

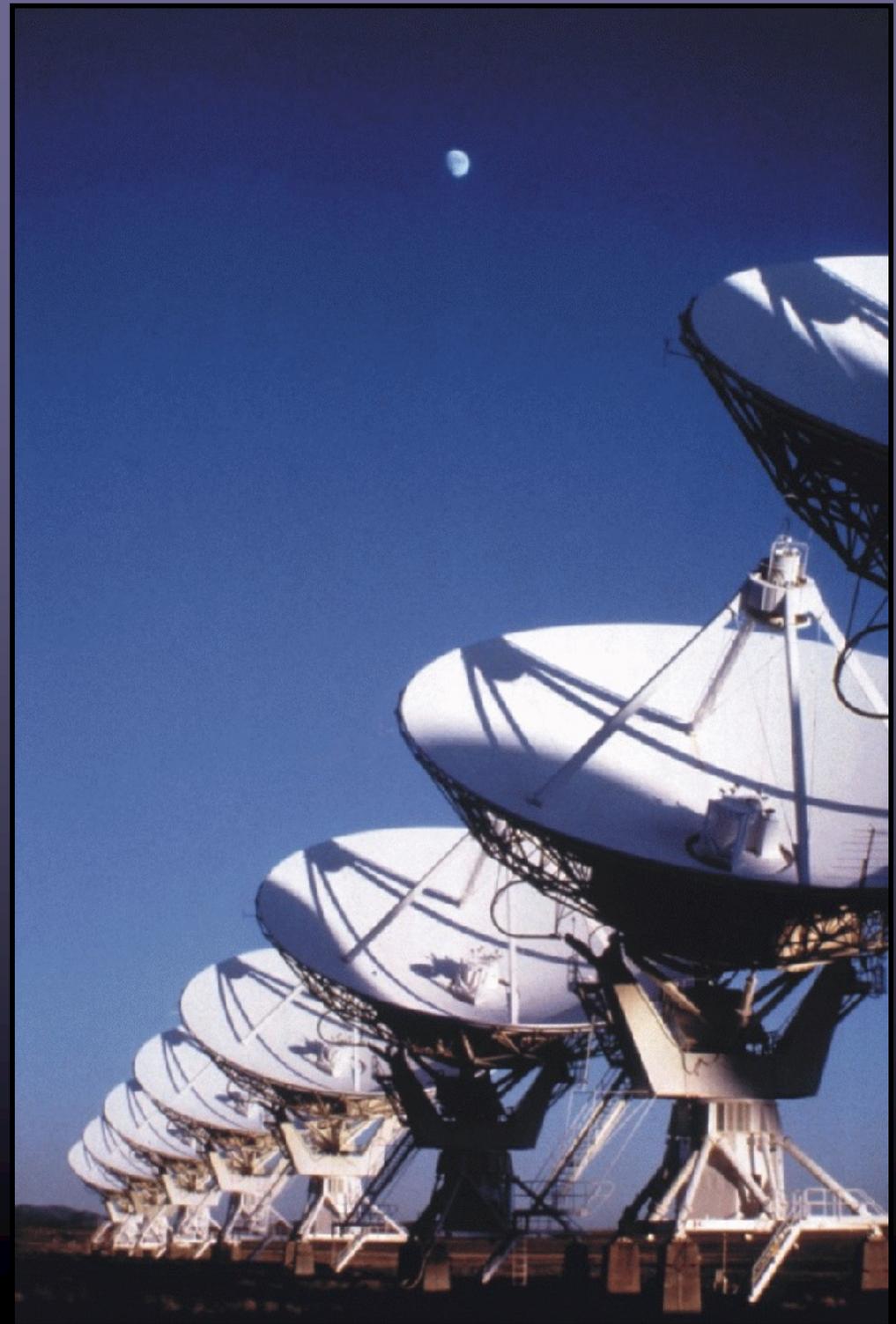
Very Long Baseline Interferometry

Greg Taylor

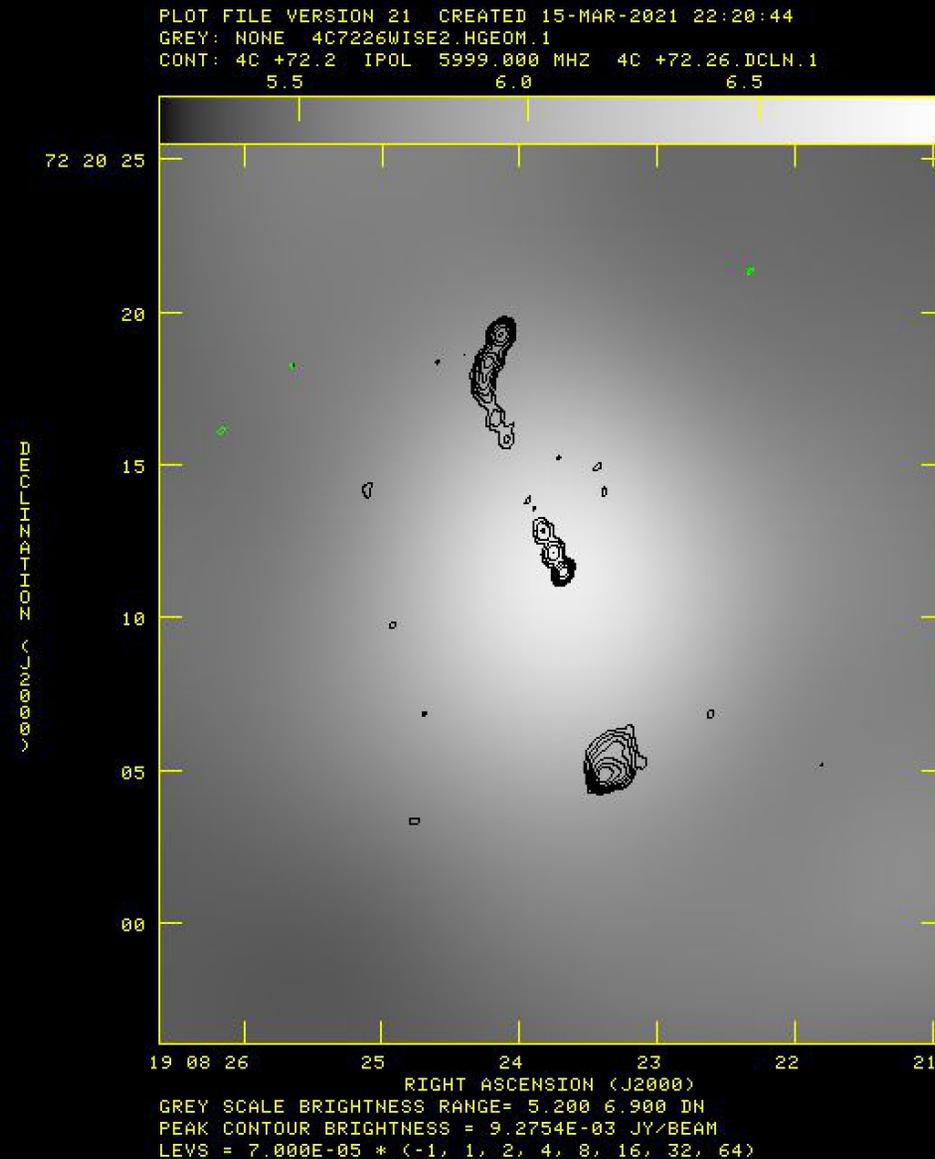
University of New Mexico

Astronomy 423 at UNM

Radio Astronomy



Homework 7 Solution



Peak: 9.3 mJy
 Noise
 21 microJy/beam

Contours start
 70 microJy/beam
 Go up by sqrt(2)
 WISE in greyscale

Announcements

- HW8 is due on Wednesday, April 9
- Project outline is due Monday, April 14
- HW9 pushed back to Monday, April 21
 - Note this involves reducing LWA observations of a pulsar scheduled for April 8
 - We will make use of the LWA cluster (lwaucf3)



Outline

- What VLBI is
- Some examples of VLBI applications
- Geodesy and Astrometry
- Differences between VLBI and connected elements
- The Very Long Baseline Array (VLBA)
- VLBA talk on Thursday by Lucas Hunt (NRAO)

*This lecture is complementary to
Chapters 22 and 23 of ASP 180 and is
based on a lecture by Craig Walker*



WHAT IS VLBI?

- Radio interferometry with unlimited baselines
 - High resolution – milliarcsecond (mas) or better
 - Baselines up to an Earth diameter for ground based VLBI
 - Can extend to space (HALCA, RadioAstron)
 - Sources must have high brightness temperature
- Traditionally uses no LO link between antennas
 - Data recorded on tape or disk then shipped to correlator
 - Atomic clocks for time and frequency– usually hydrogen masers
 - Correlation occurs days to years after observing
 - Real time over fiber is an area of active development
- Can use antennas built for other reasons
- Not fundamentally different from linked interferometry



Mark5 recorder



Maser



Mark 5 disk pack



THE QUEST FOR RESOLUTION

Resolution = Observing wavelength / Telescope diameter

Angular Resolution	Optical (5000Å)		Radio (4cm)	
	Diameter	Instrument	Diameter	Instrument
1'	2mm	Eye	140m	GBT+
1"	10cm	Amateur Telescope	8km	VLA-B
0."05	2m	HST	160km	MERLIN
0."001	100m	Interferometer	8200km	VLBI

Atmosphere gives 1" limit without corrections which are easiest in radio

Jupiter and Io as seen from Earth

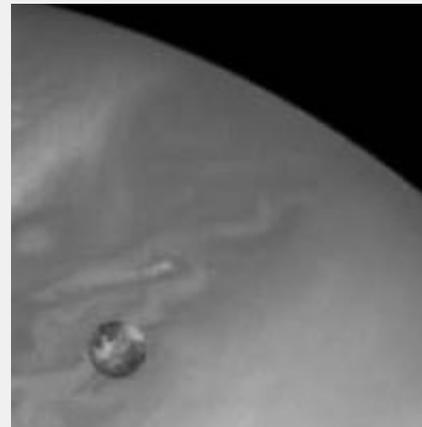
1 arcmin



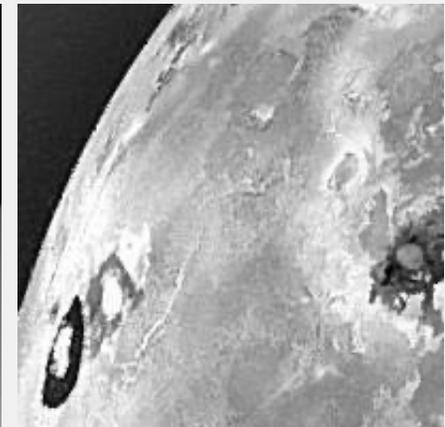
1 arcsec



0.05 arcsec



0.001 arcsec



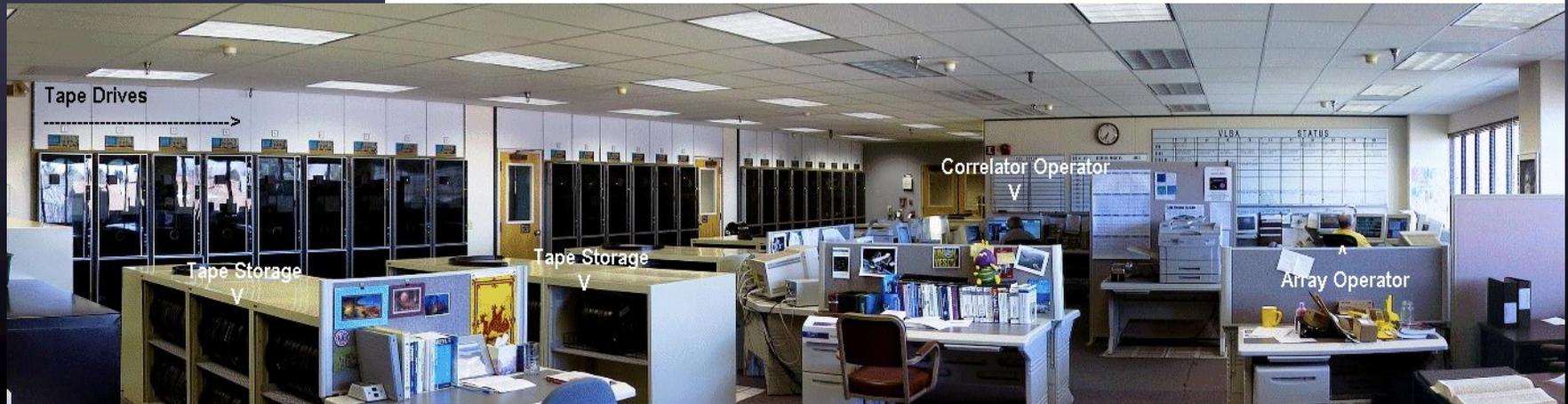
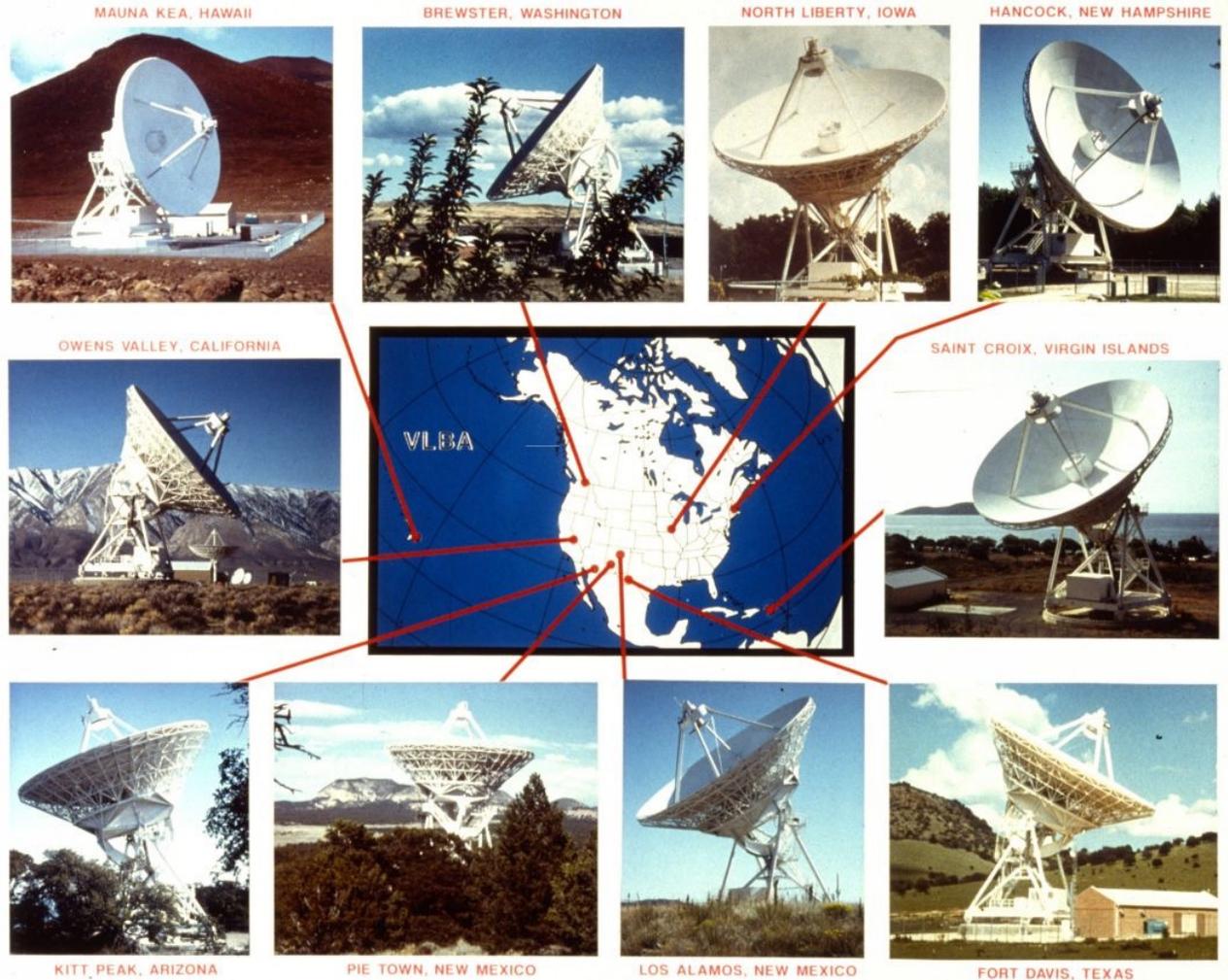
Simulated with Galileo photo

The VLBA

Ten 25m Antennas,
20 Station Correlator
327 MHz - 86 GHz

National Radio
Astronomy Observatory

A Facility of the
National Science
Foundation

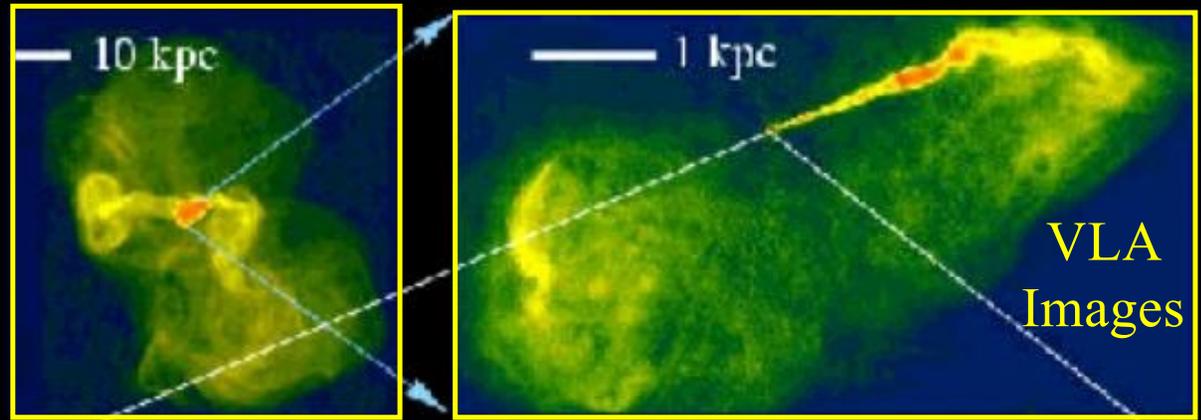
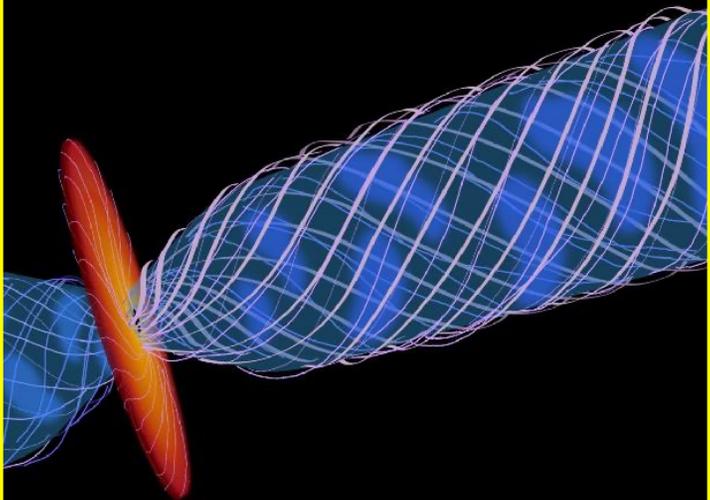


EXAMPLE 1 JET FORMATION: BASE OF M87 JET

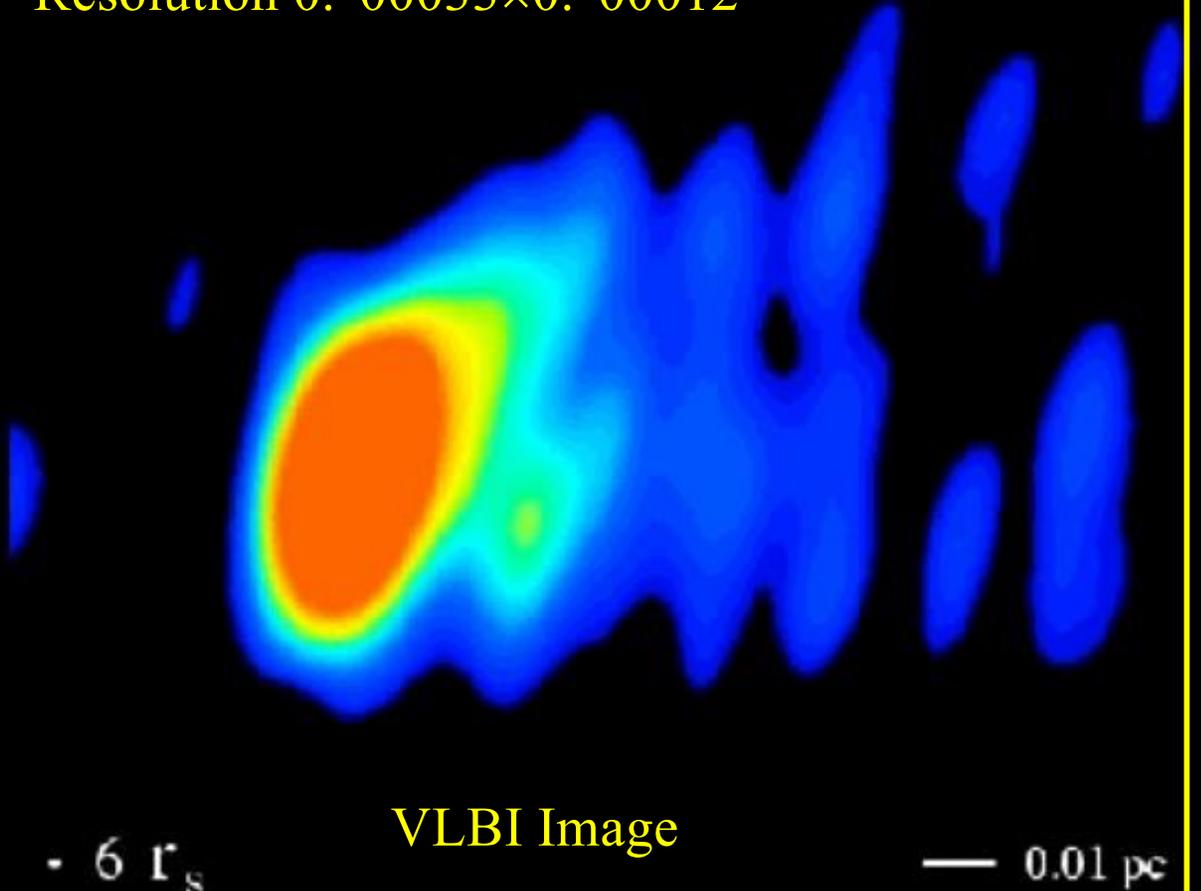
43 GHz Global VLBI
Junor, Biretta, & Livio
Nature, 401, 891

Shows hints of jet
collimation region

Black Hole / Jet Model



Resolution $0.''00033 \times 0.''00012$



Size of the Milky Way (100.000 ly)



10 arcsec
|-----|
(3.000 ly)

VLA 1.5 GHz

0,001 arcsec
|-----|
(0,3 ly)

VLBA 43 GHz

0,00001 arcsec
|-----|
(0,003 ly)

EHT 230 GHz

100 arcsec



(30.000 ly)

LOFAR 0.05 GHz

EXAMPLE 2

motion - modern example: M87



M87 INNER JET

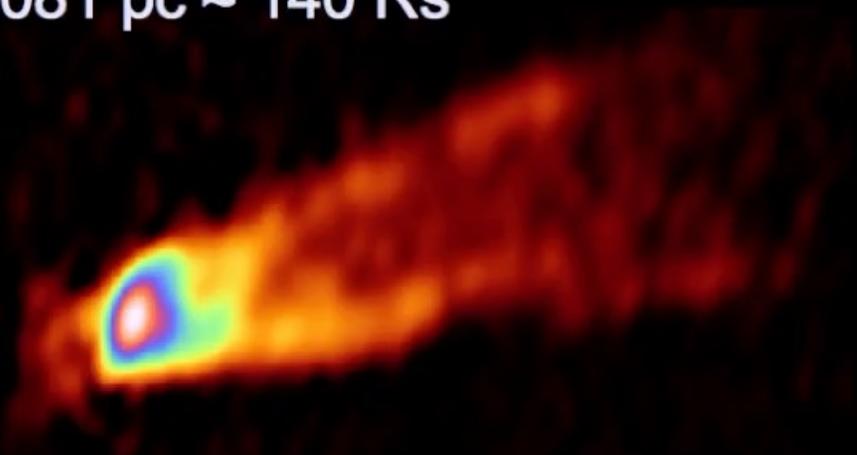
2007: Interval three weeks

VLBA at 43 GHz

Resolution 0.21×0.43 mas

Scale: 1 mas = 0.081 pc \approx 140 Rs

Walker, Hardee, Davies,
Ly, & Junor Ap. J. 2018

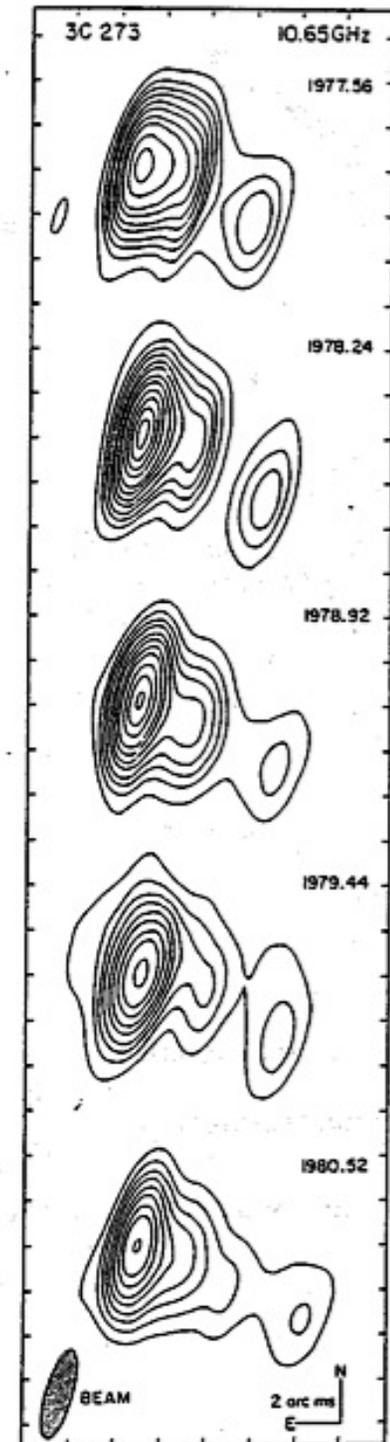


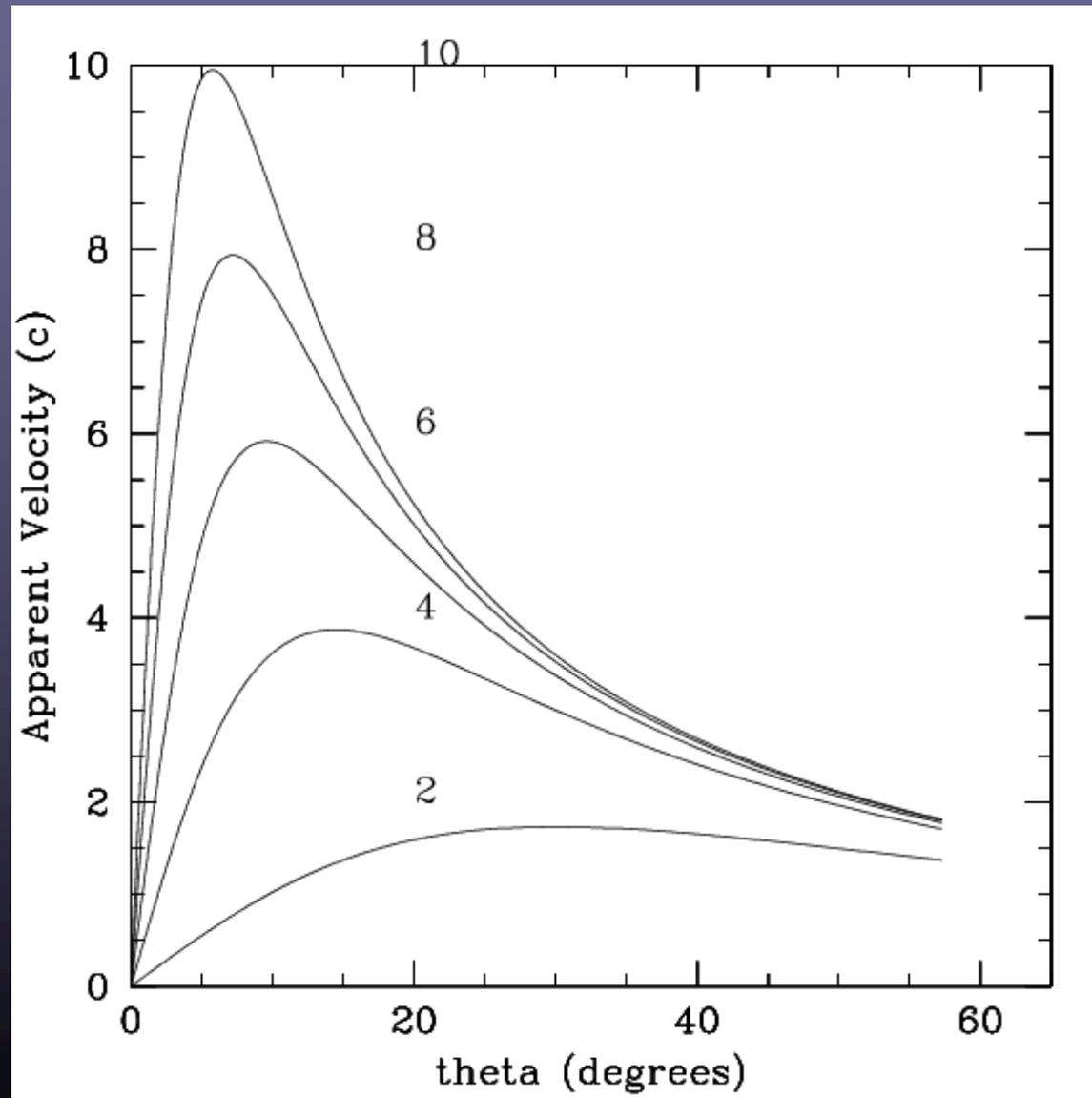
EXAMPLE 2

Superluminal motion

Pearson et al. 1981

constant expansion observed at
rate = $\Delta\theta/\text{year} = 0.76 \pm 0.04 \text{ mas/year}$
 $z = 0.158$ so $D = 940 \text{ Mpc}$
assuming $H_0 = 50 \text{ km sec}^{-1} \text{ Mpc}^{-1}$.
 $1 \text{ mas} = 10^{-3} \text{ arcsec} = 4.85 \times 10^{-9} \text{ radians}$
 $d = D\Delta\theta$ so the apparent transverse
velocity, or rate = d/year
= 10 lt-years/year
= $10 c$ [!!]



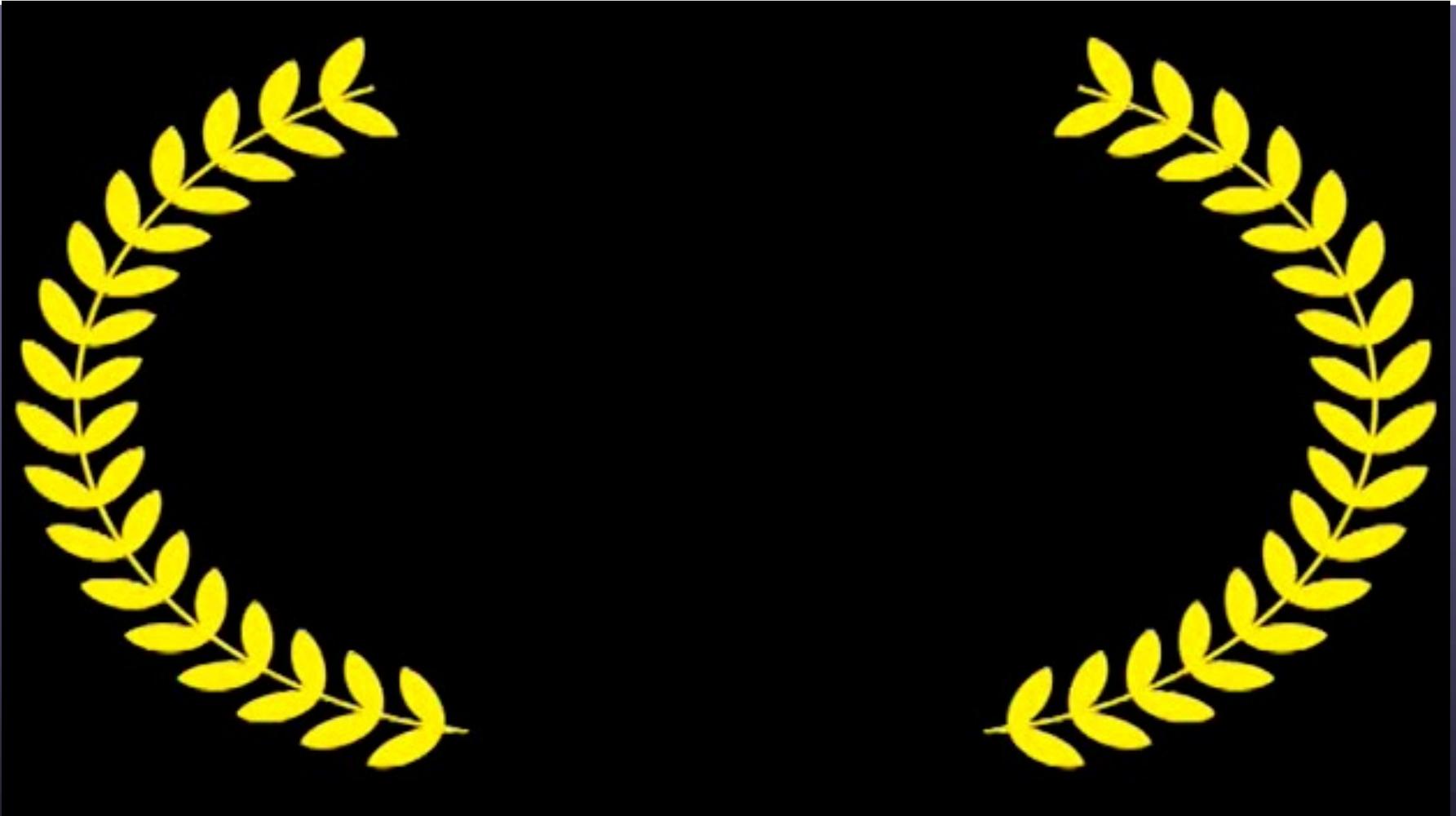


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EXAMPLE 3: JET DYNAMICS: THE SS433 MOVIE

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- Two hour snapshot almost every day for 40 days on VLBA at 1.7 GHz
 - Mioduszewski, Rupen, Taylor, and Walker

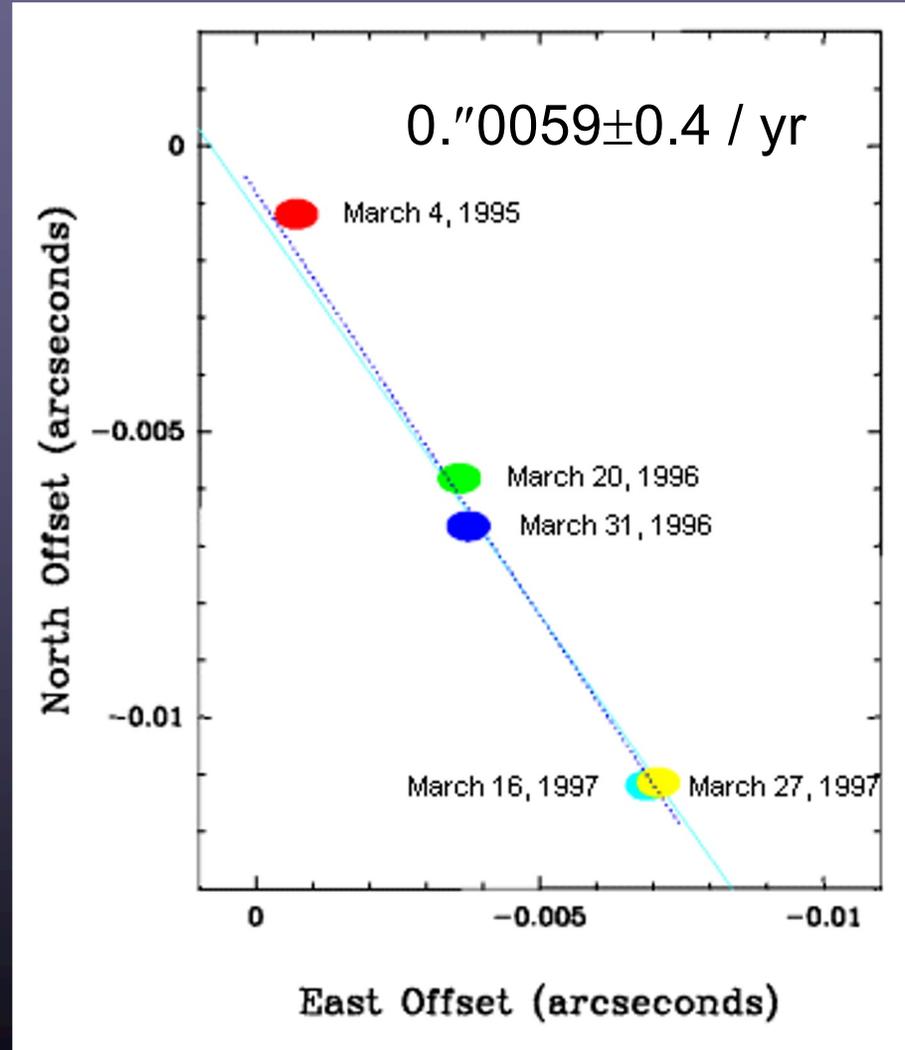
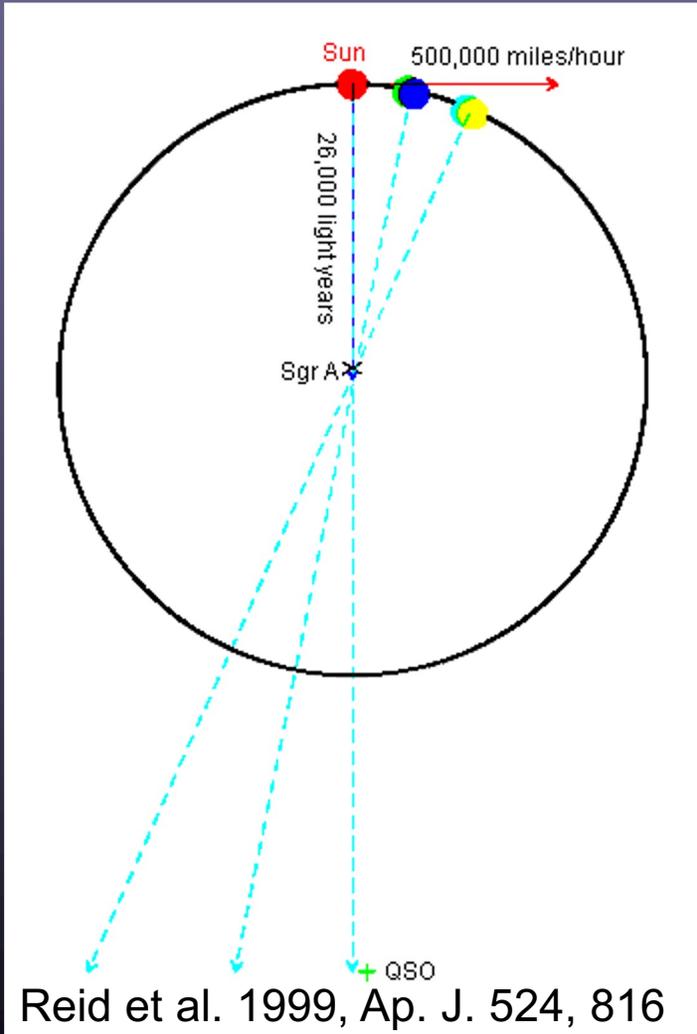


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EXAMPLE 4 MOTIONS OF SGRA*

Measures rotation of the Milky Way Galaxy



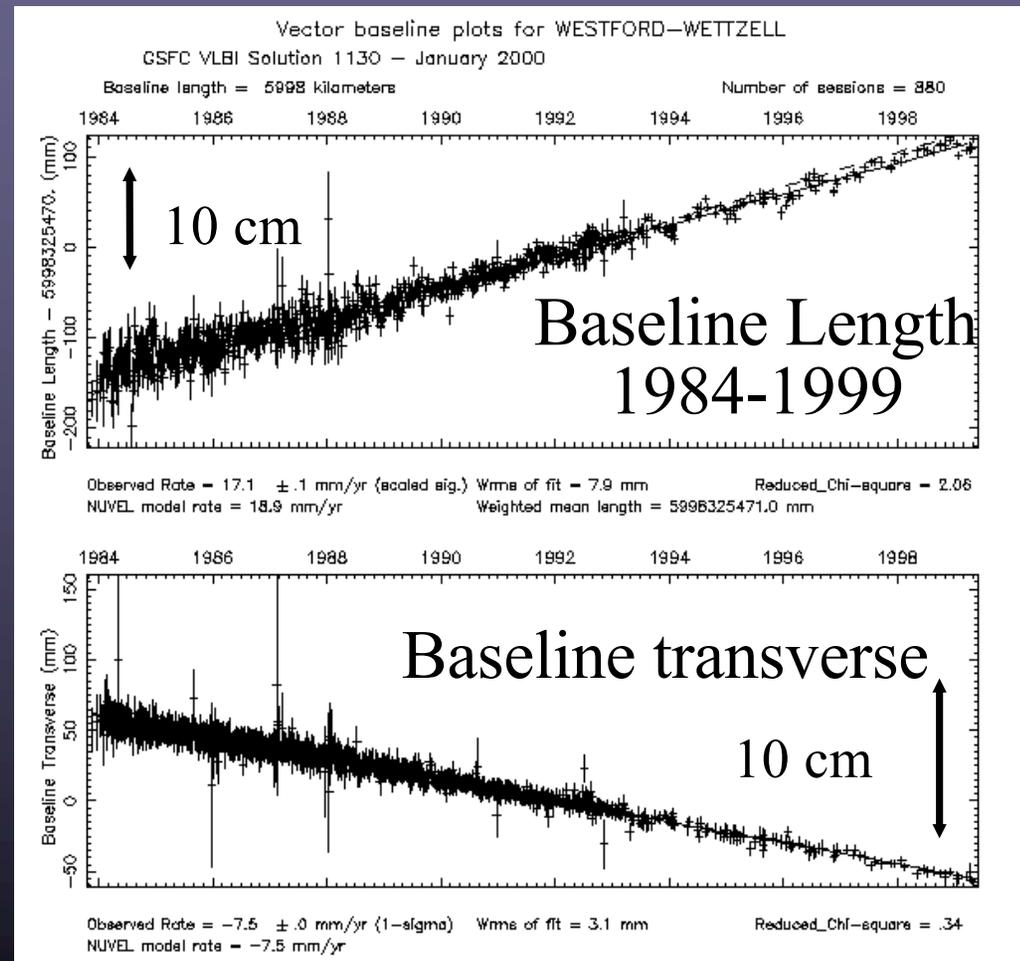
EXAMPLE 5

GEODESY and ASTROMETRY

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- Fundamental reference frames
 - International Celestial Reference Frame (ICRF)
 - International Terrestrial Reference Frame (ITRF)
 - Earth rotation and orientation relative to inertial reference frame of distant quasars
- Tectonic plate motions measured directly
- Earth orientation data used in studies of Earth's core and Earth/atmosphere interaction
- General relativity tests
 - Solar bending significant over whole sky

Germany to Massachusetts



GSFC Jan 2000



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VLBI and CONNECTED INTERFEROMETRY DIFFERENCES

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VLBI is not fundamentally different from connected interferometry

- Differences are a matter of degree.
- Separate clocks – Cause phase variations
- Independent atmospheres (ionosphere and troposphere)
 - Phase fluctuations not much worse than VLA A array
 - Gradients are worse – affected by total, not differential atmosphere
 - Ionospheric calibration useful – dual band data or GPS global models
- Calibrators poor
 - Compact sources are variable – Calibrate using T_{sys} and gains
 - All bright sources are at least somewhat resolved – need to image
 - There are no simple polarization position angle calibrators
- Geometric model errors cause phase gradients
 - Source positions, station locations, and the Earth orientation are difficult to determine to a small fraction of a wavelength



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VLBI and CONNECTED INTERFEROMETRY DIFFERENCES (CONTINUED)

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- Phase gradients in time and frequency need calibration – fringe fit
- VLBI is not sensitive to thermal sources
 - 10^5 K brightness temperature limit
 - This limits the variety of science that can be done
- Hard to match resolution with other bands like optical
 - An HST pixel is a typical VLBI field of view
- Even extragalactic sources change structure on finite time scales
 - VLBA is a movie camera
- Networks have inhomogeneous antennas – hard to calibrate
- Much lower sensitivity to RFI
- Primary beam is not usually an issue for VLBI

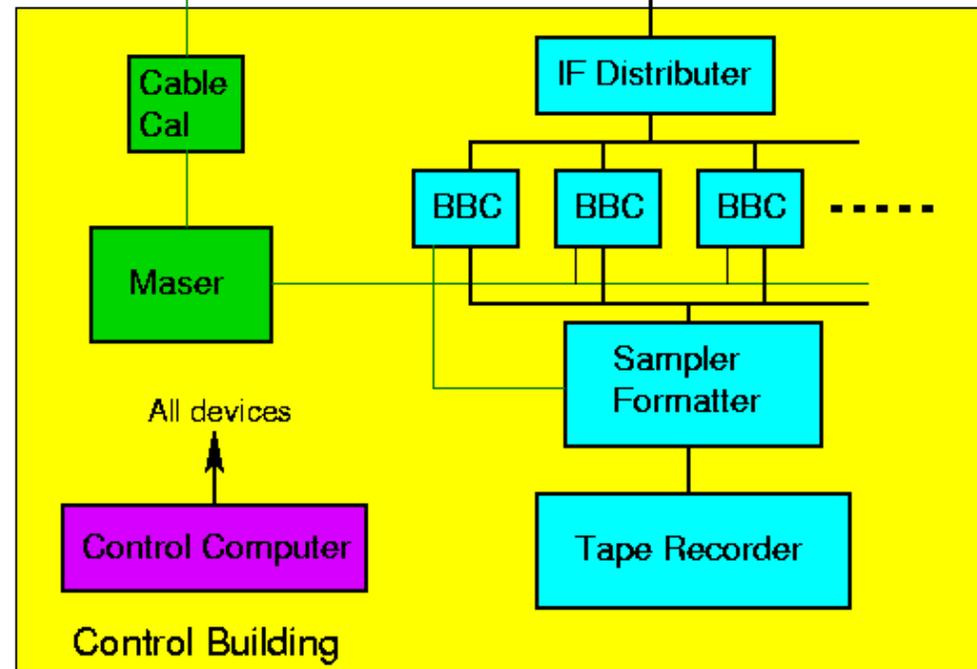
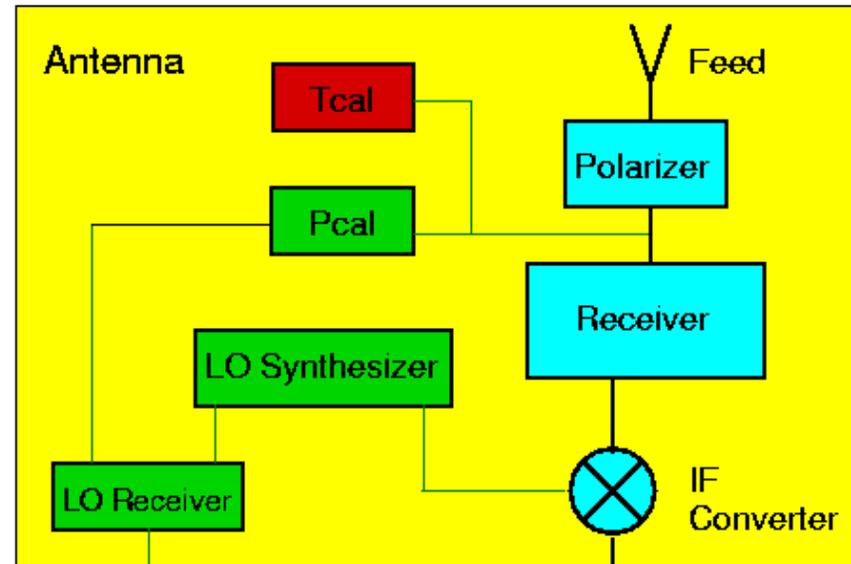


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VLBA STATION ELECTRONICS

- At antenna:
 - Select RCP and LCP
 - Add calibration signals
 - Amplify
 - Mix to IF (500-1000 MHz)
- In building:
 - Distribute to baseband converters (8)
 - Mix to baseband
 - Filter (0.062 - 16 MHz)
 - Sample (1 or 2 bit)
 - Format
 - Record to disk
 - Also keep time and stable frequency
- Other systems conceptually similar



THE DELAY MODEL

For 8000 km baseline
 1 mas = 3.9 cm
 = 130 ps

Adapted from Sovers,
 Fanselow, and Jacobs
 Reviews of Modern
 Physics, Oct 1998

Item	Approx Max.	Time scale
Zero order geometry.	6000 km	1 day
Nutation	$\sim 20''$	< 18.6 yr
Precession	~ 0.5 arcmin/yr	years
Annual aberration.	$20''$	1 year
Retarded baseline.	20 m	1 day
Gravitational delay.	4 mas @ 90° from sun	1 year
Tectonic motion.	10 cm/yr	years
Solid Earth Tide	50 cm	12 hr
Pole Tide	2 cm	~ 1 yr
Ocean Loading	2 cm	12 hr
Atmospheric Loading	2 cm	weeks
Post-glacial Rebound	several mm/yr	years
Polar motion	0.5 arcsec	~ 1.2 years
UT1 (Earth rotation)	Several mas	Various
Ionosphere	~ 2 m at 2 GHz	All
Dry Troposphere	2.3 m at zenith	hours to days
Wet Troposphere	0 – 30 cm at zenith	All
Antenna structure	< 10 m. 1cm thermal	—
Parallactic angle	0.5 turn	hours
Station clocks	few microsec	hours
Source structure	5 cm	years



The DiFX software correlator

- A C++ program running on commodity computer hardware (rack-mounted, multi-core servers)
- Development commenced in 2005, adopted by Australian Long Baseline Array in 2006, NRAO testing from 2008 and complete switch in 2010
- Supported by numerous libraries and applications for job configuration, FITS file building etc; ~10 active developers (NRAO, MPIfR, ATNF/Curtin, Haystack)



The DiFX software correlator



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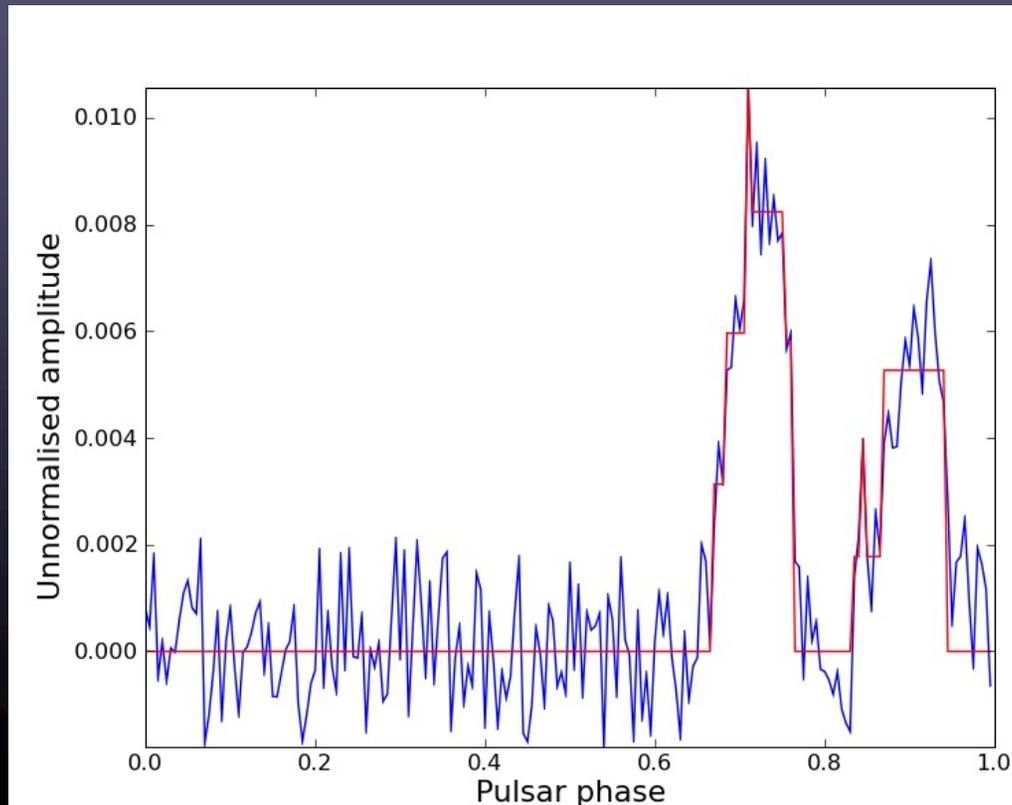
Unique DiFX capabilities

- Compatibility, expandability
 - Initial reason for adoption - needed something capable of expansion to 4 Gbps system
 - incremental nature is extremely useful (hardware purchased in 4 stages, minimizing overall cost through Moore's Law)
 - Handles all input/output VLBI formats
- Flexibility in parameter setting
 - Time, frequency resolution in particular



Unique DiFX capabilities

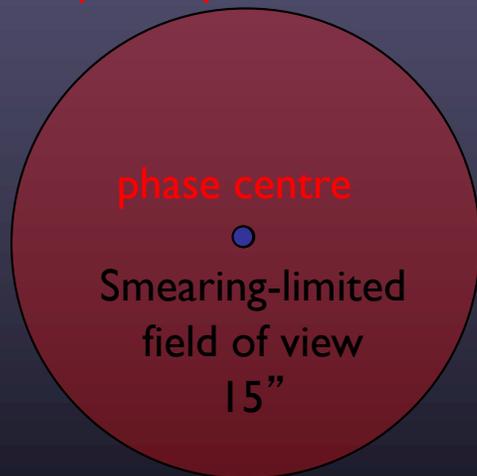
- Much more flexible pulsar processing (dynamic allocation of resources); allows pulse-phase dependant studies (binning) and “matched filtering” for recovery of optimal S/N from complex profiles



Wide-field imaging

- DiFX is the most capable VLBI correlator in the world for wide-field imaging, due to the attainable time and frequency resolution

primary beam: 30'

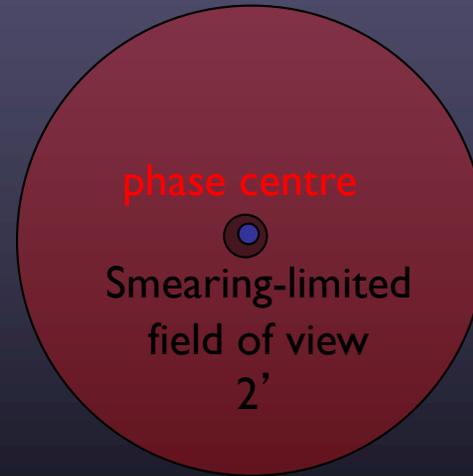


Time resolution:
2000 ms

Freq. resolution:
500 kHz

12hr VLBA dataset:
2.4 GB

primary beam: 30'



Time resolution:
200 ms

Freq. resolution:
50 kHz

12hr VLBA dataset:
240 GB

Calculations for 1.6 GHz, total smearing = 10%

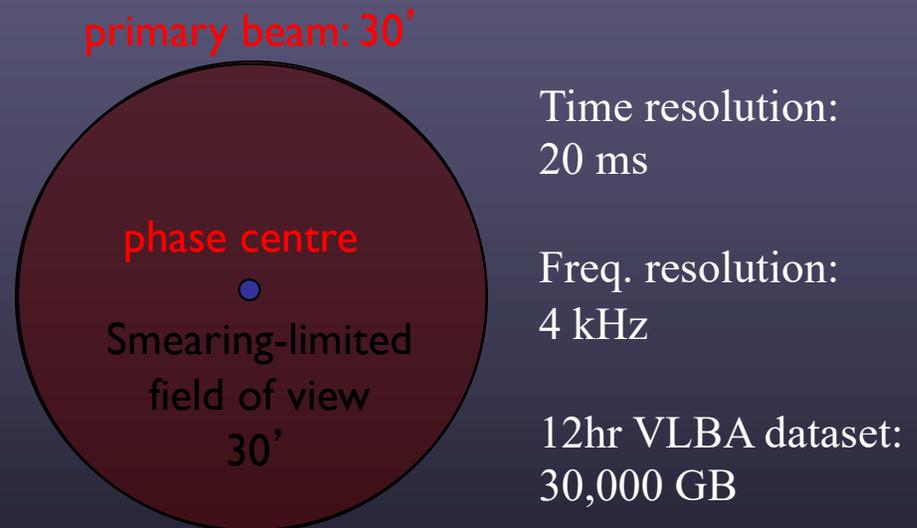


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Wide-field imaging

- This ability has been widely used since the introduction of DiFX
- However, full-beam VLBA imaging is still a logistical impracticality



Calculations for 1.6 GHz, total smearing = 10%

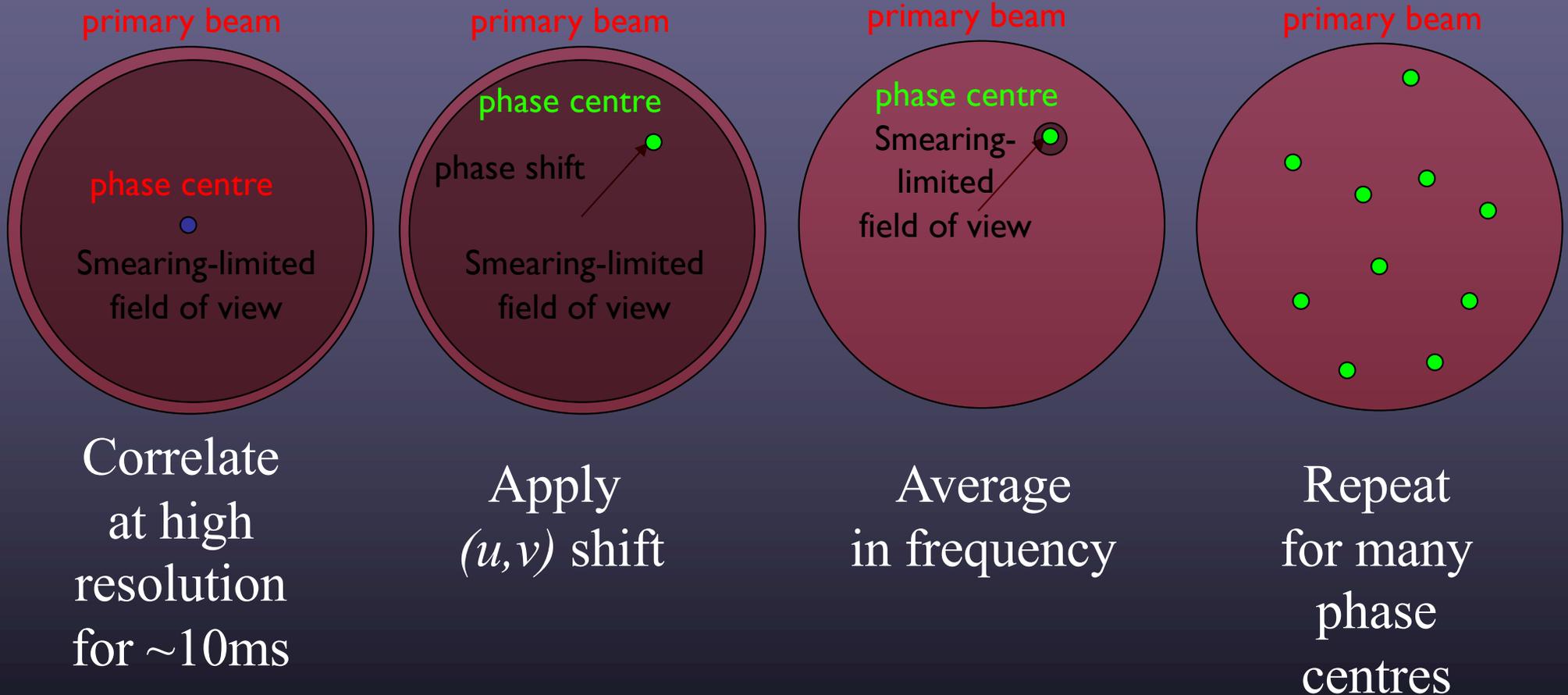


Wide-field imaging

- Generally, however, the sky is almost entirely empty at VLBI resolution
- Thus, usually do not want “full beam” imaging; rather, many targeted small “fields”
- This can be achieved by (u,v) shifting after correlation, but spectral/temporal resolution requirements are identical to imaging
- DiFX has moved the (u,v) shift inside the correlator, allowing “multi-field” correlation and avoiding the logistical problem



Multi-field imaging

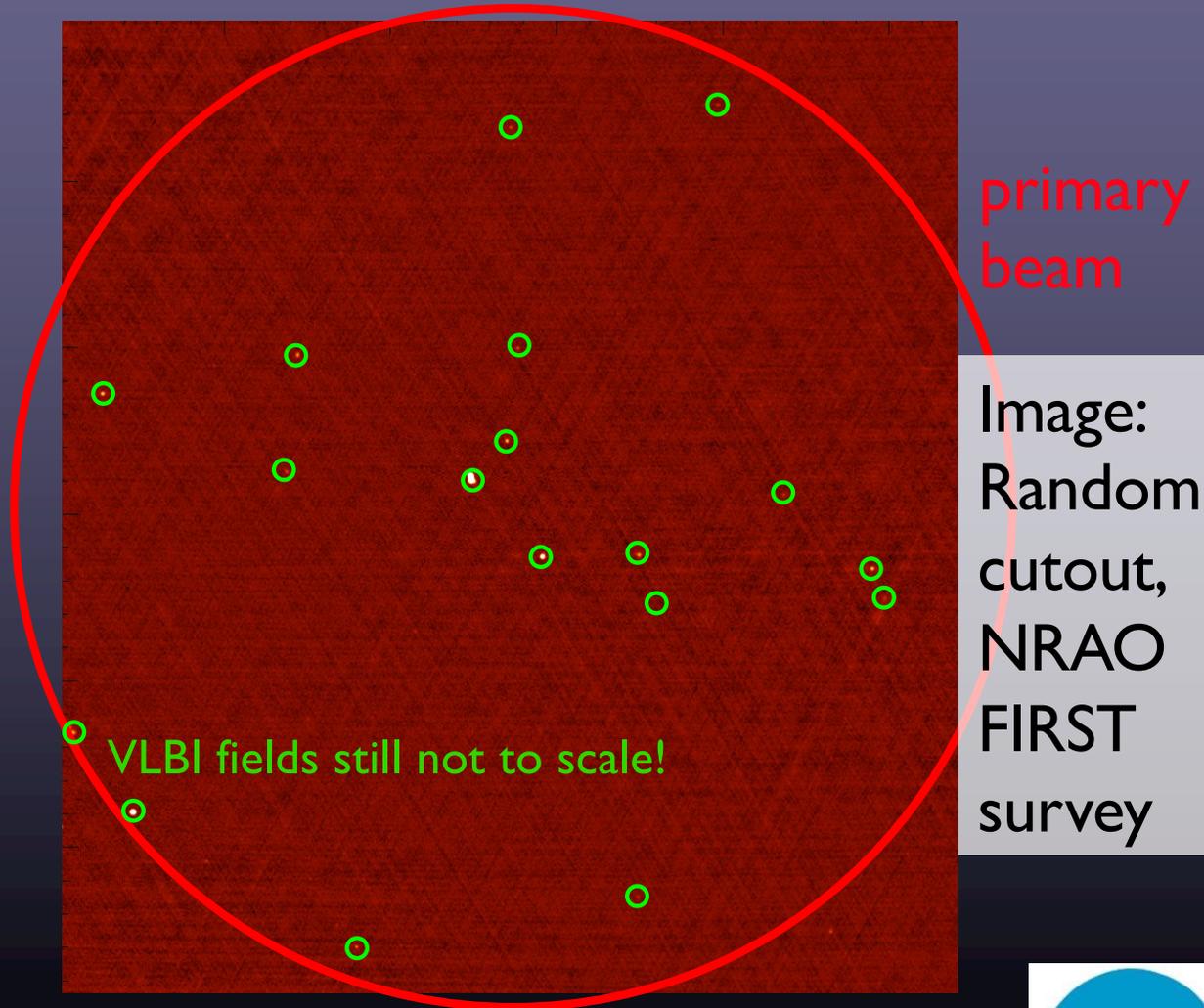


THEN: Repeat for next ~ 10 ms (average in time)



Multi-field imaging

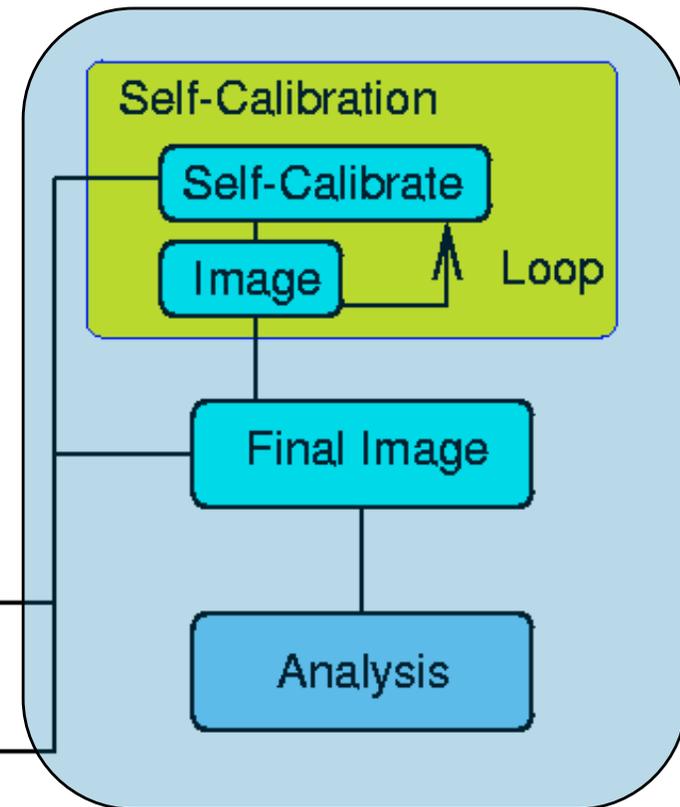
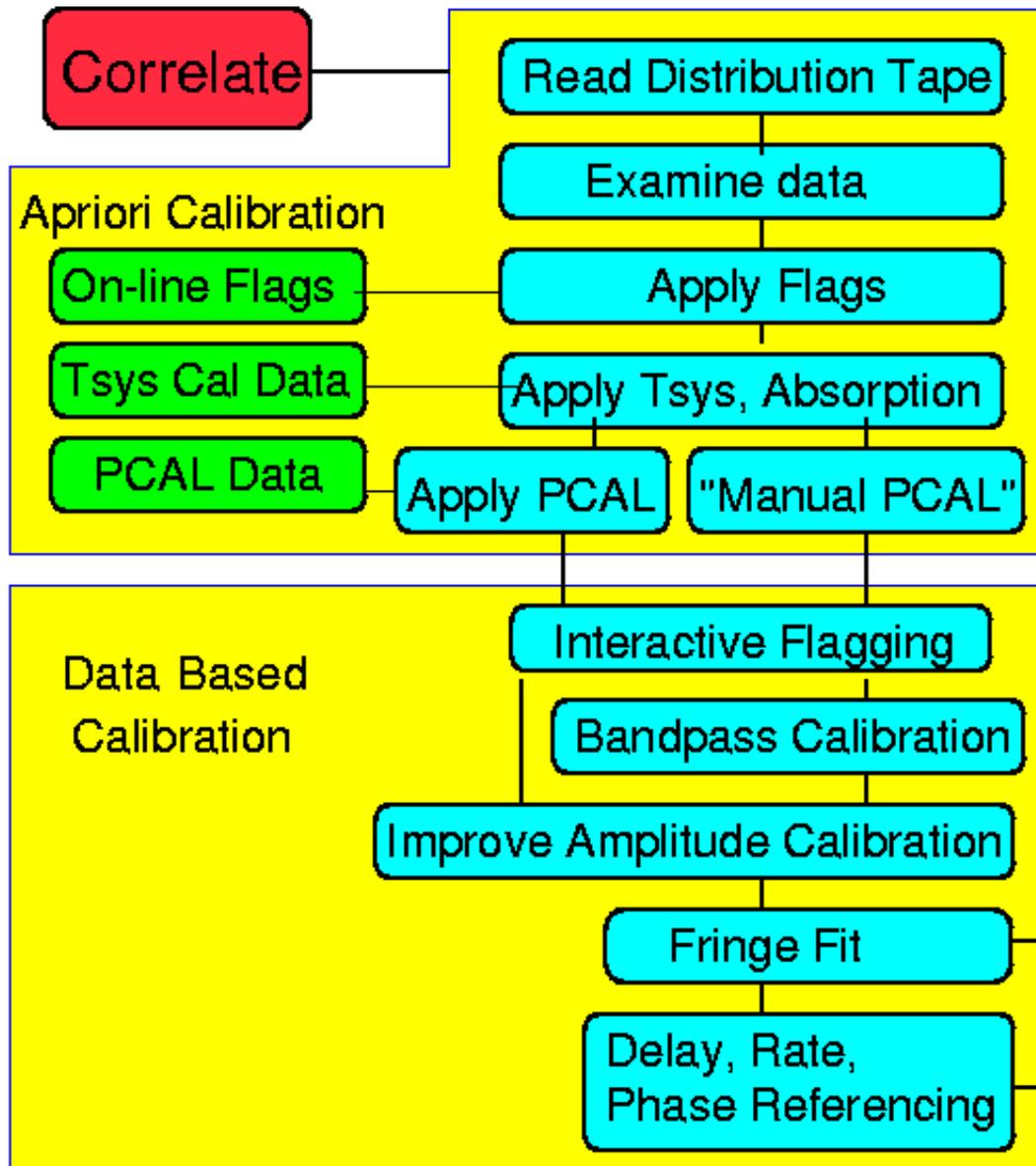
Satisfactory
“finder” catalogs
already exist
for most
applications of
this technique



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VLBI DATA REDUCTION



VLBI Amplitude Calibration

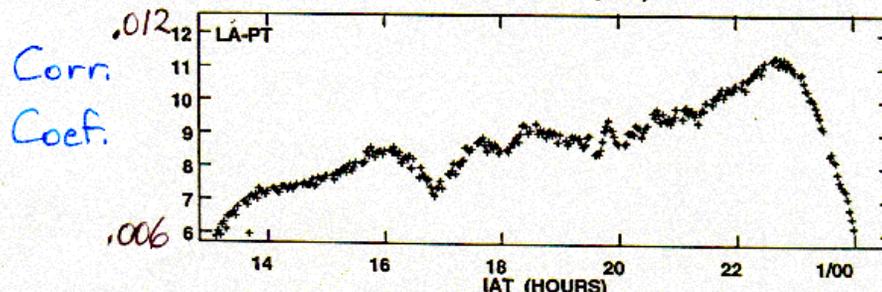
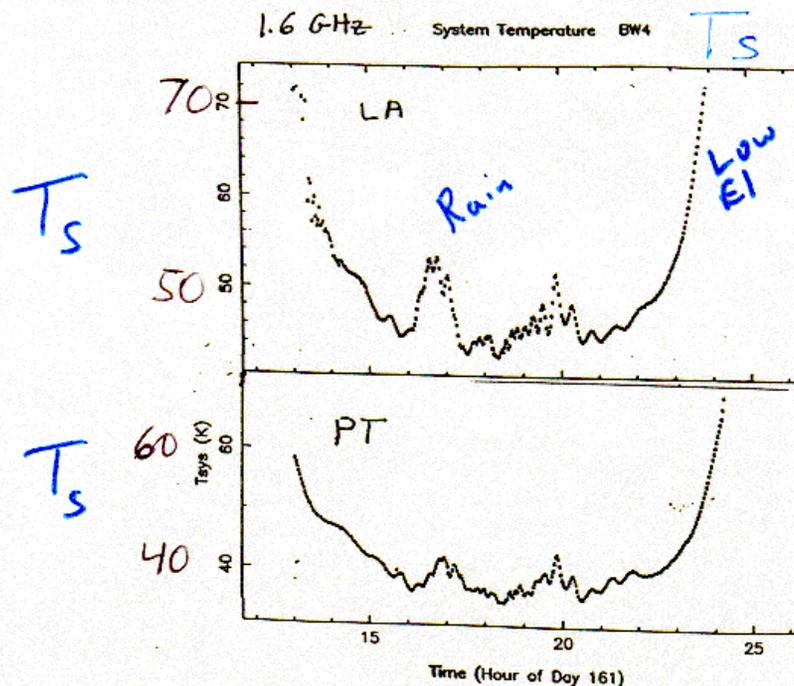
$$S_{ij} = \rho_{ij} \frac{A}{\eta_s} \sqrt{\frac{T_{si} T_{sj}}{K_i K_j e^{-\tau_i} e^{-\tau_j}}}$$

- S_{ij} = Correlated flux density on baseline $i - j$
- ρ = Measured correlation coefficient
- A = Correlator specific scaling factor
- η_s = System efficiency including digitization losses
- T_s = System temperature
 - Includes receiver, spillover, atmosphere, blockage
- K = Gain in degrees K per Jansky
 - Includes gain curve
- $e^{-\tau}$ = Absorption in atmosphere plus blockage
- Note $T_s/K = SEFD$ (System Equivalent Flux Density)

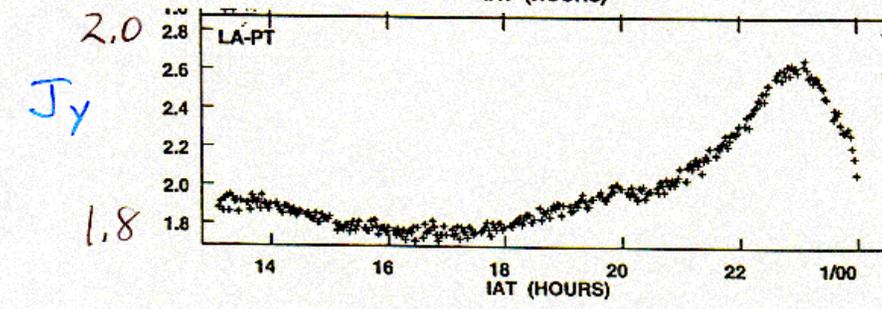


CALIBRATION WITH T_{sys}

Example shows removal of effect of increased T_s due to rain and low elevation



Not Calibrated



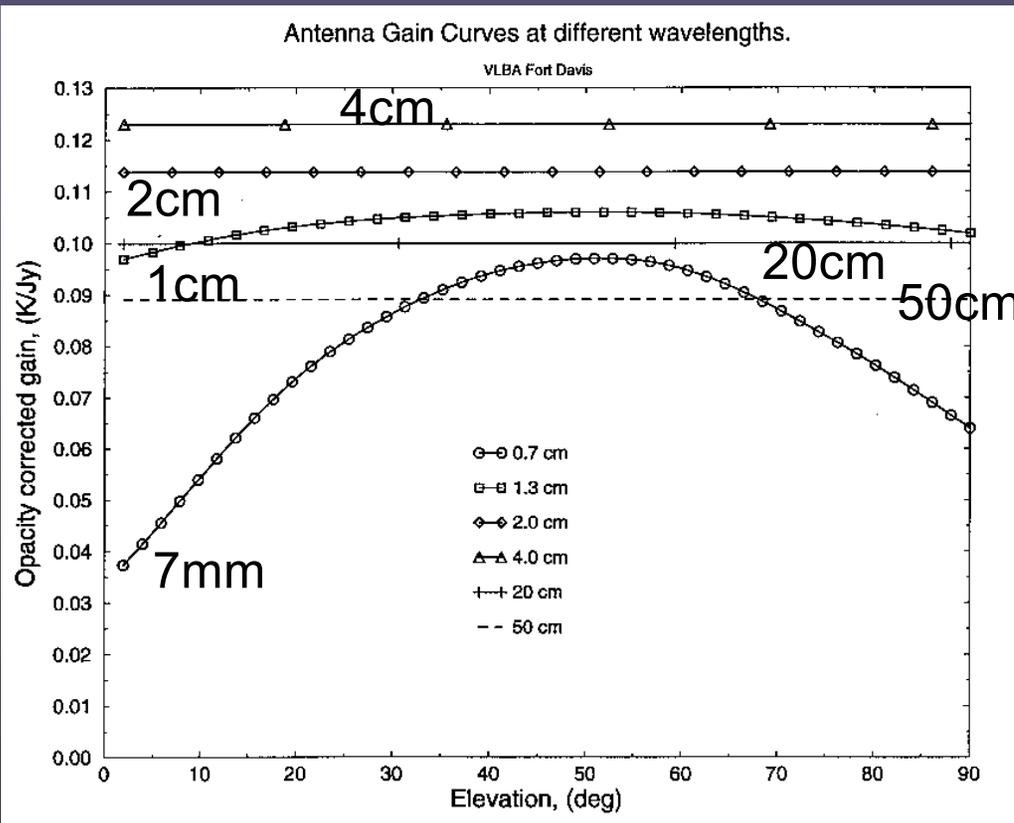
T_s Applied



GAIN CURVES AND OPACITY CORRECTION

VLBA gain curves

Caused by gravity induced distortions of the antenna as a function of elevation

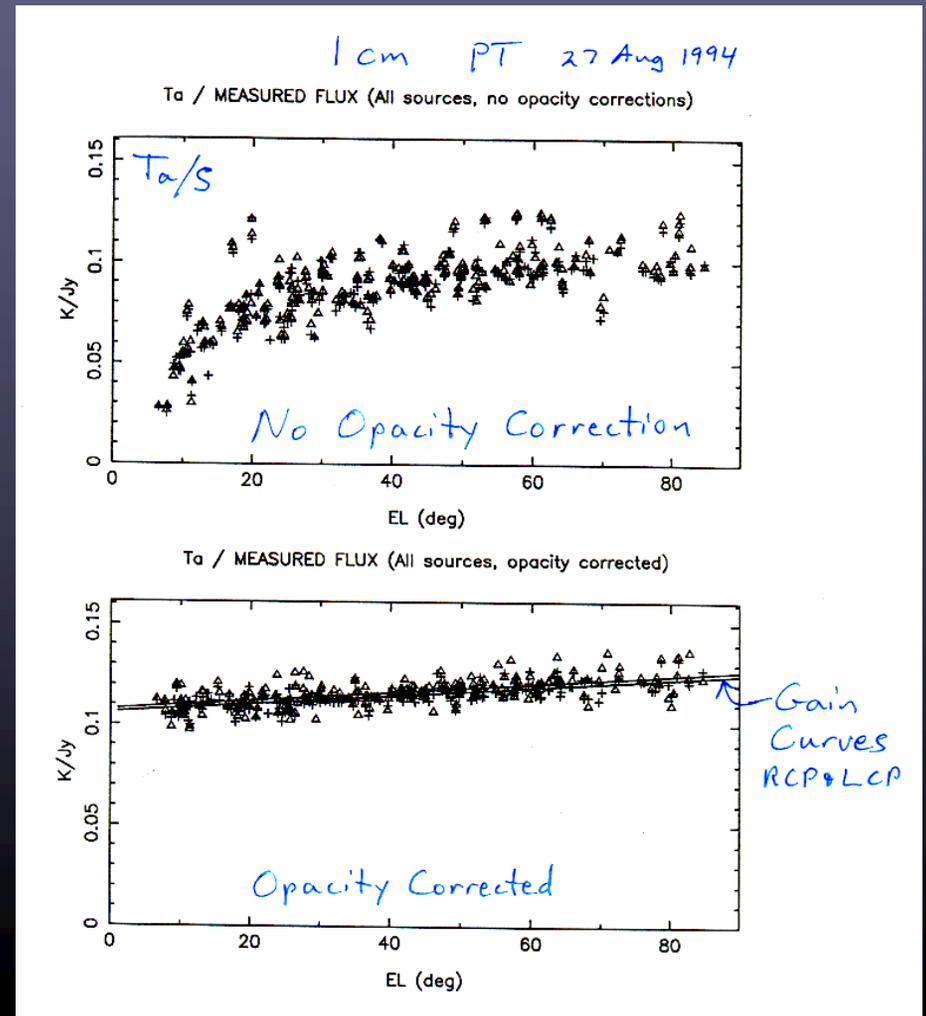


Atmospheric opacity

Correcting for absorption by the atmosphere

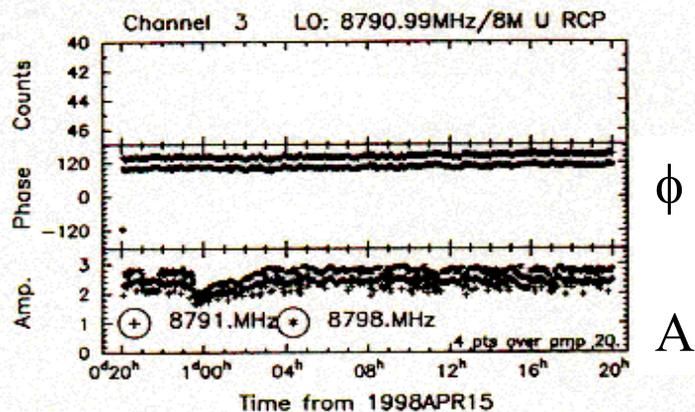
Can estimate using $T_s - T_r - T_{spill}$

Example from single-dish VLBA pointing data

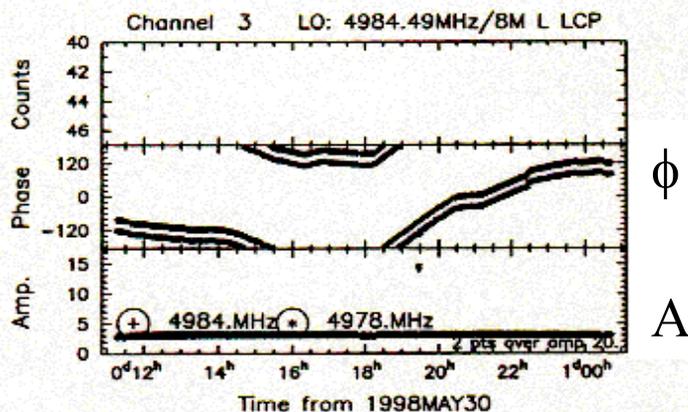


PULSE CAL SYSTEM

- Tones generated by injecting pulse once per microsecond
- Use to correct for instrumental phase shifts



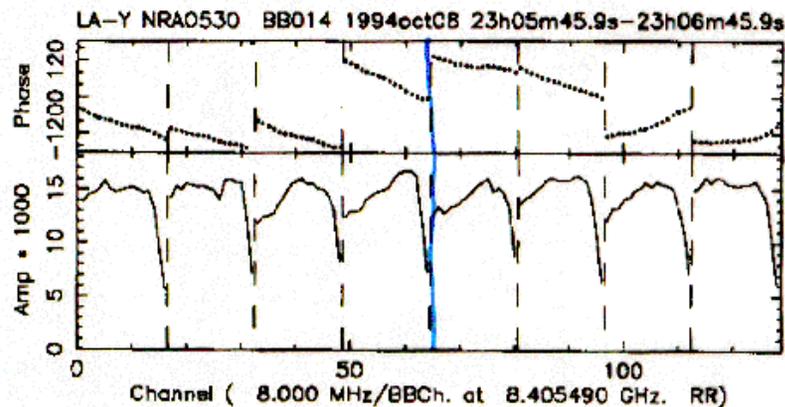
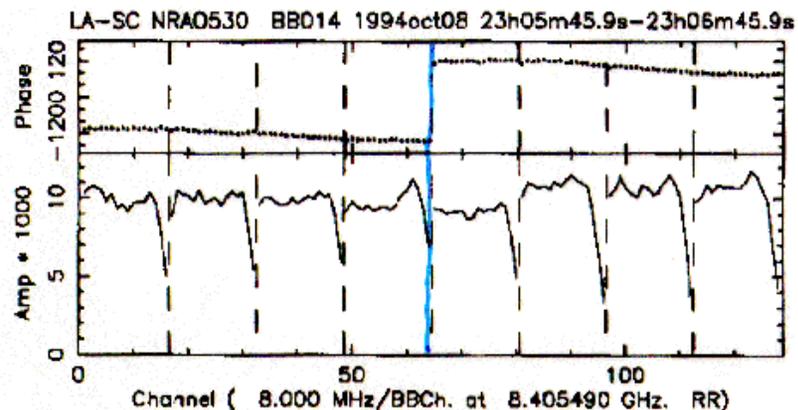
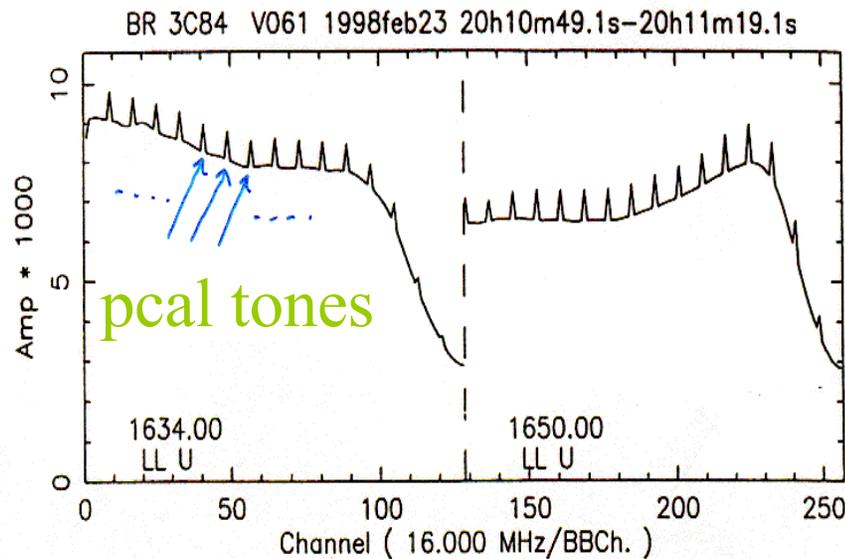
Pulse cal monitor data



Long track at non-VLBA station

Data Aligned using Pulse Cal

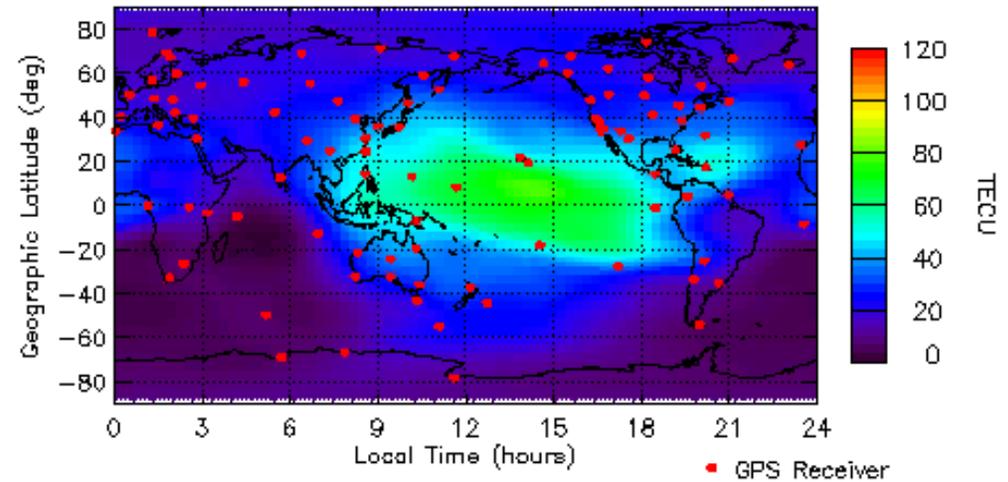
No PCAL at VLA. Shows unaligned phases



IONOSPHERIC DELAY

- Delay scales with $1/v^2$
- Ionosphere dominates errors at low frequencies
- Can correct with dual band observations (S/X)
- GPS based ionosphere models help (AIPS task TECOR)

06/11/02
00:00 - 01:00 UT Global Ionospheric TEC Map

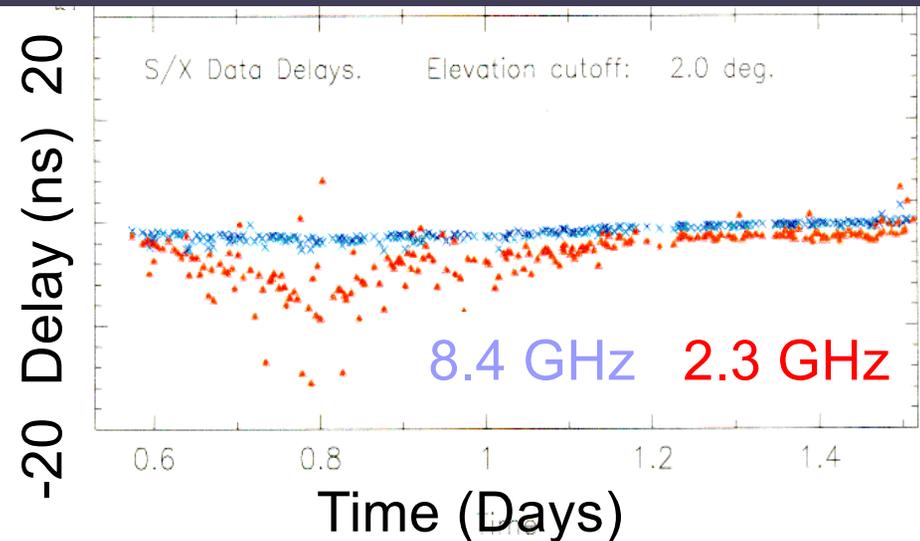


Maximum Likely Ionospheric Contributions

Freq GHz	Day Delay ns	Night Delay ns	Day Rate mHz	Night Rate mHz
0.327	1100	110	12	1.2
0.610	320	32	6.5	0.6
1.4	60	6.0	2.8	0.3
2.3	23	2.3	1.7	0.2
5.0	5.0	0.5	0.8	0.1
8.4	1.7	0.2	0.5	0.05
15	0.5	0.05	0.3	0.03
22	0.2	0.02	0.2	0.02
43	0.1	0.01	0.1	0.01

Ionosphere map from iono.jpl.nasa.gov

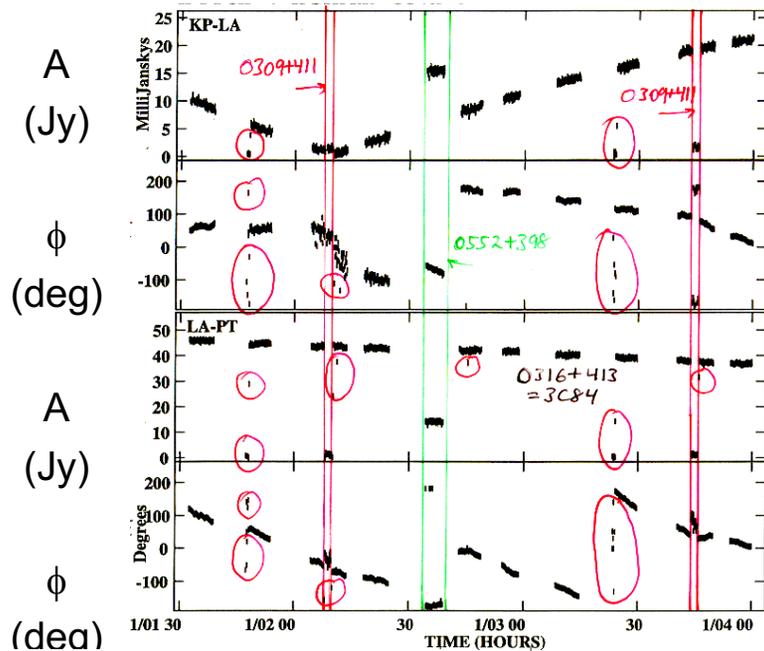
Delays from an S/X Geodesy Observation



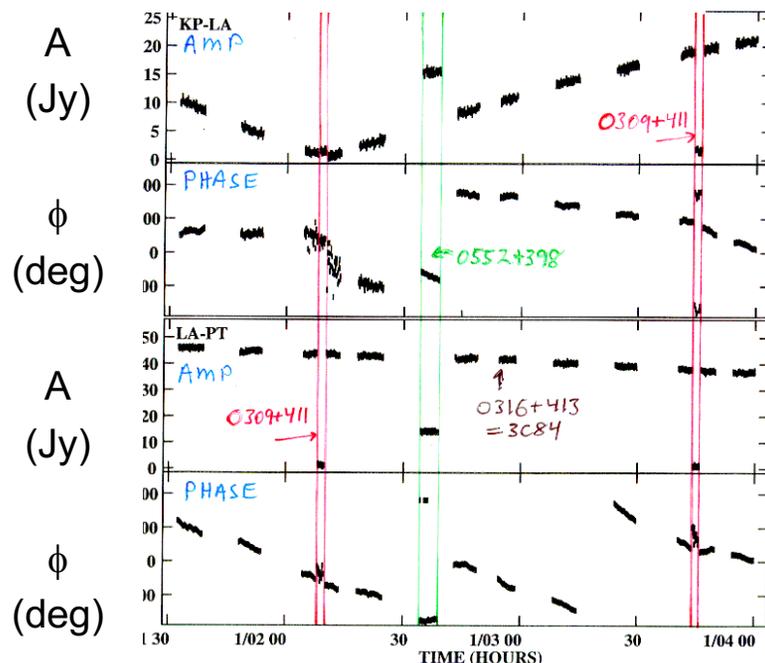
EDITING

- Flags from on-line system will remove most bad data. Examples:
 - Antenna off source
 - Subreflector out of position
 - Synthesizers not locked
- Final flagging done by examining data
 - Flag by antenna
 - Most problems are antenna based
 - Poor weather
 - Bad playback
 - RFI (May need to flag by channel)
 - First point in scan sometimes bad

Raw Data - No Edits

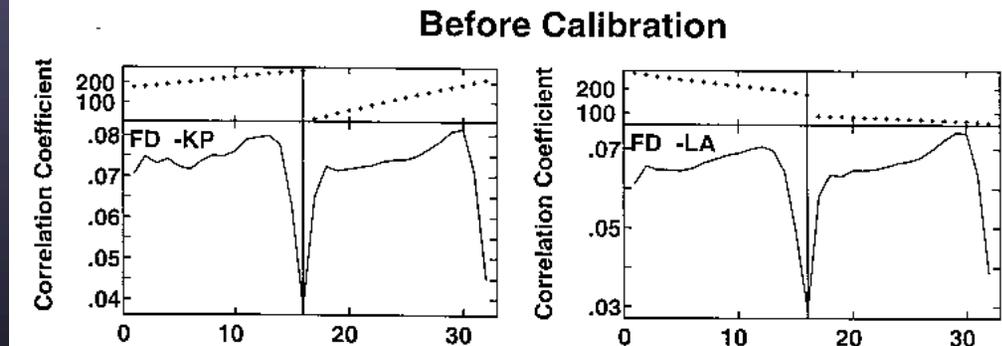
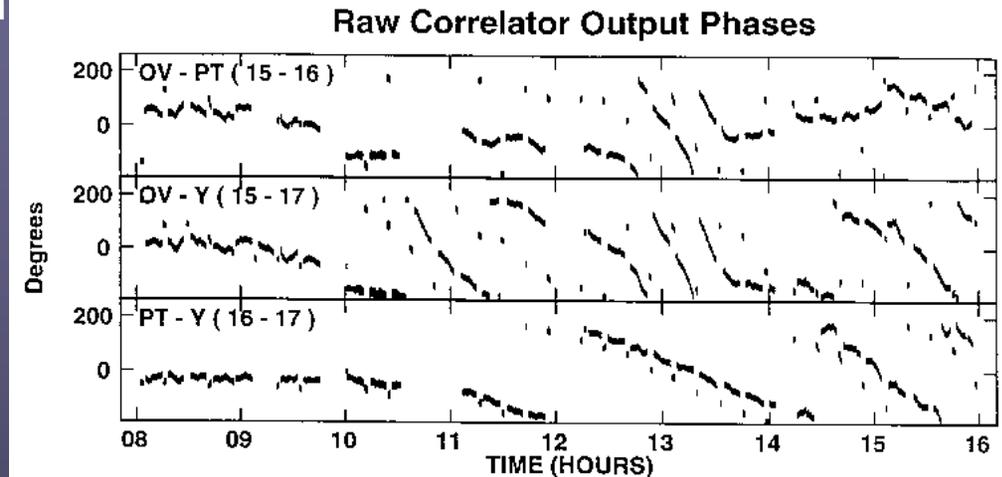


Raw Data - Edited



FRINGE FITTING

- Raw correlator output has phase slopes in time and frequency
 - Slope in time is “fringe rate”
 - Usually from imperfect troposphere or ionosphere model
 - Slope in frequency is “delay”
 - A phase slope because $\phi = \nu\tau$
 - Fluctuations worse at low frequency because of ionosphere
 - Troposphere affects all frequencies equally ("nondispersive")
- Fringe fit is self calibration with first derivatives in time and frequency



FRINGE FITTING: WHY

- For Astronomy:
 - Remove clock offsets and align baseband channels (“manual pcal”)
 - Done with 1 or a few scans on a strong source
 - Could use bandpass calibration if smearing corrections were available
 - Fit calibrator to track most variations (optional)
 - Fit target source if strong (optional)
 - Used to allow averaging in frequency and time
 - Allows higher SNR self calibration (longer solution, more bandwidth)
 - Allows corrections for smearing from previous averaging
 - Fringe fitting weak sources rarely needed any more
- For geodesy:
 - Fitted delays are the primary “observable”
 - Slopes are fitted over wide spanned frequency range
 - “Bandwidth Synthesis”
 - Correlator model is added to get “total delay”, independent of models



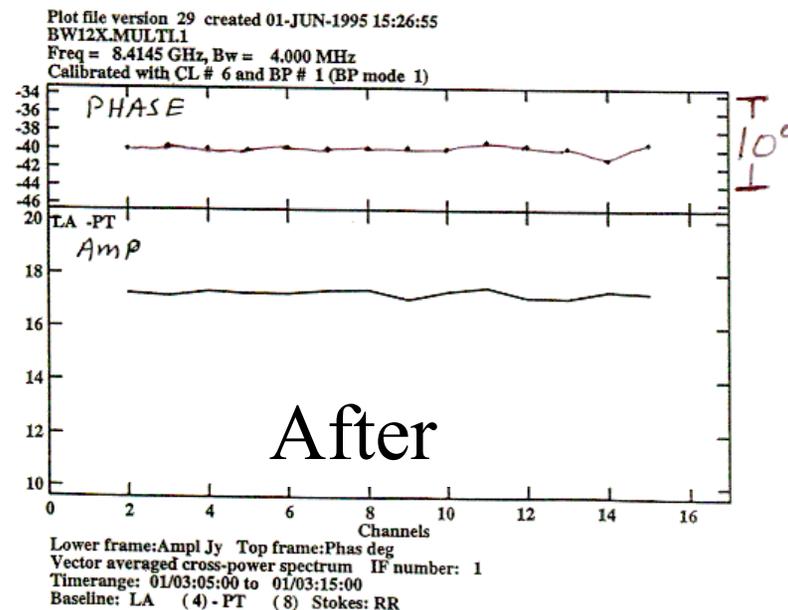
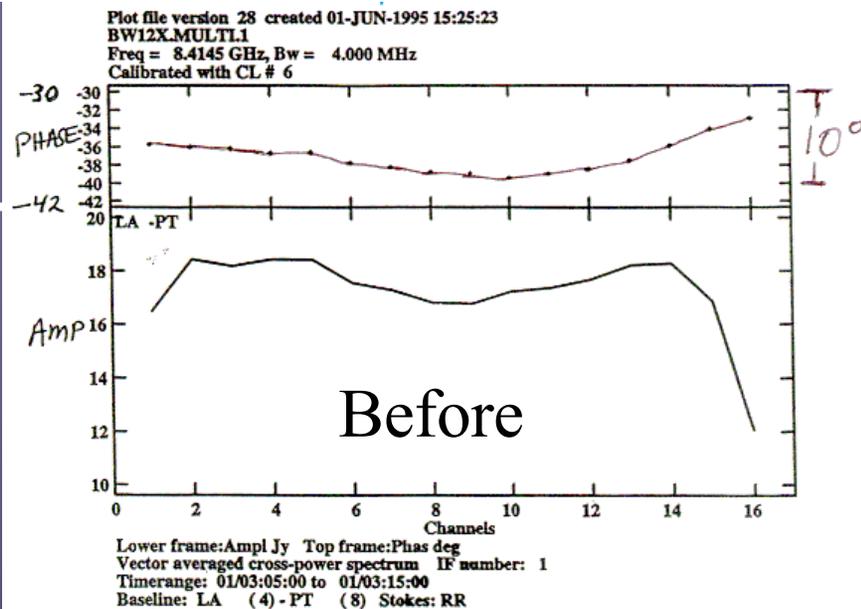
FRINGE FITTING: HOW

- Two step process (usually)
 - 2D FFT to get estimated rates and delays to reference antenna
 - Required for start model for least squares
 - Can restrict window to avoid high sigma noise points
 - Can use just baselines to reference antenna or can stack 2 and even 3 baseline combinations
 - Least squares fit to phases starting at FFT estimate
- Baseline fringe fit
 - Not affected by poor source model
 - Used for geodesy. Noise more accountable.
- Global fringe fit
 - One phase, rate, and delay per antenna
 - Best SNR because all data used
 - Improved by good source model
 - Best for imaging and phase referencing



BANDPASS CALIBRATION

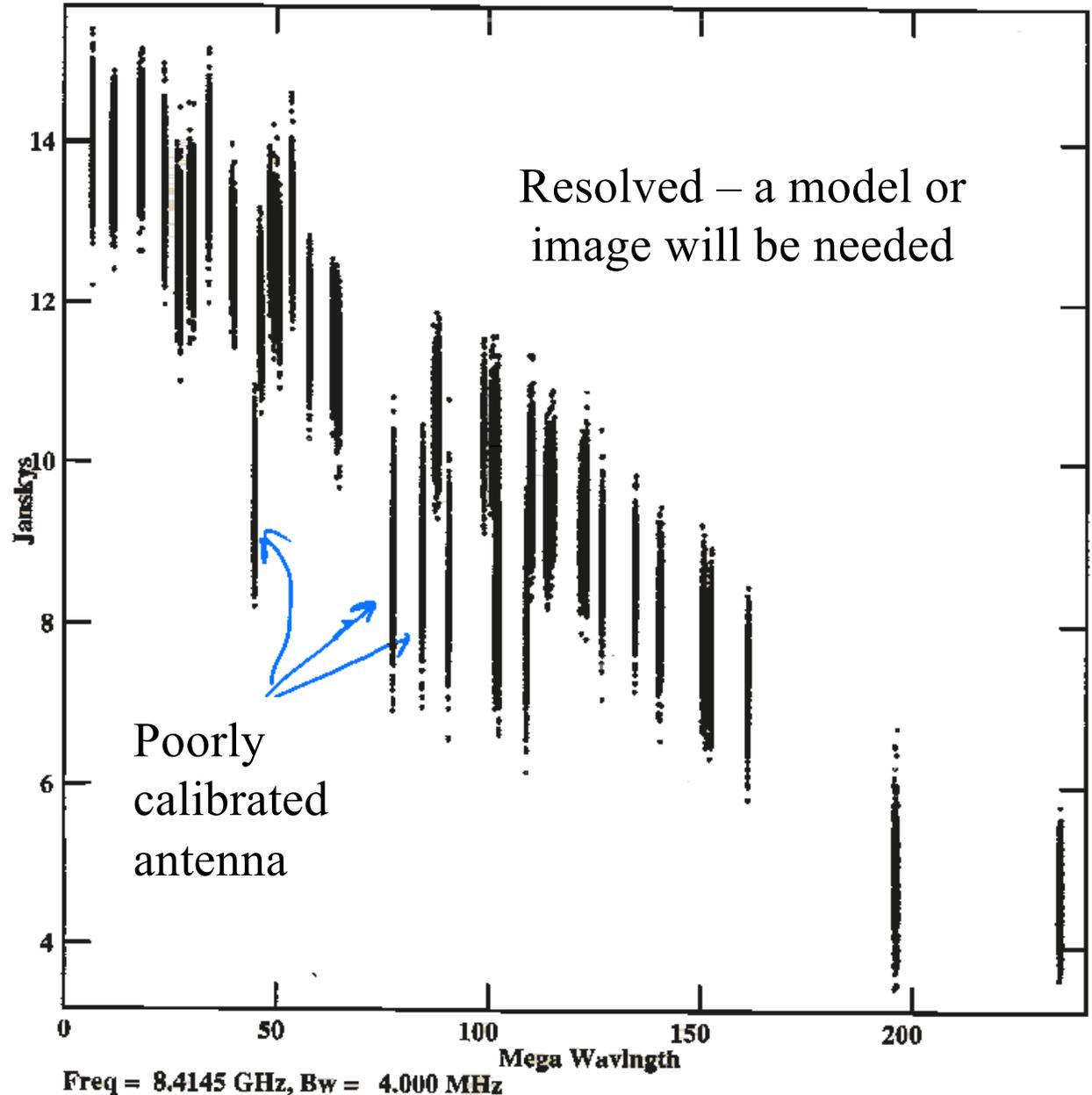
- Based on bandpass calibration source
- Effectively a self-cal on a per-channel basis
- Needed for spectral line calibration
- May help continuum calibration by reducing closure errors
- Affected by high total fringe rates
 - Fringe rate shifts spectrum relative to filters
 - Bandpass spectra must be shifted to align filters when applied
 - Will lose edge channels in process of correcting for this.



AMPLITUDE CHECK SOURCE

- Typical calibrator visibility function after a priori calibration
 - Calibrator is resolved
 - Will need to image
 - One antenna low
 - Use calibrator to fix
- Shows why flux scale (gain normalization) should only be set by a subset of antennas

Plot file version 32 created 02-JUN-1995 13:29:38
Amplitude vs UV dist for BW12X.MULTI.1 Source:0923+392
Ants * .* Stokes RR IF# 1 Chn# 2



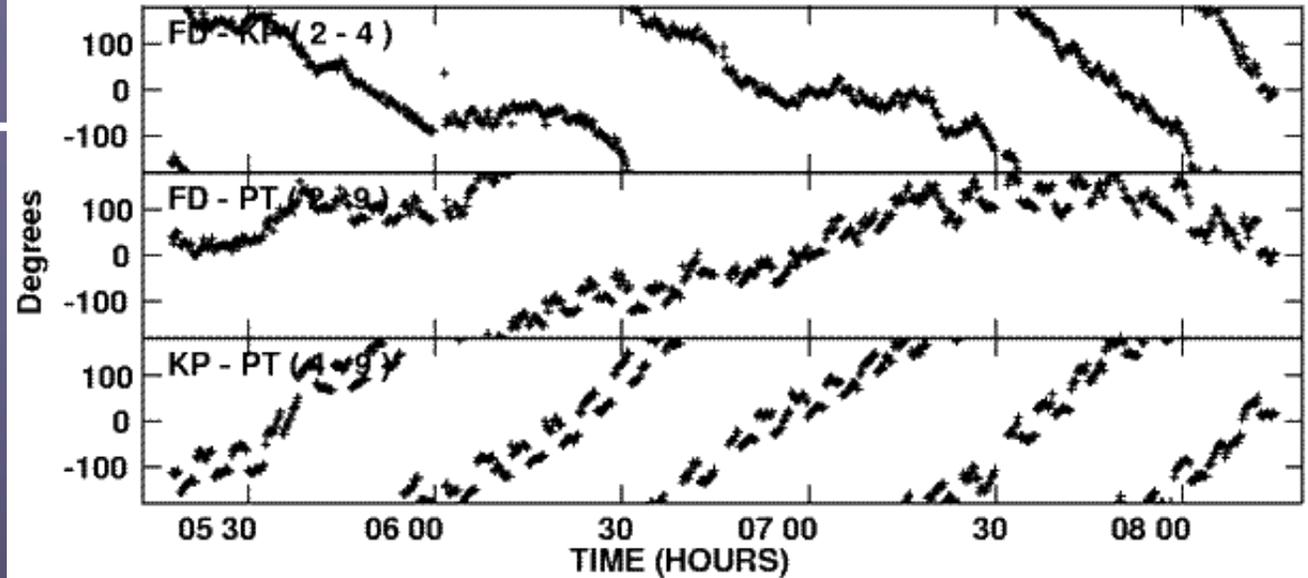
PHASE REFERENCING

- Calibration using phase calibrator outside target source field
 - Nodding calibrator (move antennas)
 - In-beam calibrator (separate correlation pass)
 - Multiple calibrators for most accurate results – get gradients
- Similar to VLA calibration except:
 - Geometric and atmospheric models worse
 - Affected by totals between antennas, not just differentials
 - Model errors usually dominate over fluctuations
 - Errors scale with total error times source-target separation in radians
 - Need to calibrate often (5 minute or faster cycle)
 - Need calibrator close to target (< 5 deg)
- Biggest problems:
 - Wet troposphere at high frequency
 - Ionosphere at low frequencies (20 cm is as bad as 1cm)
- Use for weak sources and for position measurements
 - Increases sensitivity by 1 to 2 orders of magnitude
 - Used by about 30-50% of VLBA observations

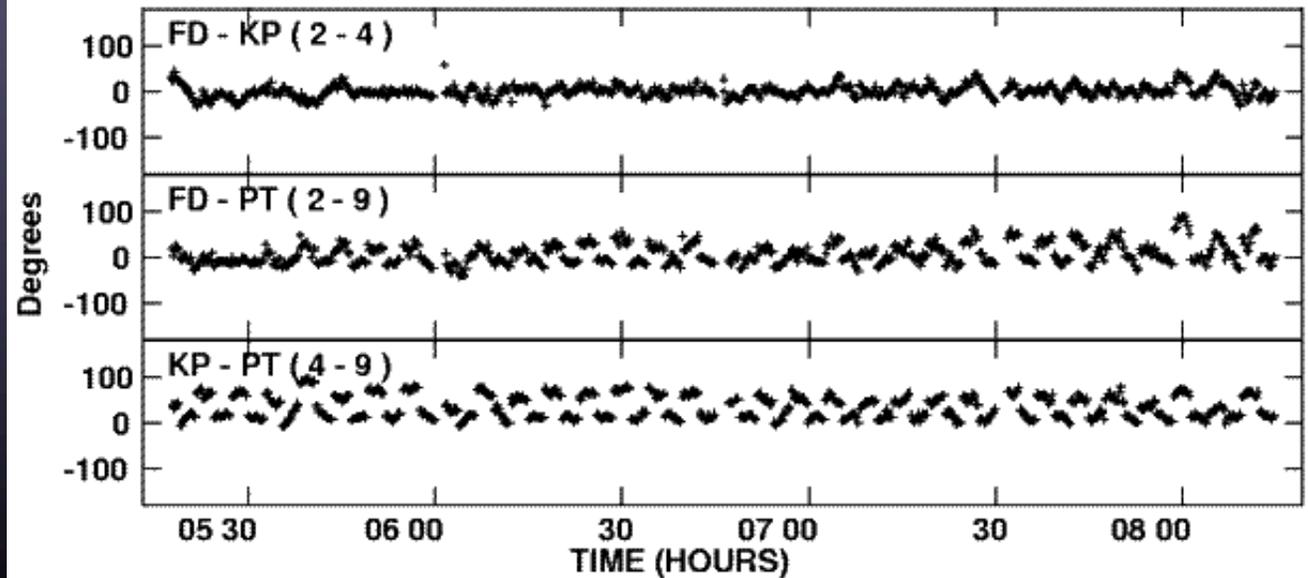
EXAMPLE OF REFERENCED PHASES

- 6 min cycle - 3 on each source
- Phases of one source self-calibrated (near zero)
- Other source shifted by same amount

Raw Correlator Output Phases



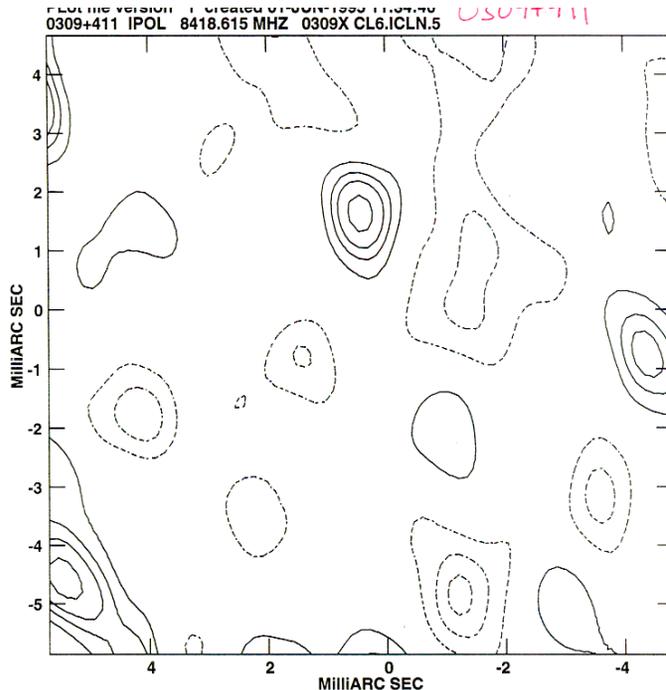
Phase Referenced Phases



Phase Referencing Example

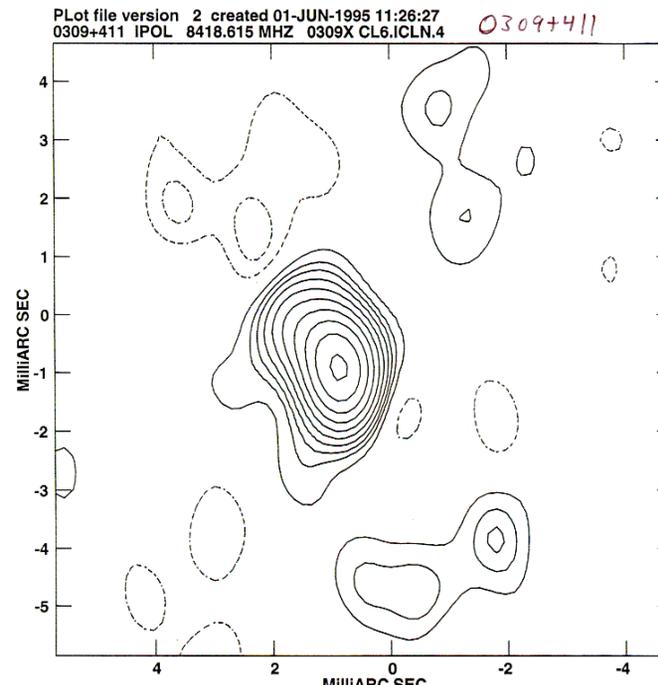
- With no phase calibration, source is not detected (no surprise)
- With reference calibration, source is detected, but structure is distorted (target-calibrator separation is probably not small)
- Self-calibration of this strong source shows real structure

No Phase Calibration



Center at RA 03 13 1.96210 DEC 41 20 1.1840
Peak flux = 9.4978E-02 JY/BEAM
Levs = 1.0000E-02 * (-2.83, -2.00, -1.00,
1.000, 2.000, 2.828, 4.000, 5.657, 8.000,
11.31, 16.00, 22.63, 32.00, 45.25, 64.00,
90.51, 128.0, 181.0, 256.0, 362.0, 512.0,
724.1, 1024., 1448., 2048., 2896., 4096.,
5793., 8192., 11585.)

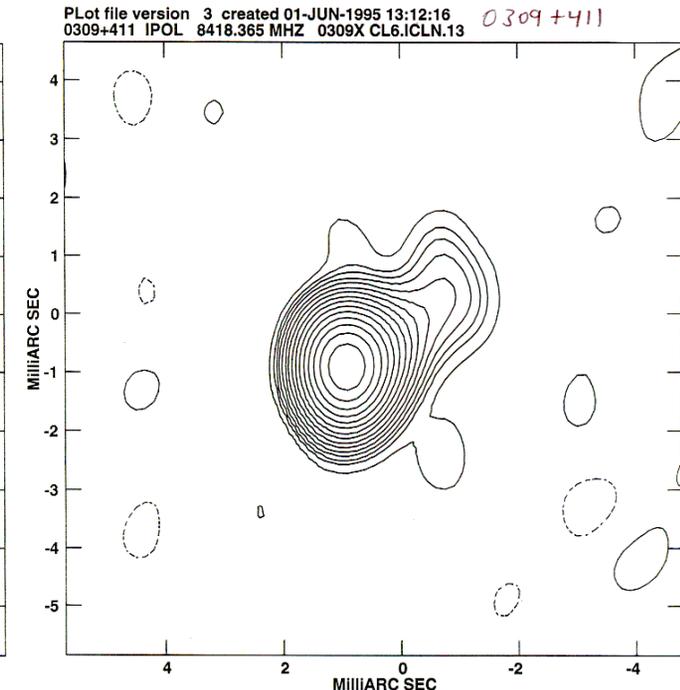
Reference Calibration



Center at RA 03 13 1.96210 DEC 41 20 1.1840
Peak flux = 3.4321E-01 JY/BEAM
Levs = 1.0000E-02 * (-2.83, -2.00, -1.00,
1.000, 2.000, 2.828, 4.000, 5.657, 8.000,
11.31, 16.00, 22.63, 32.00, 45.25, 64.00,
90.51, 128.0, 181.0, 256.0, 362.0, 512.0,
724.1, 1024., 1448., 2048., 2896., 4096.,
5793., 8192., 11585.)

*VLBA
9 SCANS
12 MINUTES DATA*

Self-calibration

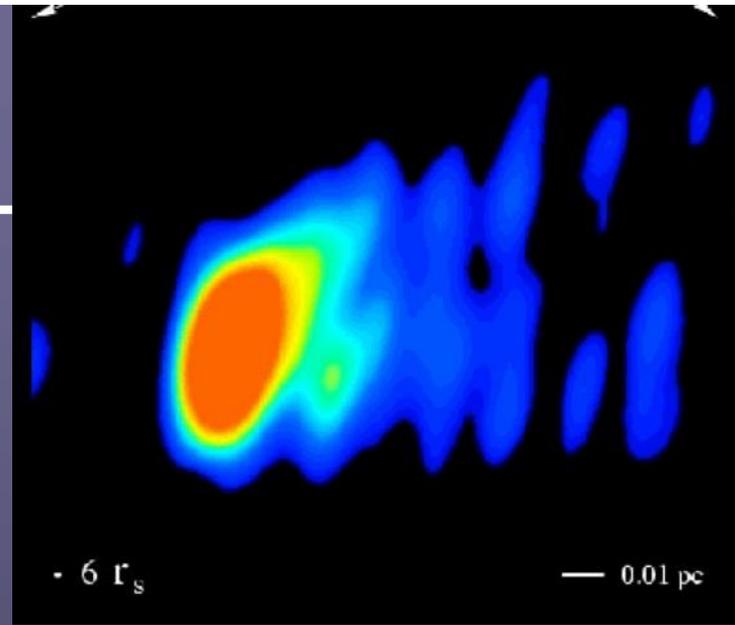
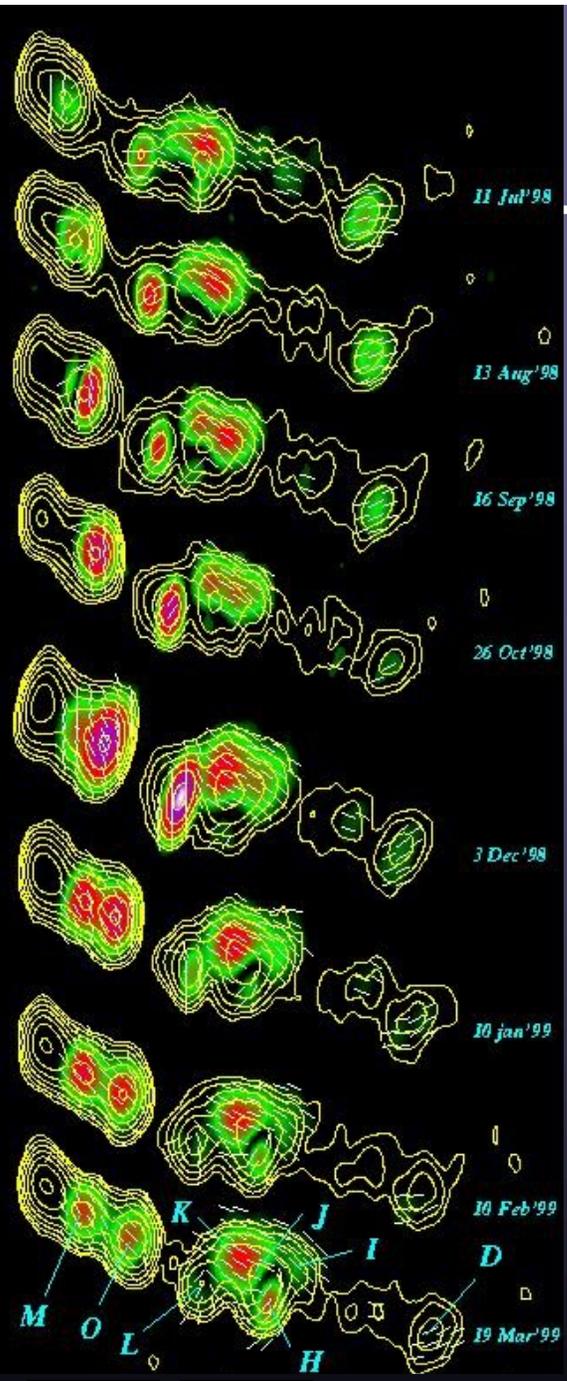


Center at RA 03 13 1.96210 DEC 41 20 1.1840
Peak flux = 3.7156E-01 JY/BEAM
Levs = 2.0000E-03 * (-2.68, -1.93, -1.00,
1.000, 1.931, 2.683, 3.728, 5.179, 7.197,
10.00, 13.89, 19.31, 26.83, 37.28, 51.79,
71.97, 100.0, 138.9, 193.1, 268.3, 372.8,
517.9, 719.7, 1000., 1389., 1931., 2683.,
3728., 5179., 7197.)

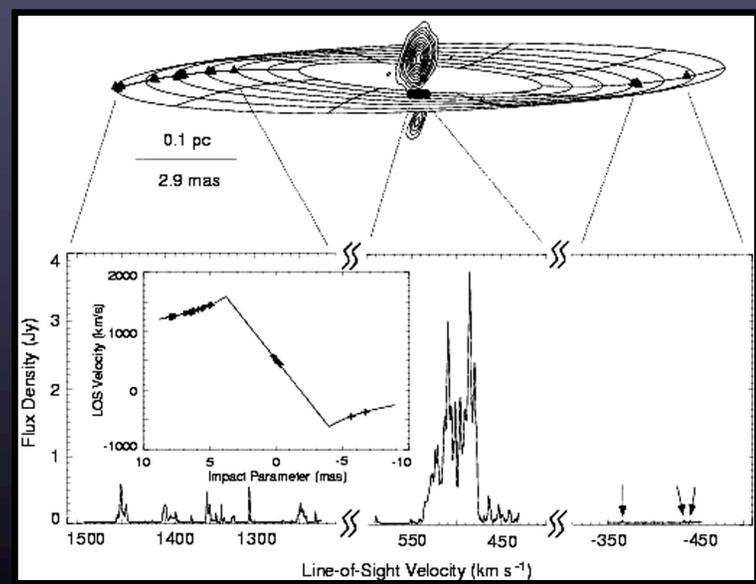
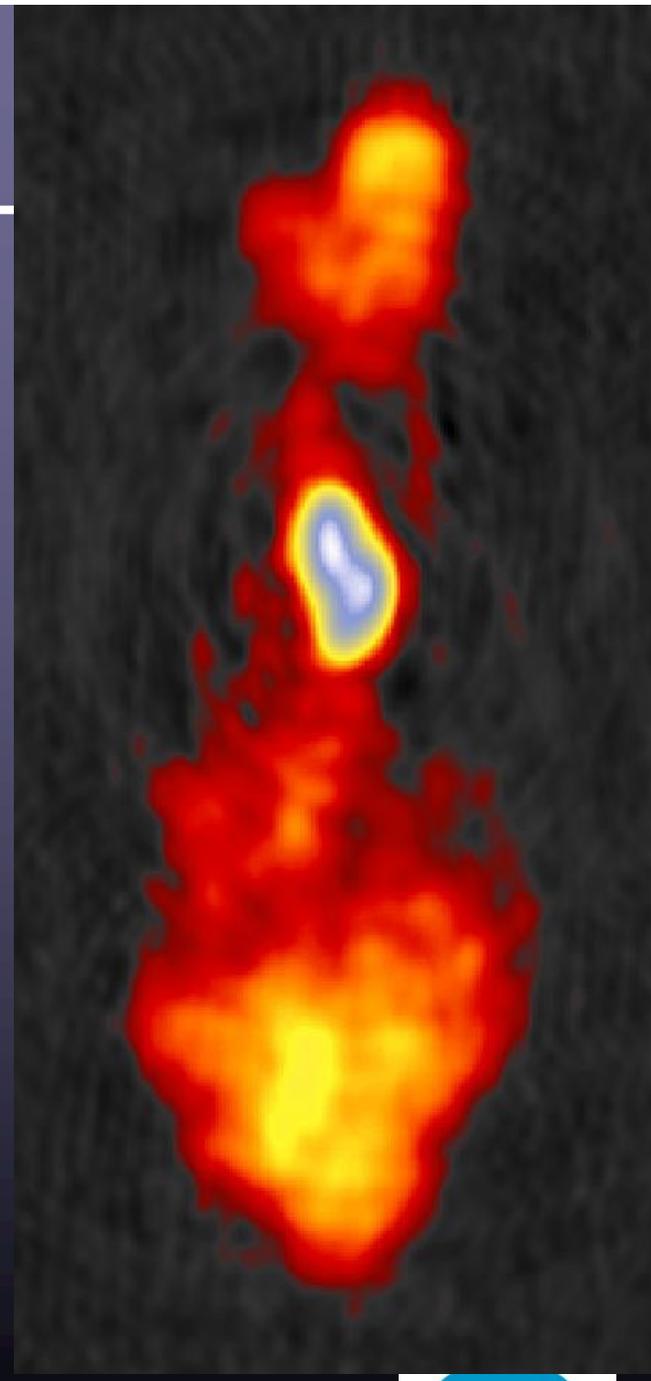
SCHEDULING

- PI provides the detailed observation sequence
- The schedule should include:
 - Fringe finders (strong sources - at least 2 scans – helps operations)
 - Amplitude check source (strong, compact source)
 - If target is weak, include a delay/rate calibrator
 - If target very weak, fast switch to a phase calibrator
 - For spectral line observations, include bandpass calibrator
 - For polarization observations, calibrate instrumental terms
 - Get good Parallactic angle coverage on polarized source or
 - Observe an unpolarized source
 - Absolute polarization position angle calibrator (Get angle from VLA)
- Leave occasional gaps for readback tests (2 min)





THE END



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Further Reading

- <http://www.nrao.edu/whatisra/mechanisms.shtml>
- <http://www.nrao.edu/whatisra/>
- www.nrao.edu

- Synthesis Imaging in Radio Astronomy
- ASP Vol 180, eds Taylor, Carilli & Perley

