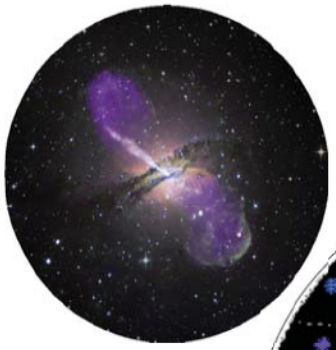
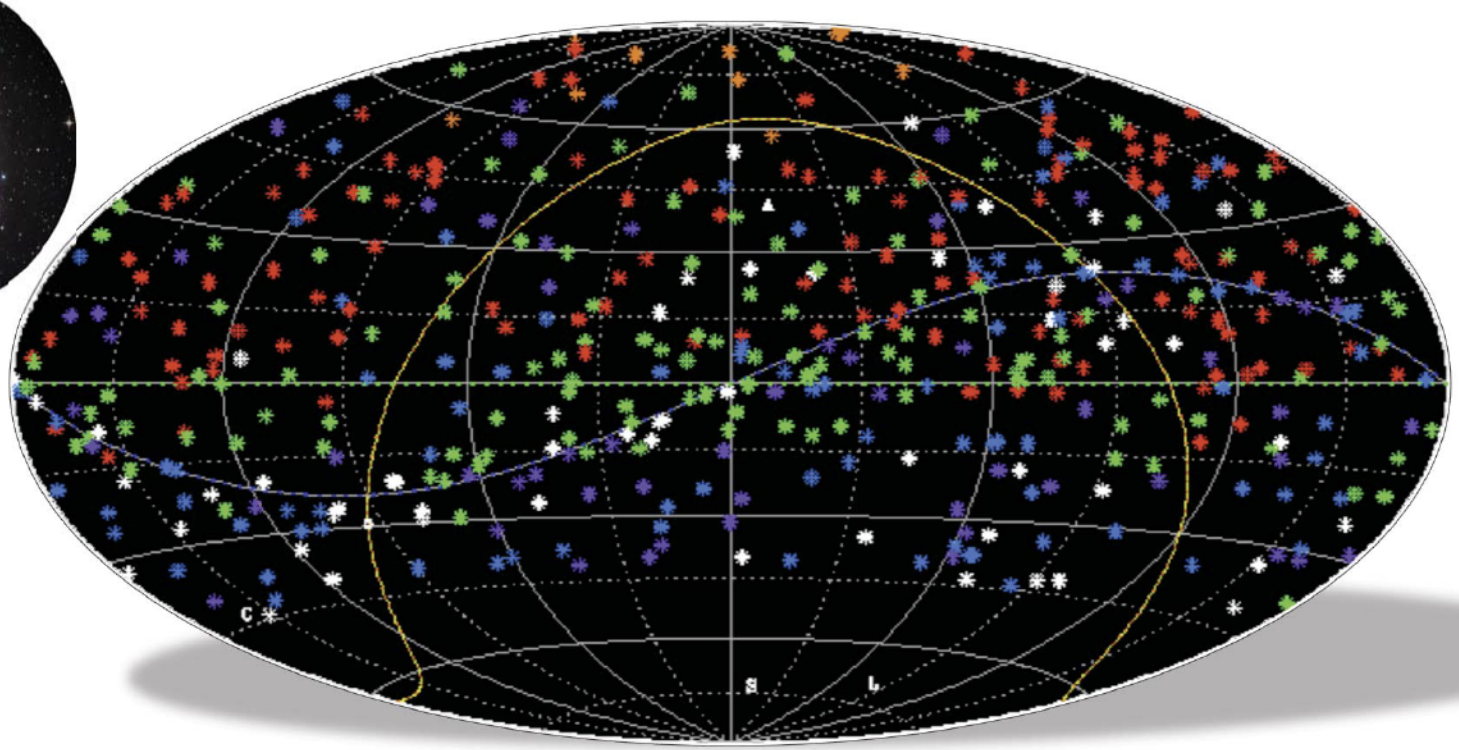
MDSCC Visiting Scientist Seminar

# VLBI: Radio Interferometry for Celestial and Terrestrial Frames



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27 September 2011

CL#10-5073, 11-4183

# Overview

- Cultural & Historical Perspective on Astrometry
- How does VLBI work? What can it do?
- How does VLBI help navigation?
    - Direct navigation observables - ΔDOR
    - Direct infrastructure - Mars ephemeris
    - Calibrations
        - Earth Orientation
        - Polar Motion, UT1-UTC
        - Nutation/Celestial ephemeris pole
        - Station Locations
    - VLBI is Arraying e.g.
      array 34m BWGs for 70m equivalent
    - **Celestial Frame – defines RA & Dec**
- Recent VLBI progress at X/Ka-band

# Why Does Navigation need VLBI?

Terrestrial Frame (Station X, Y, Z) used for

- Doppler, Range: S/C Radial Navigation
- ΔDOR, radio source catalog (Cat M&E)
- Earth Orientation Calibrations
- Antenna Arraying

Celestial Frame used for

- ΔDOR: S/C Angular Navigation
- Earth Orientation Calibrations
- Station locations
- Antenna Array Calibration: Instrumental Offsets

# Navigation:
# Historical Perspective

*Figure credit:* www.arsmachina.com/images/compass7012-1.jpg

# Paradigm of "Sailing by the stars"

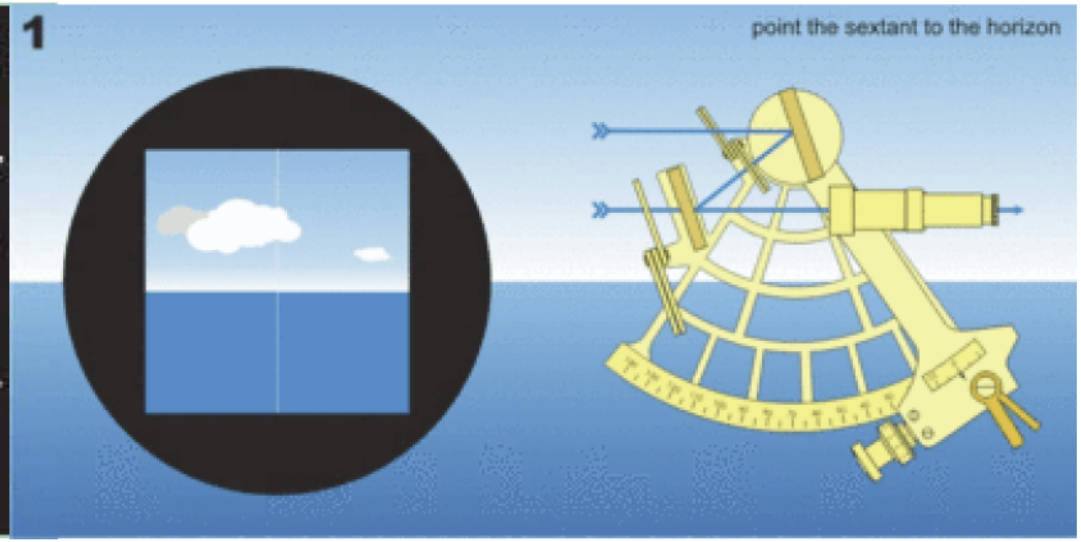


Photo Credit: Dimitry Bobroff, www.ludmillaalexander.com

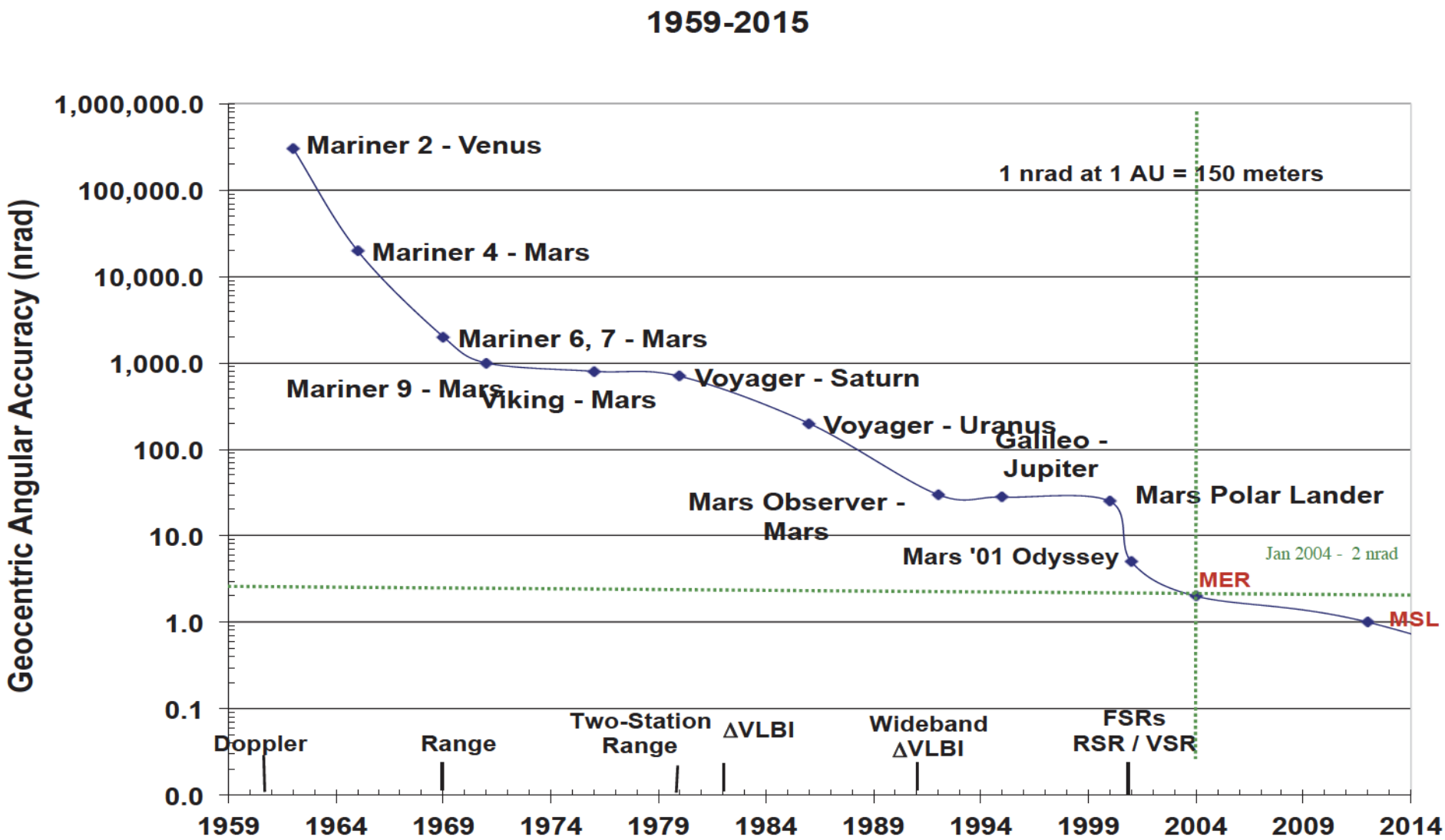


Credit for sextent/octant: en.wikipedia.org/wiki/Sextant (GNU Free Doc license)

# History of Astrometry: Star positions

| | | | |
|---|---|---|---|
| 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 $\mu$as for Vmag=18 quasar |
| 2010s | ESA-DSN? | X/Ka VLBI | 20-70 $\mu$as? 0.3 Jy quasar |

# DSN Navigation System Accuracy

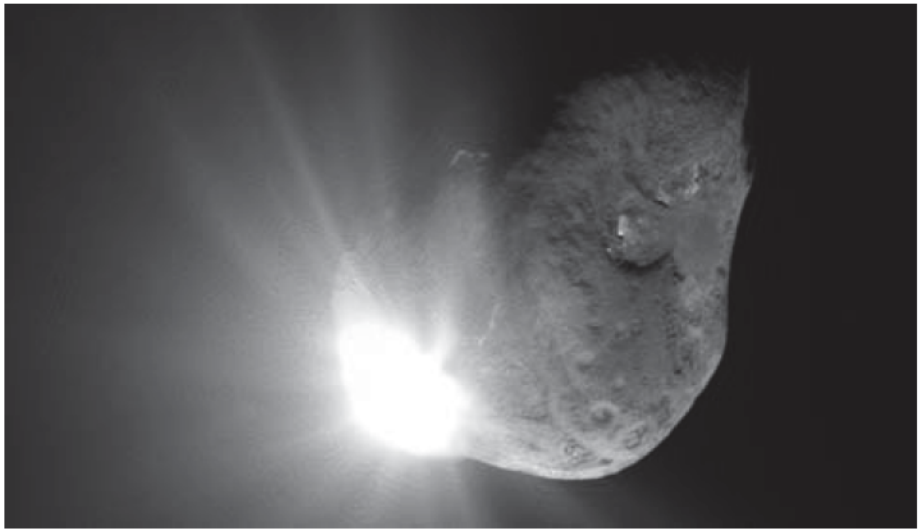



*Credit: J.E. Patterson.*

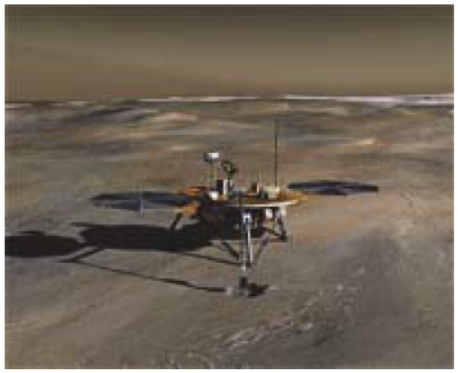
# Why do we have a Deep Space Network?

# Recent Planetary Missions

Deep Impact '05



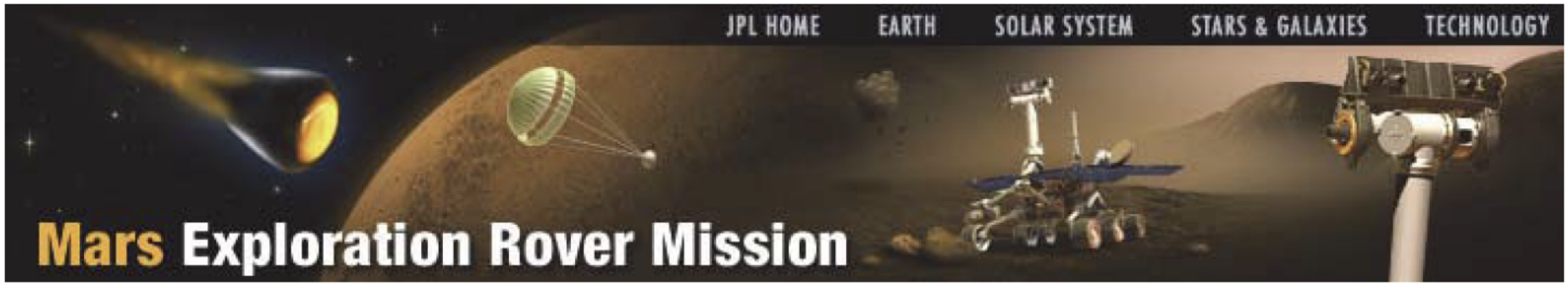
Mars Odyssey '01



Mars Phoenix '07

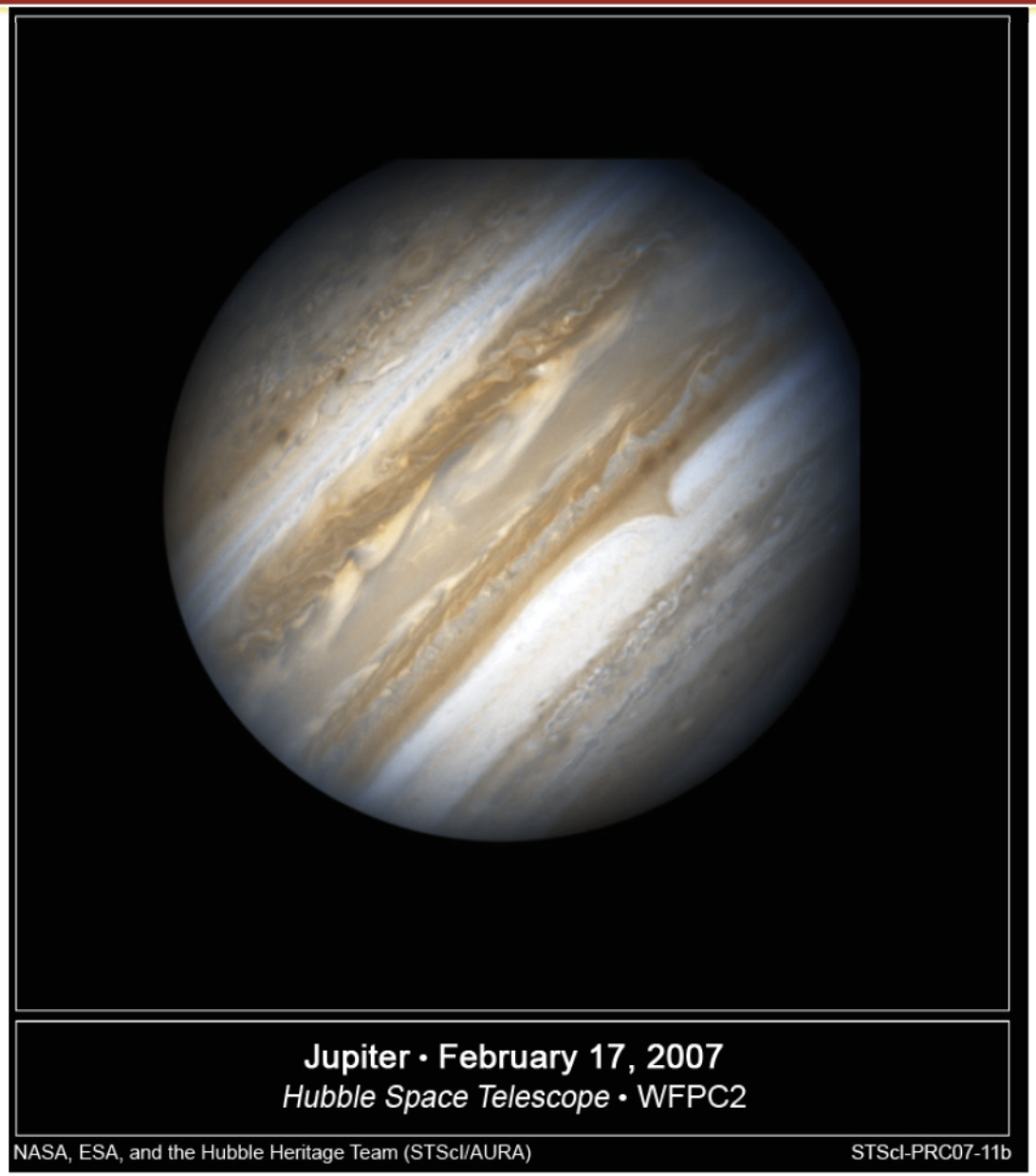
Mars Reconnaisance Orbiter '05

MER '03

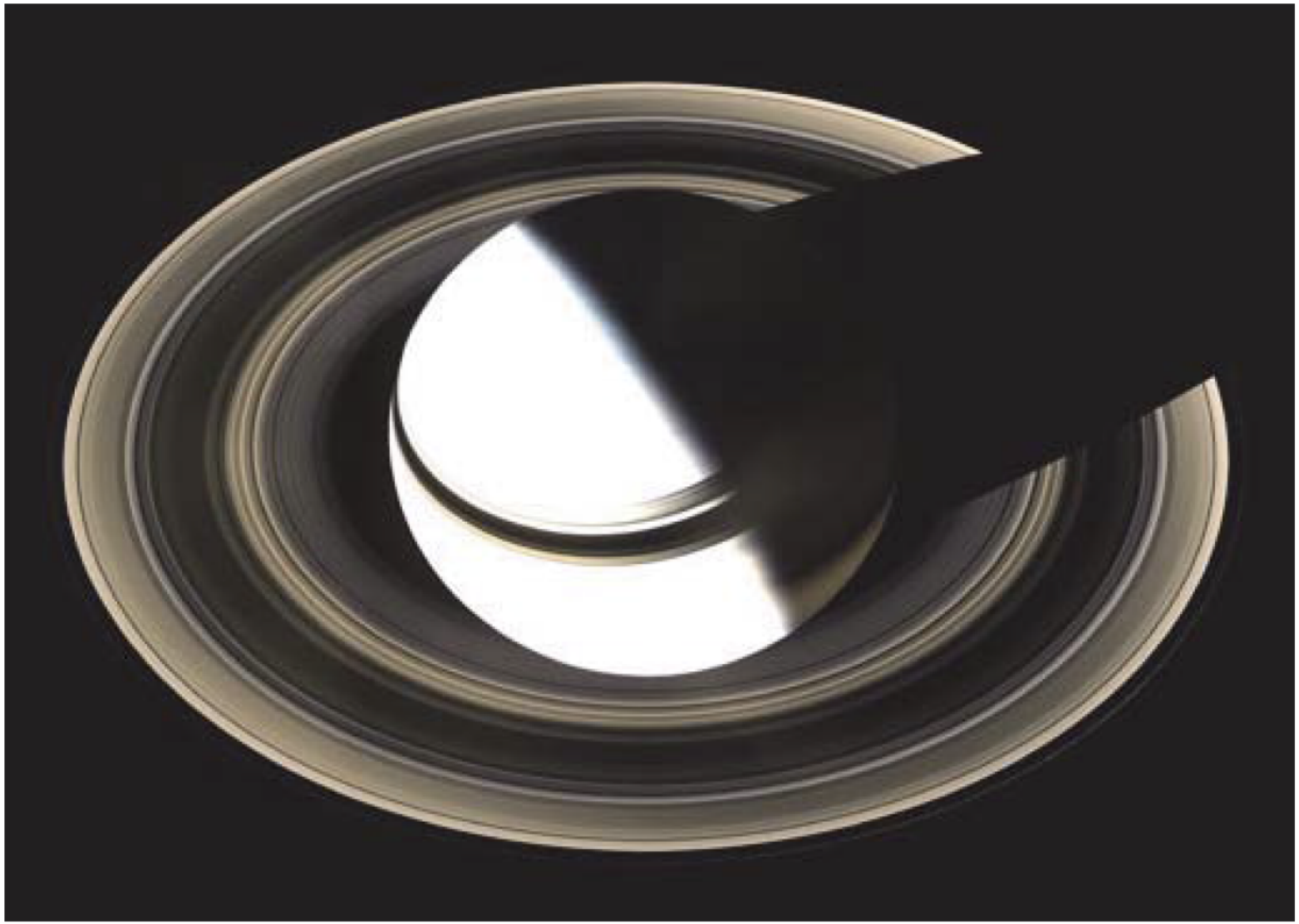



Credit: www.jpl.nasa.gov/missions/

# Jupiter


Jupiter • February 17, 2007
Hubble Space Telescope • WFPC2
NASA, ESA, and the Hubble Heritage Team (STScI/AURA)
STScI-PRC07-11b

# Saturn as seen by Cassini Spacecraft



Credit Cassini mission: photojournal.jpl.nasa.gov/catalog/PIA08362

# Sunset as seen by Rover on Mars

Credit: www.nasa.gov/multimedia/imagegallery/image_feature_347.html

# Mars Rover

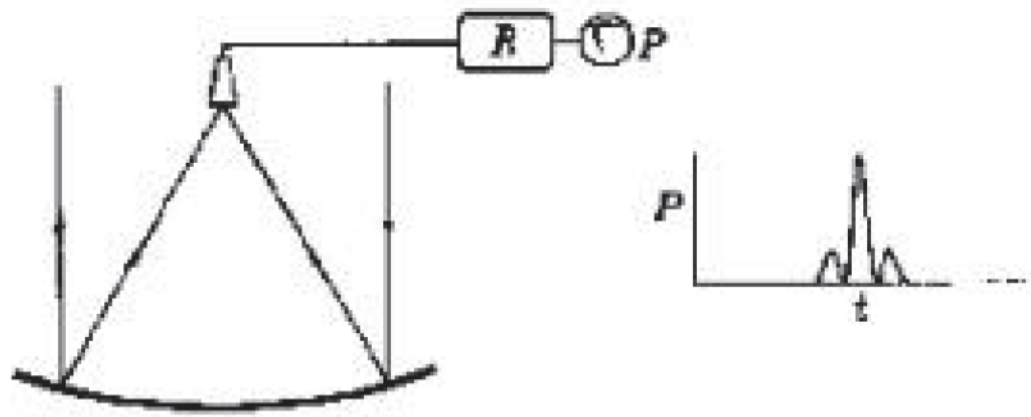
Credit MER mission: photojournal.jpl.nasa.gov/catalog/PIA04413

# 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.




beam

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

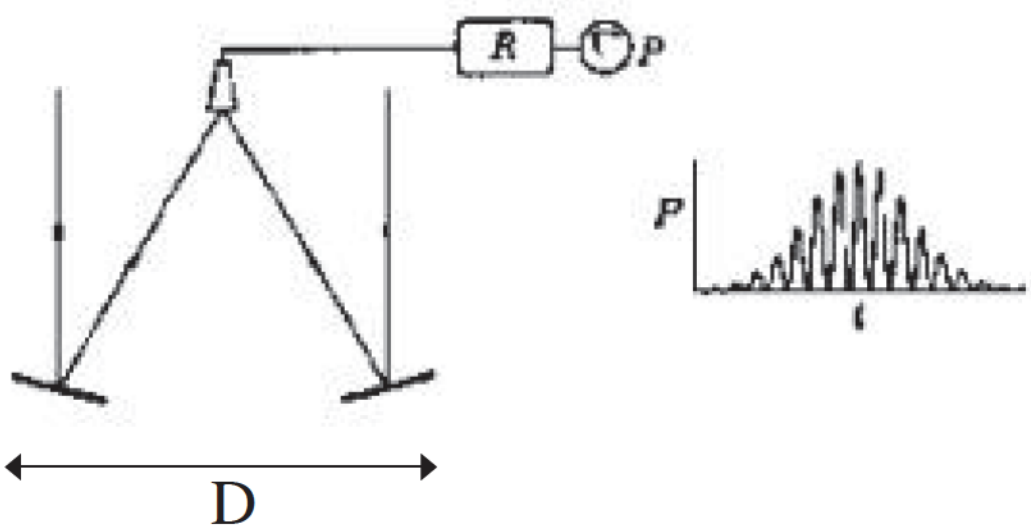
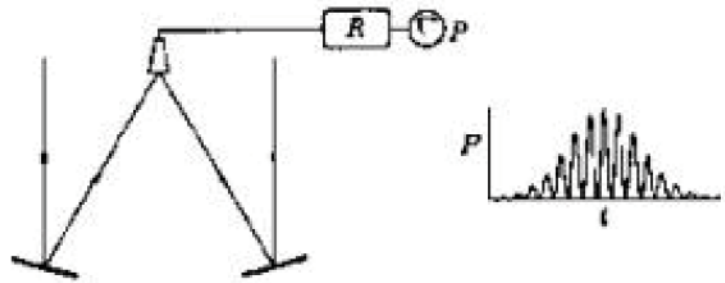



Figure credit: H. Gush

# Mechanical → electrical alignment → VLBI

Two segments of antenna

b)




"Fringes"

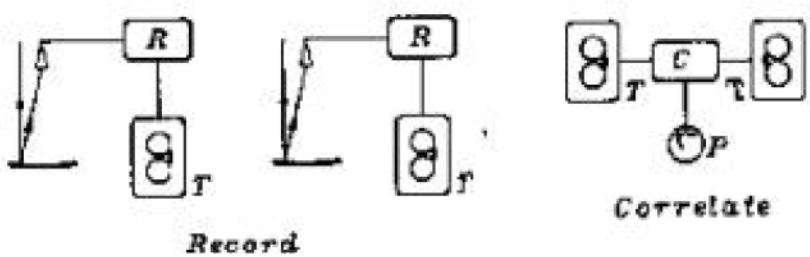
Two separate antennas with Electrical Connection

c)

Same fringes as b).

Unconnected Antennas = VLBI Time tag data and combine signals later at correlator

d)




Same fringes as b).

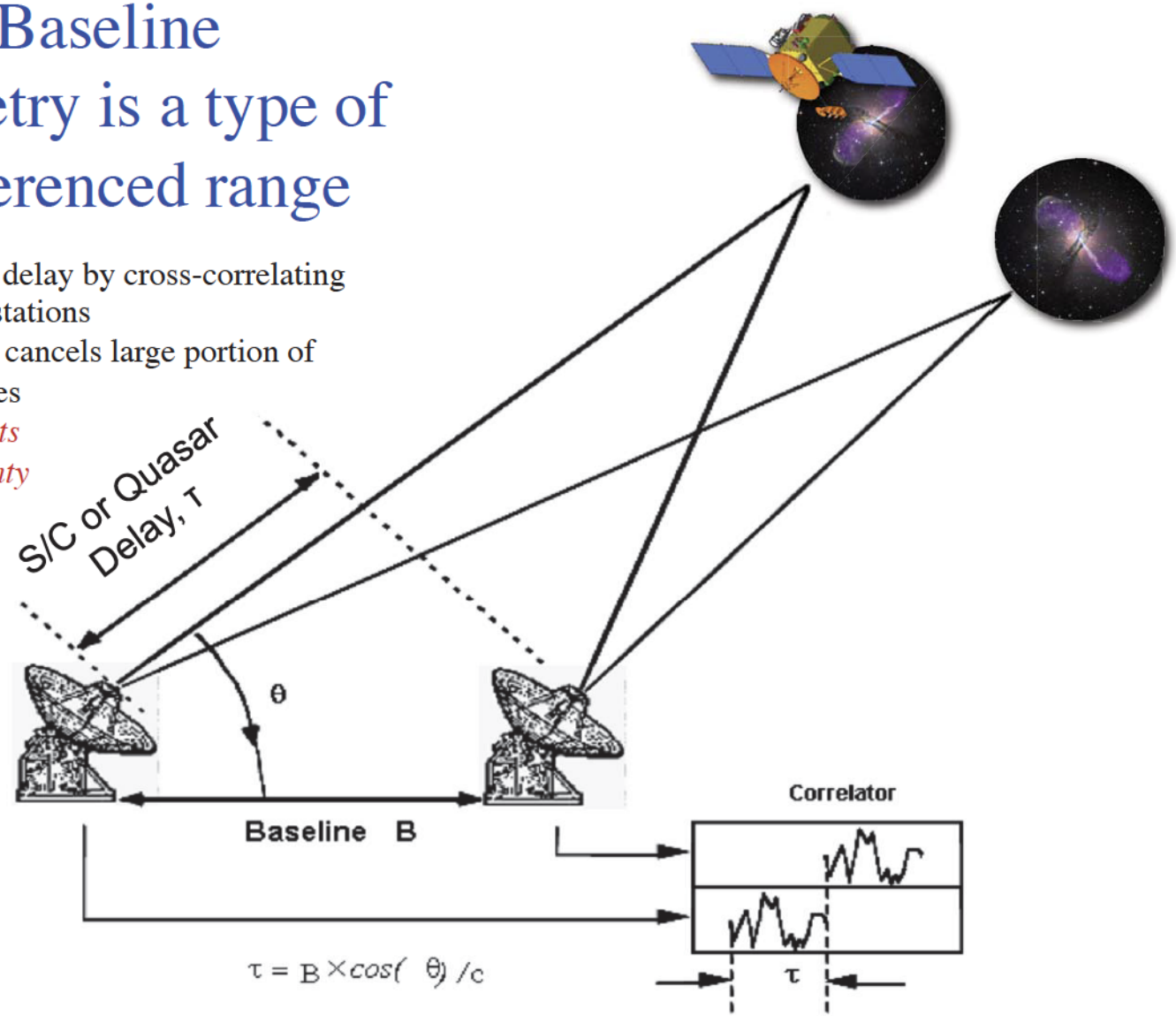


Figure credit: H. Gush

# VLBI Data Type

## Very Long Baseline Interferometry is a type of station differenced range

- Measures geometric delay by cross-correlating signal from two (2) stations
- Double-differencing cancels large portion of common error sources
  - *-instrumental effects*
  - *-baseline uncertainty*
  - *-clock errors*
  - *-media effects*



# 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**

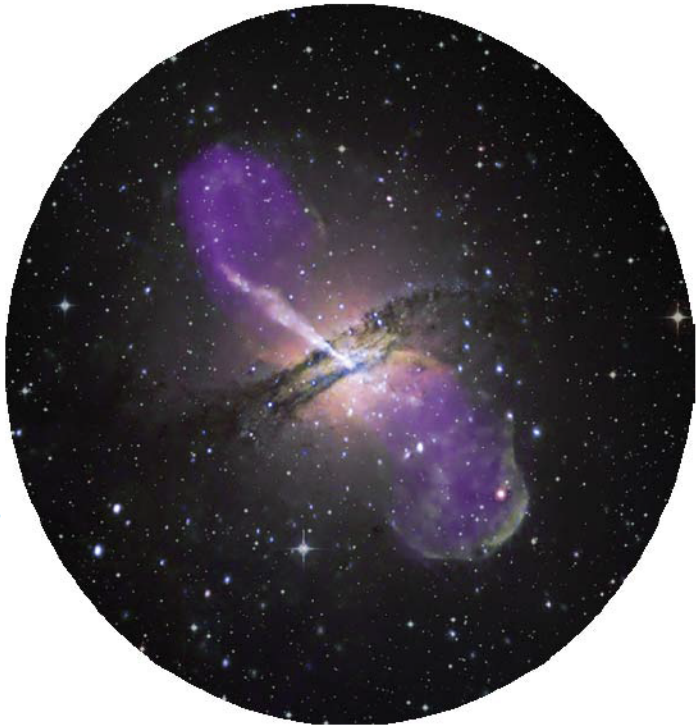
  **Laplace (1749-1827) and**

  **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**



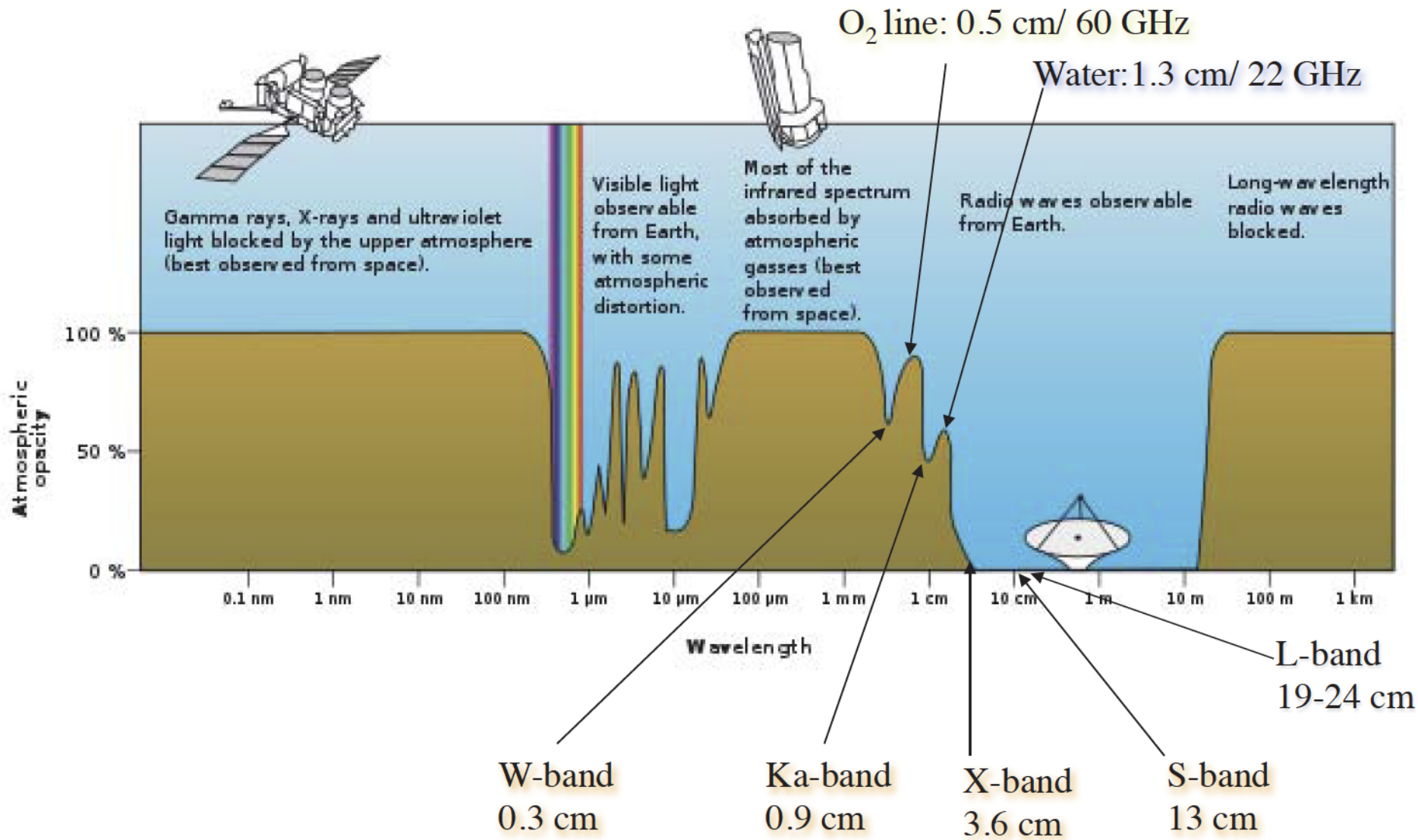
*Credit: chandra.harvard.edu/photo/2008/cena/cena_multi.jpg*

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

- **The price to be paid is**

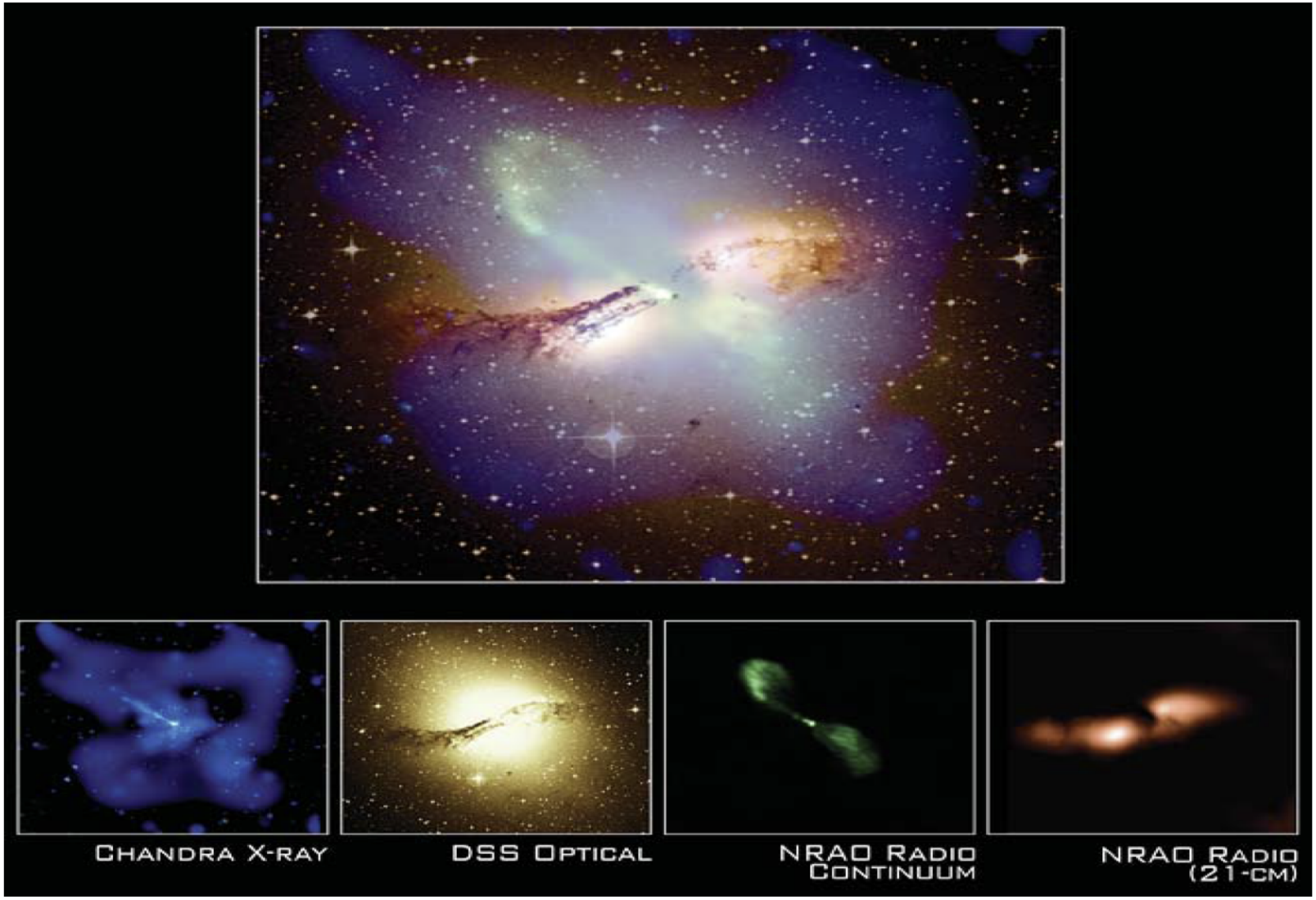
| | |
|---|---|
| **Very weak sources** | **1 Jy = 1.0E-26 watt/m**2/Hz** |
| **need lots of square meters** | **=> 34 - 70m Antenna** |
| **lots of Hz bandwidth** | **=> 0.1 to 4 Gbps** |
| **low system temperature** | **=> Tsys = 20 - 40 Kelvin** |

# Why observe in Radio? The 'Window'



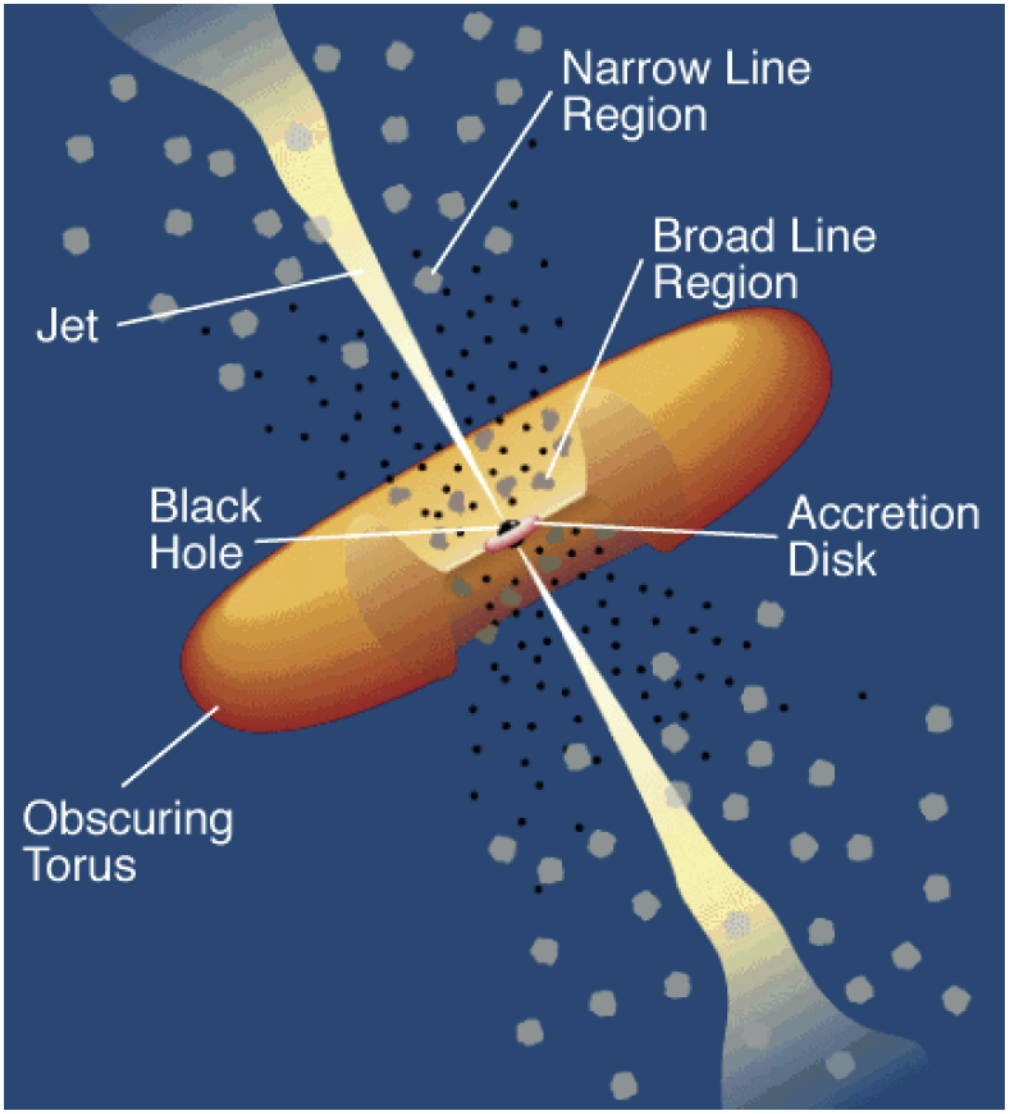

*Credit: NASA; http://en.wikipedia.org/wiki/Radio_window*

# 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

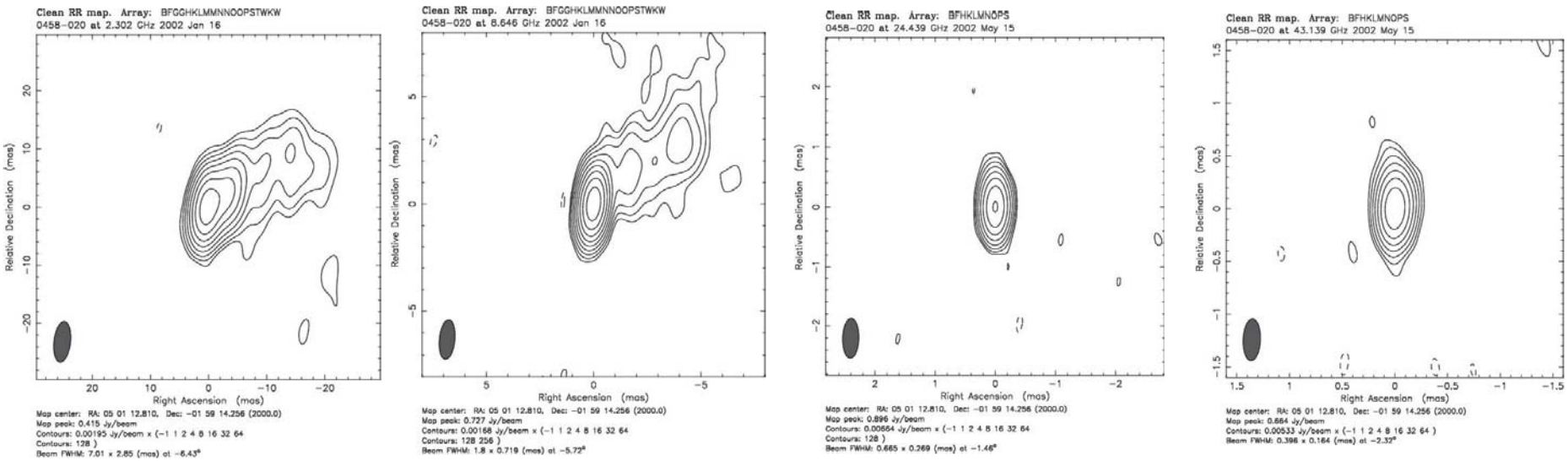
Schematic of
*Active Galactic Nuclei*
Redshift z~ 0.1 to 5
Distance:
billions light years
*Parallax = 0*
*Proper motion*
< 0.1 nrad/yr

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)

Credit: C.M. Urry and P. Padovani

# Source Structure vs. Frequency



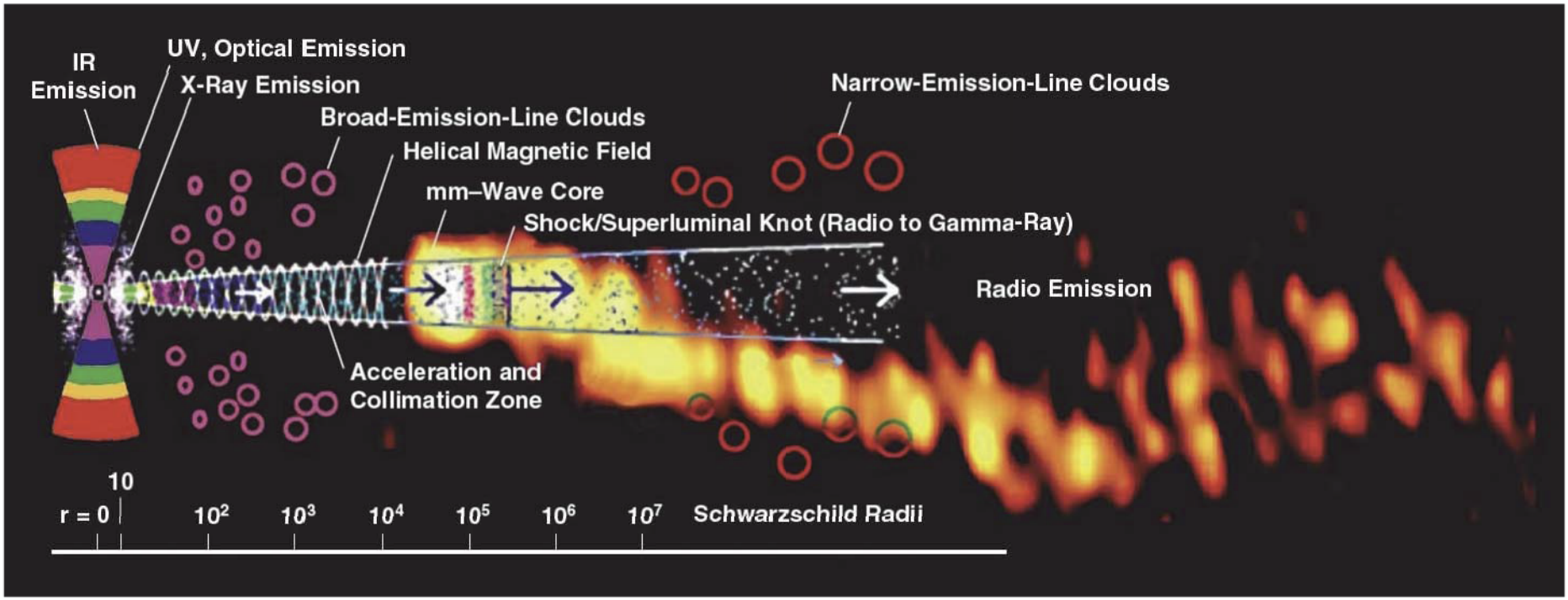

| S-band | X-band | K-band | Q-band |
|---|---|---|---|
| 2.3 GHz | 8.6 GHz | 24 GHz | 43 GHz |
| 13.6cm | 3.6cm | 1.2cm | 0.7cm |

The sources become better ----->

Ka-band
32 GHz
0.9cm

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

# Active Galactic Nuclei (*Marscher*)




R~0.1-1 $\mu$as 1mas

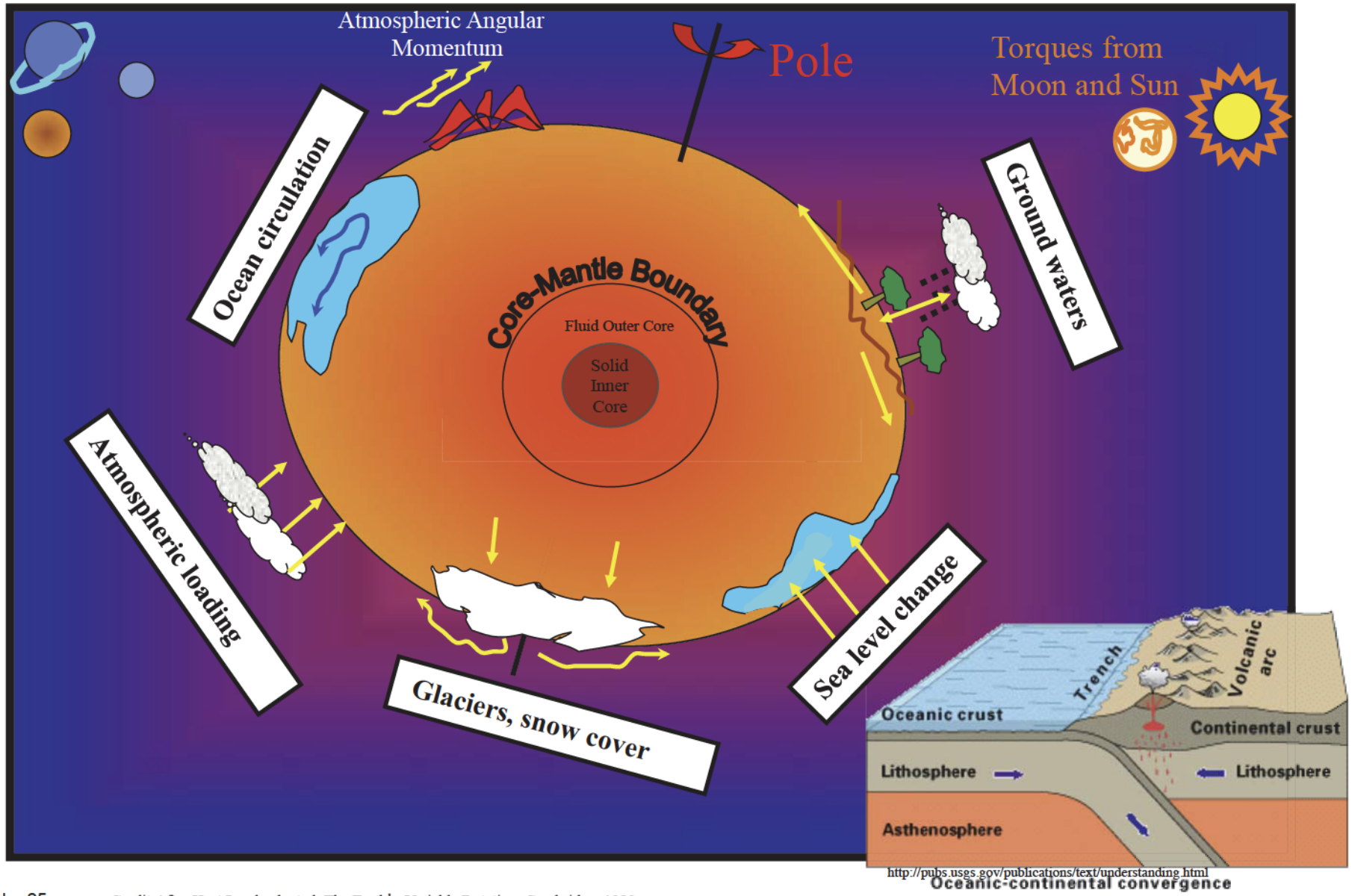
Features of AGN: *Note the Logarithmic length scale.*
"Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not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

Credit: 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)

# How Does VLBI Work?

## *The Observing Platform*

# Moving Platform: UT1, Polar Motion, Nutation, Tectonics




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



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

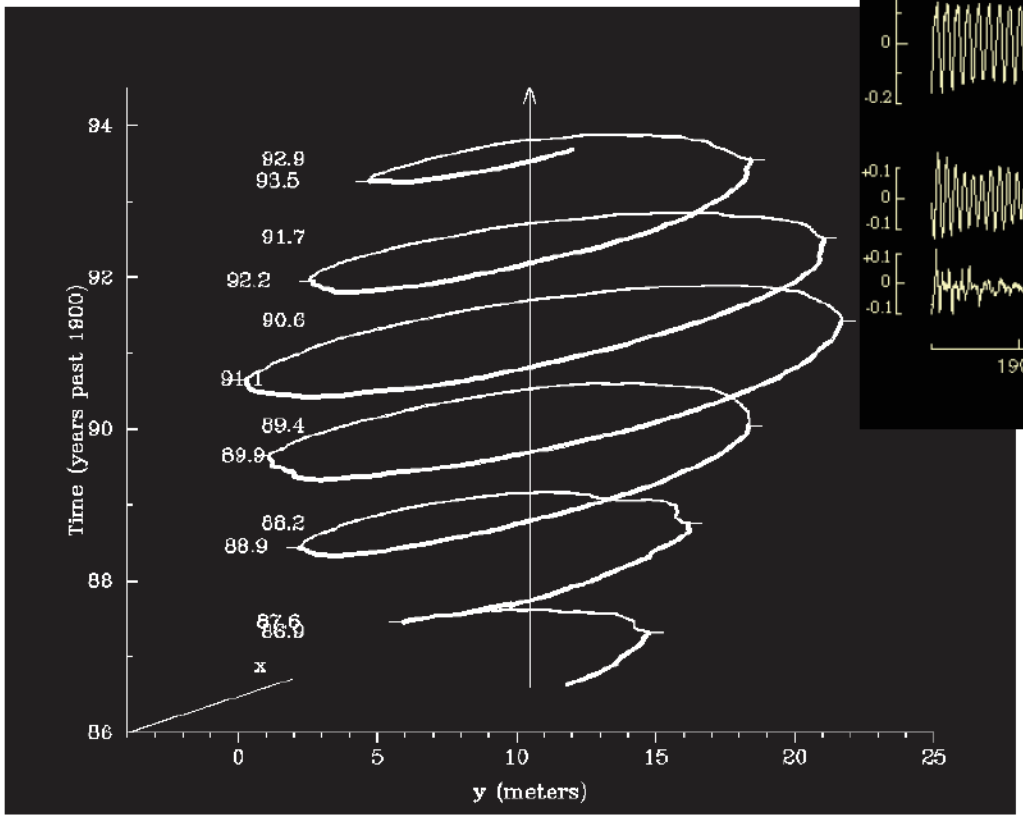
# "Budget" of Effects contributing to Interpretation of Results

| 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** |

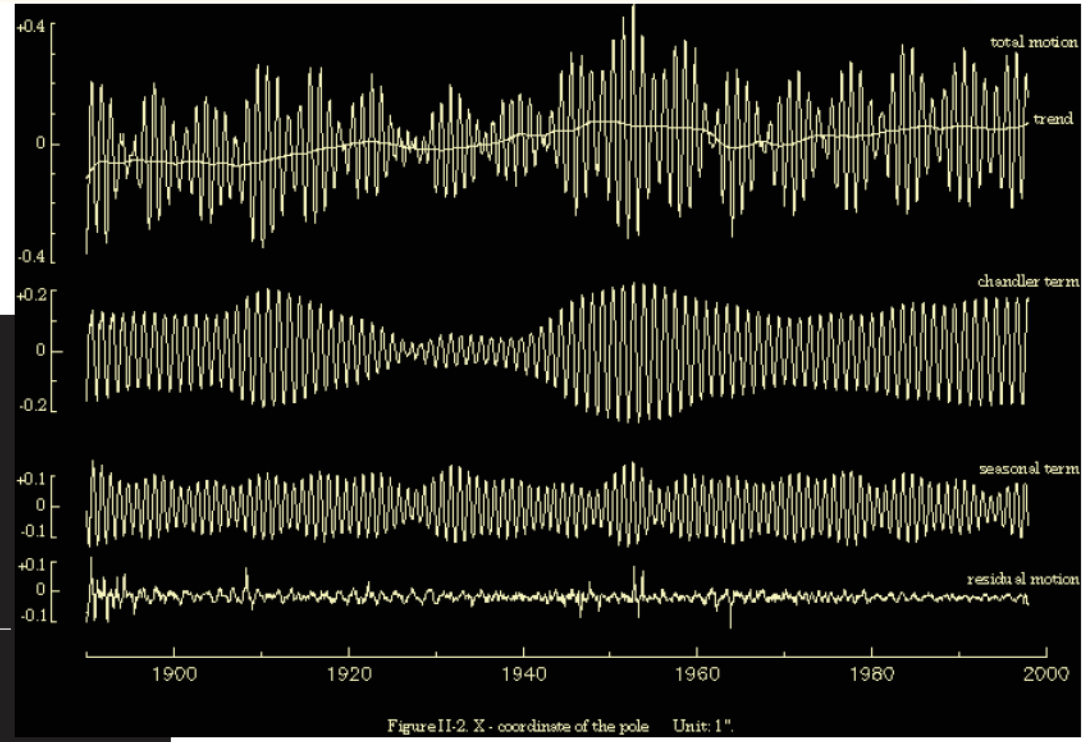
Credit: Sovers, Fanselow, & Jacobs, Rev Mod Phys 70, 4, 1998

# Polar Motion Spiral

## Polar Motion vs. Time




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



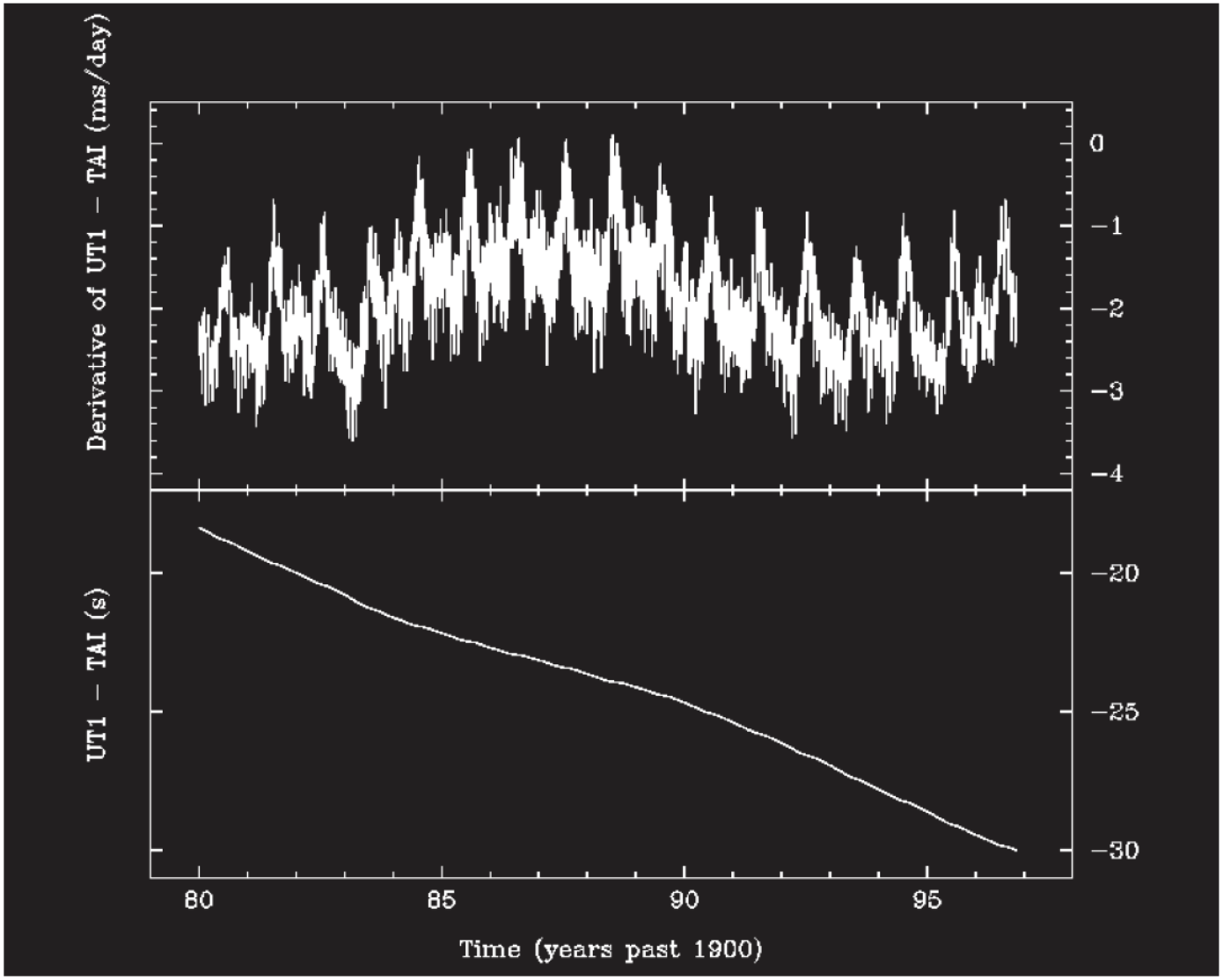

(credit http://www.iers.org/iers/earth/)

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.*

# *Earth Orientation: GPS is not sufficient*

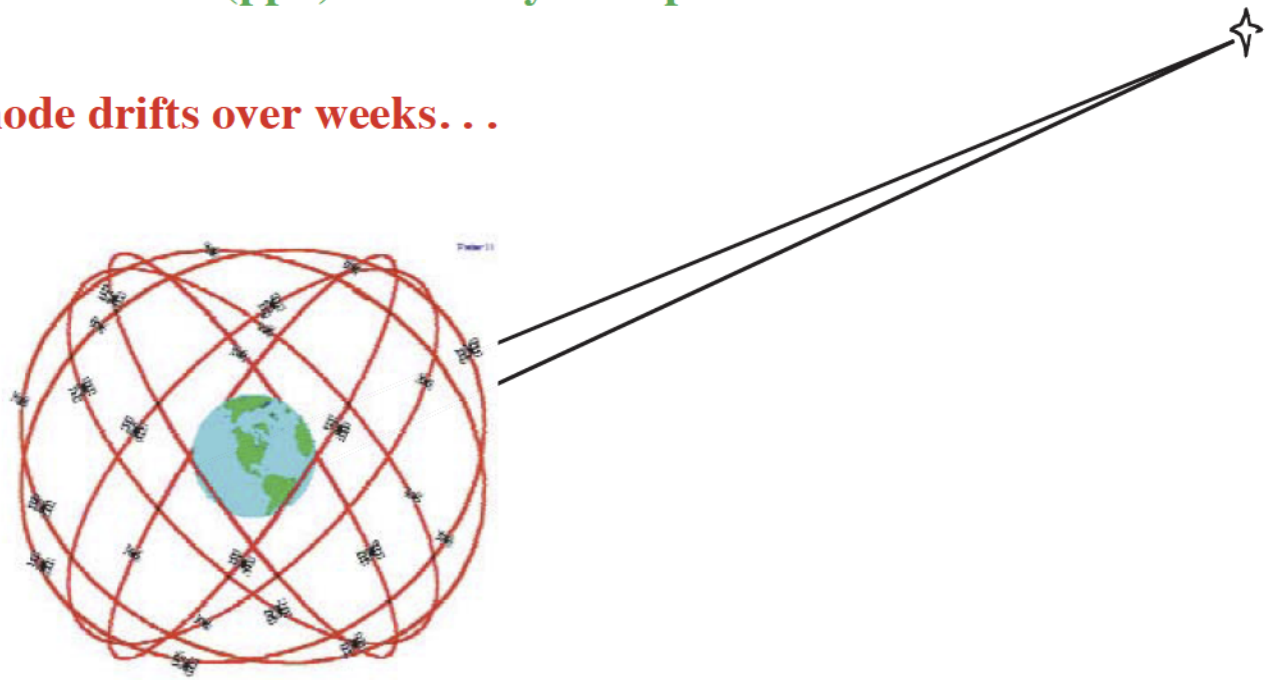
**Earth Orientation: Relative to what?**

**One must define stable (ppb) reference directions**

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

***But . . .***

**- GPS constellation node drifts over weeks. . .**



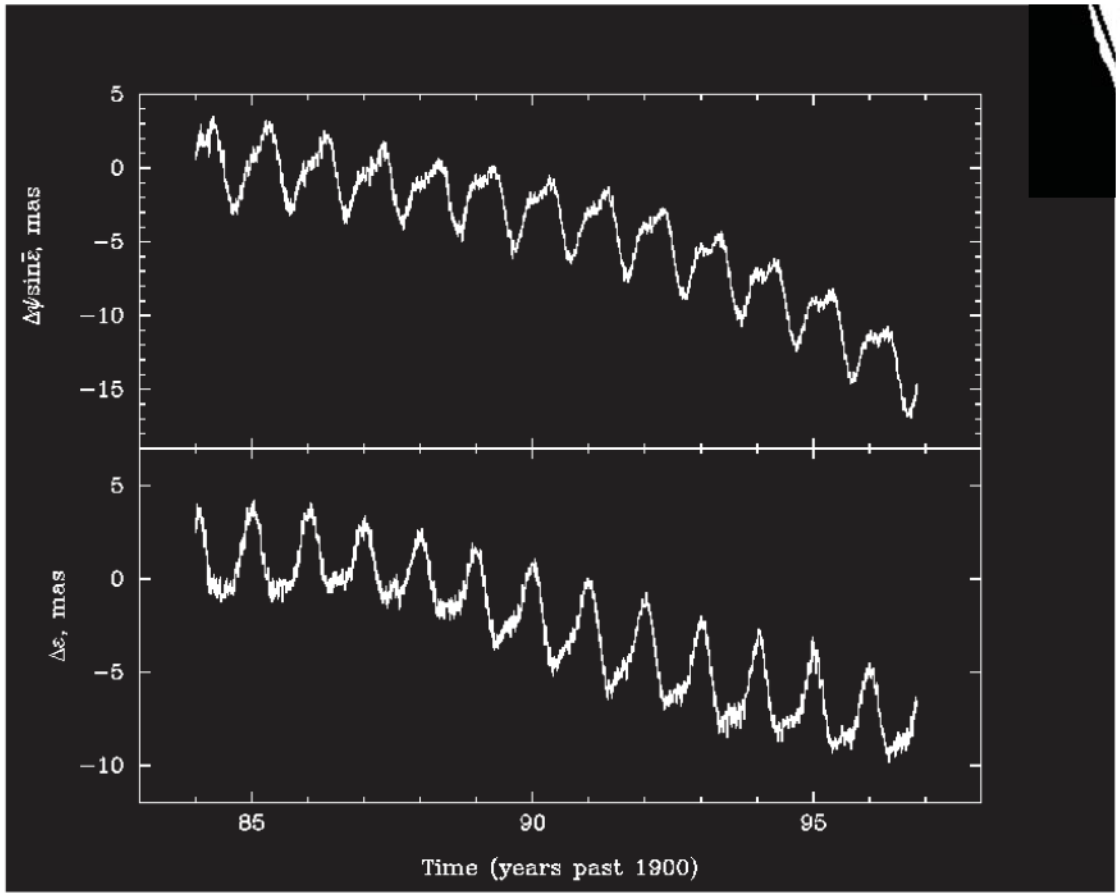
**Solution: Change source from range of GPS's nano-Ly to VLBI's Giga-LightYear ~eighteen (18) orders of magnitude!**

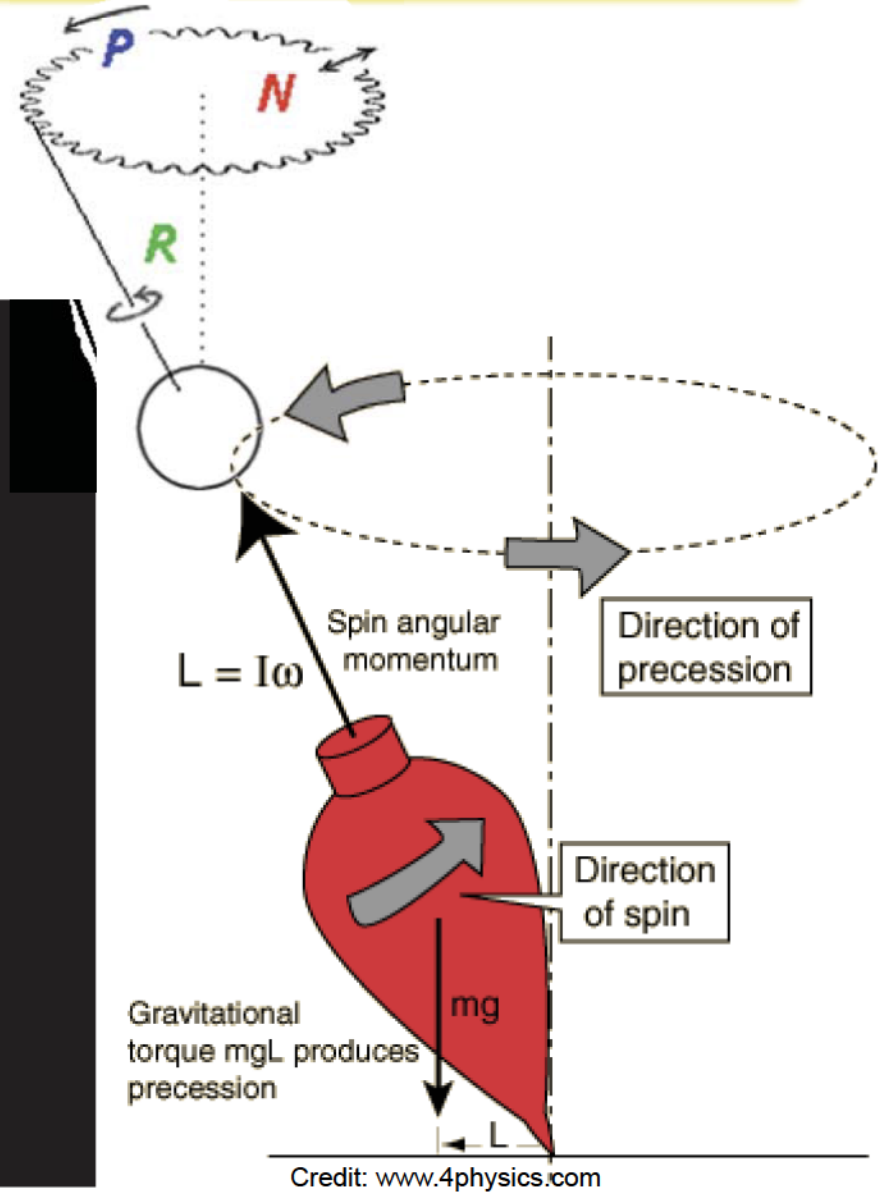
Credit: www.international.gc.ca/arms-armes/assets/images/bourbonniere_img6.jpg

# Nutation: The Earth's axis is like a Top

From German Wikipedia, by User Herbye.

1980 IAU Model vs.
VLBI observed
Nutation

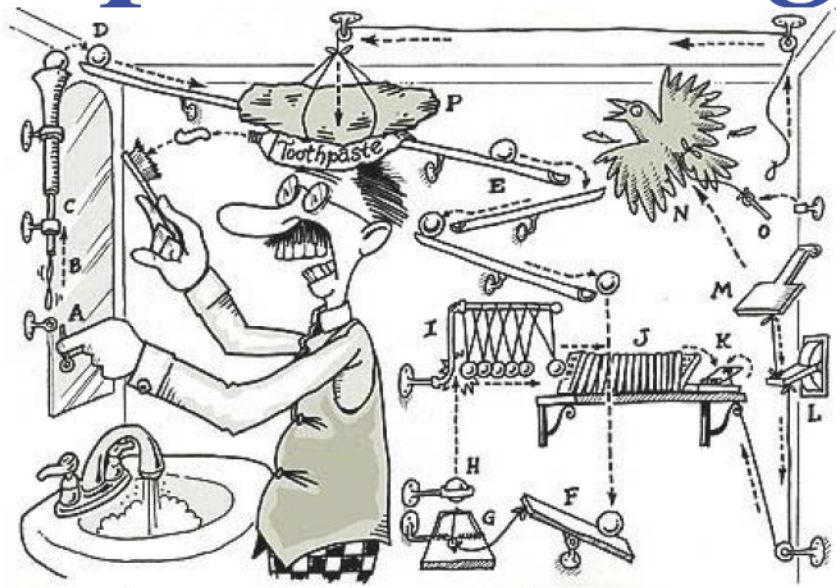



*Credit Sovers, Fanselow, Jacobs, Rev Mod Phys 70, 4, Oct 1998.*

# How Does VLBI Work?

## *Implementing a*



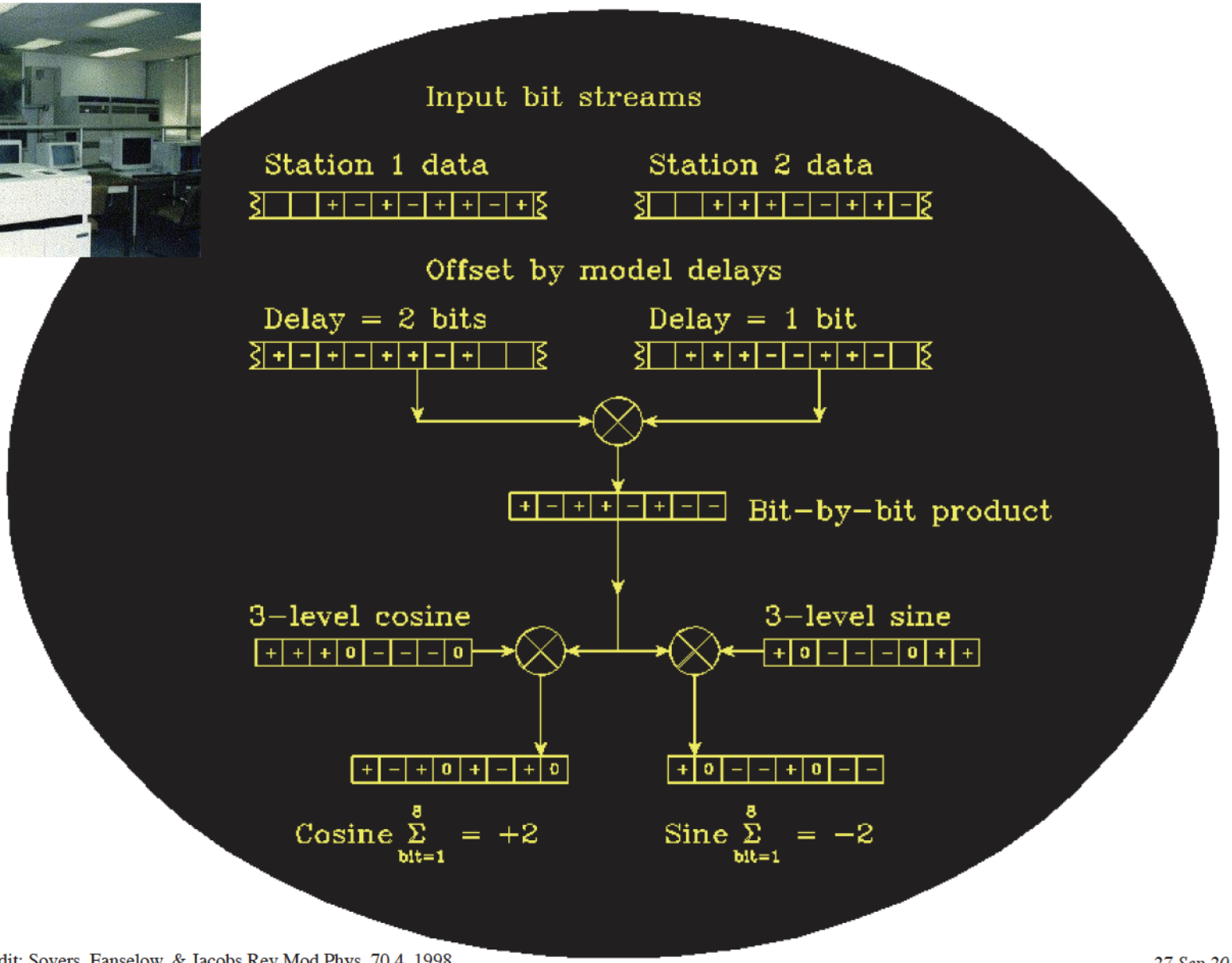

*Cartoon credit: Rube Goldberg*

## *Group Delay Machine*



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

# Correlation Scheme




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

# VLBI Observables

***Measure from two stations voltages $V_1$, $V_2$***

$$\textit{Correlation} = \int dt\, V_1(t)\ V_2^*(t-\tau)$$

***Take cosine,sine components => Get phase (Ø) and Amplitude***

***Measure @ many frequencies, f, times, t:***

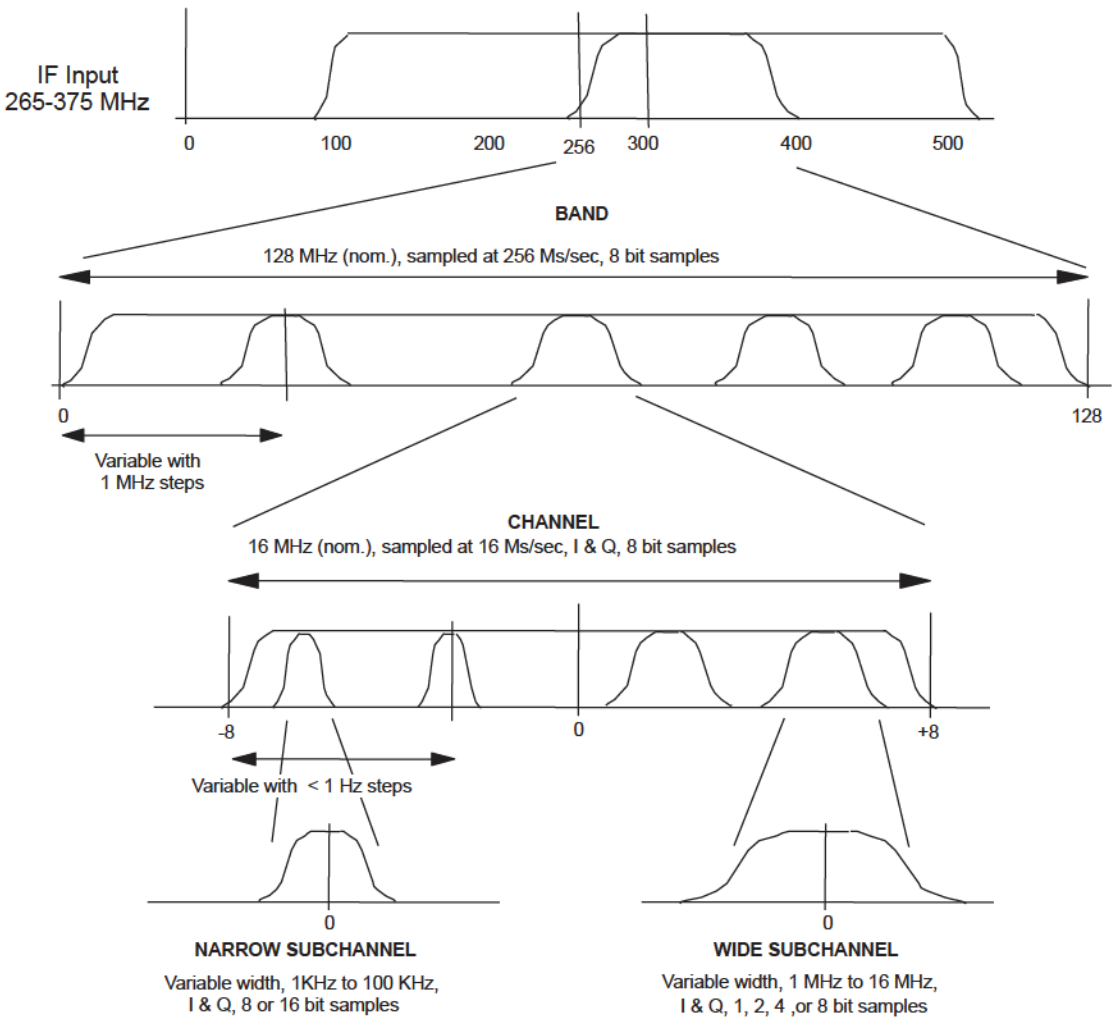
$$Ø(f,t) = Ø_o + \partial Ø / \partial f + \partial Ø / \partial t$$

| | | |
|---|---|---|
| *phase* | *group delay* | *Doppler/ phase rate* |

# VSR Processing Bands

**RF Front End**

**400 MHz**




**IF**

**128 MHz**

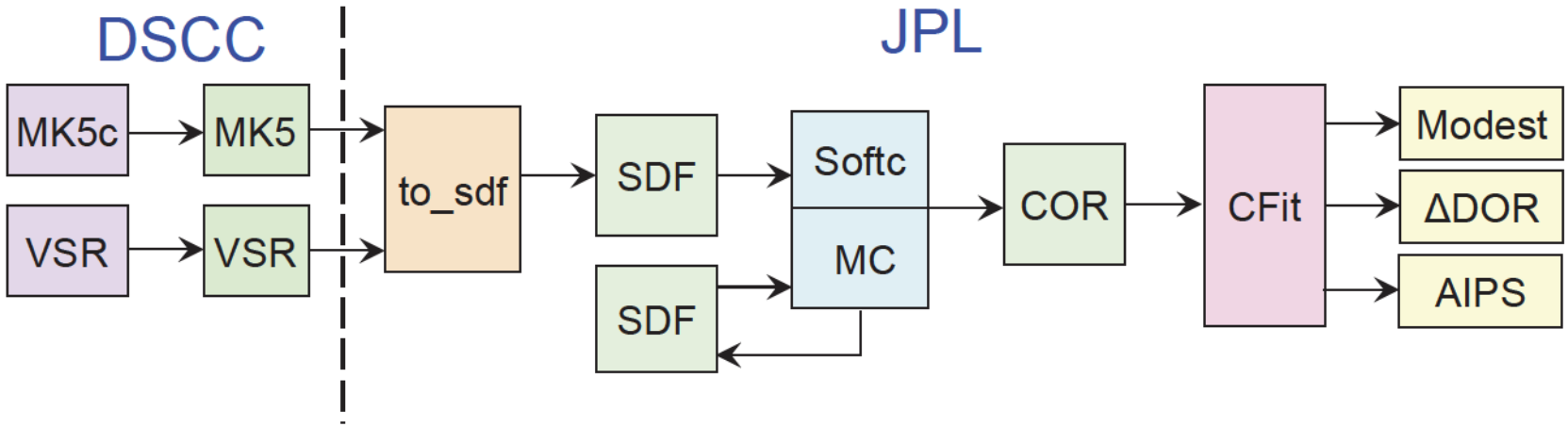
**VSR channel**

**16 MHz**

**Sub-channel**

**1 MHz**

# VLBI Signal Processing

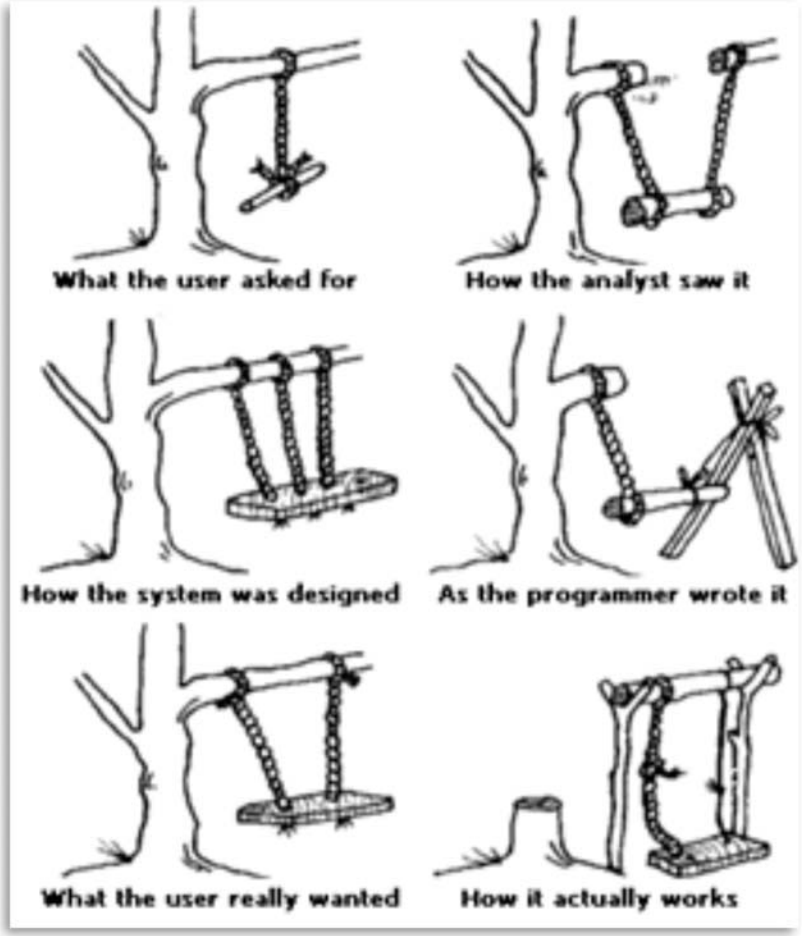



- to_sdf - converts data from multiple input formats to internal correlator format
- SDF - input Station Data Format
- Softc - Software Correlator program
- MC - Monte Carlo data simulator for testing
- COR - CORrelator out file
- Cfit - Correlator post-processing Fitting
- Modest - MODel and ESTimate astrometry/geophysics
- AIPS - Astronomical Image Processing System



Credit: Steve Lowe

# VLBI Requirements?



# Requirements (Berry et al)

| Tracking Error Requirement, 1σ | units | Current Reqt | Current Capability | 2020 | 2030 |
|---|---|---|---|---|---|
| Doppler, Random (60s) | mm/s | 0.05 | 0.02 | 0.03 | 0.02 |
| Doppler, Systematic (60s) | | | 0.04 | 0.003 | 0.002 |
| Range, Random | m | 1 | 0.5 | 0.3 | 0.1 |
| Range, Systematic | | 0.6 | 0.5 | 2 | 1 |
| Delta-DOR | nrad | 2.5 | 2 | 1 | 0.5 |
| Troposphere | cm | 1 | 0.8 | 0.5 | 0.3 |
| Ionosphere | TECU | 5 | 5 | 3 | 2 |
| Earth Orientation, real-time | cm | 30 | 7 | 3 | 2 |
| Earth Orientation, after update | cm | 5 | 5 | 2 | 0.5 |
| Station Locations | cm | 3 | 2 | 2 | 1 |
| Quasar Coordinates | nrad | 1 | 1 | 1 | 0.5 |

- Green: VLBI used directly
- Black: VLBI provides station XYZ, Earth Orientation
- Red, Orange: VLBI provides independent cross-check

# Performance Metrics

| System | Availability | |
|---|---|---|
| Antenna Mech. | 0.9925 | JC 080415. Maintenance? |
| Ant. Microwave | 0.9883 | 821-110 rev B--RS286 |
| Freq. & Timing | 0.9999 | 821-110 rev B--RS286 |
| Pointing | 0.98? | X-band OK; Ka-band a problem |
| Analog sub-total | 0.965 | |
| Digitizer/baseband | 0.995 | |
| Recorder | 0.99 | |
| Digital sub-total | 0.985 | |
| **Requirement** | **0.950** | RSO Functional Req. #172 |

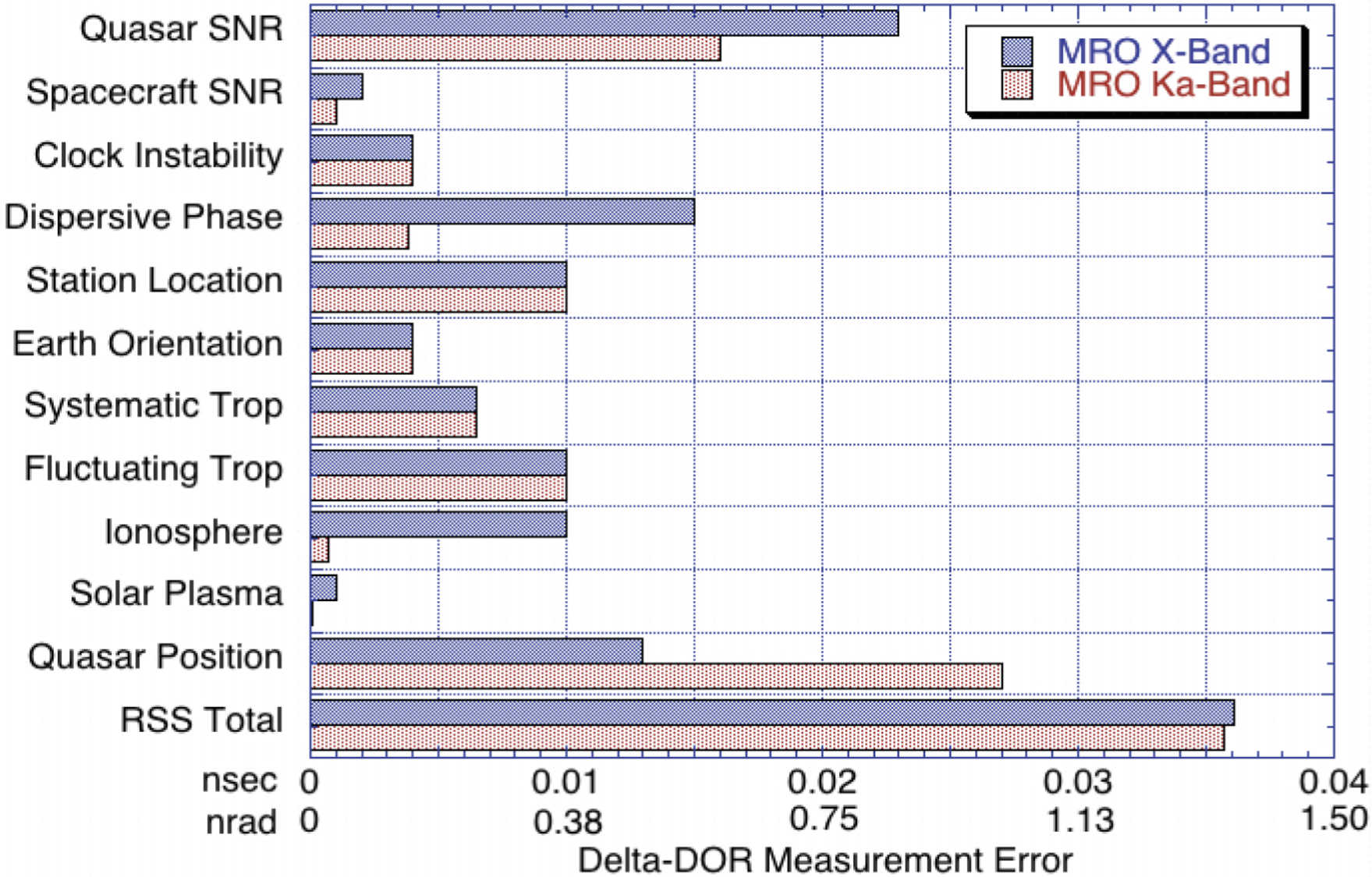
# Error Budget for Reference Frame VLBI

## *The Tall Tent Poles*



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

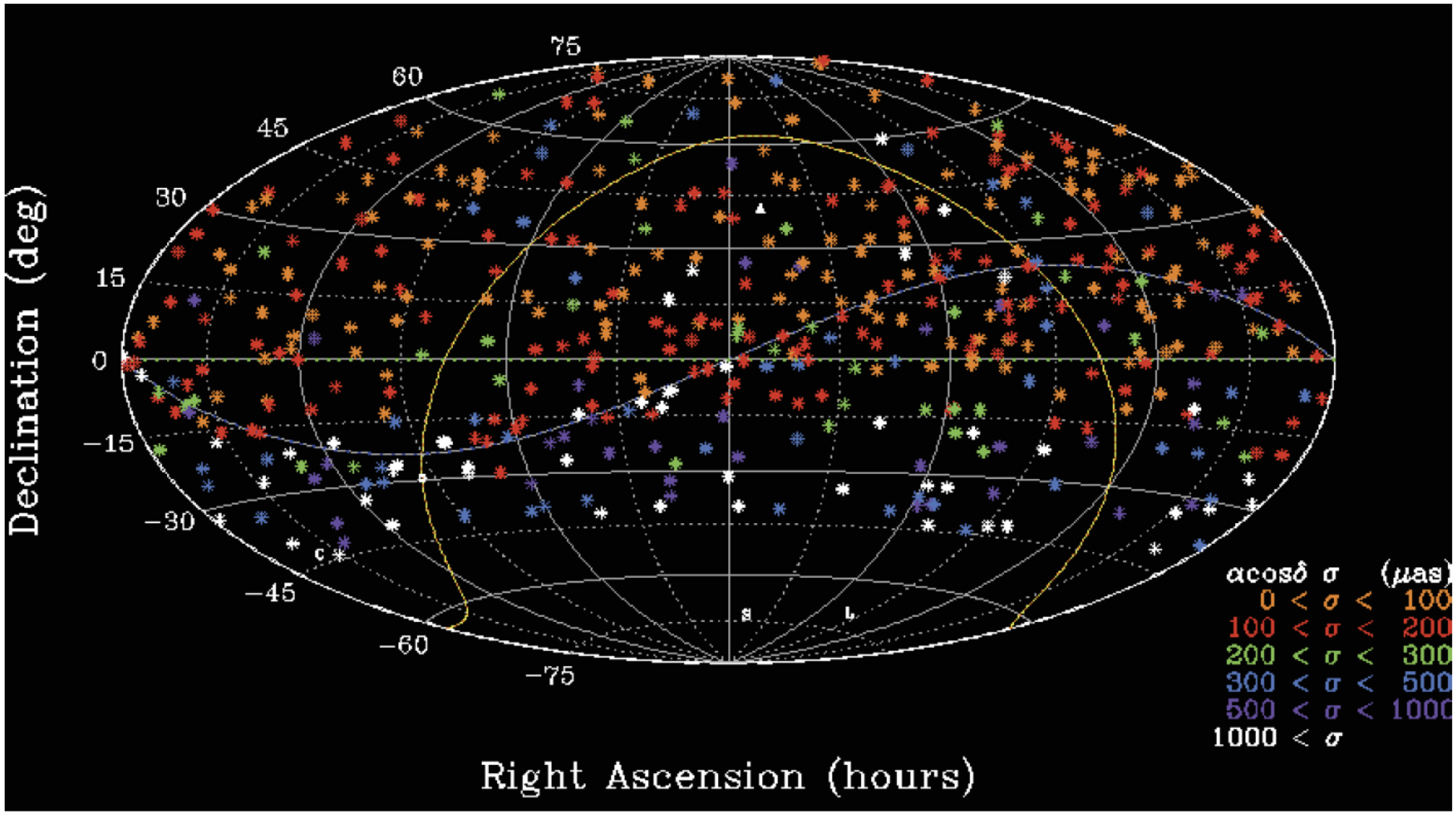
# ΔDOR Error Budget





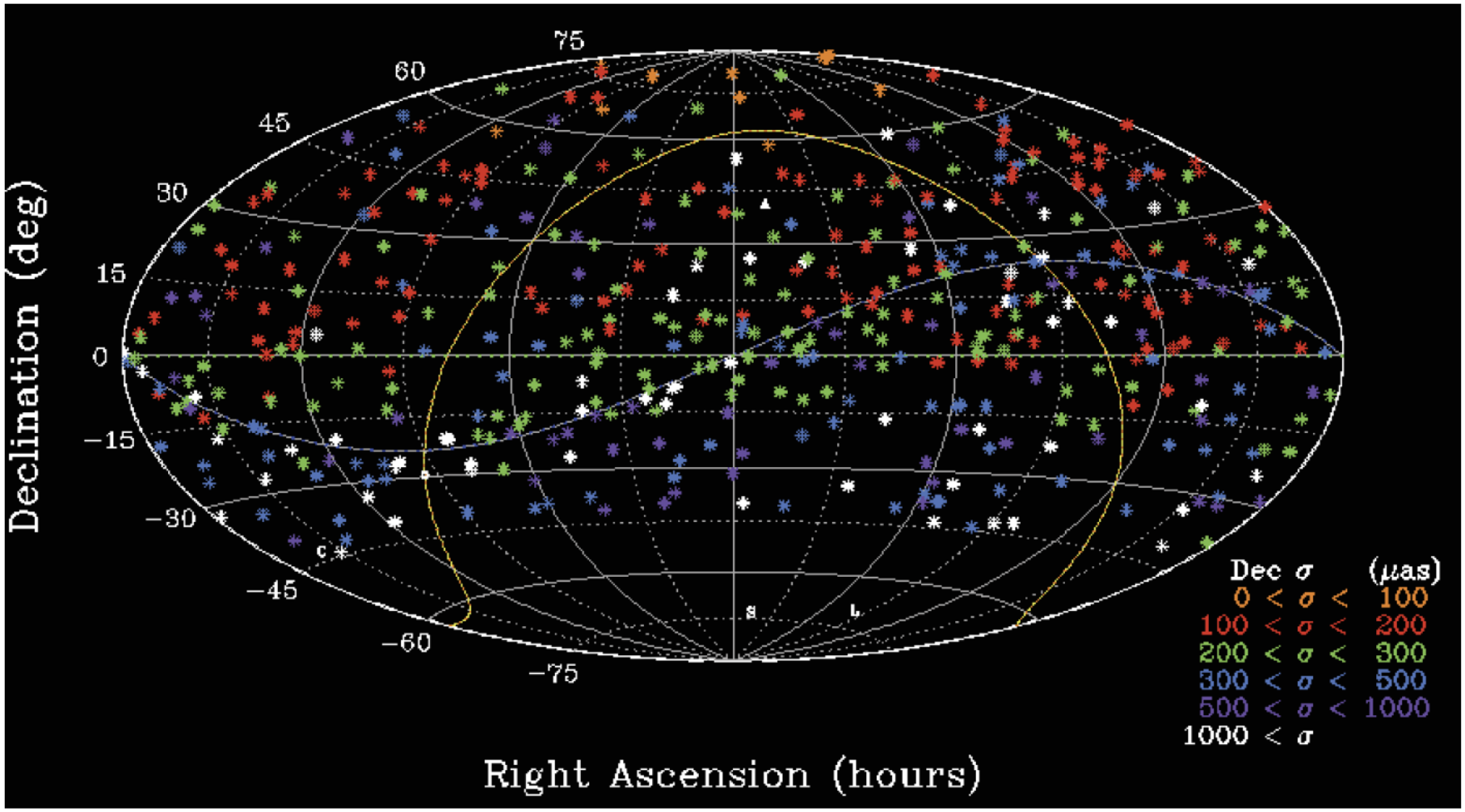

Credit: DDOR budget from J.S. Border

# X/Ka current RA results: 466 Sources




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

# X/Ka current Dec results: 466 Sources




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

# Focus Work on the Tall Tent Poles

## Systems Analysis shows dominant Errors are

- **Limited SNR/sensitivity**
  - already increasing bit rates: 112 to 448 Mbps. Soon to 2048?
- **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 $\mu$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//

# 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:**

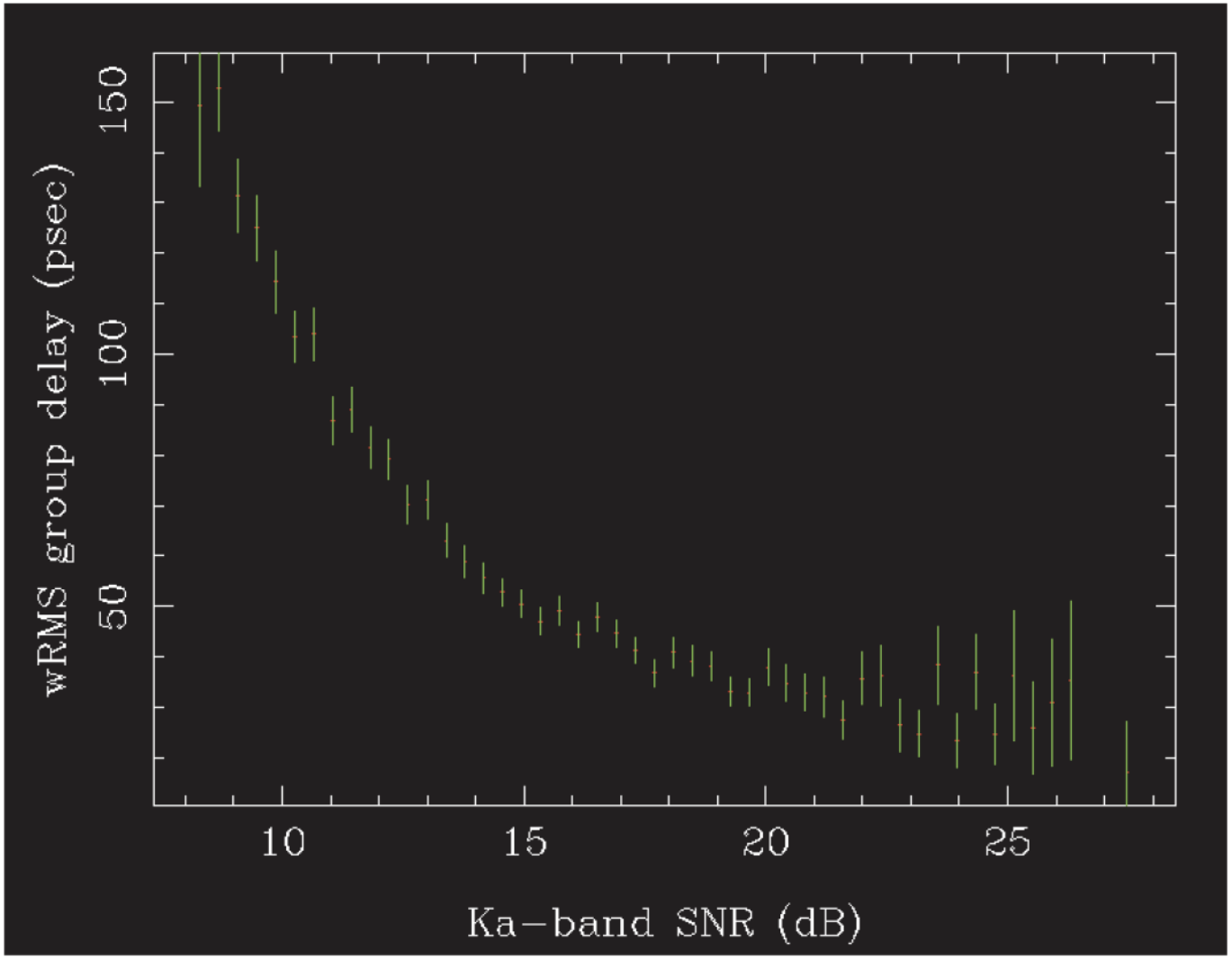
**1) More bits:**
- 4X operational
- 16X R&D
  - in ~6-12 months

Will yield +3-6 dB SNR increase

**2) Ka pointing**

Now with improved Pointing calibrations ~3 dB more SNR

Total vs. early passes +6-9 dB SNR increase!




**Results have been SNR limited for SNR < 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**

**9 recent @ 448 Mbps (X/Ka 160/288 ) ~ 5X**

**in 6-12 mo. @ 2048 Mbps (X/Ka 192/1856 ) ~32X**

Total Ka improvement 56 to 576 Mbps => 10 psec delay precision

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

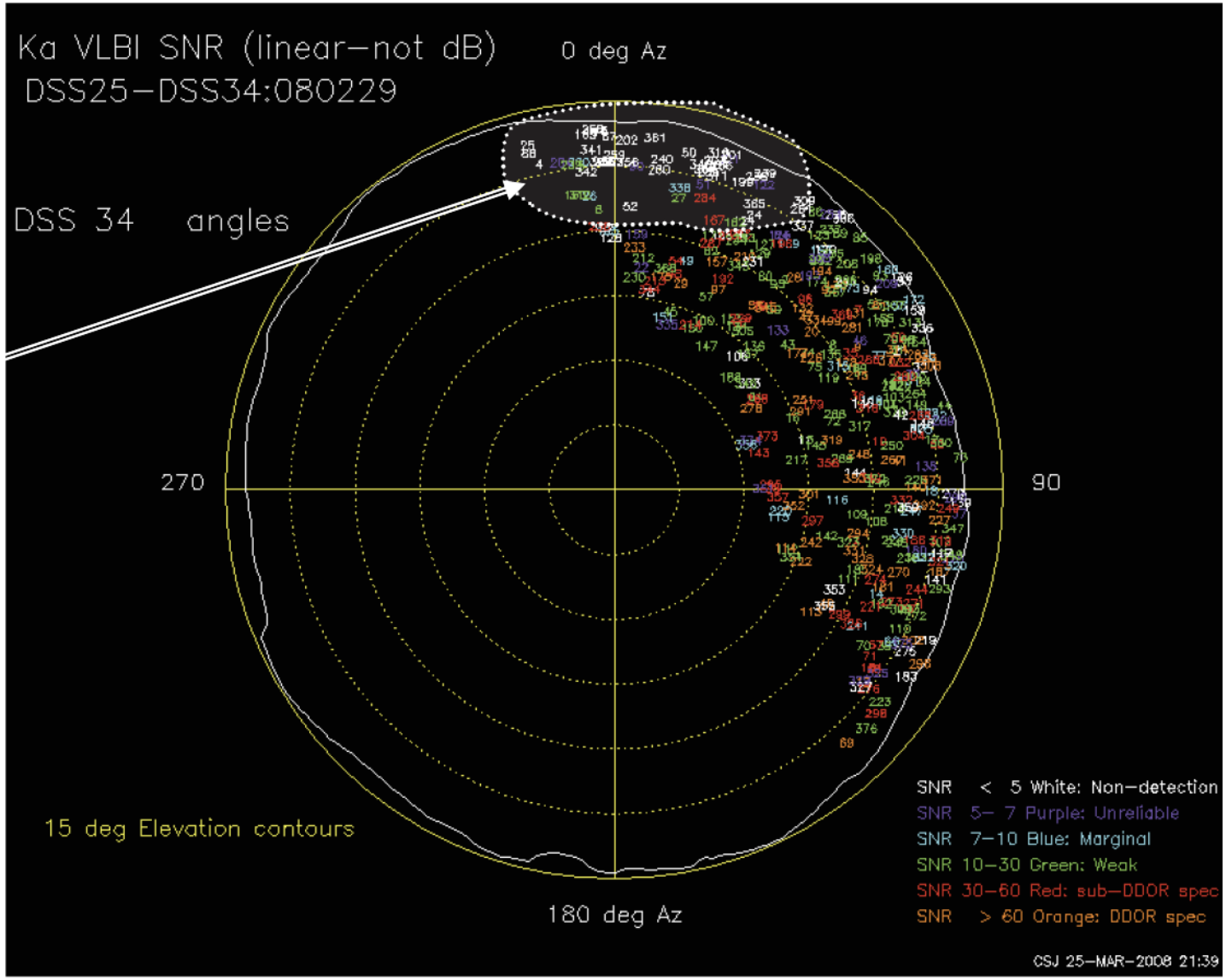
Credit: C. Jacobs, D. Bagri, E. Clark, C. Garcia-Miro, C. Goodhart, S. Horiuchi, S. Lowe, E. Moll, L. Skjerve, L White

# 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

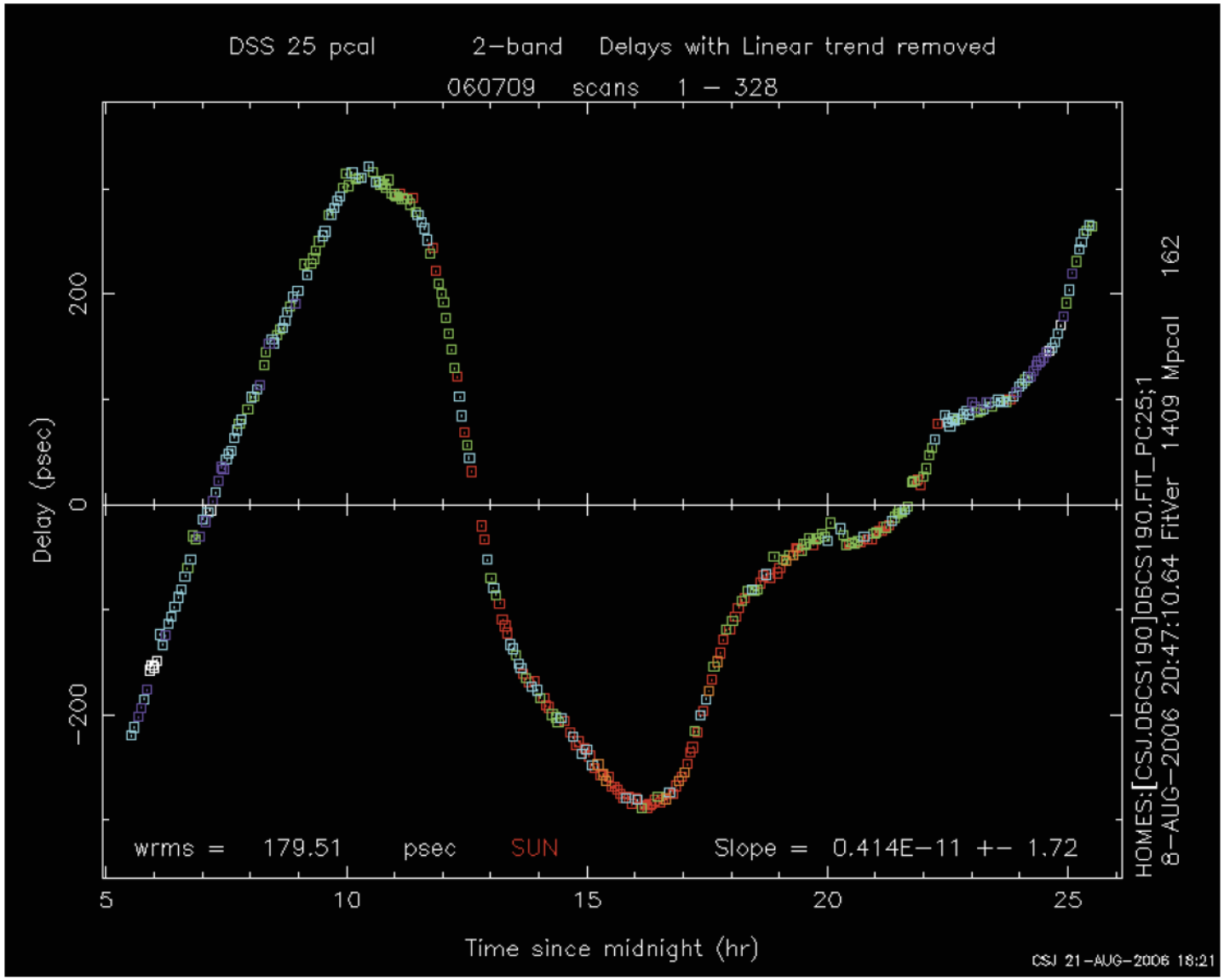
# Results limited by No BWG Phase cal

**Problem:**

**180 psec ~diurnal effect**

**Solution:**

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

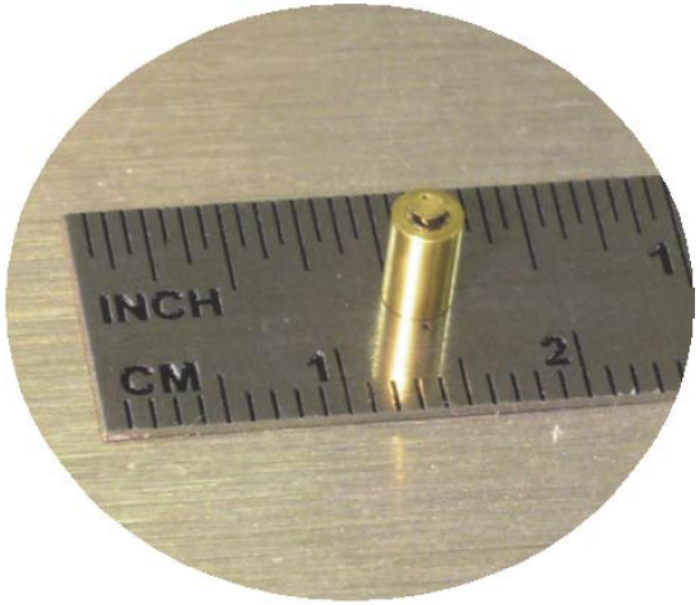





Credit: C. Jacobs, B. Tucker, L. Skjerve

# *BWG Phase Calibrator*

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



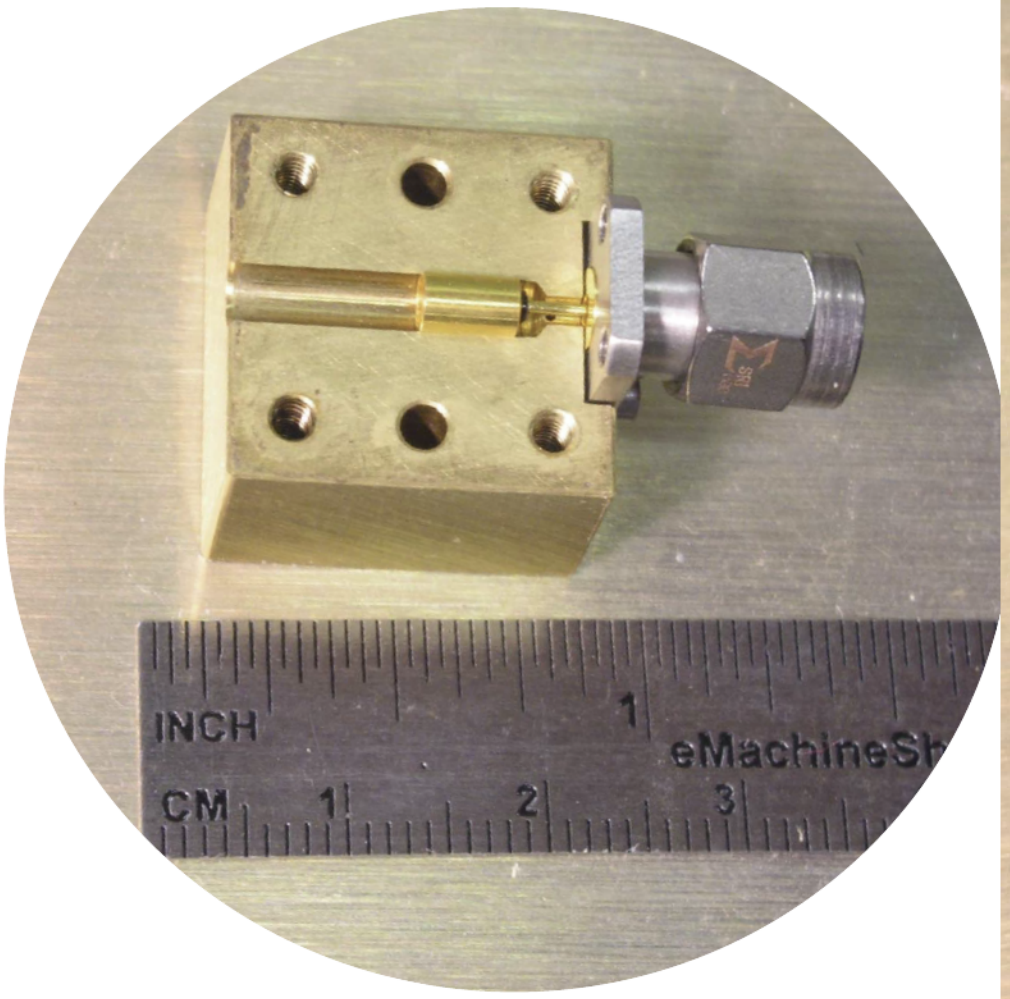

Tunnel Diode Chip
0.055" diameter by
0.020" thick
Mounted on
0.119" diameter carrier
for solid grounding

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

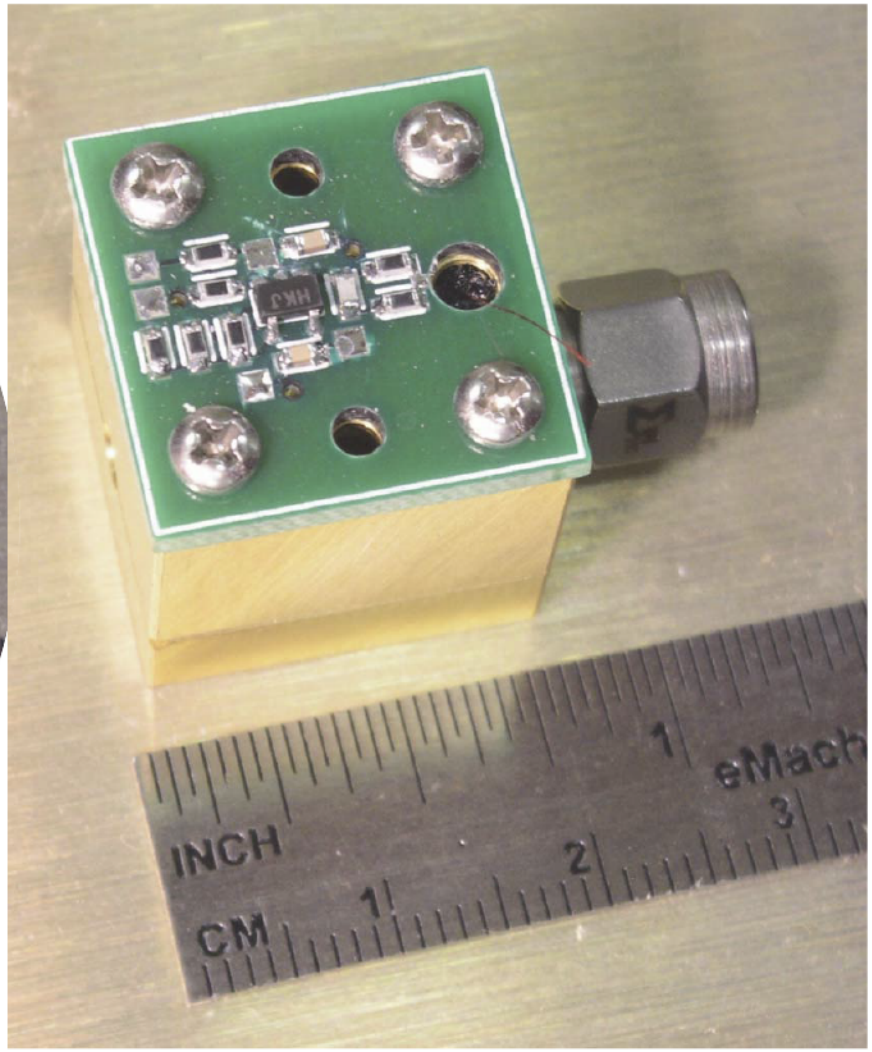
  *tmo.jpl.nasa.gov/progress_report/42-154/154H.pdf*

- Production units: Blake Tucker

# *Beam Wave Guide phase calibrator*




Direct interface to K connector inside coaxial structure.




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

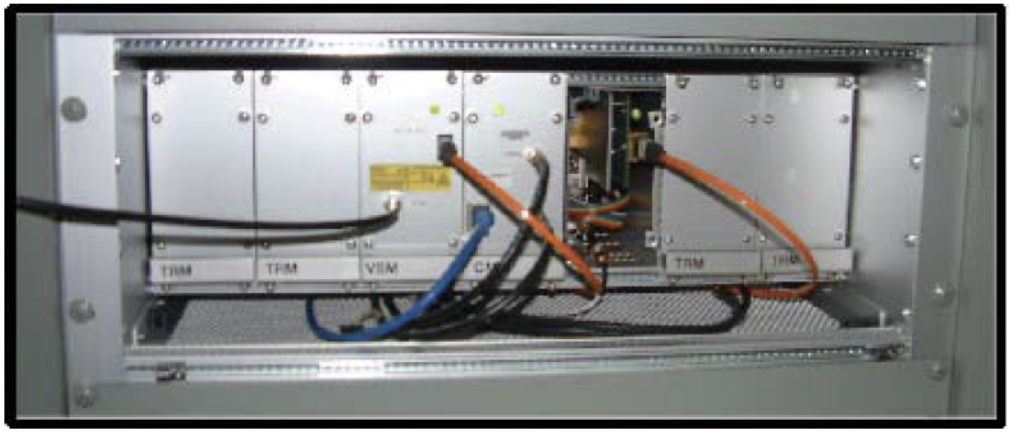
*Credit: Blake Tucker*

# *Sample, Baseband convert, Filter, Record*

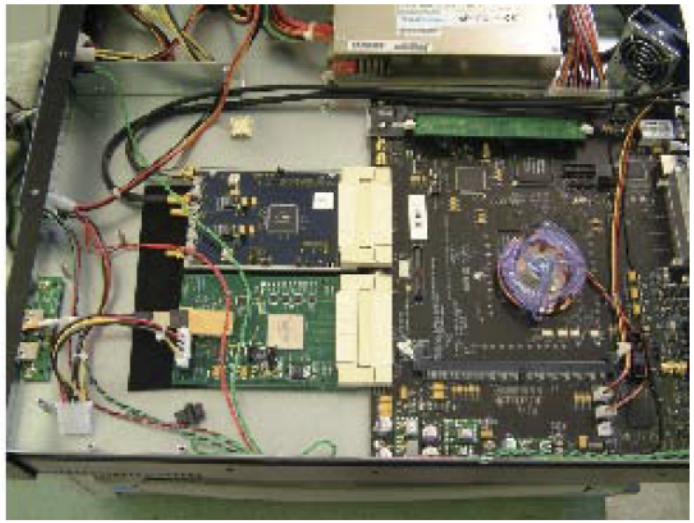
IF select switch:
12 inputs allows
multiple bands,
multiple antennas

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

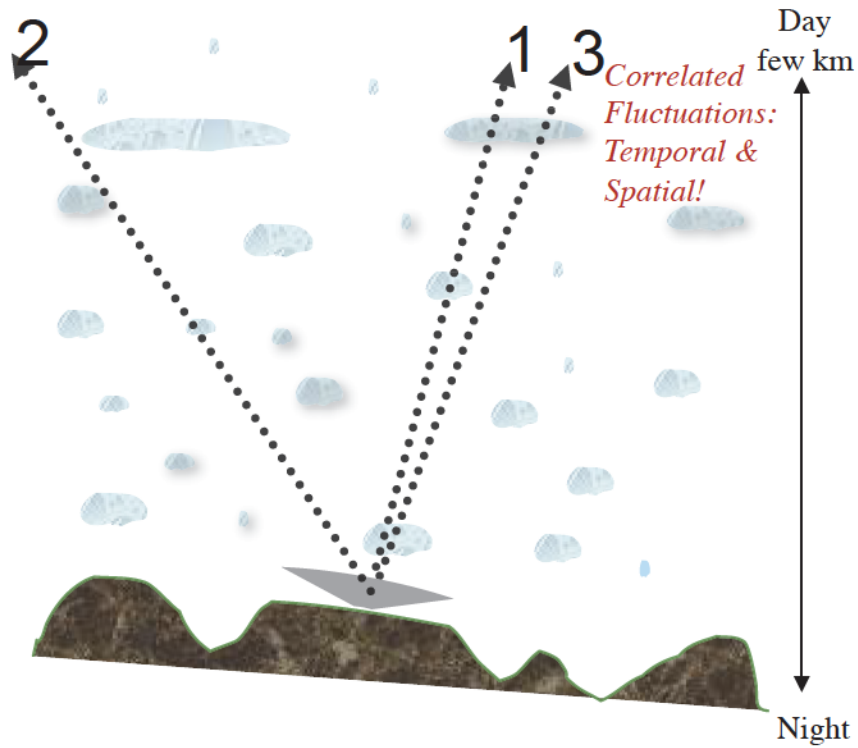
# Troposphere Solution 1: Better Estimation

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

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

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

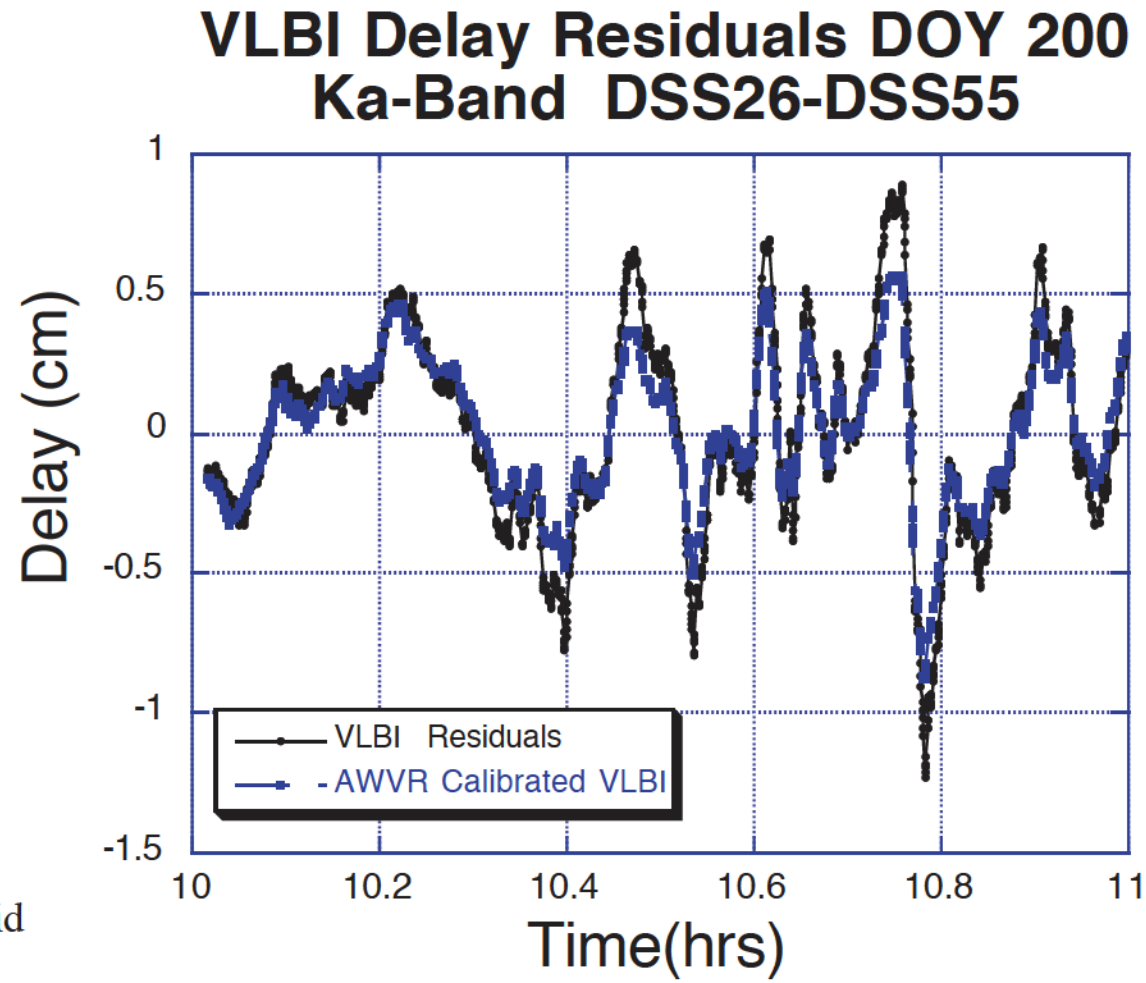
- Validation: Currently improves agreement X/Ka vs. S/X catalogs by about 10% in Declinations.
  Expect ~30% after SNR & phase cal errors peeled away to reveal troposphere errors.



# 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

- Initial demos show 1mm accuracy Goldstone-Madrid 8000 km baseline using X/Ka phase delays
  - *Jacobs et al, AAS Winter 2005.*
  - *Bar Sever etal , IEEE, 2007.*
- A-WVRs deployed at Goldstone/Madrid Seeking funding for Tidbinbilla, Aus
- A-WVR not used yet for Operations



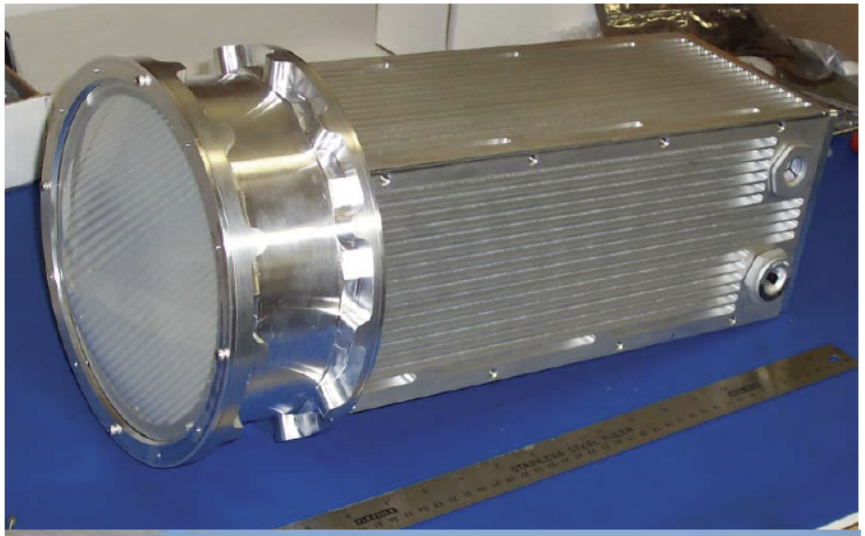
# Troposphere Cal: Cheaper WVR?

- Advanced R&D WVR is very accurate
  but expensive on order ~$500K
  Mounted 50-100m from VLBI antenna

- Investigated "Radiometrics" WVR
  - 21 channels cover 20-30 GHz
  - "Inexpensive" at $120K (U.S.)
  - Light weight: ~7 kg

- Subreflector mounting
  - enabled by low weight
  - ideal co-pointing, no offset
  - better match with VLBI beam volume
  - enables calibration of doppler/rate
  - improves performance at high freq.

- Gain stability needs investigation



Credit: M. Britcliffe, M. Franco

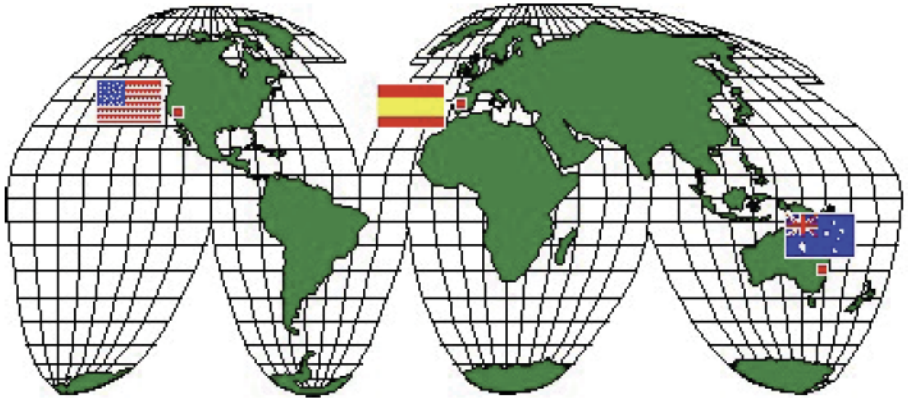
# Attacking the Error budget

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

  Phase calibration with test signals

  Digital Baseband Conversion & Filtering
- Troposphere cals: WVR

- **Southern Geometry**

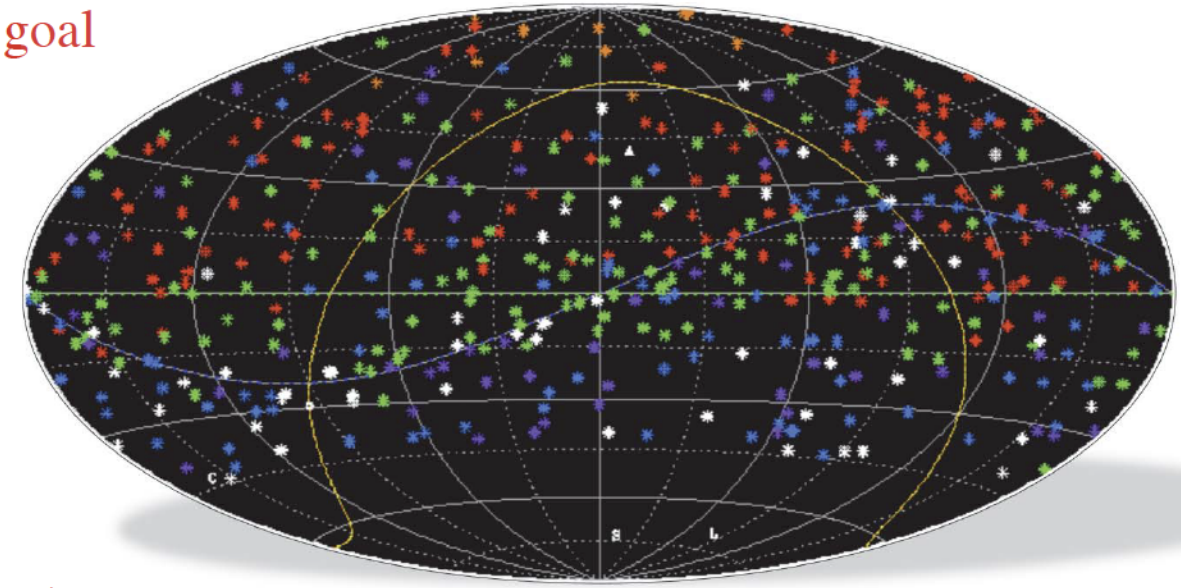


www.spacetoday.org/images/SolSys/DeepSpaceNetwork/NASA_DSN_WorldMap.gif

# Need 2nd Station in South

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

Current DSN X/Ka Frame



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

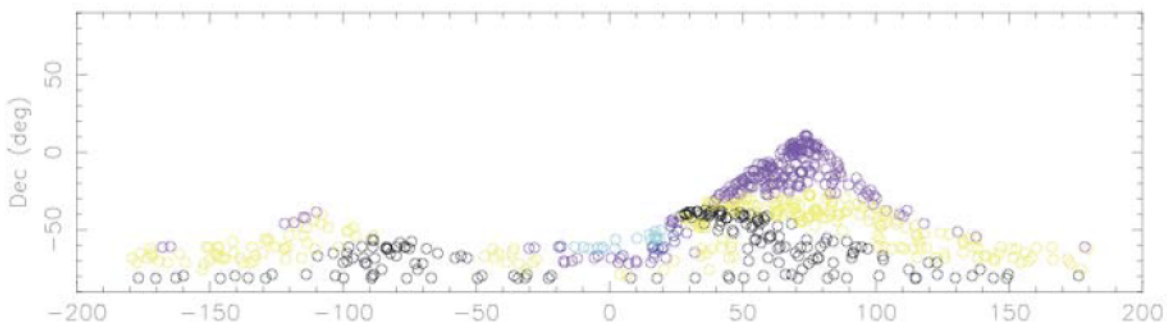
- DSN weakly covers southern Ecliptic: only one strong baseline as California-Spain is weak in south

Declination 1-sigma

| | | |
|---|---|---|
| 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 Stations?

- ESA Deep Space Antennas (DSA-1, 2, 3)
  - Cebreros, Spain: duplicate geometry to DSN in Robledo
  - New Norcia/Perth, Australia (helps but only 3000km from DSN Tidbinbilla)
  - **Malargue, Argentina:** Ideal, online mid-2012? NASA/CSIRO collaborate?
    - 35m, X/Ka-band, 9,500 km baseline
    - Dry desert site is good for Ka-band
    - HA-Dec coverage: Tidbinbilla to Malargue:

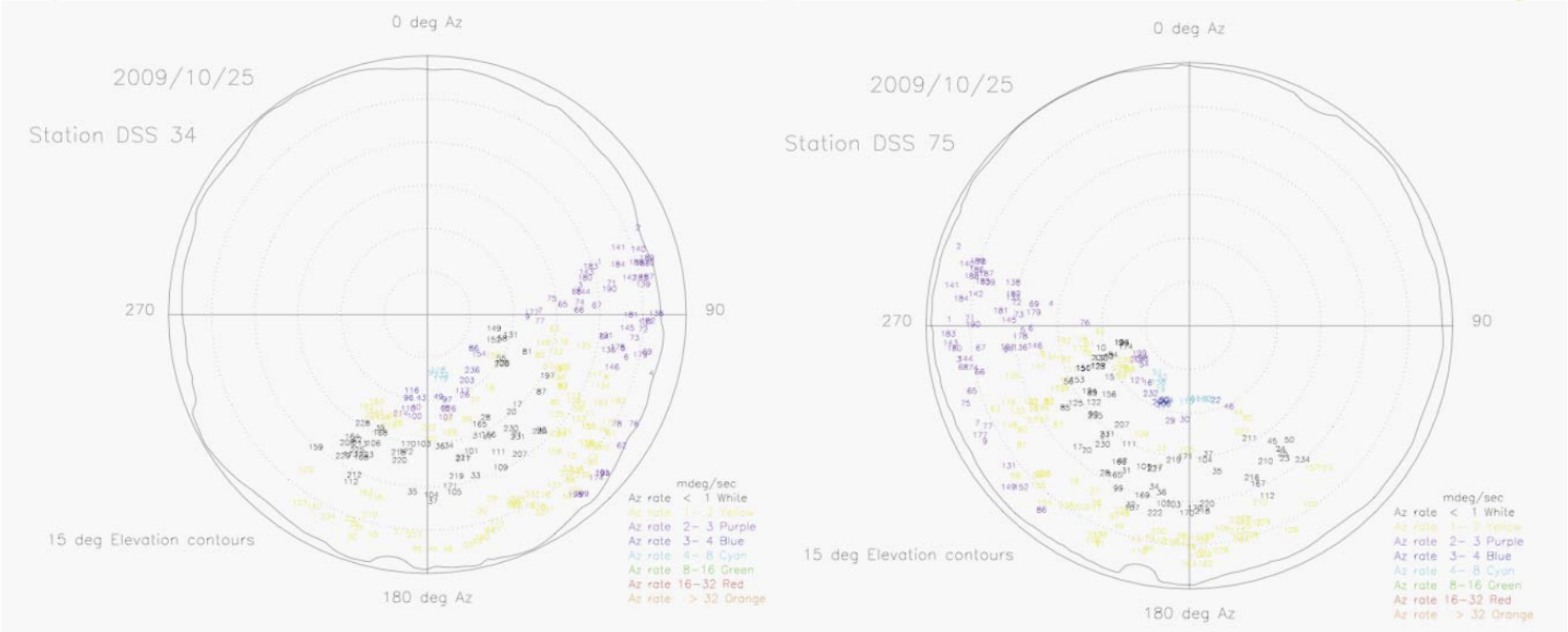



- Hart, South Africa
  - Old DSS 51 diameter 26m
    - Was broken ~2yr, Recently repaired
    - Resurfaced in 2005 (0.5mm RMS) efficient to 22 GHz

ESA Deep Space Antenna
*35m, Ka-band capable*

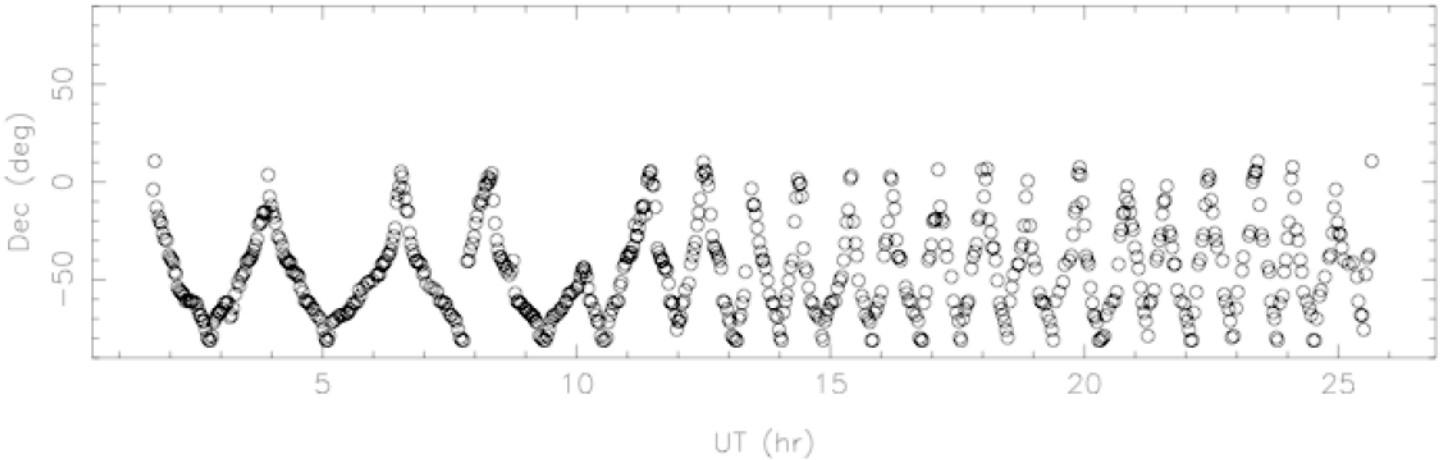
Credit: www.esa.int/esaMI/Operations/SEMGSDSMTWE_0.html

# DSS 34 to Malargue, Argentina (DSA-3)

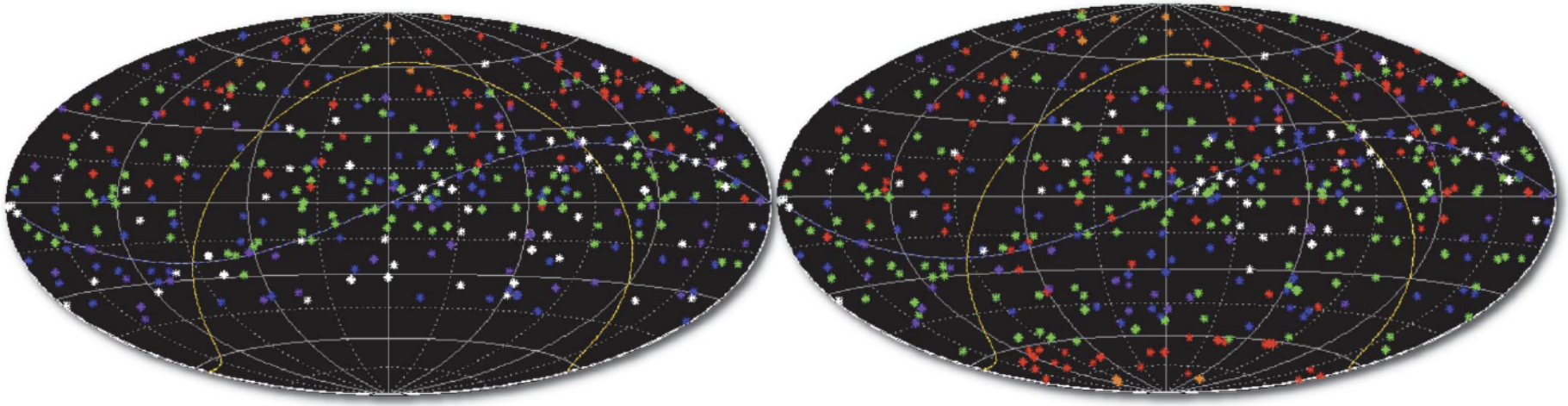



Simulated Coverage:

**Dec +10 deg to –90 deg**



# Simulation of Added Southern Station



*Before Southern Data* *After*

**Declination Sigma**

Orange: < 100 $\mu$as
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 $\mu$as (1 nrad) precision in south polar cap,
  mid south 200-1000 $\mu$as, all with just a few days observing.

# Conclusions

- VLBI is a type of station differenced range using
  - natural radio sources (quasars)
- Requirements call for ~part per billion level accuracy in
  - Terrestrial Frame (station XYZ)
  - Celestial Frame (quasar RA, Declination)
- Systems Analysis shows dominant Errors are
  - Limited sensitivity
    - Improve pointing: New automated system achieves ~4 mdeg
    - Higher recorded bit rates: 16X higher rates on the way
  - Troposphere: Better calibrations with Water vapor radiometer
  - Instrumental Calibration: Prototype demo'd, ops in works
  - Lack of southern stations: Don't meet requirements in south
    - Repaired DSS 34, start to build DSS 35
    - Add station in South Africa and/or South America: need studies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# The Challenge of Future: Opportunities

- Neutrino astronomy – GLUE, ANITA (Gorham et al)
- Pulsar astronomy (Majid et al)
- Dark Matter searches (King, Gorham, Romero-Wolf, et al)
- Holography (Manuel)
- DSN automation (Cristina, Esther, Ioana)
- Radio Imaging "Zoom lens" (Cristina)

Da Capri, ***Opportunity*** *& Regret*

- ESA joint missions: Cebreros, Malargue (Juan, Ioana, Cristina, Manuel)
- Ka-band worldwide Network – resolution 100X Hubble (Ioana, Cristina, Jose)

Girolamo Da Capri, *Opportunity and Regret*,1541, Gemäldegalerie (Old Masters), Dresden, Germany,
The Yorck Project: 10.000 Meisterwerke der Malerei. DVD-ROM, 2002. ISBN 3936122202. DIRECTMEDIA Publishing GmbH

# The Potential for a

# Ka-band Worldwide VLBI Network

C. S. Jacobs[1],

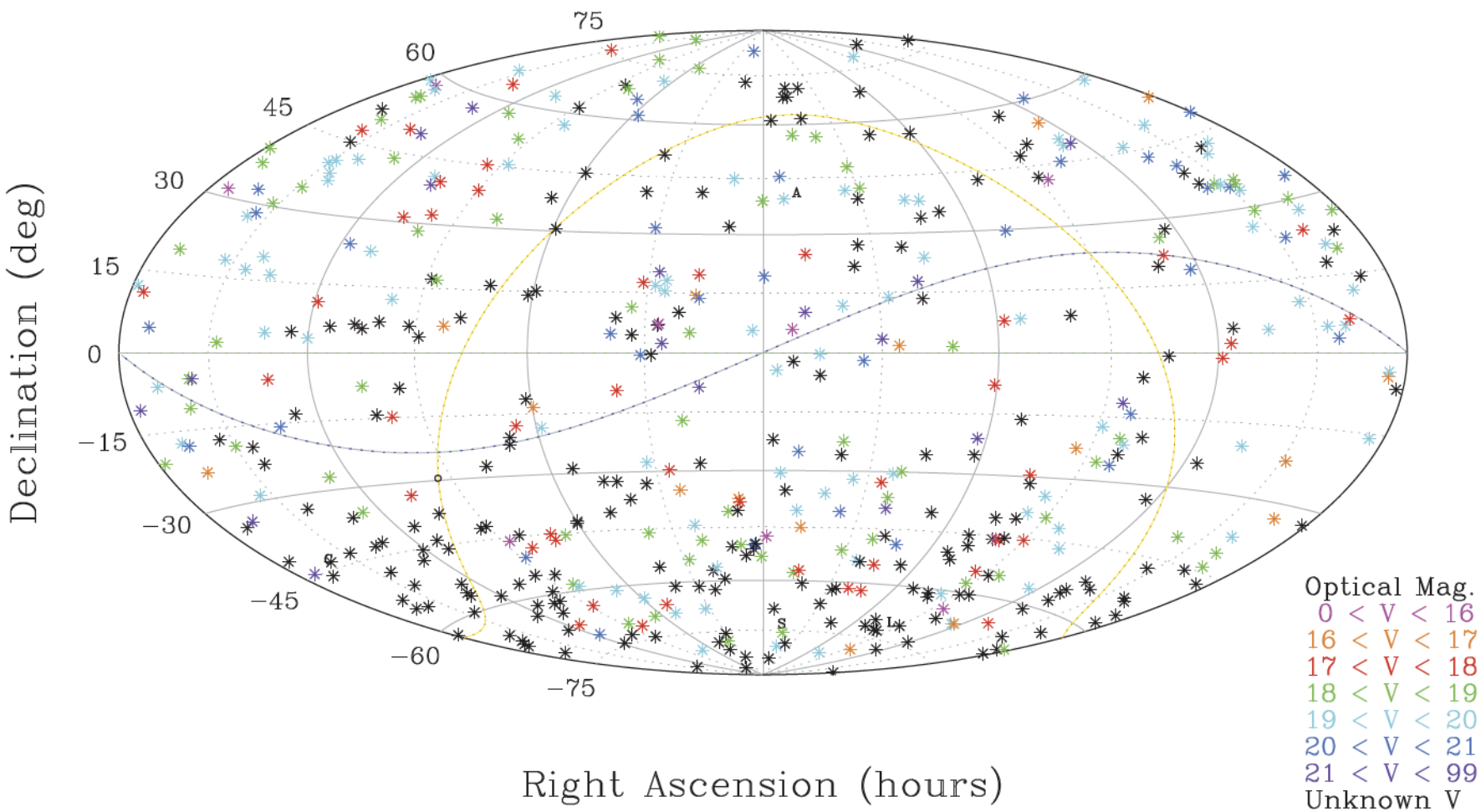
U. Bach[6], F. Colomer[7], C. Garcia-Miro[2], J. Gomez-Gonzalez[7], S. Gulyaev[9], S. Horiuchi[3], R. Ichikawa[12], A. Kraus[6], G. Kronschnabl[5], J.A. Lopez-Fernandez[7], J. Lovell[8], W. Majid[1], T. Natusch[9], A. Neidhardt[4], C. Phillips[13], R. Porcas[6], A. Romero-Wolf[1], L. Saldana[14], U.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

(1) Jet Propulsion Laboratory, California Institute of Technology/NASA (2) Madrid Deep Space Communications Complex/NASA, INSA,, Spain, (3) Canberra Deep Space Communications Complex/NASA, C.S.I.R.O., Australia (4) Technische Universitaet Muenchen, Germany (5) Bundesamt fuer Kartographie und Geodaesie, Bad Koetzting, Germany (6) Max-Planck-Institut fuer Radioastronomie, Bonn, Germany (7) Instituto Geografico Nacional, Madrid, Spain (8) University of Tasmania, Hobart, Australia (9) Institute for Radio Astronomy and Space Research, Auckland University of Technology, New Zealand (10) Sternberg State Astronomical Institute, Moscow, Russia (11) ISAS/JAXA, Sagamihara, Japan (12) Kashima Space Research Center, NICT, Kashima, Japan, (13) CSIRO Astronomy and Space Science, Australia, (14) ITT Mission Systems, Monrovia, CA




*27 Sep 2011*

# Ka-band candidates: 498 sources identified



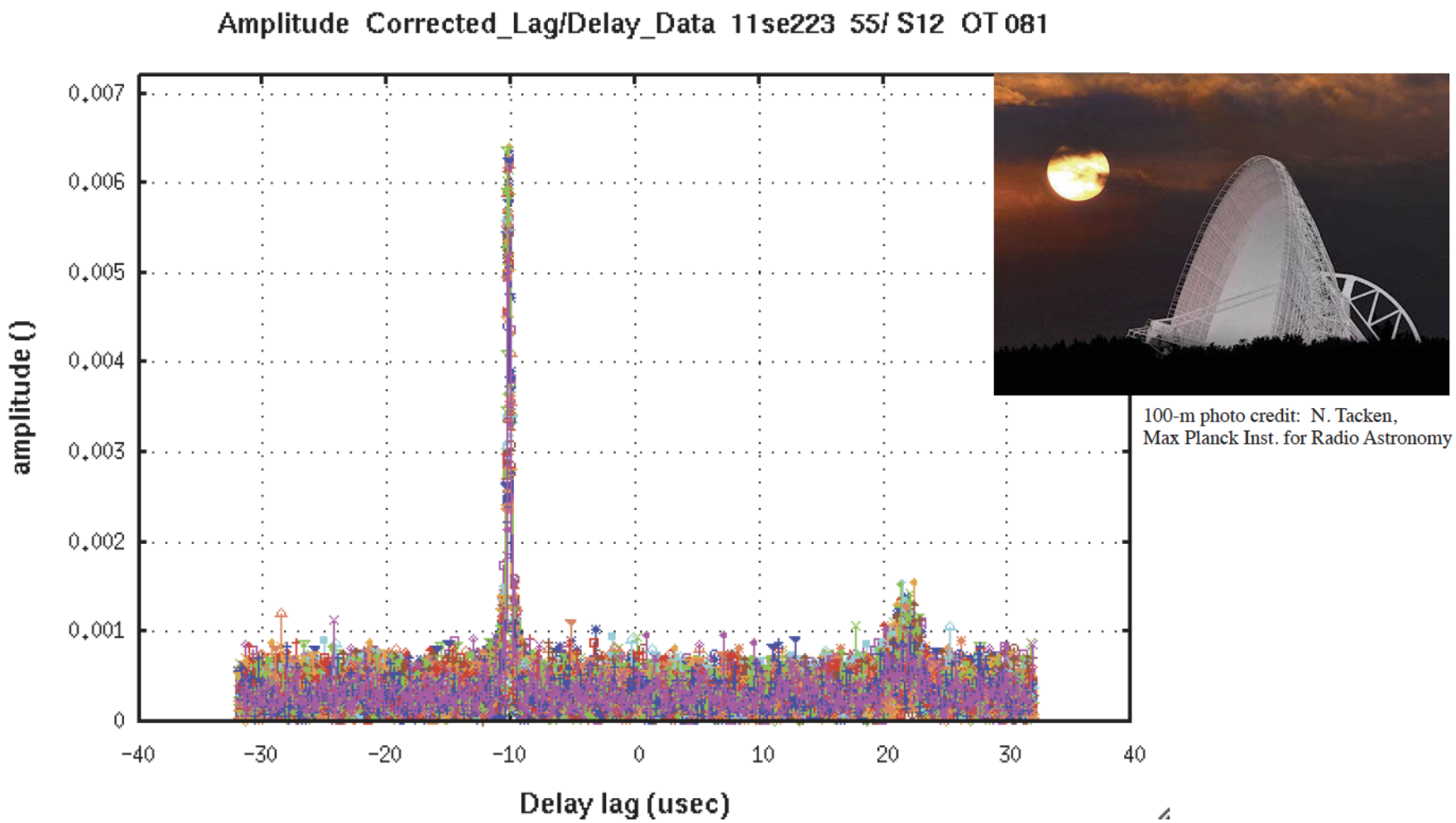

Ka candidate criteria: 200 mJy, 70% flux in unresolved X-band core

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