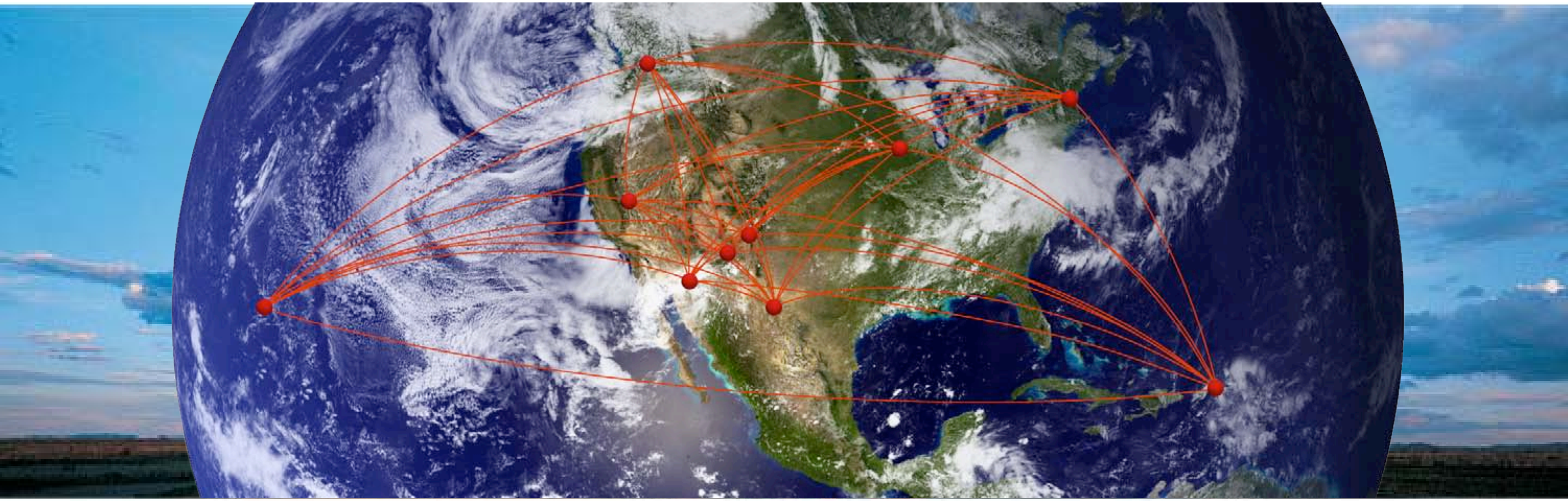
The Very Long Baseline Array

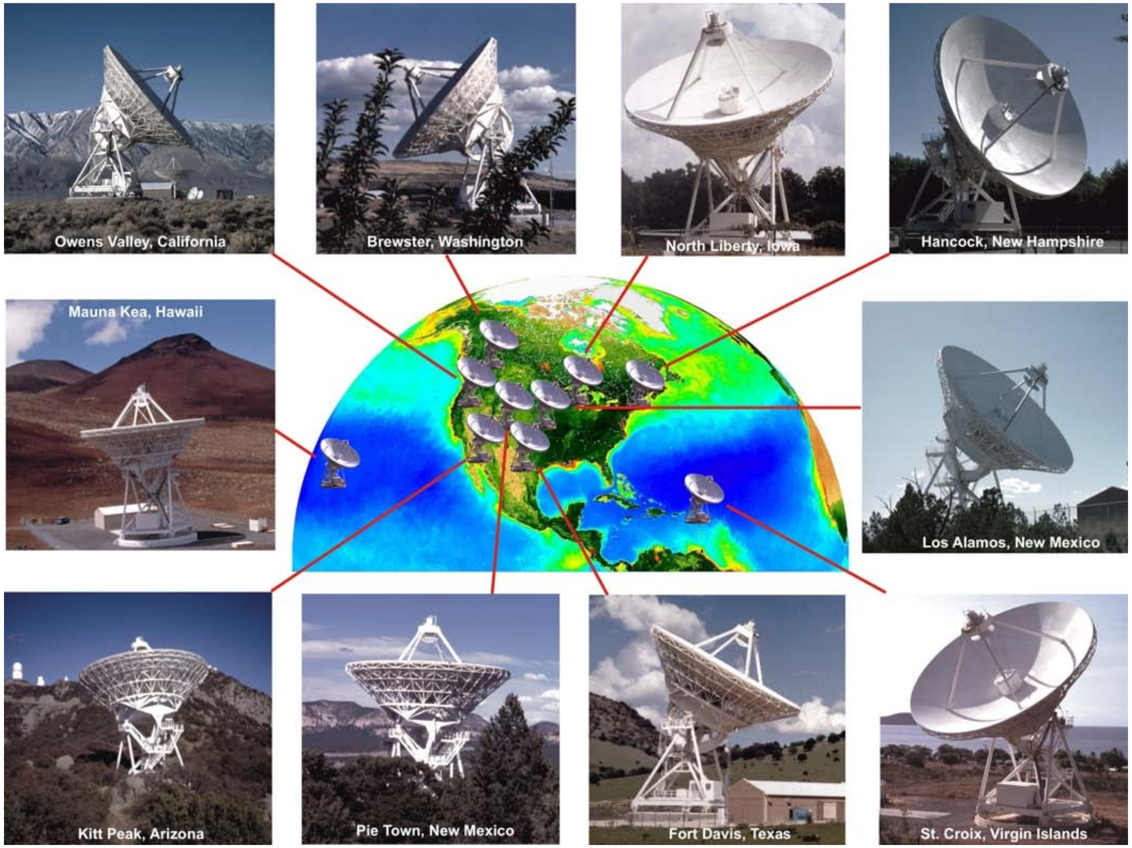


Amy Mioduszewski & Emmanuel Momjian (NRAO)

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

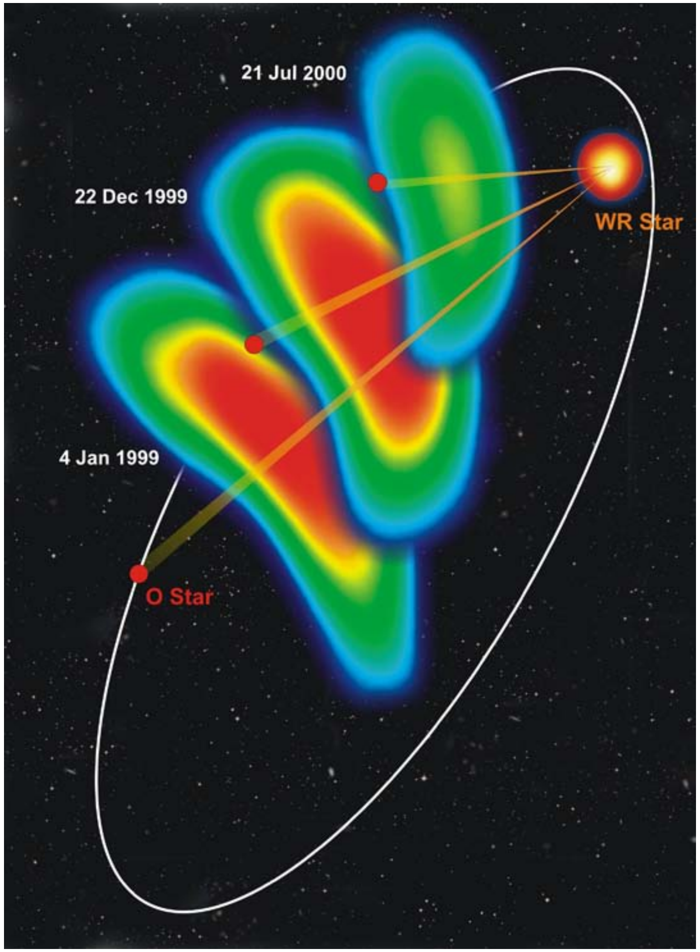
Basics

- 10 x 25 meter antennas.
- Spread from Mauna Kea, Hawaii to St. Croix, Virgin Islands.
- Baseline lengths range from 200 to 8600 km.
- Sensitive to compact structures with brightness temperatures above 10^5 K.
- Correlated on a software correaltor, DiFX.



What is the VLBA good for?

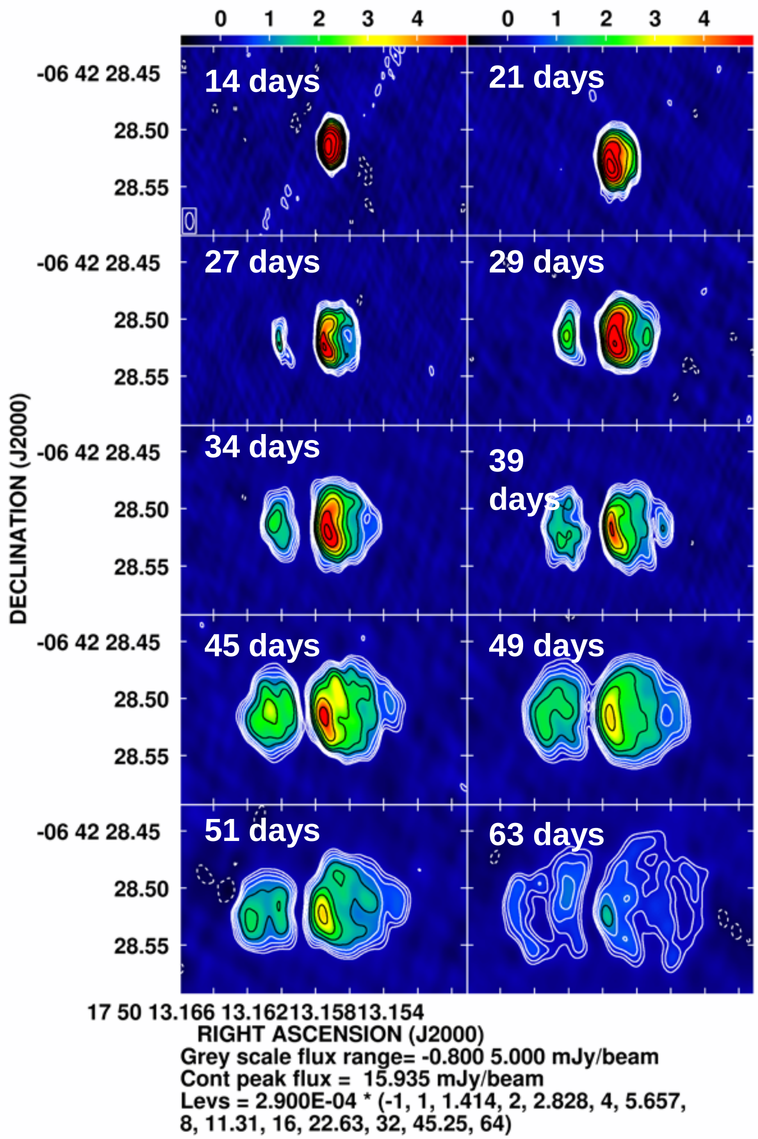
- Resolution
  - 0.08 to 25 mas
    - In the galaxy (100pc-10kpc): 1 mas resolution is 0.1-10 AUs (even less than a stellar radius for nearby stars)
    - For nearby extragalactic (1-1000Mpc): 1 mas resolution is 1000 AU-5pc
  - E.g., WR140, colliding wind region in Wolf-Rayet binary star system



Dougherty et al. 2005

What is the VLBA good for?

- Monitoring/fast response
  - Dedicated array
  - Targets of Opportunity
  - Watching objects evolve
    - E.g. 1.6 GHz observations of recurrent nova RS Oph.



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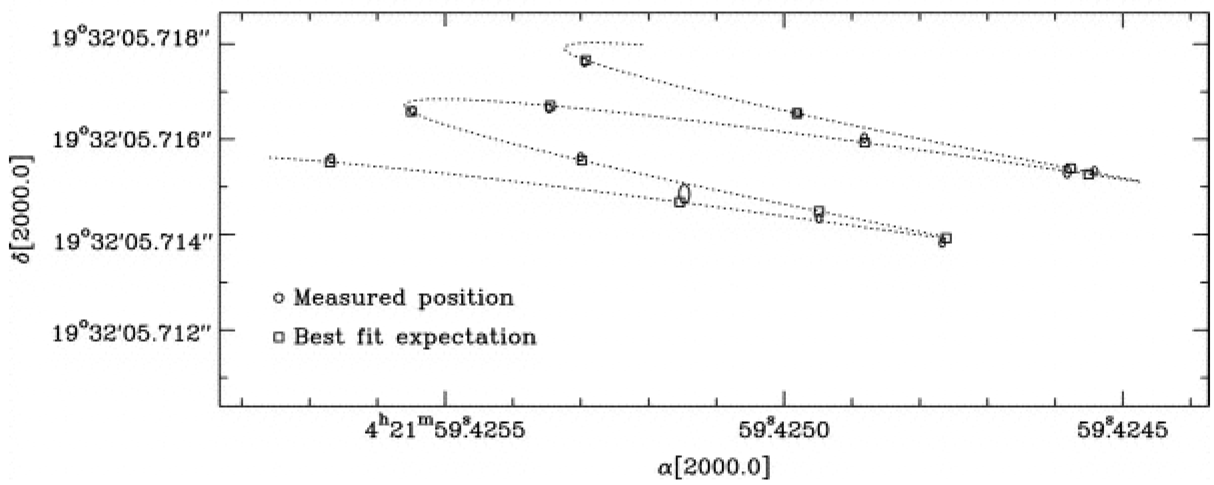
What is the VLBA good for (cont.)?

- Geodesy
  - Earth Rotation and Orientation, tectonic plate motions
- Astrometry
  - Fundamental reference frame
  - Parallax, proper motions… (e.g., TTauSb Loinard et al. 2007)



d = 147.6 ± 0.6 – 0.4% precision

Frequency bands and sensitivity

λ(cm)	ν(GHz)	σ(μJy/beam) in 4 hrs at 2Gbps
90 cm	0.312 - 0.342	277*
50 cm	0.596 - 0.626	782*
21 cm	1.35 - 1.75	13-14
13 cm	2.15 - 2.35	14
6 cm	4.6 - 5.1	13
6 cm (upgrade)	4.1 - 7.9	8
4 cm	8.0 - 8.8	13
2 cm	12.0 - 15.4	24
1 cm	21.7 - 24.1	18-22
7 mm	41.0 - 45.0	66
3 mm	80.0 - 90.0	316†

- Maximum bandwidth 256 MHz with two polarizations - available Feb 2012 proposal deadline
- More later about:
  - Sensitivity upgrade
  - C-band upgrade
  - Increasing sensitivity by adding more/larger telescopes to the array

* Narrower bandwidths

† 8 stations

High Sensitivity Array (HSA)

- Adding the Green Bank Telescope (GBT), Arecibo (AR), Effelsberg (EB) and/or the phased VLA (Y27, currently unavailable) with the VLBA can increase the sensitivity by an order of magnitude
  - The VLBA + any two of these telescopes is considered an HSA experiment
- All these telescopes have a smaller field of view than the VLBA and may not have all the frequencies available at the VLBA.
- Can be proposed for in the normal NRAO proposal cycle
- Y27 under development and can be proposed for in the 2012 August 1 deadline.

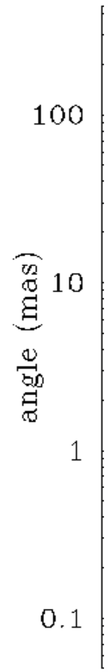


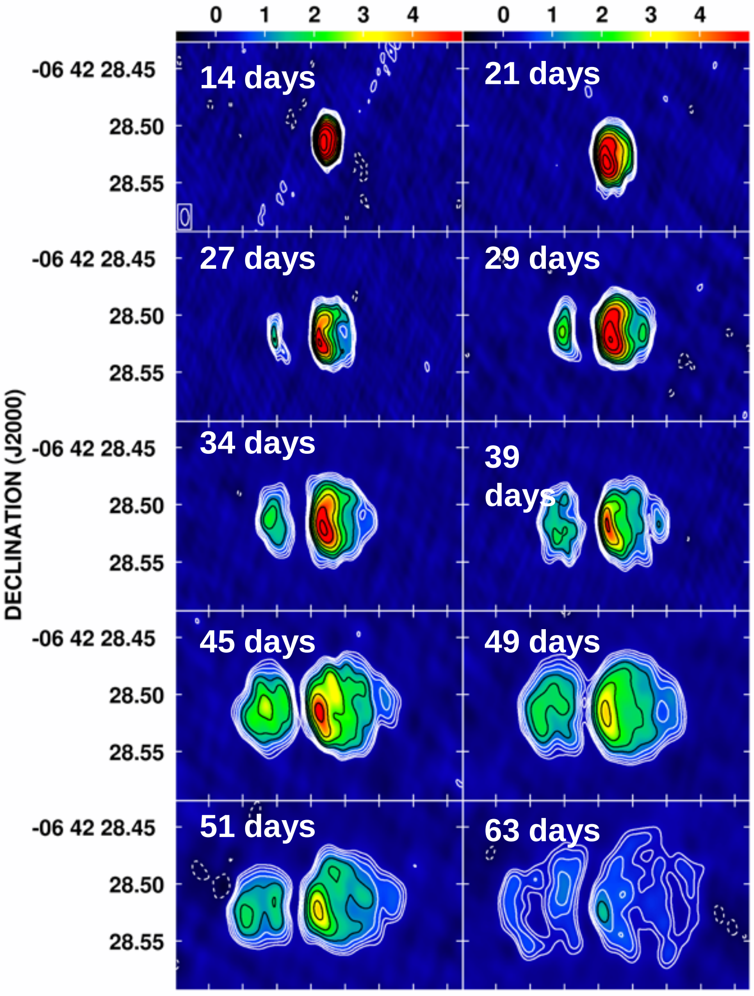

Global VLBI

- Add telescopes from the European VLBI Network (EVN) to the VLBA.
- The EVN has many large sensitive telescopes adding them increases the sensitivity as well as improving *uv* coverage (e.g. EVN has many more short baselines so can be more sensitive to larger structures)
- Proposed for through the EVN Northstar system. Deadlines are Feb 1, June 1 and Oct 1.

Resolution and Largest

- Depending on frequency the resolution of the VLBA is anything from 0.08 to 25 mas
- The largest angular scale determines the largest structure the telescope is sensitive to.
  - E.g. 1.6 GHz observations of recurrent nova RS Oph. At 63 days remnant is starting to be over resolved.





Sensitivity Upgrade

- There are many parts to the sensitivity upgrade, some have already been implemented:
  - DiFX correlator: allows several new capabilities (more later)
  - Wider bandwidths: for a total of 256 MHz, dual polarization. This gives a total bit rate of 2 Gbps, and enables twice the sensitivity of the current VLBA. Available the 2012 Feb 1 proposal deadline.
- Some in the process of being implemented:
  - C-band upgrade: replace the VLBA's 6 cm receivers
    - To expand the tuning range to 4.1 - 7.9 GHz. Which will enable observations of the 6.7 GHz transition of methanol.
    - To increase sensitivity, noise will go down by ~35%
    - Expected to be completed mid-2012

DiFX Correlator Capabilities I: Spectral Resolution

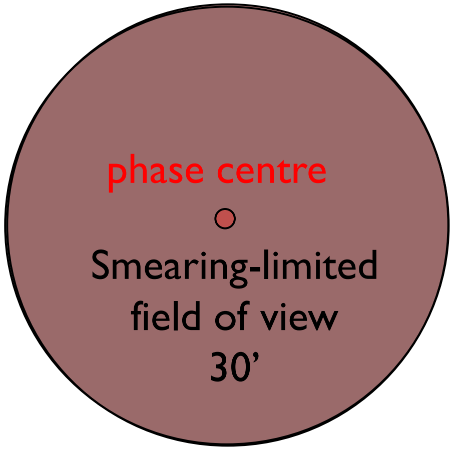
- DiFX is a software correlator in Socorro, NM
- Supports up to 4096 channels per sub-band routinely
- Up to 32,768 channels if required and adequately justified
- Spectral zooming – can do higher spectral resolution in one or more sub-bands. Useful for:
  - Masers with in-beam continuum calibrators: wide bands used for maximum sensitivity on calibrator while at the same time high spectral resolution on maser lines.
  - Masers with multiple transitions: wide bands are used to cover a large number of widely separated maser transitions, spectral zooming allows the empty portions of high-resolution spectrum to be discarded

DiFX Correlator Capabilities II: Wide Field Imaging

- DiFX enables wild field imaging due to high spectral and time resolution.
- This ability has been widely used since the introduction of DiFX
- However, full-beam VLBA imaging is still a logistical impracticality,

<u>12hr VLBA dataset: 30,000 GB!</u>

primary beam: 30'



Time resolution:
20 ms

Freq. resolution:
4 kHz

Calculations for 1.6 GHz, total smearing = 10%

DiFX Correlator Capabilities III: Multi-Field Imaging

- The sky is almost entirely empty at VLBI resolution
  - "full beam" imaging not needed; rather, many small "fields" (phase centers)
- In previous correlators, multiple fields required multiple correlator passes (usually at same or twice the rate of observation time)
  - Impractical for more than a few fields.

DiFX Correlator Capabilities III: Multi-Field Imaging

- Using *uv* shifts inside the correlator
  - DiFX allows many phase centers in one correlator pass
  - The overhead is ~2.5 and is only weakly dependent on the number of phase centers
- For reasonable spectral and time resolution requirements, **200 phase centers require only 20% more correlator time than 2 phase centers**.

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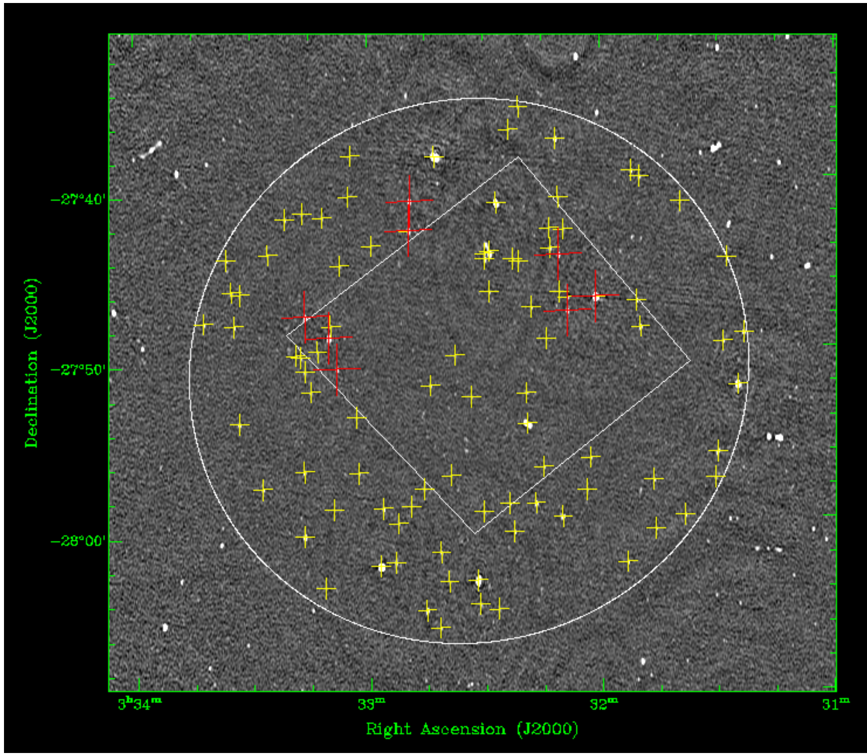
DiFX Correlator Capabilities III: Multi-Field Imaging

- This enables new science:
  - mJy-sensitivity secondary calibrator searches within a beam
  - Efficient VLBI surveys of mJy and sub-mJy objects are feasible. E.g. Middelberg et al. (2011) already published VLBA results on Chandra Deep Field South



From Middelberg et al., 2011

Observing Strategies

- Amplitude calibration done with system temperature and gain curve, no amplitude calibrator is needed
- Three kinds of calibrators are needed (they can be the same source):
  - Delay calibrator (fringe finder) – few minutes on a strong source
  - Bandpass calibrator – on a strong source
  - Phase calibrator – nearby source
    - If target is strong then occasionally observe as a check source
    - If target is weak *and/or* absolute positions are needed then observe often to set phases

Phase referencing

- Observe a phase calibrator every ~30s to few minutes depending on observing frequency.
- Very powerful tool for both weak targets and targets for which position is important

→ **overhead 30-50%, maybe more**

Phase referencing

- Need a nearby source that is strong enough to determine the phase
  - Distance depends on frequency and weather
    - < 1° is golden, aim for < 3°
    - Should be closer for higher frequencies
  - Strength depends on your array and frequency of observation. For wide bandwidth and middle frequencies (1.4-22GHz)
    - for VLBA only >50mJy is safe
    - with more sensitive antennas (e.g., GBT, AR…) >10mJy is required
- Used for Astrometry with some extra calibration (next slide)

Astrometry

- Main problem in astrometry is the difference in the atmosphere between the target and the calibrator
  - ideal situation is if you have a very close (<0.5 $^{\circ}$ or even better in-beam) calibrator and hopefully a high dec target
- If not, then to increase the precision of position measurement extra calibration steps have to be taken (these methods are complimentary)
  - Geodetic type blocks: in these observe 20ish strong calibrators scattered across the sky with widely spaced subbands to fit the atmospheric zenith delay
    - Rule of thumb is 30 minute blocks every ~3 hours
  - Fit local delay wedge: observe ~3 calibrators around your target and fit a phase slope.
    - Rule of thumb is ~4 minutes every ~30 min

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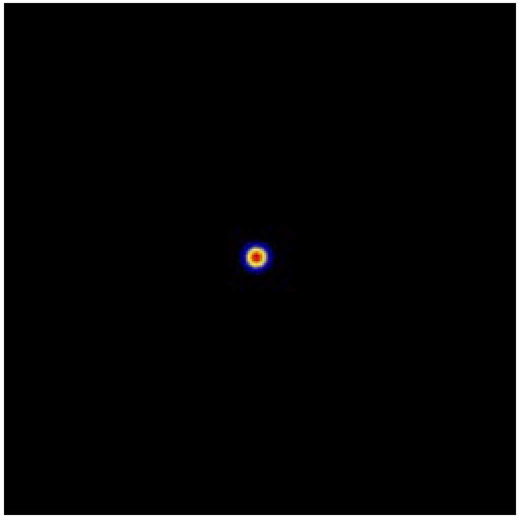
Important Links

- VLBA Observational Status Summary
  http://www.vlba.nrao.edu/astro/obstatus/current/
- EVN Sensitivity Calculator
  http://www.evlbi.org/cgi-bin/EVNcalc
- HSA pages
  https://science.nrao.edu/facilities/vlba/proposing/HSA
- Proposal Submission Tool
  my.nrao.edu
- SCHED – observation preparation software
  http://www.aoc.nrao.edu/software/sched/index.html
- AIPS – data reduction software
  http://www.aips.nrao.edu/index.shtml

SN1993J in M81



10 mas

36,000 AU

Bartel et al. 2000