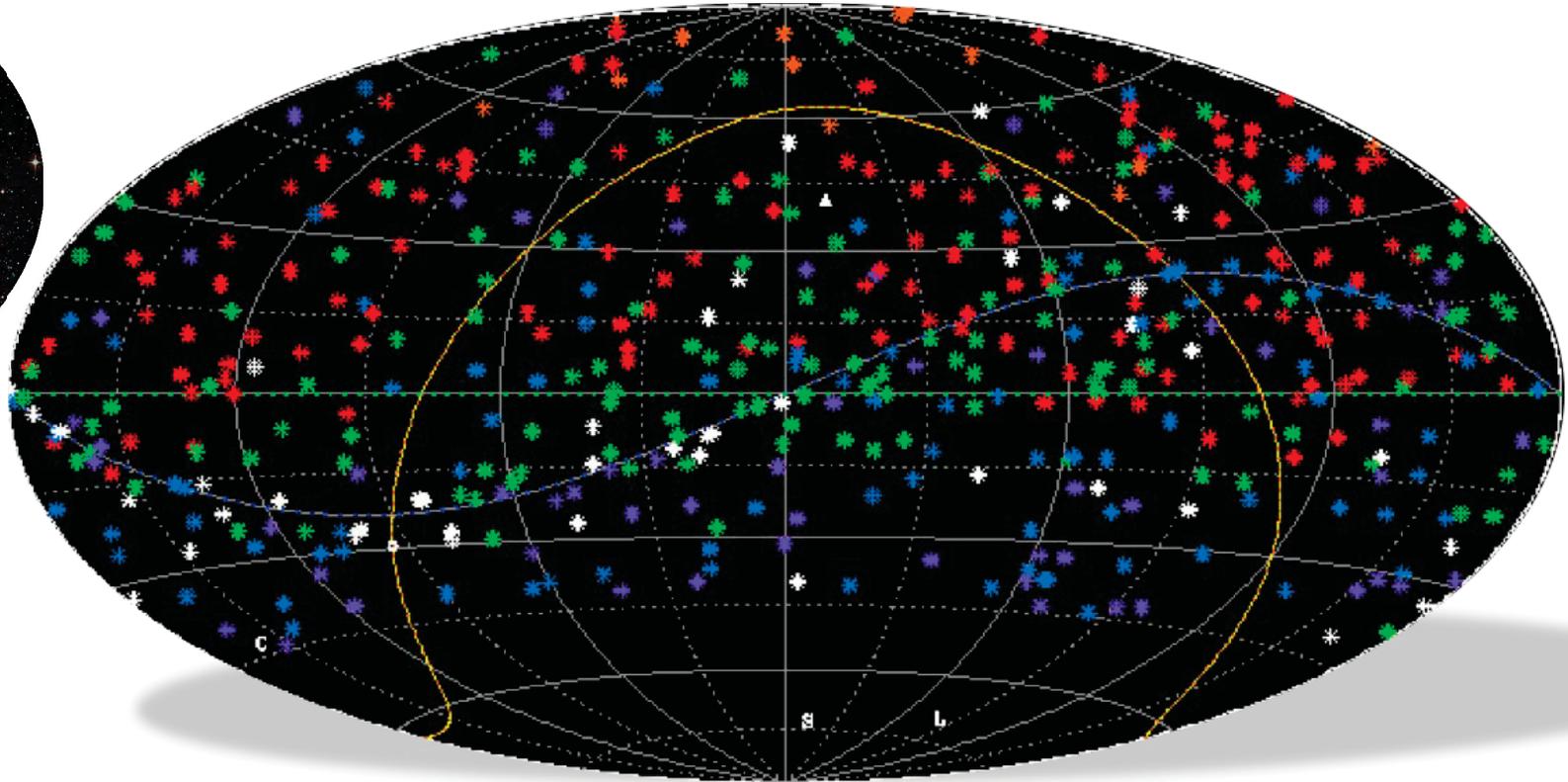
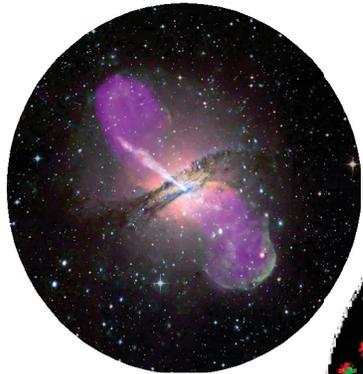




# The X/Ka-band Extragalactic Reference Frame



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**S. Horiuchi**

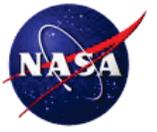
Canberra Deep Space Communications Complex/NASA, C.S.I.R.O. Astronomy and Space Science, Canberra, Australia

**L.G. Snedeker**

Goldstone Deep Space Communications Complex/NASA, ITT Exelis, Ft. Irwin, California, USA



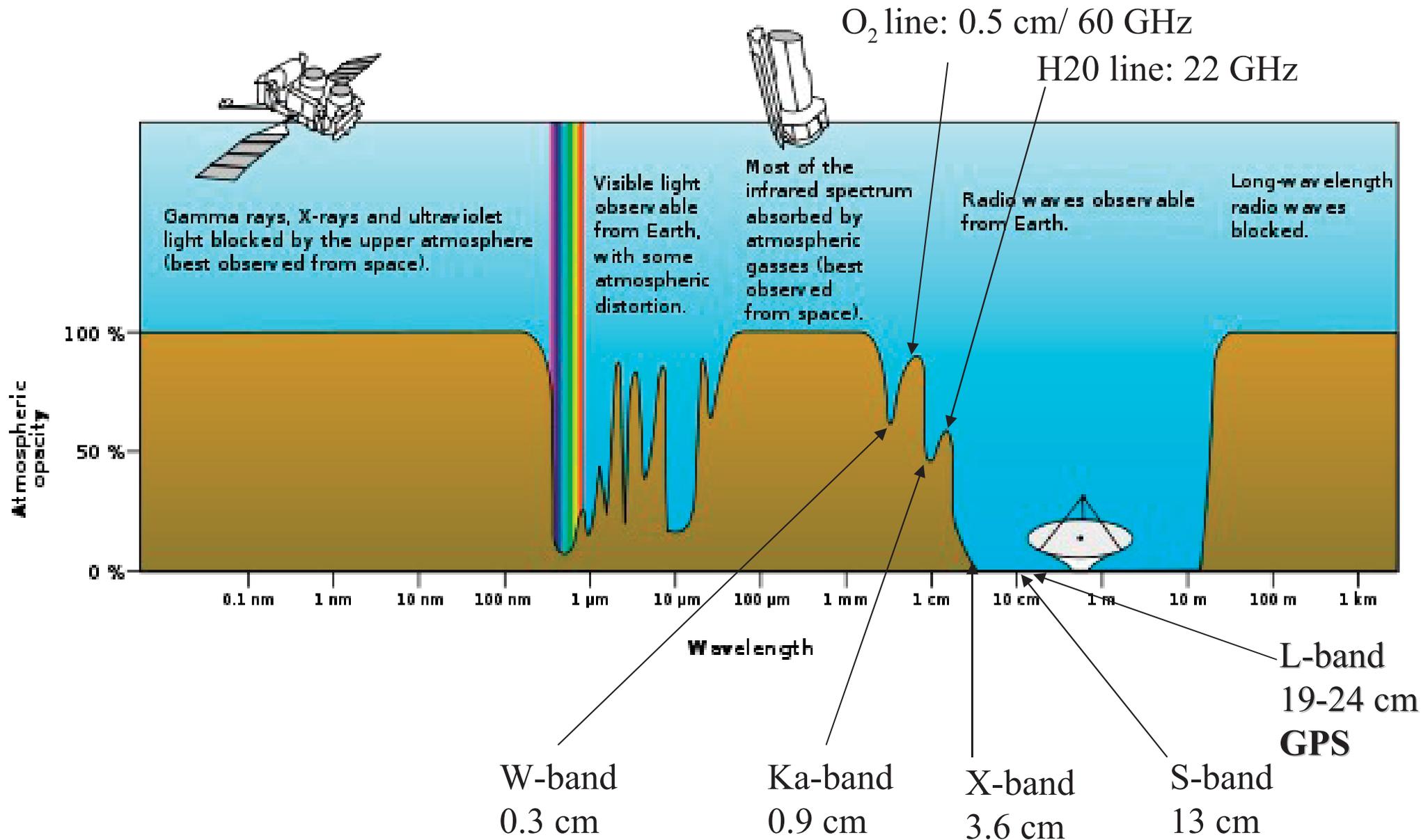
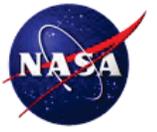
# Overview



- Ka-band pros and cons
- Status of current radio-based celestial frames
  - ICRF2: wavelength 3.6cm, 3.4K objects, 40-100  $\mu\text{as}$
  - K-band: wavelength 1.2cm, 0.3K objects, 100-250  $\mu\text{as}$
  - X/Ka: wavelength 9mm, 0.5K objects, 200-300  $\mu\text{as}$
- Need southern stations: **complementary geometry**



# Ka-band on Edge of Radio Window





# 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 calcs

## Ka-band (9mm/32 GHz) Advantages

- 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

## Disadvantages of Higher radio frequencies:

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



<http://mars.jpl.nasa.gov/mro/multimedia/images/?ImageID=3373>

Mars Reconnaissance Orbiter 2005 demonstrated Ka-band Communications and Navigation.



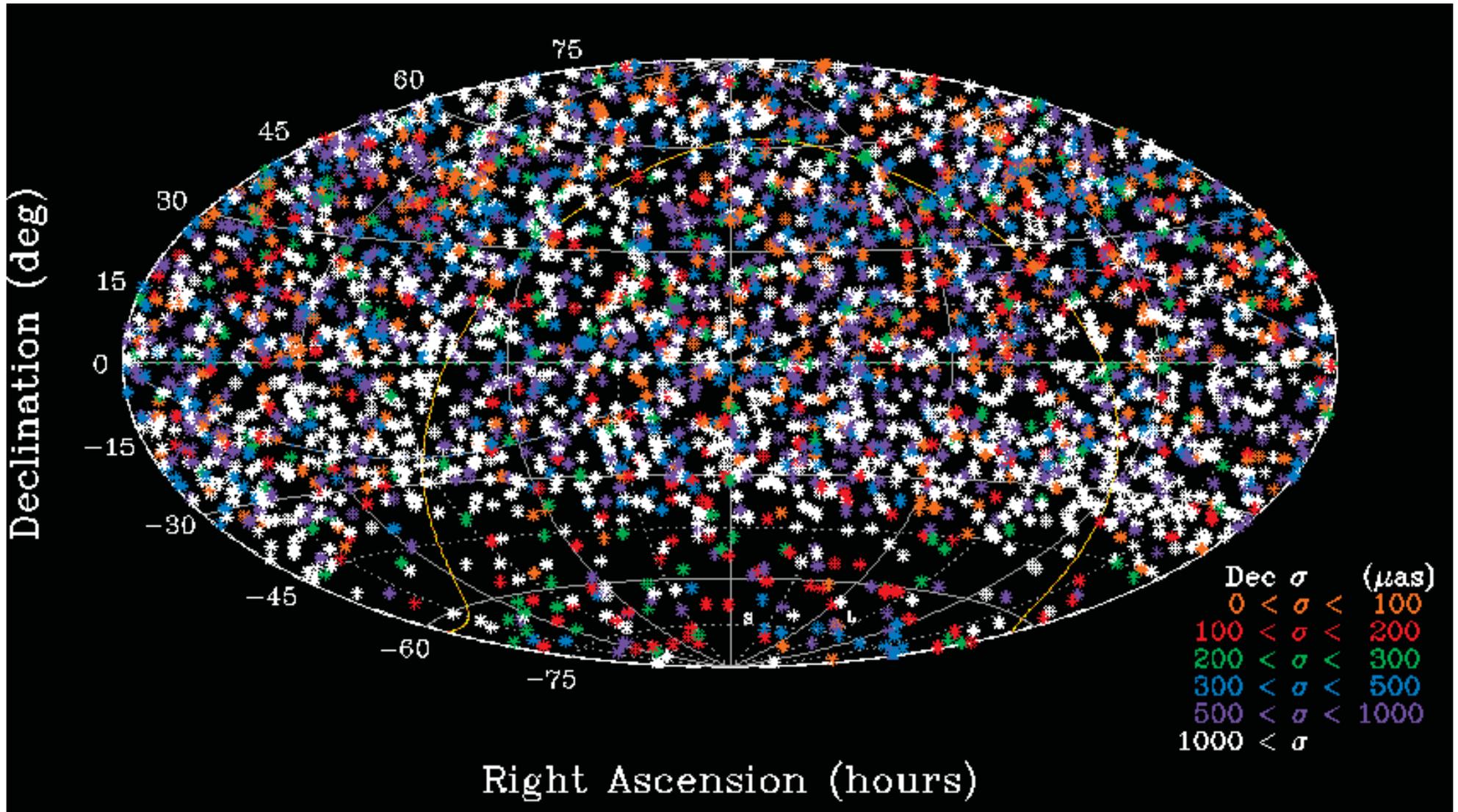
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# Current Status of Celestial Reference Frames at radio wavelengths:

**S/X ICRF2:** 3.6cm, 8 GHz

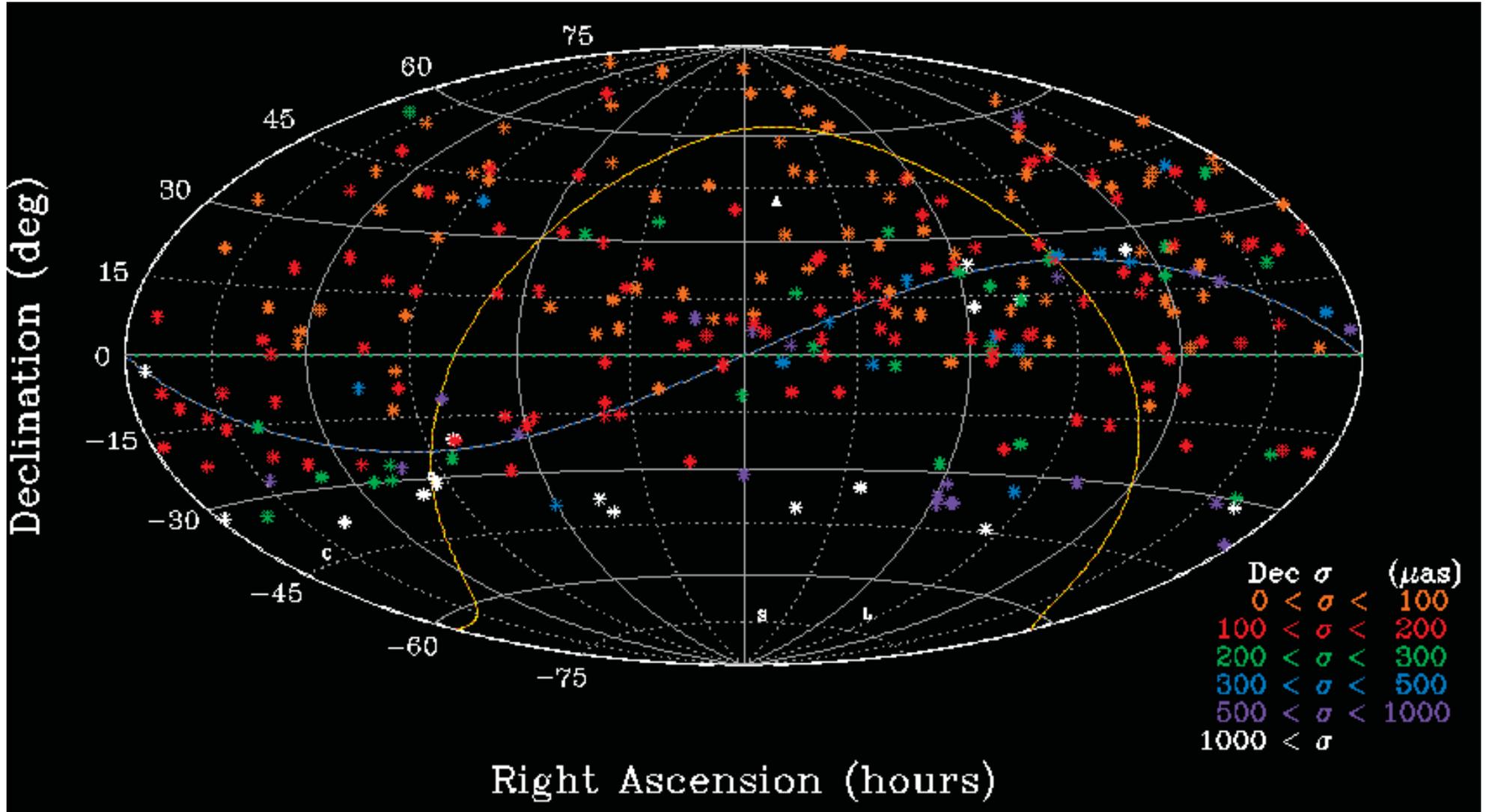
**K-band:** 1.2cm, 24 GHz

**X/Ka-band:** 9mm, 32 GHz



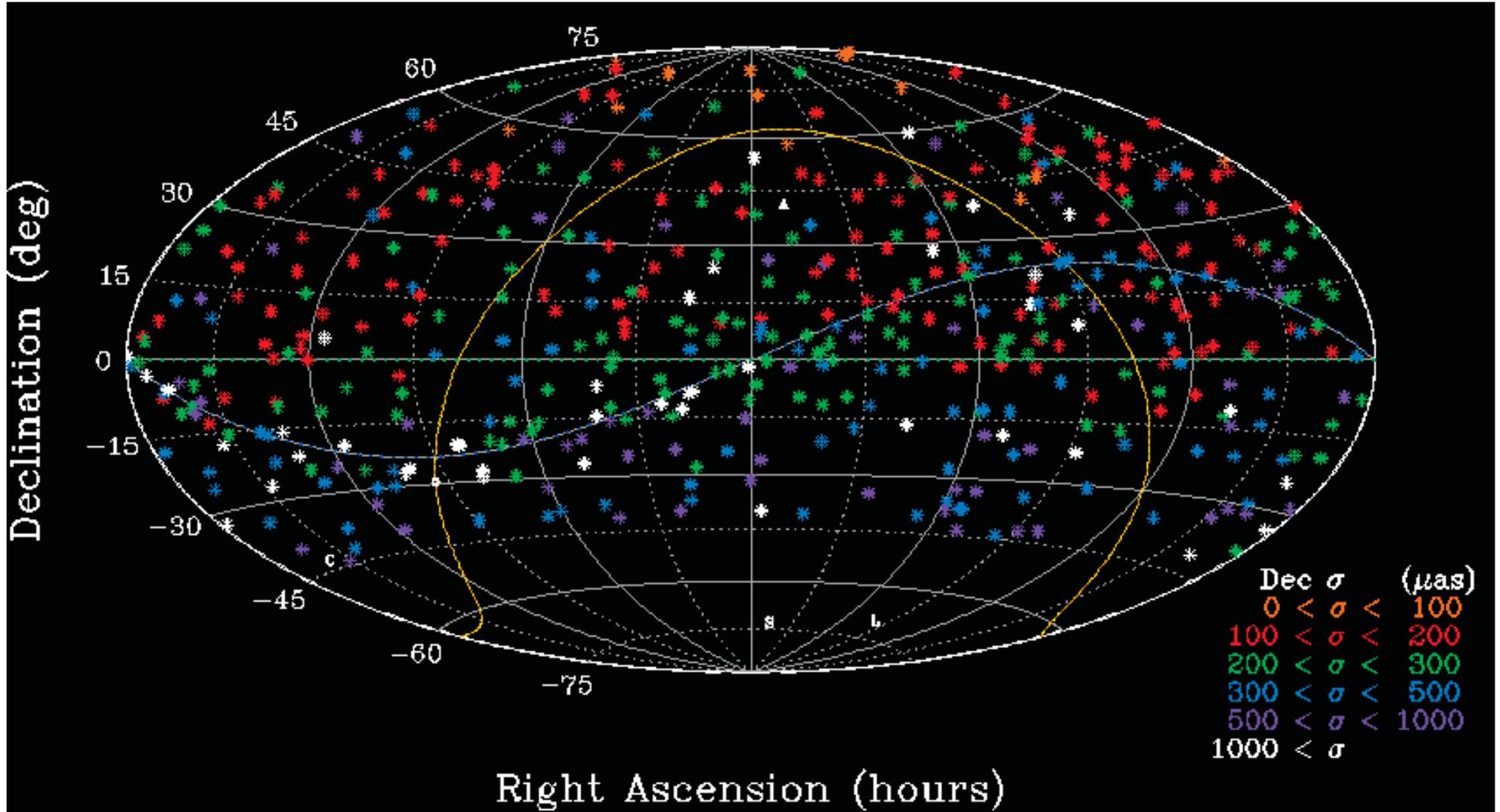
40  $\mu\text{as}$  floor.  $\sim 1200$  obj. well observed,  $\sim 2000$  survey session only

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

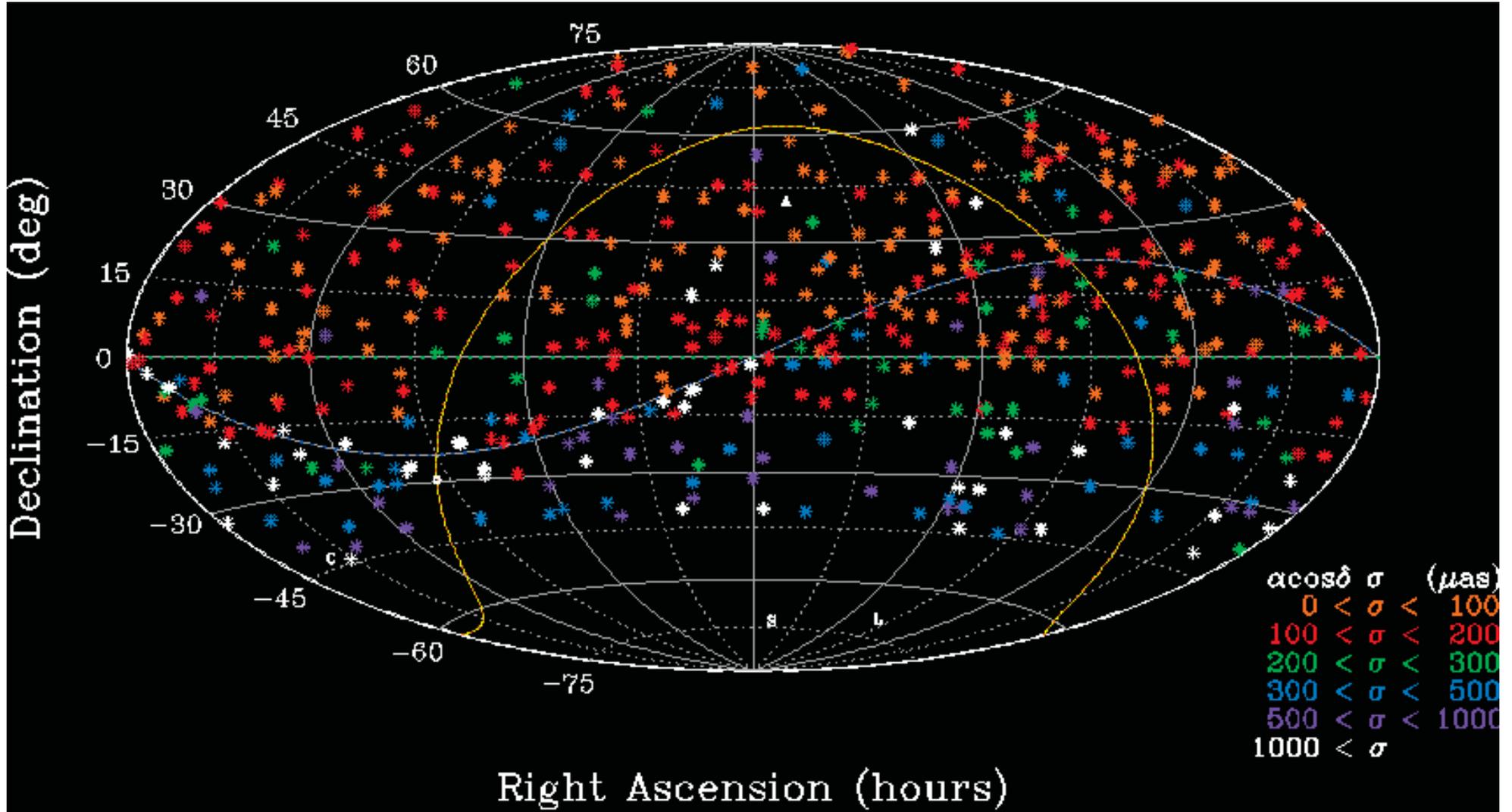


VLBA all northern, poor below Dec.  $-30^\circ$ .  $\Delta$ Dec vs. Dec tilt =  $500 \mu$ as

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



Cal. to Madrid, Cal. to Australia. **Weakens southward.** **No  $\Delta\text{Dec}$  tilt**



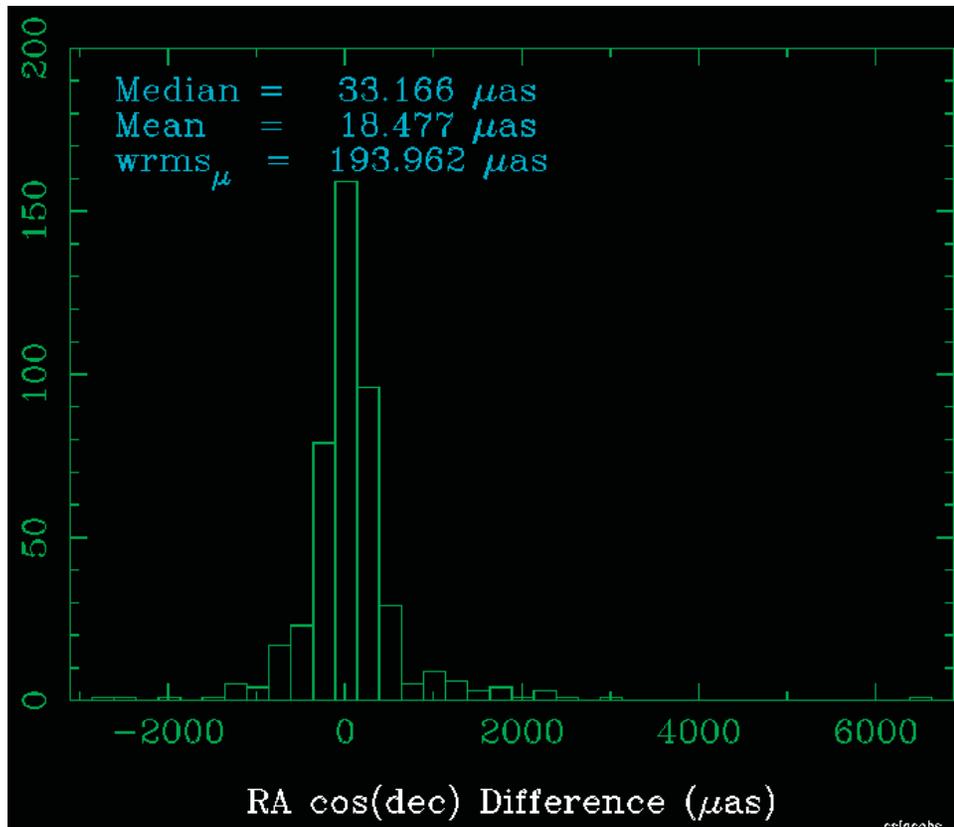
Cal. to Madrid, Cal. to Australia. **Weakens south of Dec = -15deg**



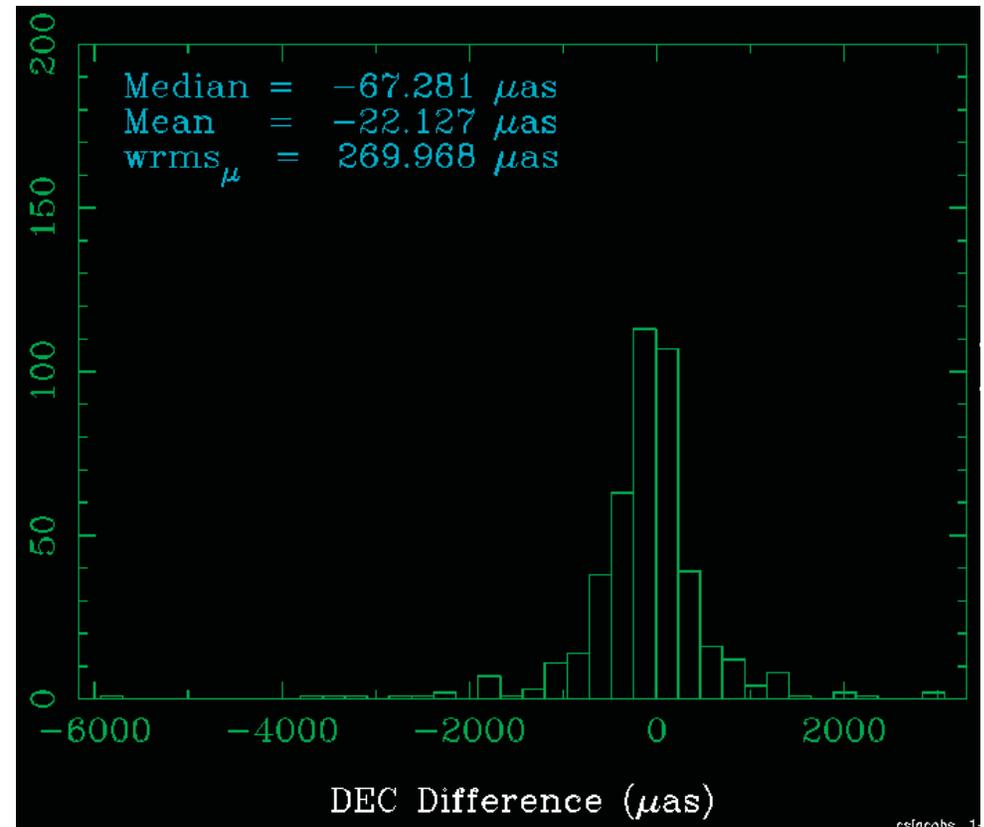
# X/Ka (9mm) vs. ICRF2 at S/X (3.6cm)



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



**RA: 194  $\mu\text{as}$  = 0.9 nano-rad**



**Dec: 270  $\mu\text{as}$  = 1.3 nano-rad**

*S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, IERS, Germany, 2009*



# Improving VLBI



## Systems Analysis shows dominant Errors are

- Limited SNR/sensitivity
  - already increased bit rates: 112 to 448 Mbps. Soon to 2048?
- Instrumentation: already building better hardware
  - Ka-band phase calibrators, Digital Back Ends (filters)
- Troposphere: better calibrations being explored
- **Weak geometry in Southern hemisphere**
  - Limits accuracy to about 1 nrad (200  $\mu$ as) level
  - No observations below Declination of -45 Deg!
  - DSN at X/Ka has only Canberra, Australia (DSS 34)
  - Need 2nd site in the Southern hemisphere especially for upcoming southern ecliptic missions



# How do we improve accuracy? Southern Coverage!

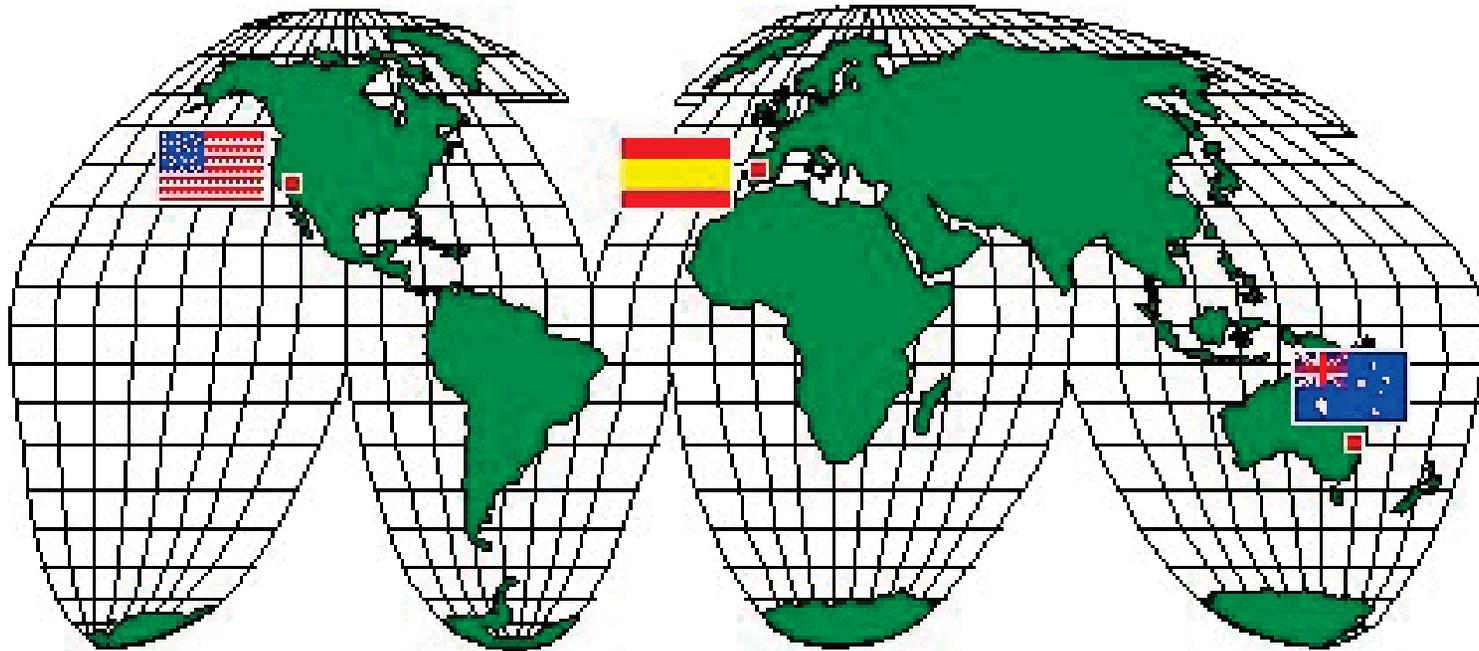
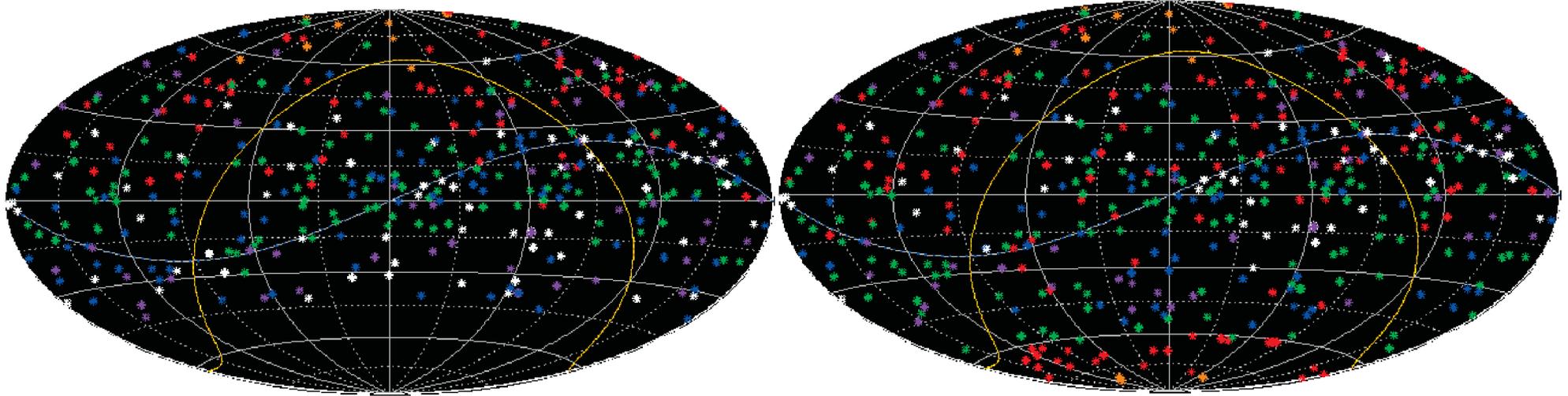
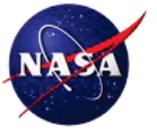


Figure credit: [www.spacetoday.org/images/SolSys/DeepSpaceNetwork/NASA\\_DSN\\_WorldMap.gif](http://www.spacetoday.org/images/SolSys/DeepSpaceNetwork/NASA_DSN_WorldMap.gif)



# Simulation of Added Southern Station



*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  
200  $\mu$ as (1 nrad) precision in south polar cap,  
mid south 200-1000  $\mu$ as, all with just a few days observing.
- Horiuchi et al talk will show plan to attack this area.

**Declination Sigma**

Orange: < 100  $\mu$ as

Red: < 200

Green: < 300

Blue: < 500

Purple: < 1000

White: > 1000



# Gaia-Optical vs. VLBI-radio:

## 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  $\mu\text{as}$  @  $V=18$   
25  $\mu\text{as}$  @  $V=16$

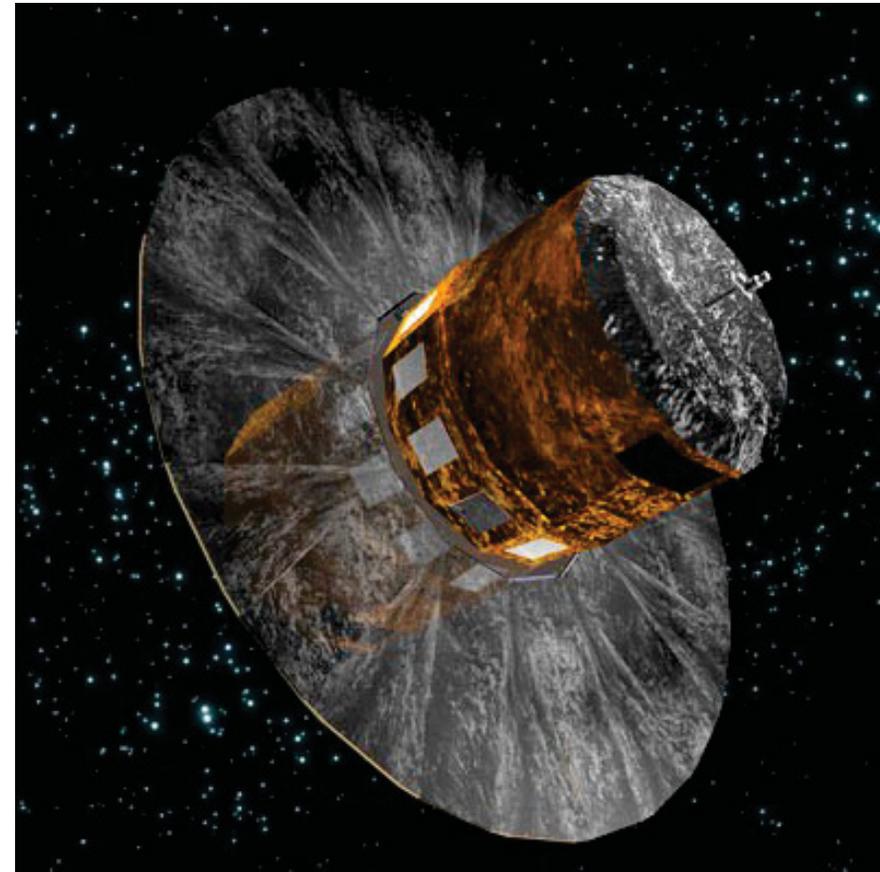
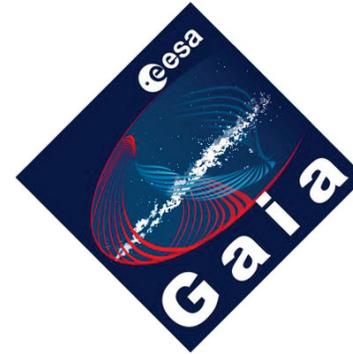
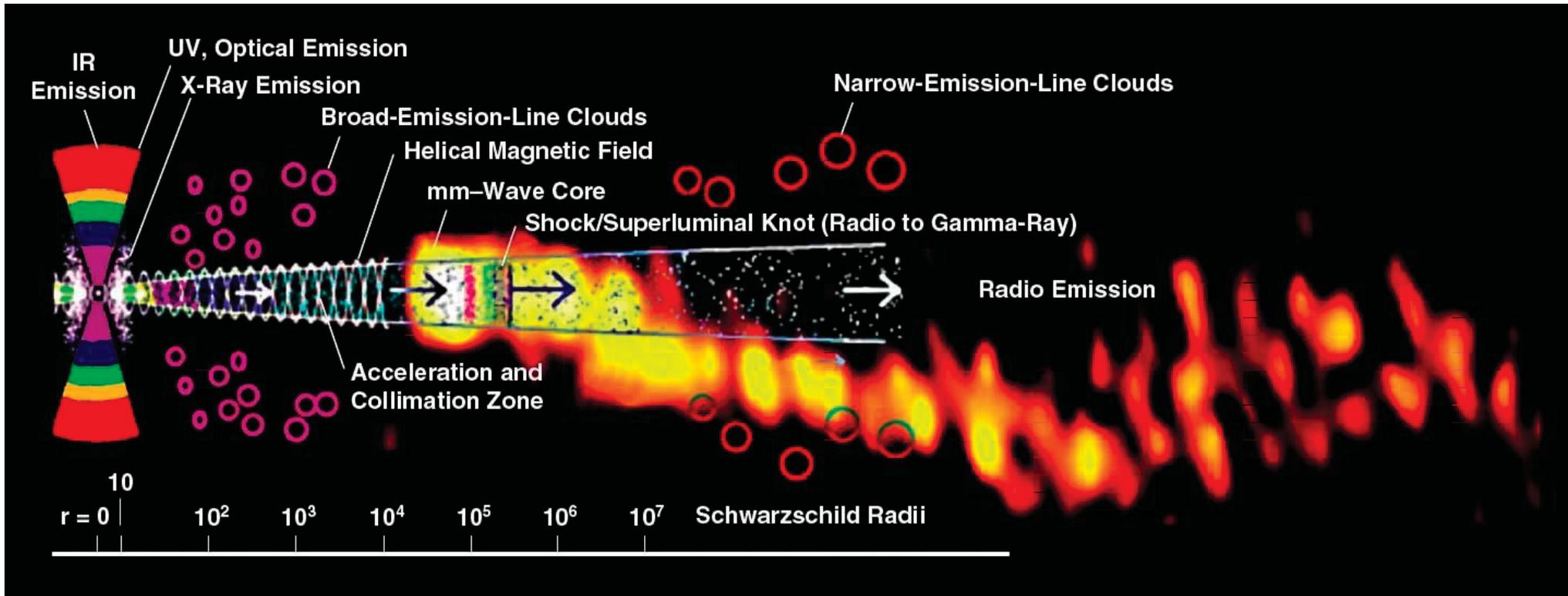
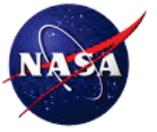


Figure credit: [http://www.esa.int/esaSC/120377\\_index\\_1\\_m.html#subhead7](http://www.esa.int/esaSC/120377_index_1_m.html#subhead7)



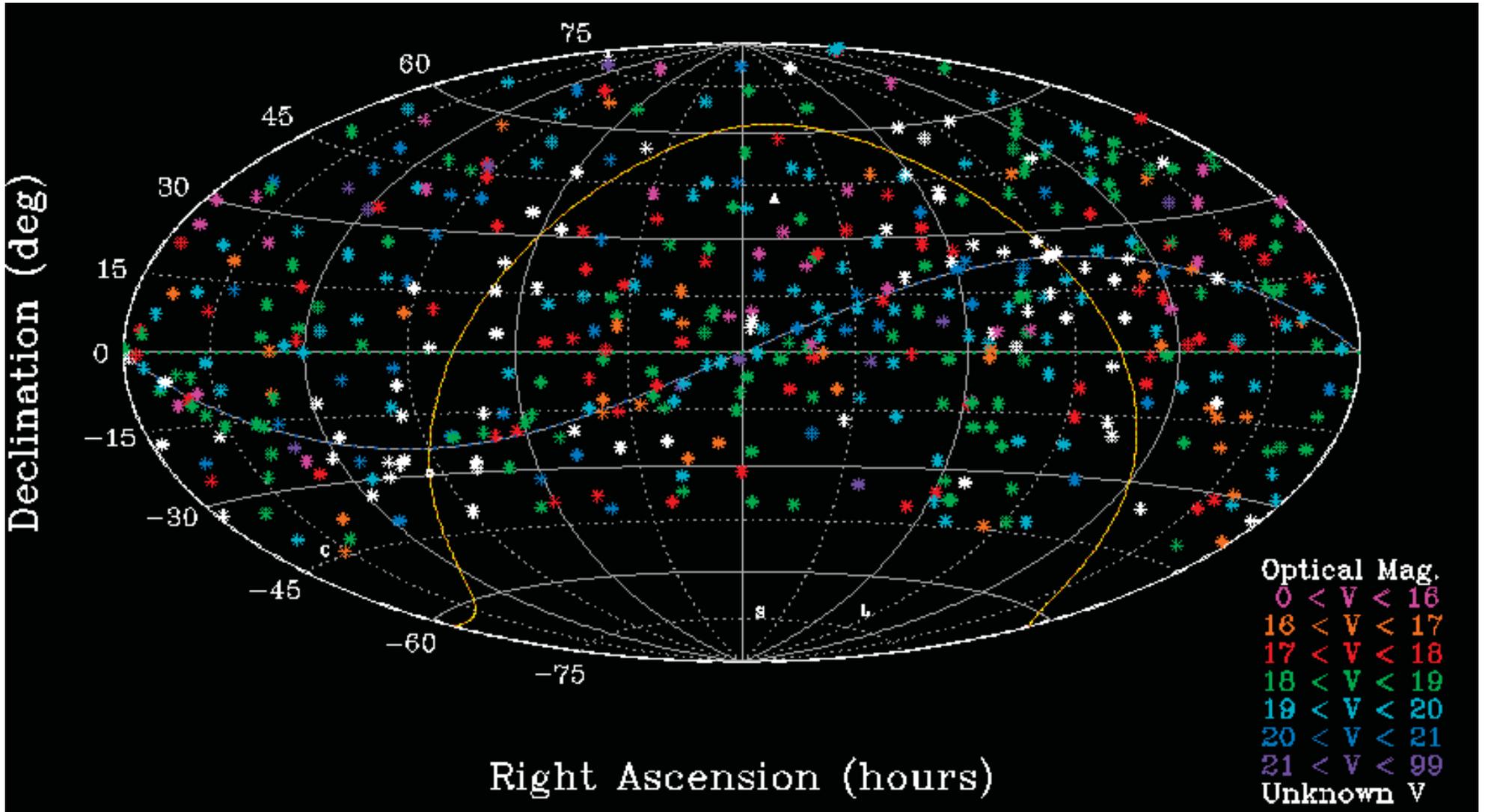
# 9mm vs. 3.6cm? Core shift & structure



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  $\mu$ as in phase delay centroid?*
- *$\ll 100 \mu$ as in group delay centroid?* (Porcas, AA, 505, 1, 2009)
- shorter wavelength closer to Black hole and Optical: *9mm X/Ka better*
- Majid et al talk will give complementary info on source physics



Median optical magnitude  $V_{\text{med}} = 18.6$  magnitude (*71 obj. no data*)  
 > 130 objects optically bright by Gaia standard ( $V < 18$ )



# 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  $\sim 100 \mu\text{s}$  per component
- VLBI 9mm radio sigmas  $\sim 200 \mu\text{s}$  per component and improving
- Covariance calculation of 3-D rotational tie  
using **current 9mm radio sigmas** and **simulated Gaia sigmas**
  - Rx  $\pm 14 \mu\text{s}$       **<- Weak. Needs south polar VLBI (Dec  $< -45$ )**
  - Ry  $\pm 11 \mu\text{s}$
  - Rz  $\pm 10 \mu\text{s}$
- Now limited by radio sigmas for which 2-3X improvement possible.  
Potential for rotation sigmas  $\sim 5 \mu\text{s}$  per frame tie component



# Conclusions



- Future tracking is moving to Ka-band: +5 to 8dB telemetry
- Quasar astrophysics: Ka position closer to optical position than S/X-based ICRF2, less extended structure expected
- Ka-band Celestial Frame: 469 Active Galactic Nuclei
- **However, DSN lacks 2nd southern station**
- Simulated Southern Geometry shows great promise
- **Gaia tie:**
  - >130 objects radio loud @9mm *and* optically bright  $V < 18$
  - Ties Gaia optical to VLBI radio frame
  - Study astrophysics: core shift, jet vs. accretion disk
  - Independent check on Gaia accuracy at 70-100  $\mu\text{as}$  level
  - 5-15  $\mu\text{as}$  potential precision for 3-D frame tie