Very Long Baseline Interferometry

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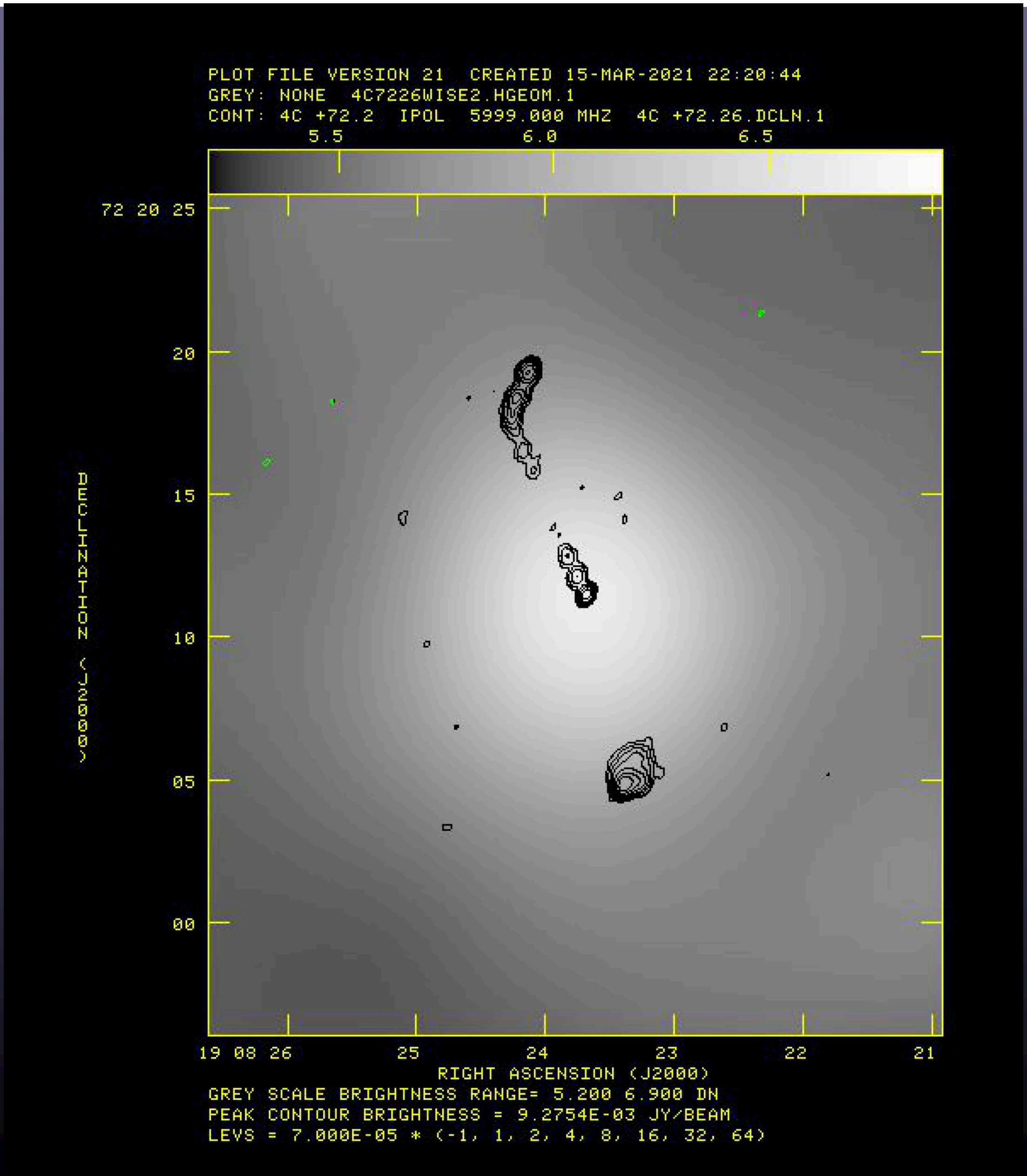
Astronomy 423 at UNM

Radio Astronomy

Homework 7 Solution



PLOT FILE VERSION 21 CREATED 15-MAR-2021 22:20:44
GREY: NONE 4C7226WISE2.HGEOM.1
CONT: 4C +72.2 IPOL 5999.000 MHZ 4C +72.26.DCLN.1

GREY SCALE BRIGHTNESS RANGE= 5.200 6.900 DN
PEAK CONTOUR BRIGHTNESS = 9.2754E-03 JY/BEAM
LEVS = 7.000E-05 * (-1, 1, 2, 4, 8, 16, 32, 64)

Noise
21 microJy/beam

Announcements

- HW8 is due on Wednesday, April 7
- HW9 pushed back to Monday, April 19
  - Note this involves scheduling LWA observations of a Pulsar on April 12

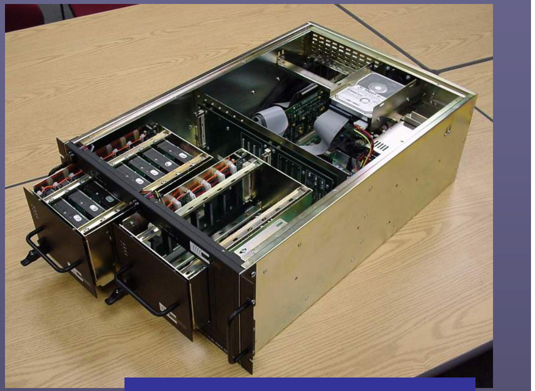
Outline

- What VLBI is
- Some examples of VLBI applications
- Geodesy and Astrometry
- Differences between VLBI and connected elements
- The Very Long Baseline Array (VLBA)

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

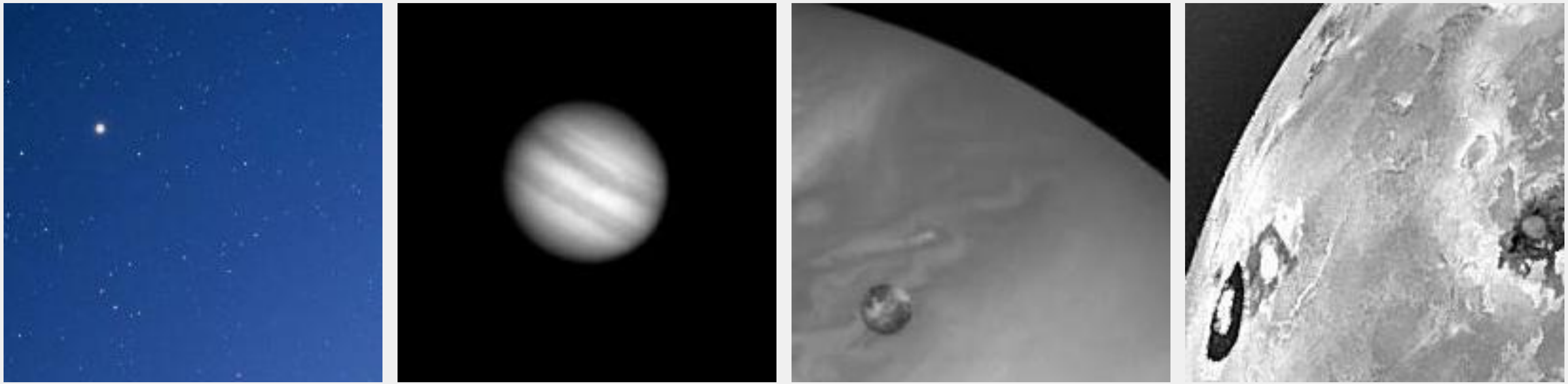
THE QUEST FOR RESOLUTION

Resolution = Observing wavelength / Telescope diameter

Angular	Optical (5000A)		Radio (4cm)	
Resolution	**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

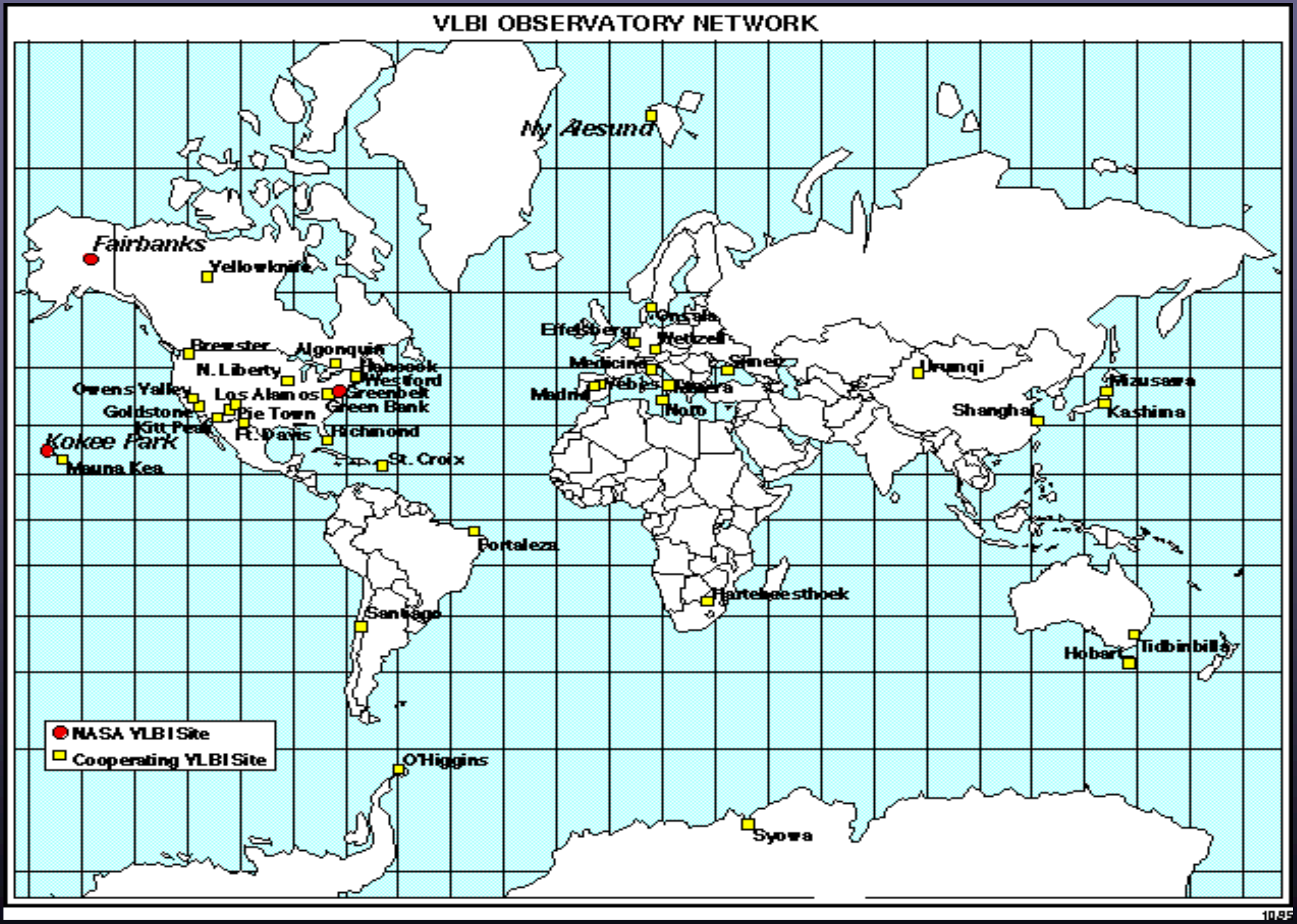
0.05 arcsec

0.001 arcsec

Simulated with Galileo photo

GLOBAL VLBI STATIONS

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

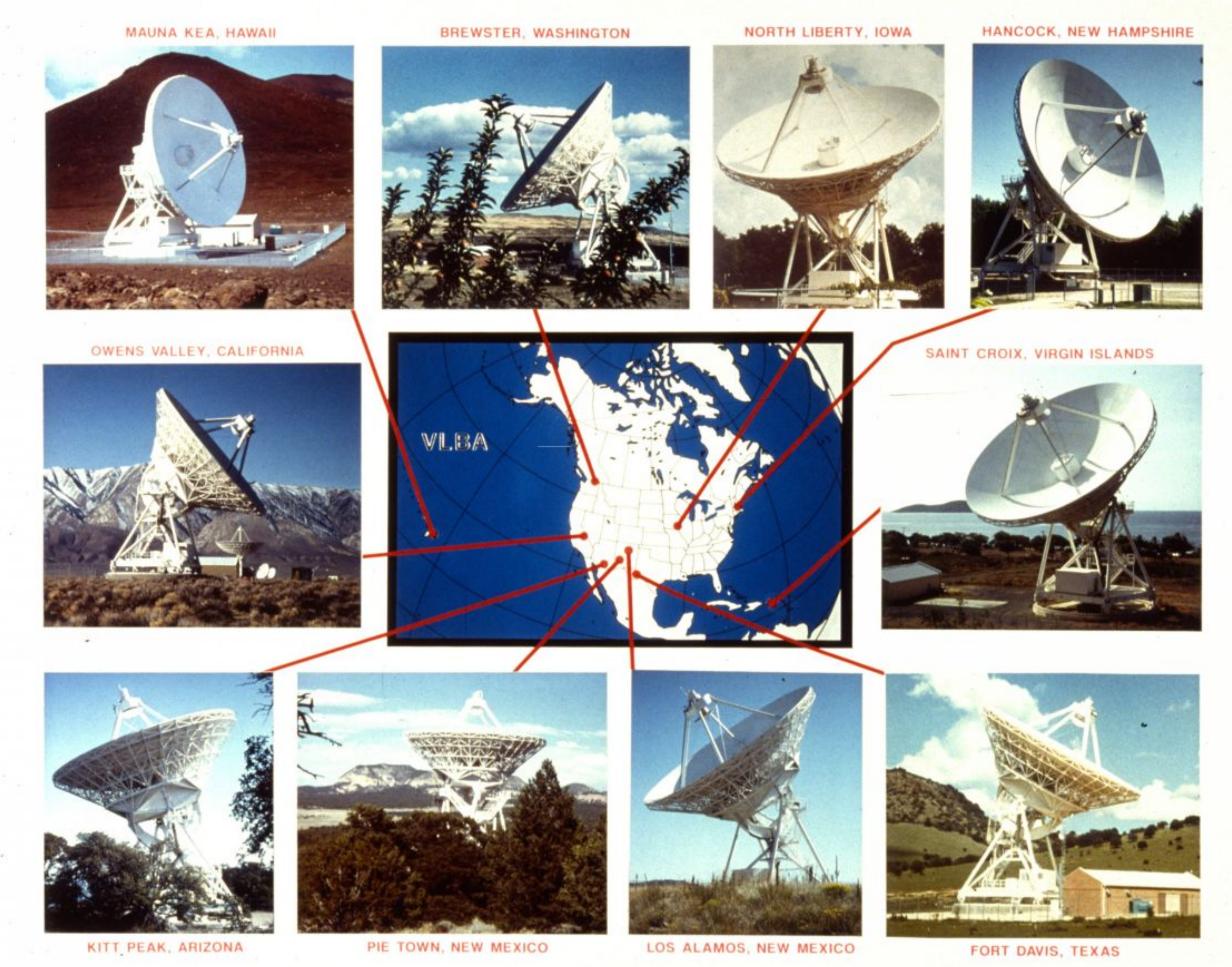


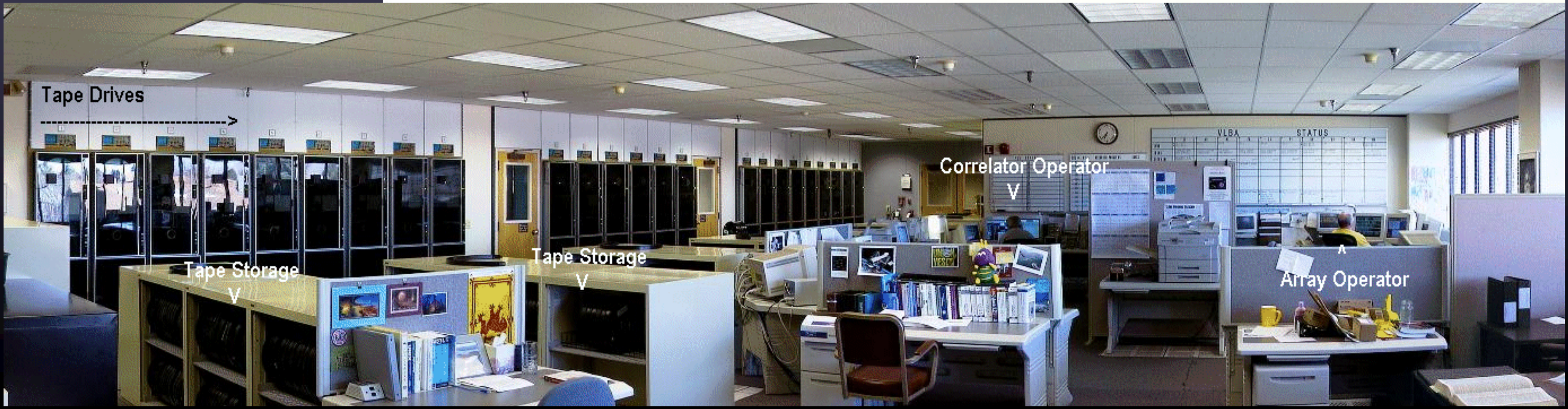
The VLBA

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

National Radio
Astronomy Observatory

A Facility of the
National Science
Foundation



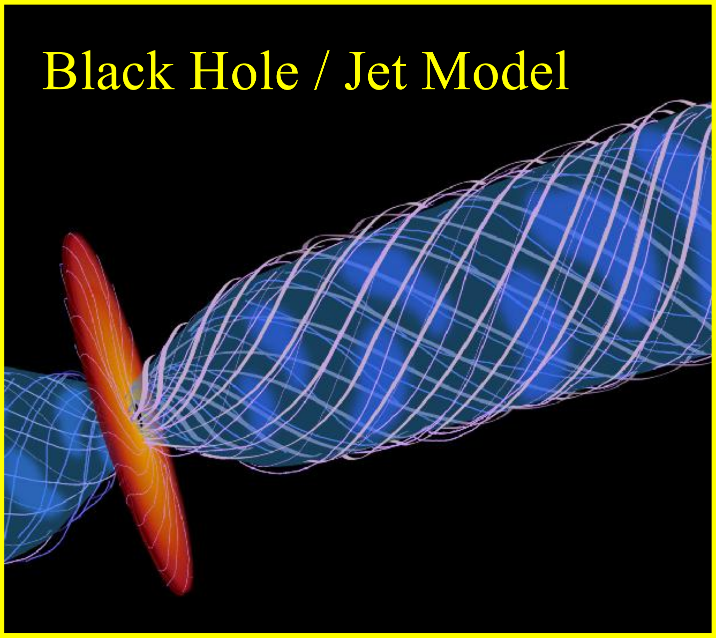


EXAMPLE 1
JET FORMATION: BASE OF M87 JET

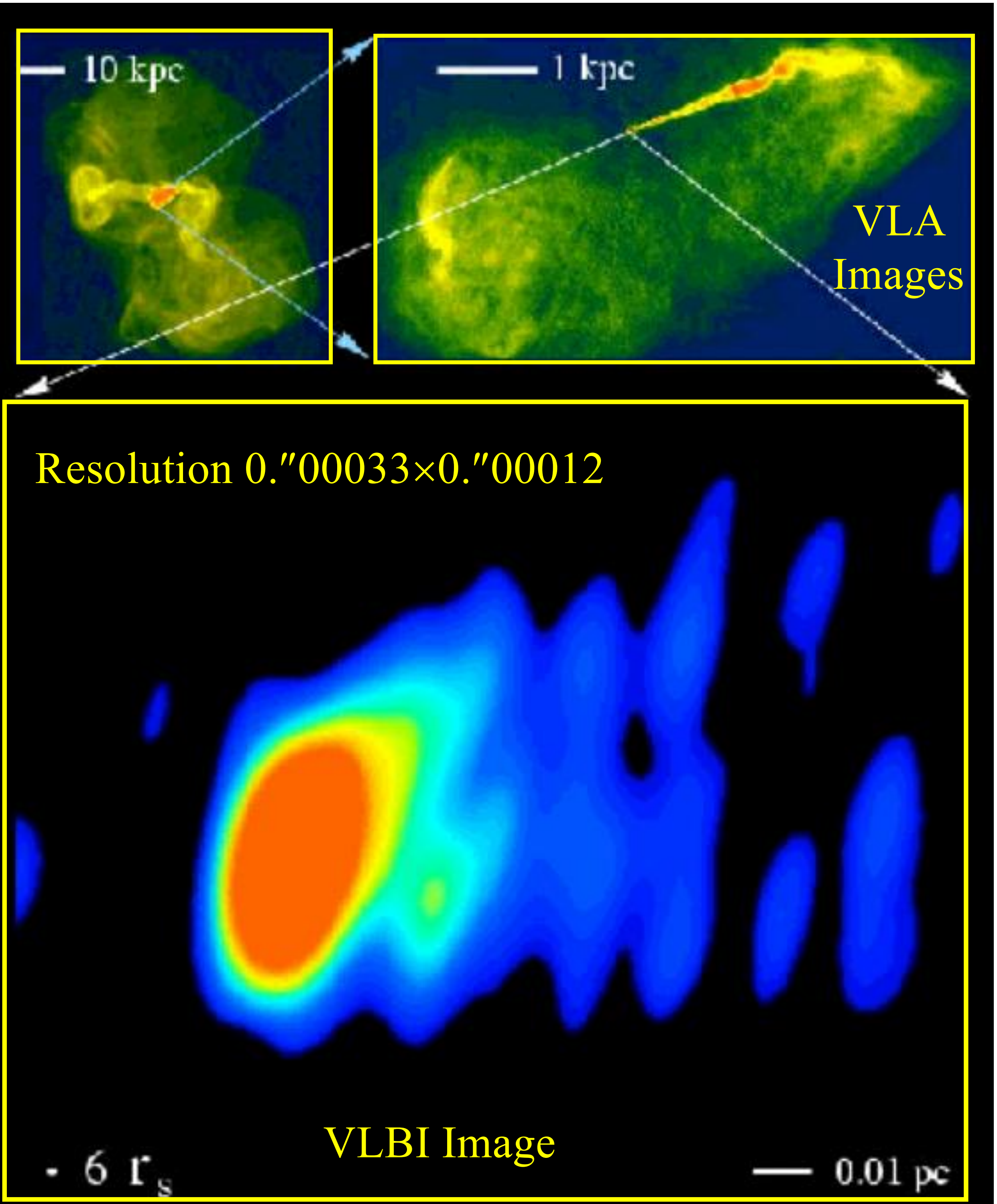
43 GHz Global VLBI

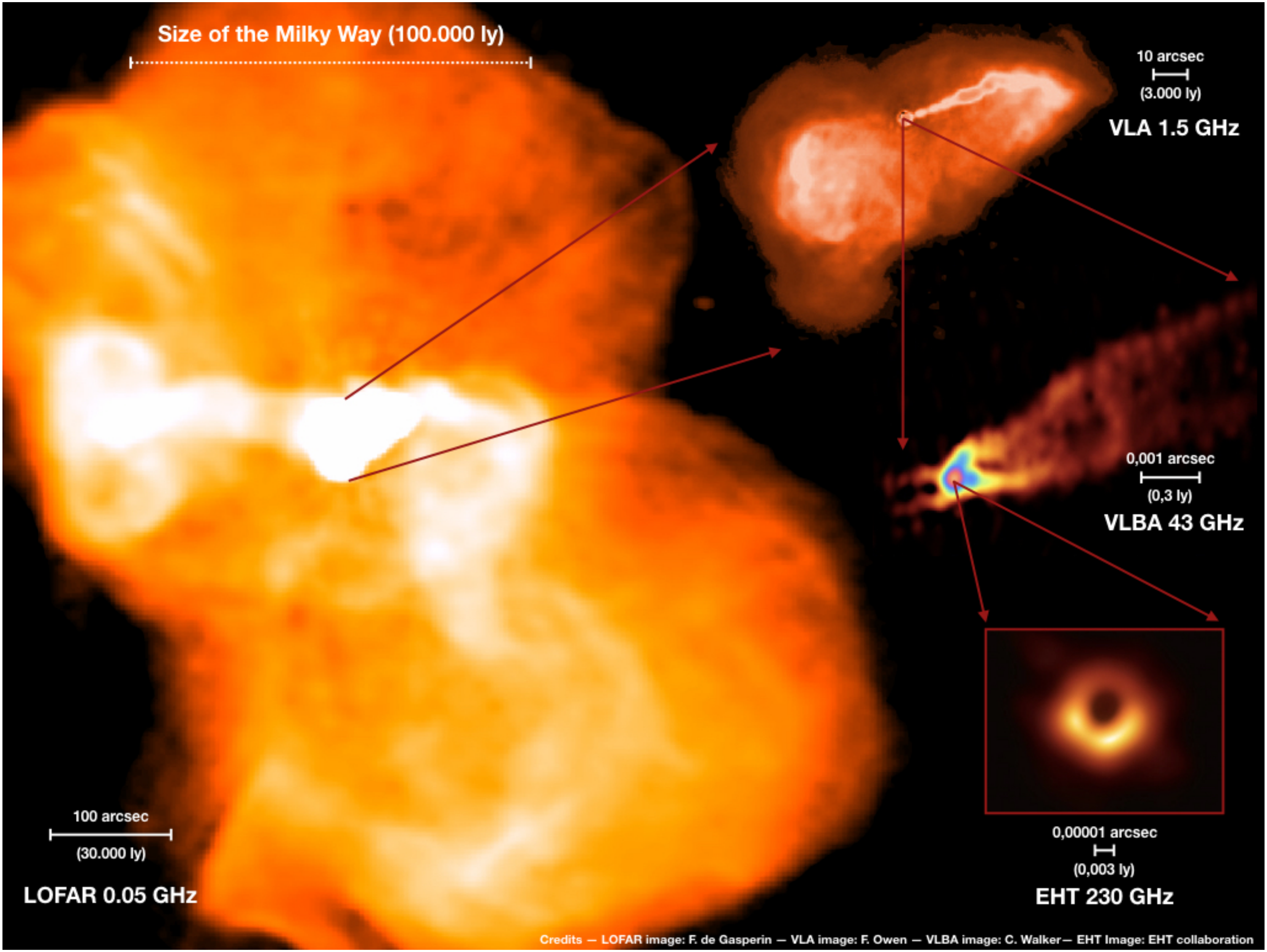
Junor, Biretta, & Livio
Nature, 401, 891

Shows hints of jet collimation region



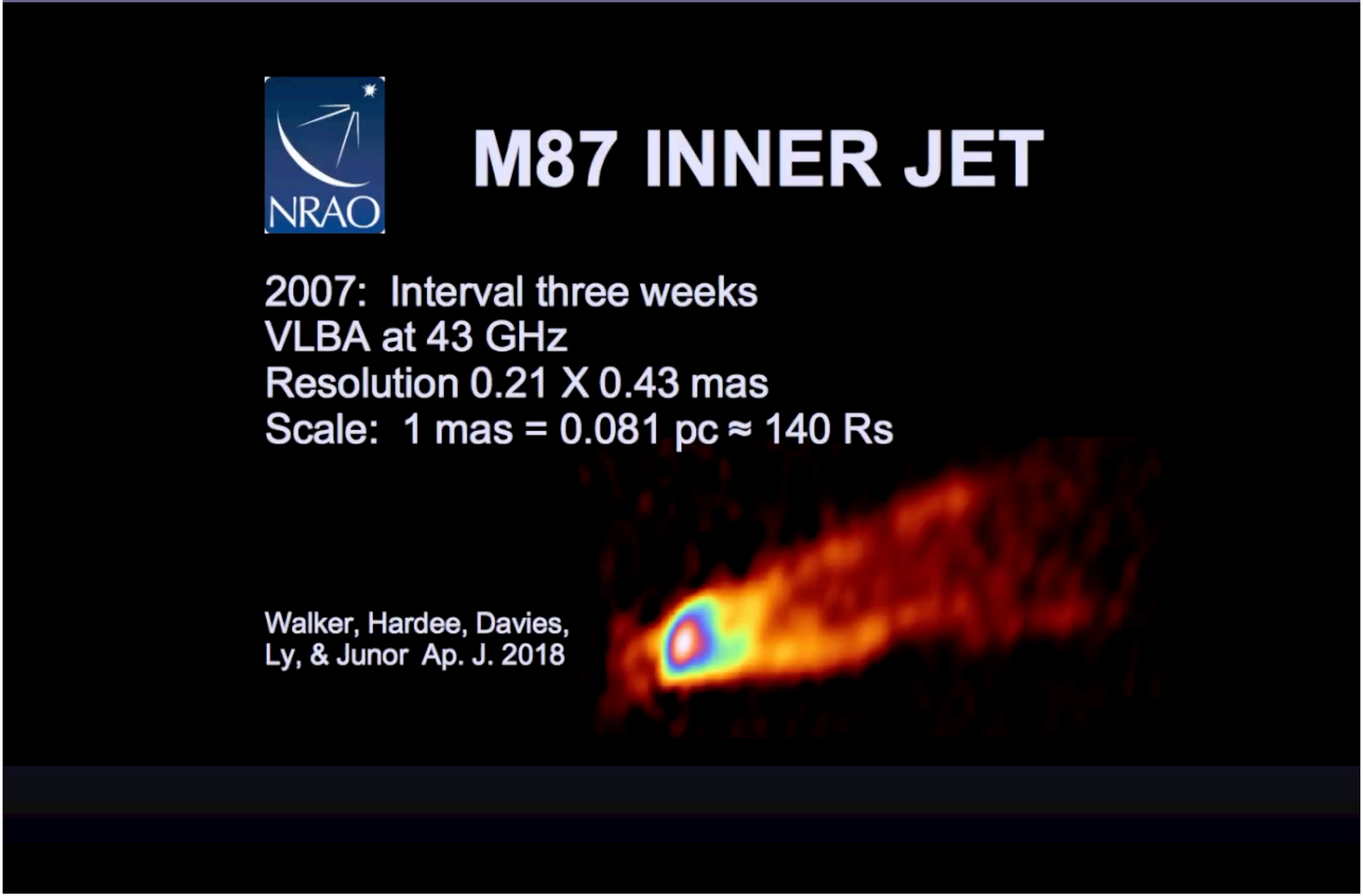
Black Hole / Jet Model





Credits — LOFAR image: F. de Gasperin — VLA image: F. Owen — VLBA image: C. Walker— EHT Image: EHT collaboration

EXAMPLE 2
motion - modern example: M87



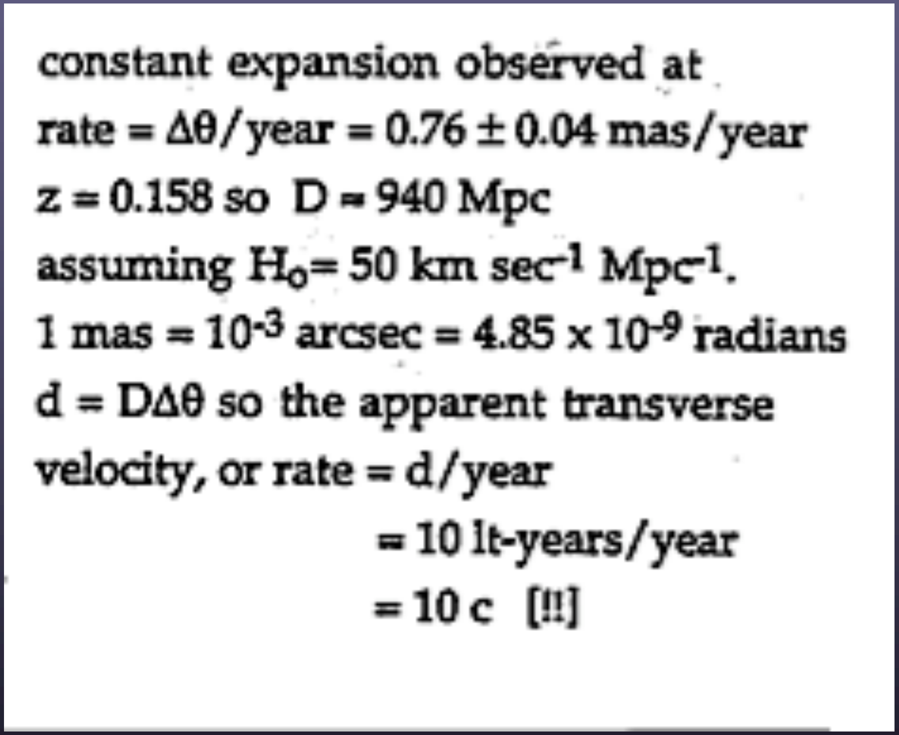
M87 INNER JET

2007: Interval three weeks
VLBA at 43 GHz
Resolution 0.21 X 0.43 mas
Scale: 1 mas = 0.081 pc ≈ 140 Rs

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

EXAMPLE 2 Superluminal motion

Pearson et al. 1981



constant expansion observed at

rate = $\Delta\theta$/year = 0.76 ± 0.04 mas/year

$z = 0.158$ so $D = 940$ Mpc

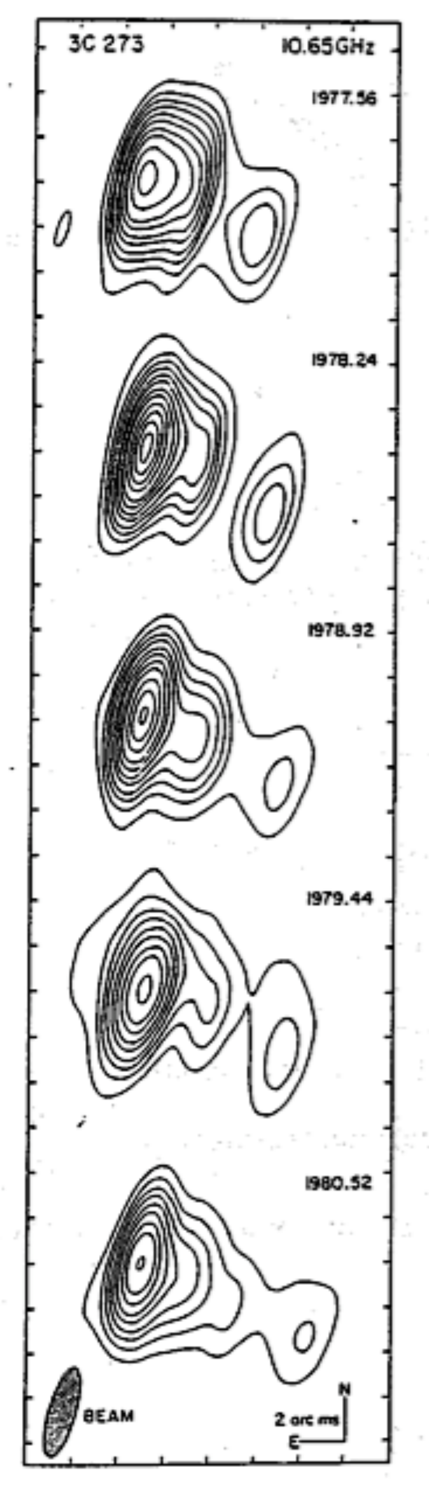
assuming $H_0 = 50$ km sec^{-1} Mpc^{-1}.

1 mas = 10^{-3} arcsec = 4.85×10^{-9} radians

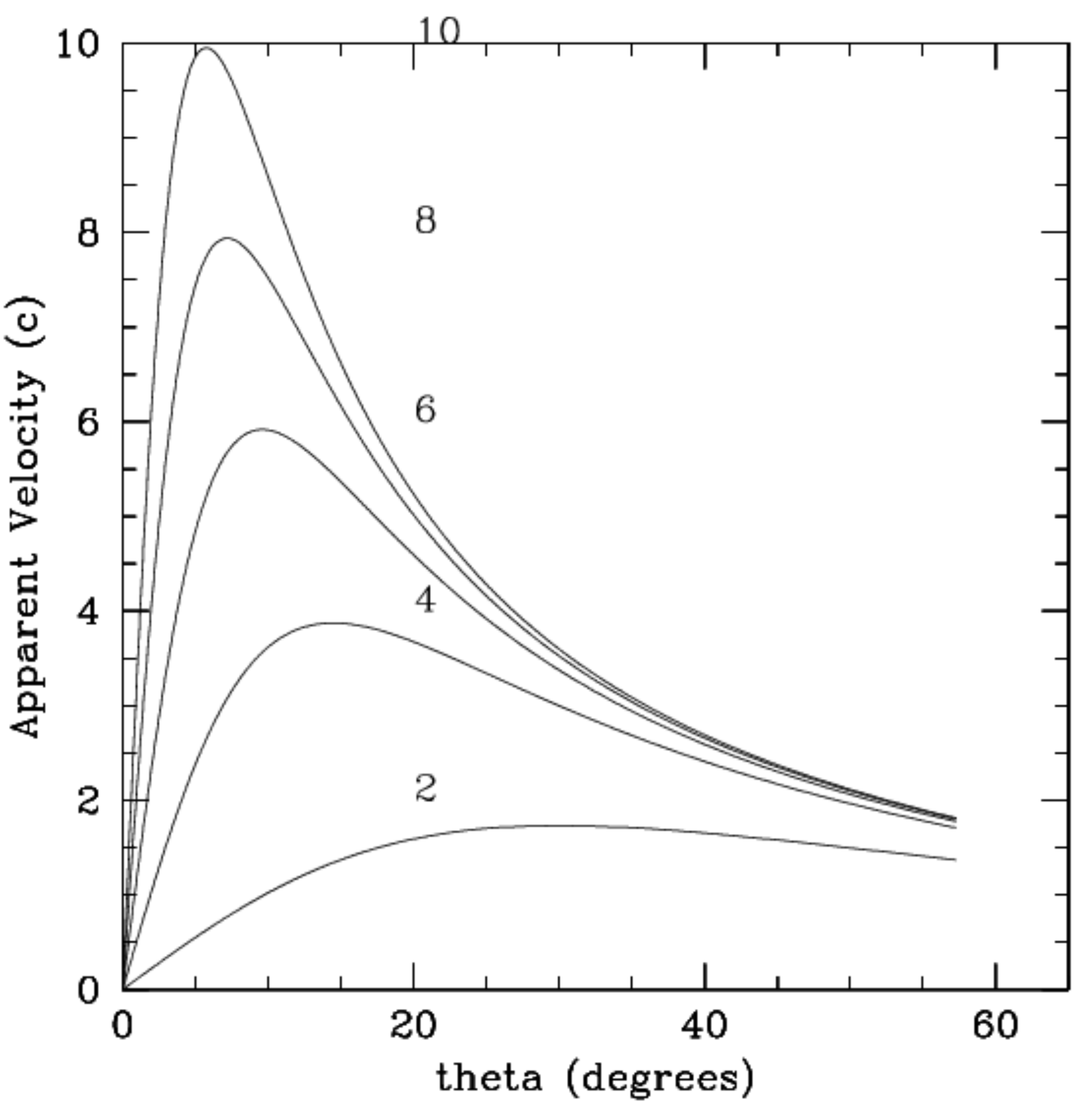
$d = D\Delta\theta$ so the apparent transverse velocity, or rate = d/year

= 10 lt-years/year

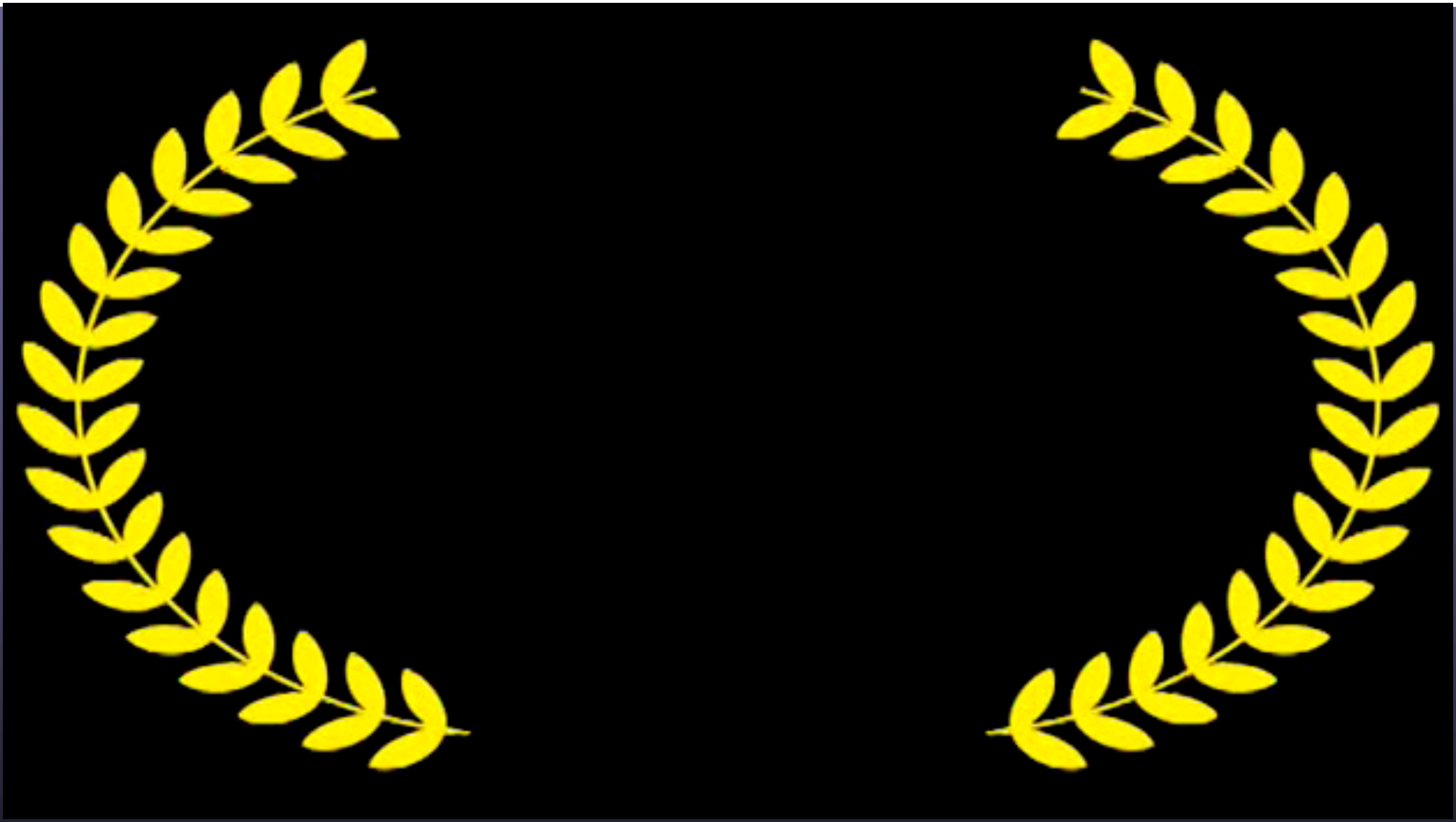
= 10 c [!!]



Apparent Velocity as a function of angle



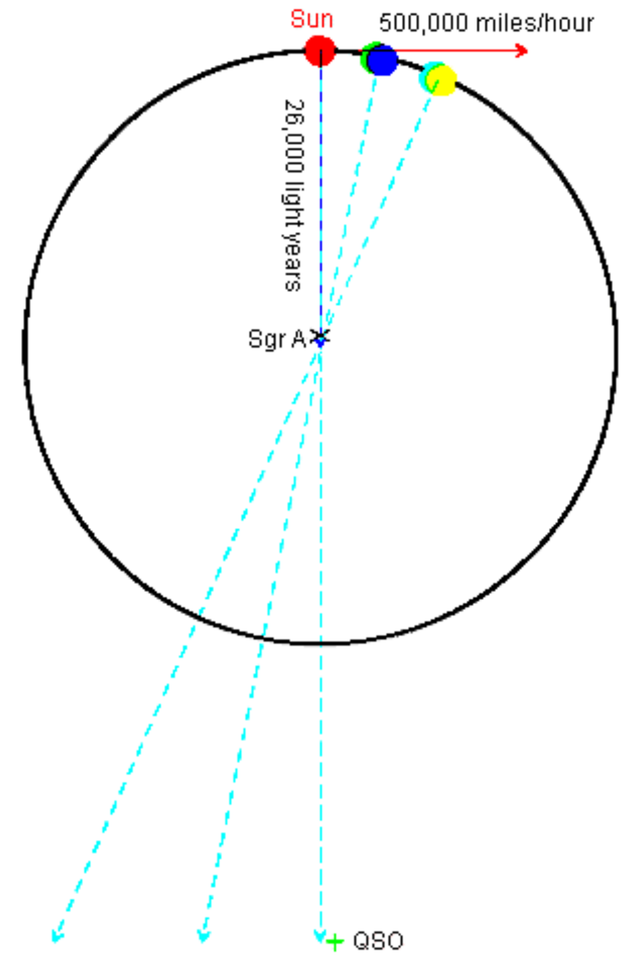
EXAMPLE 3:
JET DYNAMICS: THE SS433 MOVIE



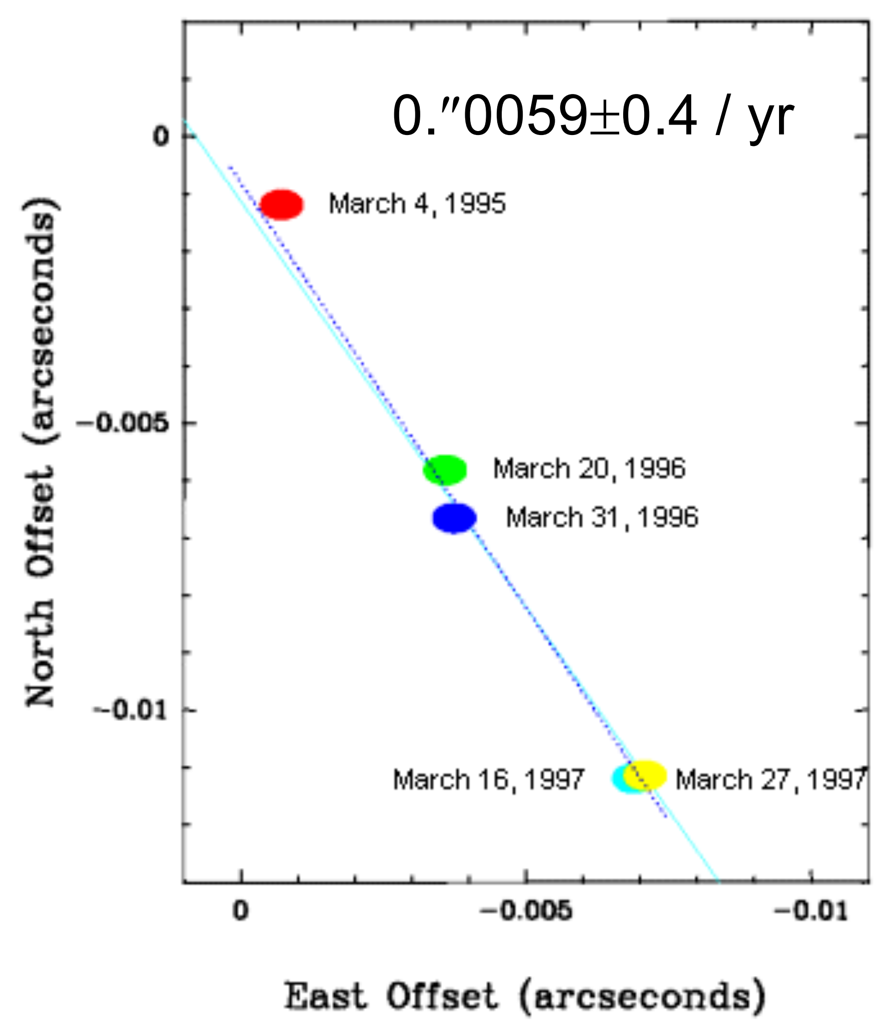
- Two hour snapshot almost every day for 40 days on VLBA at 1.7 GHz
    - Mioduszewski, Rupen, Taylor, and Walker

EXAMPLE 4
MOTIONS OF SGRA*

Measures rotation of the Milky Way Galaxy



Reid et al. 1999, Ap. J. 524, 816

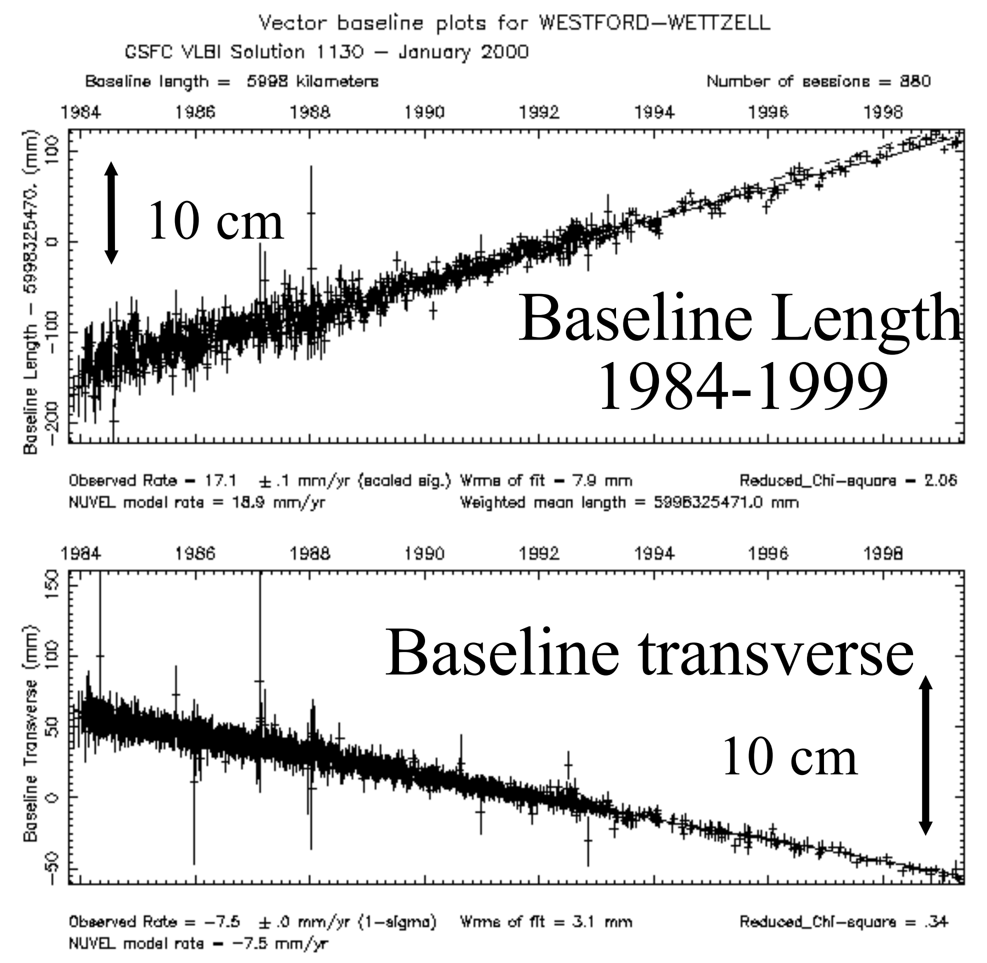


0.″0059±0.4 / yr

EXAMPLE 5
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.

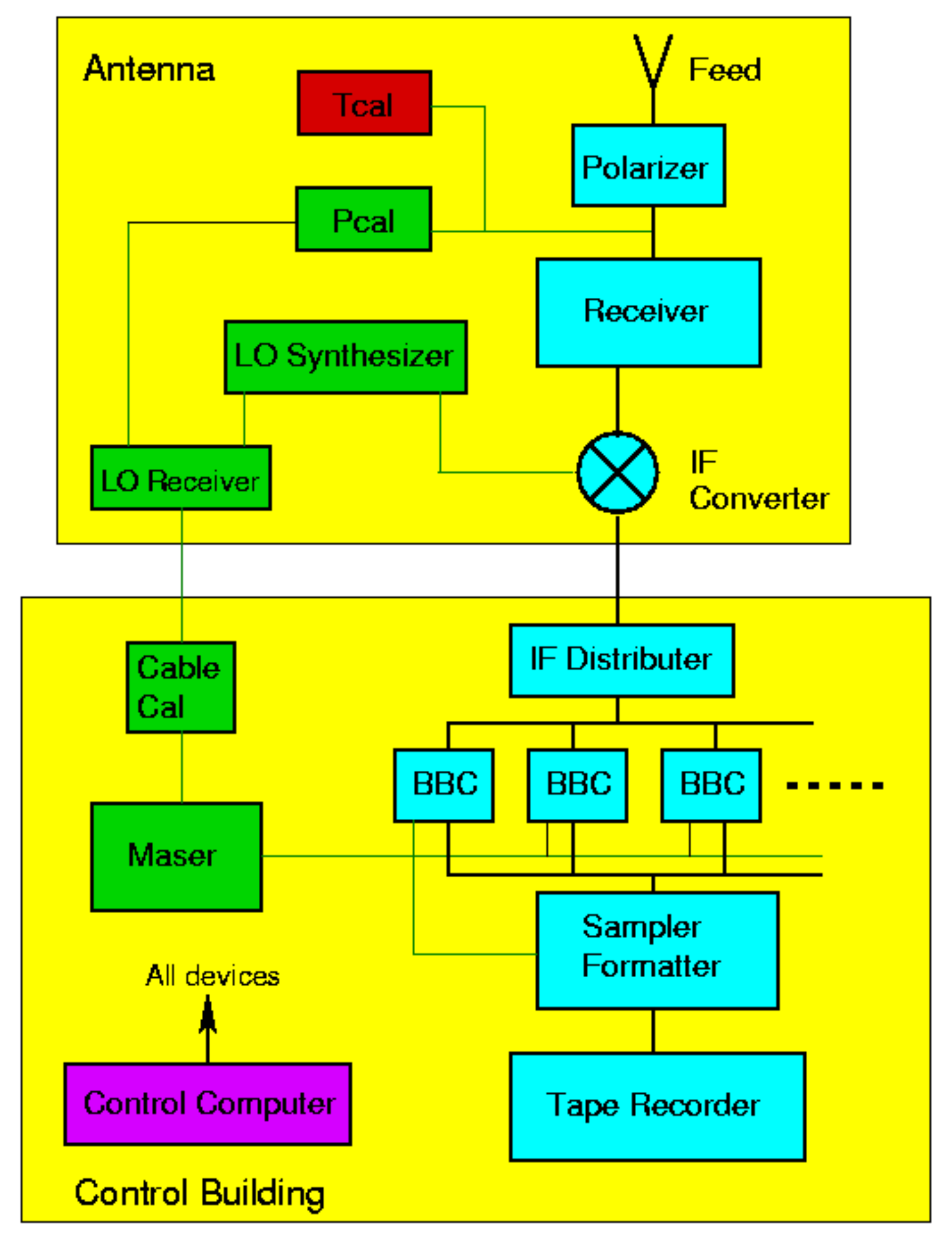
- Separate clocks – Cause phase variations
- Independent atmospheres (ionosphere and troposphere)
  - Phase fluctuations not much worse than VLA A array
  - Gradients are worse – affected by total, not differential atmosphere
  - Ionospheric calibration useful – dual band data or GPS global models
- Calibrators poor
  - Compact sources are variable – 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
  - 10^5 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

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	∼ 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)

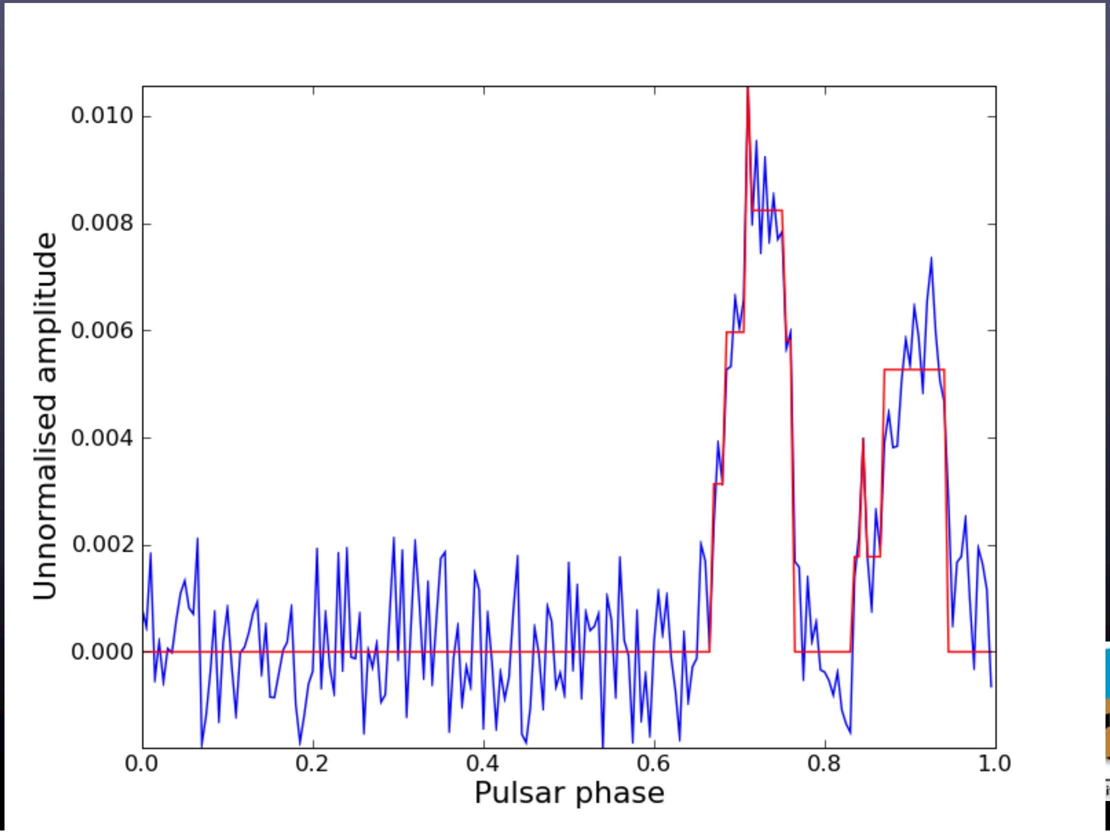
The DiFX software correlator

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

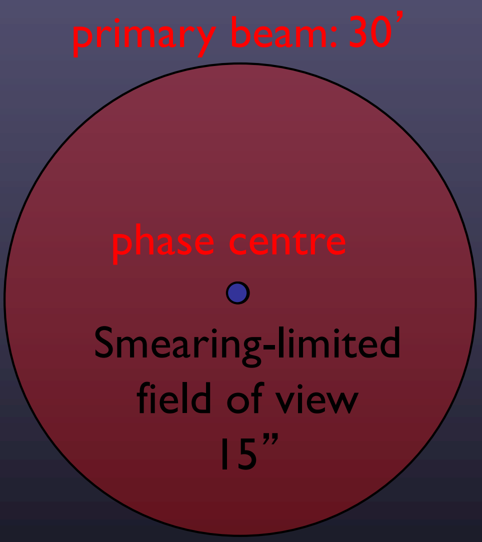
Unique DiFX capabilities

- 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



Time resolution:
2000 ms

Freq. resolution:
500 kHz

12hr VLBA dataset:
2.4 GB

Time resolution:
200 ms

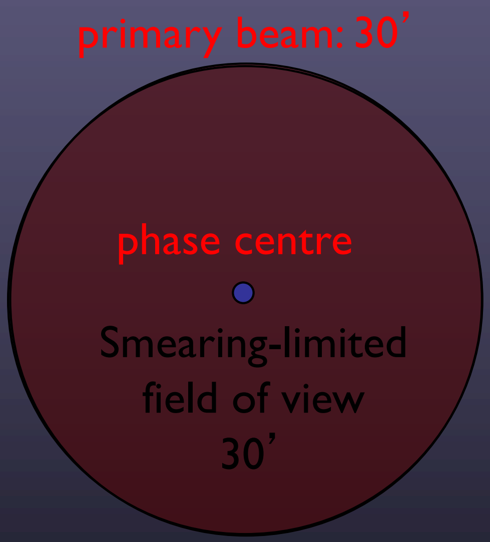
Freq. resolution:
50 kHz

12hr VLBA dataset:
240 GB

Calculations for 1.6 GHz, total smearing = 10%

Wide-field imaging

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



Time resolution:
20 ms

Freq. resolution:
4 kHz

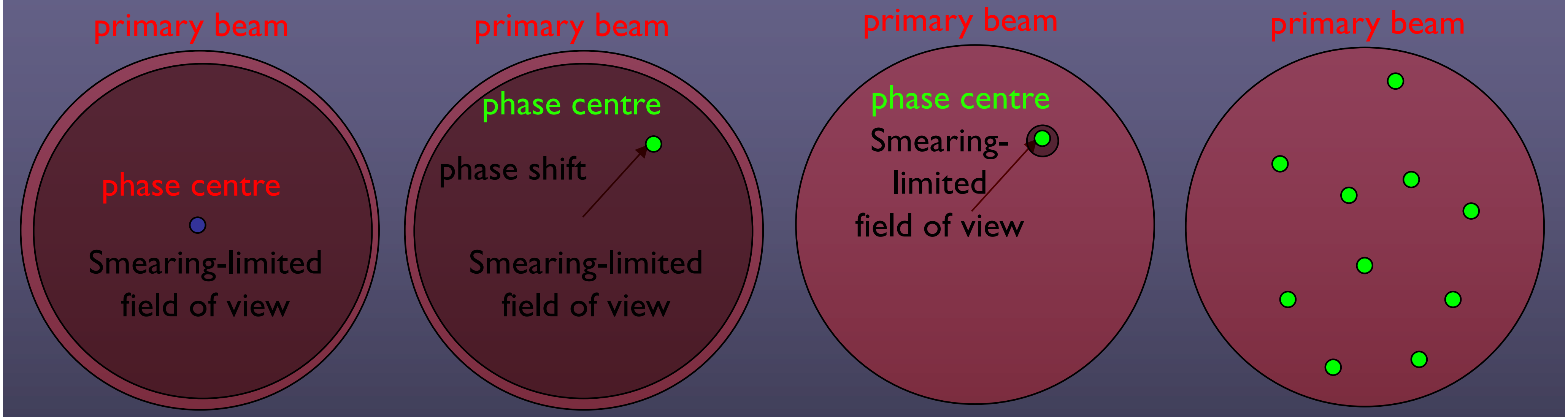
12hr VLBA dataset:
30,000 GB

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



Correlate at high resolution for ~10ms

Apply *(u,v)* shift

Average in frequency

Repeat for many phase centres

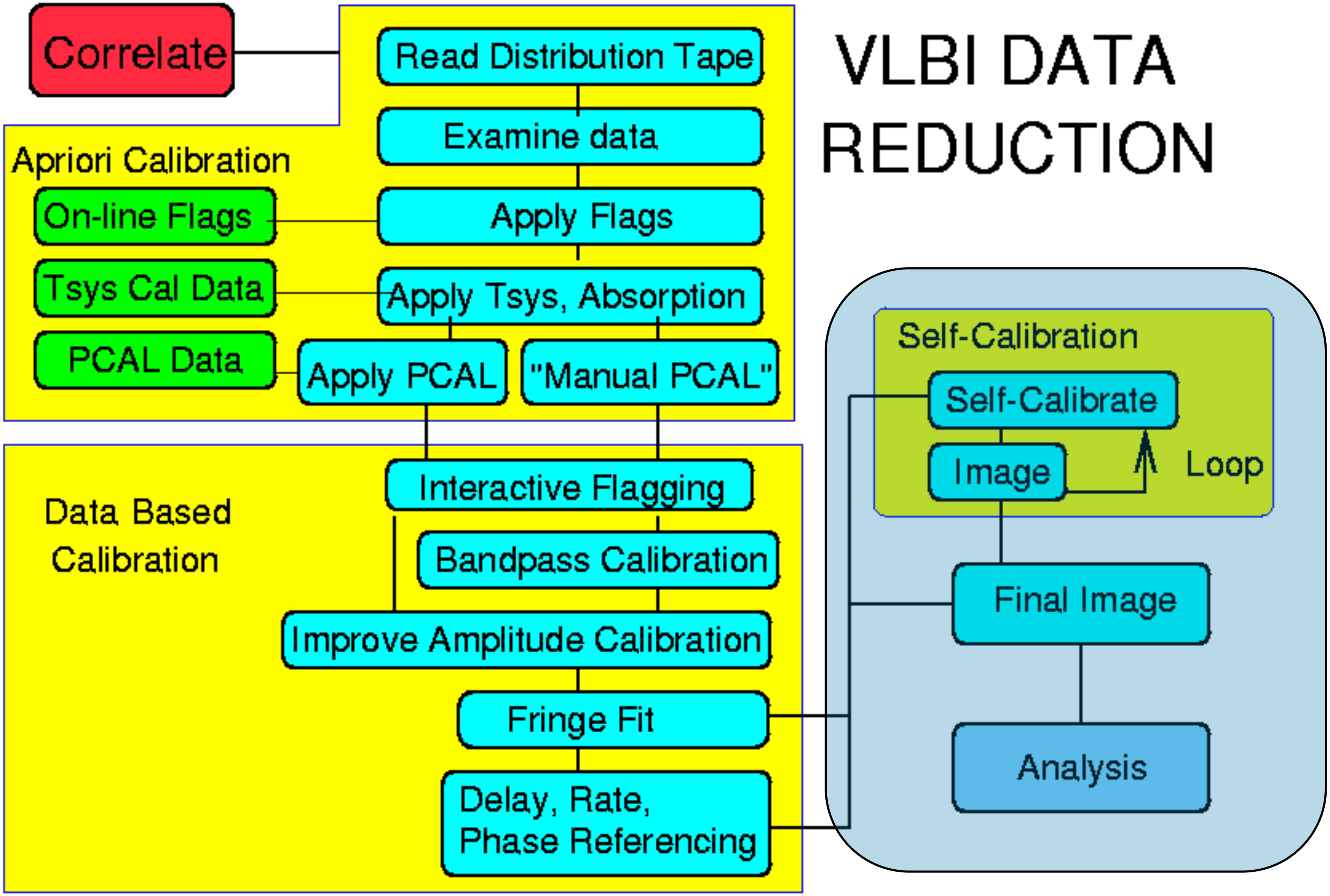
THEN: Repeat for next ~10ms (average in time)

Multi-field imaging

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

Image: Random cutout, NRAO FIRST survey

VLBI DATA REDUCTION



Correlate

Read Distribution Tape

Examine data

Apriori Calibration

On-line Flags

Apply Flags

Tsys Cal Data

Apply Tsys, Absorption

PCAL Data

Apply PCAL

"Manual PCAL"

Data Based Calibration

Interactive Flagging

Bandpass Calibration

Improve Amplitude Calibration

Fringe Fit

Delay, Rate,
Phase Referencing

Self-Calibration

Self-Calibrate

Image

Loop

Final Image

Analysis

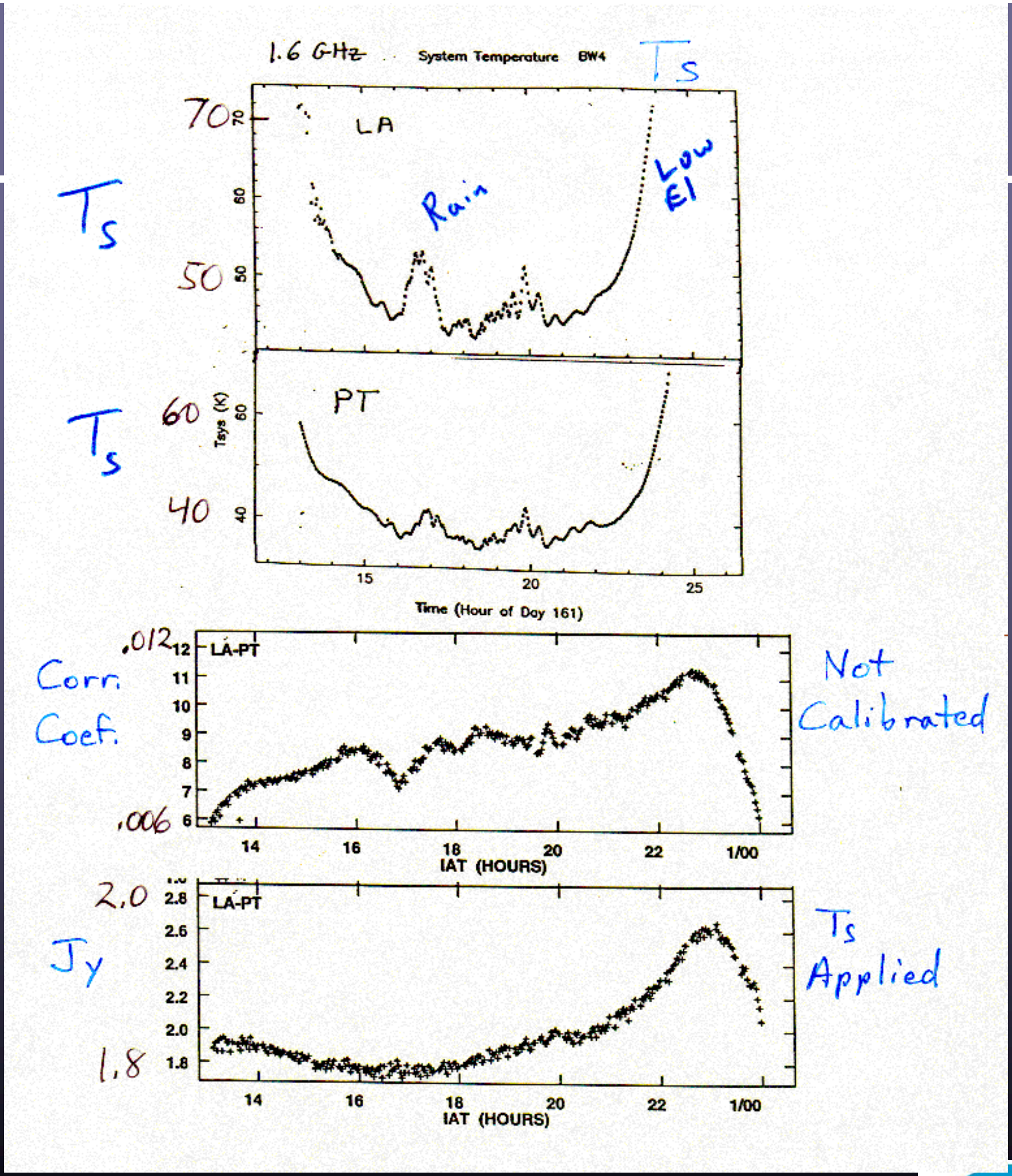
VLBI Amplitude Calibration

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

- 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 Tsys

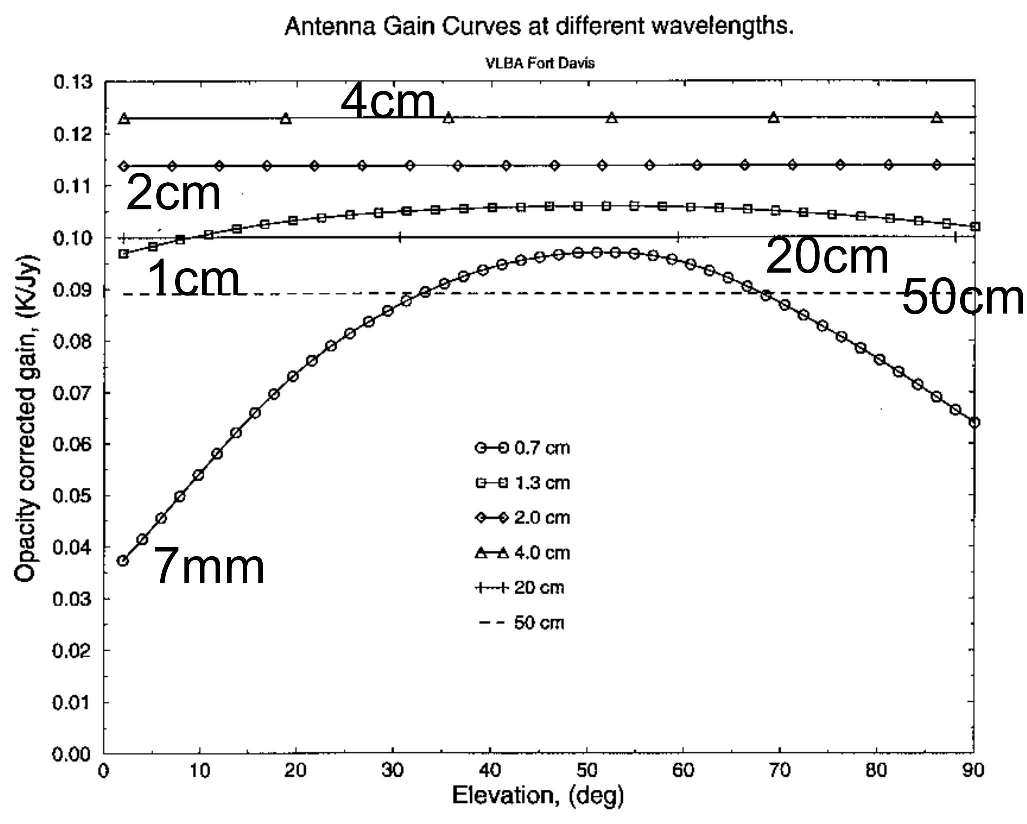
Example shows removal of effect of increased Ts due to rain and low elevation



GAIN CURVES AND OPACITY CORRECTION

VLBA gain curves

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

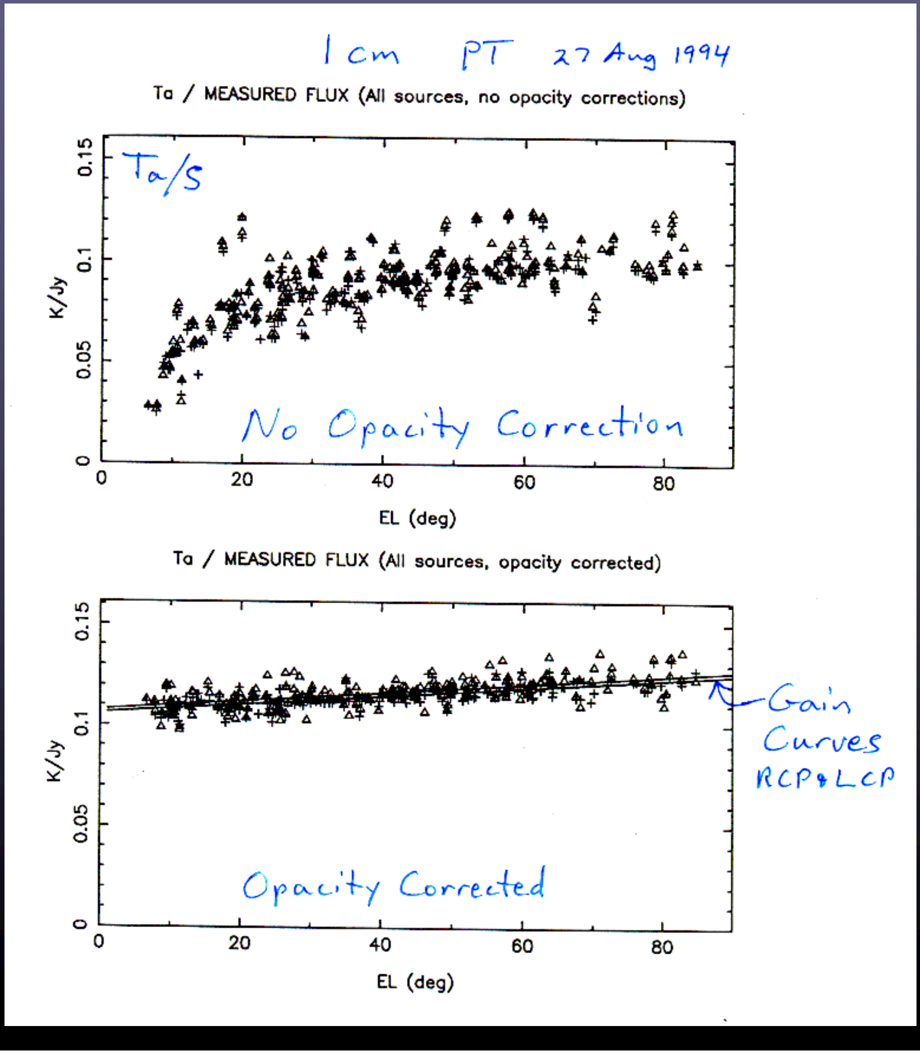


Atmospheric opacity

Correcting for absorption by the atmosphere

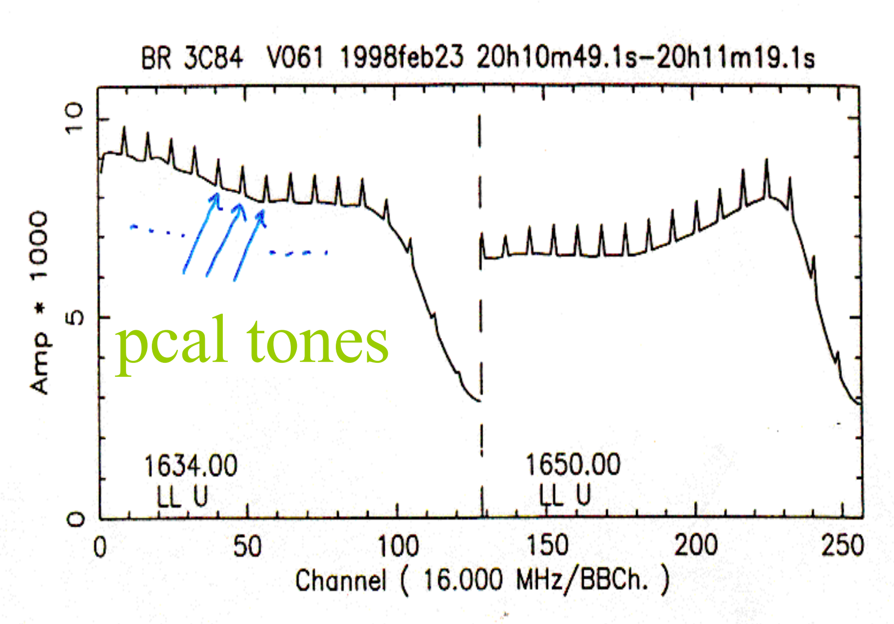
Can estimate using Ts – Tr – Tspill

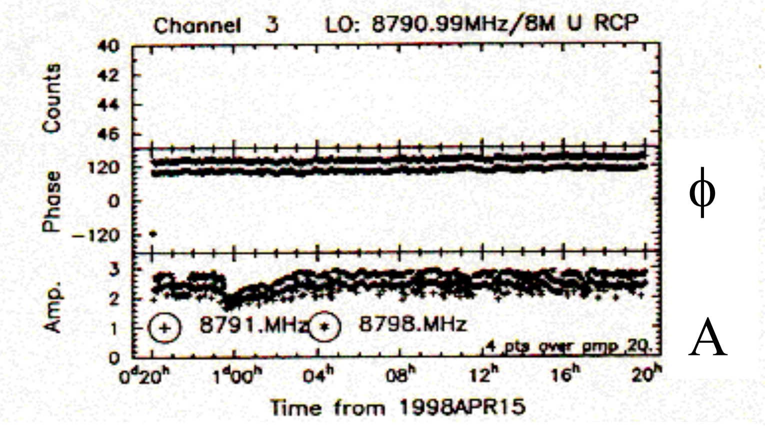
Example from single-dish VLBA pointing data



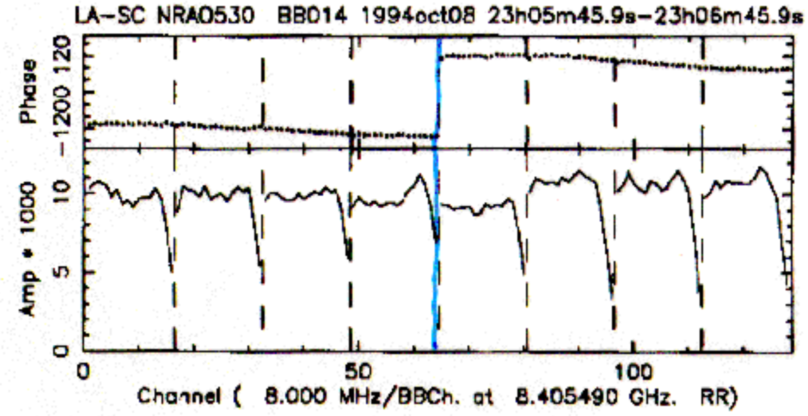
PULSE CAL SYSTEM

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

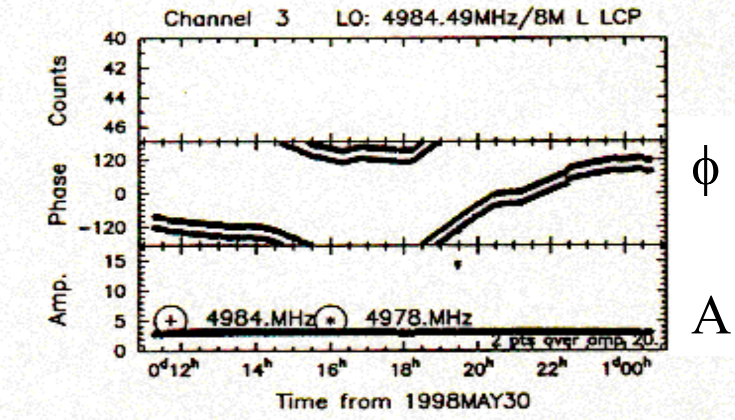




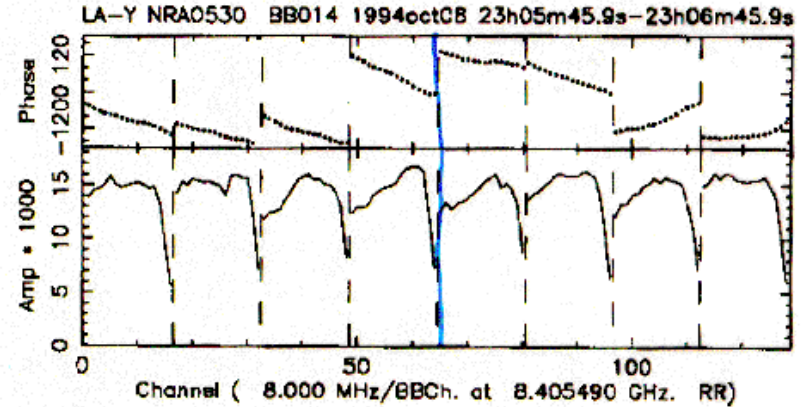
Pulse cal monitor data



Data Aligned using Pulse Cal



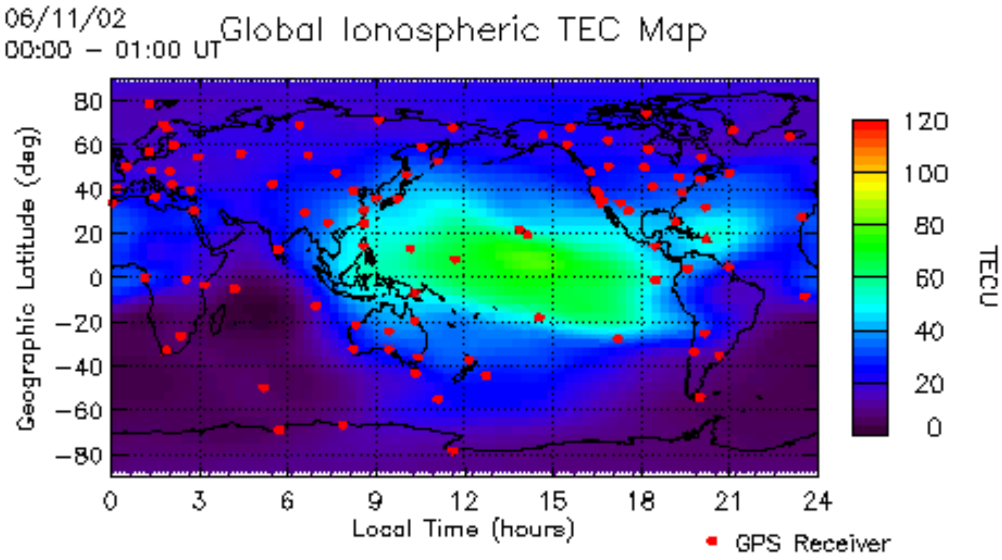
Long track at non-VLBA station



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)

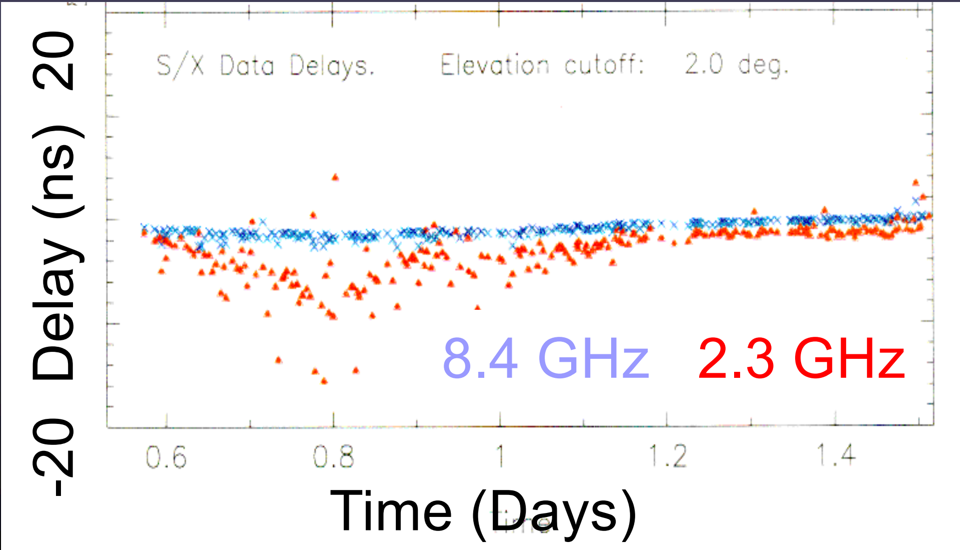


Ionosphere map from iono.jpl.nasa.gov

Maximum Likely Ionospheric Contributions

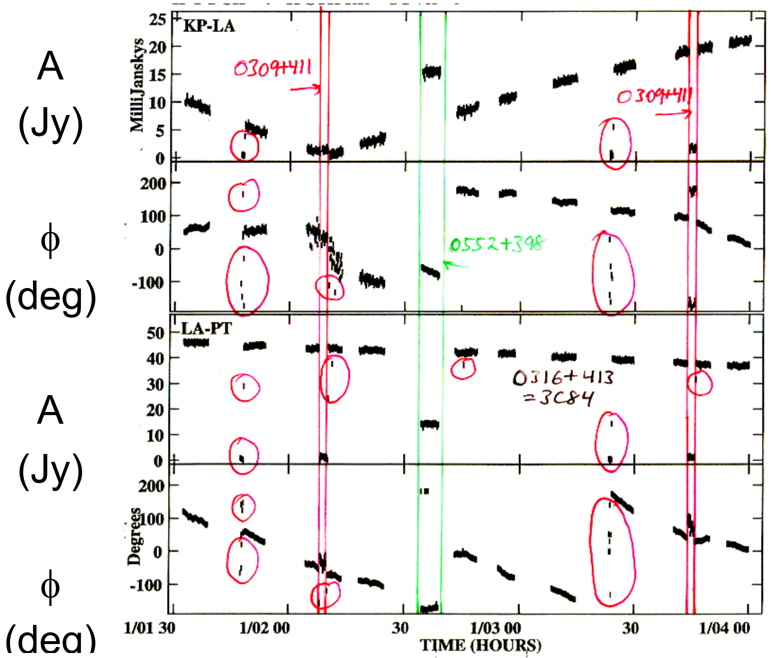
Freq GHz	Day Delay ns	Night Delay ns	Day Rate mHz	Night Rate mHz
0.327	1100	110	12	1.2
0.610	320	32	6.5	0.6
1.4	60	6.0	2.8	0.3
2.3	23	2.3	1.7	0.2
5.0	5.0	0.5	0.8	0.1
8.4	1.7	0.2	0.5	0.05
15	0.5	0.05	0.3	0.03
22	0.2	0.02	0.2	0.02
43	0.1	0.01	0.1	0.01

Delays from an S/X Geodesy Observation

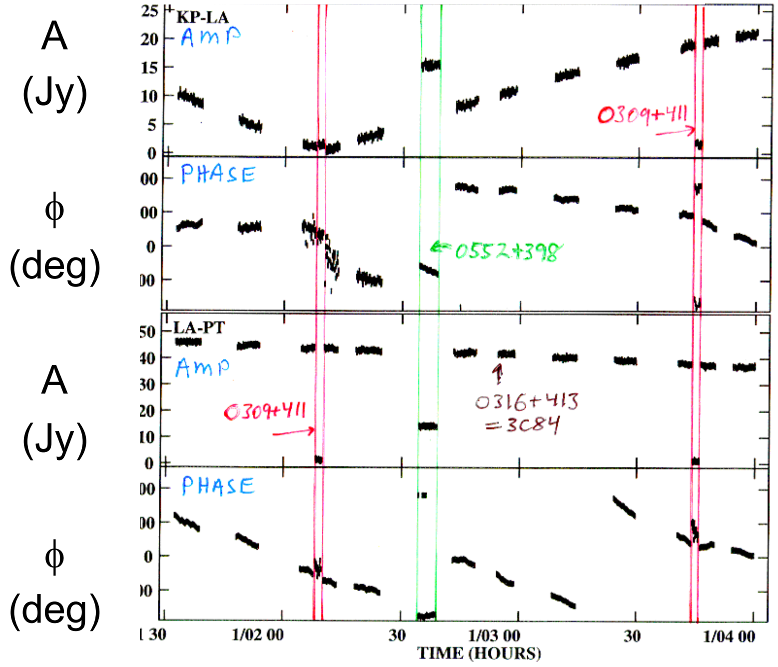


EDITING

Raw Data - No Edits



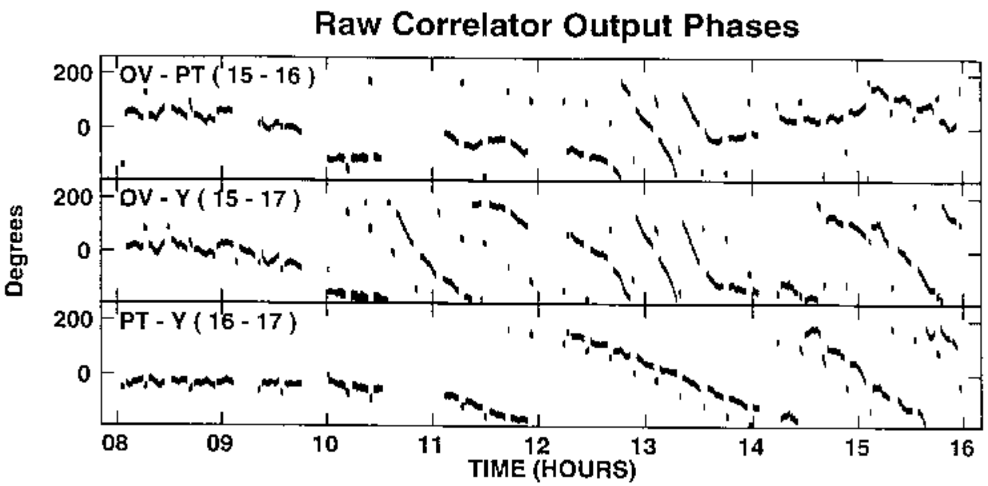
Raw Data - Edited

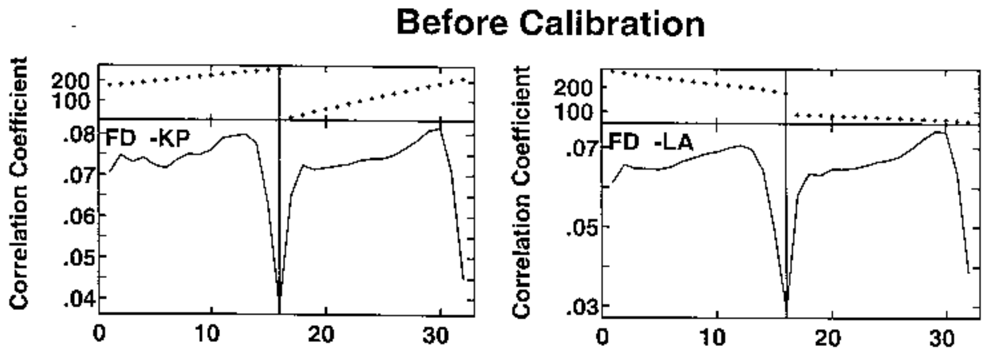


- Flags from on-line system will remove most bad data. Examples:
  - Antenna off source
  - Subreflector out of position
  - Synthesizers not locked
- Final flagging done by examining data
  - Flag by antenna
    - Most problems are antenna based
  - Poor weather
  - Bad playback
  - RFI (May need to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

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

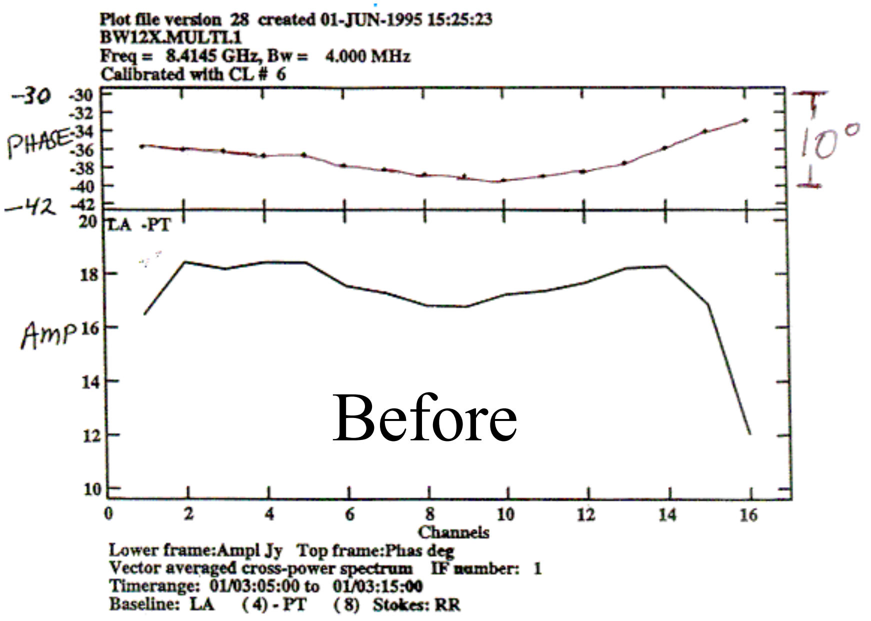
- For Astronomy:
  - Remove clock offsets and align baseband channels (“manual pcal”)
    - Done with 1 or a few scans on a strong source
    - Could use bandpass calibration if smearing corrections were available
  - Fit calibrator to track most variations (optional)
  - Fit target source if strong (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)
  - 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

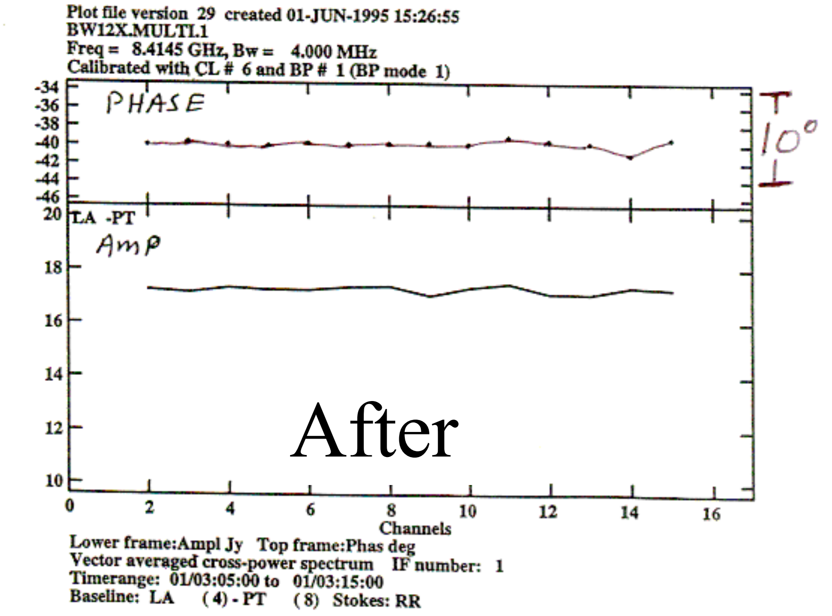
BANDPASS CALIBRATION

- 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.



Plot file version 28 created 01-JUN-1995 15:25:23
BW12X.MULTI.1
Freq = 8.4145 GHz, Bw = 4.000 MHz
Calibrated with CL # 6

Lower frame:Ampl Jy Top frame:Phas deg
Vector averaged cross-power spectrum IF number: 1
Timerange: 01/03:05:00 to 01/03:15:00
Baseline: LA (4) - PT (8) Stokes: RR



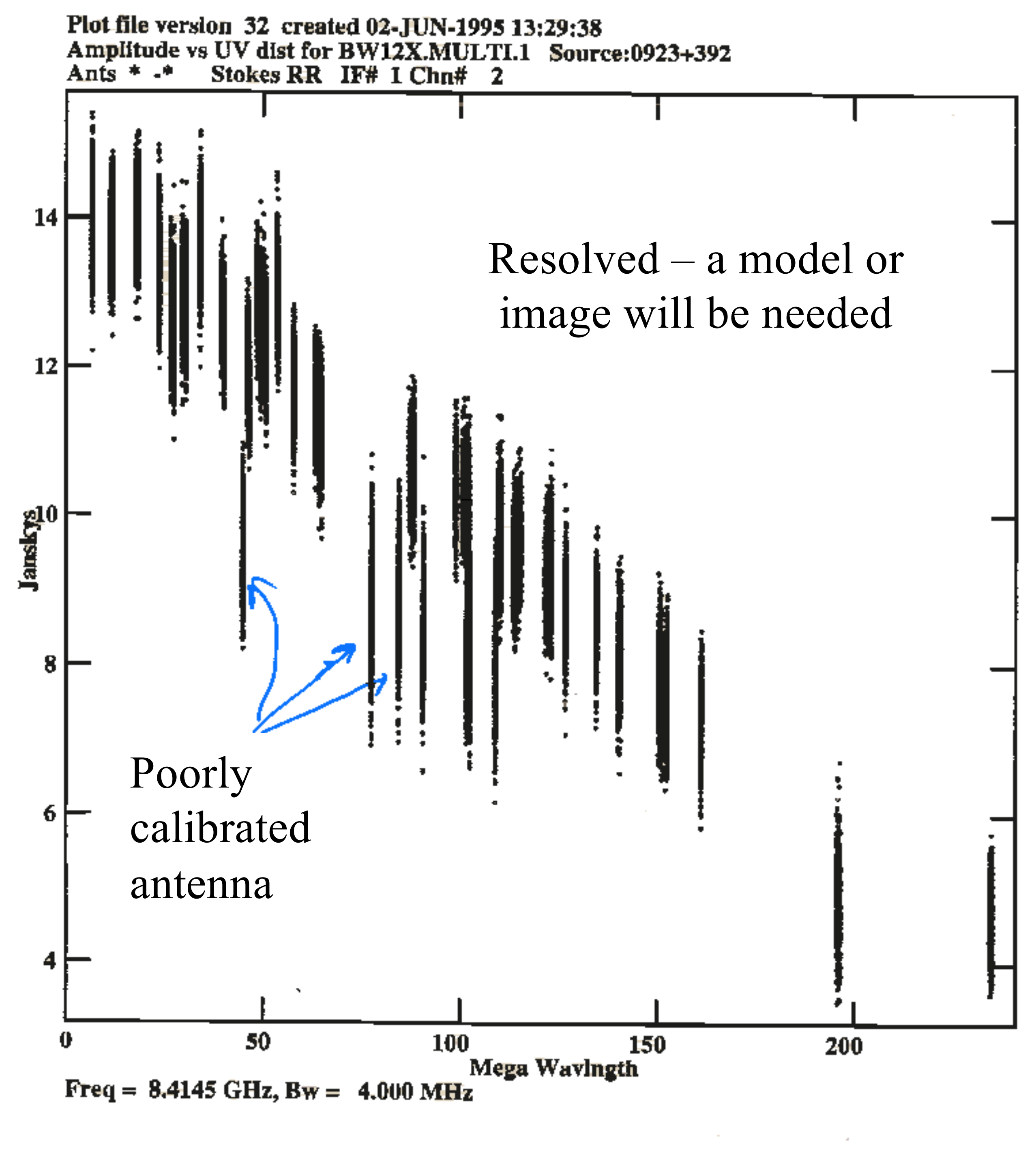
Plot file version 29 created 01-JUN-1995 15:26:55
BW12X.MULTI.1
Freq = 8.4145 GHz, Bw = 4.000 MHz
Calibrated with CL # 6 and BP # 1 (BP mode 1)

Lower frame:Ampl Jy Top frame:Phas deg
Vector averaged cross-power spectrum IF number: 1
Timerange: 01/03:05:00 to 01/03:15:00
Baseline: LA (4) - PT (8) Stokes: RR

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



Resolved – a model or image will be needed

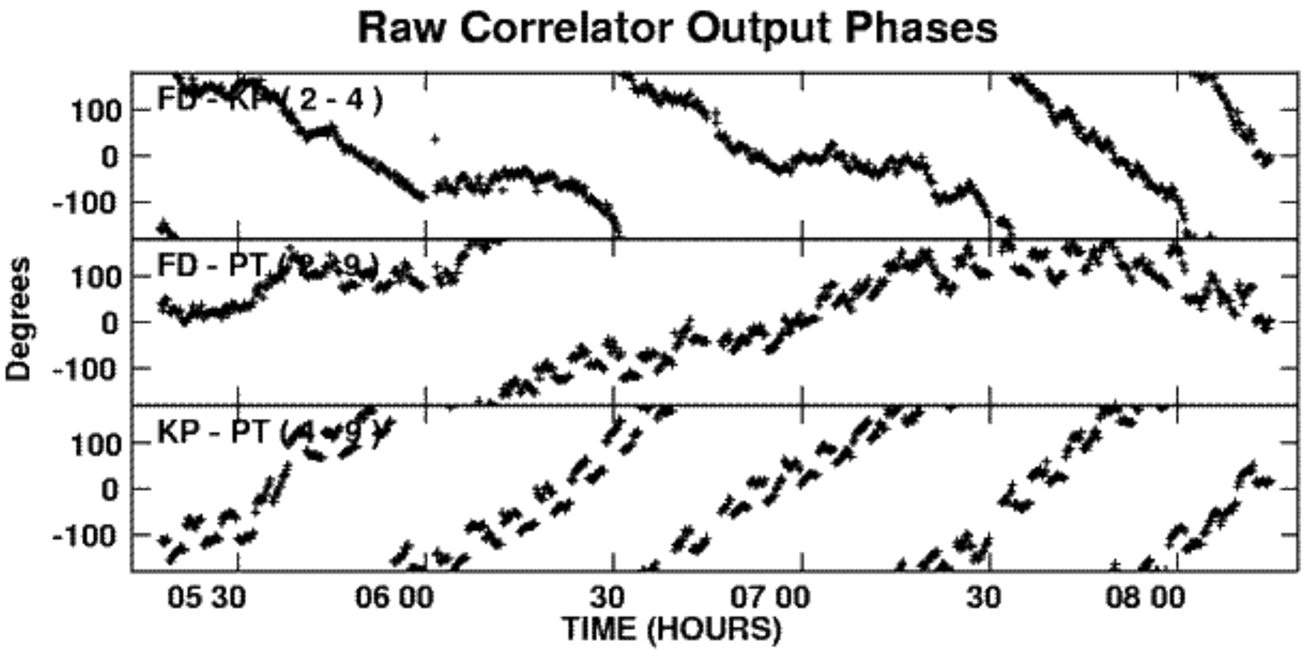
Poorly calibrated antenna

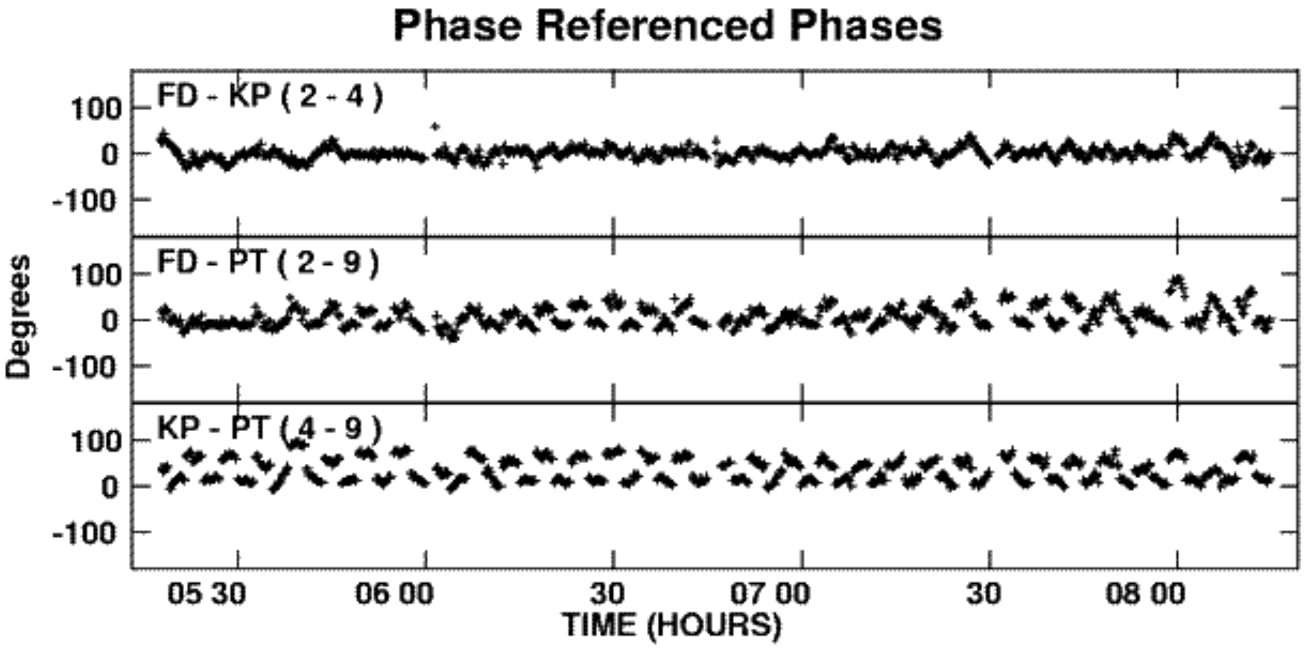
PHASE REFERENCING

- 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



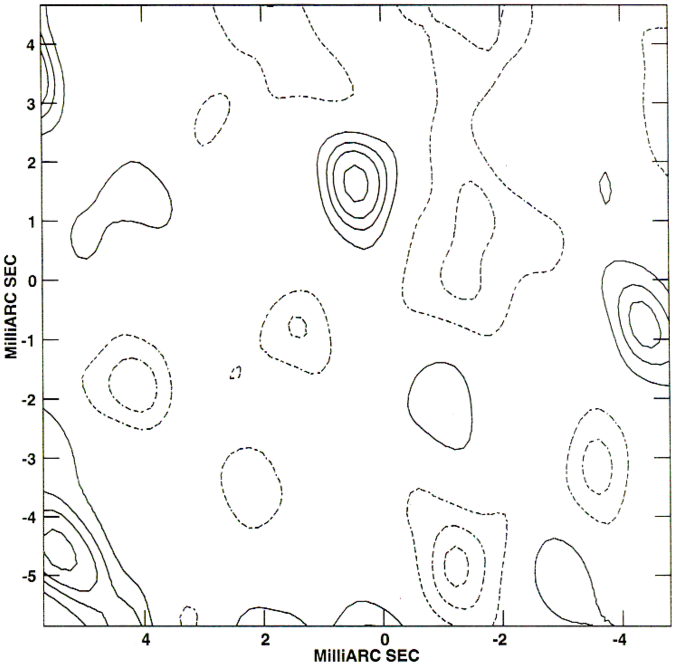


Phase Referencing Example

- 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

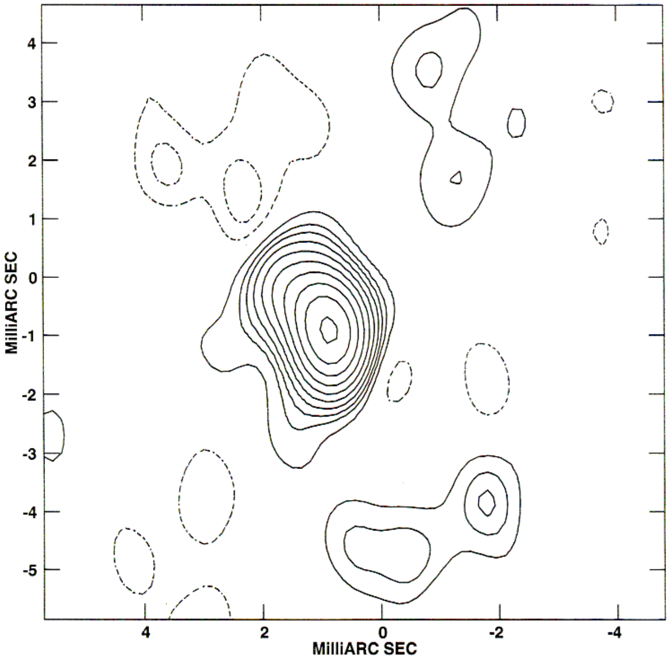
PLot file version 1 created 01-JUN-1995 11:34:40 0309+411
0309+411 IPOL 8418.615 MHZ 0309X CL6.ICLN.5



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

PLot file version 2 created 01-JUN-1995 11:26:27 0309+411
0309+411 IPOL 8418.615 MHZ 0309X CL6.ICLN.4

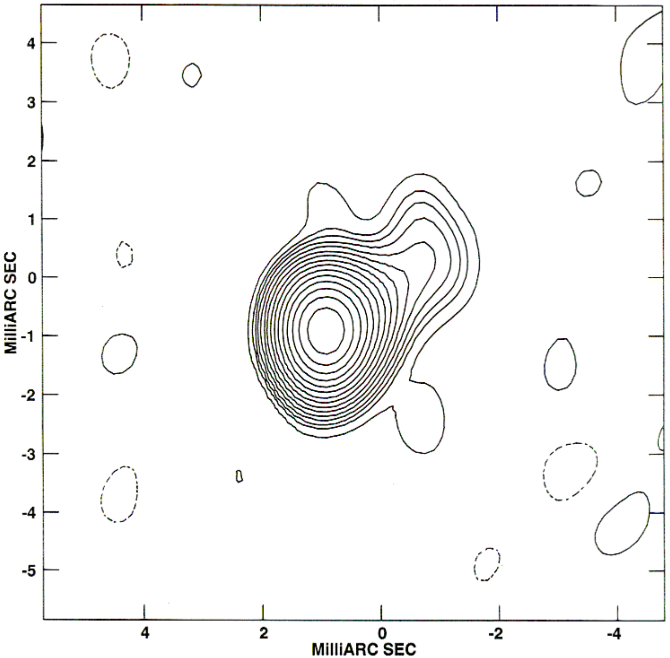


Center at RA 03 13 1.96210 DEC 41 20 1.1840
Peak flux = 3.4321E-01 JY/BEAM
Levs = 1.0000E-02 * (-2.83, -2.00, -1.00,
1.000, 2.000, 2.828, 4.000, 5.657, 8.000,
11.31, 16.00, 22.63, 32.00, 45.25, 64.00,
90.51, 128.0, 181.0, 256.0, 362.0, 512.0,
724.1, 1024., 1448., 2048., 2896., 4096.,
5793., 8192.,11585.)

VLBA
9 SCANS
12 MINUTES DATA

Self-calibration

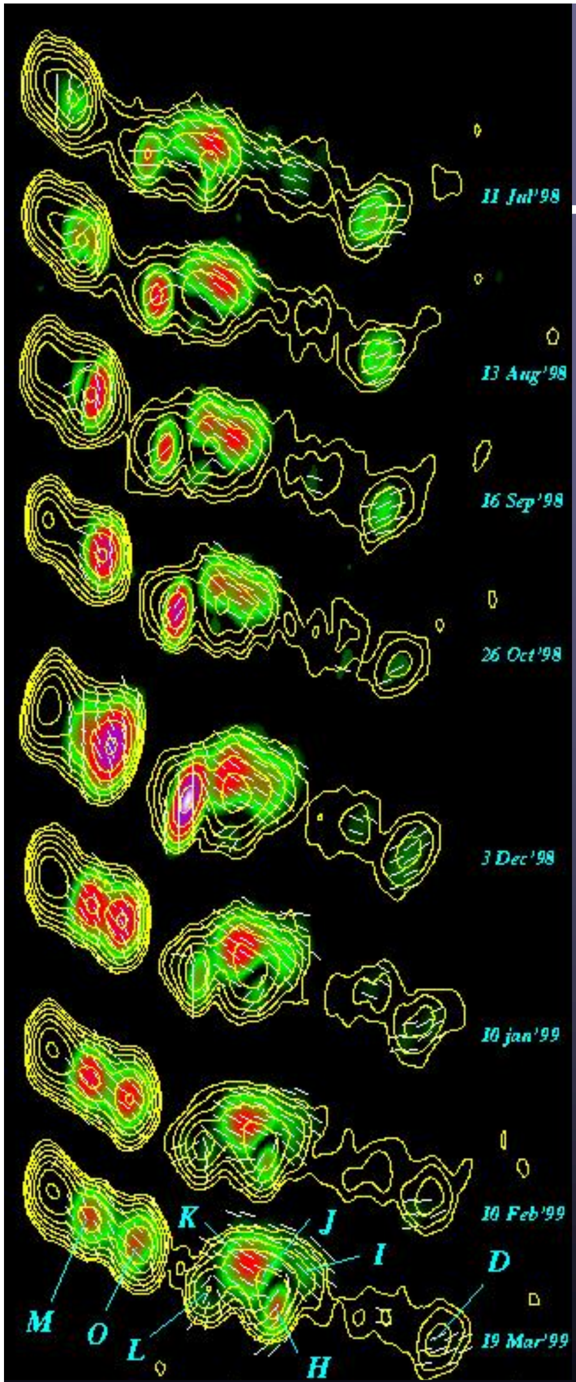
PLot file version 3 created 01-JUN-1995 13:12:16 0309+411
0309+411 IPOL 8418.365 MHZ 0309X CL6.ICLN.13

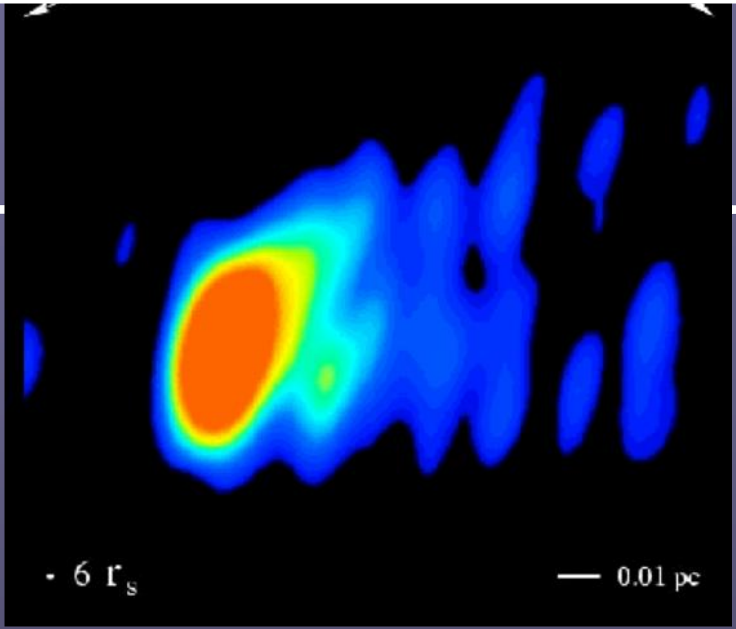


Center at RA 03 13 1.96210 DEC 41 20 1.1840
Peak flux = 3.7156E-01 JY/BEAM
Levs = 2.0000E-03 * (-2.68, -1.93, -1.00,
1.000, 1.931, 2.683, 3.728, 5.179, 7.197,
10.00, 13.89, 19.31, 26.83, 37.28, 51.79,
71.97, 100.0, 138.9, 193.1, 268.3, 372.8,
517.9, 719.7, 1000., 1389., 1931., 2683.,
3728., 5179., 7197.)

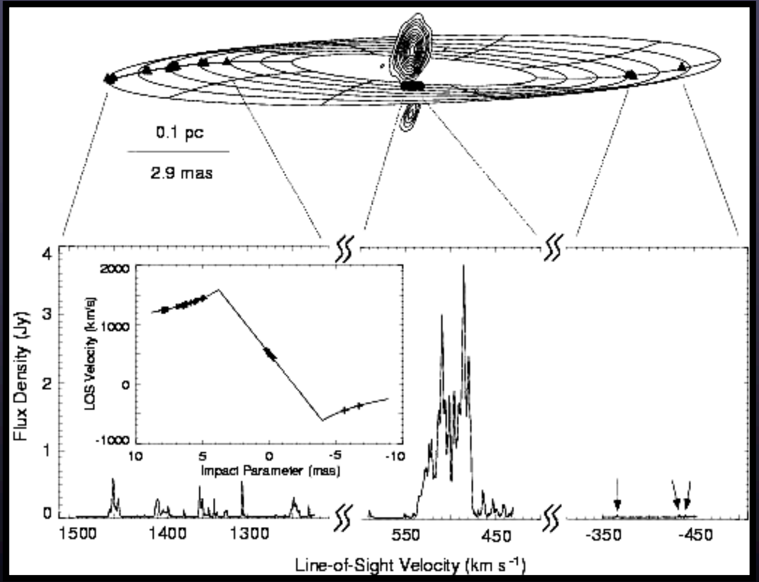
SCHEDULING

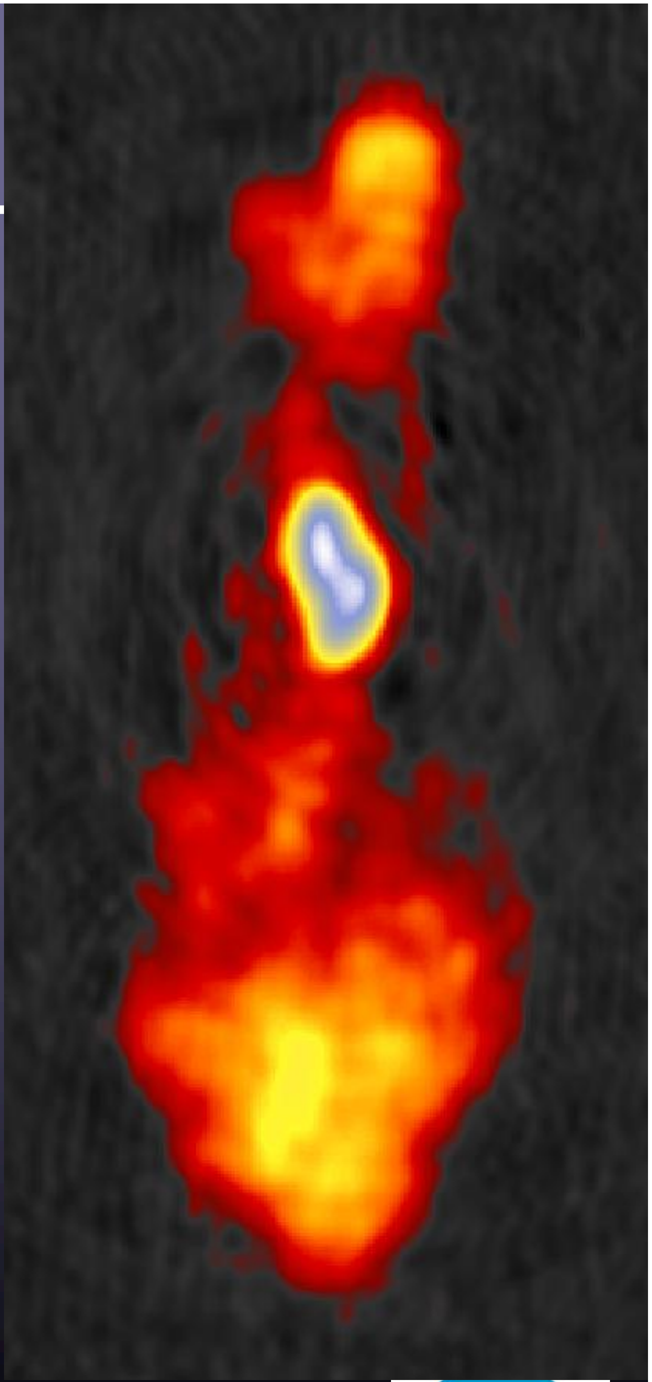
- PI provides the detailed observation sequence
- The schedule should include:
  - Fringe finders (strong sources - at least 2 scans – helps operations)
  - Amplitude check source (strong, compact source)
  - If target is weak, include a delay/rate calibrator
  - If target very weak, fast switch to a 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)


11 Jul'98
13 Aug'98
16 Sep'98
26 Oct'98
3 Dec'98
10 jan'99
10 Feb'99
19 Mar'99
K
J
I
D
M
O
L
H


6 r_s
0.01 pc

THE END


0.1 pc
2.9 mas
Flux Density (Jy)
4
3
2
1
0
LOS Velocity (km/s)
2000
1000
0
-1000
10
5
0
-5
-10
Impact Parameter (mas)
1500
1400
1300
550
450
-350
-450
Line-of-Sight Velocity (km s⁻¹)



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