Very Long Baseline Interferometry

Justin Linford

NRAO GREEN BANK OBSERVATORY NSF AUI

Very Long Baseline Interferometry

WARNING

- There is a lot of information in this presentation!
- It may feel a bit like trying to drink from a fire hose

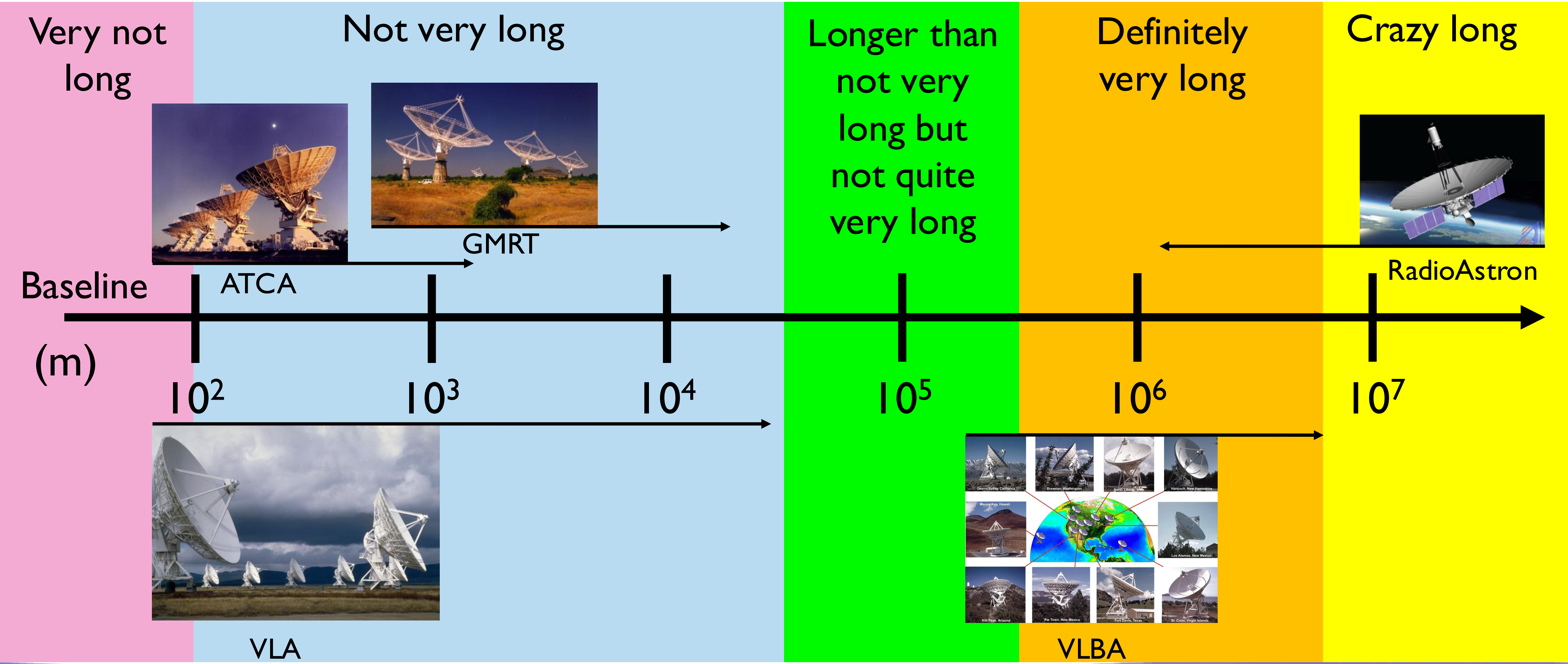
From "UHF", Orion Pictures, 1989

Outline

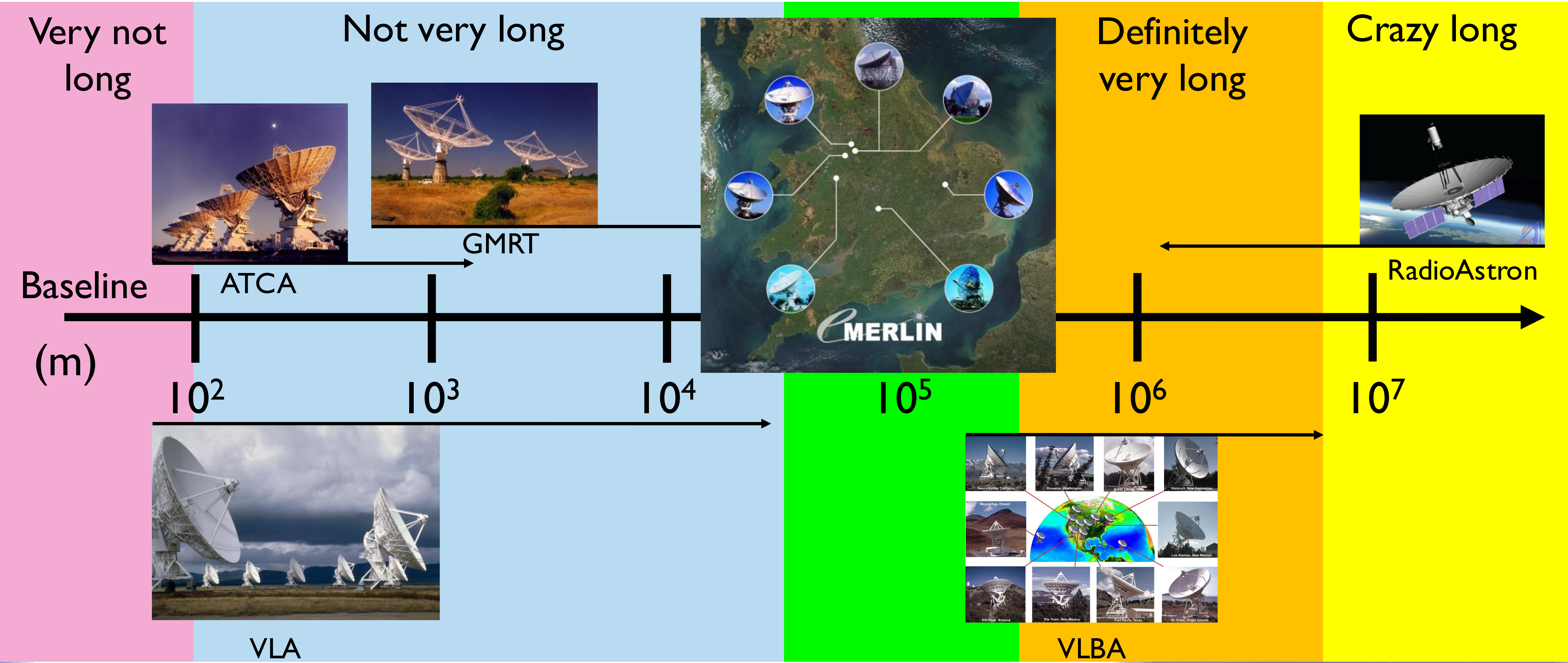
- What is VLBI?
- Science applications
- Current VLBI arrays
- Practicalities
  - Proposing
  - Observing
  - Calibration and imaging
- Future of VLBI

Acknowledgement: I ~~stole~~ ~~borrowed~~ drew inspiration from Prof. Adam Deller's previous versions of this talk

How long is "very long"?



How long is "very long"?



What makes it "VLBI"?

- VLBI is more than just the baseline lengths
  - Adam Deller: "It's more like a 'syndrome' than a 'disease'."
- There is no fundamental difference between VLBI and "regular" interferometry
  - Primary differences are in the technology used

Connected Element Interferometry	Very Long Baseline Interferometry
All antennas share the same frequency and time standard	Each antenna has its own independent frequency and time standard
Data are fed directly to the correlator	Data often recorded separately and later sent to correlator
Weather and ionosphere over all antennas is mostly the same	Weather and ionosphere over each antenna is unique
Baselines are usually <100km	Baselines are usually >100km

VLBI - Extreme Angular Resolution

Very few things are point sources to VLBI

- $\theta_{HPBW} \approx 2063 \times \frac{\lambda[cm]}{B_{max}[km]}$ milliarcseconds
  - θ_{HPBW} = half-power beam width
  - $\lambda[cm]$ = observing wavelength in cm
  - $B_{max}[km]$ = maximum baseline in km (For VLBA, $B_{max}[km] \approx$ 8600)

Band	L (20cm)	S (13cm)	C (6cm)	X (4cm)	Ku (2cm)	K (1cm)	Q (7mm)	W (3mm)
VLBA θ_{HPBW} [mas]	4.8	3.2	1.4	0.85	0.47	0.32	0.17	0.12

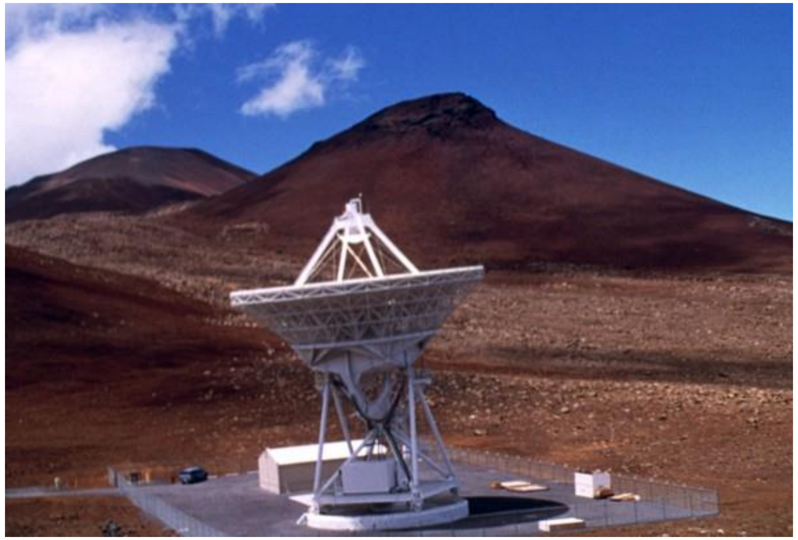
- Obligatory ridiculous comparison:
  - A school bus on the moon would have angular dimensions of about 6.5 milliarcseconds long by 1.4 milliarcseconds wide by 1.7 milliarcseconds tall

Peculiarities of VLBI

- VLBI instruments are only sensitive to high surface brightness objects
  - If the brightness temperature is below a few x 10^5 K, VLBI probably will not detect the object
- Missing short baselines lead to largest angular scale being pretty small
  - Large, diffuse sources are not going to be detectable
  - Note: With the VLBA, you can request to add one VLA antenna (Y1) to get two shorter baselines (PT-Y1 and LA-Y1)
    - During A-configuration, you can request to add the three VLA antennas at the end of the arms (Y3) to add even more short baselines
- Structure on scales larger than the synthesized beam can lead to destructive interference
  - Can sometimes recover it with weighting schemes and/or "tapering" the beam

Science applications of VLBI

- VLBI provides a tool to study mas-level structure in radio sources.
  - Active Galactic Nuclei (AGN)
  - Pulsars
  - Masers
  - Explosive transients (GRBs, SNe, novae, etc.)
  - Magnetically active stars
  - X-ray binaries
  - Man-made (e.g., planetary radar)



- A VLBI detection instantly identifies a compact non-thermal source
  - Synchrotron/cyclotron radiation (electrons in a magnetic field)
  - Maser emission (stimulated emission)
  - Thermal lines in absorption against non-thermal background
  - Artificial (satellite, radar, etc.)

VLBI Science Highlights

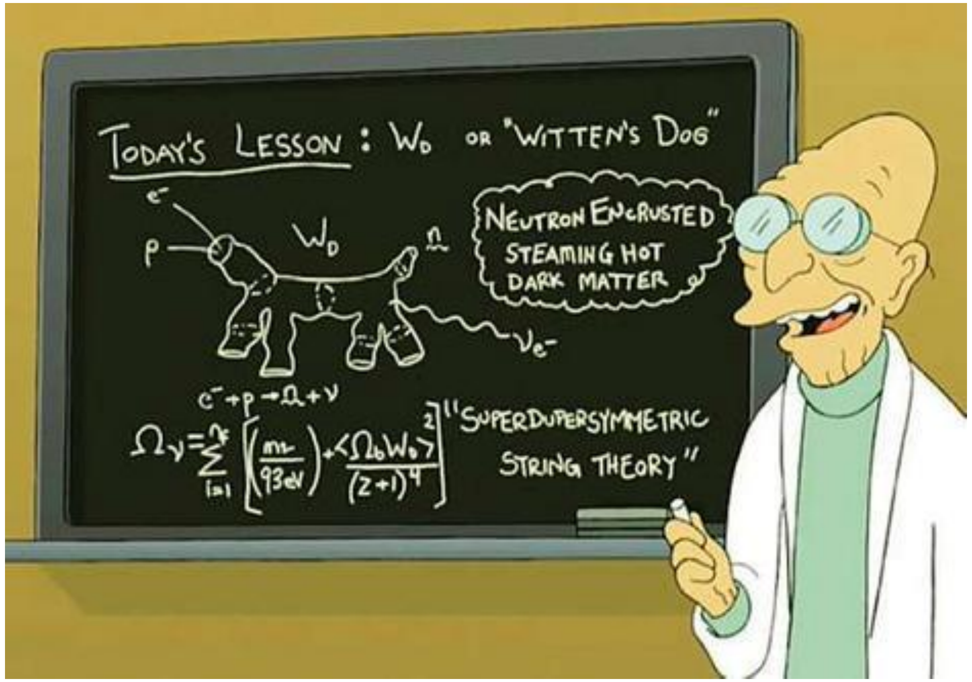
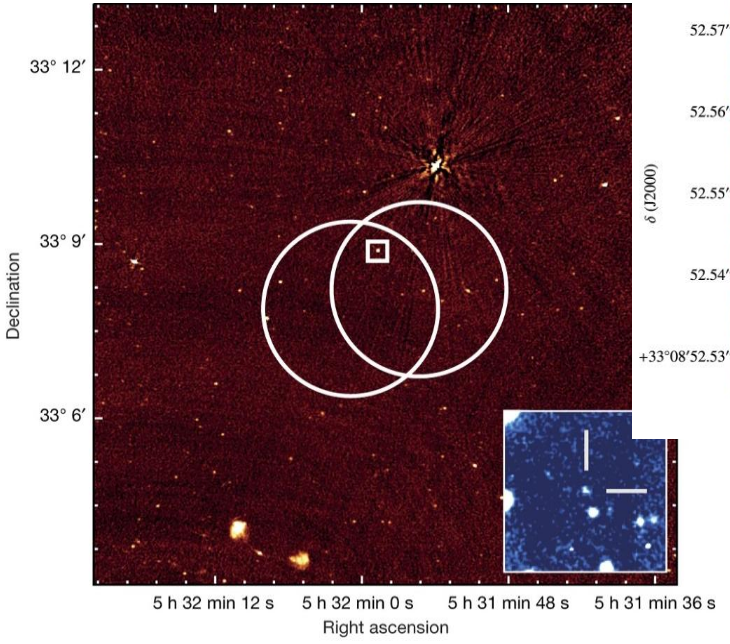


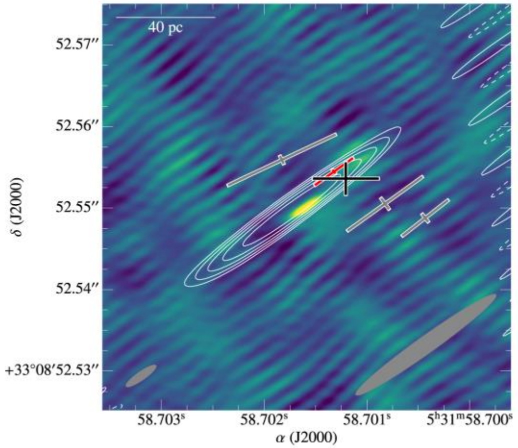
Image credit: Danielle Futselaar

FRB Localization

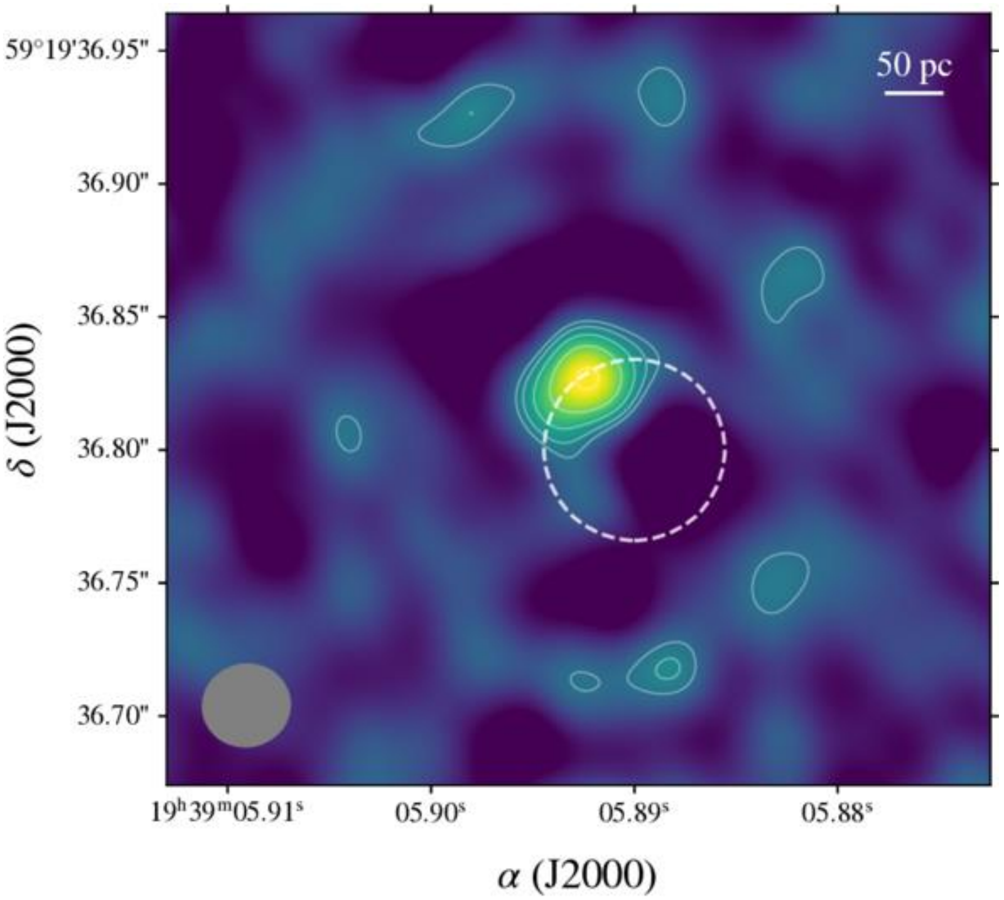
- Multiple repeating Fast Radio Bursts (FRBs) have been associated with persistent radio sources thanks to VLBI observations



VLA image of FRB 121102 from Chatterjee et al. 2017

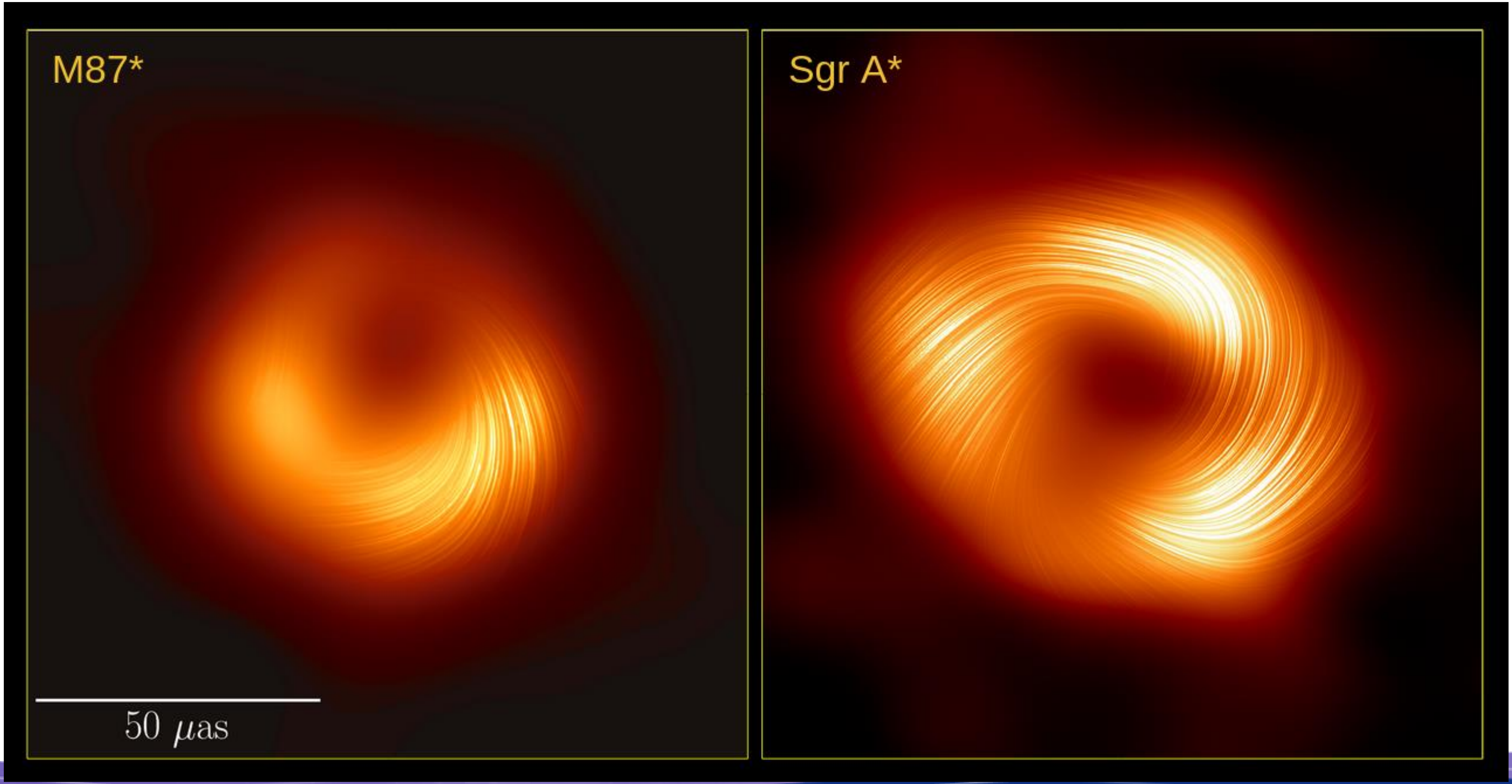


EVN image of FRB 121102 from Marcote et al. 2017



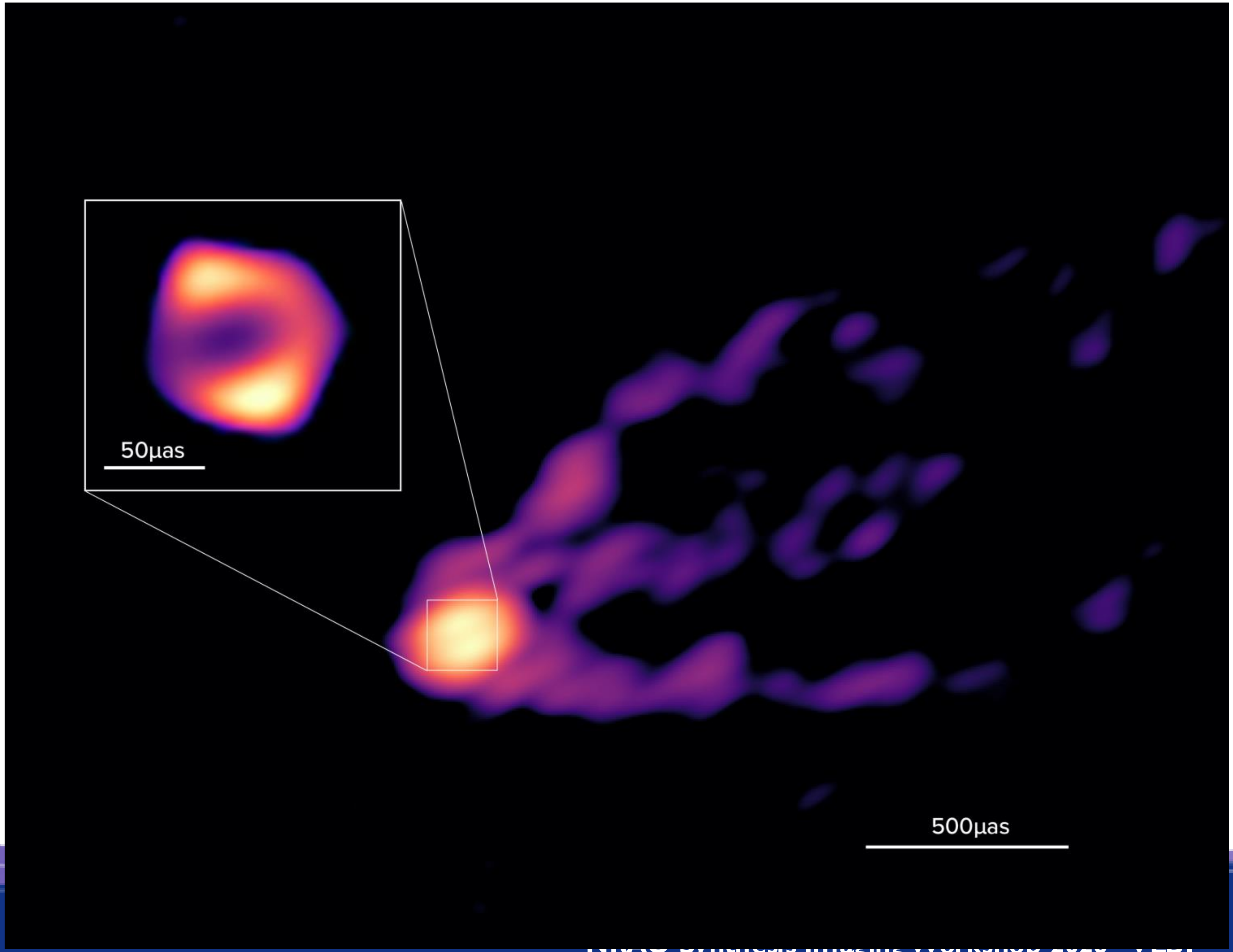
EVN image of FRB 20190147A stacked bursts. White ring indicates location of VLA detected persistent radio source. Moroianu et al. 2026

EHT Black Holes (with polarization)



M87 Black Hole Shadow + Jet

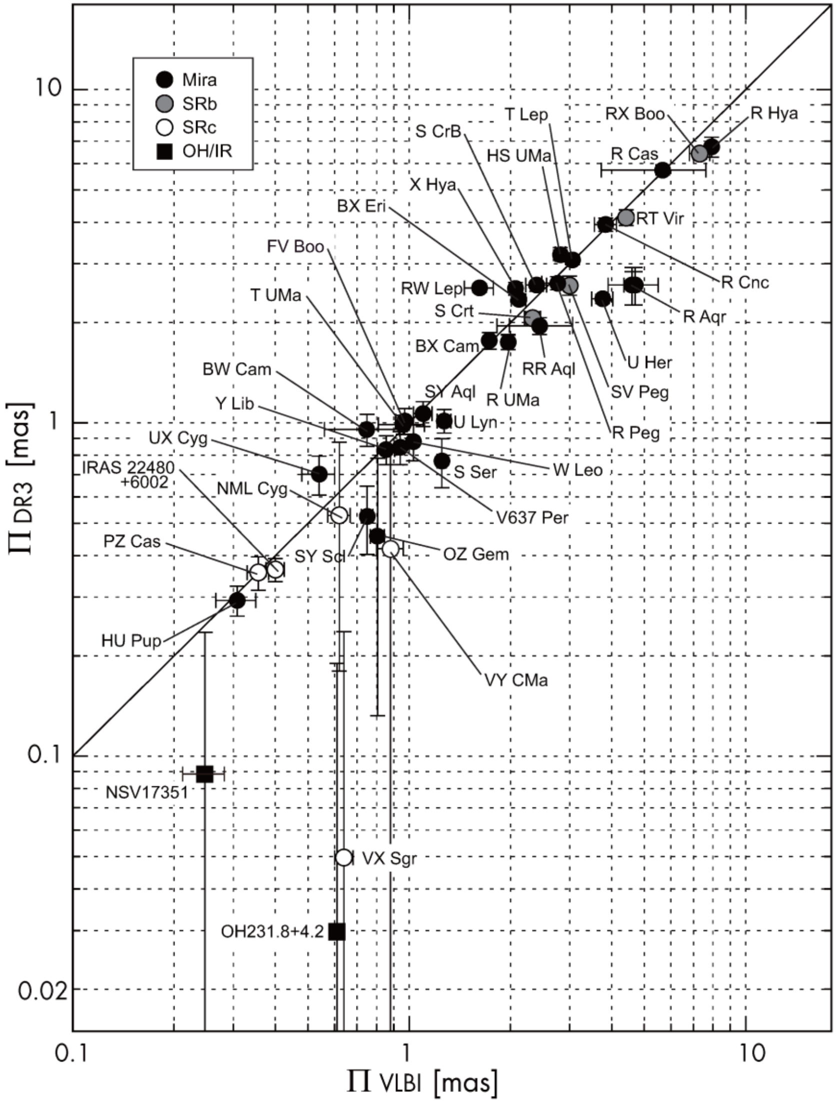
Global Millimeter VLBI Array with ALMA



- 3mm (86 GHz)
- VLBA + ALMA + GBT + GLT + European telescopes
- Imaged jet and black hole shadow
- Comparable to the EHT images
- Lu, et al. 2023, Nature, 616, 686

Astrometry

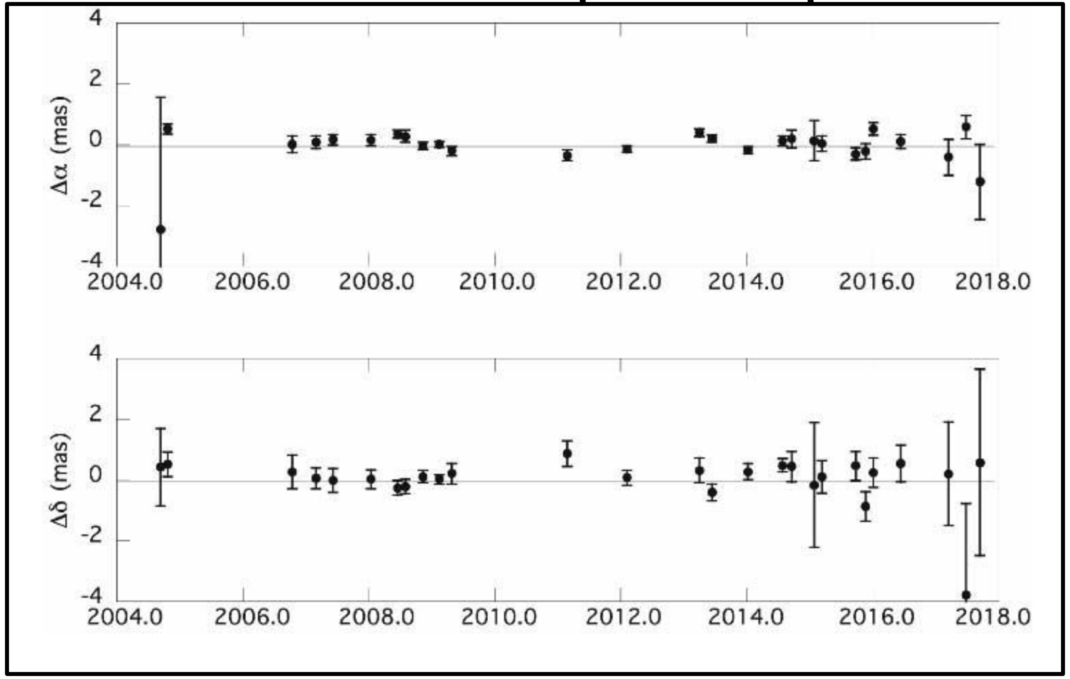
- VLBI can centroid an object's location to ~0.01 mas [(λ/D) / SNR]
  - Gaia accuracy is ~0.024 mas
  - Plus VLBI gets better access to the Galactic Plane because it can see through the dust
- Astrometry is easiest for point sources, but source structure can also be modeled
- Good astrometric targets include:
  - Masers
  - Pulsars
  - Magnetically active stars
  - Jet components



Gaia DR3 parallaxes vs VLBI parallaxes
From Nakagawa et al. 2026

Refining the Ephemeris of Saturn

- VLBA monitored the Cassini spacecraft from 2004 to 2017.
- Observations provided accurate positions for the Saturn system barycenter in the ICRF, which led to an improved ephemeris



Post-fit residuals of Saturn's orbit to the VLBA-determined position for the Saturn system barycenter (Jones et al. 2020)

Astrometry of Magnetar Swift J1818.0-1617

- Magnetar age estimate = 860 years
- Hao Ding and collaborators used the VLBA over 3 years to measure the parallax and transverse velocity of the magnetar
  - Distance = 9.4 kpc
  - Transverse velocity = 48 km/s
- Results indicate that magnetars may form under different conditions than other young pulsars
- Ding et al. 2024, ApJ, 971, L13

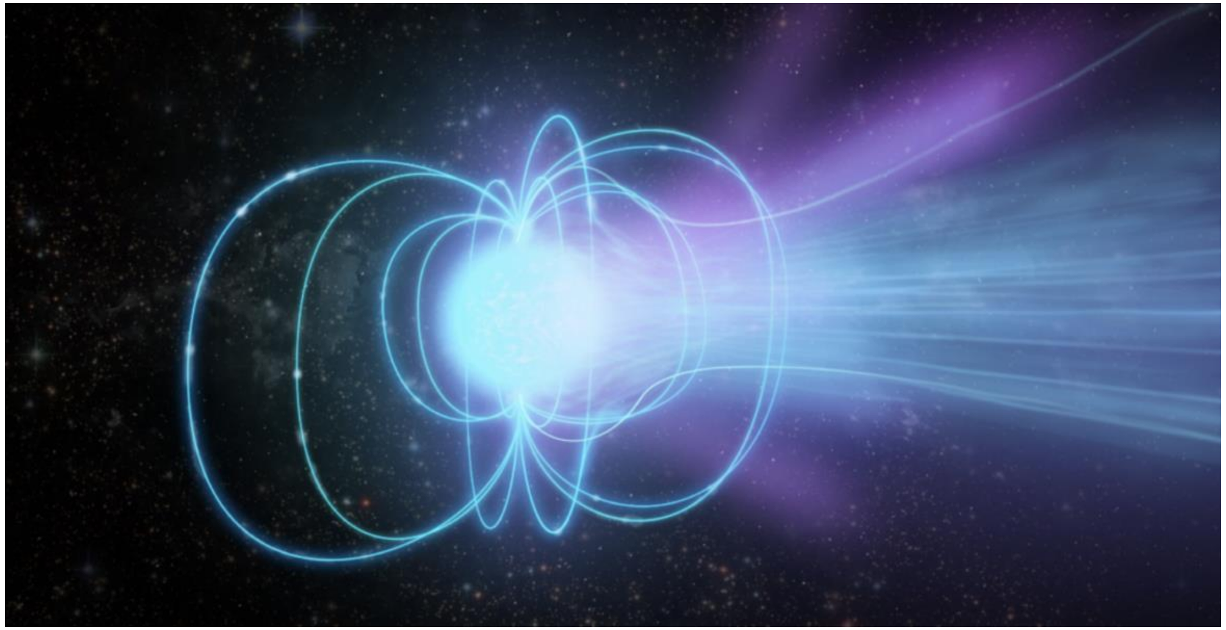
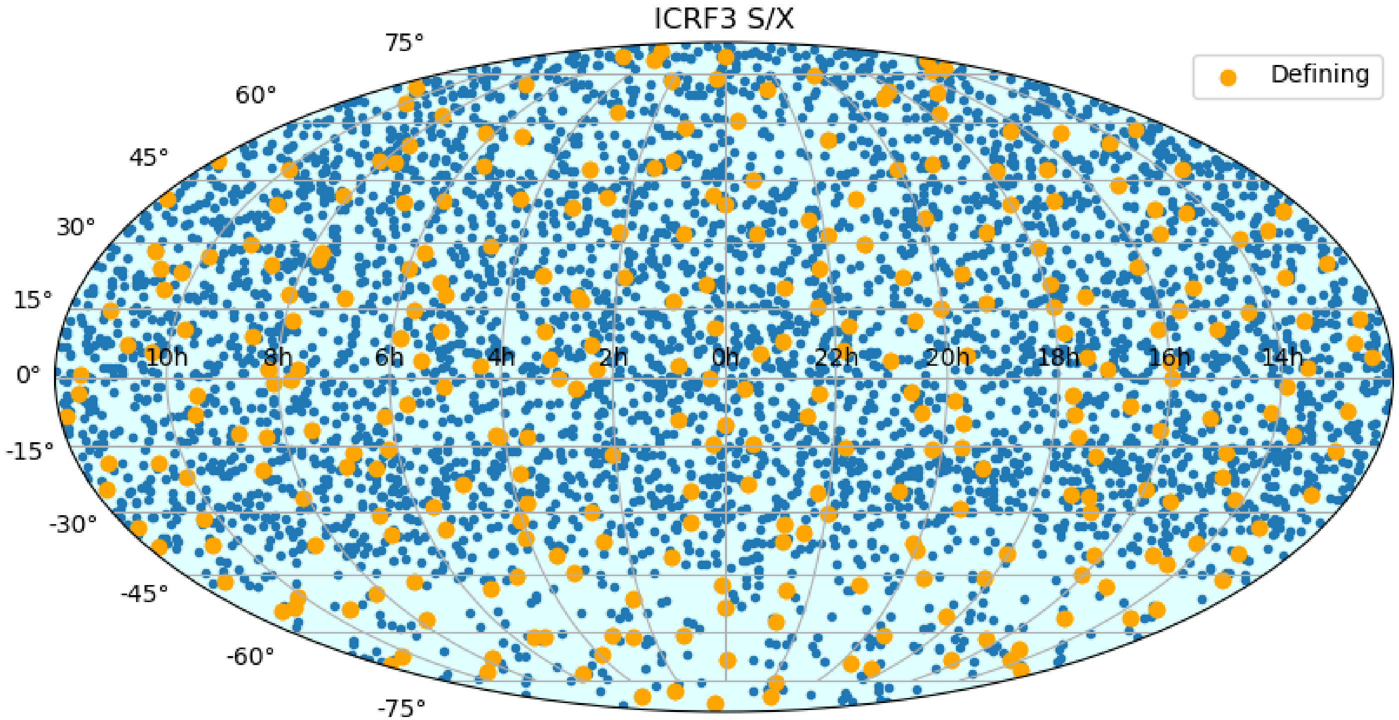


Image credit: NSF, NRAO, S. Dagnello

VLBI and the ICRF

- VLBI is used for the construction and maintenance of the International Celestial Reference Frame



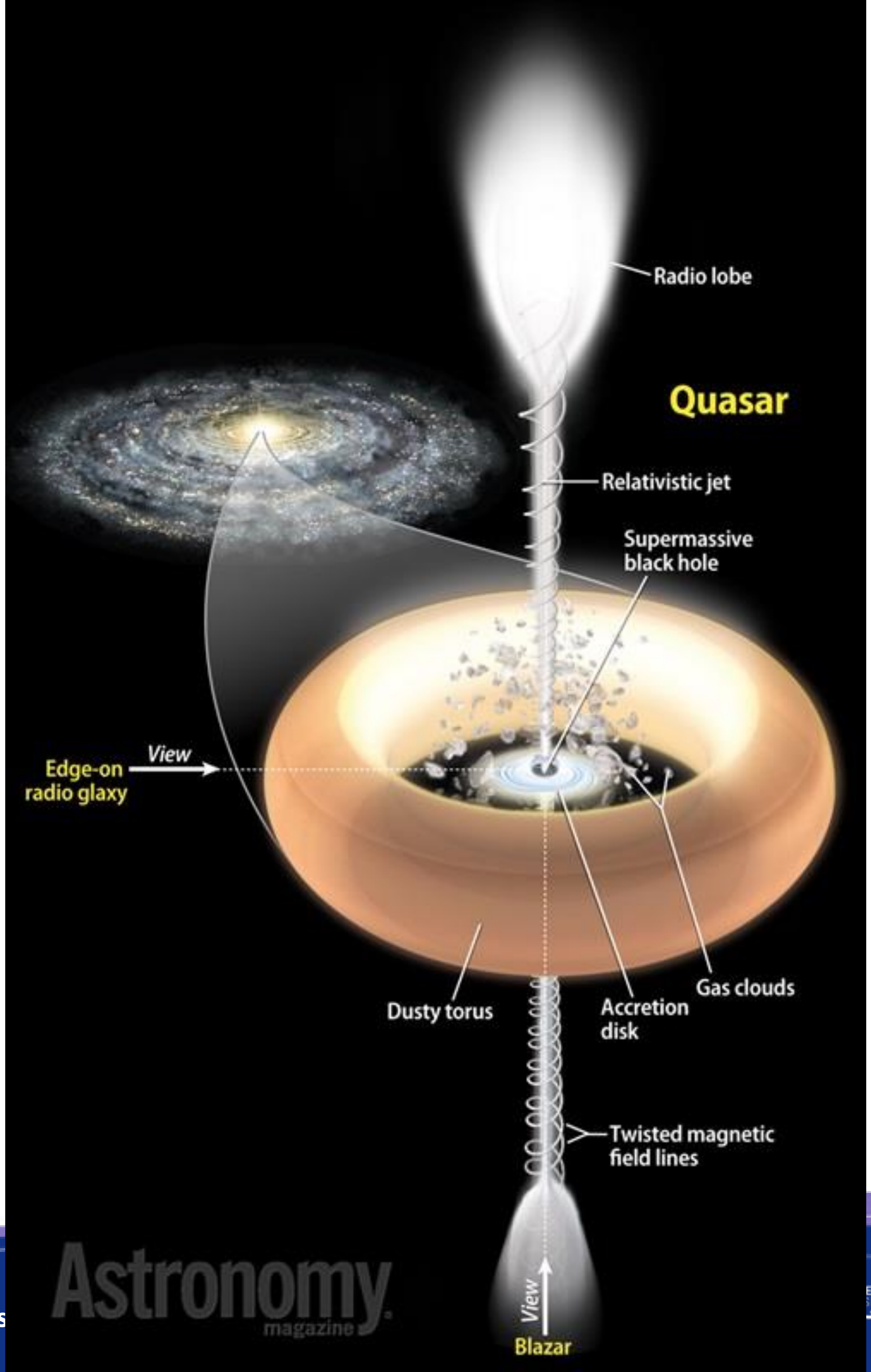
Each dot represents a quasar

From the ICRF website: https://hpiers.obspm.fr/icrs-pc/newwww/icrf/index.php

Quasars

Calibrators for VLBI

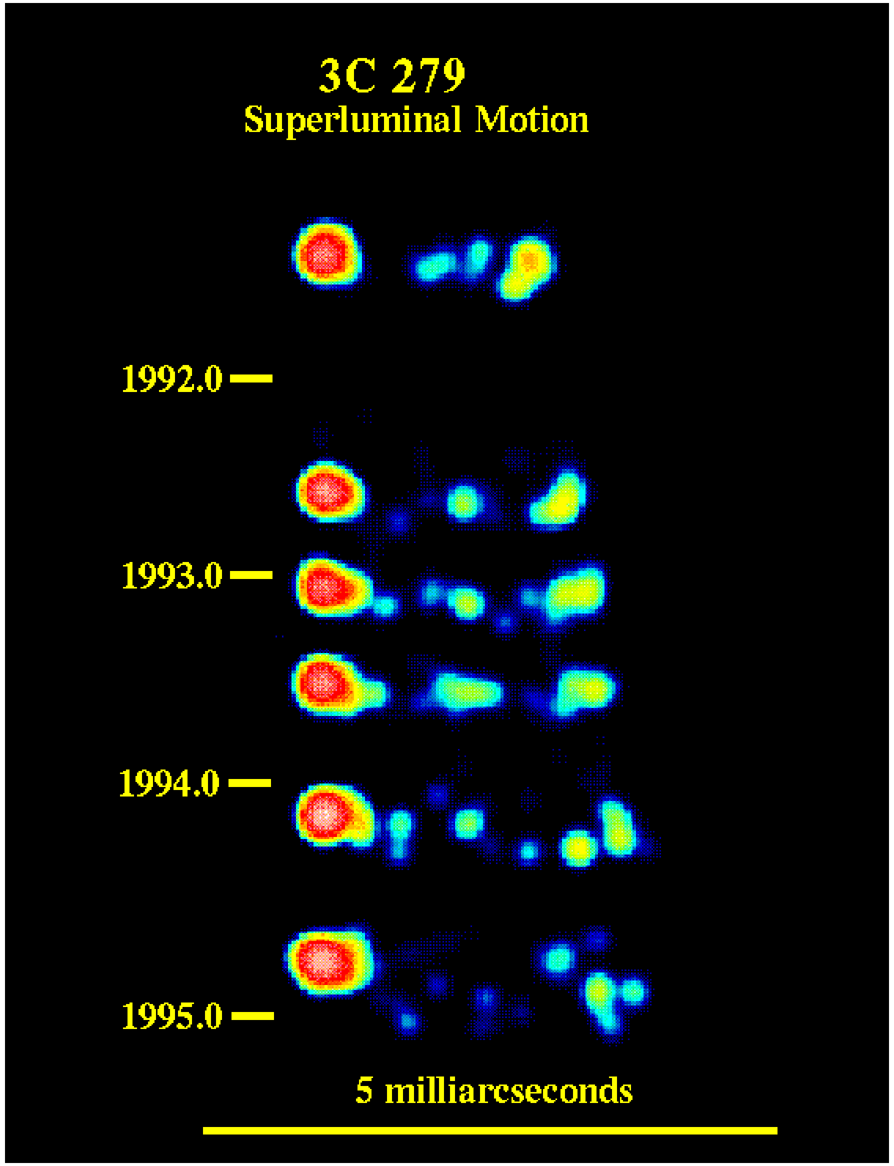
- Supermassive black holes producing jets of relativistic particles
- Very bright objects, so they can be seen out to great distances
- Do not move compared to Milky Way objects, so they are great for defining a reference frame



Quasars as Calibrators

The catch

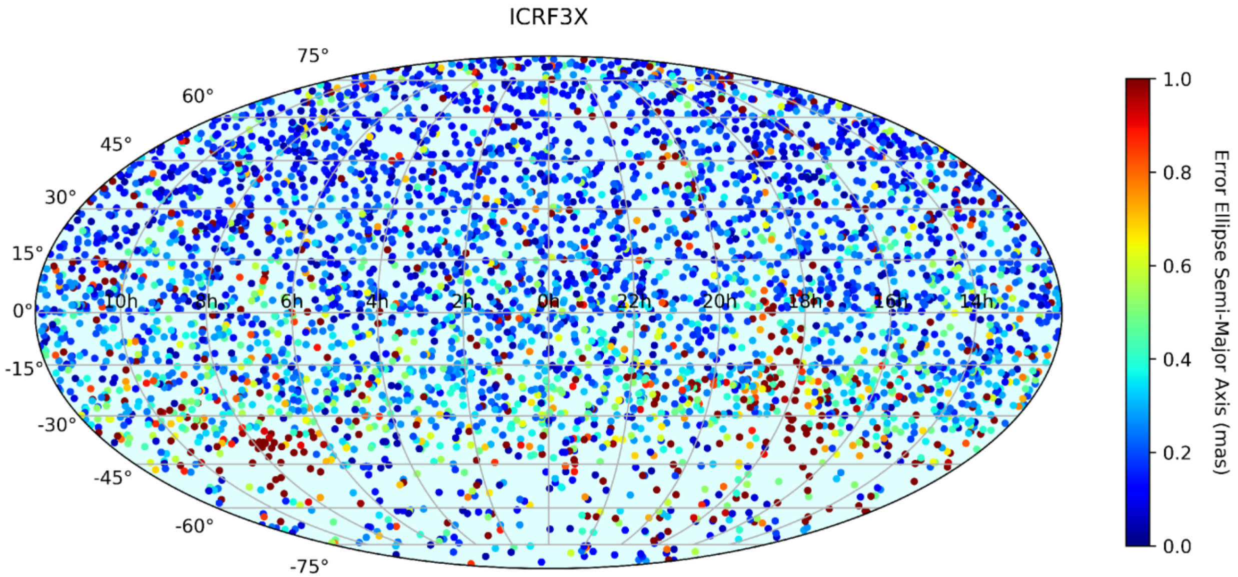
- The best calibrators are point sources, but the VLBI resolution is so good that not even most quasars are point sources.
- VLBI can track the changes in the quasar jets over time.
- Changes in the jet structure can lead to uncertainties in the quasar position.

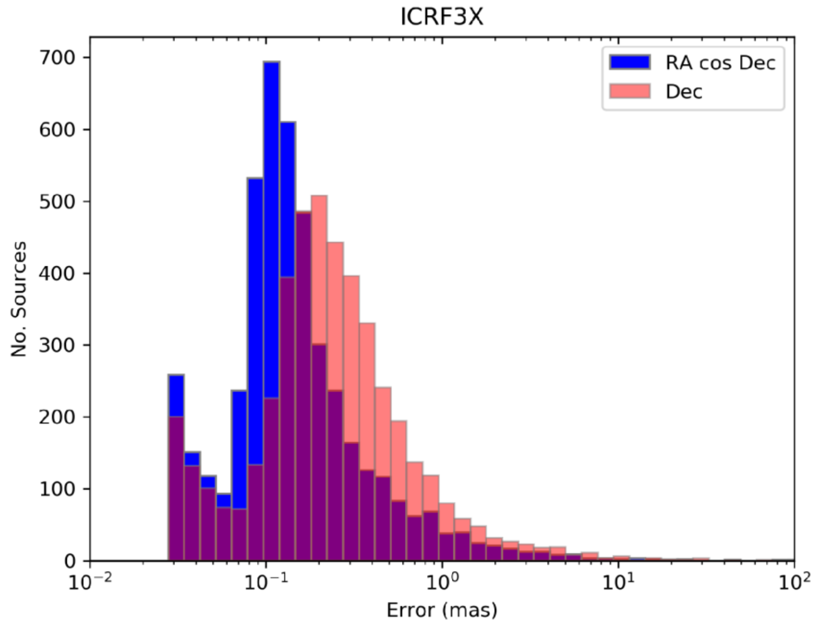


22 GHz VLBA images by A. Wehrle & S. Unwin

Absolute Precision of Calibrators

- The uncertainty in a calibrator's position limits the absolute position measurement in an observation





ICRF3 S/X coordinate uncertainties
From Charlot et al. 2020, A&A, 644, A159

VLBI and Geodesy

- Observations of many quasars with known positions can tell us about the behavior of the Earth
  - Can measure separations of antennas to learn about plate tectonics
  - Can measure the Earth Orientation Parameters
    - EOP measurements are important for maintaining GPS precision

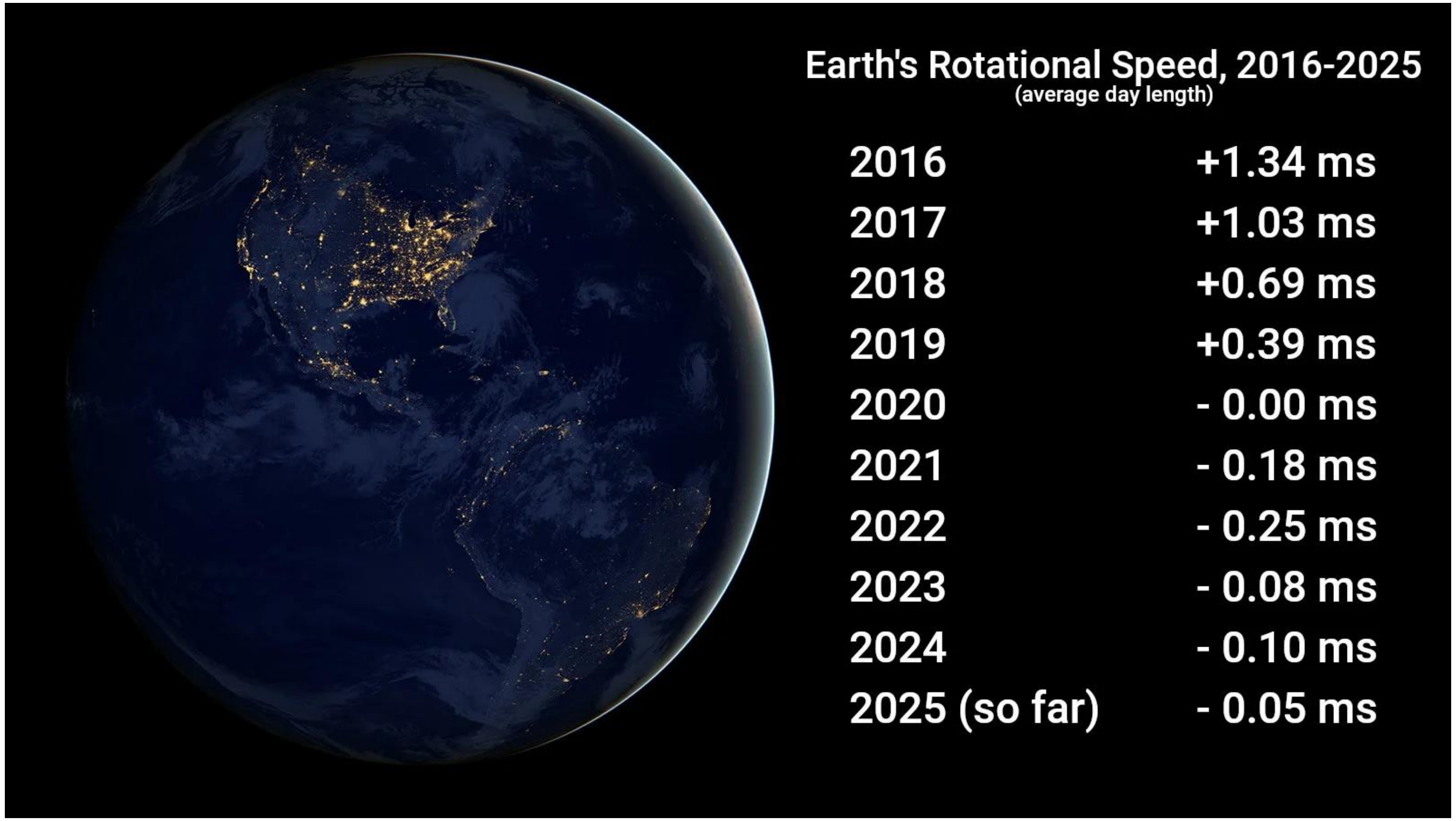


Image from theweathernetwork.com; Earth at night from NASA, data in table from IERS

VLBI Arrays

It is hard to photograph an entire VLBI array, so here are some individual antennas

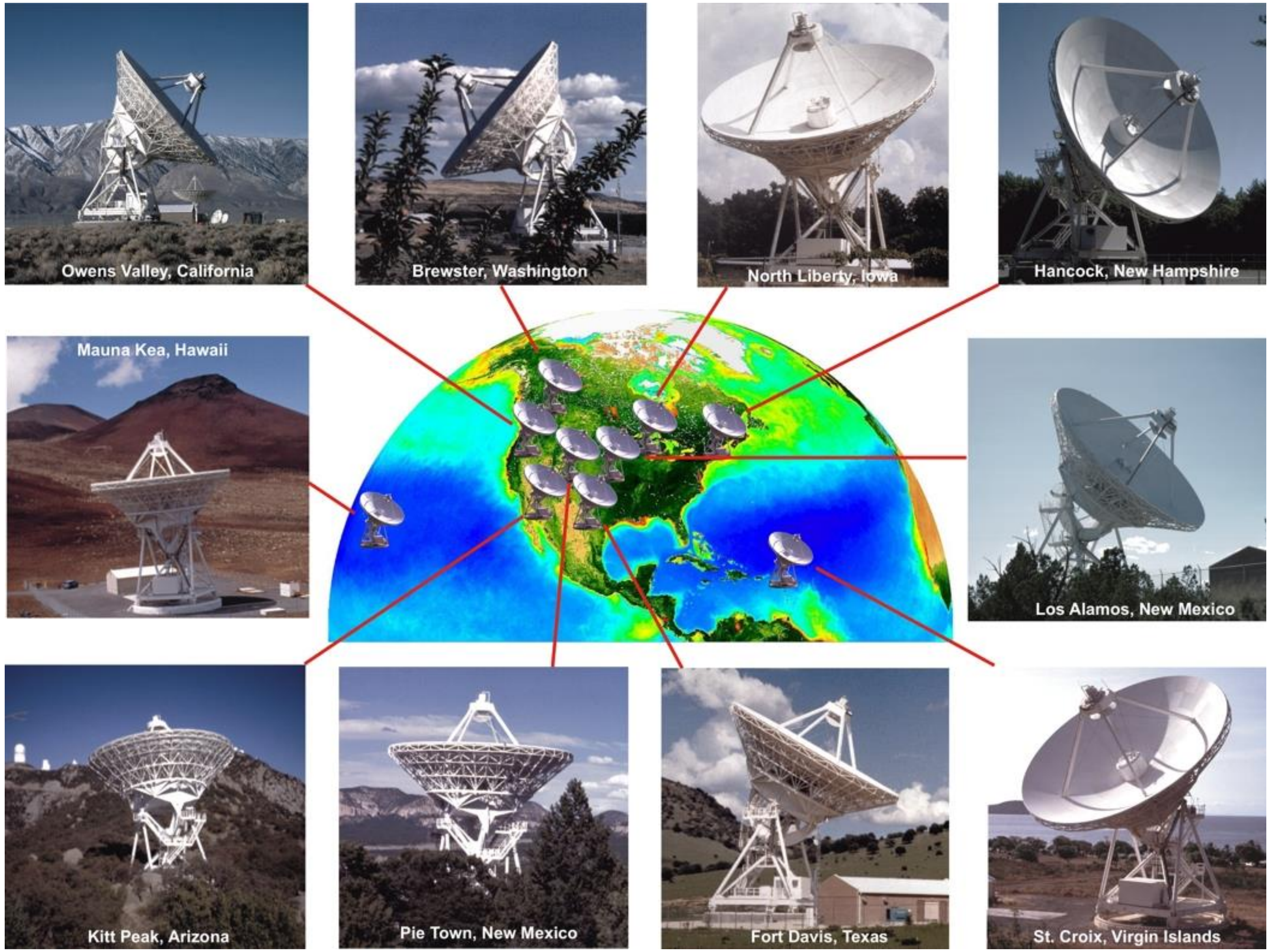
VLBA St Croix (NRAO/AUI)

Effelsberg (MPIfR/Raimond Spekking)

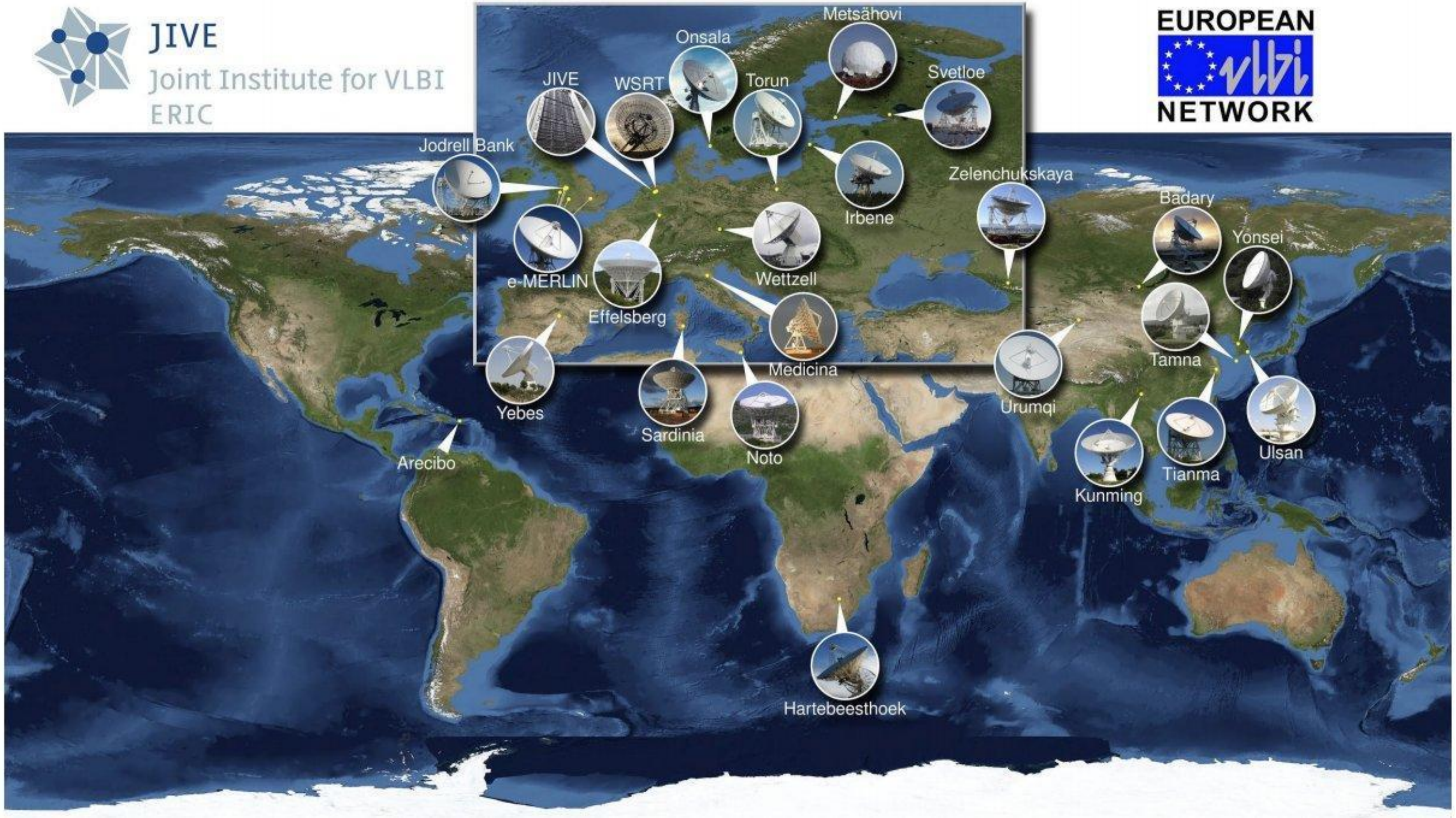
LOFAR Tautenburg (ASTRON/TLS/Michael Pluto)

The Very Long Baseline Array

- 10 Stations
- All in US or US Territories
- Identical 25m antennas
- Shortest baseline:
  200 km (PT to LA)
- Longest baseline:
  8600 km (MK to SC)
- The world's largest full-time VLBI instrument (for now)
- Two proposal calls per year
  (January/February & July/August)



European VLBI Network



- Ad-hoc array
- Three calls for proposals each year
- Supported by JIVE

Long Baseline Array

- Ad-hoc array
- Up to 8 stations
  - Hartebeesthoek (not shown in figure) often participates
- Operates about 3 weeks a year
- The only Southern Hemisphere VLBI array (for now)

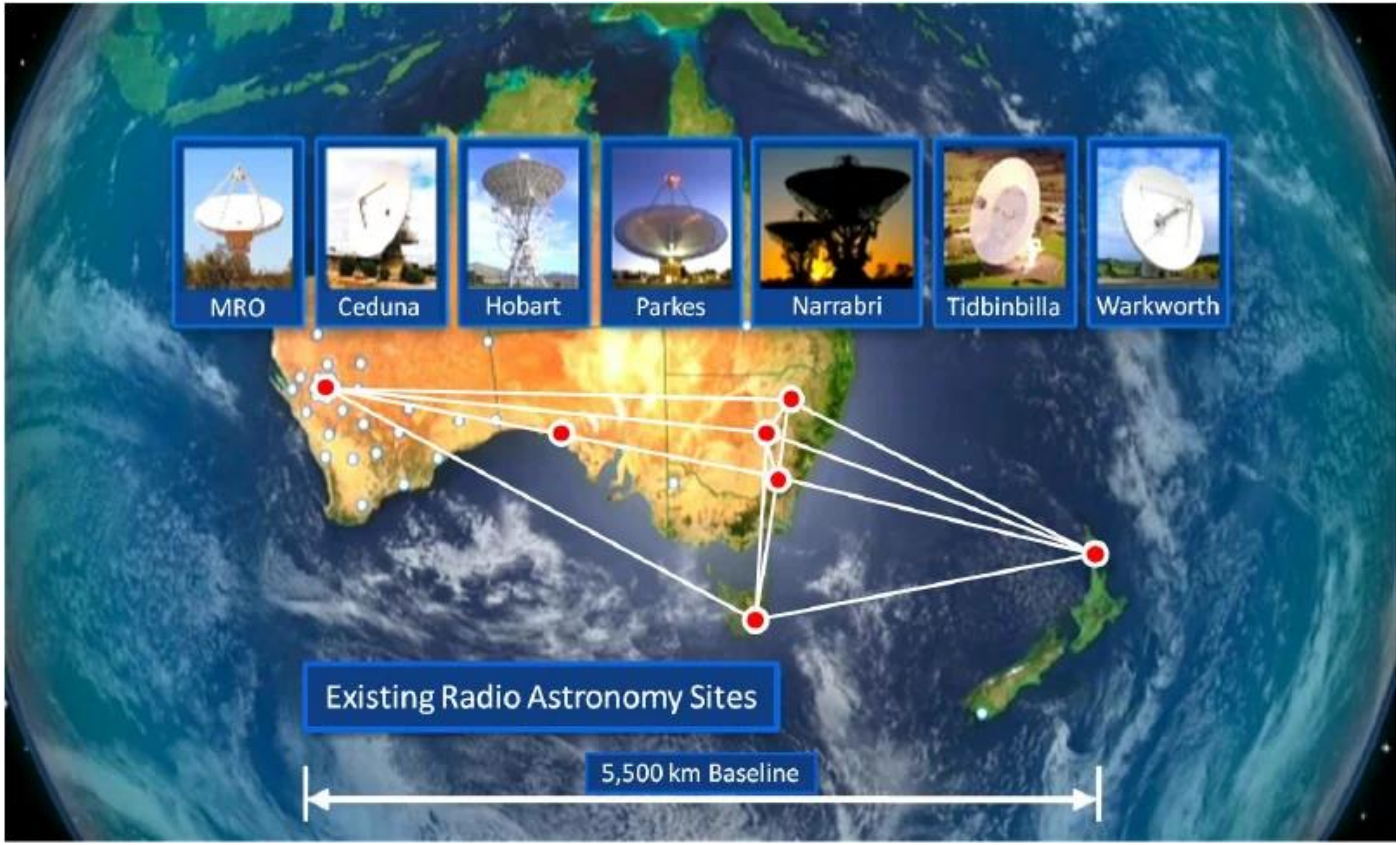


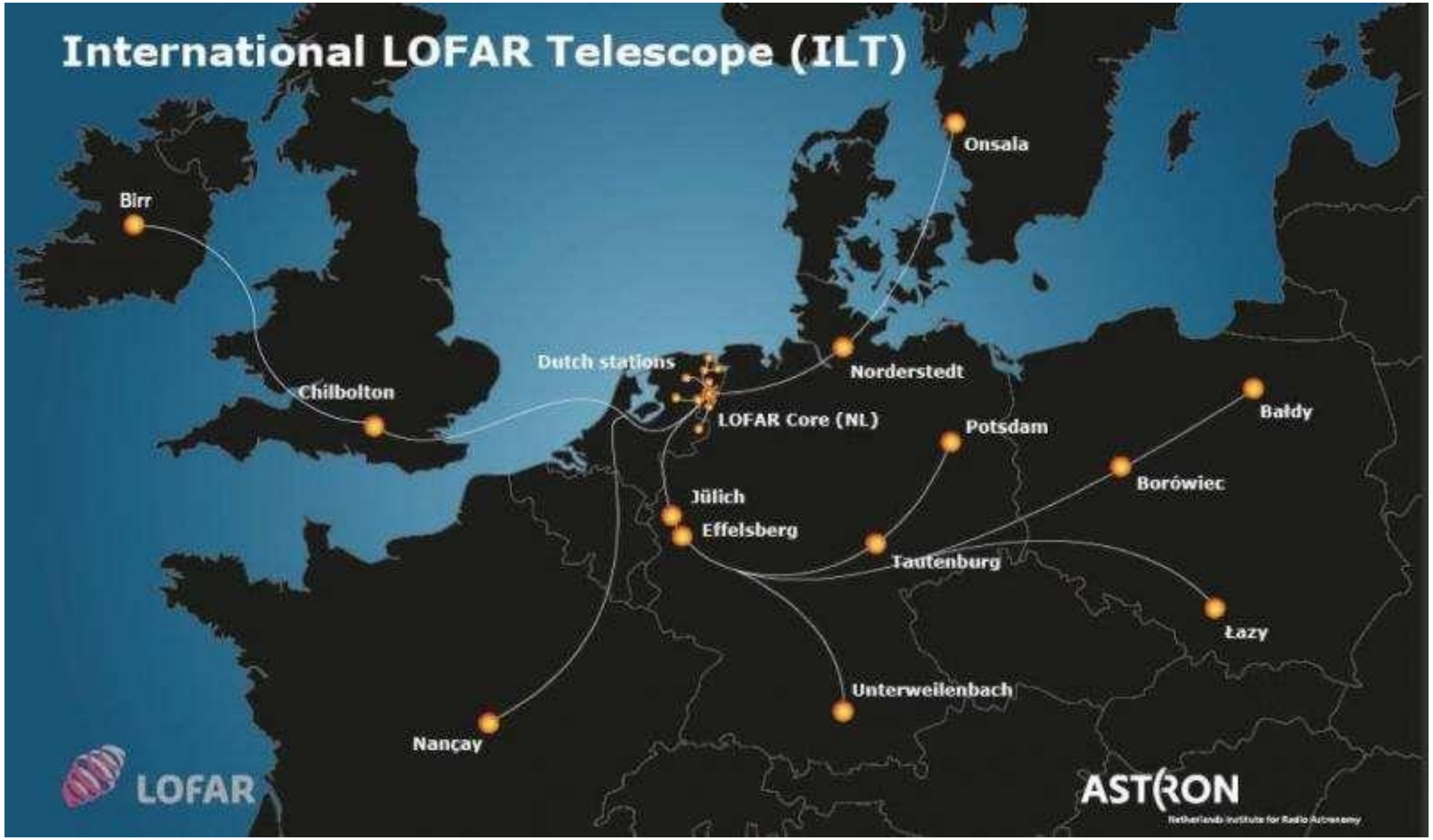
Image credit: Brian Boyle/CSIRO/IRASR

East Asian VLBI Network

- Made up of 3 separate networks
  - Korean VLBI Network (KVN; Korea)
  - VLBI Exploration of Radio Astrometry (VERA; Japan)
  - Chinese VLBI Network (CVN; China)

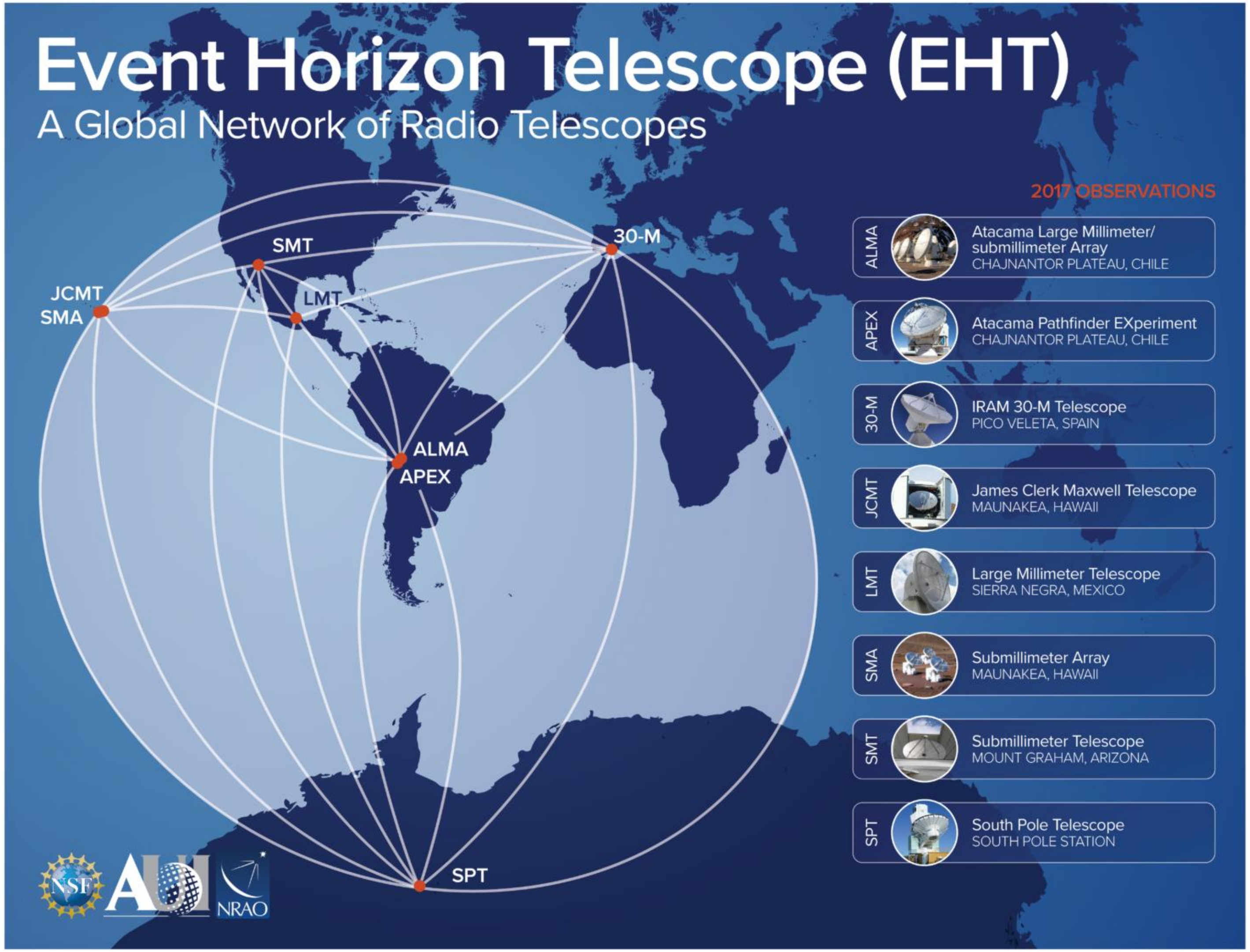
Low Frequency Array (LOFAR)

- Sub-arcsecond imaging at meter wavelengths
- 14 international stations + 15 stations in The Netherlands
- 15-240 MHz
- Proposals accepted twice per year



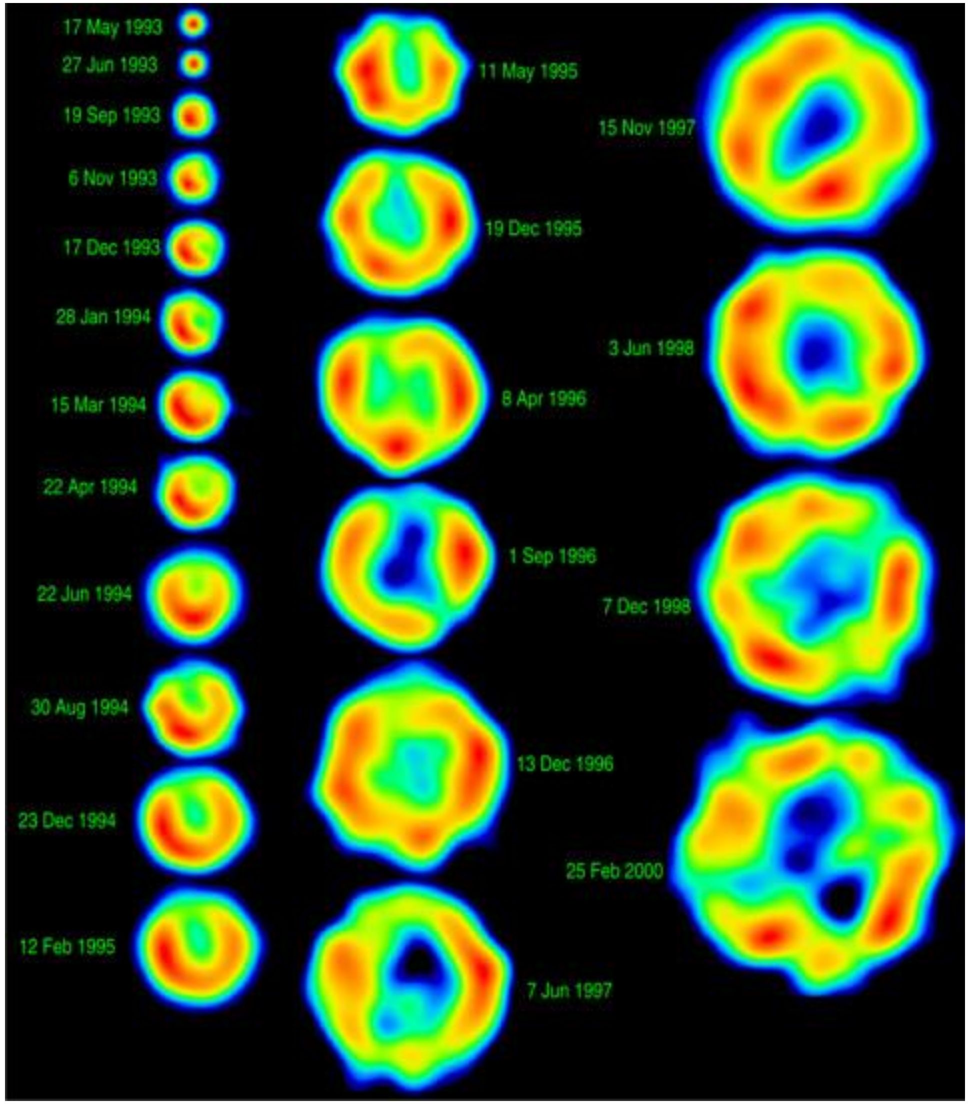
Event Horizon Telescope

- The highest angular resolution interferometer
  - About 30 microarcseconds
- Operates at 230 and 345 GHz
- Annual call for proposals



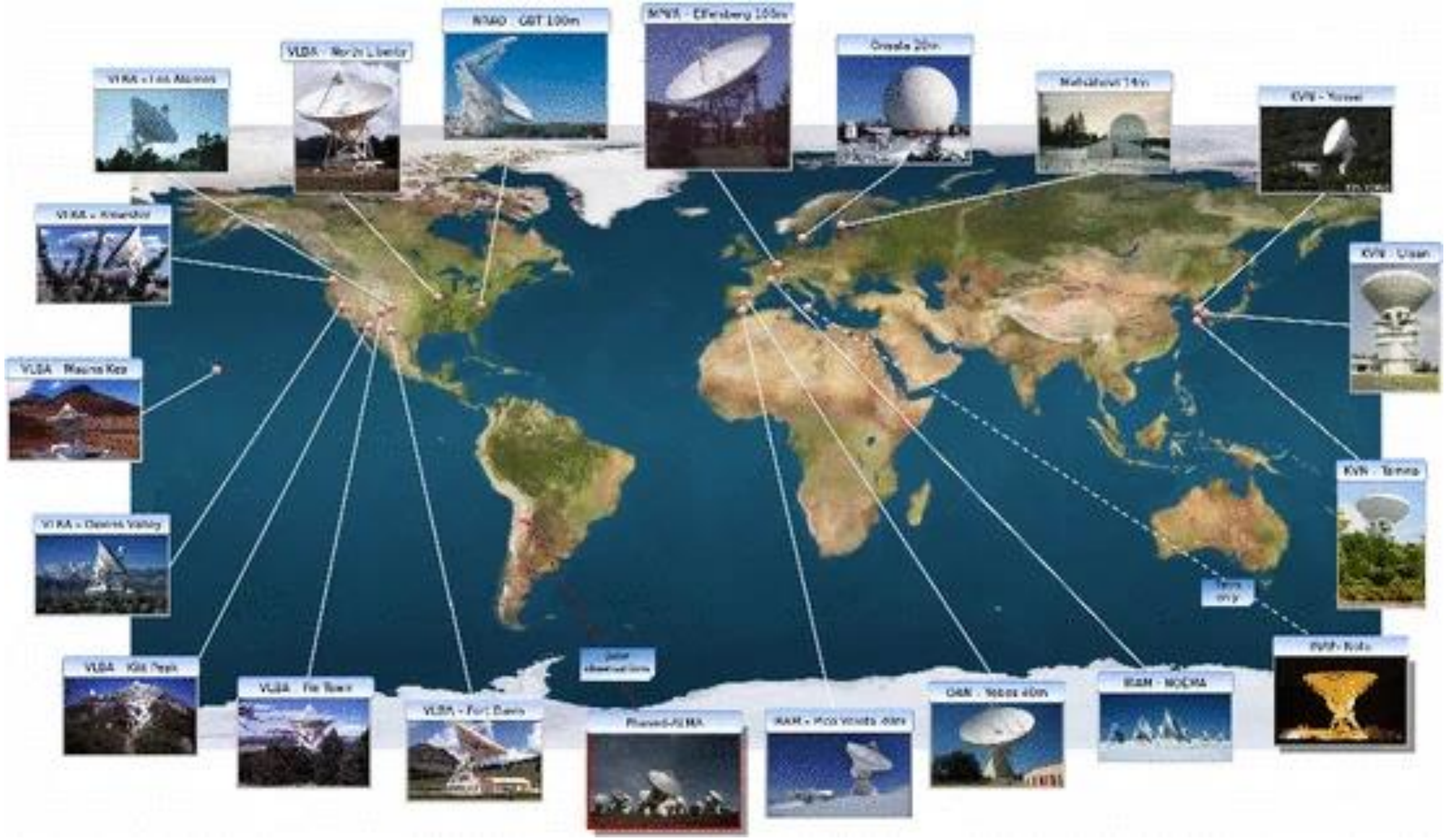
Extended arrays

- Most VLBI arrays use data formats and setups compatible with other VLBI arrays, non-VLBI arrays, and single dishes
- The VLBA routinely observes with the High Sensitivity Array (HSA), adding phased VLA, Green Bank Telescope and Effelsberg
  - Increases sensitivity by factor of ~8
- VLBA + European VLBI Network + others = the "Global VLBI Array"
- Global arrays perform geodetic observations for reference frame measurements and Earth Orientation Parameter determination.



SN1993J, 11.7 million light-years away, imaged over 10 years with VLBA+DSN+EVN (Bietenholz et al. 2003)

Global Millimeter VLBI Array



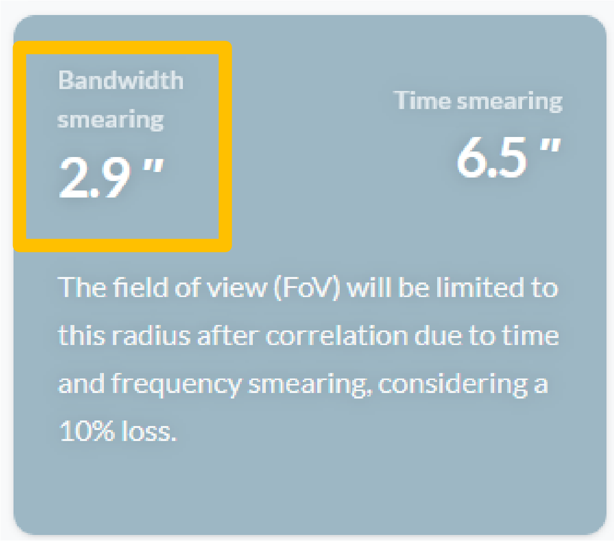
- Sub-mas imaging at 3mm (86 GHz)
- 2 sessions a year (only one with phased ALMA)
  - Times are set early and do not move to accommodate weather
- Proposals submitted via the NRAO Proposal Submission Tool

VLBI field of view

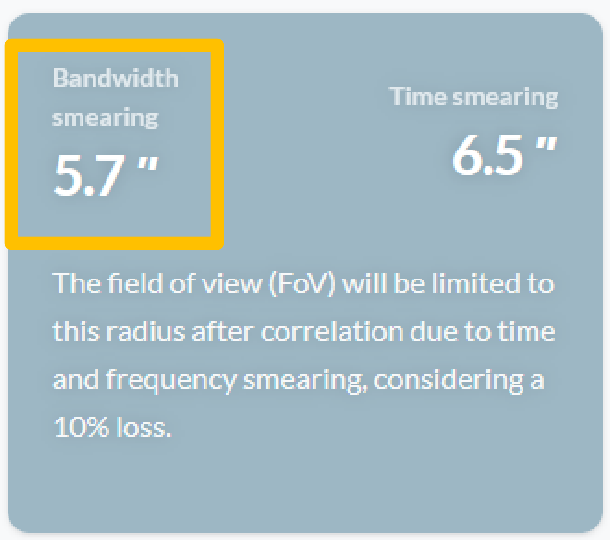
- Two settings chosen for correlation will impact the field of view:
  - Number of spectral channels and scan integration time
- Bandwidth smearing
  - Large bandwidths lead to sources being "smeared" along the radial direction (pointing from the phase center), gets worse further from phase center
  - Can mitigate with larger number of spectral channels
    - Downsides – less per-channel sensitivity and larger file sizes
- Time smearing (a.k.a., time averaging losses)
  - The fast fringe rate due to long baselines means that sources get smeared in the direction perpendicular to the radius, gets worse further from phase center
  - Can mitigate with shorter scan integration times
    - Downsides – less per-scan sensitivity and larger file sizes

Field of view – bandwidth smearing

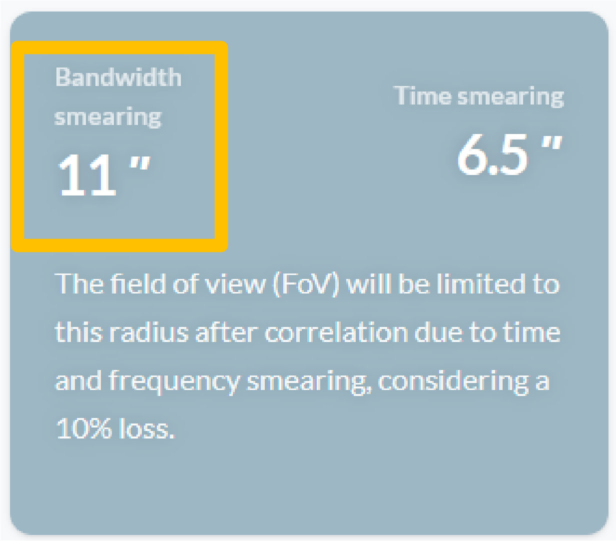
8-hour VLBA observation at 5 GHz, 128 MHz per spectral window, 2-second scan integrations



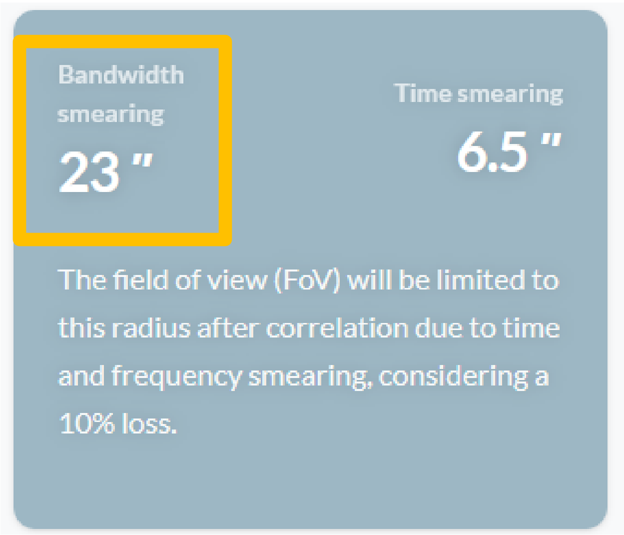
64 spectral channels per spectral window



128 spectral channels per spectral window



256 spectral channels per spectral window

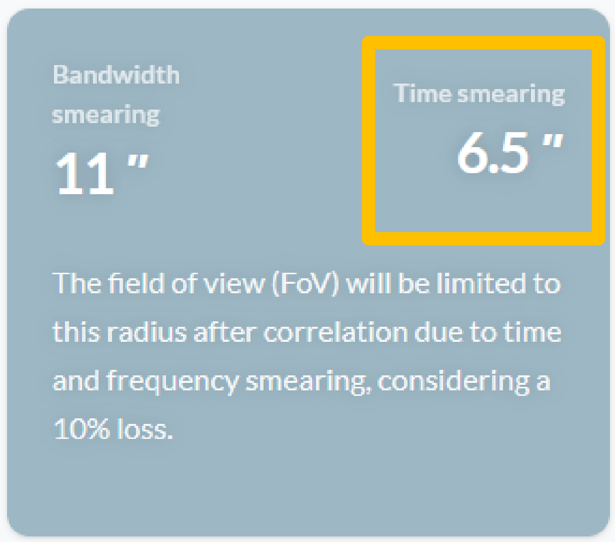


512 spectral channels per spectral window

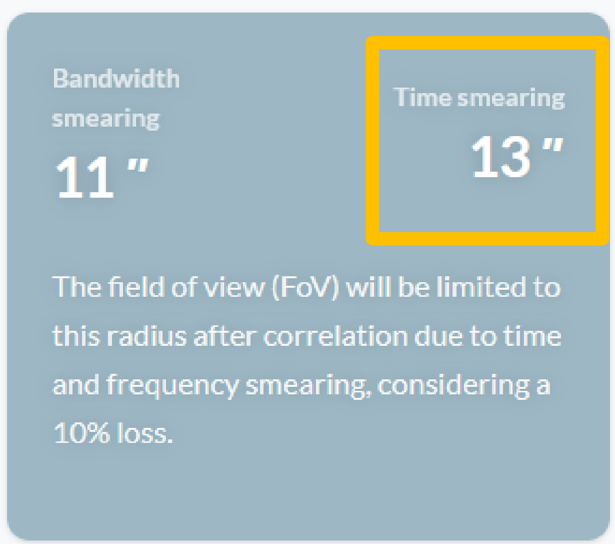
Images taken from planobs.jive.eu

Field of view – time smearing

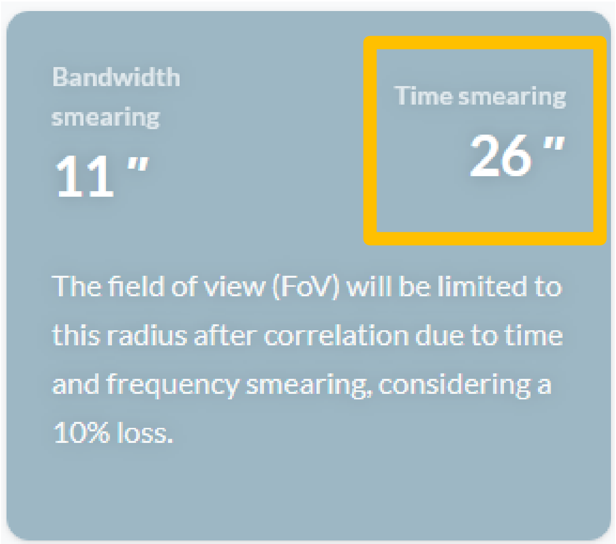
8-hour VLBA observation at 5 GHz, 128 MHz per spectral window, 256 spectral channels per spectral window



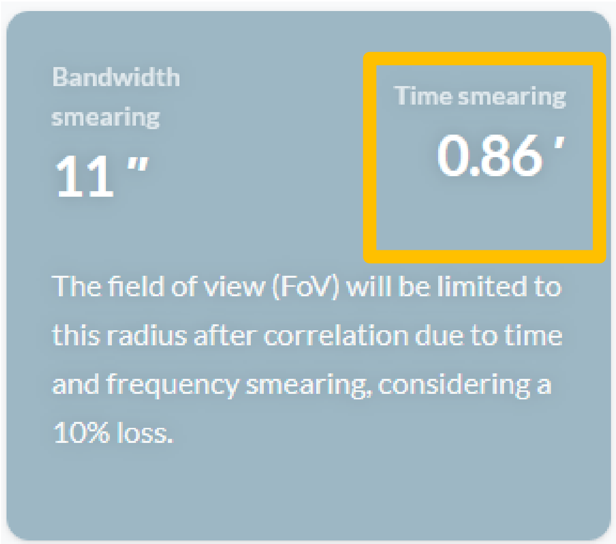
2-second scan integrations



1-second scan integrations



0.5-second scan integrations



0.25-second scan integrations

Images taken from planobs.jive.eu

Challenges

- VLBI capabilities are constantly improving, but some challenges remain

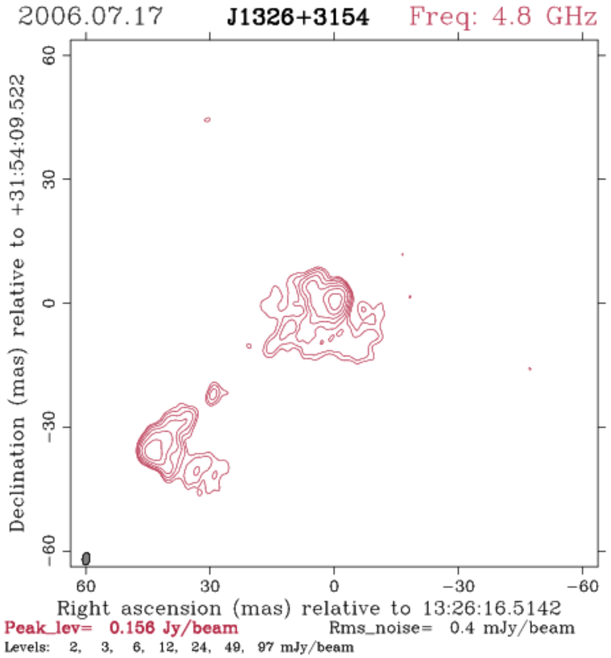
- Recent improvements:
  - Bandwidth increases for better continuum sensitivity
  - More stable electronics
  - Multi-field (multiple phase center) capabilities for imaging several sources in a beam

- Remaining challenges:
  - Uncorrelated atmosphere/ionosphere (can address with high cadence calibrator scans)
  - No absolute flux calibrators (need to use system temperature and gain)
  - Radio frequency interference (especially at 2-4 GHz)

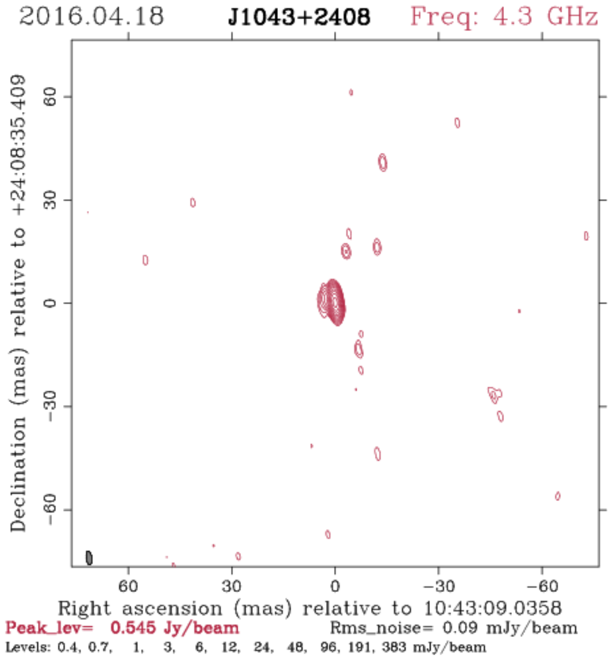
Observing – Phase Referencing

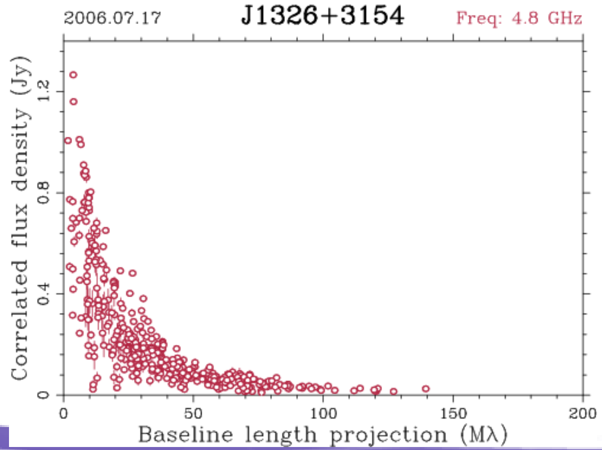
- Observing dim targets requires a strategy known as "phase referencing"
- You need to observe a relatively bright calibration target near your science target
  - Calibrator generally need to be within 5.7 degrees of the science target
  - Closer is better
  - The more point-like, the better
- You need to cycle between the calibrator and the target fast enough to account for tropospheric and/or ionospheric turbulence
  - The calibrator-target-calibrator cycle time should be less than coherence time
- The goal is to be able to interpolate the phase corrections obtained from the calibrator to the science target during calibration
- Astrometric observations may require more than one phase reference calibrator
  - "Multiview" methods

Observing - Calibrators

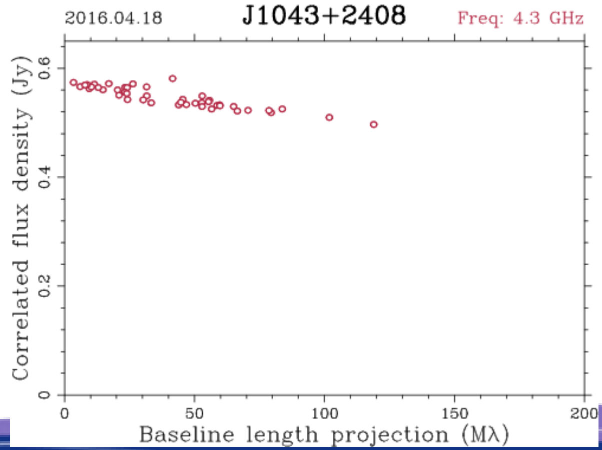


Pick Your Calibrator!

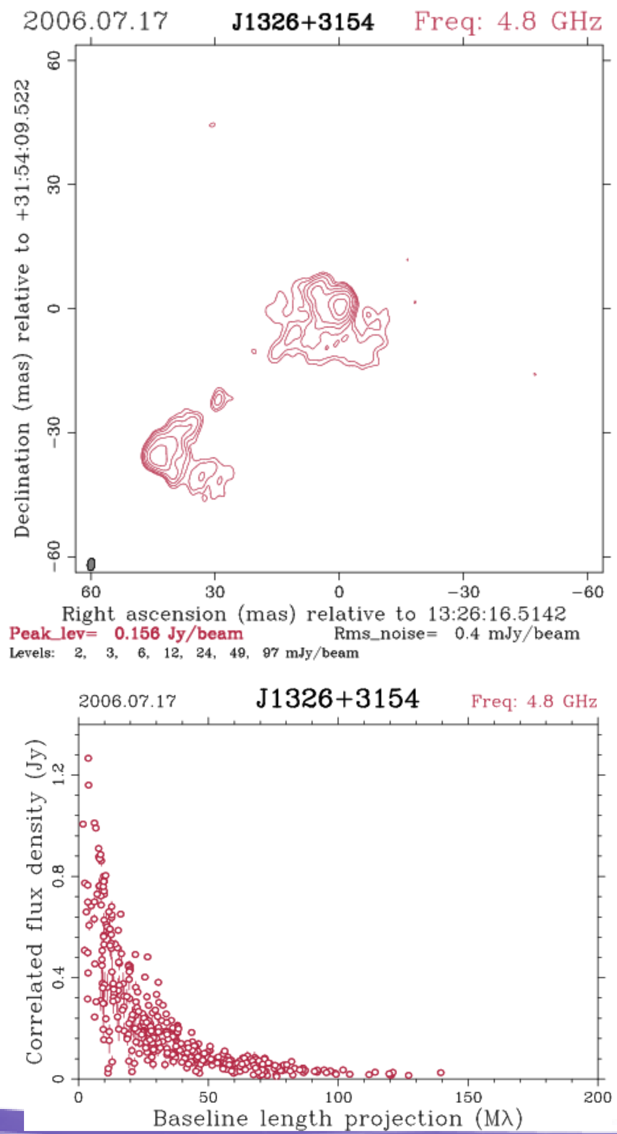




Figures from the RFC



Observing - Calibrators



Pick Your Calibrator!

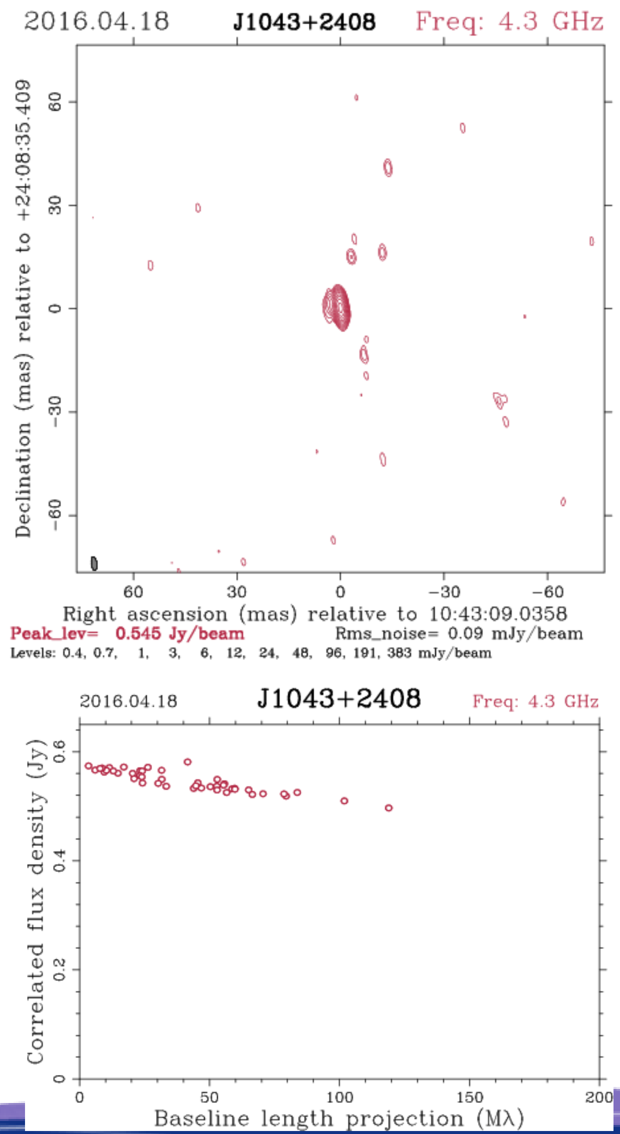
Lots of structure

Bright on short baselines, but dim on long baselines

Point-like structure

Bright enough on all baselines

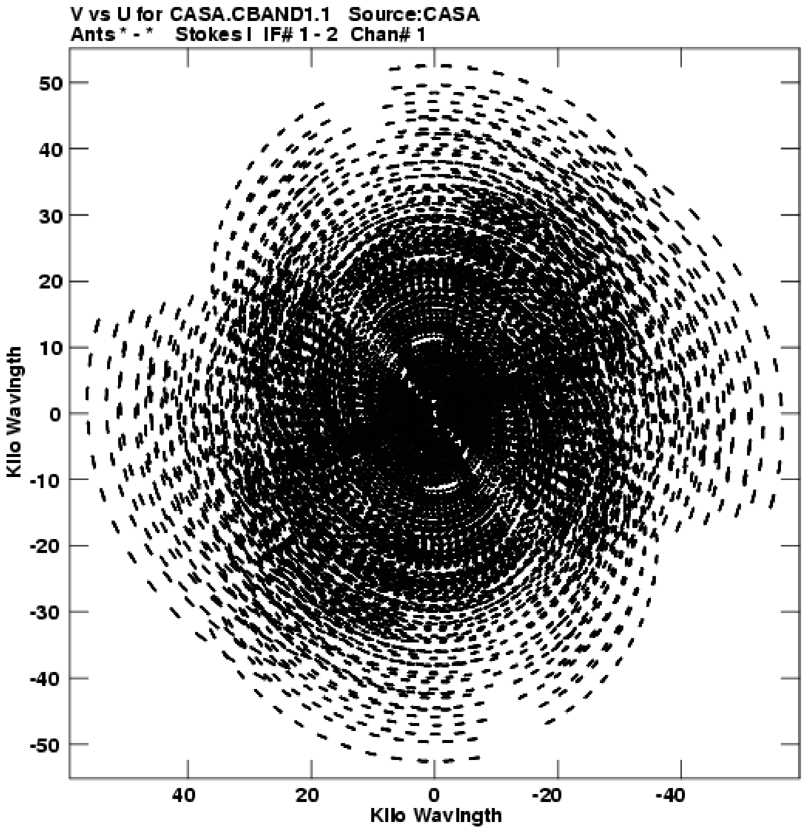
Figures from the RFC



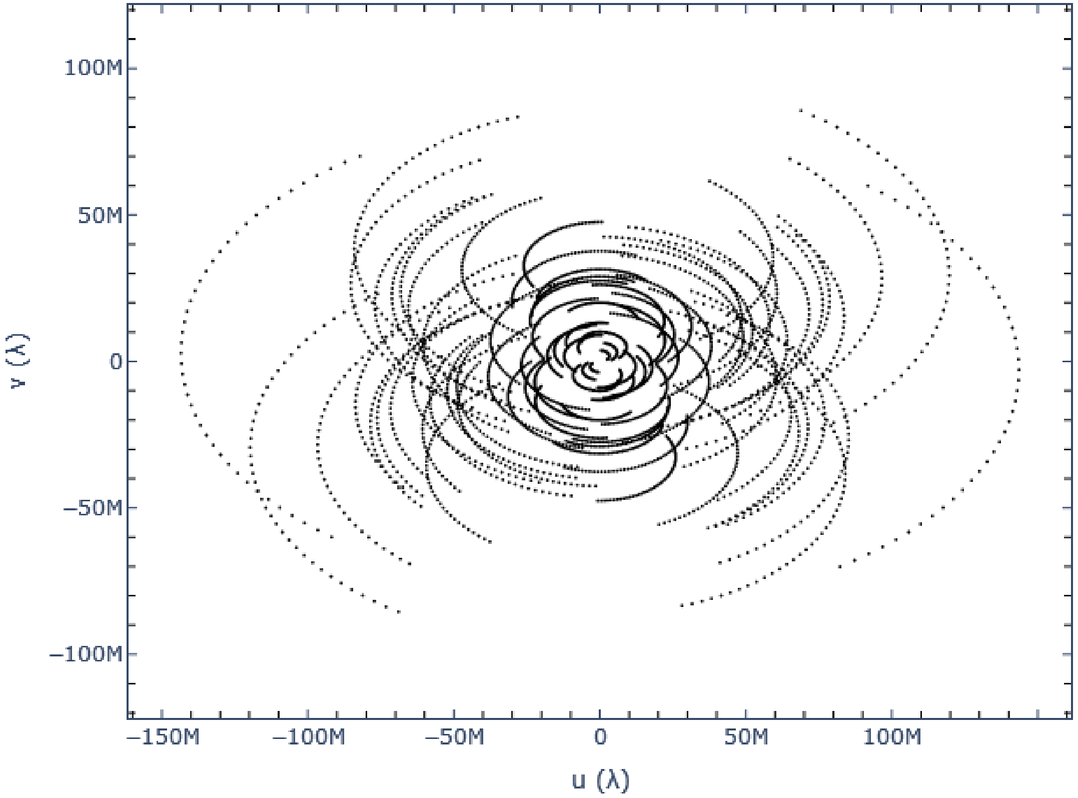
Observing – Sensitivity and UV-coverage

VLBI UV-coverage is always worse than for a connected element interferometer

VLA UV-coverage, 8 hours, Dec +34 degrees



VLBA UV-coverage, 8 hours, Dec +34 degrees

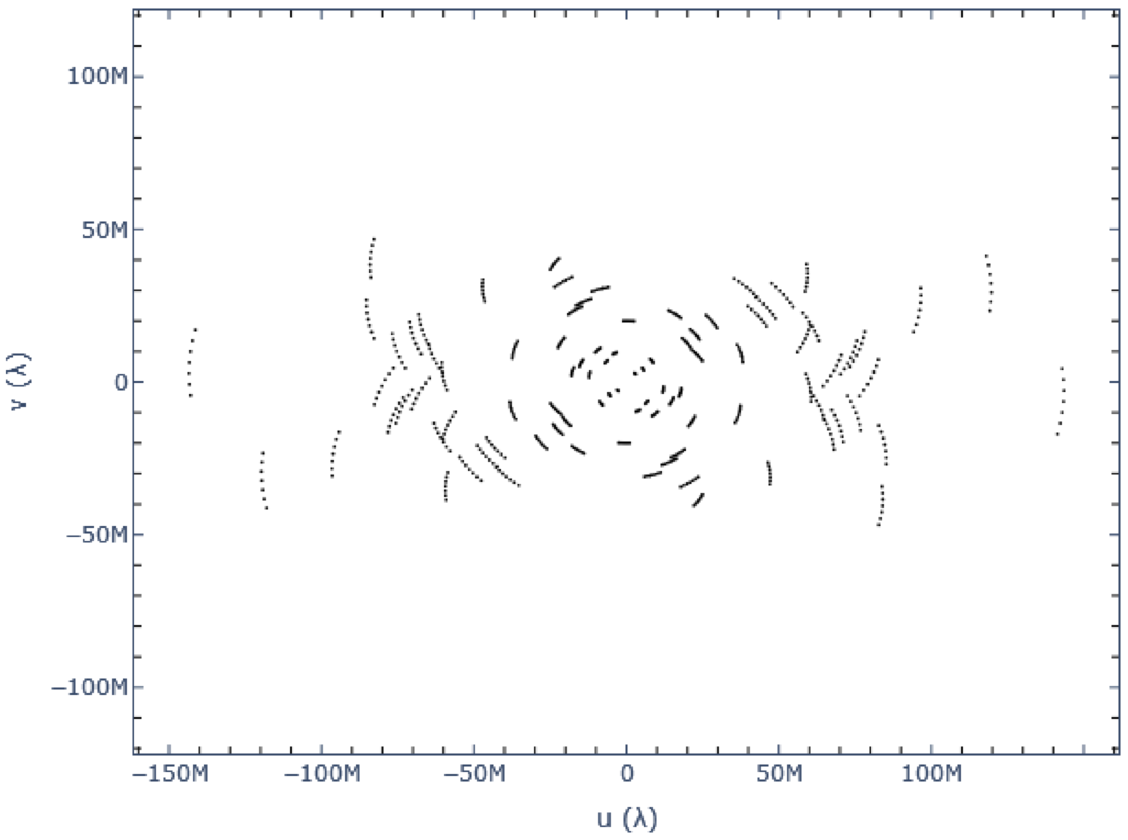


Observing – Sensitivity and UV-coverage

- **Sensitivity is not always the most important aspect of an observation**
- Remember that UV-coverage impacts images
  - Image fidelity is best when the UV-coverage is well-matched to the source brightness distribution
  - Better UV-coverage leads to better images due to improved dynamic range and improved sensitivity to different spatial scales
- Think carefully about what you really need when you write your proposal
- If you are observing one target at multiple frequencies, you can improve UV-coverage by alternating tunings throughout an observation
  - E.g., 40 minutes at 5 GHz, 40 minutes at 8 GHz, repeat to fill a 6-hour block
    - UV-coverage at both bands will be much better than two separate 3-hour blocks
  - *Caveat*: you cannot switch between PFB and DDC tunings on the VLBA

Observing – Sensitivity and UV-coverage

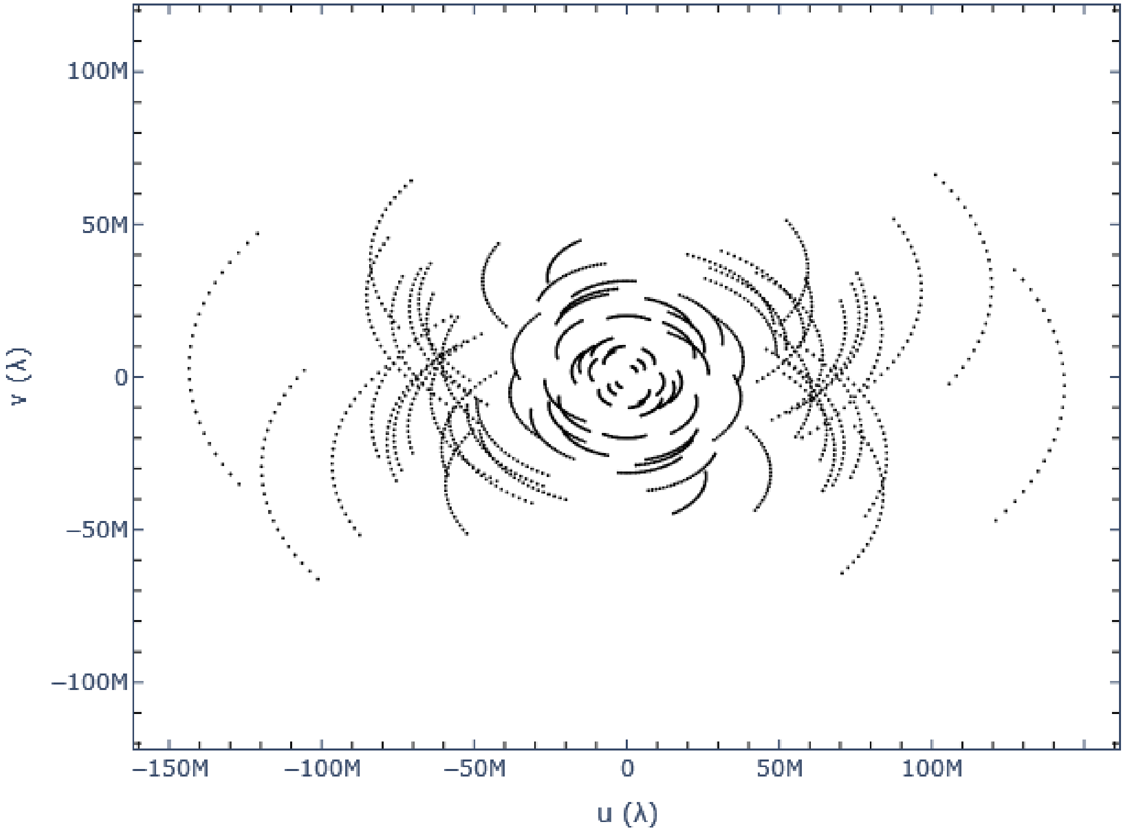
- VLBA, 1 hour, 5 GHz, 4 Gbps, 70% time on source, RA 18:20:00, DEC +34:48:00



Figures from planobs.jive.eu

Observing – Sensitivity and UV-coverage

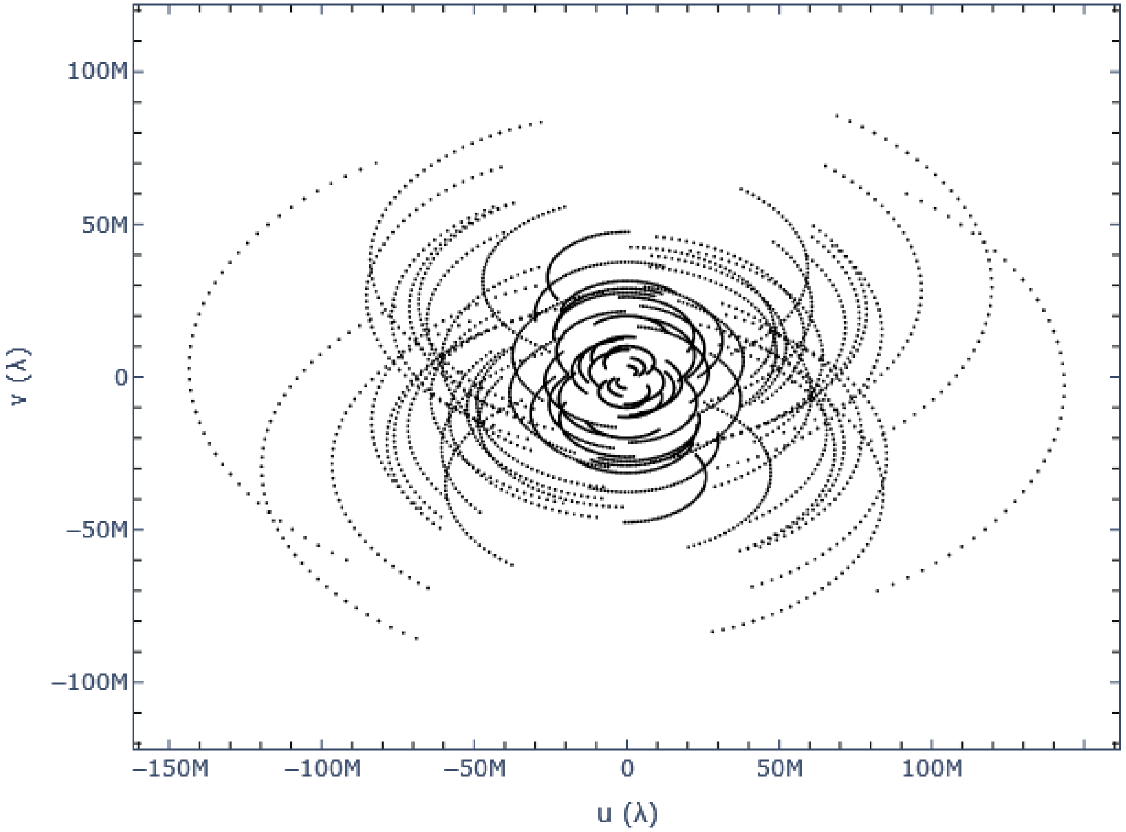
- VLBA, 4 hours, 5 GHz, 4 Gbps, 70% time on source, RA 18:20:00, DEC +34:48:00



Figures from planobs.jive.eu

Observing – Sensitivity and UV-coverage

- VLBA, 8 hours, 5 GHz, 4 Gbps, 70% time on source, RA 18:20:00, DEC +34:48:00



Observing Time: **8 h**
Time on Source: **5.6 h**

The planned observation will be conducted at a central frequency of 5 GHz (wavelength of 6 cm).

Freq. resolution: **1 MHz**
Vel. resolution: **60 km s^{-1}**

The total bandwidth of 512 MHz is divided in 8 x 64 MHz subbands, with 64 spectral channels each.

rms thermal noise (for 5.6 h on-target)

6.97 μJy $beam^{-1}$

158 μJy $beam^{-1}$ per spectral channel

153 μJy $beam^{-1}$ on 1-min integration

View sensitivity per baseline

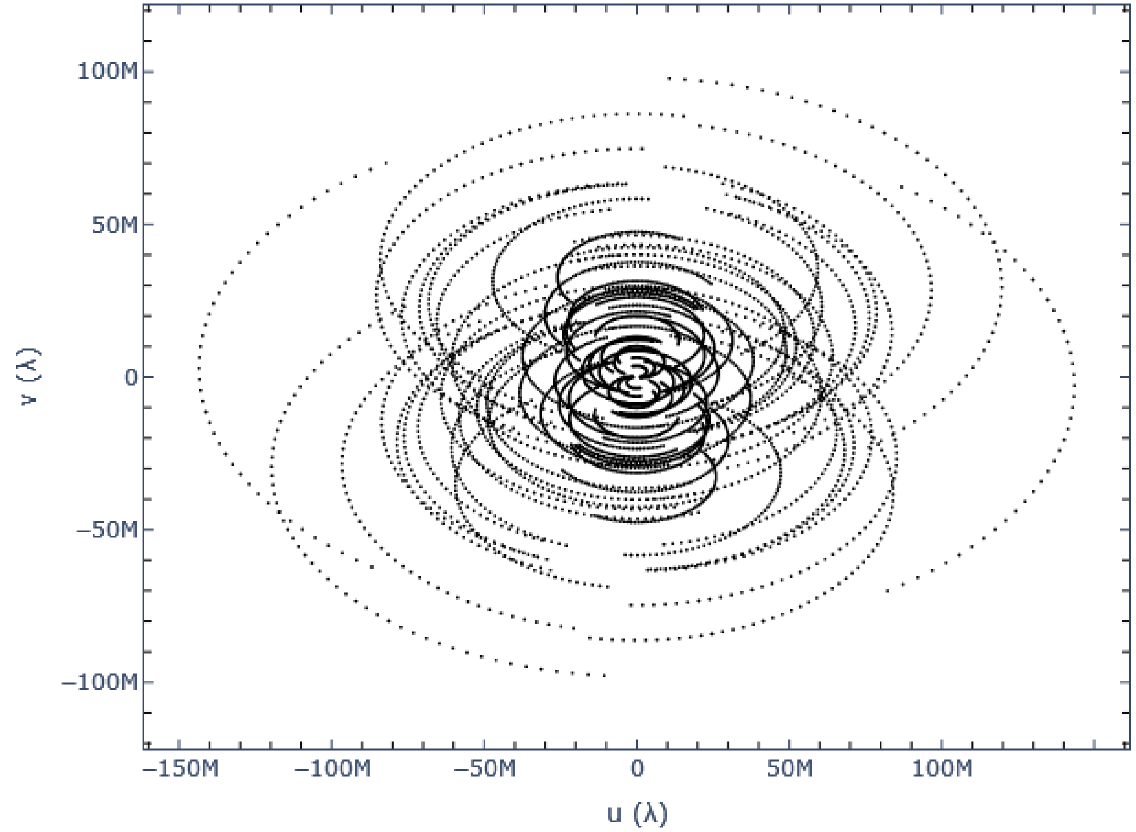
Angular Resolution

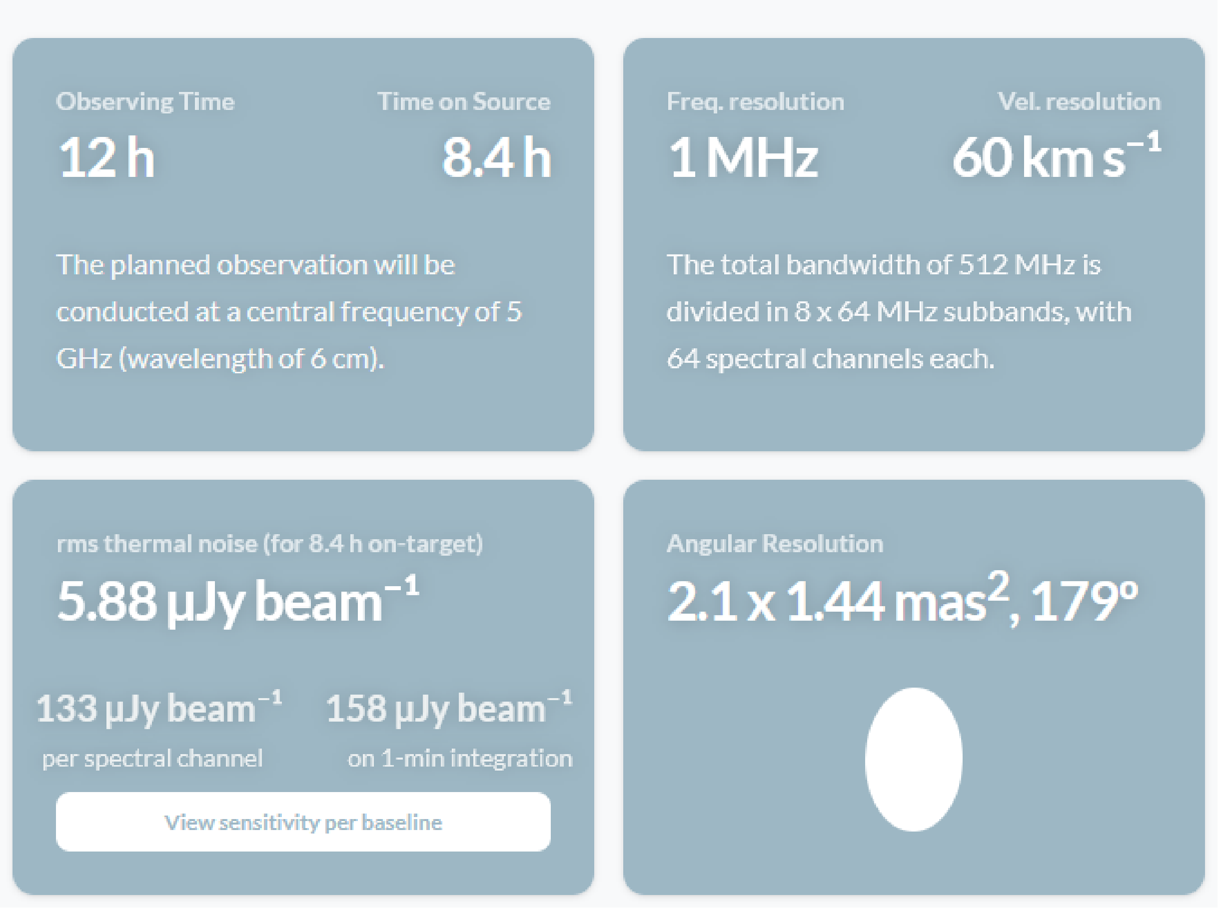
2.4 x 1.44 mas^2, 179º

Figures from planobs.jive.eu

Observing – Sensitivity and UV-coverage

- VLBA, 12 hours, 5 GHz, 4 Gbps, 70% time on source, RA 18:20:00, DEC +34:48:00

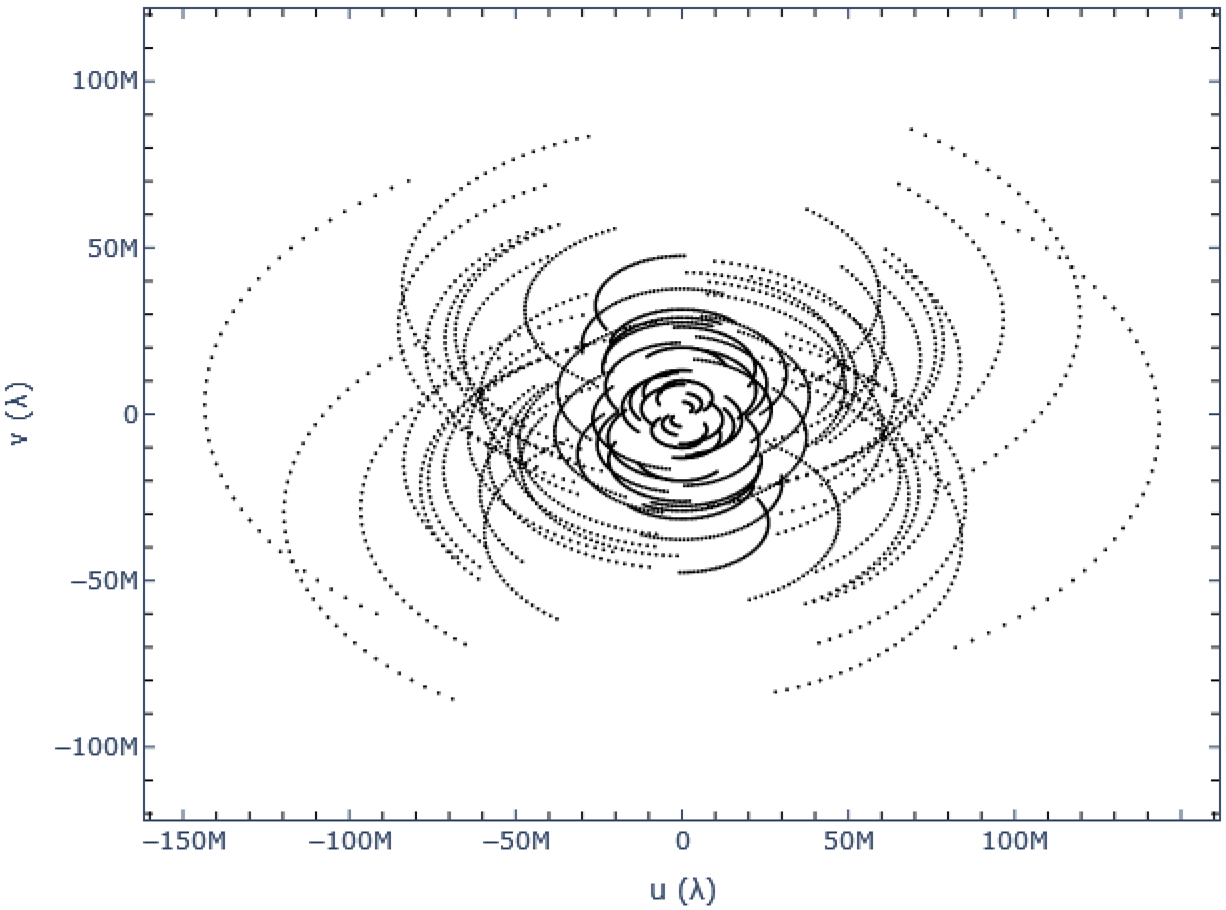




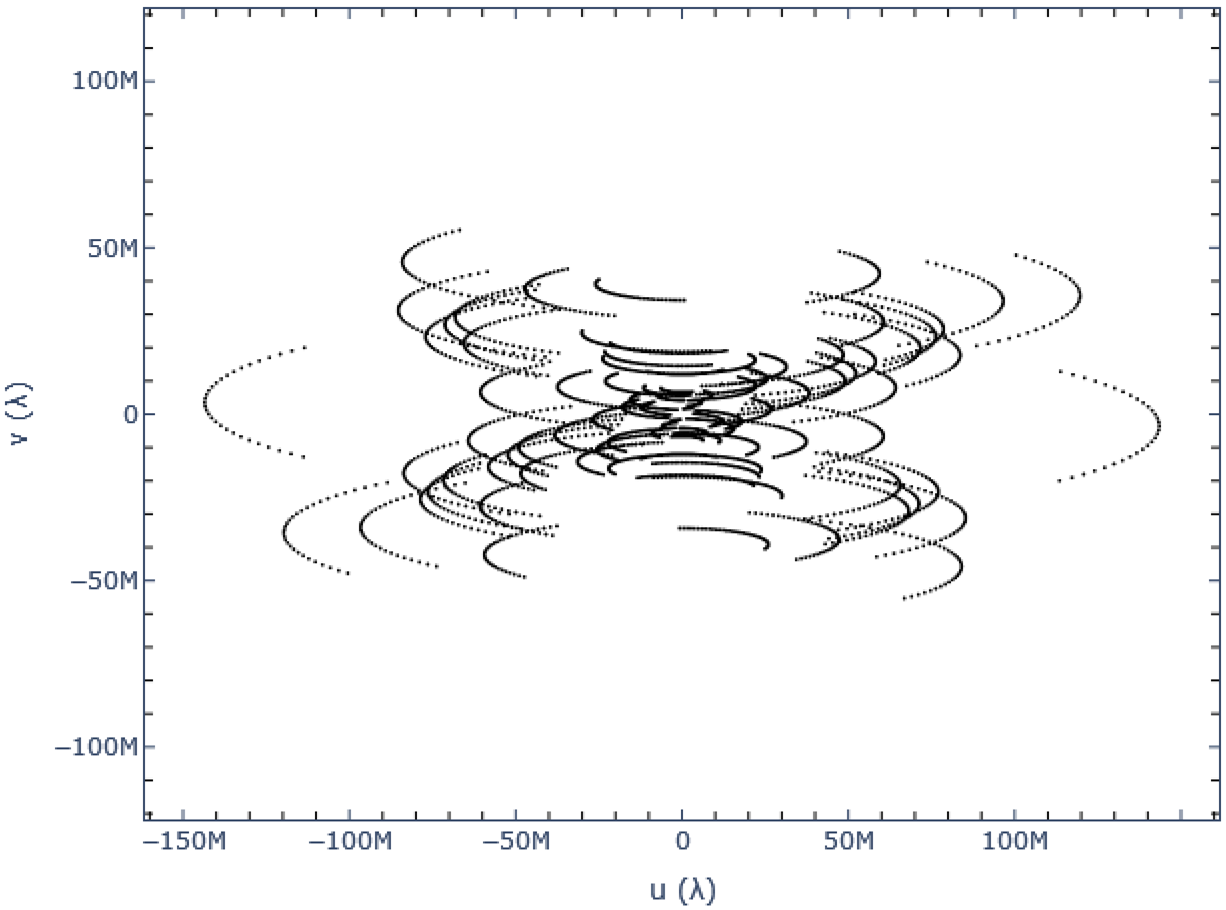
Figures from planobs.jive.eu

UV-coverage also depends on source declination

RA 18:20:00, DEC +34:48:00



RA 18:20:00, DEC -10:48:00



Both 8-hour VLBA observations

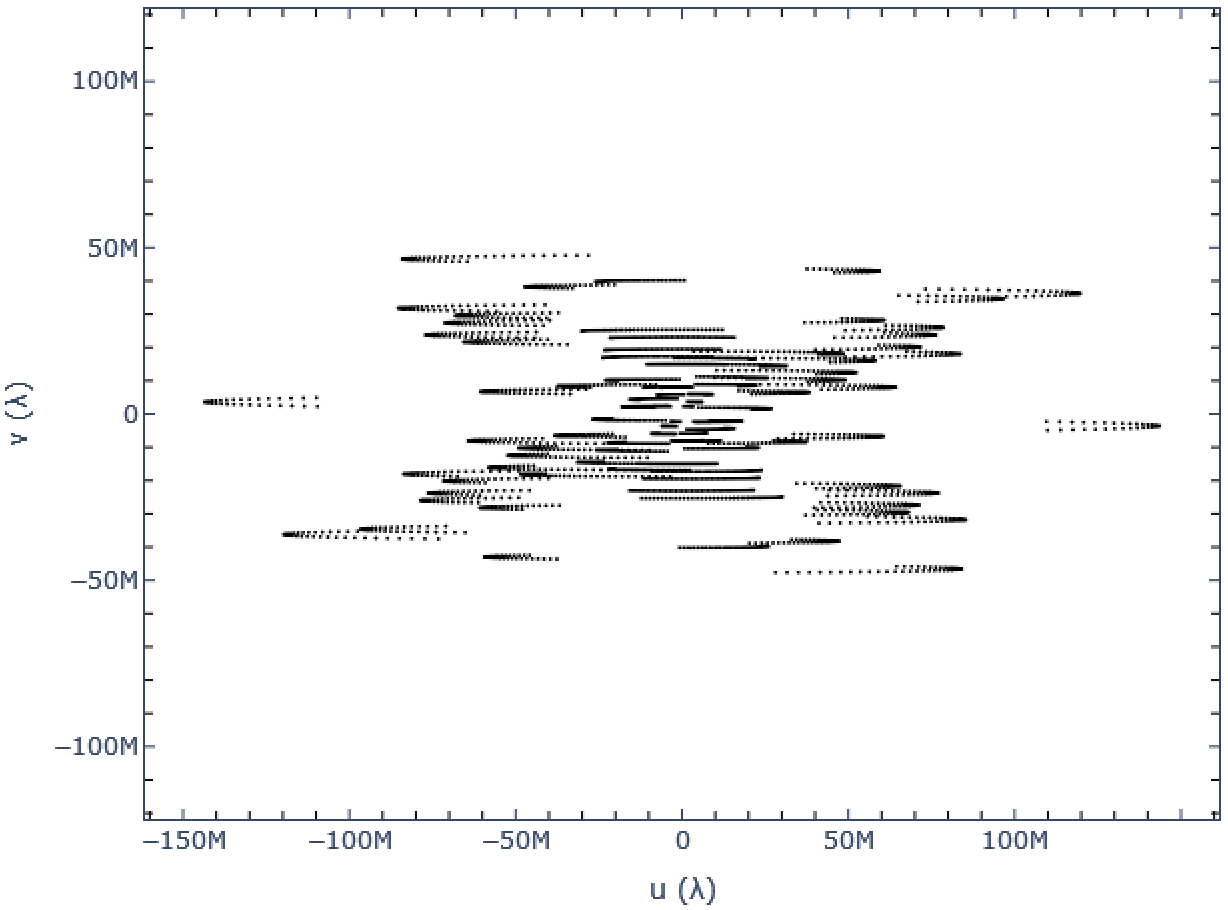
UV-coverage also depends on source declination

If your source has a declination near 0 degrees, your UV-coverage may be pretty terrible

8-hour VLBA observation

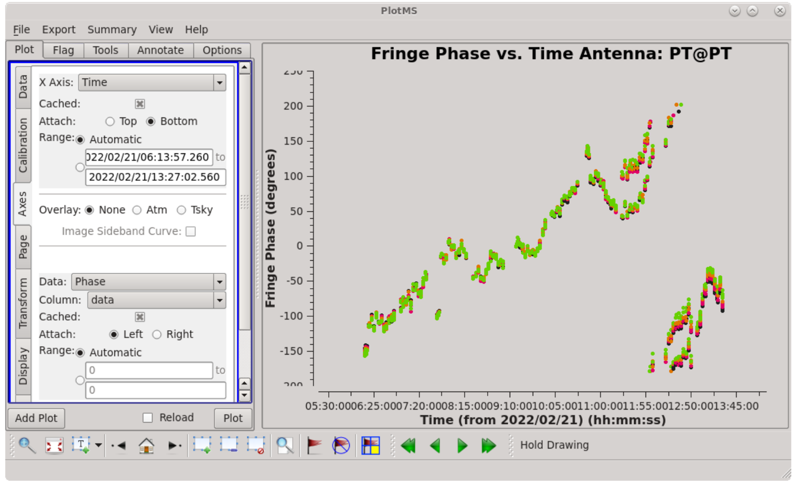
RA 18:20:00

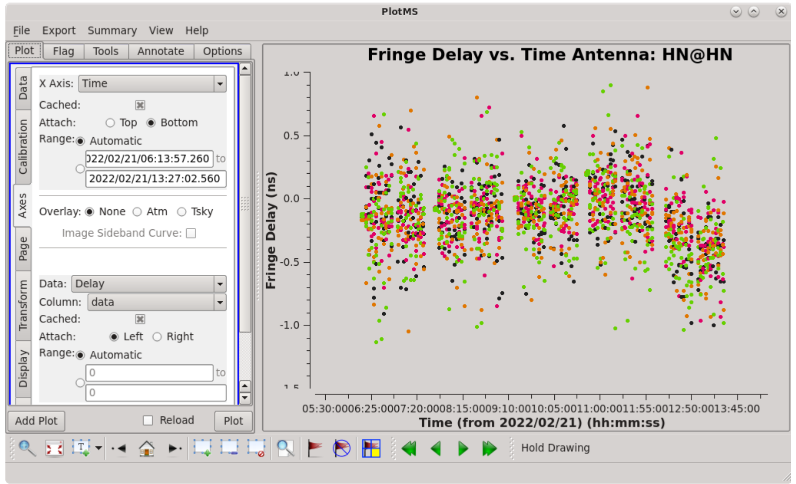
DEC +00:48:00

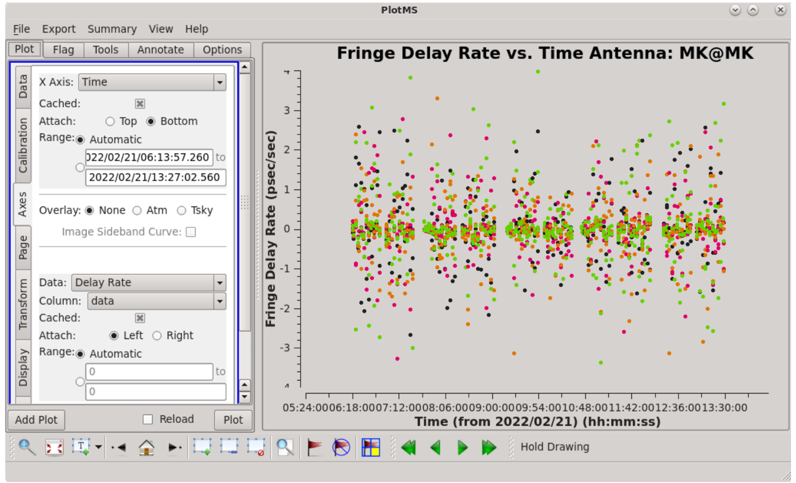


Calibration– Fringe Fitting

- The major step in VLBI calibration that is not used for most connected element calibration is called "fringe fitting"
- During this step, the software solves the relative phase error equation to eliminate (or at least reduce) errors in both frequency and time
  - $\Delta\phi(t,\nu)_{ij} = \phi_{0i} - \phi_{0j} + ([\frac{\partial\phi_i}{\partial\nu} - \frac{\partial\phi_j}{\partial\nu}]\Delta\nu + [\frac{\partial\phi_i}{\partial t} - \frac{\partial\phi_j}{\partial t}])\Delta t$
  - AIPS task: FRING; CASA task: fringefit

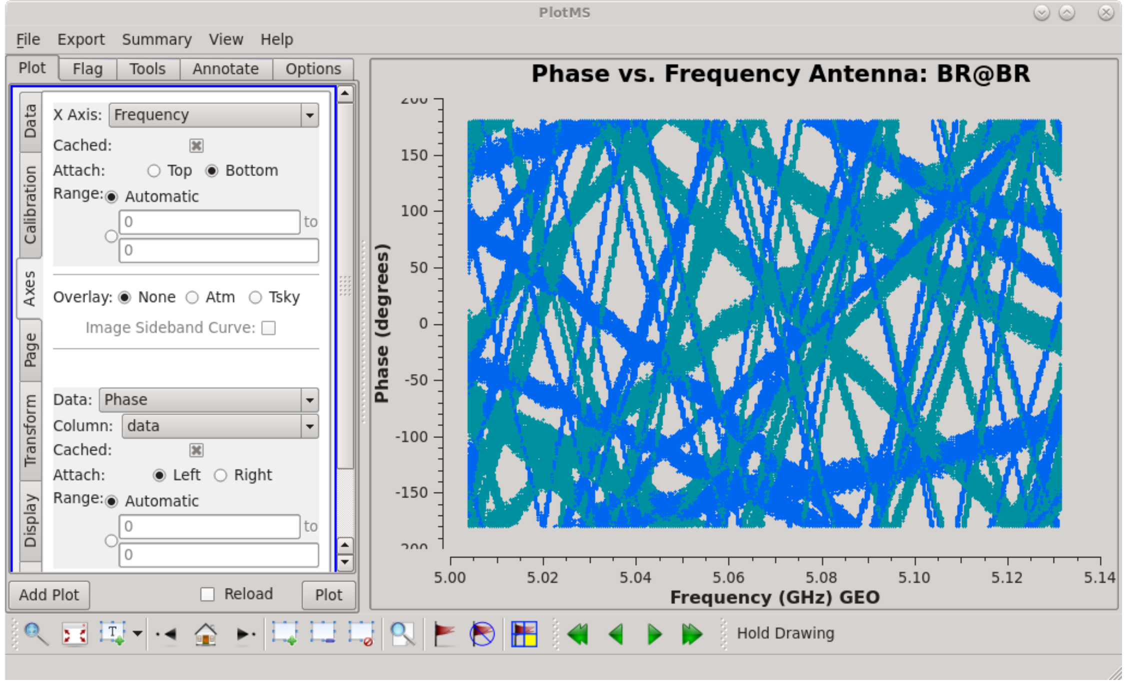




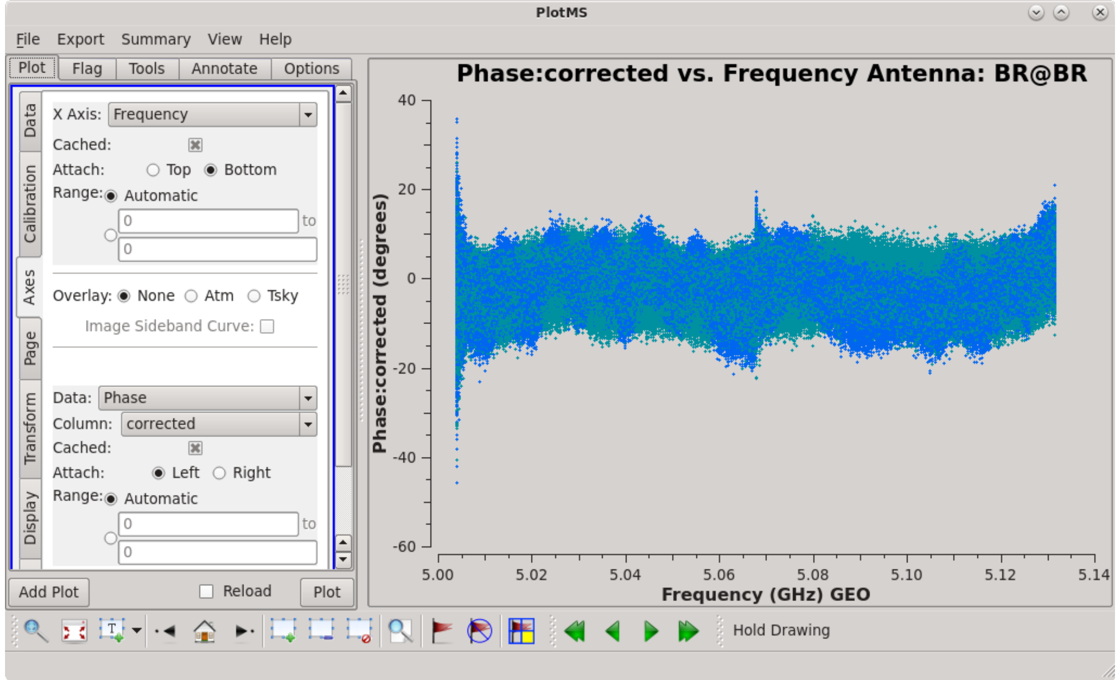


Calibration – Fringe Fitting

Results of fringe fitting



Phase vs Frequency for all baselines to Brewster, before fringe fitting



Phase vs Frequency for all baselines to Brewster, after fringe fitting

Calibration – Fringe Fit Limitations

- Fringe fitting assumes the calibrator is a point source
  - If you picked a good calibrator, this is usually fine
  - If you know the calibrator structure, you can give the fringe fit task a model that may enable it to do a better job
- The effectiveness of the fringe fit task depends on the signal-to-noise of the calibrator scans
  - If the calibrator is not bright enough, fringe fitting will fail
  - Sometimes source variability ruins your entire observation
- If the ionosphere or atmosphere is changing faster than the nodding cycle, fringe fitting will not help much
  - "Decorrelation"
  - Not much you can do unless the target is bright enough for self-calibration

Imaging

- Once VLBI data is calibrated, you can do imaging with whichever software you prefer
- Some recommendations:
  - AIPS: Lots of tools for imaging
  - Difmap: Lightweight package specifically for VLBI imaging, easy self-calibration
  - CASA: Can use tclean or iclean, easy to look over images in CARTA
- Interactive cleaning is ***STRONGLY*** recommended!
- Note that sparse UV-coverage means you need to be more careful with deconvolution
  - Setting the loop gain to a lower value than for connected element interferometers is a good idea
    - Gains of 0.05 or lower tend to work well
    - Sometimes it is useful to start with a higher gain (0.05), and lower it as you clean down closer to the noise

Self-calibration

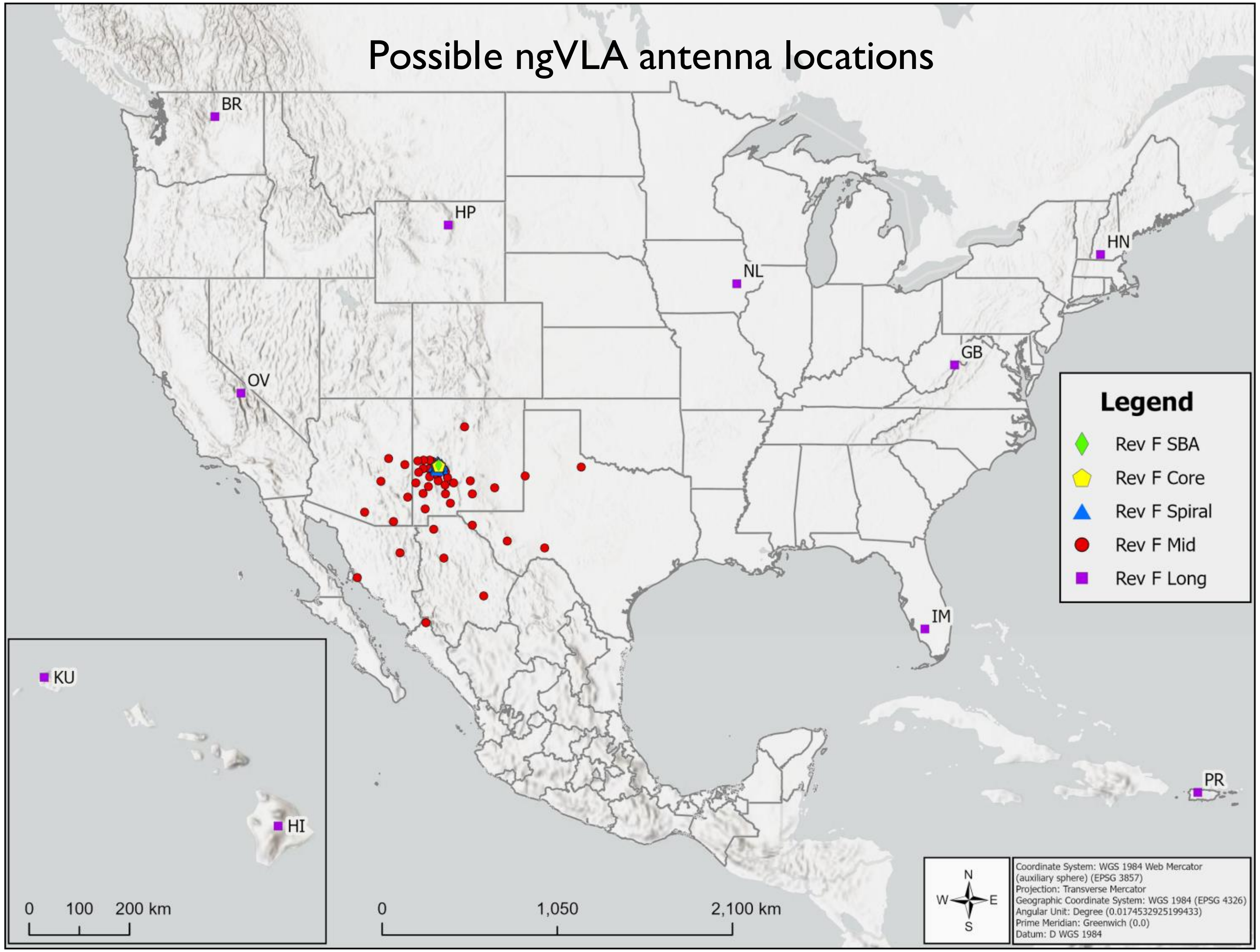
- Nearly all VLBI datasets need to refine their calibration beyond the basics
- The ionosphere and/or troposphere over each station can be very different
  - At low frequencies, the ionosphere has more impact
  - At high frequencies, the troposphere has more impact
- Self-calibration: Use a model of the source to refine the calibration further
  - Typically start with an image of the source made after initial calibration
  - For phase-referenced observations, you can apply the self-cal solutions from the phase reference calibrator to the science target
- **BE CAREFUL!**
  - Self-calibration (especially amplitude self-cal) can build in fake structure!
- See Joshua Marvil's lecture on self-calibration for more details

What is next for VLBI?

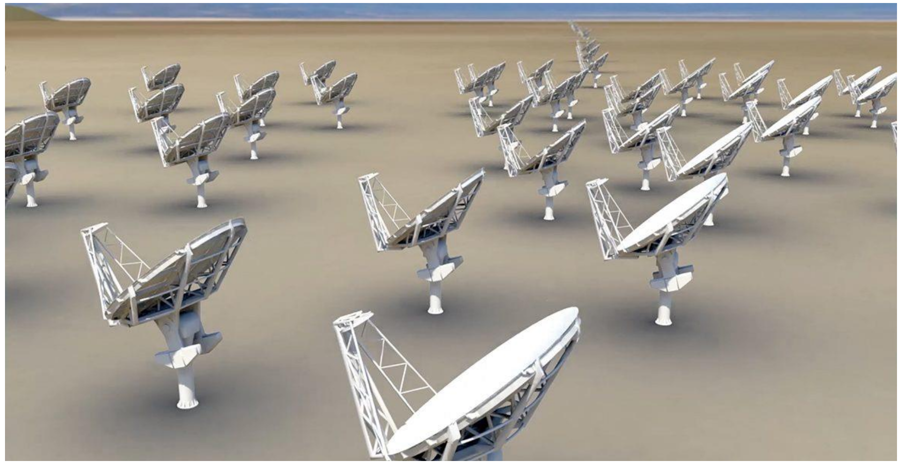
Square Kilometer Array – Phase 1 - Mid

- SKA-1 Mid will add a new station for EVN (at least for equatorial sources) and LBA (for better sensitivity and UV-coverage in the Southern Hemisphere)
- Multiple tied-array beams over small field of view may enable advanced calibration

Next Generation VLA

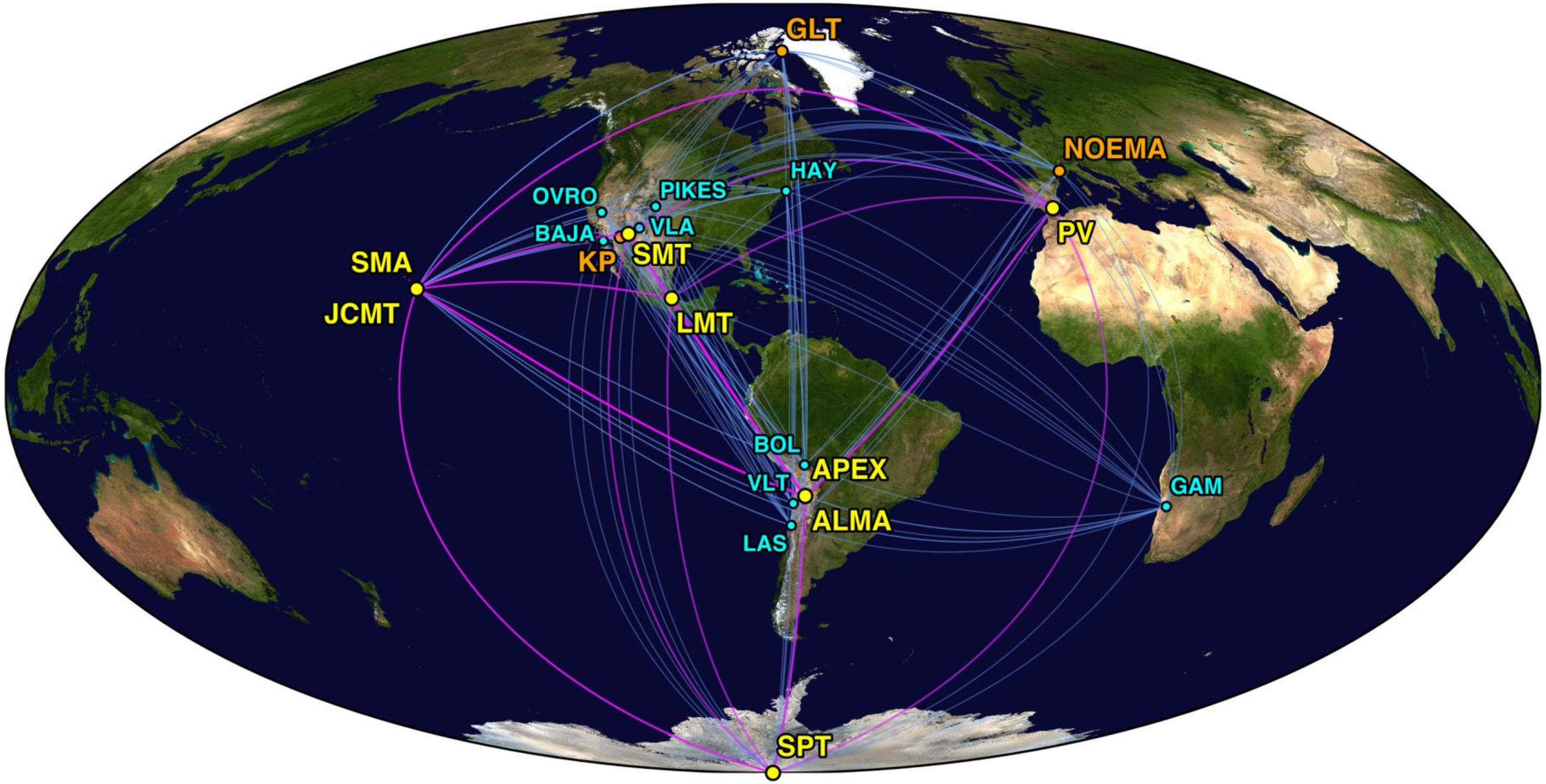


- Mid-scale baselines in the ngVLA core
- Long baselines similar to what we have for VLBA
- Better sensitivity, better UV-coverage, better images



Next Generation EHT

- Adding new stations
  - Greenland, Africa, and more
- Increasing data rate
  - Up to 128 Gbps
- Will enable observations of more targets than current EHT



VLBA Resources

https://science.nrao.edu/facilities/vlba

- VLBA Observational Status Summary
  - https://science.nrao.edu/facilities/vlba/docs/manuals/oss
- Guide to Proposing for the VLBA (and HSA/Global VLBI)
  - https://science.nrao.edu/facilities/vlba/docs/manuals/propvlba
- Guide to Observing with the VLBA (and HSA/Global VLBI)
  - https://science.nrao.edu/facilities/vlba/docs/manuals/obsvlba
- VLBA CASA Guides
  - https://casaguides.nrao.edu/index.php/VLBI_Tutorials

General VLBI Resources

- VLBA Calibrator Search Tool
  - https://obs.vlba.nrao.edu/cst/
- Radio Fundamental Catalog calibrator search tool
  - https://astrogeo.sciencecloud.nasa.gov/calib/search.html
- VLBI Observation Planner
  - https://planobs.jive.eu/
    - Big thanks to Benito Marcote!
- EVN Sensitivity Calculator
  - https://services.jive.eu/evn-calculator/cgi-bin/EVNcalc.pl
- VLBA Fringe Finder Survey
  - http://www.vlba.nrao.edu/astro/fringe_finder_survey/ffs.html

Data Calibration and Imaging Resources

- AIPS
  - https://www.aips.nrao.edu/
- CASA
  - https://casa.nrao.edu/
- Difmap
  - https://sites.astro.caltech.edu/~tjp/citvlb/

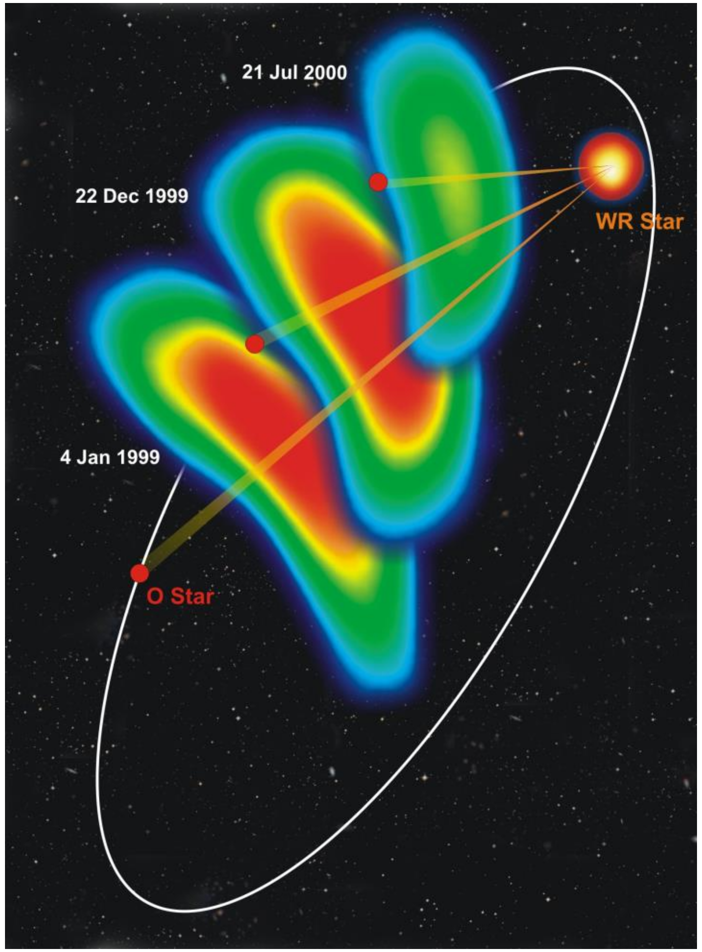
www.nrao.edu
science.nrao.edu

The NSF National Radio Astronomy Observatory is a facility of the U.S. National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Strengths of the VLBA

High dynamic range imaging at milliarcsecond resolution

- Locations of 10 antennas carefully chosen for optimal "UV coverage"
- Imaging resolution in different observing bands:
  - L-band (~1.6 GHz / 20 cm): 5 mas
  - X-band (~8 GHz / 4 cm): 0.85 mas
  - Q-band (~50 GHz / 7mm): 0.17 mas
- E.g. for ~1mas resolution
  - 1 AU at 1 kpc
  - Few-10 stellar radii at 100pc

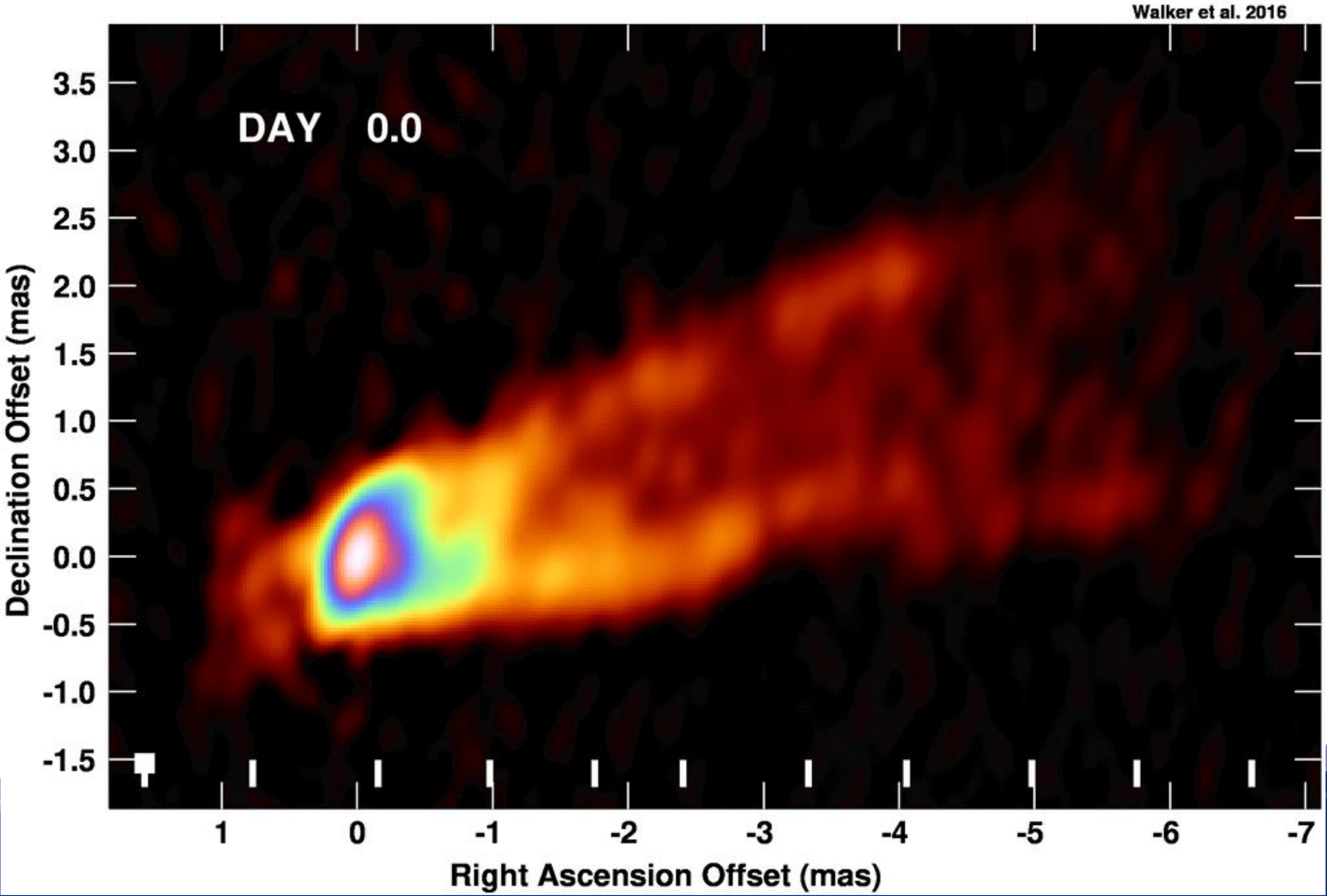


Example: WR140, imaging the evolution of the colliding wind region in Wolf-Rayet + O binary star system. Separation between stars between ~5-15 mas or 9-27 AU (Dougherty et al. 2010).

Strengths of the VLBA

High dynamic range imaging at milliarcsecond resolution

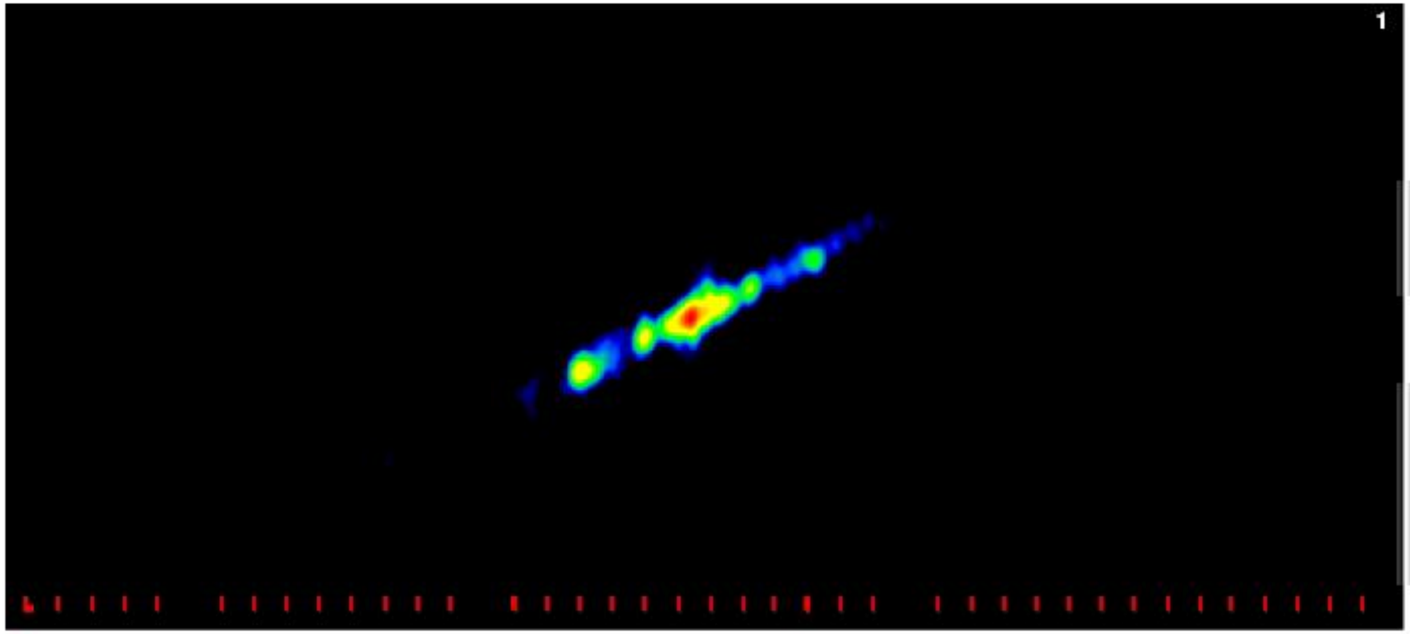
- M87 Jet at 43 GHz (R.C. Walker)
- Challenging: structure changes over time, high contrast



Strengths of the VLBA

Time-dependent phenomena

- VLBA available 24 hours per day, (almost) all year
- Can probe phenomena ranging from hours to years in duration
- VLBI sources tend to be variable in brightness, structure, and polarization



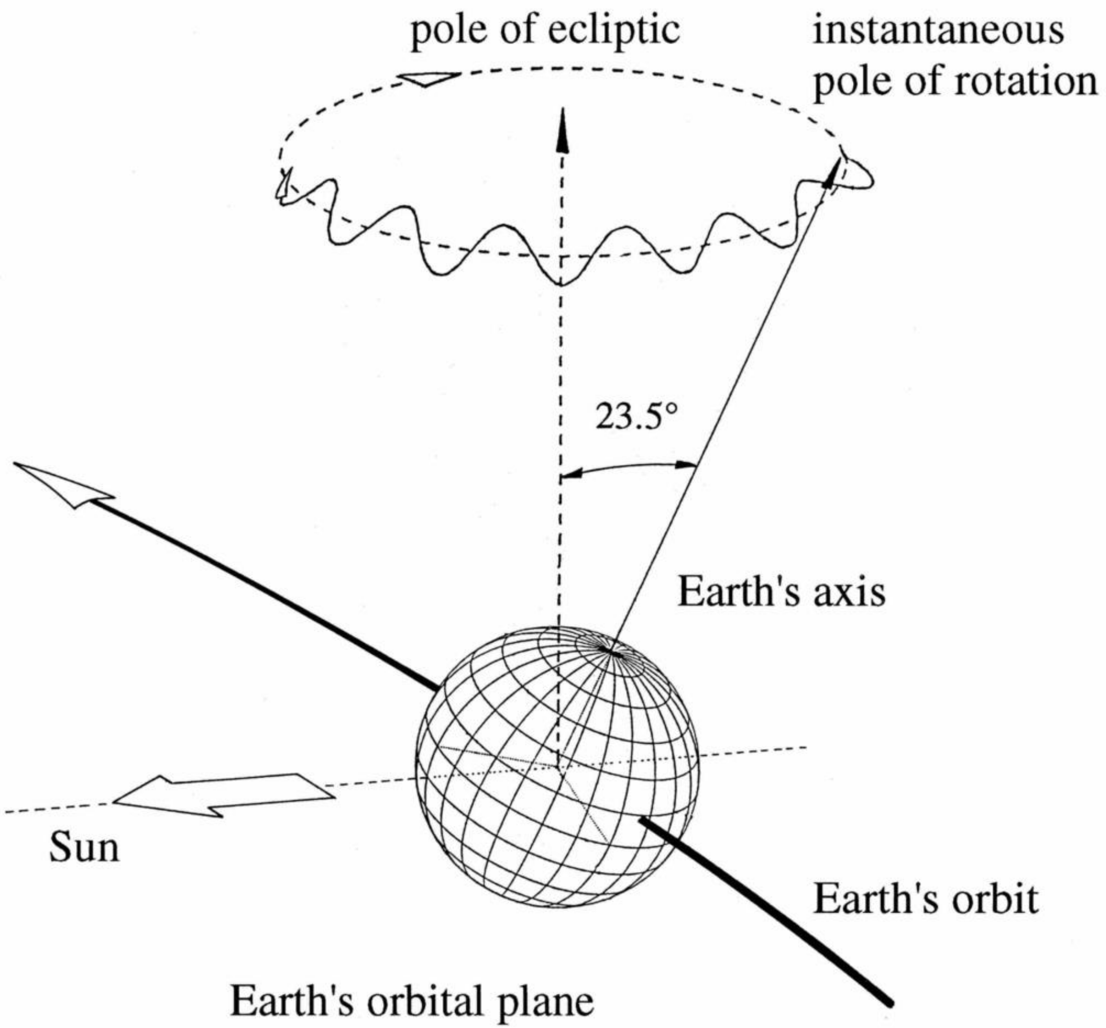
Example: Daily observations of X-ray binary SS433 over 40 days. (Mioduszewski et al)

Earth Orientation

- How to transform between celestial and terrestrial ref frame
- Five measured parameters:
  - UT1-UTC : difference between atomic time and solar time
    - Unpredictable on timescales of days to weeks
    - Change due to momentum transfer between atmosphere, ocean, and core, tsunamis, ice distribution on earth, dam releases, …
  - (x, y): location of celestial intermediate pole (CIP) on the fixed earth
    - Slow changes with earth mass and momentum distribution change
  - (X,Y): location of CIP on the celestial sphere
    - Precession and nutation
    - Changes well modeled by earth mass dipole interaction with moon, sun

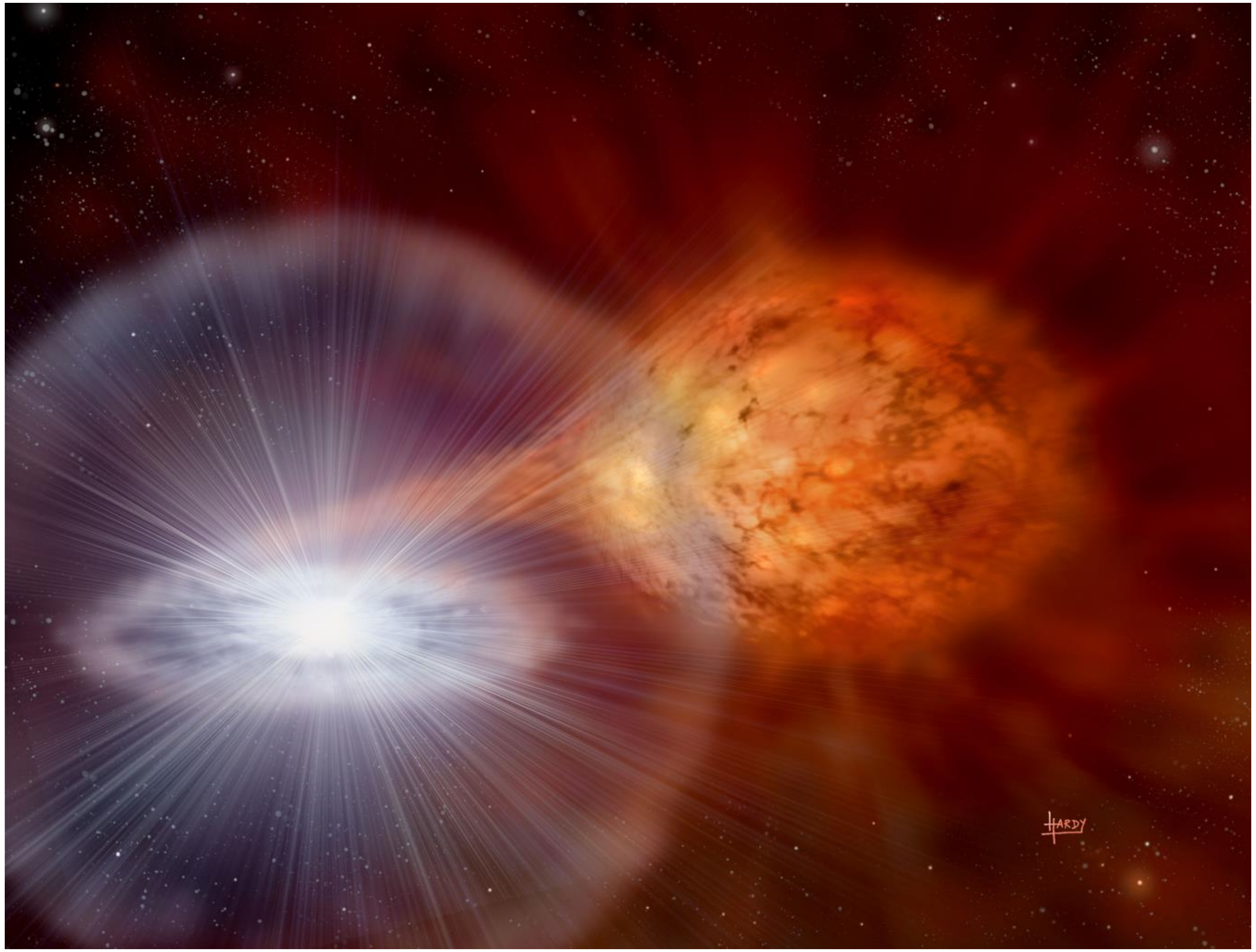
VLBI measurements of EOPs

- Observe quasars all over sky
  - Need to decouple clock offsets from geometry
- UT1-UTC measured daily
  - Needs single long east-west baseline for 1-2 hours
- Other parameters measured weekly or so
  - 24 hour observation using many baselines



Proposing

- Science Justification
  - Why are your targets interesting?
  - What questions will these observations help you to answer?
    - Why is VLBI needed? (Resolution? Astrometric precision?)
    - Will non-detections give you valuable information?



Artist's representation of a nova with a red giant companion

Proposing

- Technical Justification
  - What do you need from the instrument in order to achieve your science goals?
    - What stations do you need? What frequencies do you need?
    - Do you need anything special from the correlator, like multiple phase centers or zoom bands?
    - What is the dimmest object (or part of an object) you expect to be present?
    - Will you need to do phase referencing or is the target bright enough for self-calibration?
    - Which is more important: sensitivity or UV-coverage?
    - Do you need special calibrator scans, like polarimetric calibrators or geodetic blocks?

Old DEC10 computers

Observing – Scheduling with SCHED

- VLBI arrays use the SCHED software to create their scheduling files
  - Download and find documentation at http://www.aoc.nrao.edu/software/sched/
- In a SCHED .key (“key-in”) file, you need to provide:
  - List of stations to participate
  - Source coordinates
  - Frequency setups
  - Scan details
    - When observing a small number of targets, you can specify the exact order of the scans
    - For a large number of targets, you can use the optimization tools to build the scans
- It is possible to make loops of scans with the “group rep” options
  - Example: group 2 rep 4

    source = ‘calibratorA’ dwell = 0:50 /

    source = ‘targetA’ dwell = 2:00 /

Observing – Calibration strategies

- Every observation should have at least one bright calibrator for fringe finding and bandpass calibration
  - 1 Jy or brighter, compact, observe for 2 to 4 minutes every ~4 hours
- If your science targets are dim, you will want phase reference calibrators
  - Within 5.7 degrees of the science target
  - Bright-ish (~0.08 Jy or brighter) and compact
  - Cycle time depends on observing frequency

Observing Frequency (GHz)	VLBA Recommended Cycle Time (seconds)
1.0 to 8.4	300
15	120
22	60
43	30

Observing – Calibration strategies

- For polarimetry, you will need D-term (leakage) and EVPA calibrators
  - D-term: Bright and low polarization fraction (OQ208 or 3C84)
    - Bright and polarized will also work if you observe over a large range of parallactic angles
  - EVPA: Bright and strongly polarized
    - EVPA = Electric Vector Polarization Angle
    - Observe each one at least twice, but preferably 4 times, for 3 minutes per scan
    - Will also need connected element or single dish observations of EVPA calibrators
- For astrometry, you may need additional calibrators
  - Multiview techniques require more than one phase reference calibrator
- For spectral line projects, make sure your bandpass calibrator is very bright on all baselines
  - You need to ensure that bandpass calibration does not introduce extra noise into your spectral channels

Data Reduction - Calibration

Two main options for VLBI calibration software

AIPS

- Astronomical Image Processing System
- Pros
  - Very well-tested
  - Fast
  - Easy to get new features & tools
- Cons
  - Fortran-based
  - Harder to install than CASA

CASA

- Common Astronomy Software Applications
- Pros
  - Python-based
  - Active development
  - Extensive regression testing
- Cons
  - Slower than AIPS
  - Limited support for VLBI
    - **Currently not recommended for astrometry, polarimetry, or observations at 5 GHz or lower**