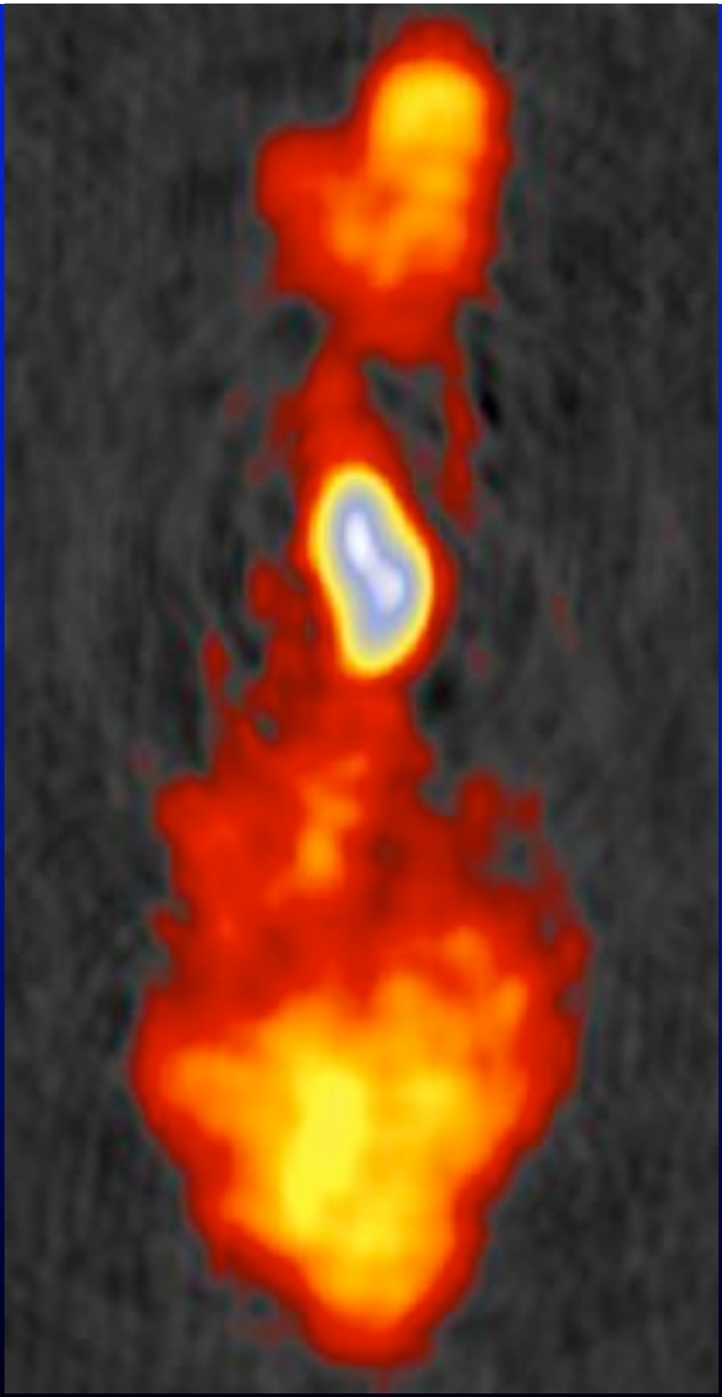
VERY LONG BASELINE INTERFEROMETRY

Craig Walker



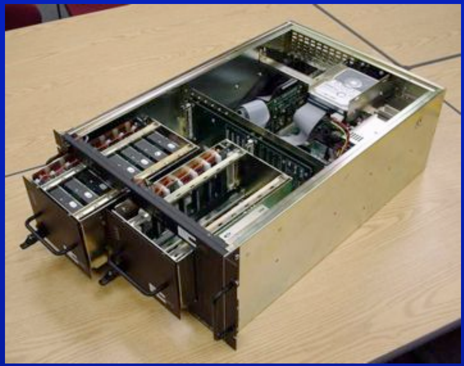
Summer Student Lecture

Socorro, July 2, 2009

Adapted from 2004 Summer School Lecture and 2005 and 2007 Summer Student Lectures

WHAT IS VLBI?

- Radio interferometry with unlimited baselines
  - High resolution – milliarcsecond (mas) or better
    - Resolve a finger nail in Los Angeles from New York
  - Baselines up to an Earth diameter for ground based VLBI
  - Can extend to space (HALCA, VSOP2)
  - Sources must have high brightness temperature
- Traditionally uses no IF or 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

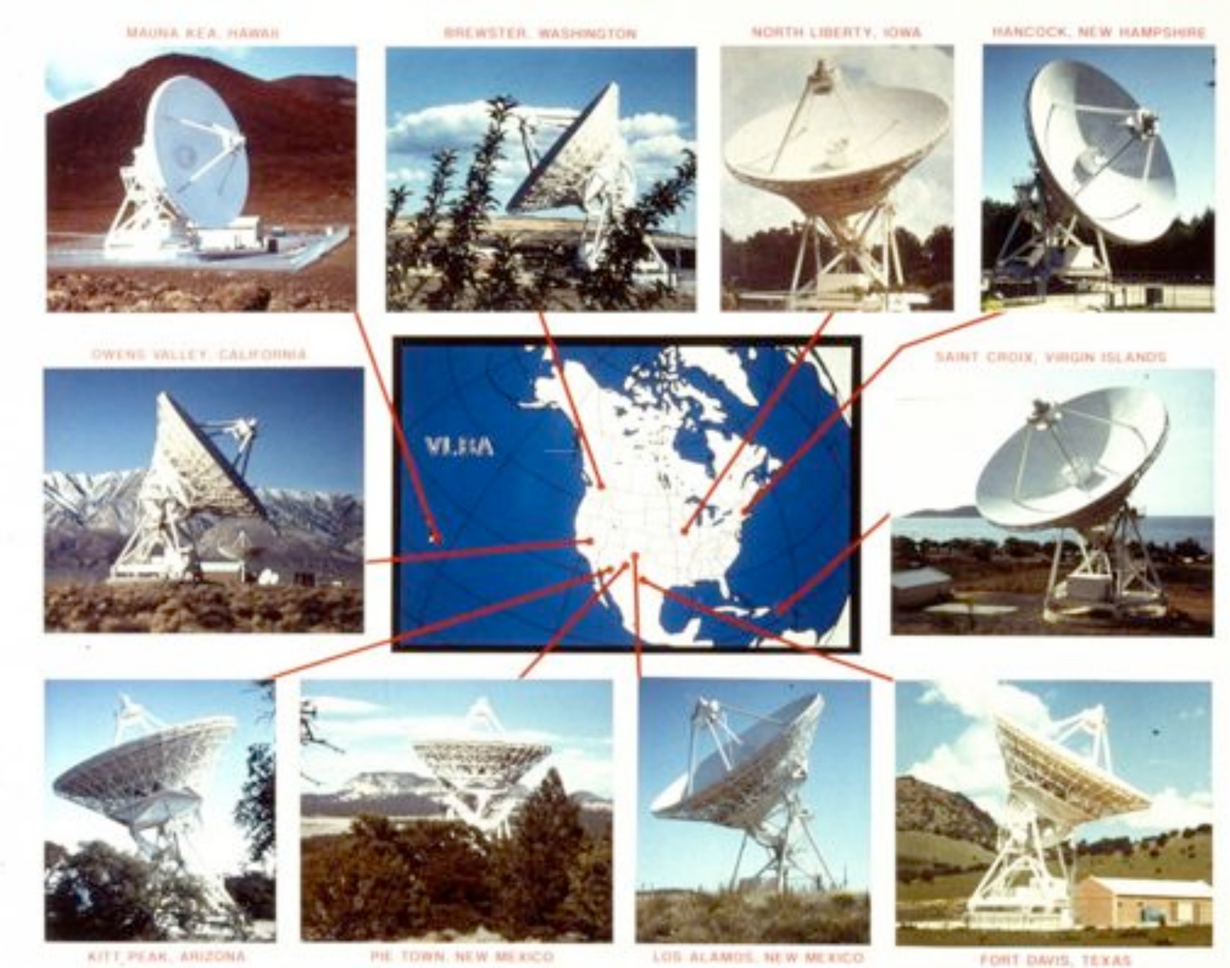
Maser

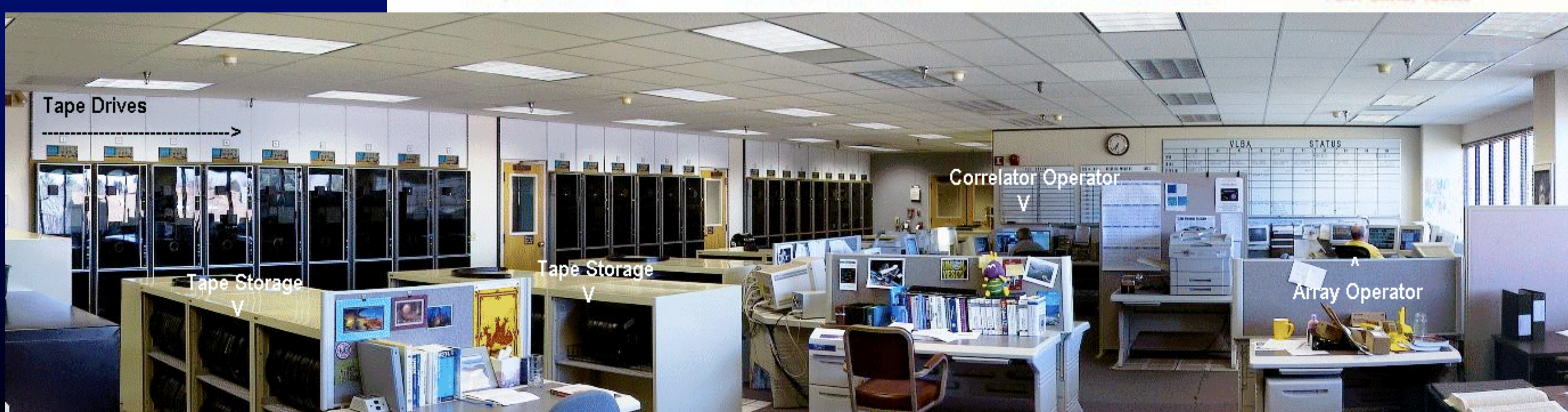
The VLBA

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

National Radio
Astronomy Observatory

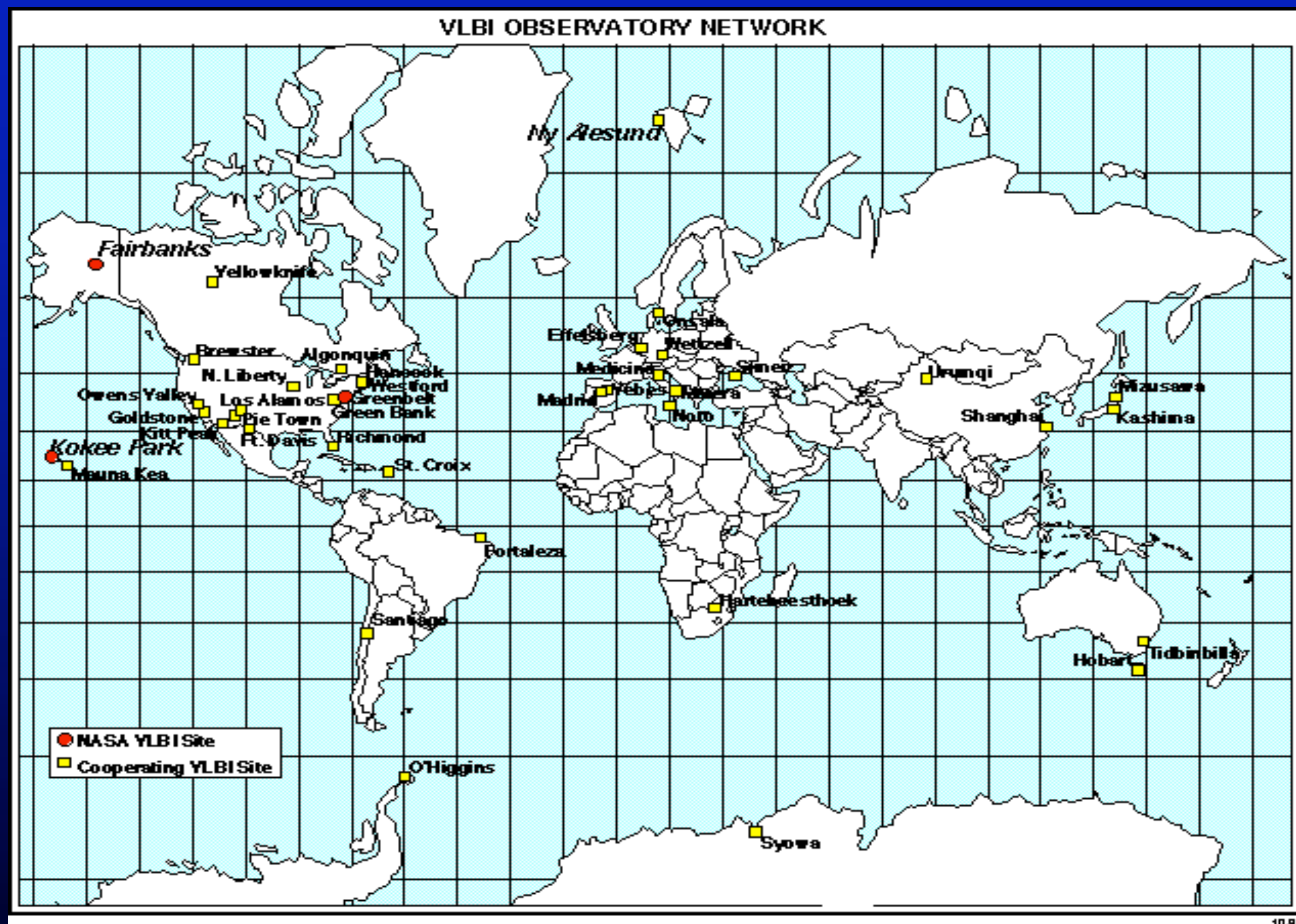
A Facility of the
National Science
Foundation



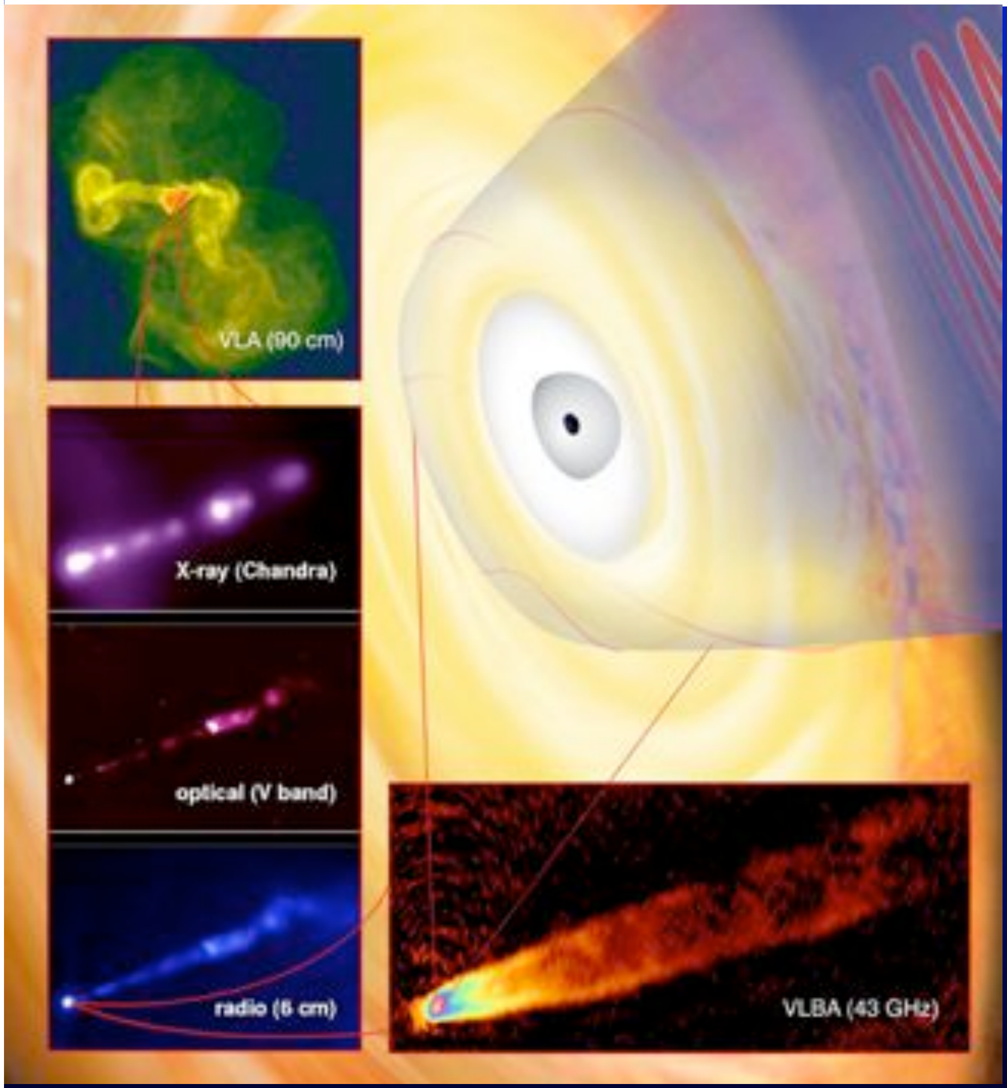


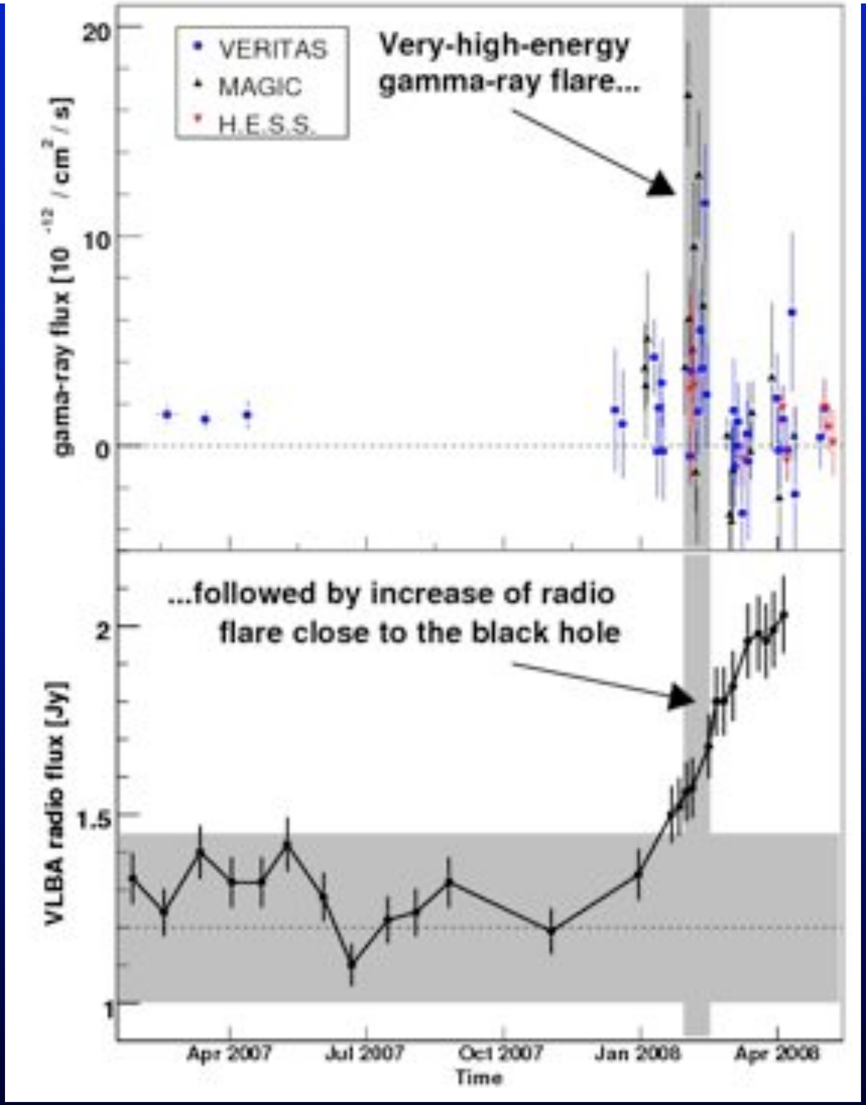
GLOBAL VLBI STATIONS

Geodesy stations. Some astronomy stations missing, especially in Europe.

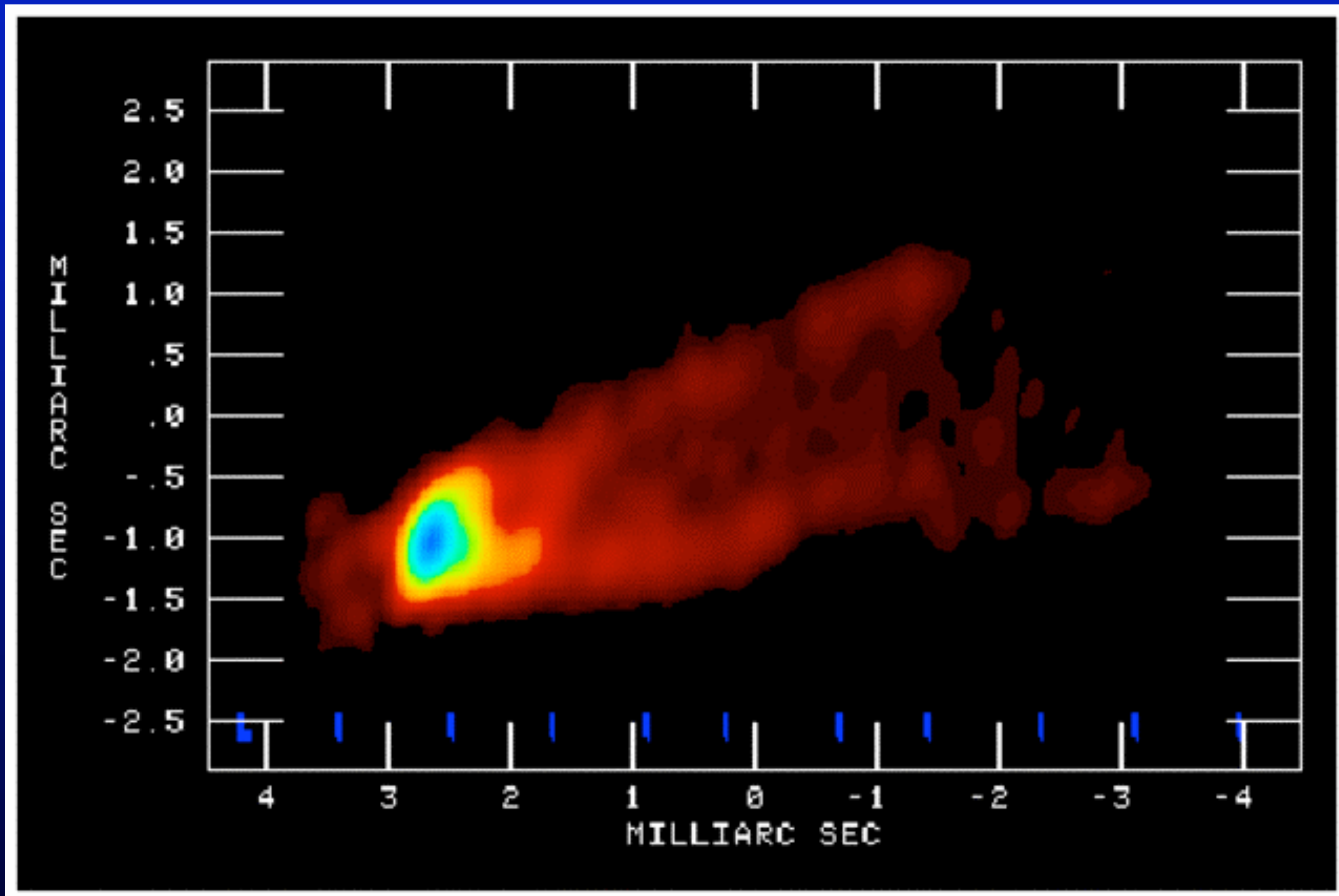


Today's Press Release and Science Express Publication
Location of TeV Emission in M87



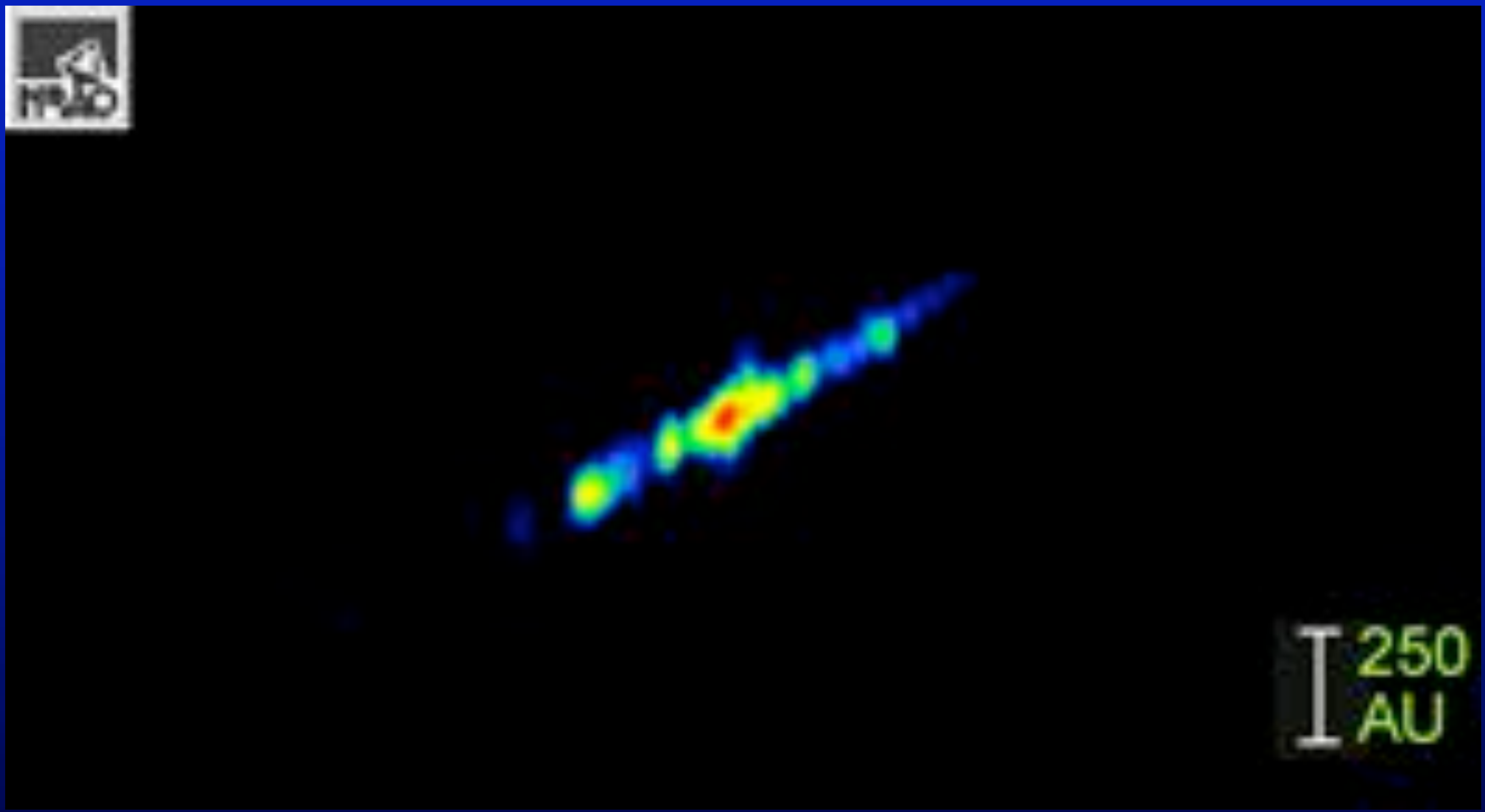


The VLBA 43 GHz M87 Movie First 11 Observations



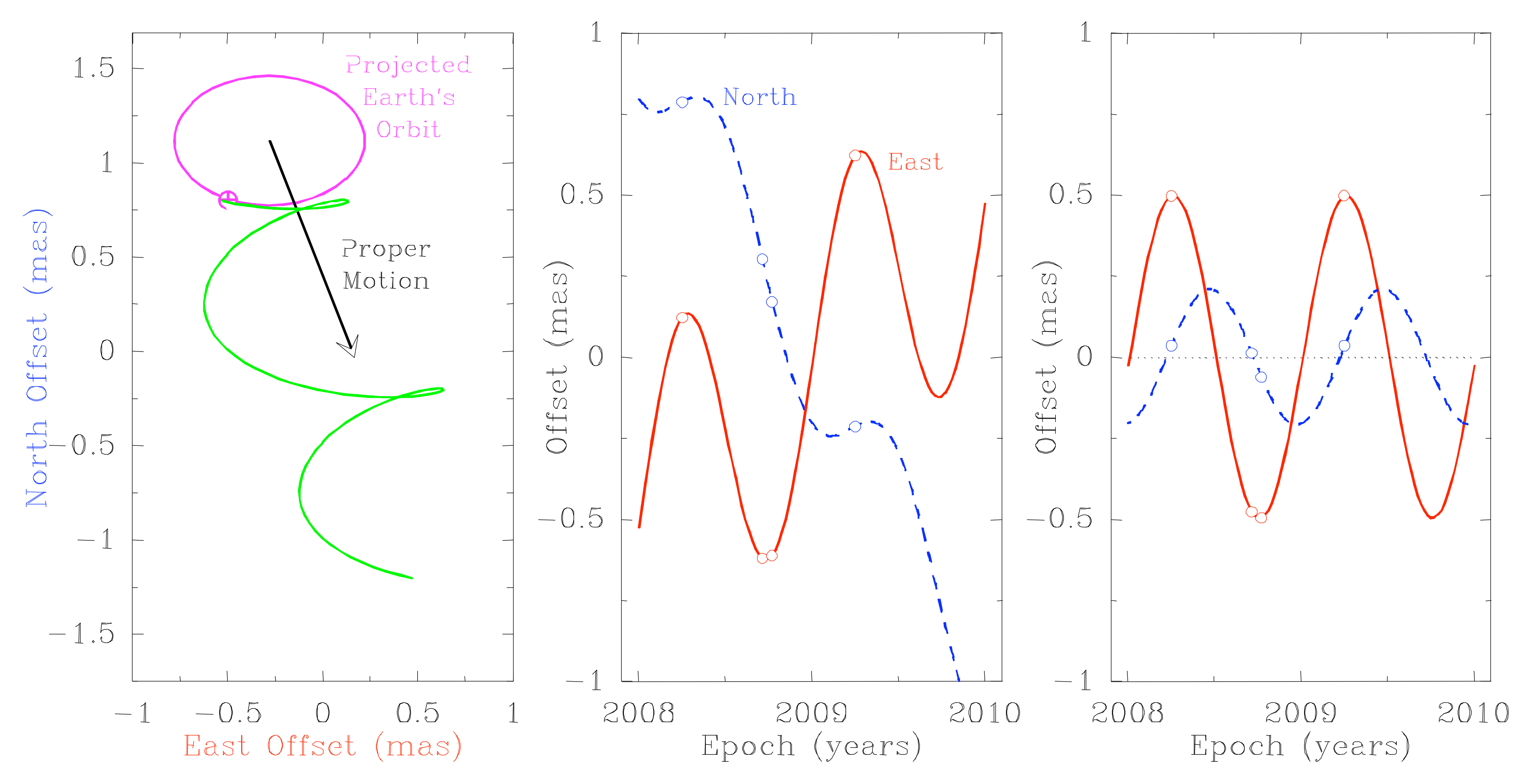
Beam: 0.43x0.21 mas   0.2mas = 0.016pc = 60R_s 1mas/yr = 0.25c

EXAMPLE 2:
JET DYNAMICS: THE SS433 MOVIE



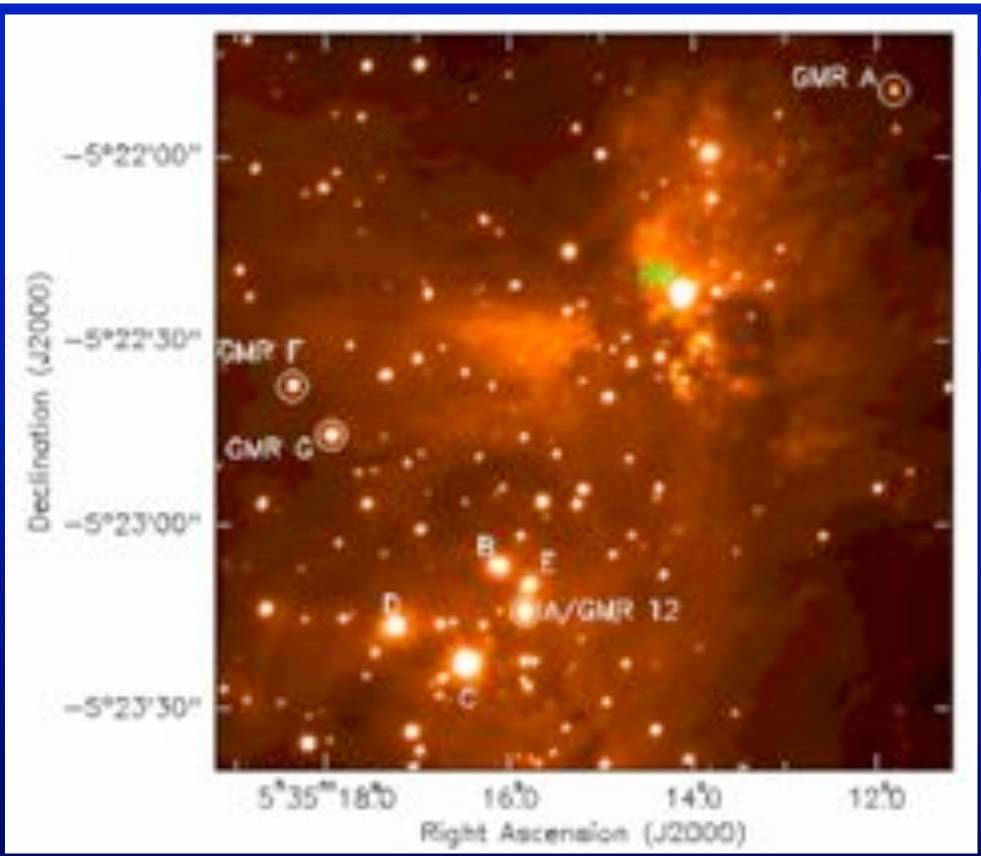
- Two hour snapshot almost every day for 40 days on VLBA at 1.7 GHz
  - Mioduszewski, Rupen, Taylor, and Walker

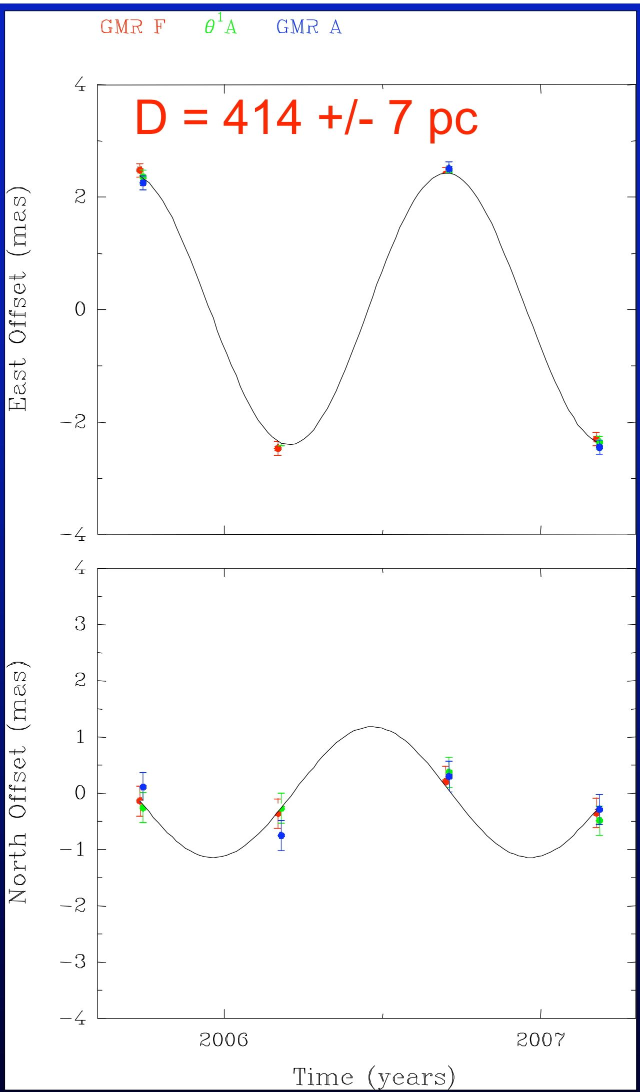
Measurement of Distance by Parallax



From M. Reid 2008 Summer School Lecture

Orion Nebular Cluster Parallax

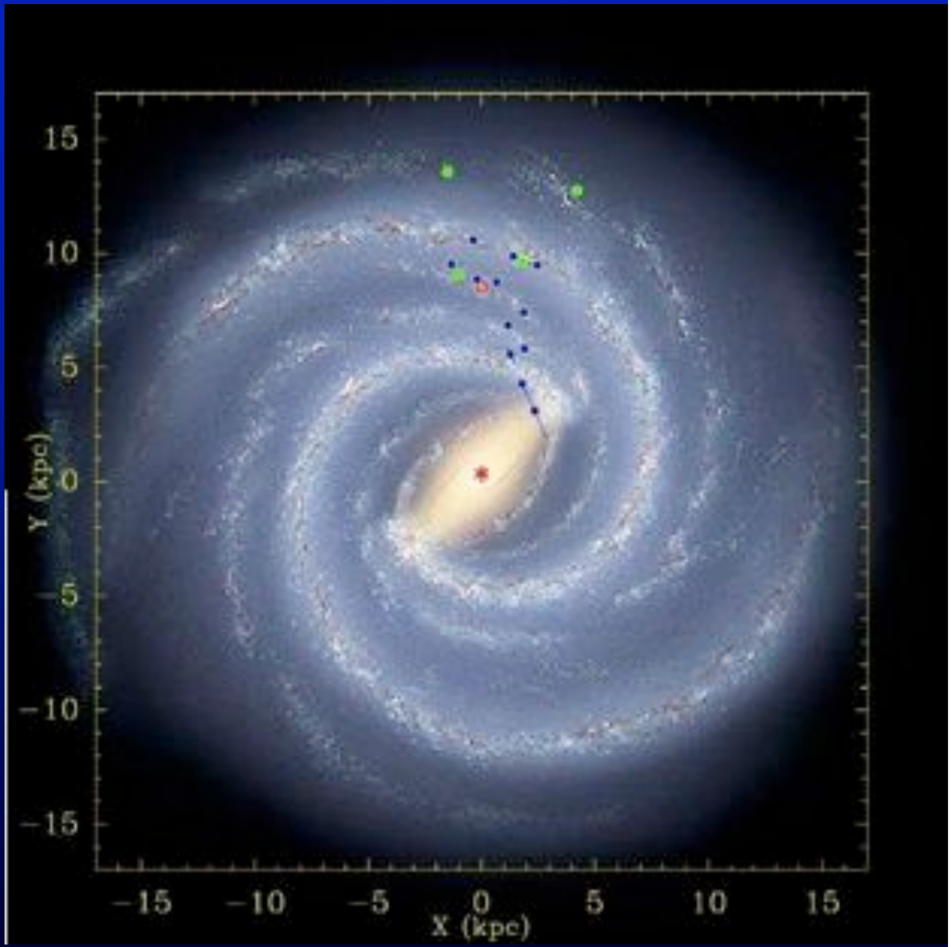




Menten, Reid, Forbrich & Brunthaler (2007)

Structure of the Milky Way and Local Group

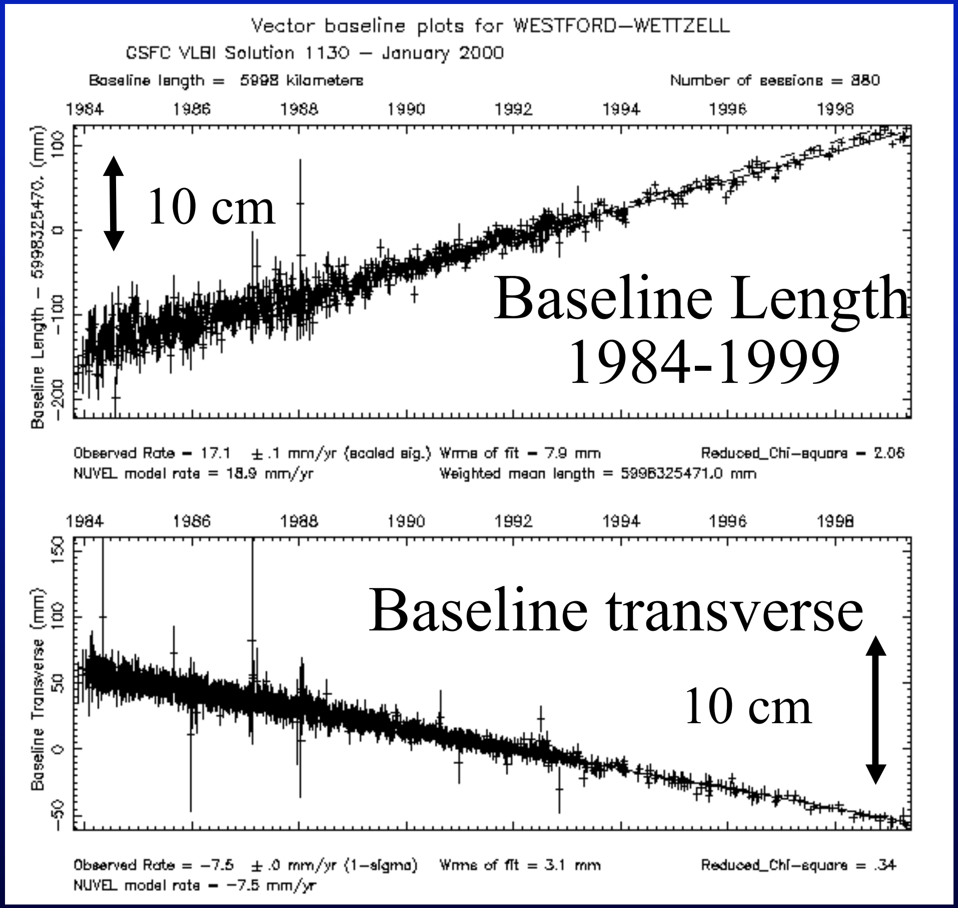
- Use masers to determine the 3D structure of the galaxy
  - Past work with 12 GHz methanol and 22 Ghz water lines
  - Future may be mainly the 6.7 GHz methanol line - masers stronger and more stable
  - Needs the 4-8 GHz receiver
  - Use wide bands for close calibrators



EXAMPLE 4
GEODESY and ASTROMETRY

- 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

VLBI and CONNECTED INTERFEROMETRY DIFFERENCES

VLBI is not fundamentally different from connected interferometry

- Differences are a matter of degree.

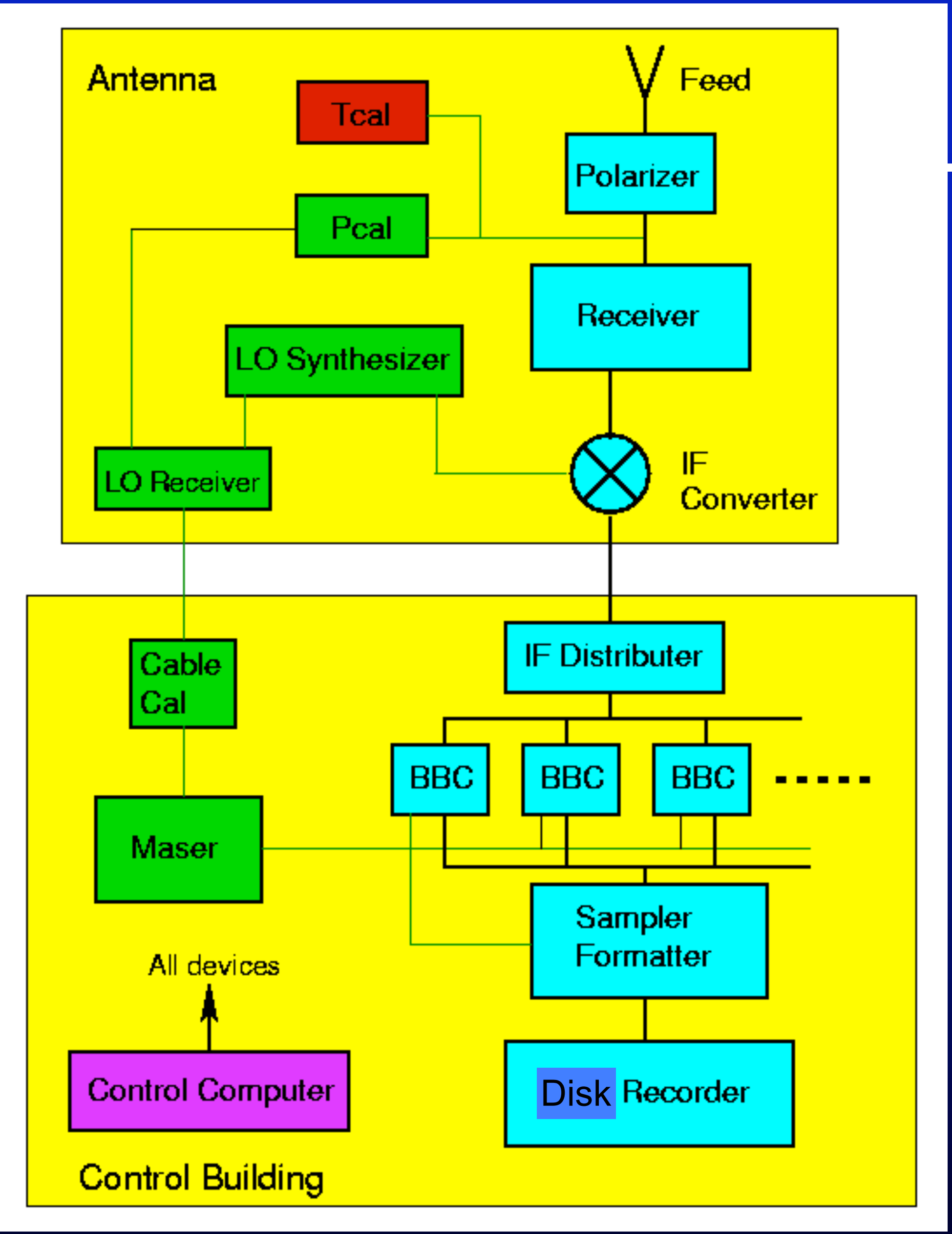
- Separate clocks – Cause phase variations
- Independent atmospheres (ionosphere and troposphere)
  - Phase fluctuations not much worse than VLA A array
  - Gradients are worse – affected by total, not differential atmosphere
  - Ionospheric calibration useful – dual band data or GPS global models
- Calibrators poor
  - Compact sources are variable – Flux calibrate using Tsys 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

VLBI and CONNECTED INTERFEROMETRY DIFFERENCES (CONTINUED)

- Phase gradients in time and frequency need calibration – fringe fit
- VLBI is not sensitive to thermal sources
  - 10^6 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
  - But sees the compact X-ray and γ-ray objects
- Even extragalactic sources change structure on finite time scales
  - The 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

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 for tape (64 track)
  - Record (Now on disk)
  - Also keep time and stable frequency
- Other systems conceptually similar
- Soon will upgrade BBCs, samplers, formatter, and recorder for wider bandwidth



VLBI CORRELATOR

JIVE Correlator in tape era

- Read disks
- Synchronize data
  - Apply delay model
    - Includes phase model $\phi = \upsilon\tau$
  - Correct for known Doppler shifts
    - Mainly from Earth rotation
    - This is the total fringe rate and is related to the rate of change of delay
- Generate cross and auto correlation power spectra
  - FX: FFT or filter, then cross multiply (VLBA, Nobeyama, ATA, GMRT)
  - XF: Cross multiply lags. FFT later (JIVE, Haystack, VLA, EVLA, ALMA …)
- Accumulate and write data to archive
- Some corrections may be required in postprocessing
  - Data normalization and scaling (Varies by correlator)
  - Corrections for sampler level offsets (ACCOR in AIPS)

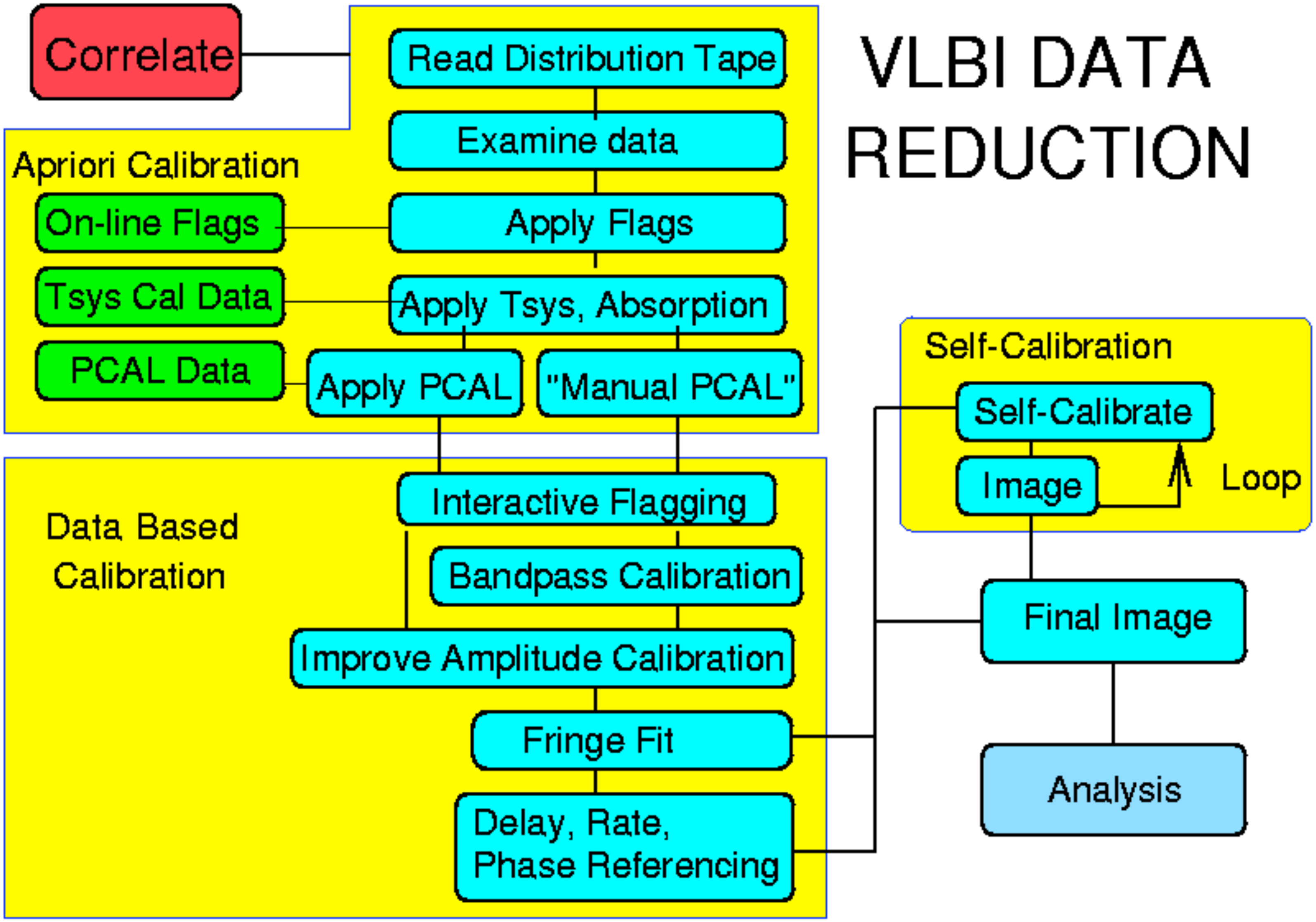
THE DELAY MODEL

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	$\sim$ 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	$\sim$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	$\sim$ 1.2 years
UT1 (Earth rotation)	Several mas	Various
Ionosphere	$\sim$ 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

VLBI DATA REDUCTION



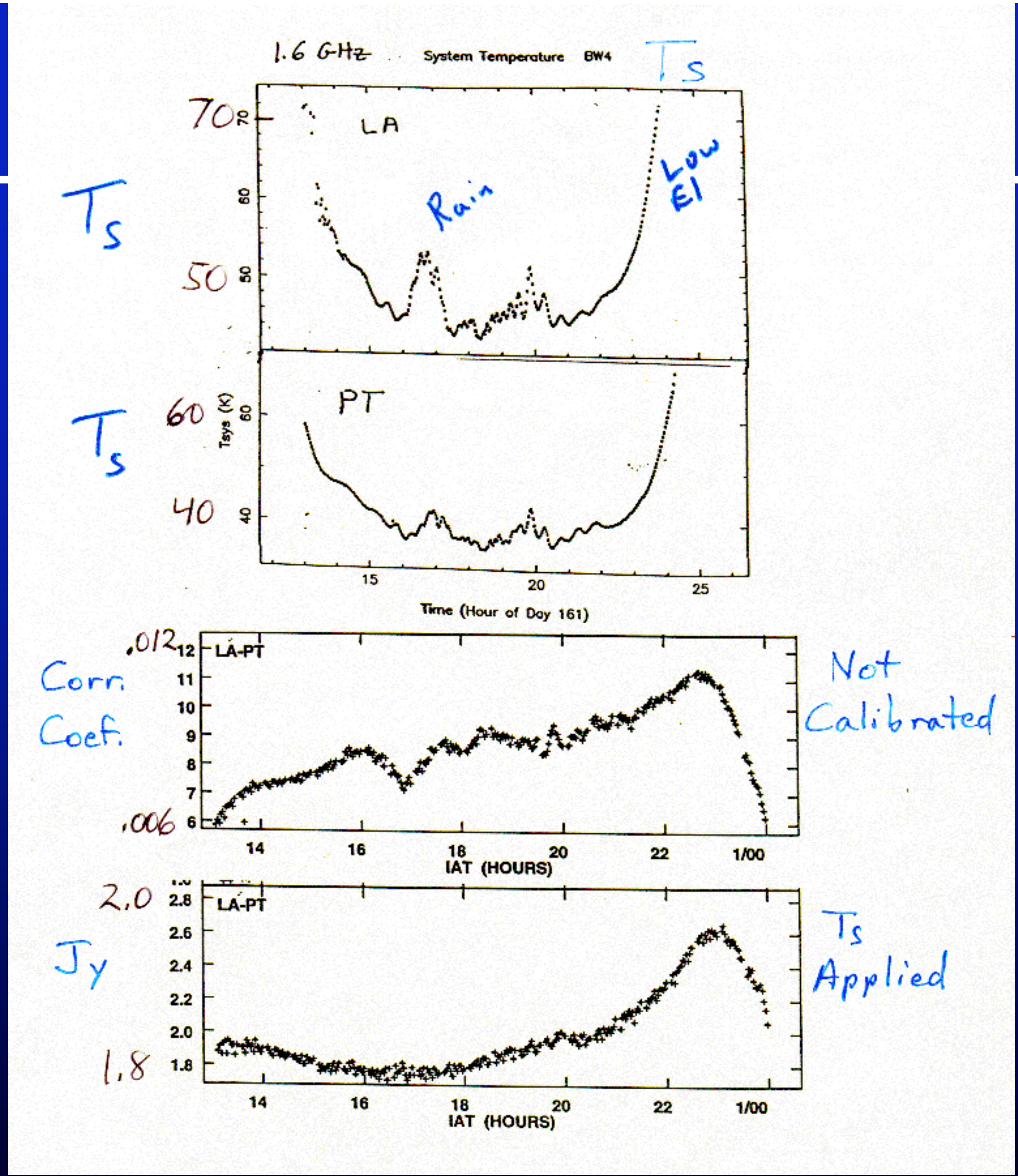
VLBI Amplitude Calibration

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

- S_{cij} = 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 Tsys

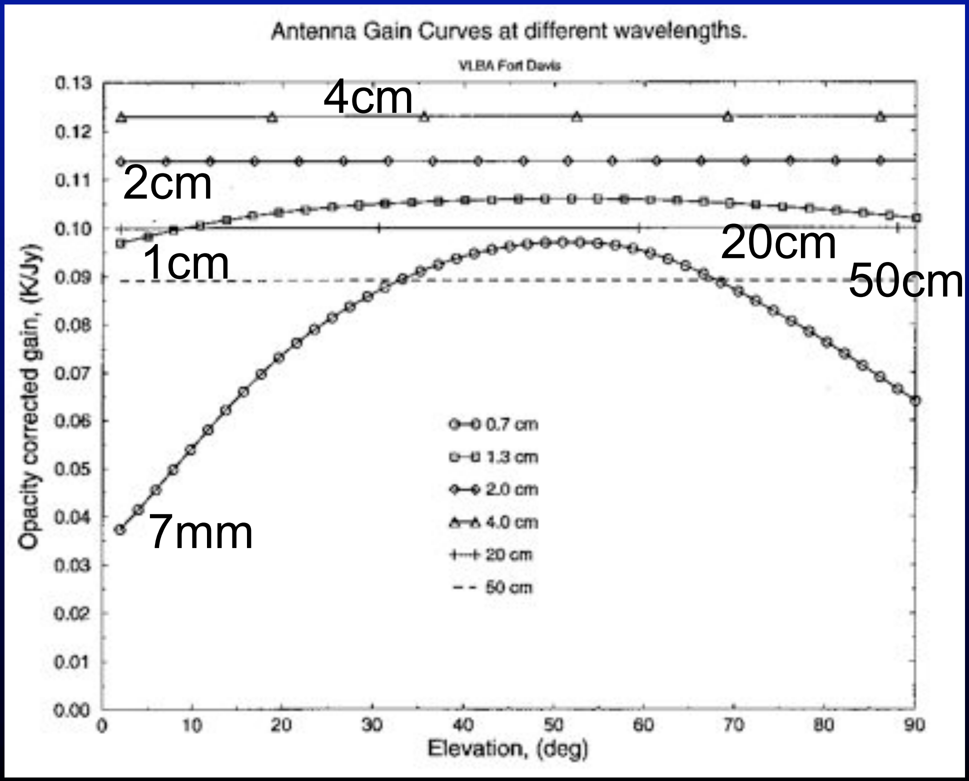
Example shows removal of effect of increased Ts due to rain and low elevation



GAIN CURVES AND OPACITY CORRECTION

VLBA gain curves

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

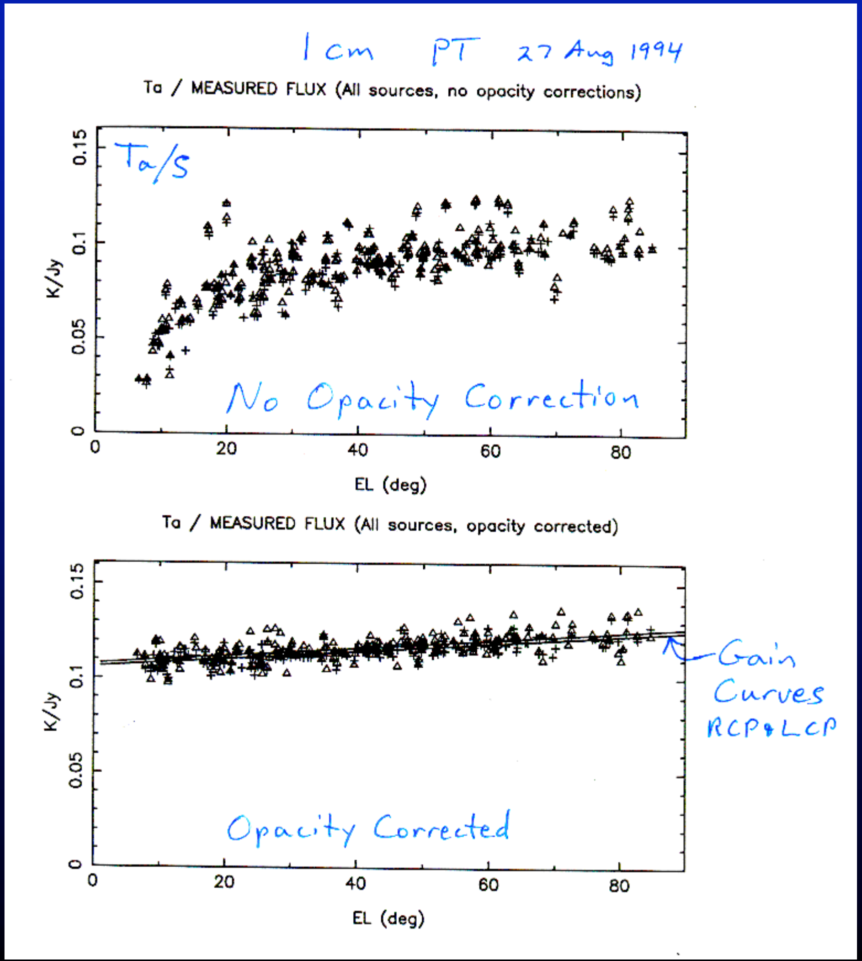


Atmospheric opacity

Correcting for absorption by the atmosphere

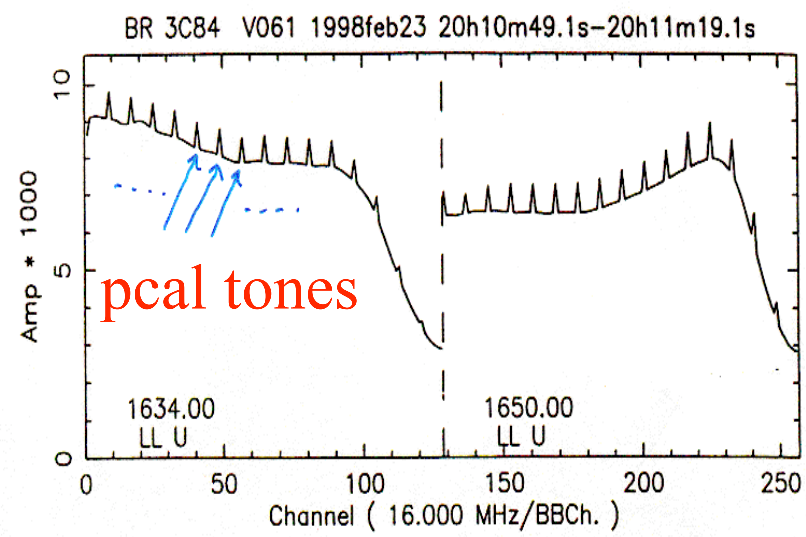
Can estimate using Ts – Tr – Tspill

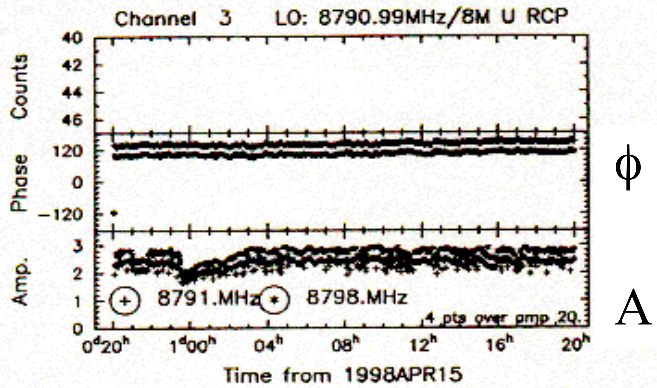
Example from single-dish VLBA pointing data



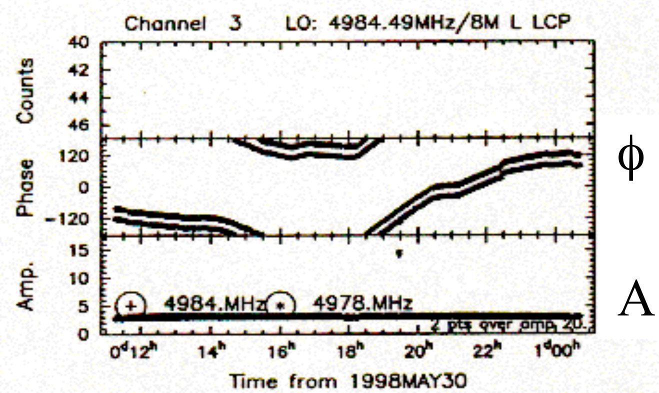
PULSE CAL SYSTEM

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



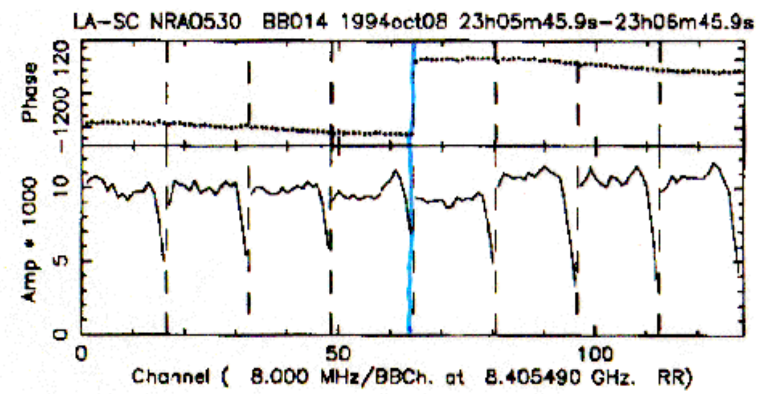


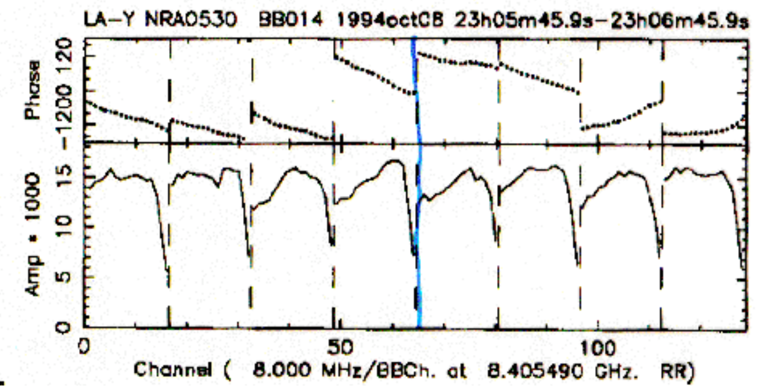
Pulse cal monitor data



Long track at non-VLBA station

Data Aligned using Pulse Cal

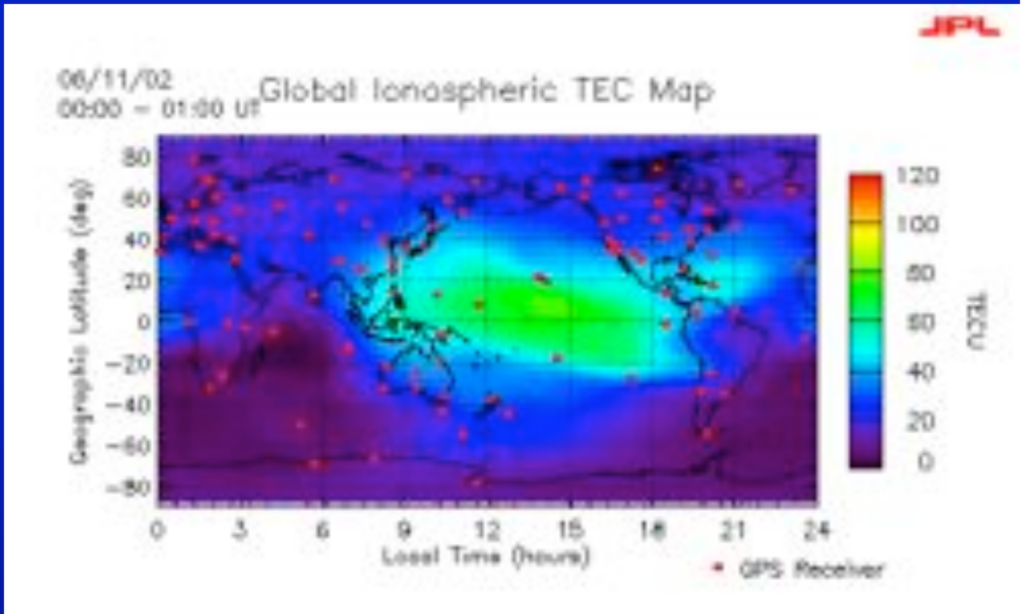




No PCAL at VLA. Shows unaligned phases

IONOSPHERIC DELAY

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

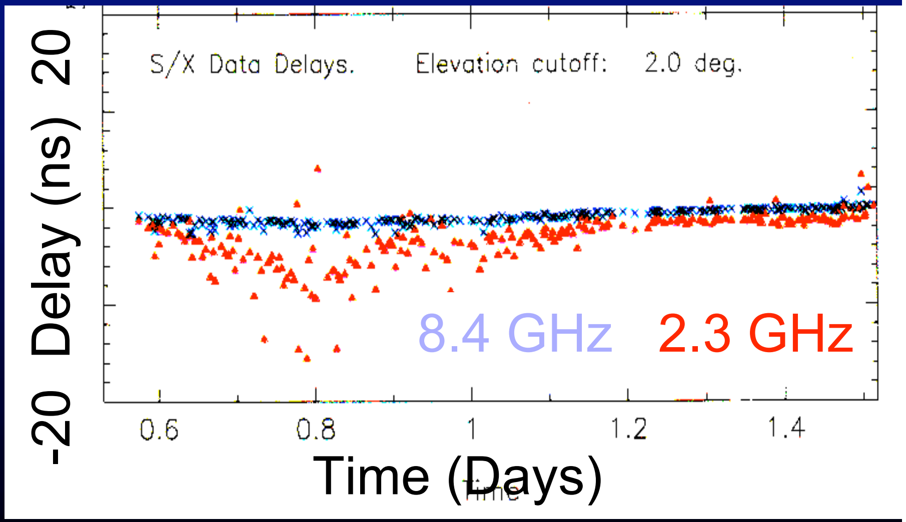


Ionosphere map from iono.jpl.nasa.gov

Maximum Likely Ionospheric Contributions

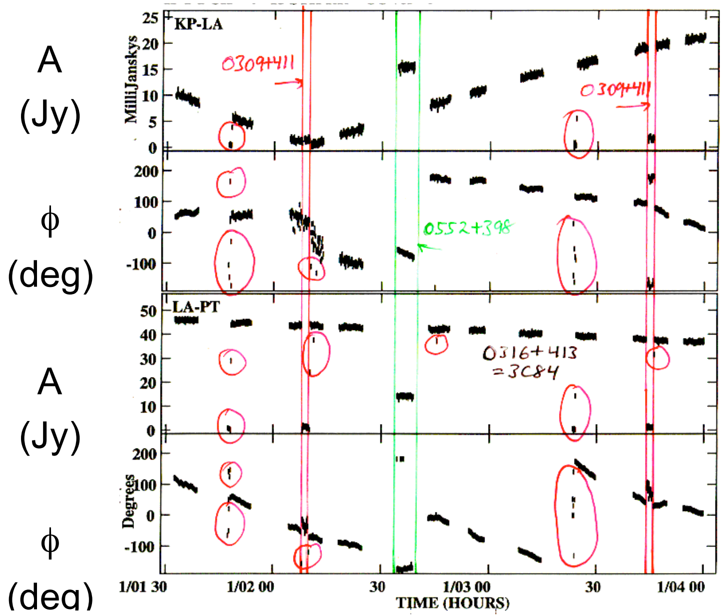
Freq GHz	Day Delay ns	Night Delay ns	Day Rate mHz	Night Rate mHz
0.327	1100	110	12	1.2
0.610	320	32	6.5	0.6
1.4	60	6.0	2.8	0.3
2.3	23	2.3	1.7	0.2
5.0	5.0	0.5	0.8	0.1
8.4	1.7	0.2	0.5	0.05
15	0.5	0.05	0.3	0.03
22	0.2	0.02	0.2	0.02
43	0.1	0.01	0.1	0.01

Delays from an S/X Geodesy Observation

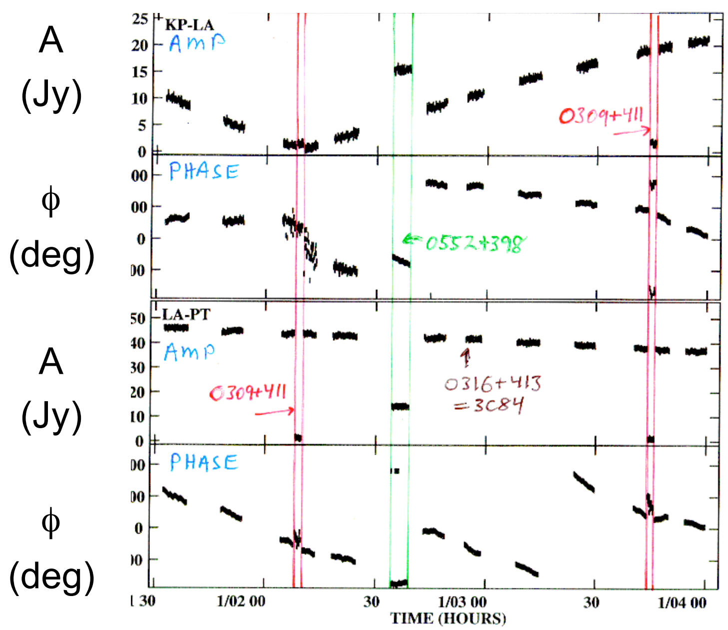


EDITING

Raw Data - No Edits



Raw Data - Edited

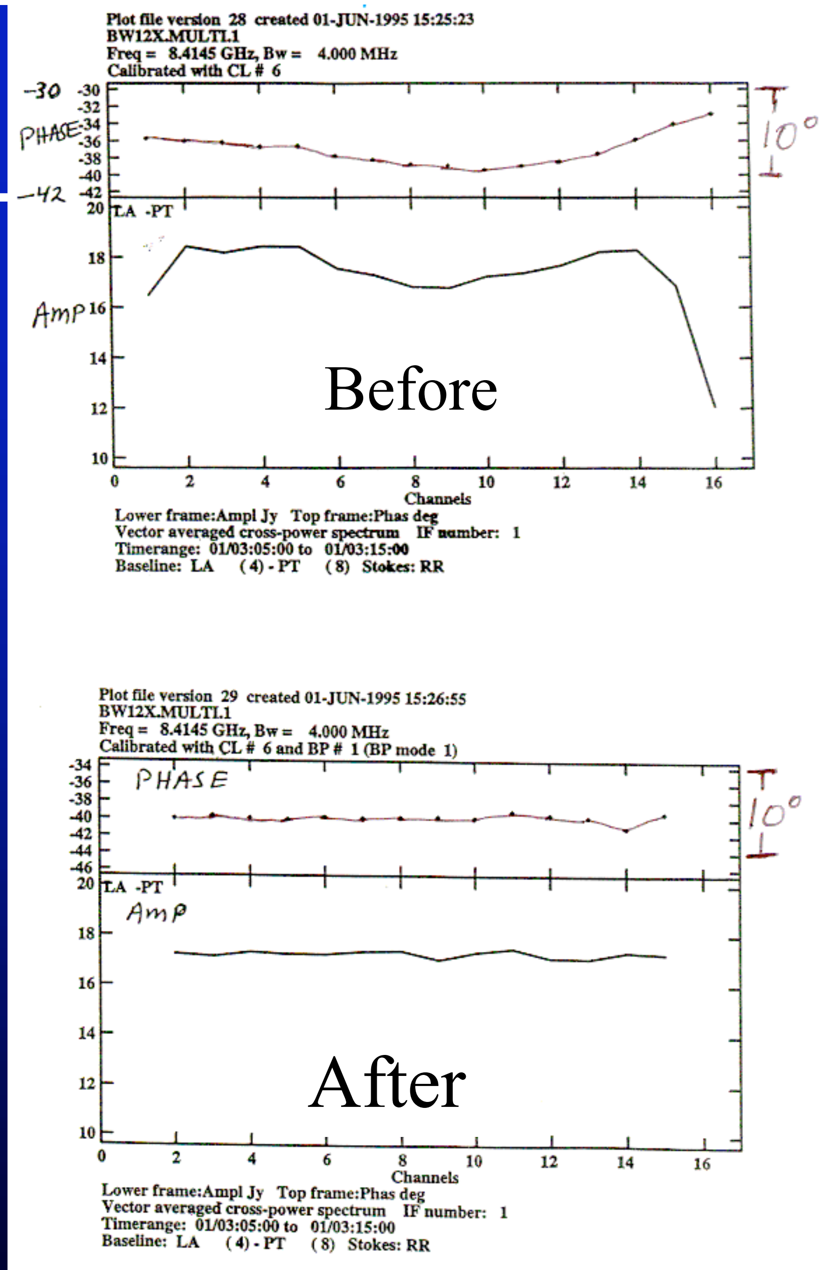


- Flags from on-line system will remove most bad data. Examples:
  - Antenna off source
  - Subreflector out of position
  - Synthesizers not locked
- Final flagging done by examining data
  - Flag by antenna
    - Most problems are antenna based
  - Poor weather
    - Examine Tsys and rain data
  - Bad playback
  - RFI (May need to flag by channel)
  - First points in scan sometimes bad
- For phase referencing, flag target if calibrator bad.

BANDPASS CALIBRATION

Covered in detail in another lecture(?)

- 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.

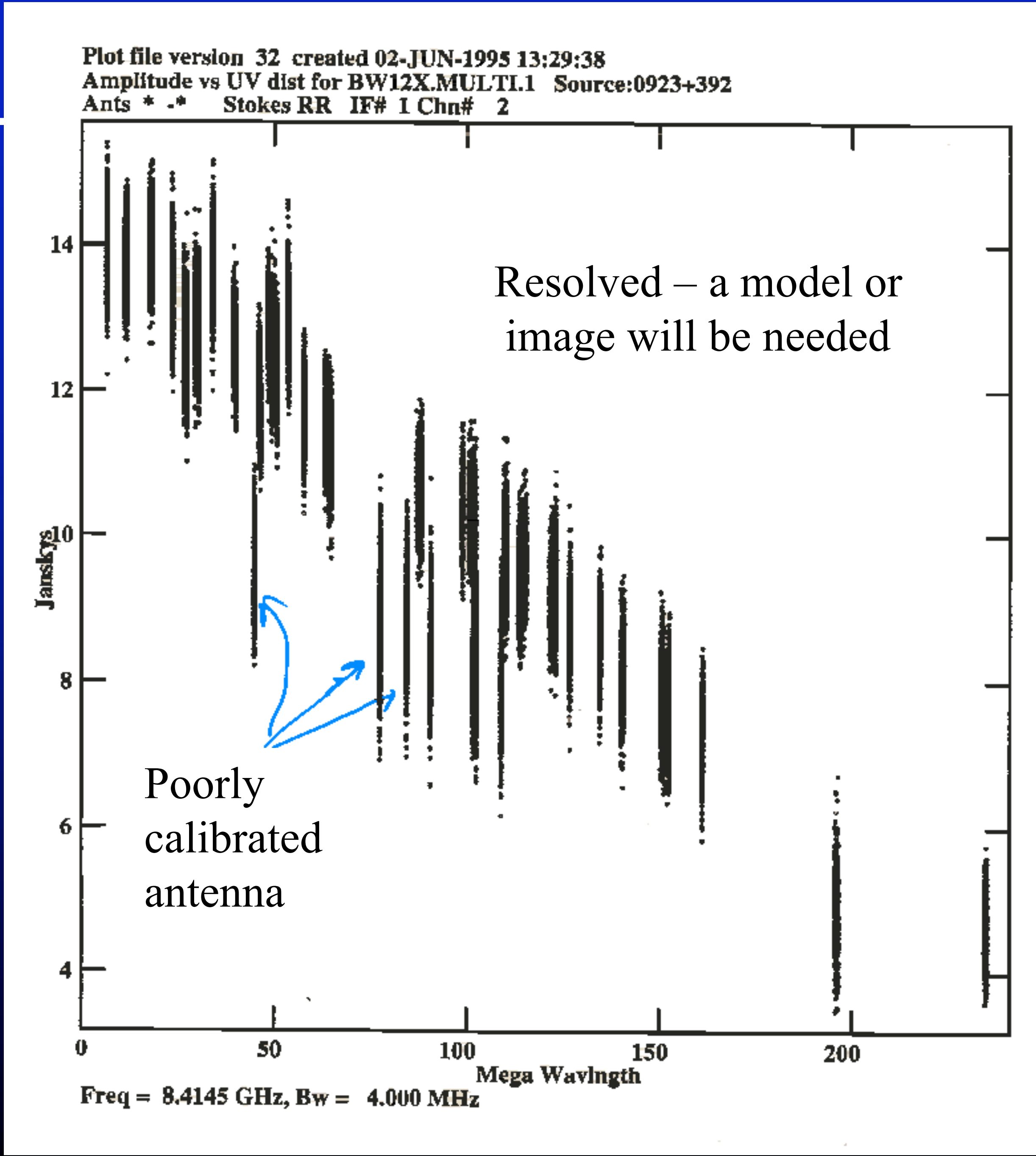


AMPLITUDE CHECK SOURCE

Typical calibrator visibility function after a priori calibration

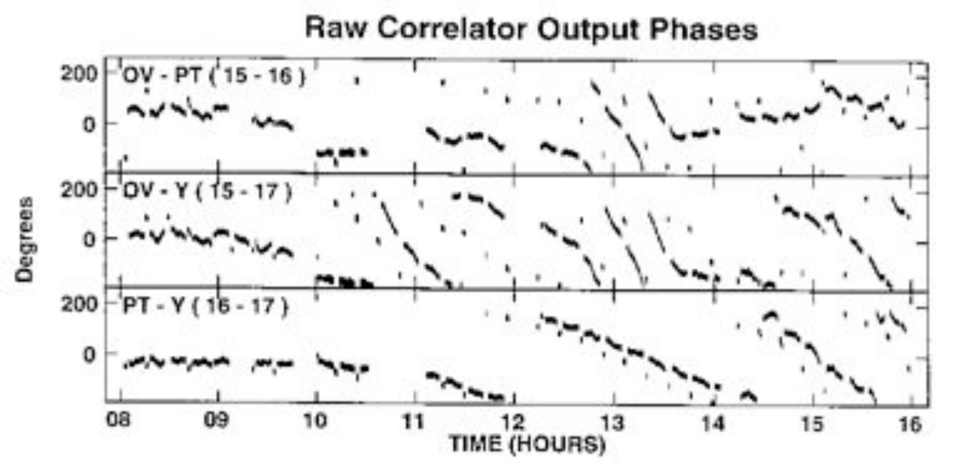
- Calibrator is resolved
- Will need to image
- One antenna low
- Use calibrator to fix

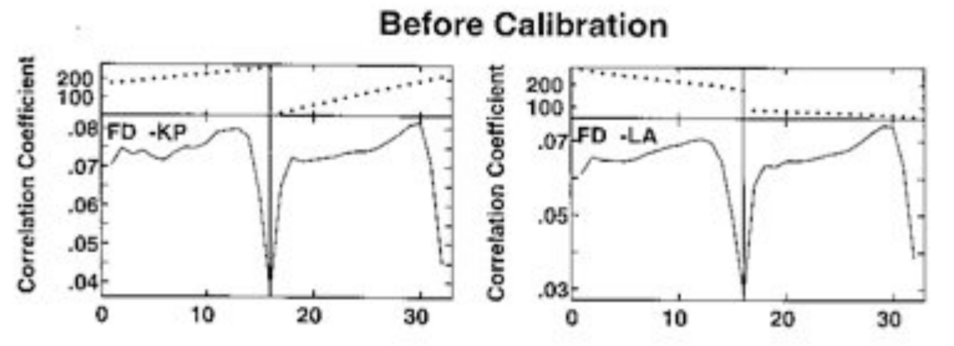
Shows why flux scale (gain normalization) should only be set by a subset of antennas



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 $\phi = \upsilon\tau$
    - 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

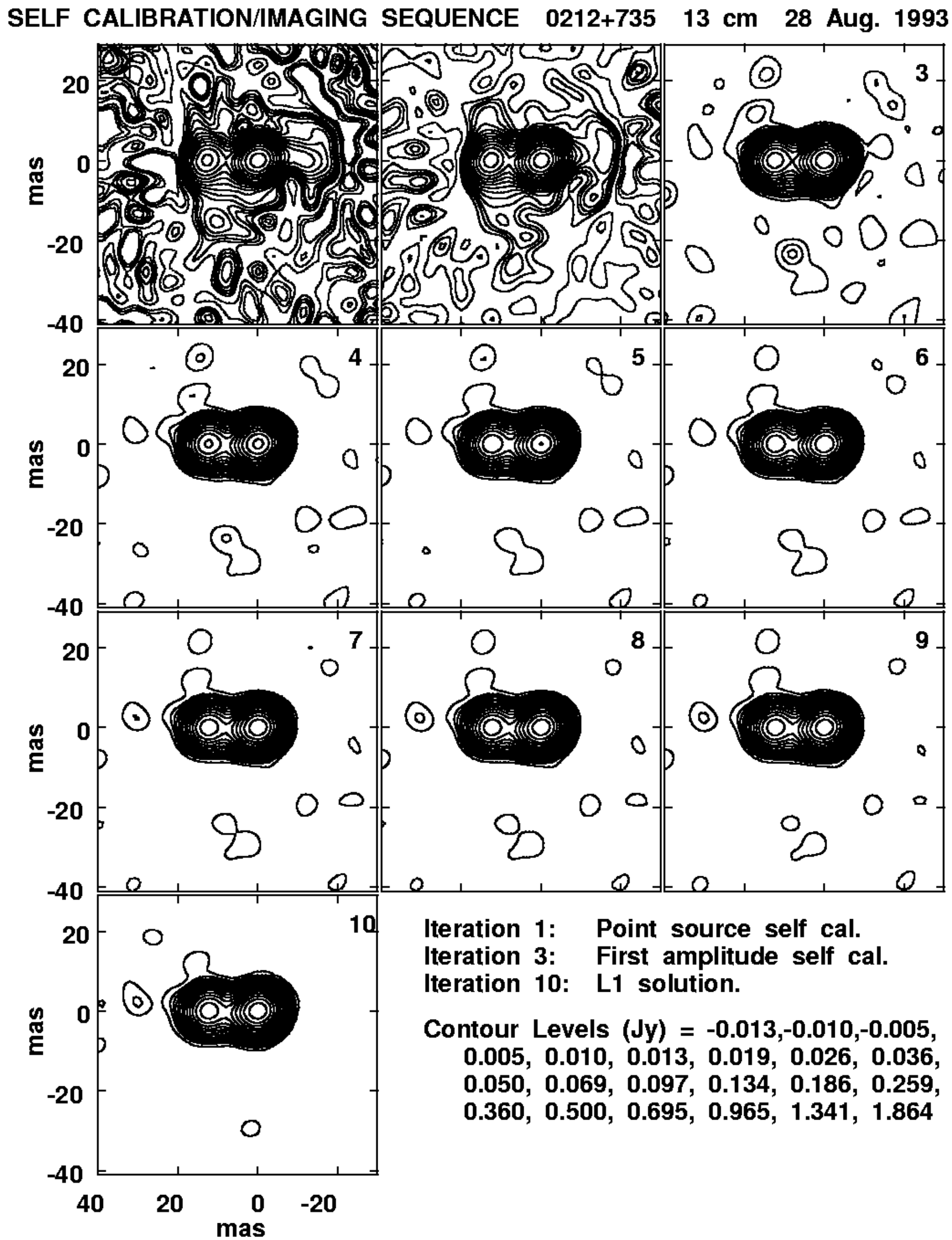
- Two step process (usually)
  1. 2D FFT to get estimated rates and delays to reference antenna
     - Required for start model for least squares
     - Can restrict window to avoid high sigma noise points
     - Can use just baselines to reference antenna or can stack 2 and even 3 baseline combinations
  2. 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

SELF CALIBRATION IMAGING

- Iterative procedure to solve for both image and gains:
  - Use best available image to solve for gains (can start with point)
  - Use gains to derive improved image
  - Should converge quickly for simple sources
    - Many iterations (~50-100) may be needed for complex sources
    - May need to vary some imaging parameters between iterations
    - Should reach near thermal noise in most cases
  - Can image even if calibration is poor or nonexistent
- Possible because there are *N* antenna gains and *N(N-1)/2* baselines
  - Need at least 3 antennas for phase gains, 4 for amplitude gains
  - Works better with many antennas
- Does not preserve absolute position or flux density scale
  - Gain normalization usually makes this problem minor
- Is required for highest dynamic ranges on all interferometers

Example Self Cal Imaging Sequence

- Start with phase only selfcal
- Add amplitude cal when progress slows (#3 here)
- Vary parameters between iterations
  - Taper, robustness, uvrange etc
- Try to reach thermal noise
  - Should get close

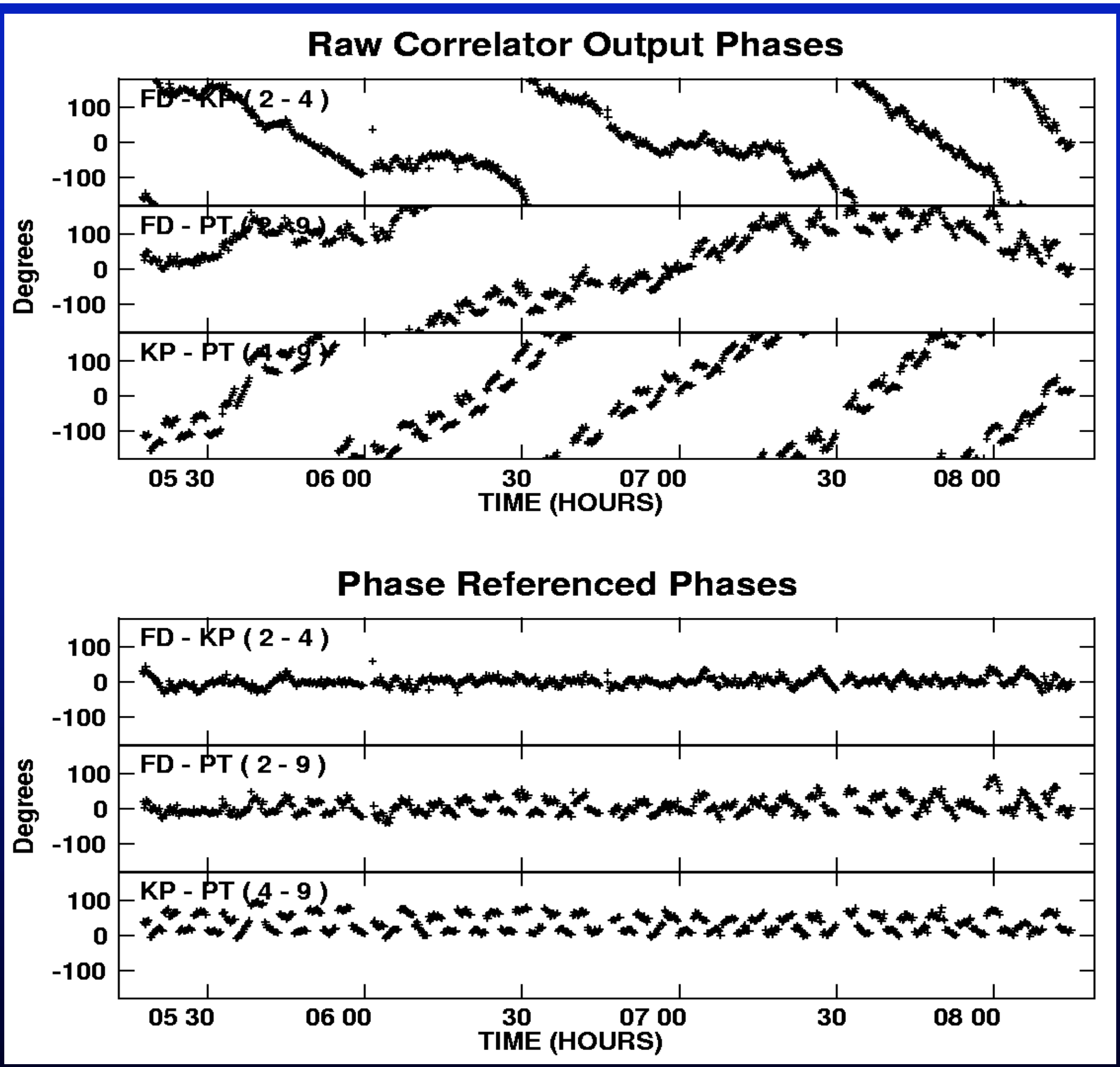


PHASE REFERENCING

- 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

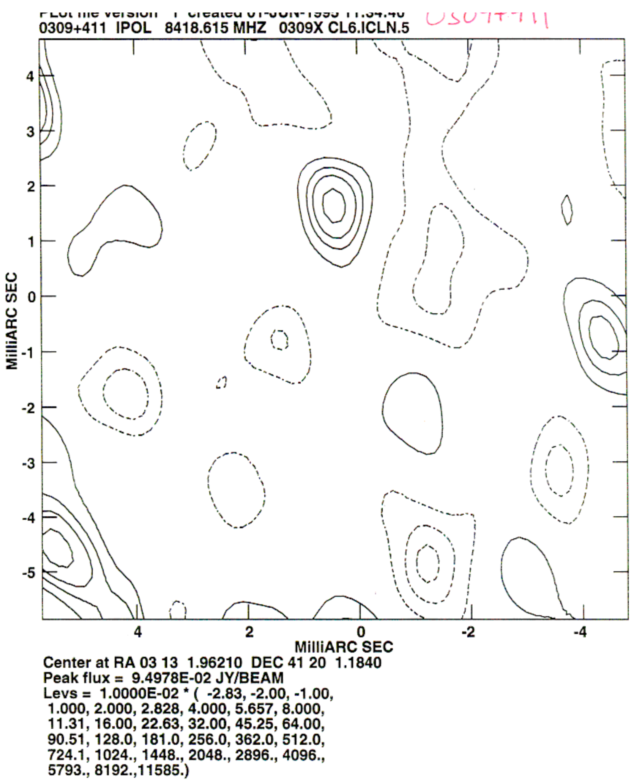
- 6 min cycle - 3 on each source
- Phases of one source self-calibrated (shift to near zero)
- Other source shifted by same amount



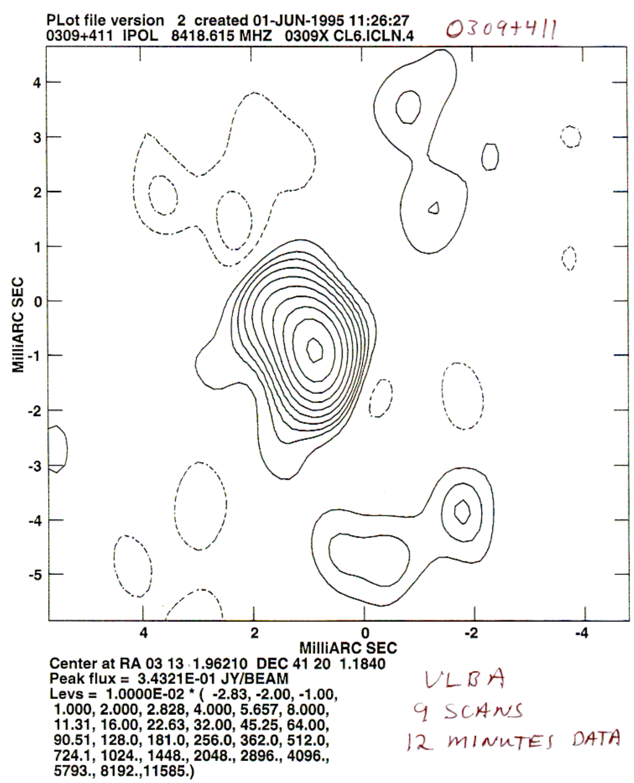
Phase Referencing Example

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

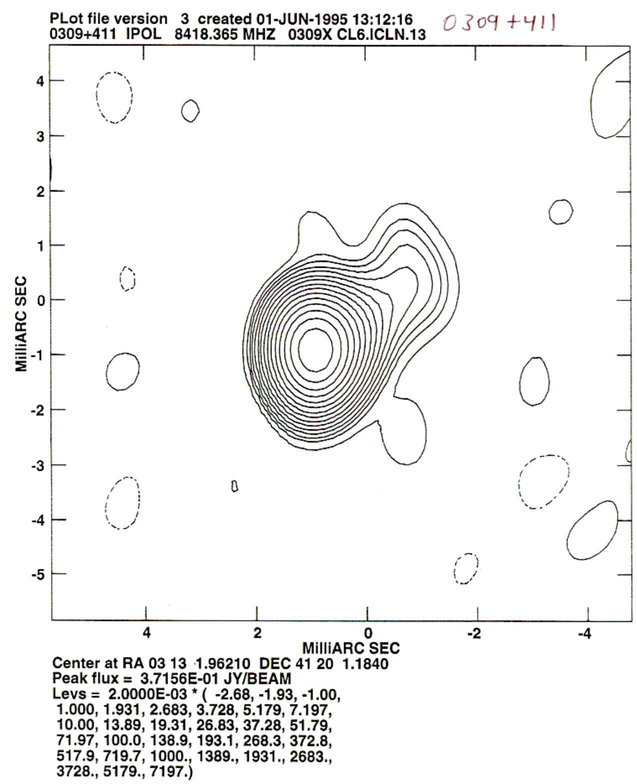
No Phase Calibration



Reference Calibration



Self-calibration

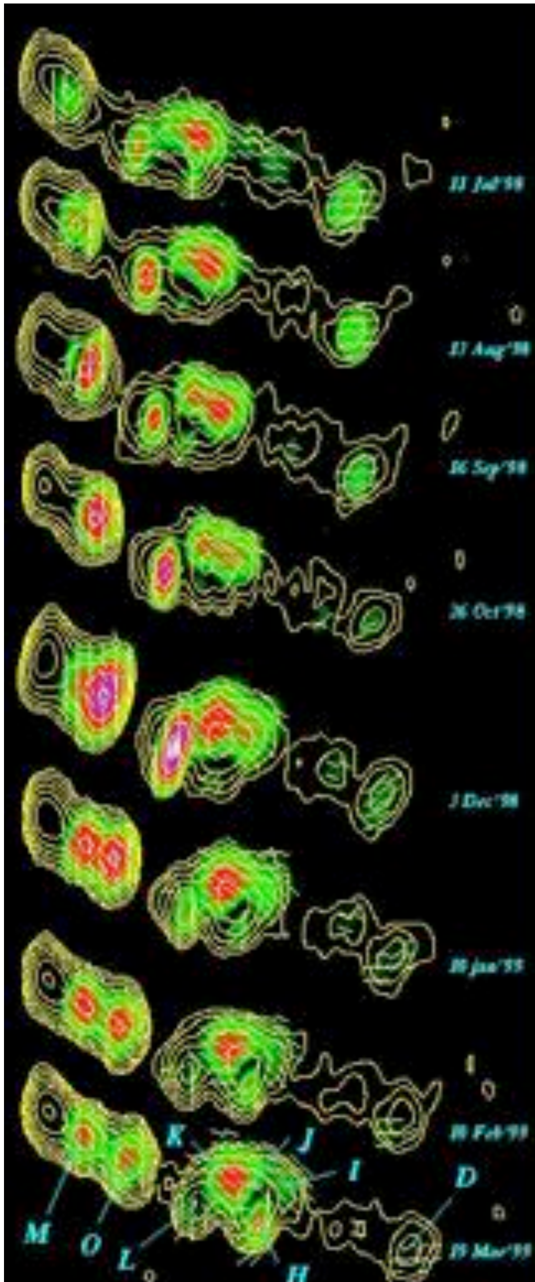


SCHEDULING

- 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)
- No longer need to worry about tape management.
  - With Mark5, only worry about total data volume

VLBA SENSITIVITY UPGRADE

- Increase bandwidth to 1 GHz (4 Gbps)
  - Current bandwidth 32 MHz sustainable, 128 MHz peak
  - Sensitivity increase by factor >5 (sustainable rates)
  - New digital backend (DBE)
  - New recording system (Mark5C)
  - New software correlator (DiFX)
  - The major cost is disk supply
- Improved 22 GHz amplifiers
  - About 30% sensitivity gain
  - MPIfR funding
  - Project finished in January 2008
- Proposed addition of 4-8 GHz EVLA style receivers



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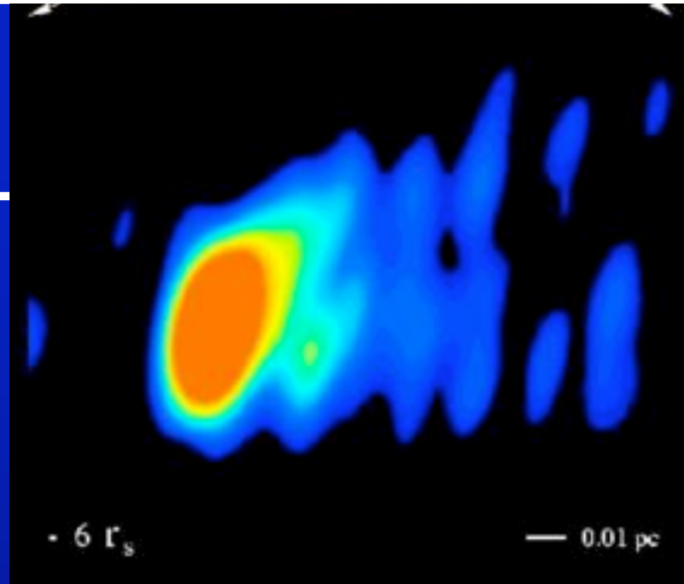
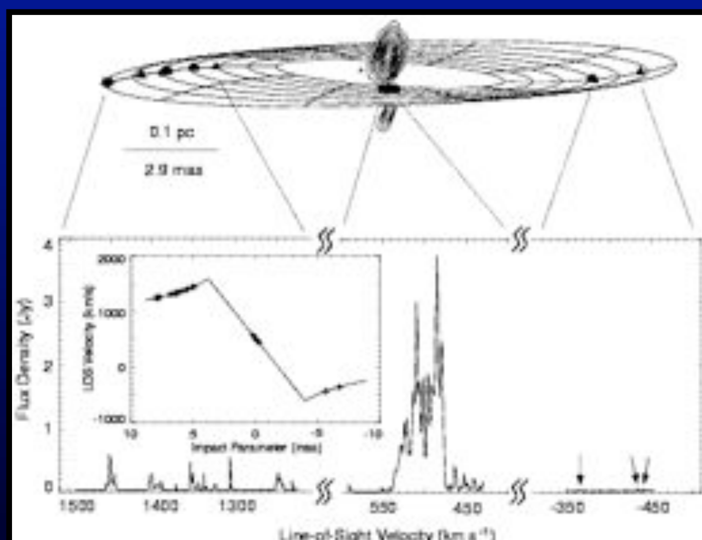
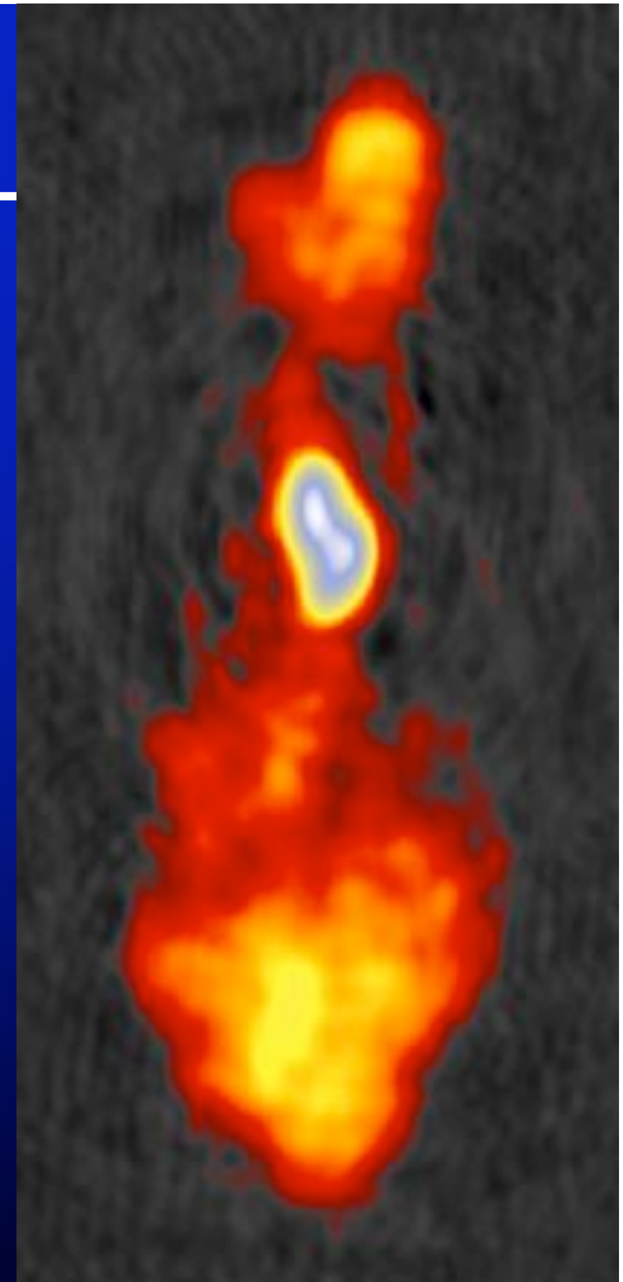


6 r_s
0.01 pc

THE END



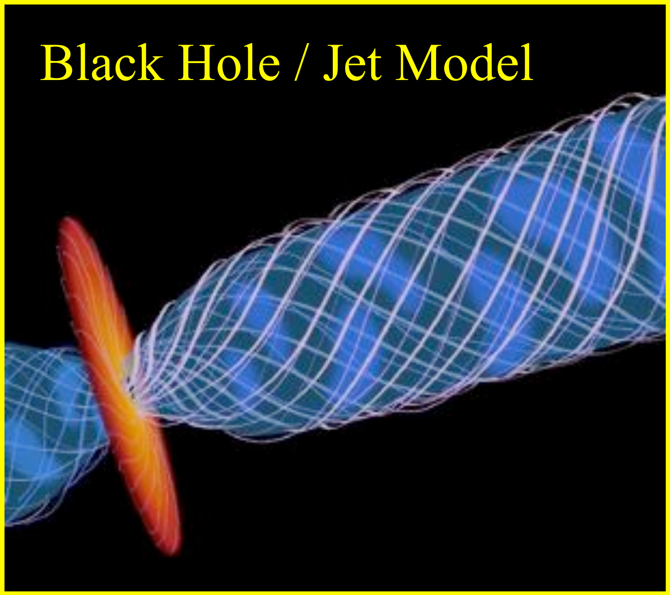
0.1 pc
2.9 mas
Flux Density (Jy)
LOS Velocity (km/s)
Impact Parameter (mas)
Line-of-Sight Velocity (km s⁻¹)

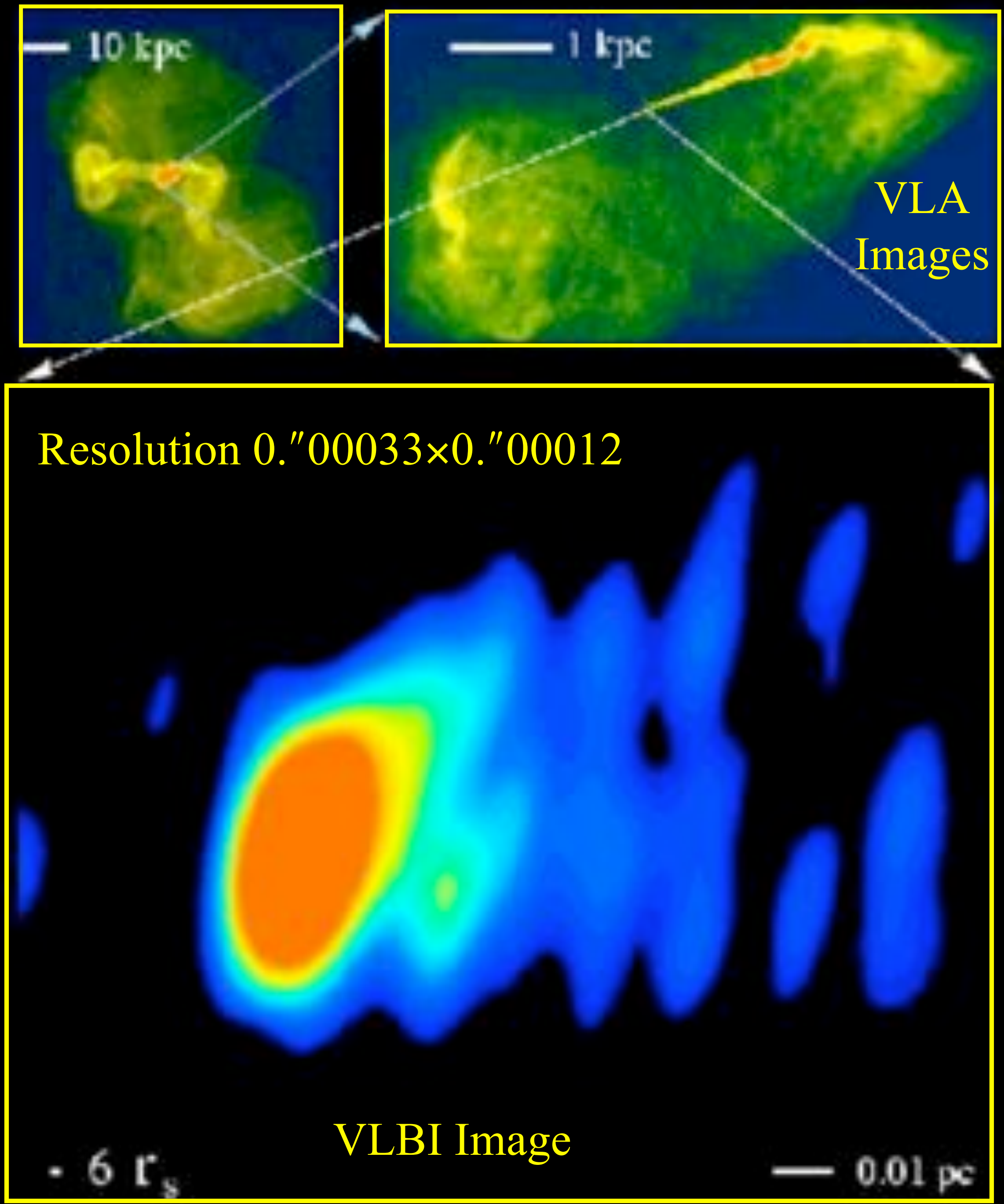


EXAMPLE 1
JET FORMATION: BASE OF M87 JET

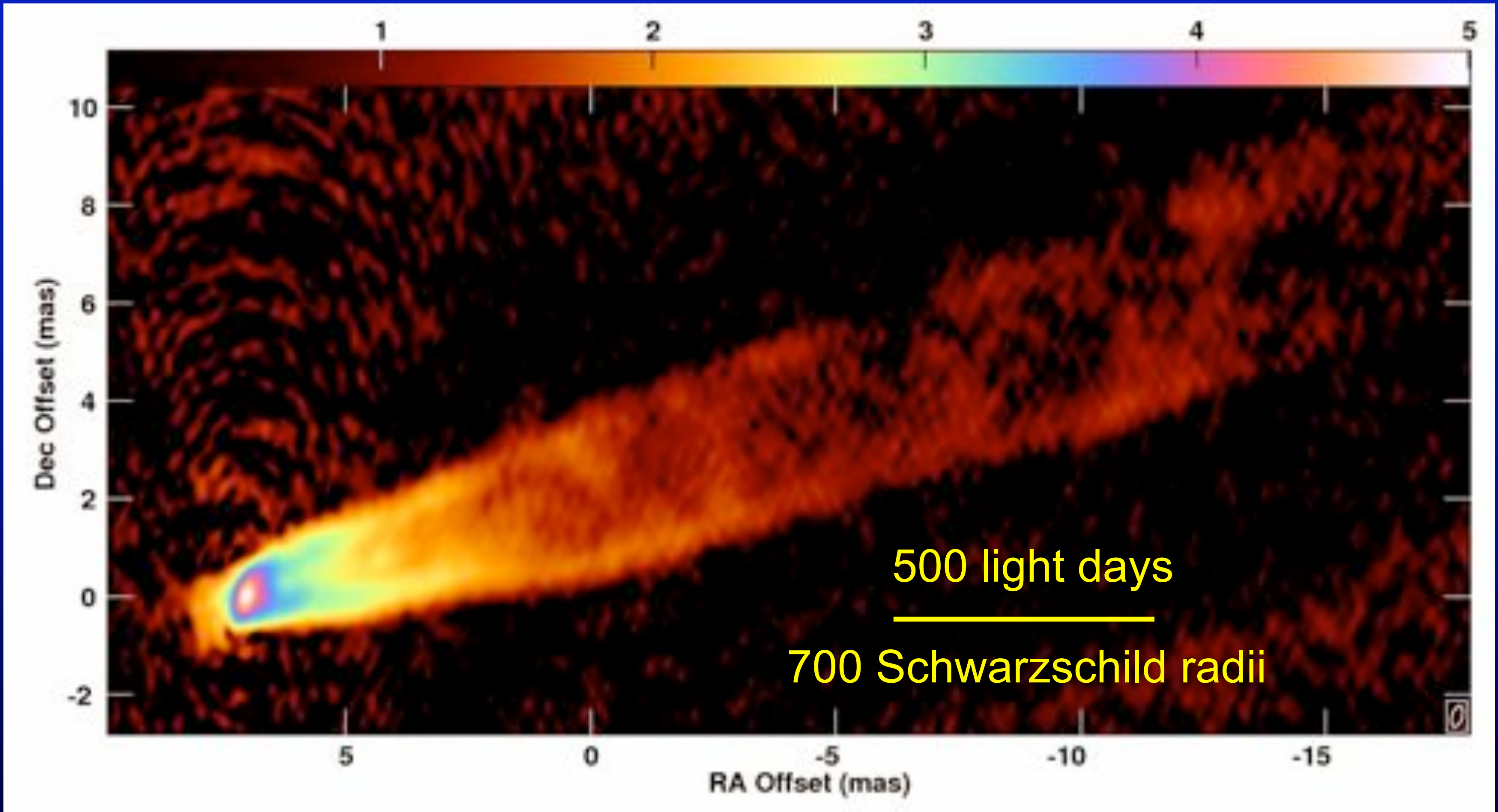
43 GHz Global VLBI
Junor, Biretta, & Livio
Nature, 401, 891

Shows hints of jet collimation region





THE VLBA 43 GHz M87 MOVIE
23 OBSERVATIONS STACKED



Beam: 0.43x0.21 mas $0.2mas = 0.016pc = 60R_s$ 1mas/yr = 0.25c