Very Long Baseline Interferometry

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Outline

www.physics.purdue.edu/~mlister/vlbitalk/

- What distinguishes VLBI from other kinds of interferometry?
- Why use VLBI?
- How, where, when and who can use VLBI?
  - stages of a VLBI observing project, from idea to publication

What distinguishes VLBI?

- Very long baseline interferometry uses the exact same principles as connected interferometers such as the EVLA and ATNF.

- **Primary difference: all antennas are not at the same physical site.**
  - variety of local atmospheric and radio interference conditions
  - different source rise/set times
  - antennas and associated electronics are not always identical
  - signals not typically correlated in real time, but time stamped with atomic clock signals (exception: e-VLBI)

Angular resolution:

$$\theta_{\mathrm{HPBW}} = 0.24\,\lambda_{\mathrm{cm}} \left(\frac{B_{\max}}{8612\ \mathrm{km}}\right)^{-1} \quad \text{milliarcsec}$$

milliarcsec

	EVN	VLBA	Global	RadioAstron
$B_{\max,\mathrm{km}}$	2 500	8 612	10 000	300 000

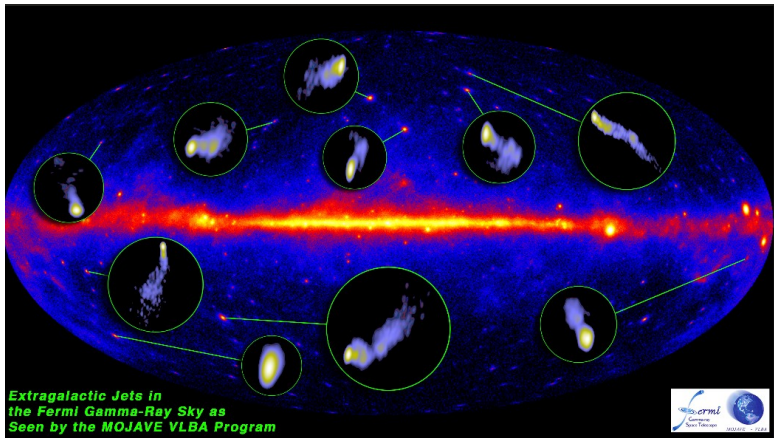
- θ_{HPBW} corresponds to half power width of the Gaussian restoring beam.
- Positional accuracy of discrete features can be a small fraction of the restoring beam width for high signal to noise ratios
- Using astrometric techniques, centroid positional accuracies of ~ 10 μas can be achieved.

  10 μas → apparent width of an astronaut's finger seen on the moon

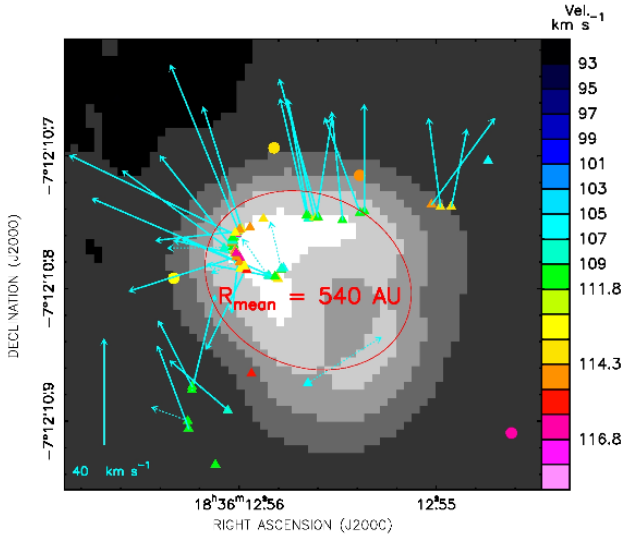
Why use VLBI?

1. Ultrahigh angular resolution (sub-milliarcsecond scale).

2. Precise (microarcsecond scale) positional accuracy for astrometry.



1 million factor zoom-in views of γ-ray-loud AGNs (MOJAVE program)



Maser proper motions in HII region G24 (L. Moscadelli)

What kinds of science use VLBI?

Any sufficiently compact radio source can be studied with VLBI

- **Astrometry related:**
  - geodesy and geophysics
  - direct distances to asteroids, planets, stars, masers, pulsars
  - black hole masses
  - Milky Way structure
  - exoplanet searches
  - tests of gen. relativity
  - spacecraft navigation

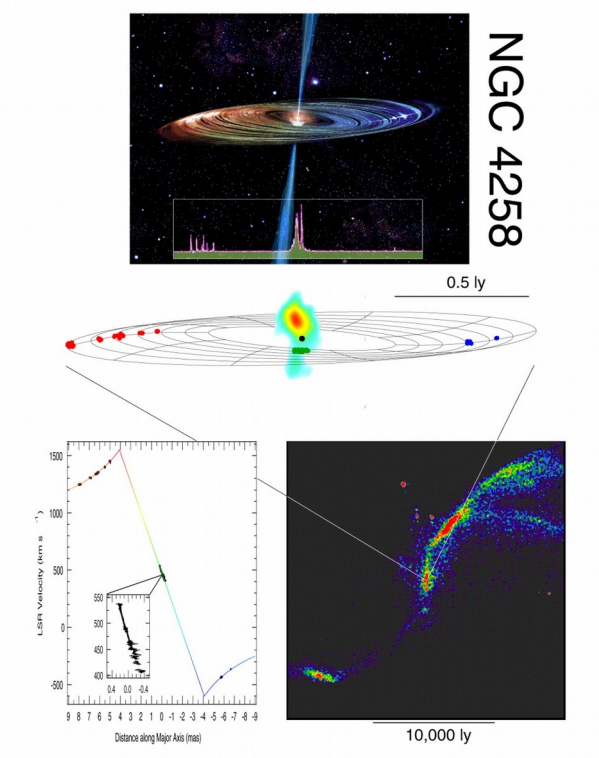


Image: credit: L. Greenhill

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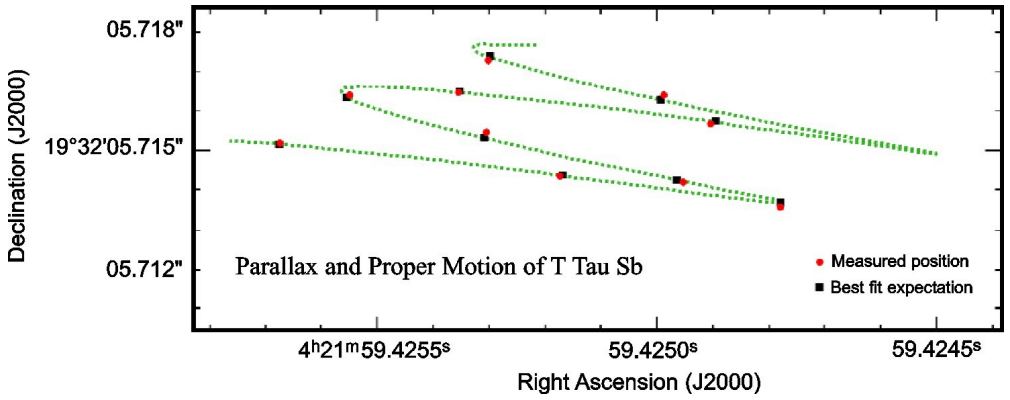

Parallax and proper motion of the star T Tau Sb, yielding a distance of 146.7 ± 0.6 pc, two orders of magnitude better than the Hipparcos value (Loinard et al. 2007)

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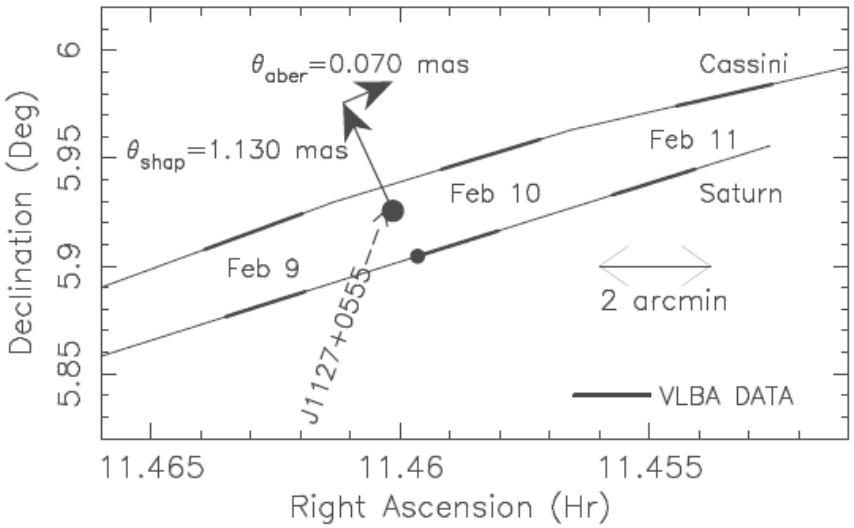
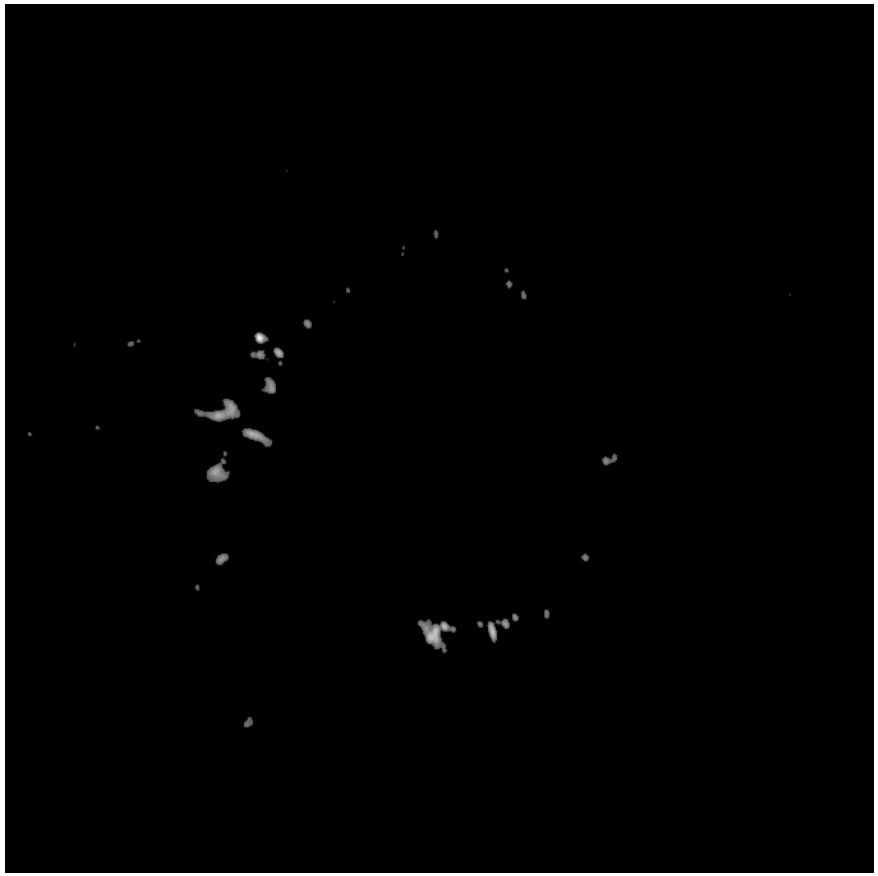


Figure 2. The Source Configuration for the February 2009 Aberration Experiment:

Fomalont et al. ArXiv:0912.3421

What kinds of science use VLBI?



TX Cam maser ring (P. Diamond et al.)

- **Imaging related:**
  - masers
  - supernovae
  - x-ray binaries
  - active galactic nuclei
  - galactic center
  - gamma-ray bursters

What kinds of science use VLBI?

SN 1993J expansion (M. Bietenholz et al.)

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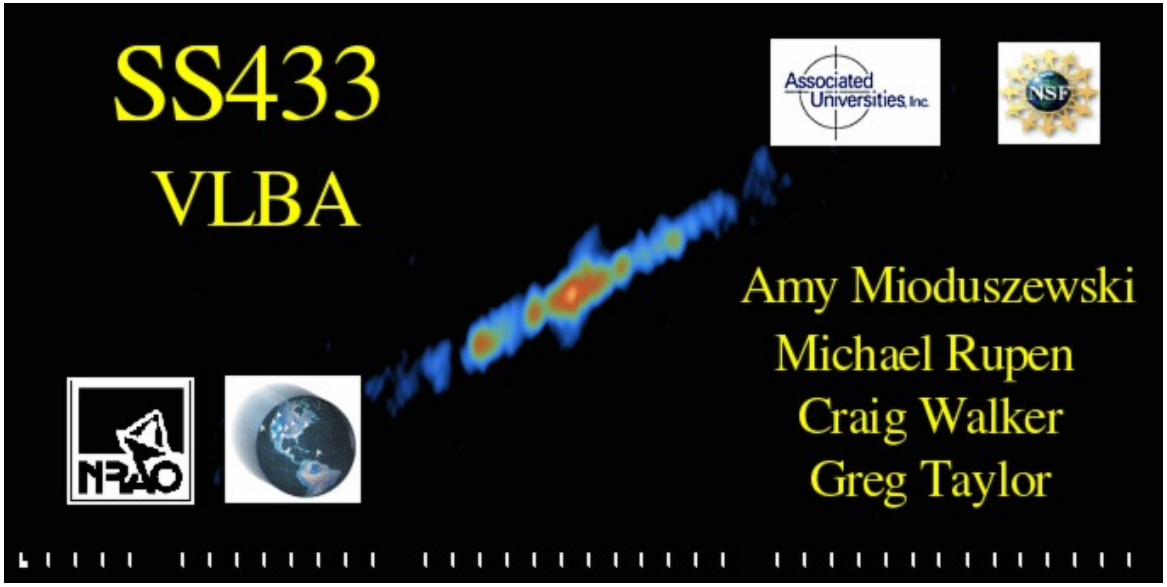

SS 433 Twin Jets: (A. Mioduszewksi et al.)

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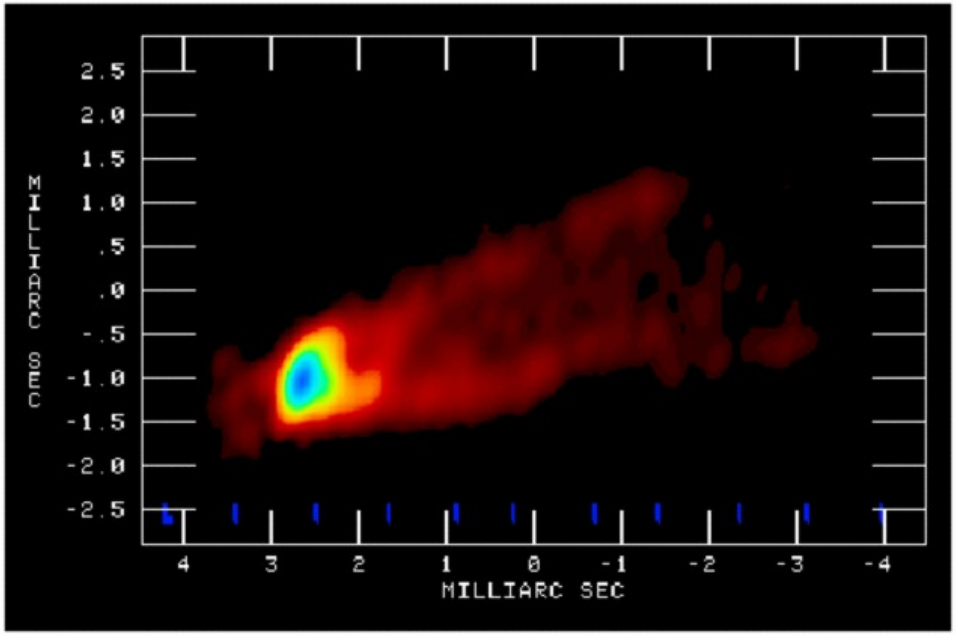

Inner 2 pc of M87 AGN jet (C. Walker et al.)

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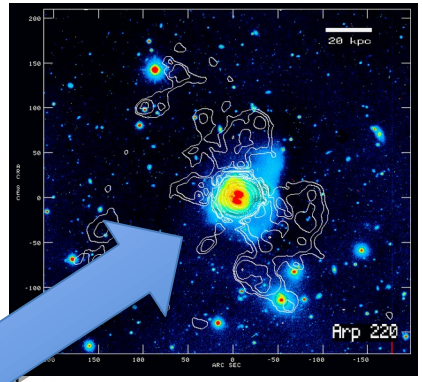


J. Hibbard (NRAO)

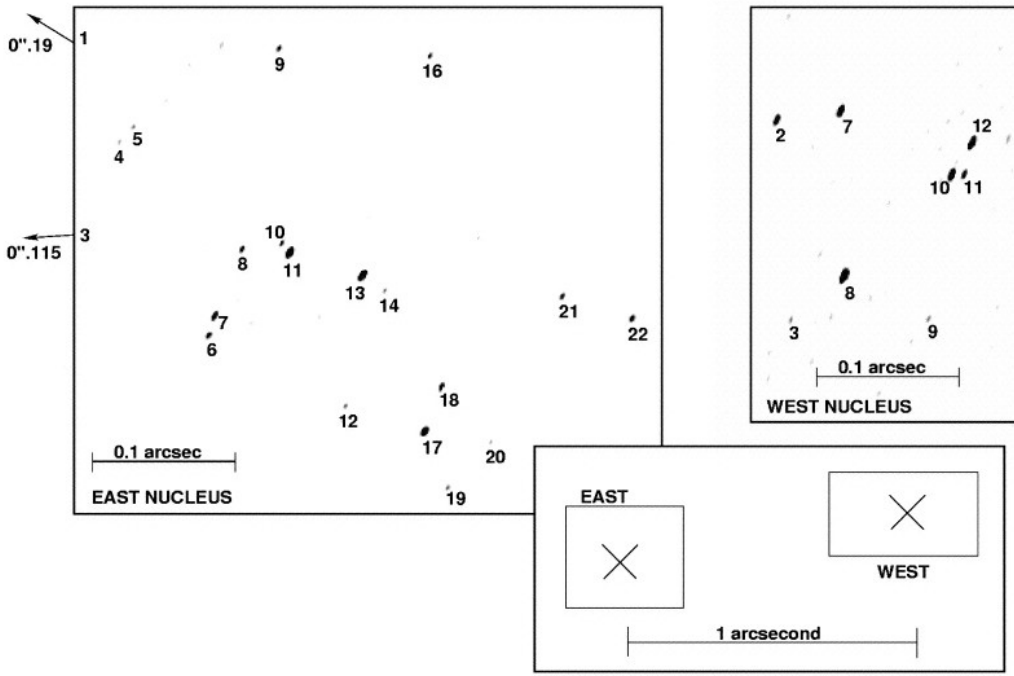


Image rms ~ 6 μJy/beam !

VLBI images of supernovae in the nuclei of the galaxy Arp 220
(Lonsdale et al. 2007)

What VLBI arrays can I use?

The Very Long Baseline Array (VLBA)

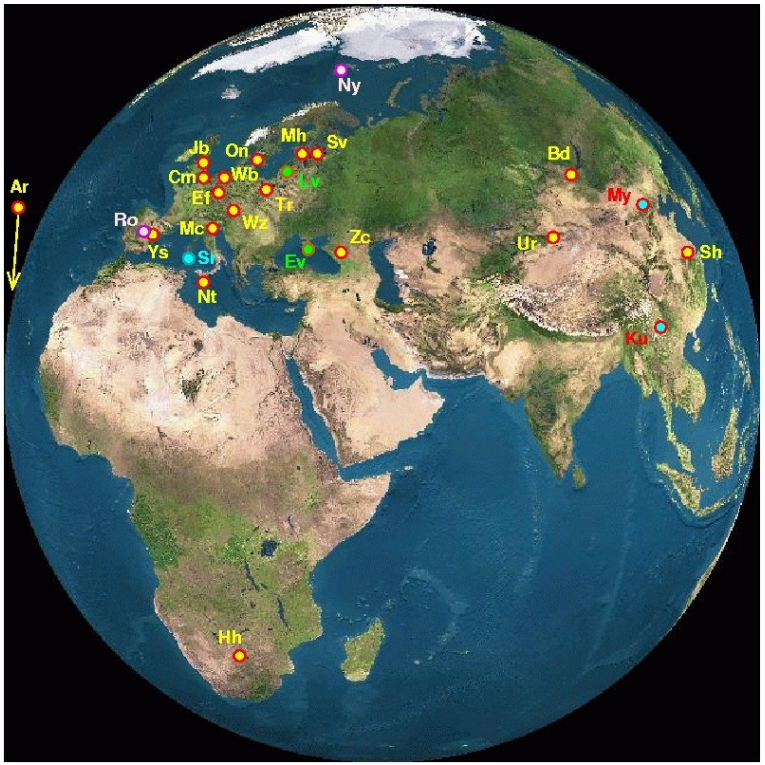
- ten identical 25m antennas
- 0.3 - 86 GHz
- maximum baseline ~8,600 km

science.nrao.edu/vlba

- Advantages:
  - full time dedicated VLBI array
  - identical antennas & full polarization capability

- Disadvantages:
  - only ten antennas (sub-optimal u,v coverage for equatorial and low declination sources)
  - no 'large' antenna element for fringe detection of weak sources

- **The European VLBI Network (EVN) & Global mm VLBI Array (GMVA)**
- collection of 18+ different antennas
- 0.3 - 86 GHz
- maximum baseline ~8,000 km

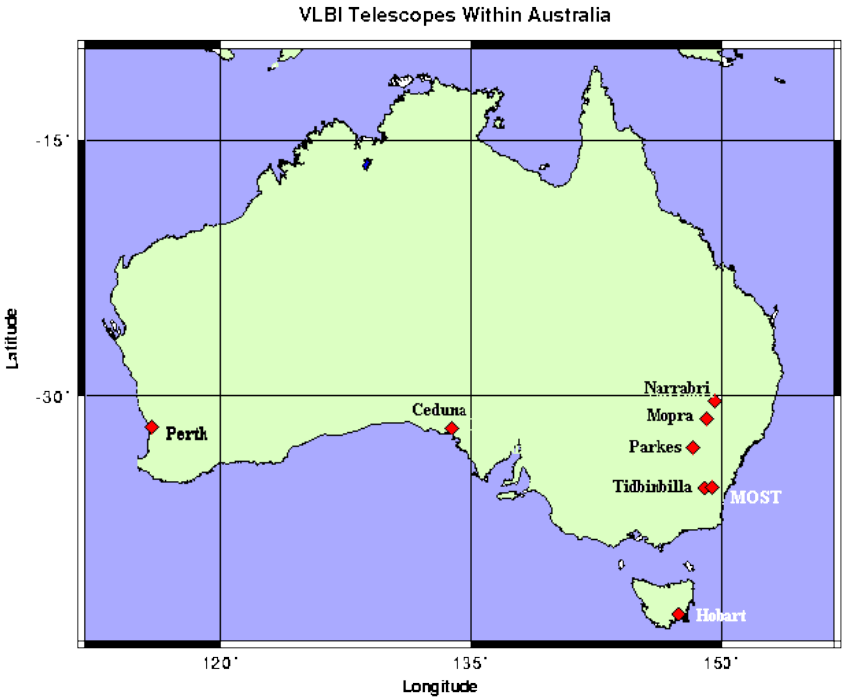


- Advantages:
  - high sensitivity
  - good u,v coverage
  - e-VLBI capability

www.evlbi.org

- Disadvantages:
  - heterogeneous set of antennas,
  - non-continuous operation (2 to 3 sessions/yr)
  - limited southern declination coverage

- **The Australian Long Baseline Array (LBA)**
- collection of 8+ different antennas
- 1.4 - 22 GHz
- maximum baseline ~3,000 km



- Advantages:
  - southern sky coverage

- Disadvantages:
  - heterogeneous set of antennas
  - non-continuous operation (four 1-week sessions/yr)
  - limited u,v coverage

www.atnf.csiro.au/vlbi

Global VLBI

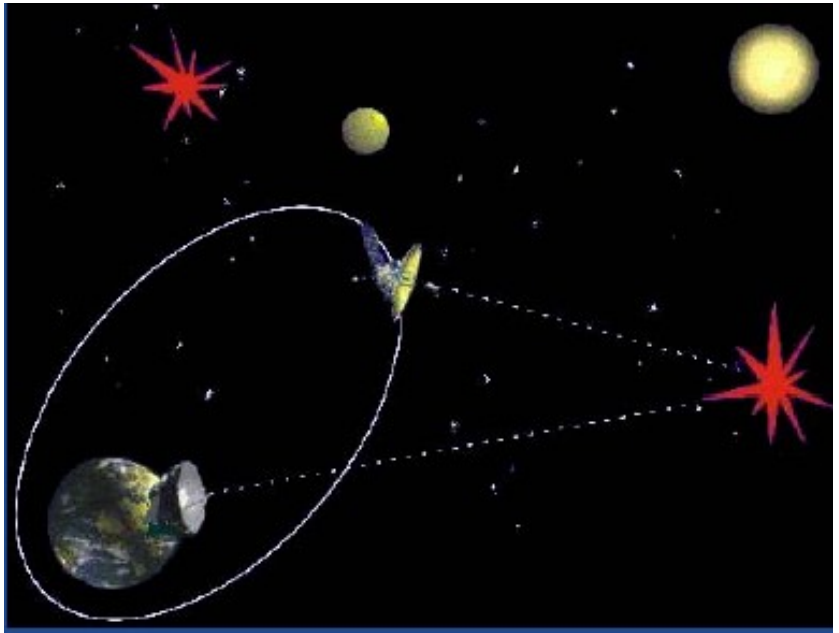
- Also possible to request larger 'joint' arrays that include large telescopes:
  - phased EVLA, GBT, Effelsberg, Arecibo
  - extremely high imaging sensitivity: a few microJy
  - limited available observing bands and times of year

Other (non-public) VLBI Arrays

- Japanese VLBI network (JVN)
- Korean VLBI network (KVN)
- International Geodetic VLBI Arrays
  - http://ivscc.gsfc.nasa.gov/stations/ns-map.html

RadioAstron

- Russian mission launched in July 2011
- Bands: 0.3 to 22 GHz
- Highest angular resolution: 10 μas



Parameters of the Orbit

Period (variable)	7 - 10 days.
Major semi-axis	189 000 km.
Initial inclination	51.6°.
The perigee variation [orbit evolution due to the Moon gravity]	From 10 000 to 70 000 km.

Summary

- VLBI is not fundamentally different than other radio interferometry, and offers the highest angular resolution of any telescope
  → time domain astronomy at its finest

- Explores interesting science associated with compact non-thermal emission, including masers, AGNs, supernovae, galactic center

- VLBI astrometry is a crucial component of cosmic distance ladder

Useful Resources

- NRAO guide to using the VLBA: https://science.nrao.edu/facilities/vlba/novice
- VLBA Status Summary : www.vlba.nrao.edu
- VLBA Summer School Proceedings (2005): PASP Conference series

MANY SLIDES WITH PRACTICAL DETAILS MOVED PAST "THE END"

THE END

Stages of a VLBI project

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2. Consider practical observational details:
   -- desired angular resolution, field of view, image sensitivity, observing frequencies, spectral resolution, polarization, temporal coverage
   -- select an appropriate telescope/array
3. Submit an observing proposal
4. Construct an observing schedule file
5. Download, reduce, and analyze the data
6. Publish your results
7. Book your ticket to Stockholm

Is my target source suitable for VLBI?

Q1: Is its SKY POSITION known to within ~ one arcsecond?

- check http://astrogeo.org/calib/search.html
- if not, can you observe it first with the EVLA or ATNF?

Q2: Can you estimate its brightness temperature (COMPACTNESS)?

-- see formulae on next slide

Q3: Is there a suitable VLBI array with sufficient SENSITIVITY?

- use the EVN sensitivity calculator

How compact does the source need to be?

$$T_b = 1.36\ \lambda_{\rm cm}^2\ \theta_{\rm arcsec}^{-2}\ S_{\rm mJy} \quad {\rm K}$$

But the half power beam width is

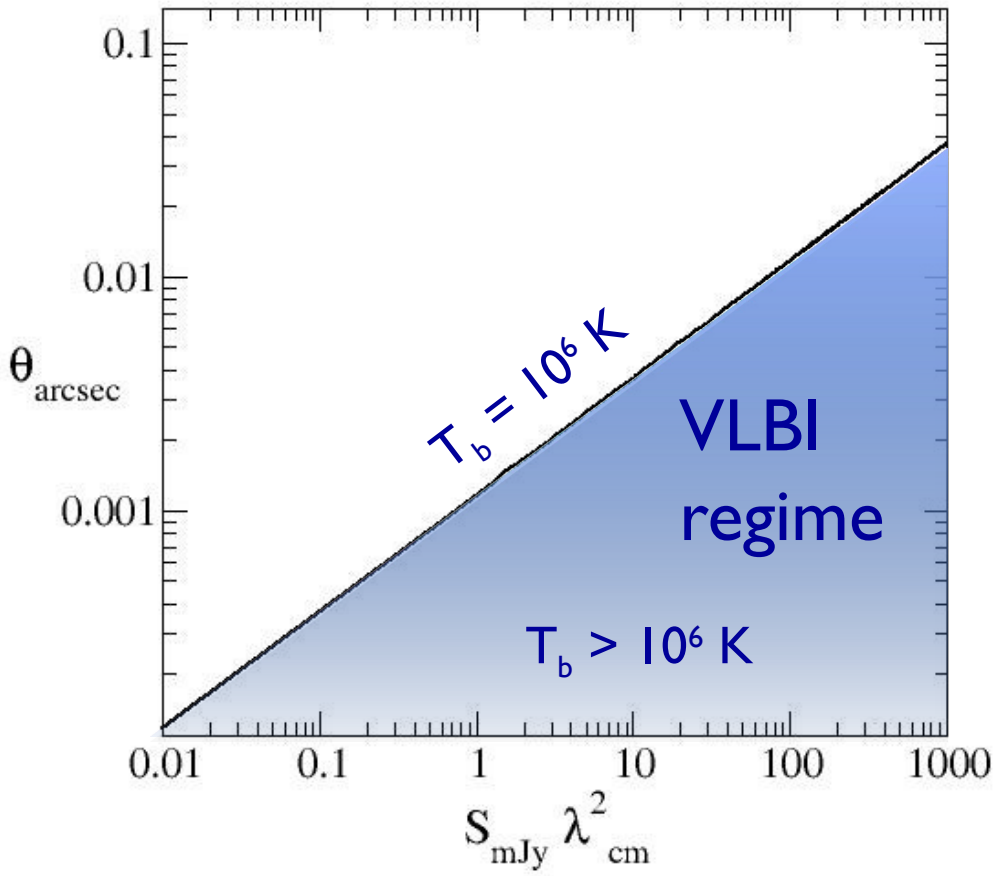
$$\theta_{\rm arcsec} = 2.063\ \frac{\lambda_{\rm cm}}{B_{\rm max,\,km}}$$

Thus,

$$T_b = 10^6 \left(\frac{S}{40\ \mu{\rm Jy}}\right)\left(\frac{B_{\rm max}}{8612\ {\rm km}}\right)^2 \quad {\rm K}$$

- High resolution comes with a price tag in terms of sensitivity:

  → **current VLBI needs a (non-thermal) source above ~10^6 K**



B_{max} for VLBA = 8612 km

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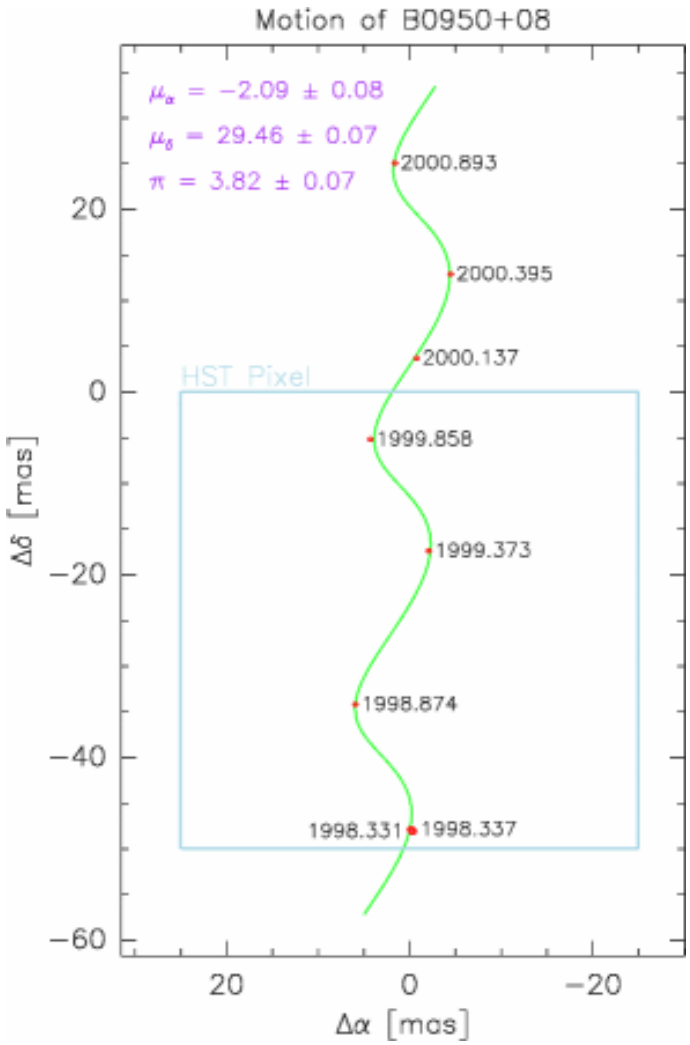
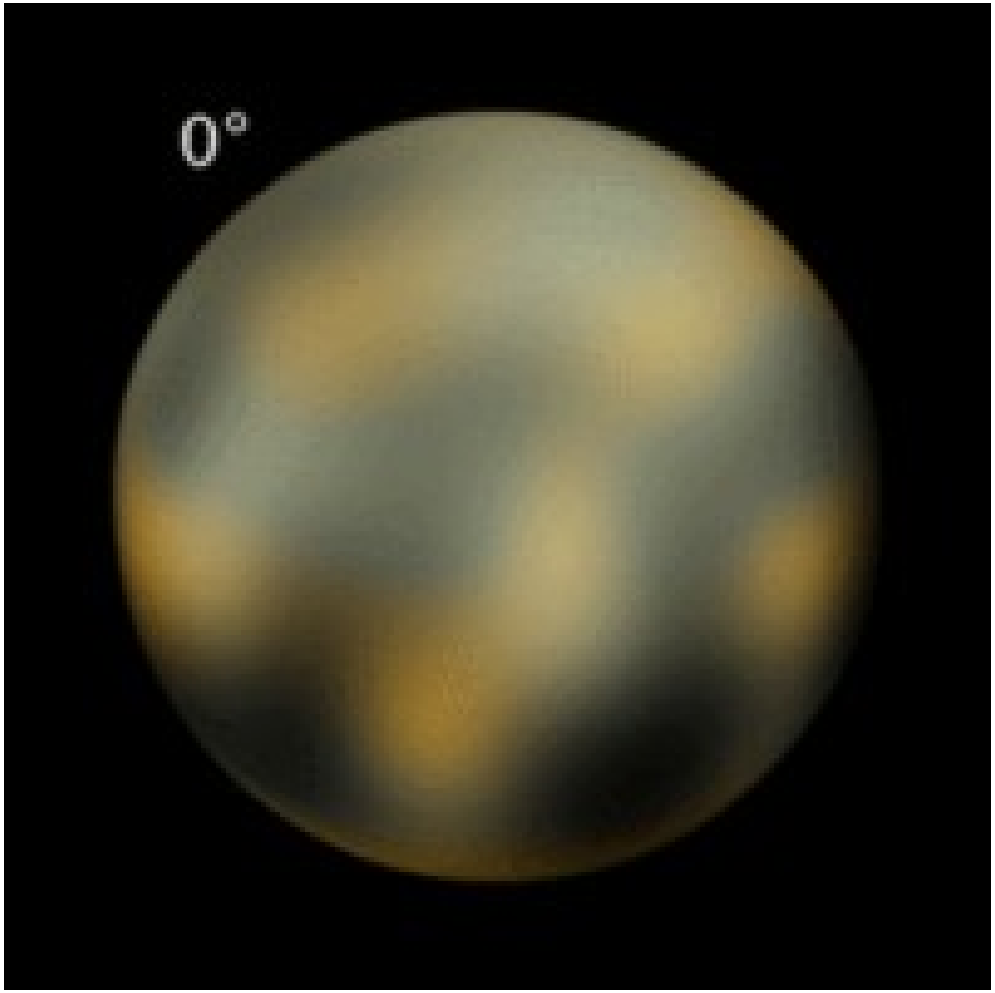


Pluto on same angular scale



mas-level pulsar parallax measurement (W. Brisken et al.)

VLBI field of view

- Much smaller (1/1000th) than primary antenna beam area, which is $\theta_{\rm arcmin} = 1.5 \lambda_{\rm cm} \left(\frac{D_{ant}}{25\ {\rm m}}\right)^{-1}$, where $D_{ant} = 25$ m for the VLBA
- VLBI F.o.V. is limited to much smaller sky area by time averaging of data:

$$\theta_{\rm max} \cong 2.2 \frac{\lambda_{\rm cm}}{\tau_{\rm avg,sec}} \left(\frac{B_{\rm max}}{8612\ {\rm km}}\right)^{-1} \quad {\rm arcsec}$$

- and by averaging over a frequency band
- and by averaging over a frequency band $\Delta\nu$:

$$\theta_{\rm max} \cong 0.8\, \theta_{\rm HPBW} \frac{\nu}{\Delta\nu}$$

- and is also limited by the curvature of the Earth:
- and is also limited by the curvature of the Earth:

$$\theta_{\rm max} \cong 2.3\ \lambda_{\rm cm}^{1/2} \left(\frac{B_{\rm max}}{8612\ {\rm km}}\right)^{-1/2} \quad {\rm arcsec}$$

VLBI field of view (minus the equations)

- In most cases the VLBI imaging field of view is limited to 1-2 arcseconds.

- At any rate, imaging the full VLBI field of view at full resolution is rather computationally demanding due to the very small restoring beam:

  at 3 pixels per beam → VLBI image could be > 50000 pixels across!

Why you shouldn't attempt a 50Kx50K image clean in CASA

VLBI field of view (continued)

- Don't forget that emission structures larger than

$$\theta \cong 8.7\,\lambda_{\mathrm{cm}} \left(\frac{B_{\mathrm{min}}}{237\ \mathrm{km}}\right)^{-1} \ \mathrm{mas}$$

are completely invisible to the array, even if they fit in the field of view

are completely invisible to the array, even if they fit in the field of view

	EVN	VLBA	Global	RadioAstron
$B_{\mathrm{min,km}}$	266	237	237	54 000

- What to do if you want to image a source(s) just outside the field of view?
- What to do if you want to image a source(s) just outside the field of view?
  - *VLBI correlators can now do multiple passes (i.e., produce images) at different phase reference centers within the primary beam. (Similar concept to multi-fiber spectroscopy).*

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VLBI baseline sensitivity

- To detect interference fringes on at least one baseline, source must be stronger than 3-5 times the baseline thermal noise:

$$\Delta I_m = \frac{1}{\eta_s}\frac{1}{\sqrt{2}}\sqrt{\frac{SEFD_1 SEFD_2}{\Delta\nu\,\tau}}$$

where η_s is typically ~ 0.5,

SEFD = system equivalent flux density of the antennas (typically a few hundred Jy)

$\Delta\nu$ = observing bandwidth in Hz (typically 32-100 MHz),

τ = fringe fit interval in sec. (typically ~ 1600 s at 1 GHz, to < 30 s above 43 GHz)

- At frequencies of a few GHz, ΔI_m is typically a few mJy for most VLBI arrays

http://www.evlbi.org/cgi-bin/EVNcalc

VLBI Phase Referencing

- **Technique**:
  - observe a strong calibrator near the target on the sky
  - solve for atmospheric and instrumental phase errors using calibrator
  - apply solutions to the target source

- **Advantages**:
  - allows for imaging of sources fainter than baseline sensitivity limit
  - preserves absolute sky position information (essential for astrometry)

- **Disdavantages:**
  - more overhead involved in calibrator observations, data processing
  - suitable nearby calibrator(s) not always available

Image sensitivity

- Same formula as a connected interferometer:

$$\Delta I_m = \frac{1}{\eta_s} \frac{SEFD}{\sqrt{N\,(N\,-1)\,\Delta\nu\,\tau_{int}}}$$

where η_s is typically ~ 0.5,

N = # of antennas (typically 10 to 20),

$\Delta\nu$ = observing bandwidth in Hz (typically 32-100 MHz),

τ_{int} = on source integration time in seconds (can be several hours),

SEFD = antenna system equiv. flux density (typically a few hundred Jy)

- For integration times of a few hours and ~100 MHz bandwidth, large VLBI arrays achieve image sensitivities of a few microJy per beam.

VLBI observing proposals

- VLBA: http://my.nrao.edu
  - deadlines: 1st of Feb, Aug
- EVN: http://www.evlbi.org/proposals/
  - deadlines: 1st of Feb, Jun, Oct
- LBA: http://www.atnf.csiro.au/observers/apply
  - deadlines: 15th of Jun, Dec
- Other arrays:
  - contact an experienced user about becoming a collaborator

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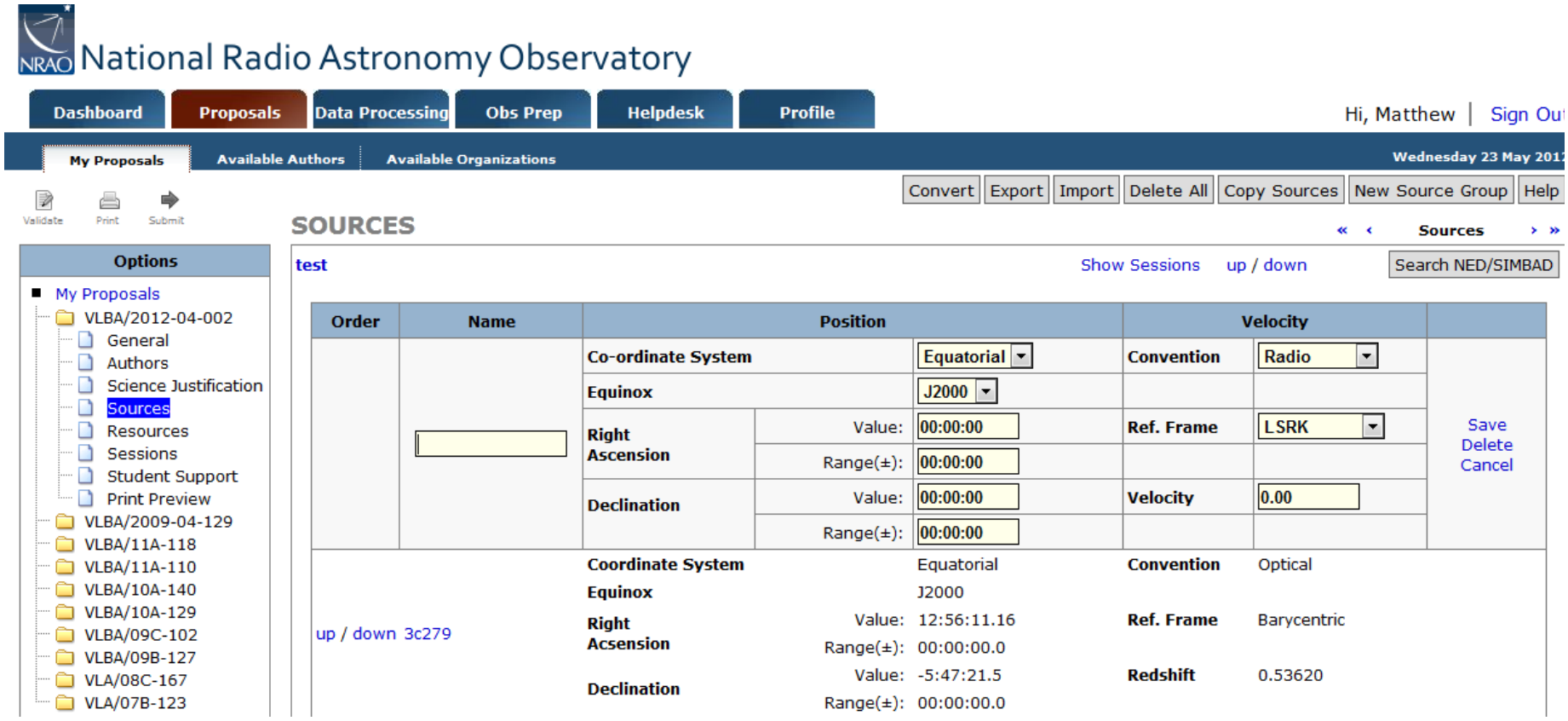
Preparing a VLBA proposal



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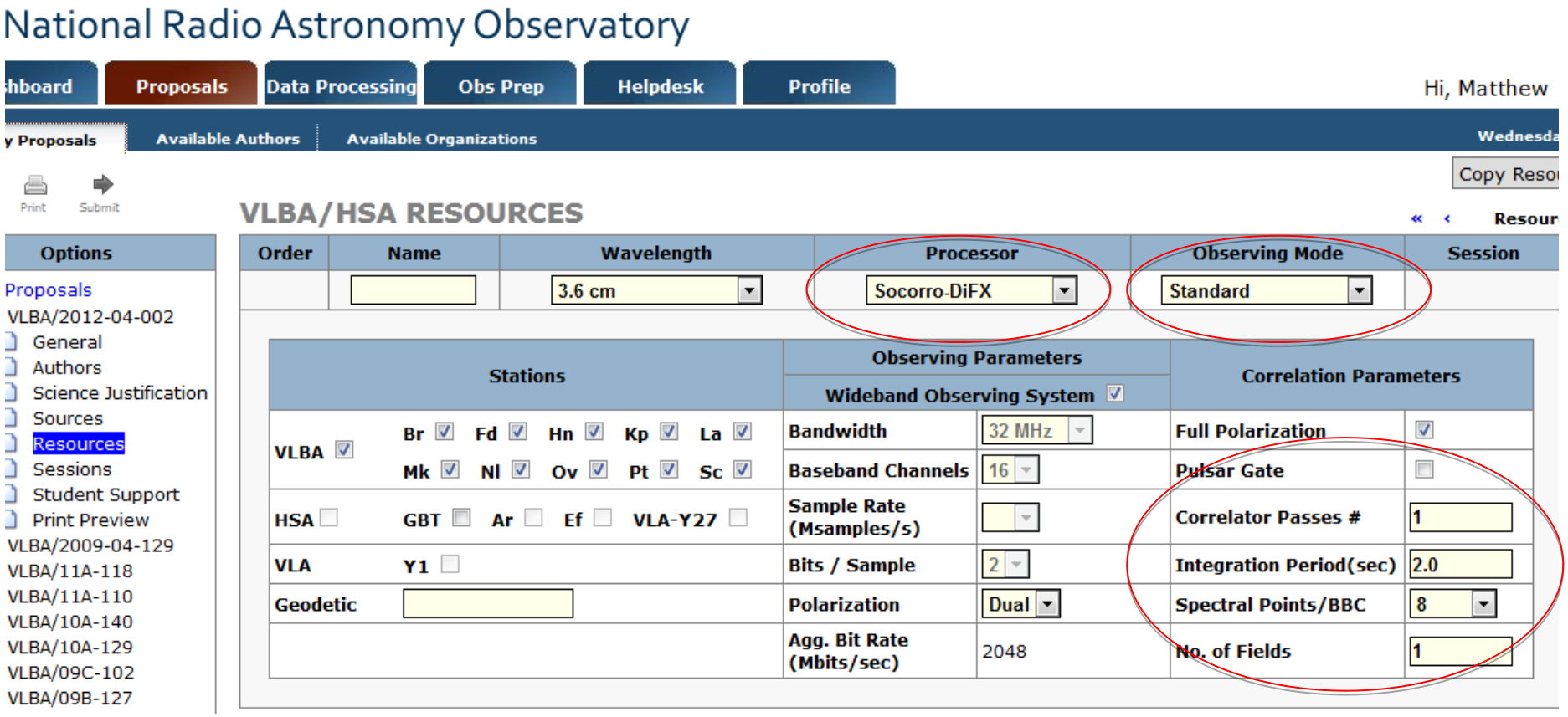

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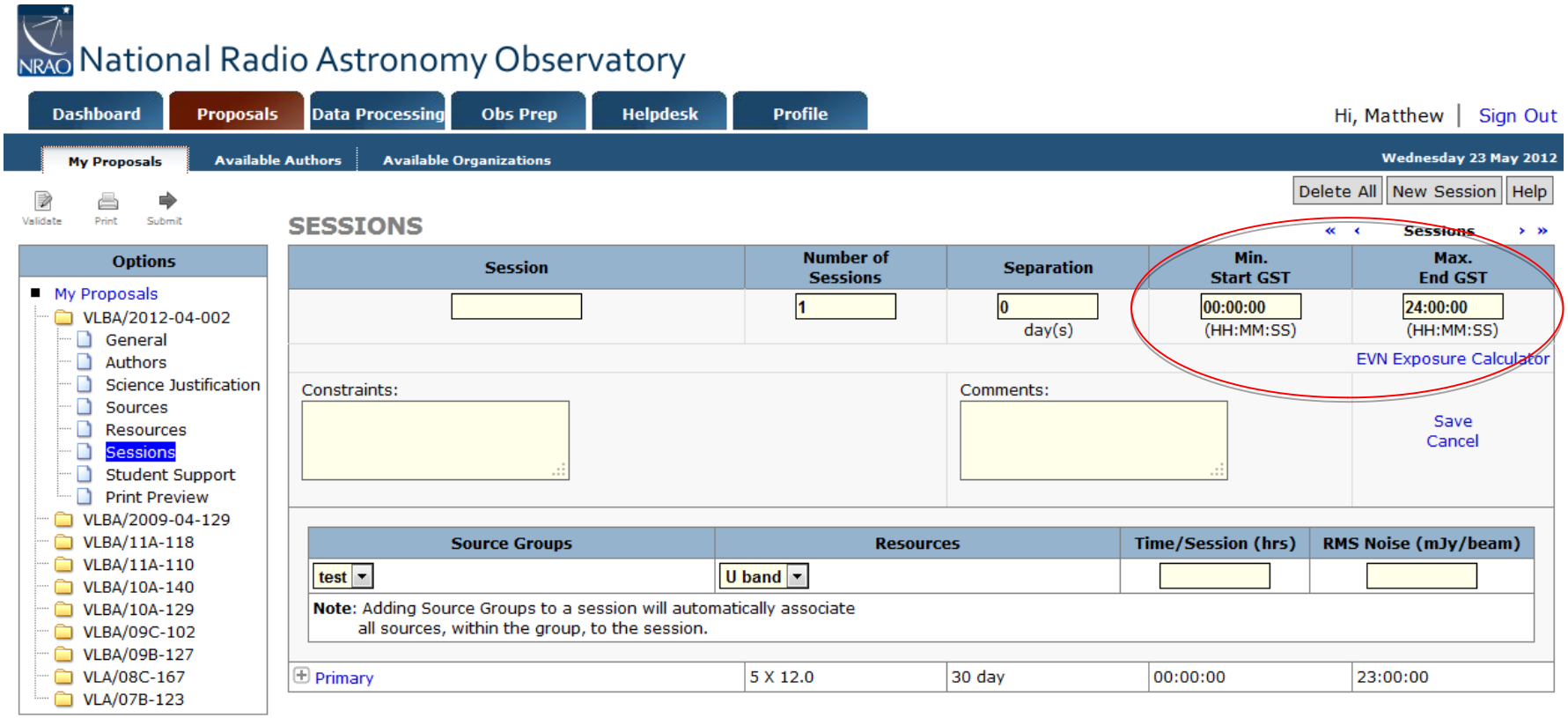

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VLBA telescope scheduling: SCHED

- For simple continuum projects, a VLBA telescope control file will consist of a 'setup' for each observing frequency band, and a scheduled list of scans.

- Craig Walker's linux-based SCHED program contains basic observing setups, source sky coordinate catalog, telescope locations, and factors in antenna slew times, frequency band change times, etc.

  www.aoc.nrao.edu/software/sched

- Beginner's approaches:
  - adapt a previous key file: www.vlba.nrao.edu/astro/VOBS/astronomy/
  - NRAO staff can provide assistance

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Obtaining and Reducing VLBA Data

- There is typically a ~3 week delay between observation and when your data are available due to shipping of disk drives and the correlator queue

- Correlated data are downloadable from archive.nrao.edu

- **End-to-end VLBA data processing is not yet implemented in CASA**
  - VLBA data processing still requires AIPS
  - VLBI chapter of AIPS Cookbook

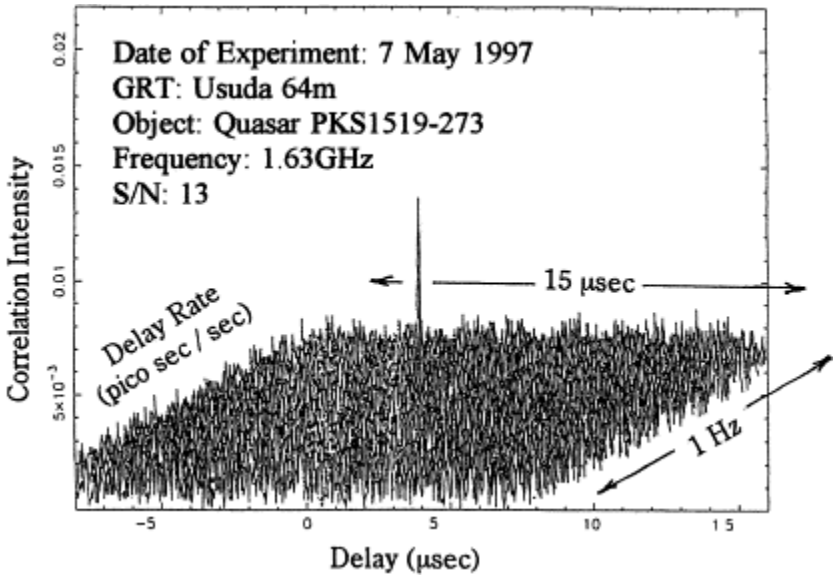
- Very useful tool for imaging and model fitting: DIFMAP:
  ftp://ftp.astro.caltech.edu/pub/difmap

Differences in VLBA and EVLA Reduction

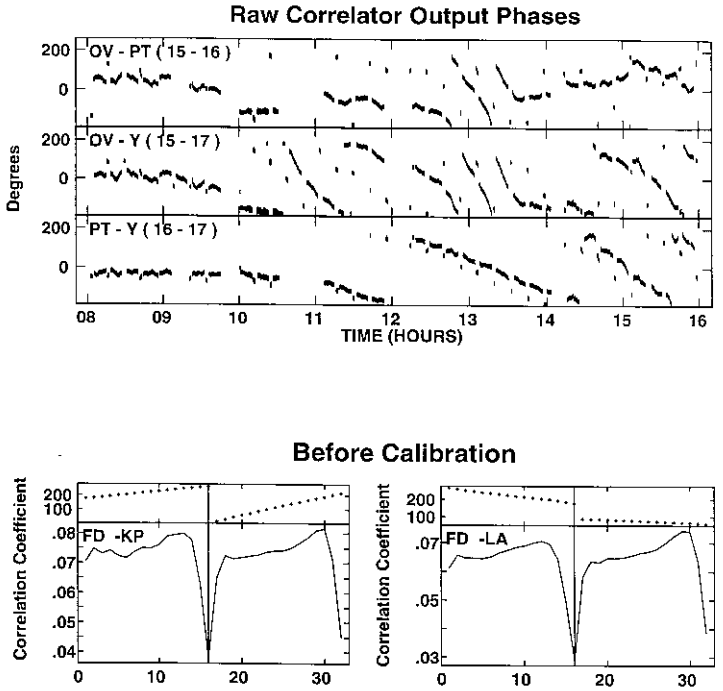
- Each VLBA antenna has slightly different:
  - atmospheric conditions
  - phase stability (atomic clock and electronics)

- Correlator model attempts to predict source and antenna locations, Earth orientation, but these are not precisely known to a fraction of λ.

- **Solution:** average in time and frequency band to boost S/N ratio and search for interference fringe in delay ($d\phi/d\nu$) vs delay rate ($d\phi/dt$) space
  - relatively trivial task for VLBA data on bright calibrators
  - VLBA provides instrumental phase-delay calibration 'tones' (not in spectral line mode though)
  - can apply fringe-fit solutions to fainter targets (phase referencing)



First ground-space fringe detection of a quasar made by the HALCA satellite.



(S. Doeleman)

Uncalibrated VLBA data showing phase drifts and uncorrected delays

Differences in VLBA and EVLA Reduction

- Very few true 'point' calibrators
  - can cause some difficulties with phase referencing & astrometry
  - polarization calibration can be difficult at some bands

- Often have much sparser (u,v) coverage
  - leads to larger imaging artifacts
  - but smaller field of view and typically compact source morphology leads to rapid clean model and self-calibration convergence

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6. Publish your results:
   -- NRAO funds 100% of page charges for U.S.A. –based authors!

VLBI Observing Bands

- Low frequency (< 1 GHz):
  - Pros: larger field of view, sources are brighter (esp. pulsars)
  - Cons: poor resolution, short spacing problems, ionospheric calibration, fewer calibrator sources, human radio frequency interference

- Mid-frequencies (1-15 GHz):
  - Pros: easiest to calibrate, best tradeoff between resolution and sensitivity
  - Cons: moderate resolution

- High frequency (22 – 86 GHz):
  - Pros: highest resolution, less source opacity
  - Cons: atmospheric stability/opacity, fewer antennas, poorer sensitivity, fewer calibration sources

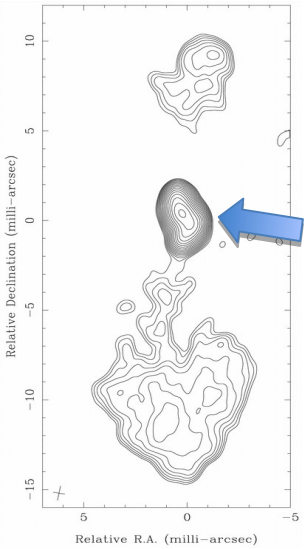
VLBI Polarimetry

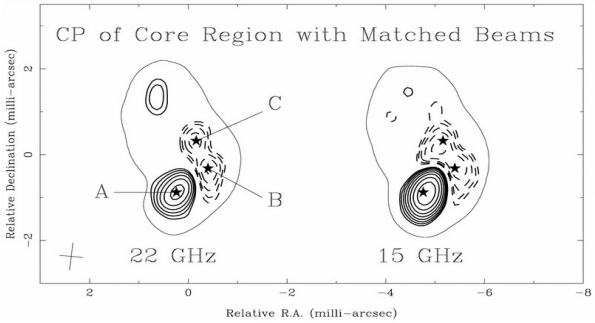
- Easiest when antennas in the array are identical (e.g., VLBA)
- Most arrays have circularly polarized feeds, which make them most suitable for measuring linear polarization. Circ. pol measurements are also possible.
- Standard VLBA observing mode is now to record full polarization data.

If you plan to make polarization images, you must also observe:

- 2 or 3 bright calibrators for determining antenna leakage terms:
  - pick ones that are unpolarized or have simple polarization structure
  - schedule several (> 6) scans over a wide range of parallactic angle.

- 1 or 2 linearly polarized calibrators that have a known absolute electric vector position angle on the sky.





Linear polarization evolution of the inner jet of AGN 3C 279 (Lister et al.)

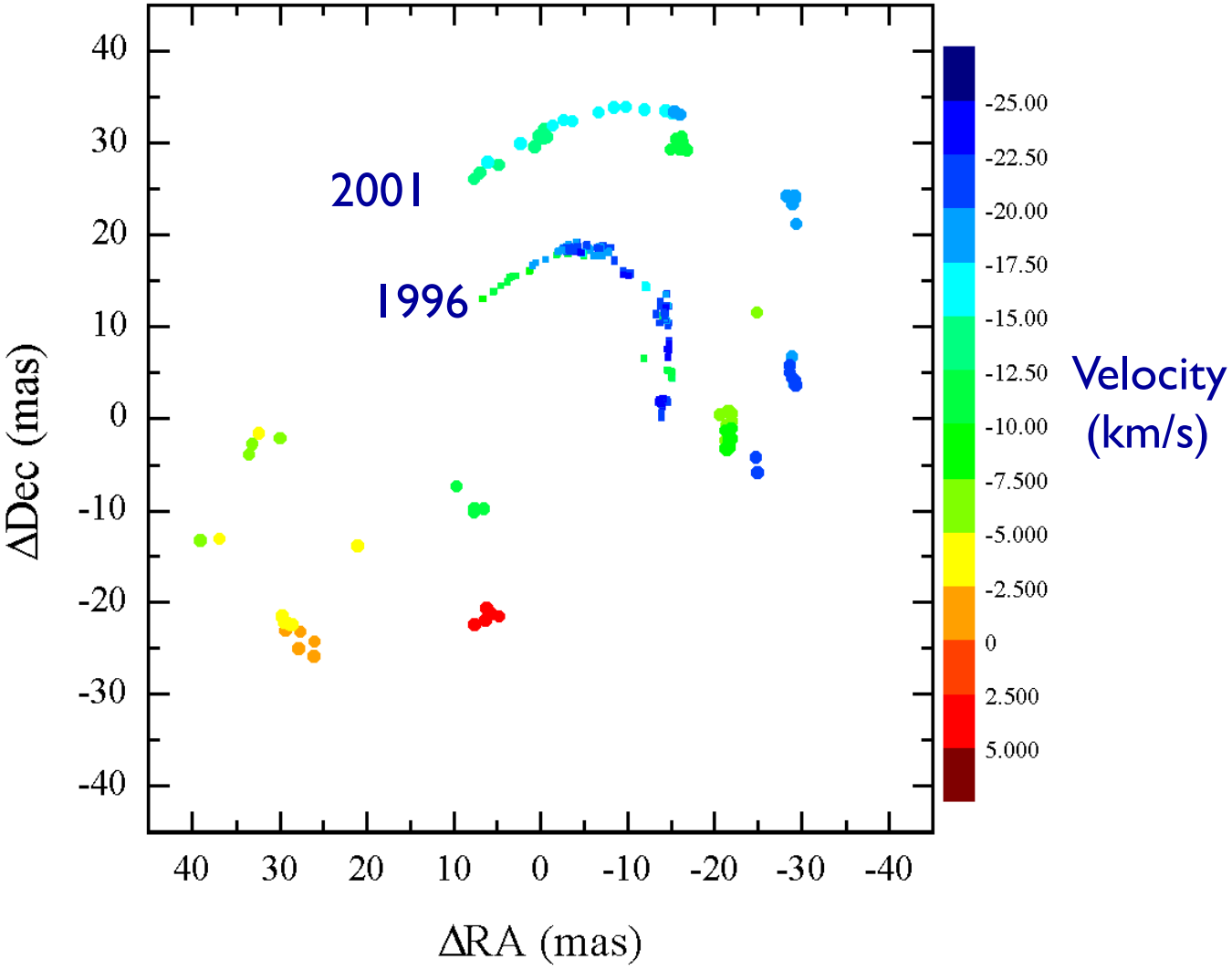
Circular polarization in the inner pc of the AGN 3C84 (Homan and Wardle 2004)

VLBI Spectroscopy

- Narrow line bandwidths mean the source must be incredibly compact (>10^8 K) for VLBI detection:
  - masers (galactic and extragalactic)
  - thermal absorption of a compact background source (AGN)

- Modern digital correlators are very flexible spectroscopically
  - able to 'zoom-in', and discard blank spectral regions

- Main concerns:
  - field of view: maser regions can be hundreds of square arcseconds
  - high sensitivity/recording rate required for narrow velocity resolution
  - need to observe a bright 'delay' calibrator nearby the target and a bright bandpass/fringe calibrator



- Expansion of water maser spots in Cept A HW 2 (Gallimore et al.)

VLBI Monitoring

- Angular resolution of VLBI is so high that most sources are seen to evolve on timescales << human lifetime

- But most VLBI arrays are not available all the time:
  - EVN: three 3-4 week long sessions/yr
  - GMVA: two 1-week long sessions/yr
  - LBA: four 1-week long sessions/yr

- The VLBA operates year-round and is thus best suited for long term multi-epoch projects.

Stages of a VLBI project

1. Formulate observational science question(s) you wish to investigate.
2. Consider practical observational details:
   -- desired angular resolution, field of view, image sensitivity, observing frequency, polarization, spectral resolution, temporal coverage
   -- select an appropriate telescope array
3. Submit an observing proposal
4. Construct an observing schedule file
5. Download, reduce, and analyze the data
6. Publish your results