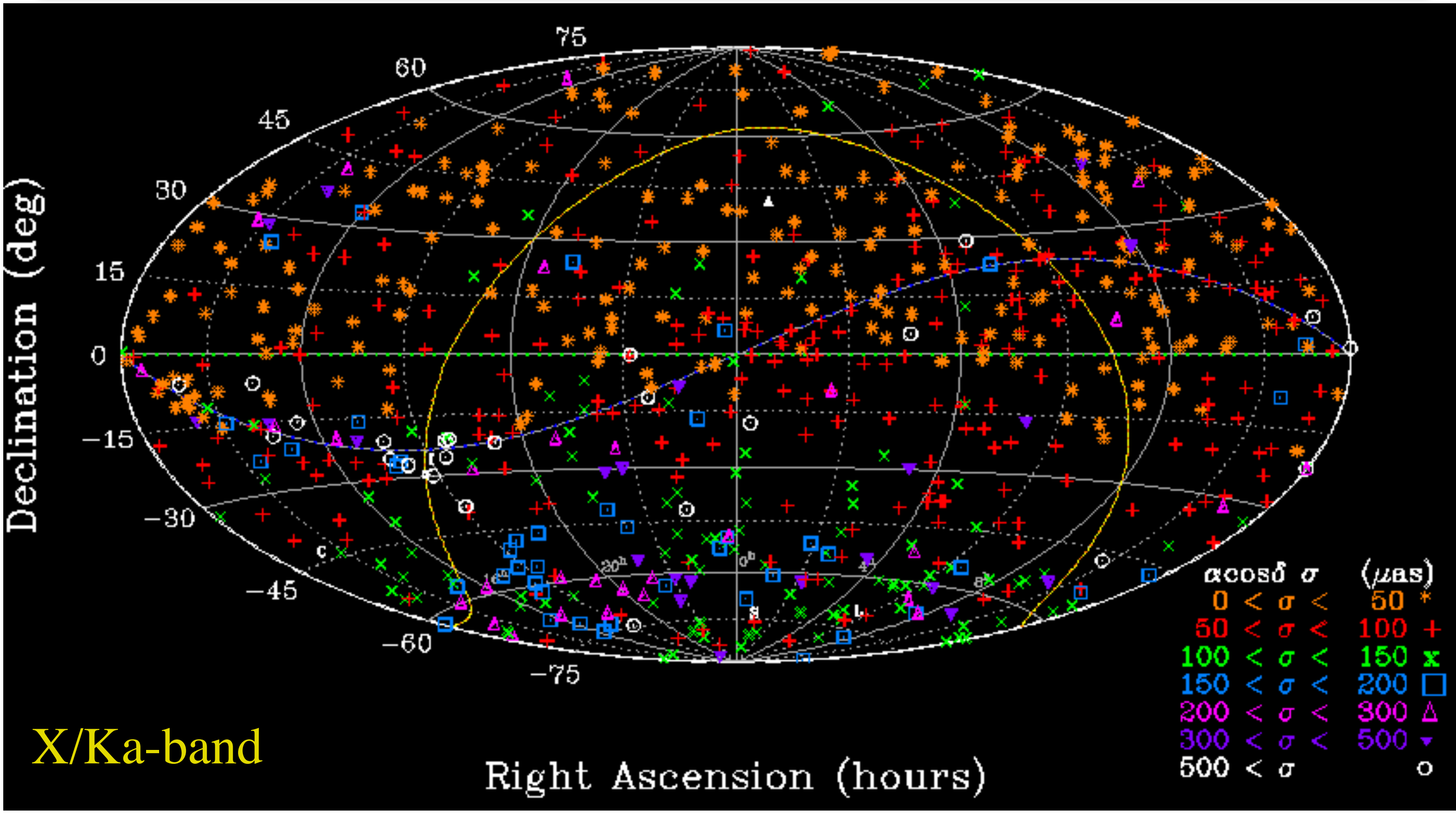
K-band (24 GHz) CRF: 826 sources



VLBA 35 sessions @2Gbps to densify the north *(de Witt et al, EVGA, 2017)*

Hart-Hobart (Tianma): 15 sessions. Archive (Lanyi et al, 2010, Petrov et al, 2006).

X/Ka-band (8/32 GHz) CRF



- Deficiency: Weaker in the south. S. cap 134 sources (dec< -45); 27 ICRF2 Defining
- Full sky coverage (681 sources): NASA baselines CA to Madrid & Australia
  + recently added ESA Malargüe, Argentina to Tidbinbilla, Australia, PI: Jacobs

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III.D. Gaia Optical Frame

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

Celestial Frame tie
and
Accuracy Verification

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

Launched Dec 2013
(Francois Mignard)

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)

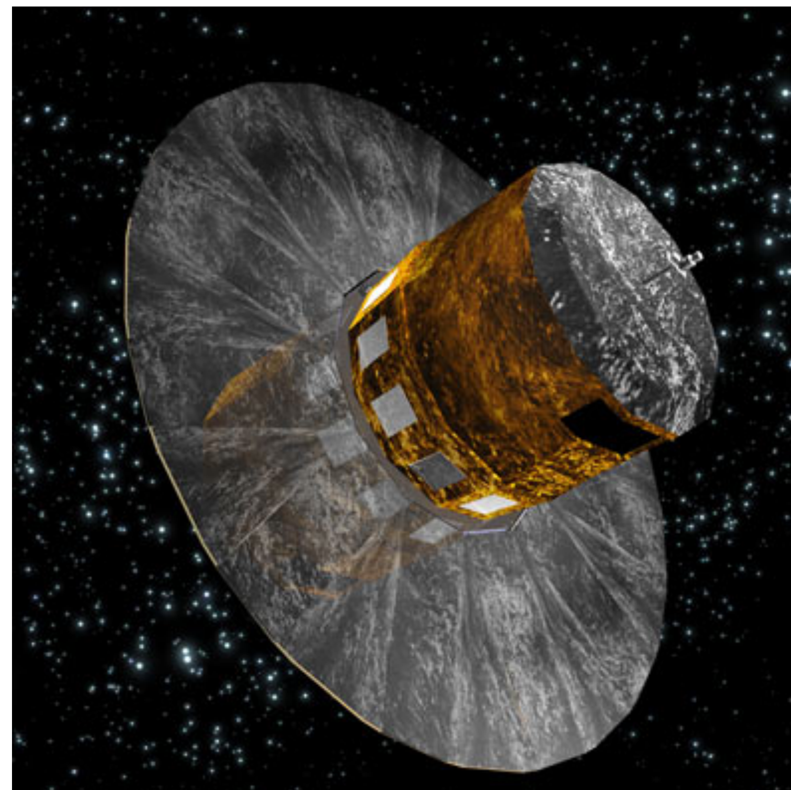


Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7

Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids

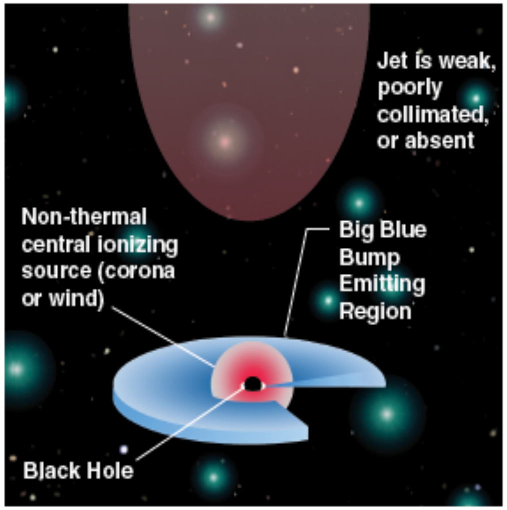
  - radio: synchrotron from jet

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

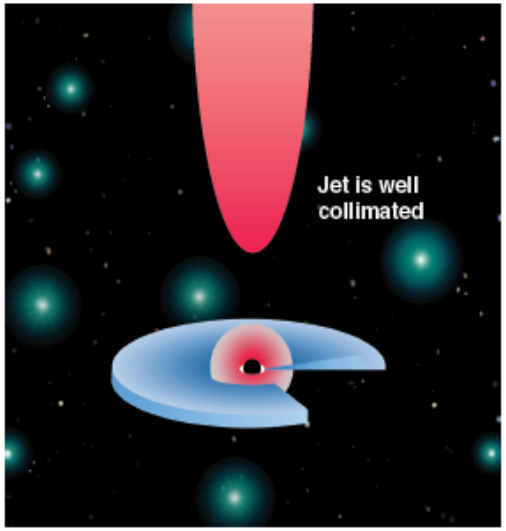
- Instrumental errors both radio & optical

- Analysis errors

Radio-quiet Quasar

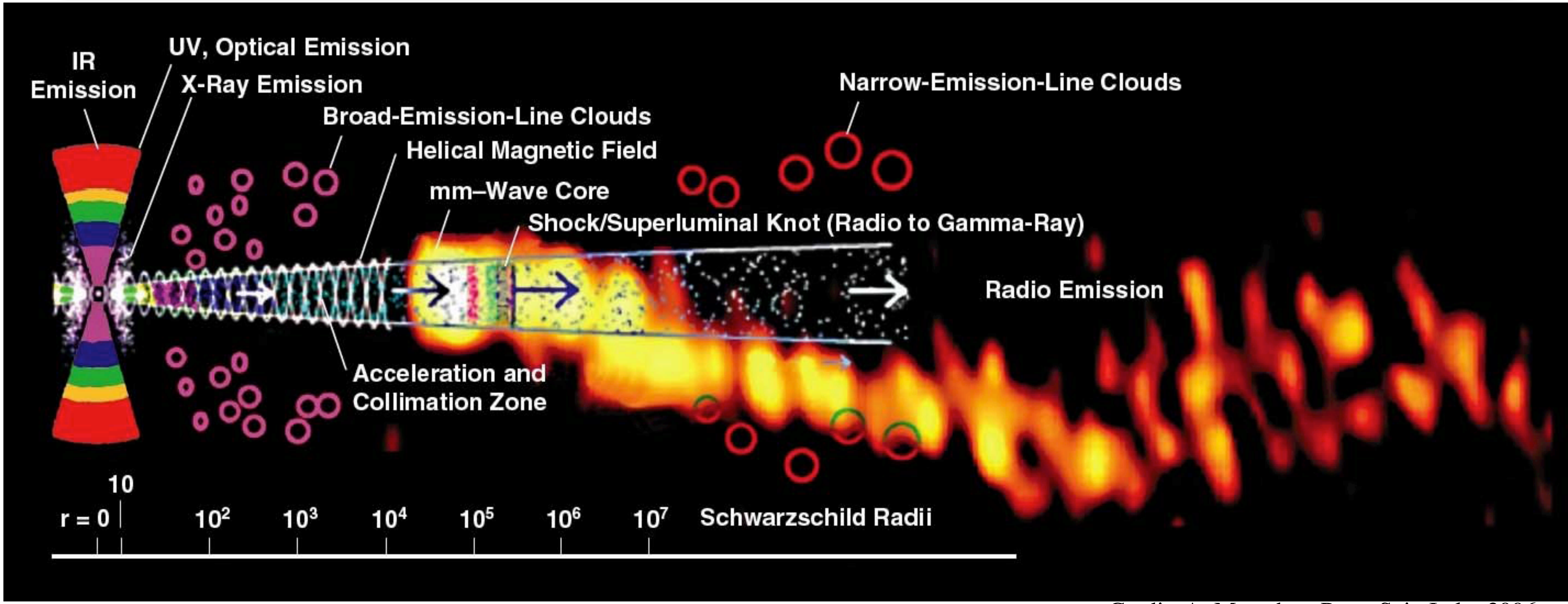


Radio-loud Quasar



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

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.

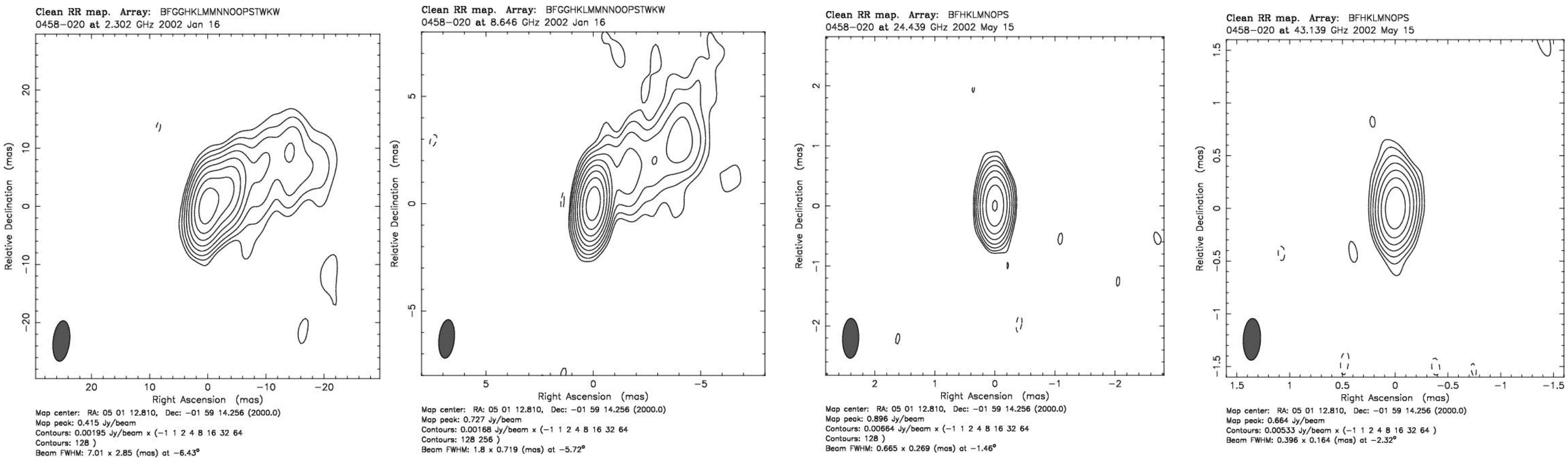
Positions differences from 'core shift'

- 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
- Event Horizon Telescope (230 GHz) probing ~10 Schwarzschild radii (Doelman et al)

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

Image credits: Pushkarev & Kovalev A&A, 544, 2012 (SX); P. Charlot et al, AJ, 139, 5, 2010 (K)

Optical brightness of X/Ka sources

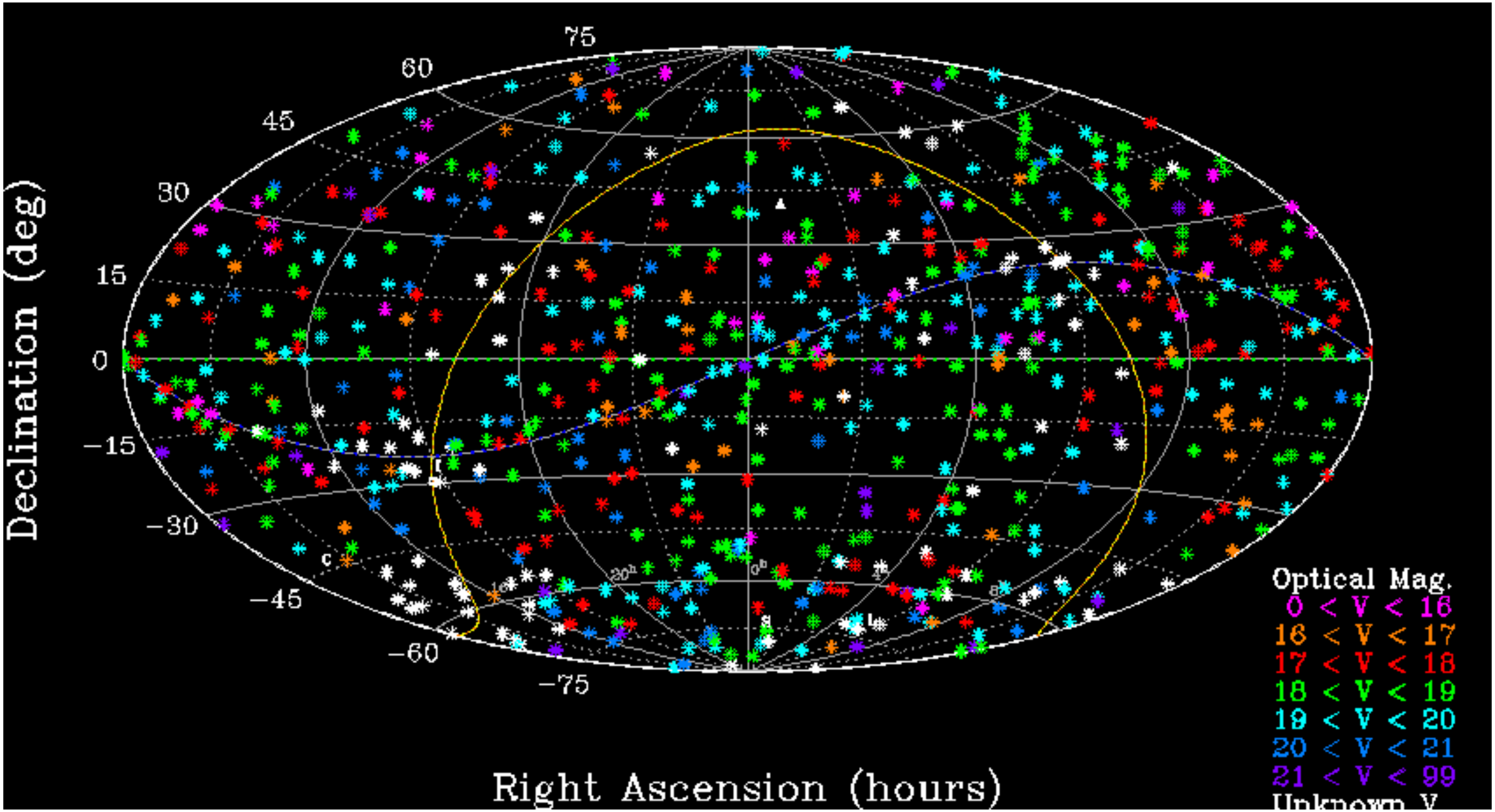


Figure credit: Garcia-Miro et al, EVN, 2014

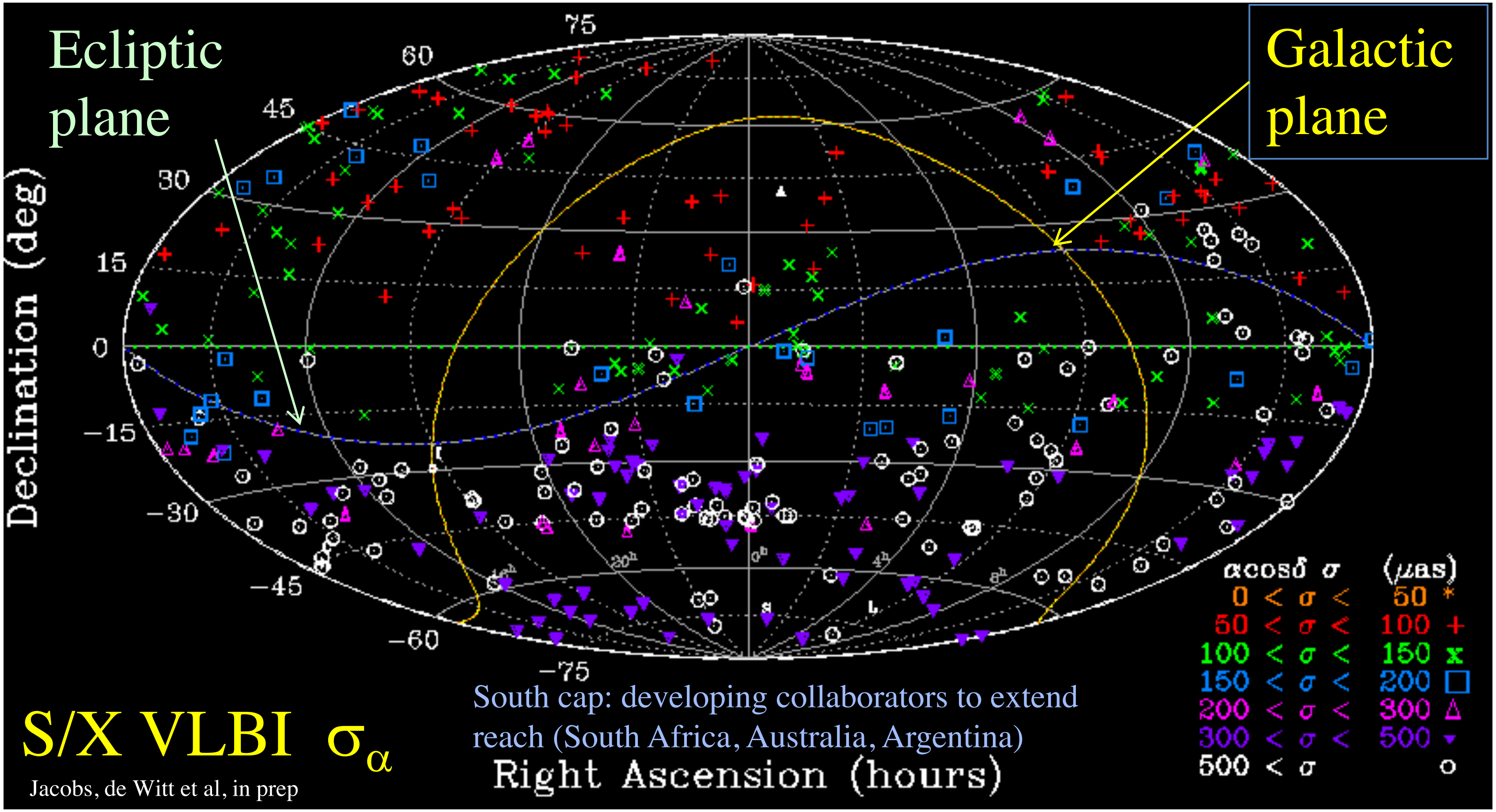
Median optical magnitude V_{med} = 18.6 magnitude *(some obj. no data)*

~200 of 674 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

Adding optically bright sources to radio

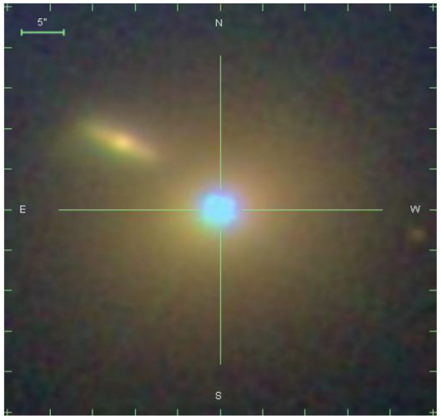
Credit: G. Bourda et al, 2014; Garcia-Miro, EVN, 2014; Jacobs et al, 2016



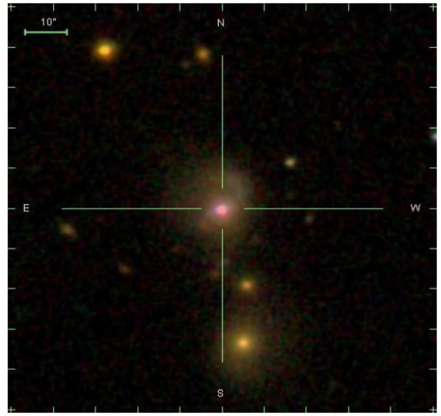
- S/X (3.6cm): Adding ~300 optically bright sources to radio frame
- Southern hemisphere additions from HartRAO-Hobart
- XKa (9mm) will only see a fraction of these due to sensitivity limits

Optical vs. Radio systematics offsets

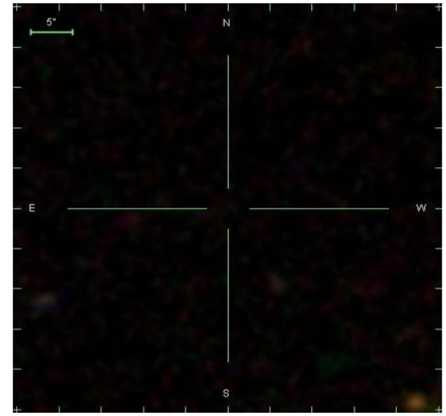
Credit: SDSS



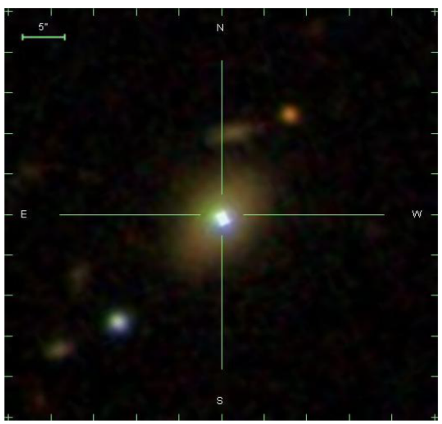
1101+384



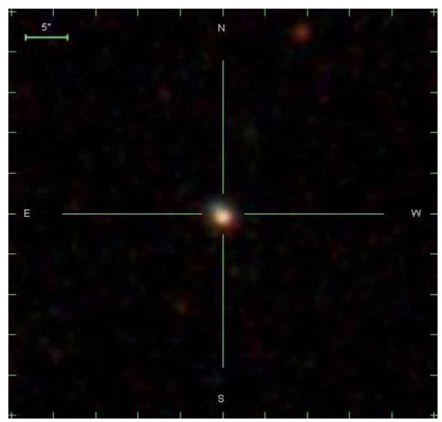
0007+106



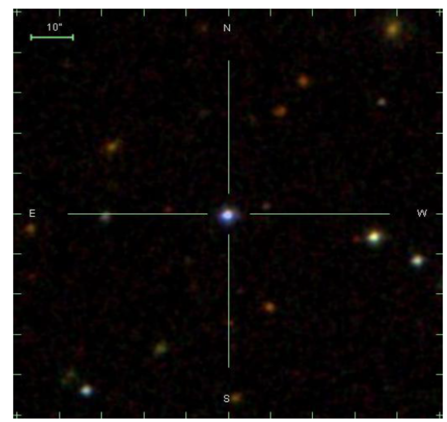
0920+390



1418+546



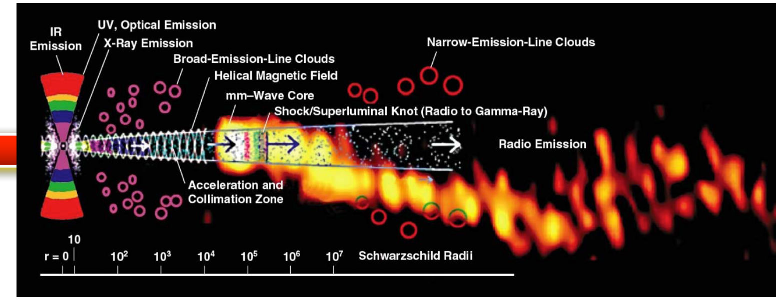
1514+192



1546+027

- Optical structure: The host galaxy may not be centered on the AGN or may be asymmetric.
- Optical systematics: fraction of millarcsecond optical centroid offset? (Petrov & Kovalev, IAU 330, 2017).
- Optical imaging generally 10s of milliarcsecond. In general, no sub-mas optical imaging.

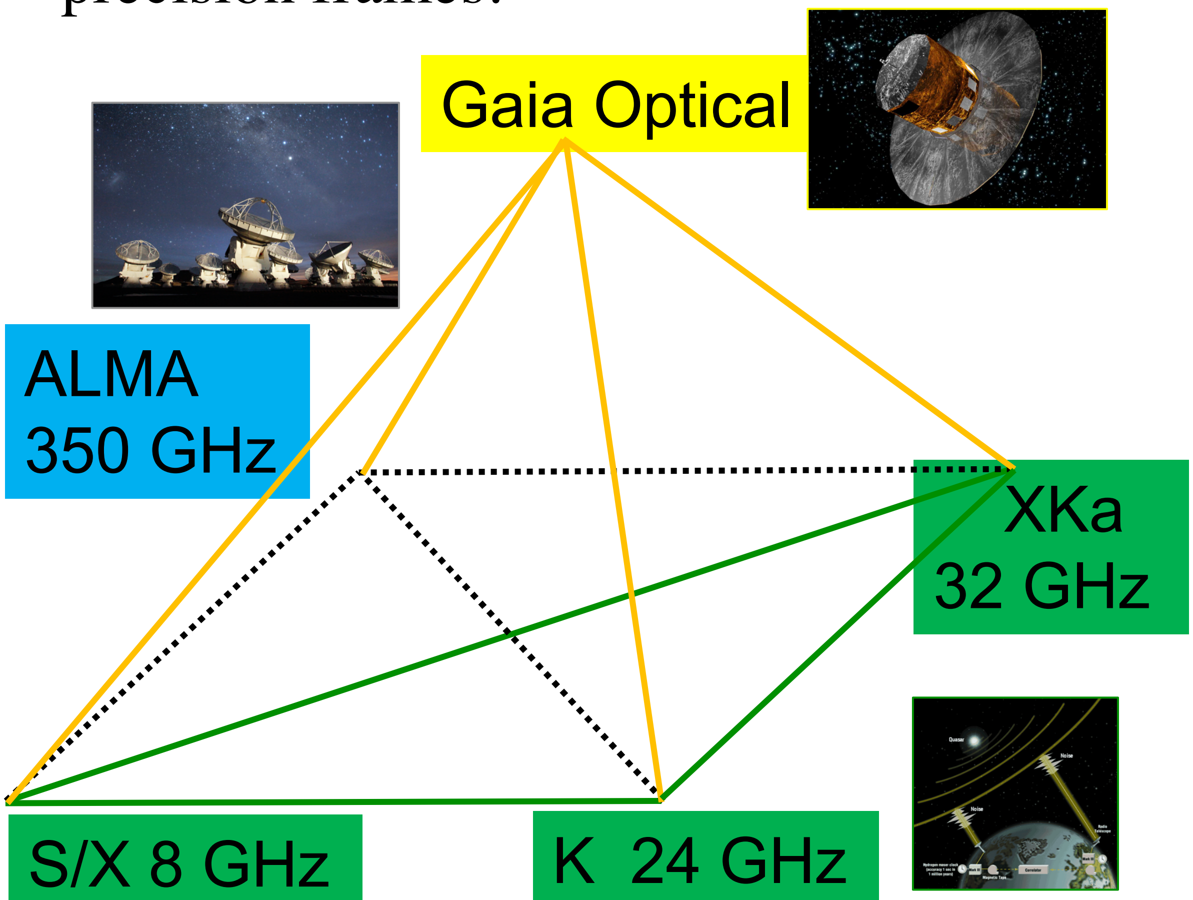
Frame Tie Comparisons



Credit: Marscher+, Krichbaum+

Tying Optical and Radio Celestial Frames

Systematics to be flushed out via Inter-comparison of multiple high precision frames.



<u>Systematics:</u>

Gaia: 60 mas beam sees
Host galaxy, foreground stars, etc.

ALMA: pilot obs bright end ~5^{mag}
Waiting on 10km+ configurations

VLBI: All bands need more southern data

S/X: Source structure
K: Ionosphere
XKa: Argentina baselines under-observed

Gaia Data Release 1 optical vs. VLBI radio: 0.5 mas

Credit: SDSS

	SX-band 8 GHz 3.6cm	K-band 24 GHz 1.2 cm	XKa-band 32 GHz 0.9 cm
# Observations	12 million	0.25 million	0.06 million
# sources	1984	481	413
# outliers > 5σ	106	13	7
% outliers	5.0 %	2.6 %	1.7 %
α wRMS	536 μas	439 μas	434 μas
δ wRMS	544 μas	455 μas	423 μas
R_x	32 +- 13	100 +- 24	56 +- 24
R_y	5 +- 11	-7 +- 21	32 +- 21
R_z	28 +-13	0 +- 23	15 +- 24
Δα vs. δ tilt (μas/deg)	0.28+- 0.25	1.70 +- 0.55	-2.82 +- 0.58

Credit: Jacobs et al, IAU 330, 2017

Hints that results improve by going to higher radio frequency
However, the above results do not use exact same objects

Gaia Optical vs. X/Ka frame tie

- Gaia Data Release #1 2016 September:
  median sigmas ~ 500 μas per component
  Gaia Data release #2 2018 April

- VLBI XKa radio sigmas ~100 μas per component and improving

- 3-D rotational sigmas ~ 20 μas

- Potential for rotation sigmas ~5 μas per frame tie component after which the limitation is the number of XKa sources.

- Expect that accuracy will be limited by systematic errors— In particular zonal errors vs. Dec in the VLBI frames

Jacobs et al, ISSFD, 2012. http://adsabs.harvard.edu/abs/2012sfd..confE...1J

Conclusions

I. **Concepts and Background:**

A. Desire nonrotating, non-accelerating frame. Use a quasi-inertial with some accelerations

B. Networks: The instruments used to build the frame

ad hoc, VLBA, EVN, Global, NASA-ESA DSN, ESA, LBA, AuScope, etc.

C. Brief history of Astrometry: The ‘fixed’ stars aren’t so fixed.

1. Precession, proper motion, nutation, parallax
2. Invention of radio astronomy. VLBI’s pursuit of sub-milli-arsecond accuracy.

II. **Celestial Frames built using VLBI**

A. Surveys: Single dish,

connected arrays: Jodrell-VLA (JVAS, north), ATCA 20 GHz (AT20G, south),

VLBI ~mas: VLBA Cal Survey (north), LBA Cal Survey (south)

B. ICRF-1 (1998): The IAU moves to from optical (stars) to 212 Defining quasars.

ICRF-2 (2009) : 295 defining sources, 3414 total, 40 μas systematic floor

C. Higher frequency radio frames: K & Q (24 & 43GHz), X/Ka (32 GHz)

100 to 200 μas agreement with SX

III. **The Path to the Future:**

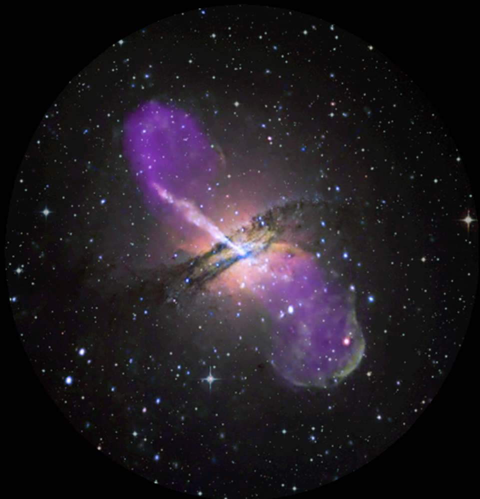
A. Error Budgets: a tool for allocating resources for improvement

B. Case study: Improved X/Ka Frame: SNR, Instrumentation, Troposphere, ***Geometry***

C. ICRF-3 goals: 2018, improve south, improve VCS, improve K & X/Ka

D. Gaia: 2024 the return of optical, 500,000 quasars, ~billion total sources

Thank You for your Attention



Estrellas, que rodean, señas,
Ojos, mis ojos captan la luz,
suave palpitar de mi corazón,
llevado en alto por la brisa
vuelo de mi alma,
libre, nacida de nuevo
bajo un cielo maravilloso.

-C.S. Jacobs

(inspirado en un verso de Abraham Kron)

Y yo, minimo ser,
ebrio del gran vacío constelado,
a semejanza, a imagen del misterio,
me sentí parte pura del abismo,
rodé con las estrellas,
mi corazón se desató en el viento.
- Pablo Neruda

And I, infinitesimal being,
inebriated on the great starry void,
likeness, image of mystery,
I felt myself a pure part of the abyss,
I rode with the stars,
my heart broke free onto the open sky.

NGC 2207 & IC 2163:, Credit: NASA and The Hubble Heritage Team (STScI/AURA)
Acknowledgment: D.M. Elmegreen (Vassar College) and B.G. Elmegreen (IBM Research Division)