Very Long Baseline Interferometry

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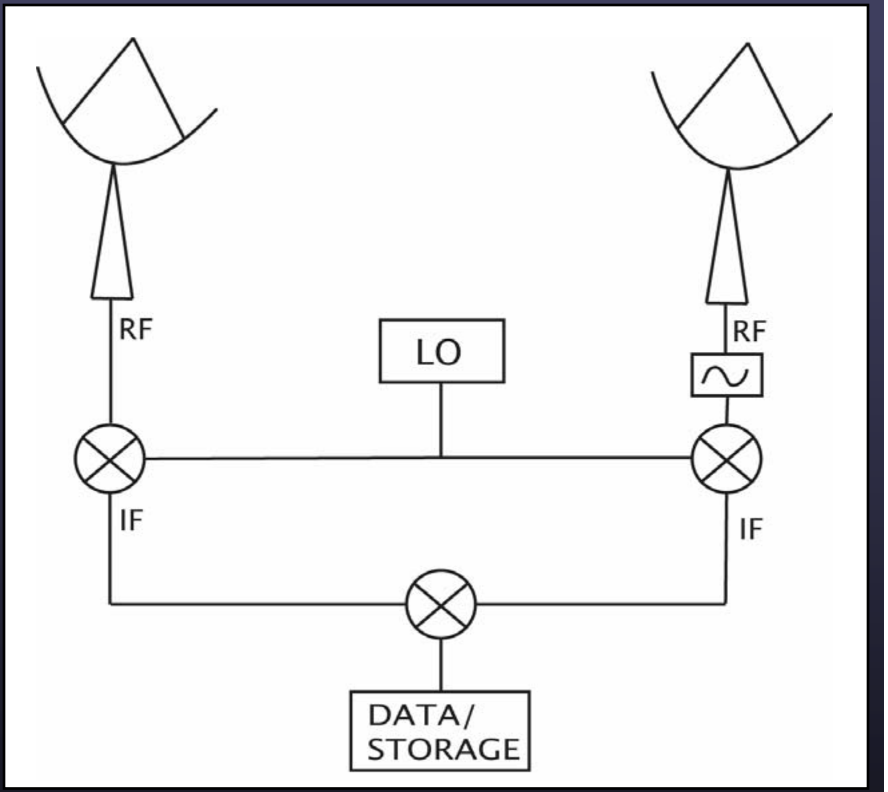
Eleventh Synthesis Imaging Workshop

Socorro, June 10-17, 2008

What is VLBI?

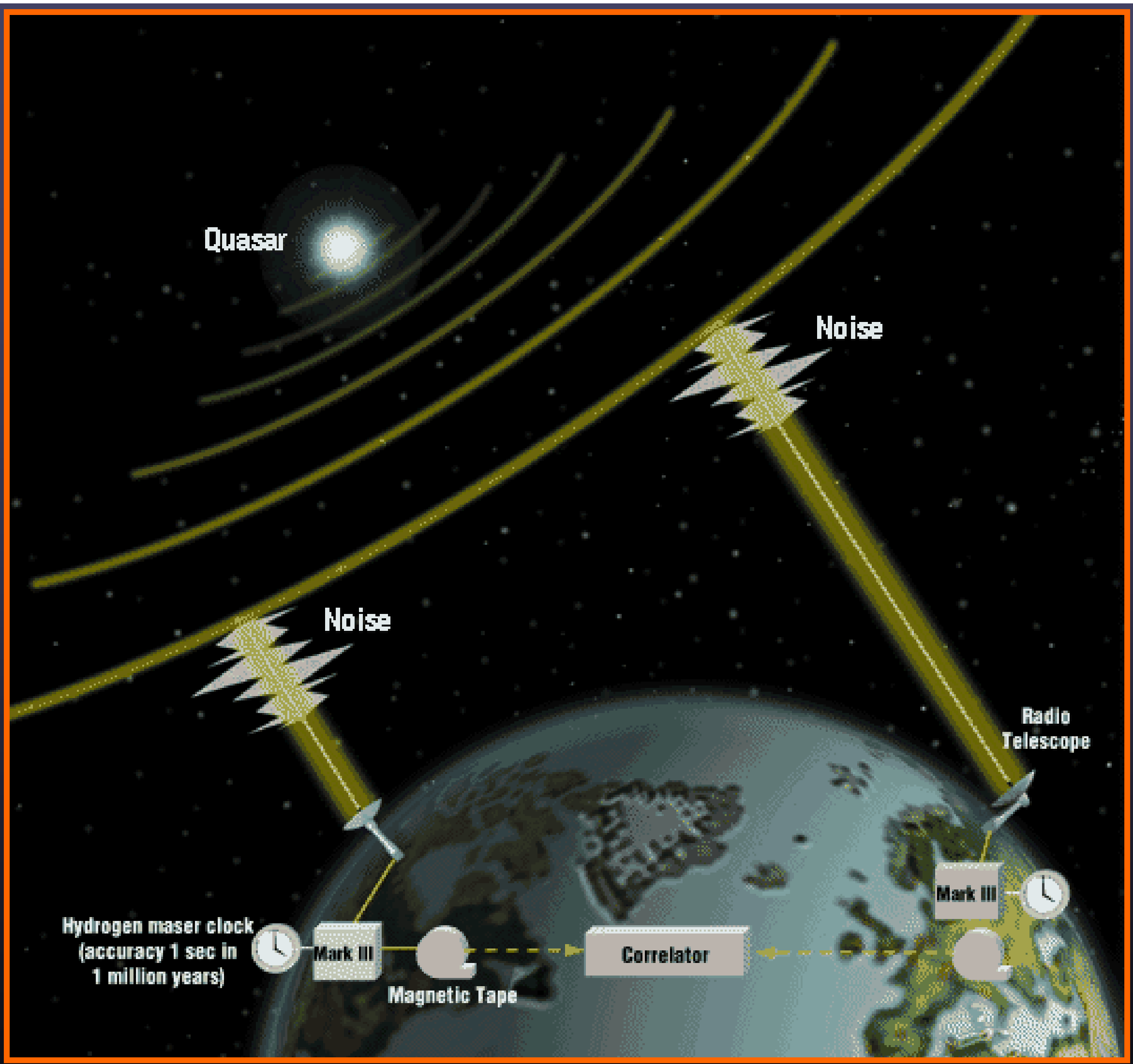
- VLBI is interferometry with disconnected elements
- No fundamental difference from connected element interferometry
- The basic idea is to bring coherent signals together for correlation, and to get fringes from each interferometer
- Can look at radio interferometry as Young's double slit experiment in reverse.



Connected elements: done via cables

VLBI versus connected elements

- In VLBI there are no wired connections between antennas.
- Instead accurate time standards and a recording system are used to preserve phase of the incoming wave front.



VLBI correlators

The correlation is not real-time but occurs later on.

Disks/tapes shipped to the correlators

Examples are the VLBA and the Haystack correlator.

Software Correlators coming on-line.

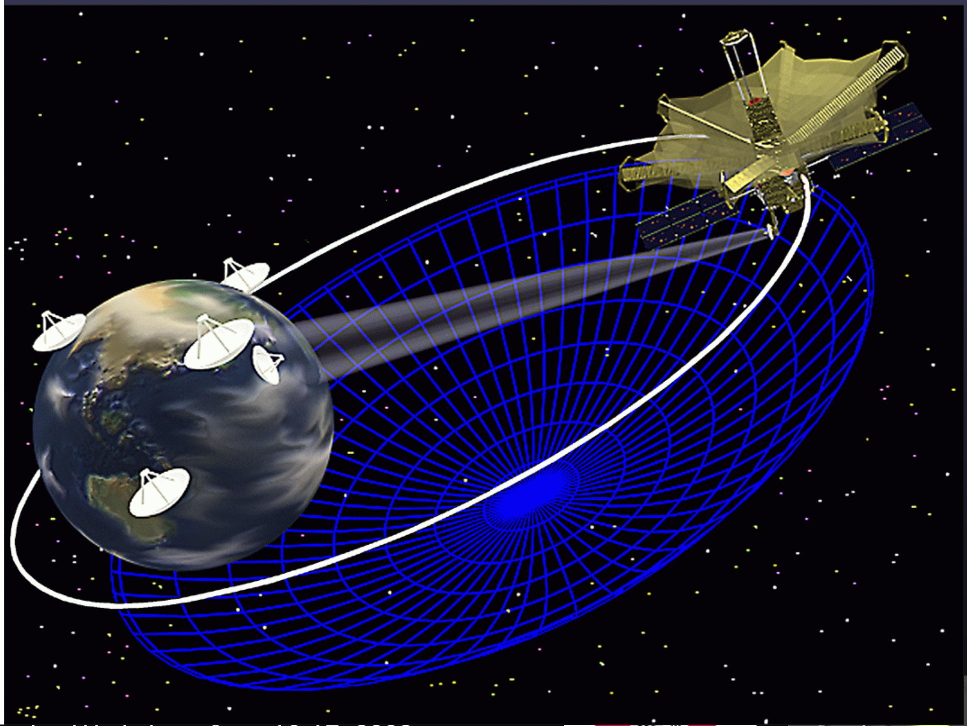
The University of New Mexico

New Mexico Consortium's IAS Institute for Advanced Studies at Los Alamos National Laboratory

One Main Reason for VLBI: Extreme Resolution

- 'Very Long Baselines' implies high angular resolution ($\theta \sim \lambda/B$)
- The Very Long Baseline Array (VLBA) 0.1 - 5 mas
- 230GHz VLBI on 8000km baselines: 20-40 micro arcsec

Optical VLBI?



Another Key Reason for VLBI: Extreme Sensitivity


Arecibo 300m


Westerbork ~90m


Effelsberg 100m

GBT 100m



Lovell 76m

Area > 0.1 km^2

	1 Gb/s	2 Gb/s	4 Gb/s
L Band Array	2.3 μJy	1.8 μJy	1.3 μJy
C Band Array	3.1 μJy	2.4 μJy	1.7 μJy

The black hole in NGC4258

- Tangential disk masers at Keplerian velocities
- First real measurement of nuclear black hole mass
- Add time dimension (4D) => geometric distance

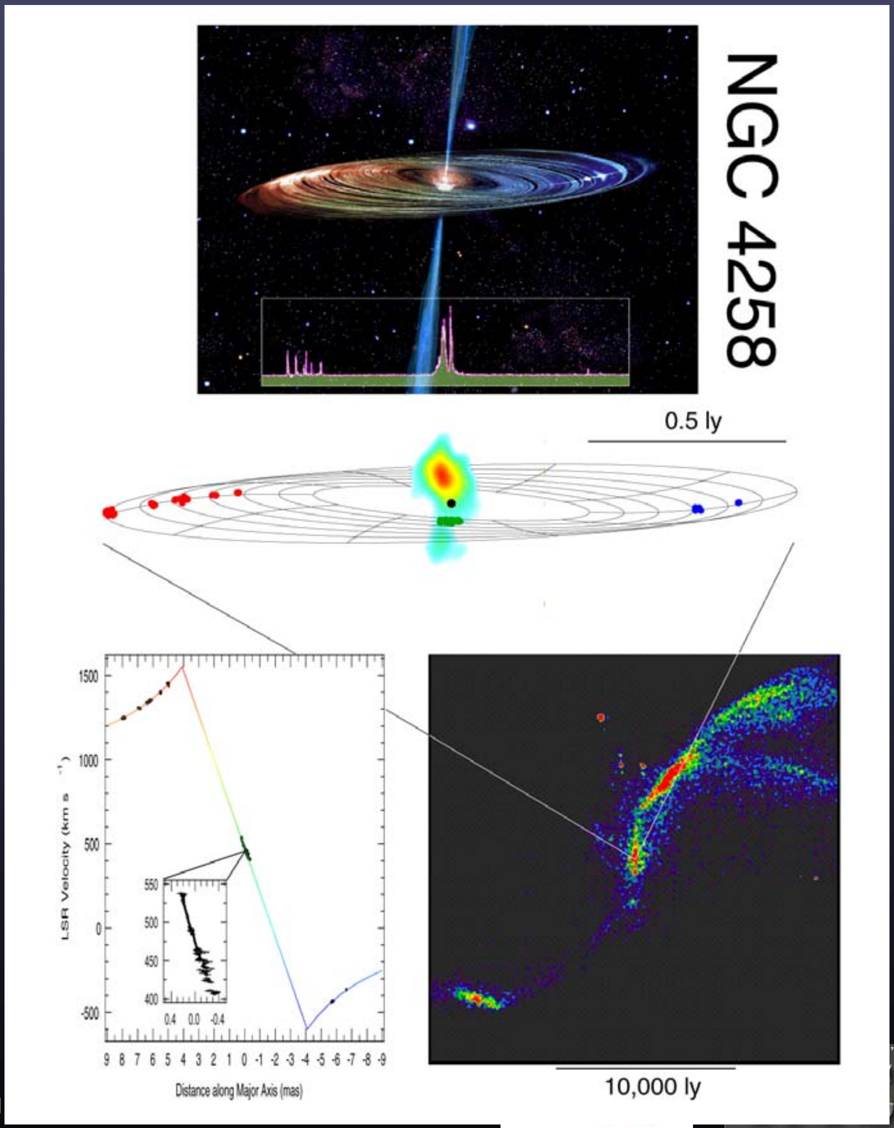
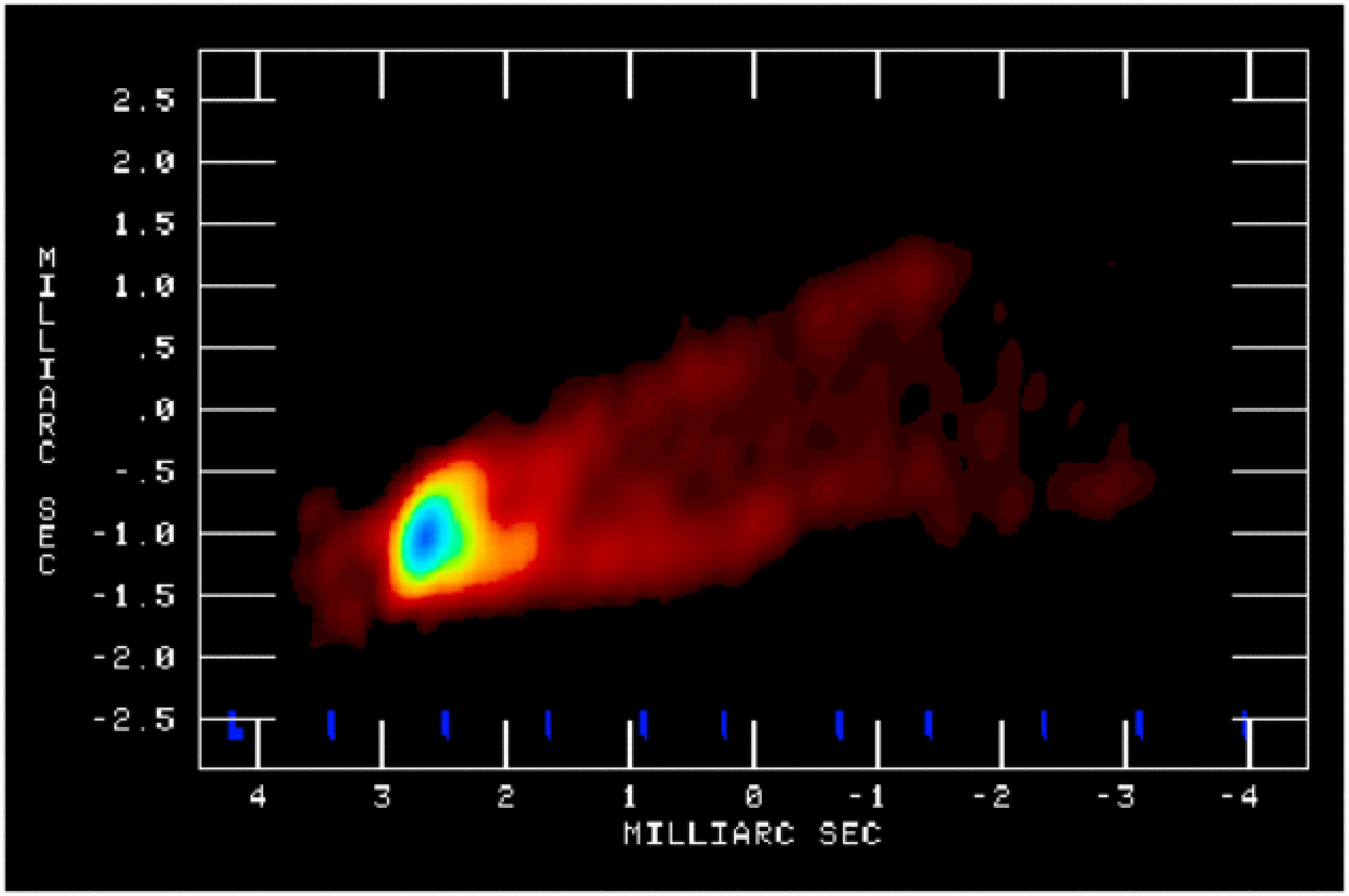


Image courtesy: L. Greenhill

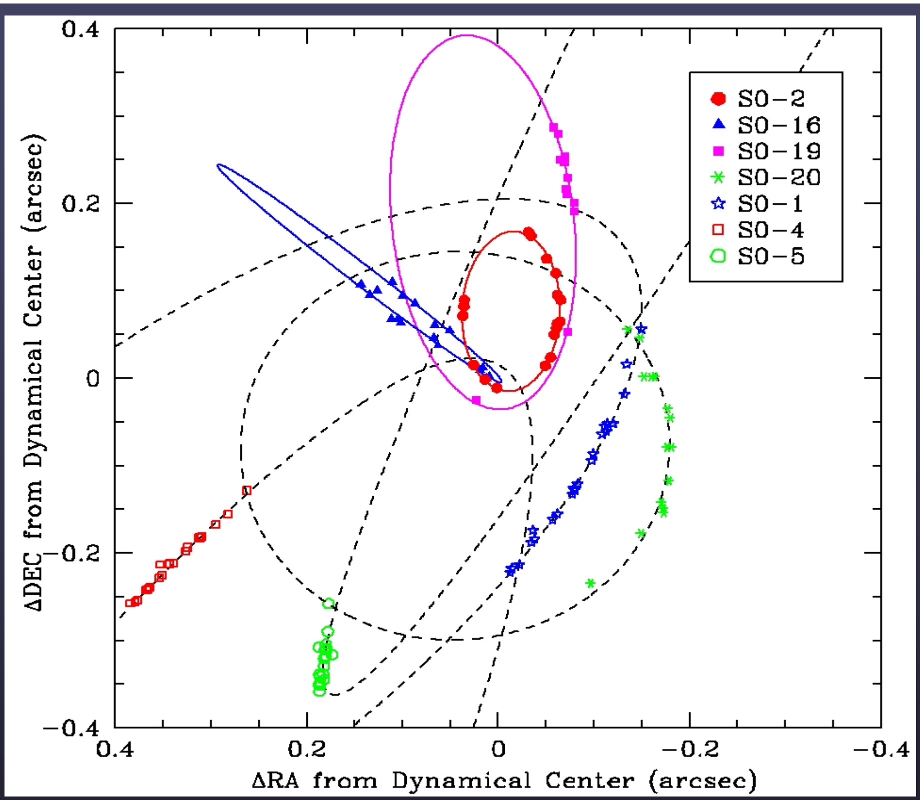
The VLBA 43 GHz M87 Movie First 11 Observations

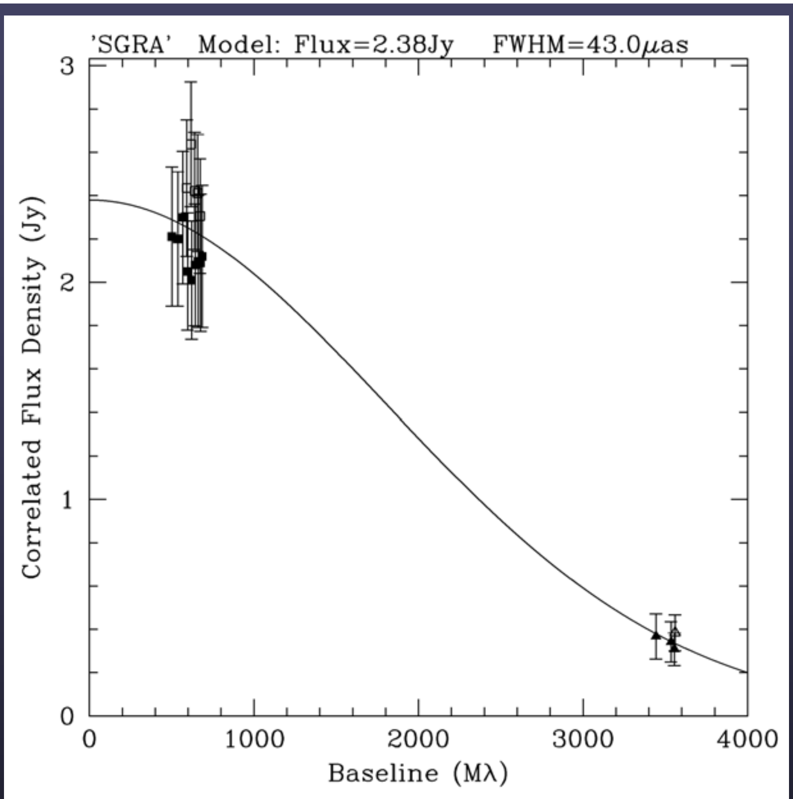


Walker, Ly, Junor & Hardee 2008

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

The super massive black hole in the Milky Way

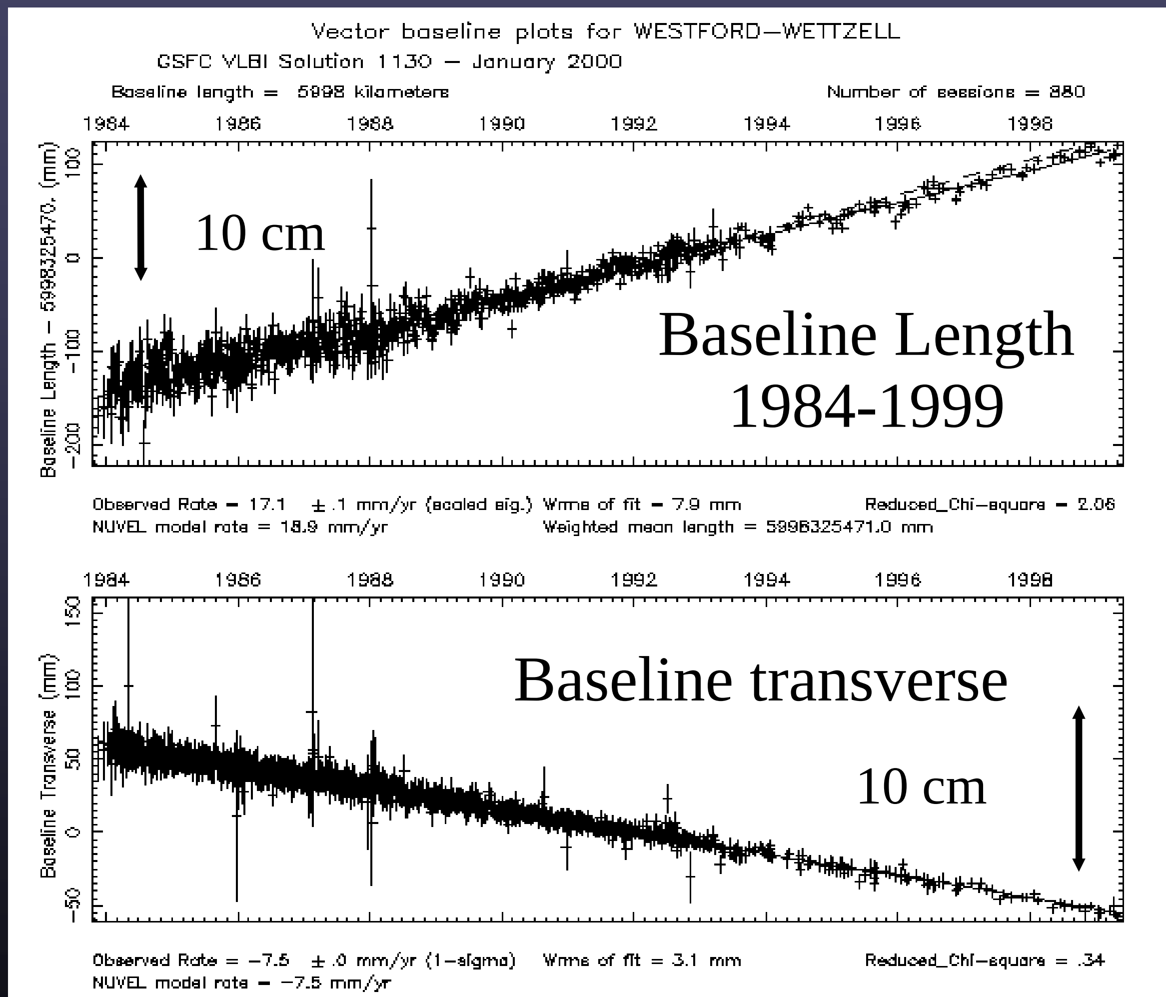




Unseen mass = 3.7 x 10^6 Msol

VLBI at 230GHz give size of 3.7 Rsch
Compelling evidence for BH.

Geodesy: Plate Tectonics



Masers tracing dynamics of stellar photosphere

QuickTime™ and a
decompressor
are needed to see this picture.

TX Cam SiO masers in turbulent shocked photosphere.

VLBI resolves structure much smaller than stellar disk.

Diamond & Kemball

Differences VLBI and connected interferometry

- Not fundamentally different, only issues that lead to different considerations during calibration

- Rapid phase variations and gradients introduced by
  - Separate clocks
  - Independent atmosphere at the antennas
  - Phase stability varies between telescope electronics.
  - Model uncertainties due to inaccurate source positions, station locations, and Earth orientation, which are difficult to know to a fraction of a wavelength
  - Want to average in time and frequency to build SNR.

  - *Solve by fringe fitting (aka performing a fringe search)*

Differences VLBI and connected interferometry (continued)

- The calibrators are not ideal since they are a little resolved and often variable
  - No standard flux calibrators
  - No point source amplitude calibrators
  - *Solve by using T_{sys} and gains to calibrate amplitudes*
  - *Or…in case of spectral-line: use line fits to calibrate.*
- Only sensitive to limited scales
  - Structure easily resolved out
  - *Solve by including shorter baselines (MERLIN, VLA)*

Differences VLBI and connected interferometry (continued)

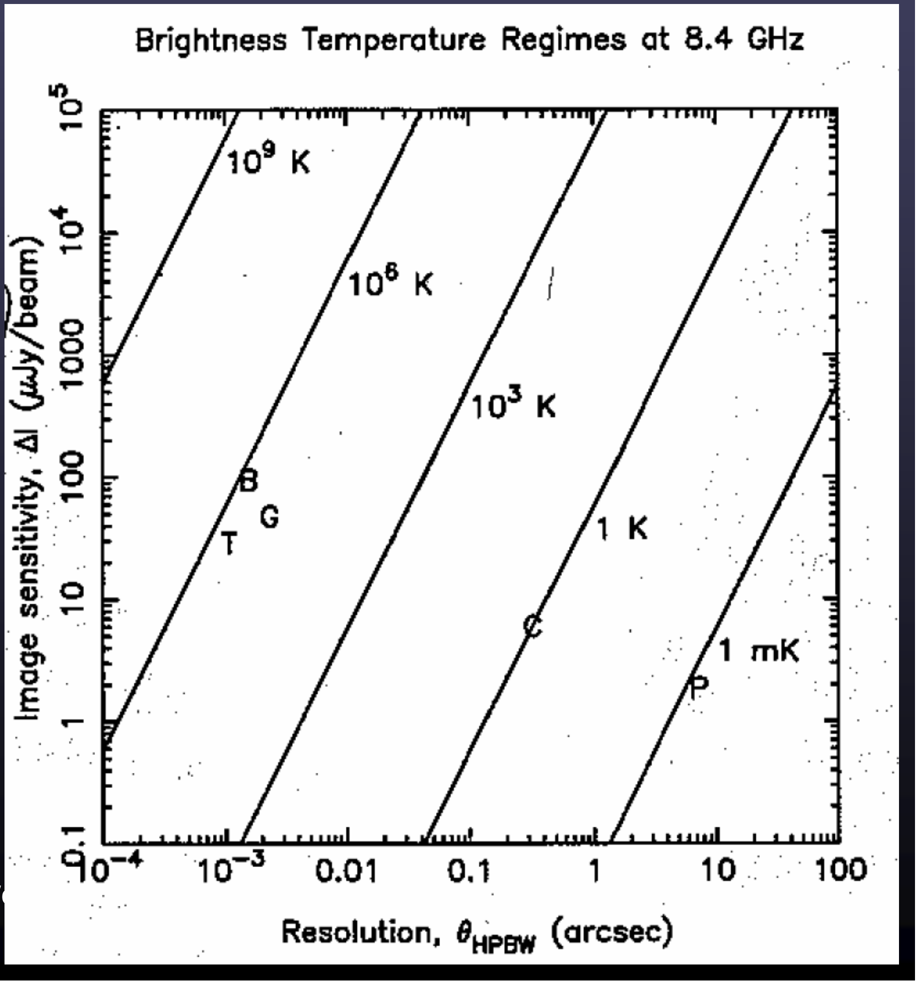
- Only sensitive to non-thermal emission processes ($T_{b,min} \propto \theta^{-2}_{HPBW}$)
  - 10^6 K brightness temperature limit
  - Tailored science cases

To improve sensitivity

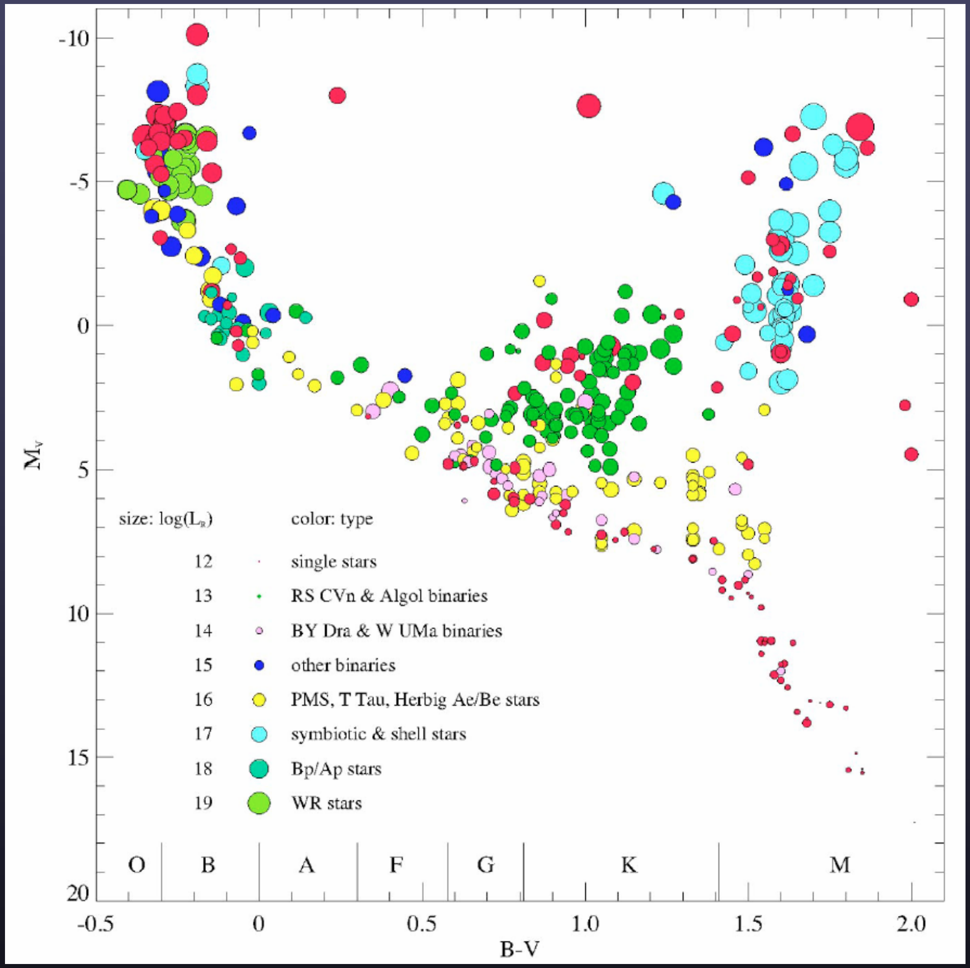
Use bigger telescopes (HSA)

For continuum, use a higher data rate (wider bandwidth), MkV (disk based recording) can reach 1GBps

VLBI moving rapidly to 4 Gb/s.



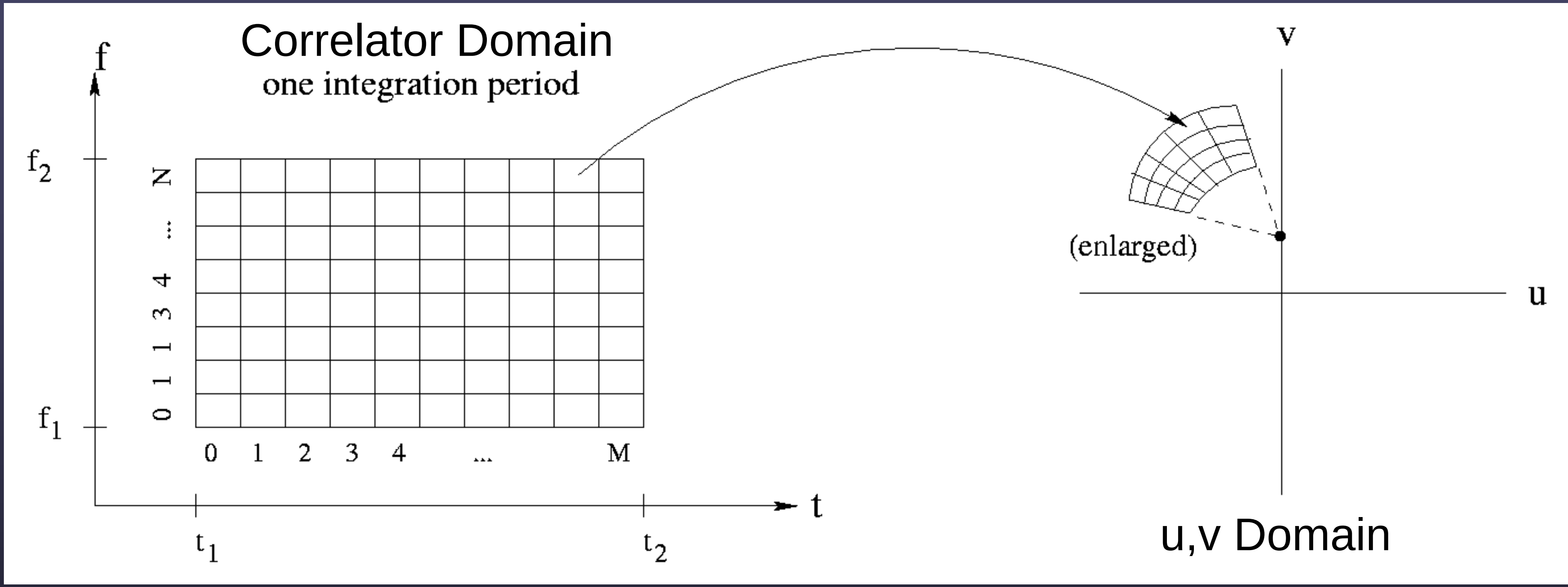
Stellar VLBI: Radio-Active Stars



Stars exhibit radio activity all over HR diagram.

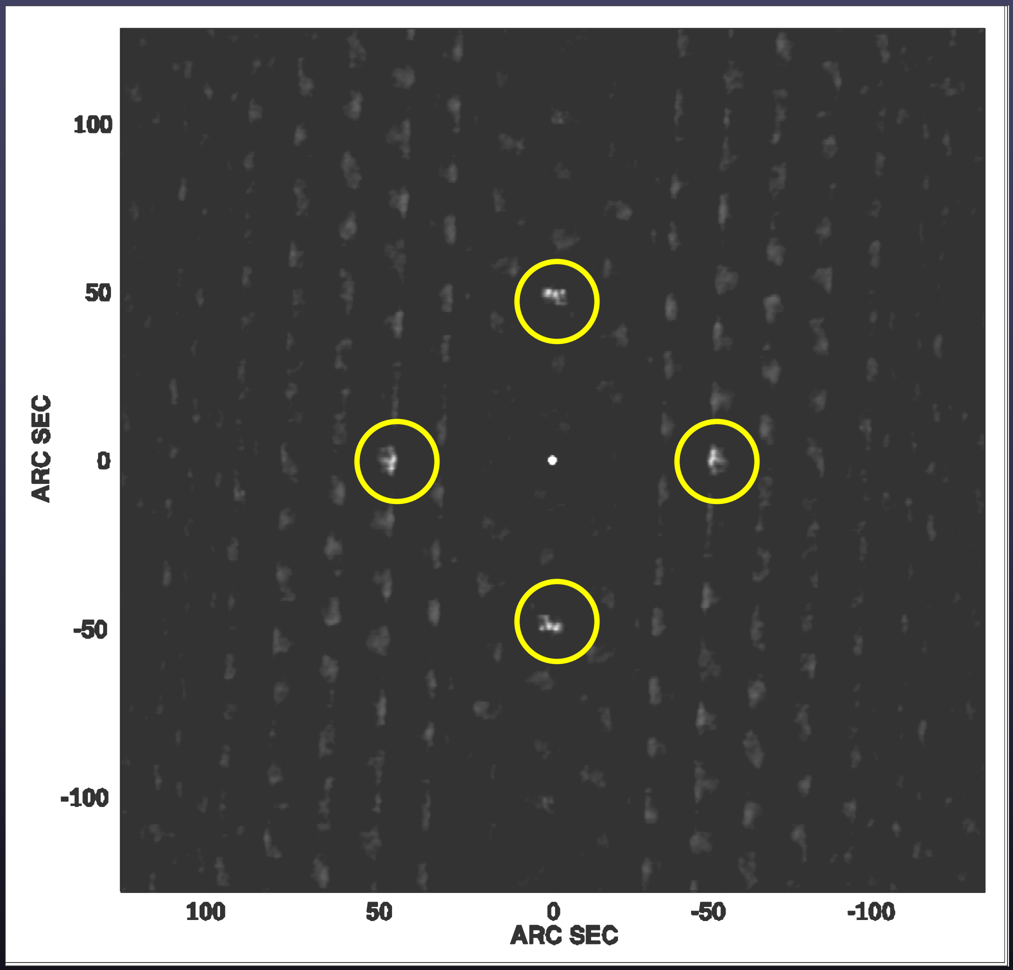
Due to VLBI-scale non-thermal processes.

Field of View : Time and Bandwidth 'smearing'



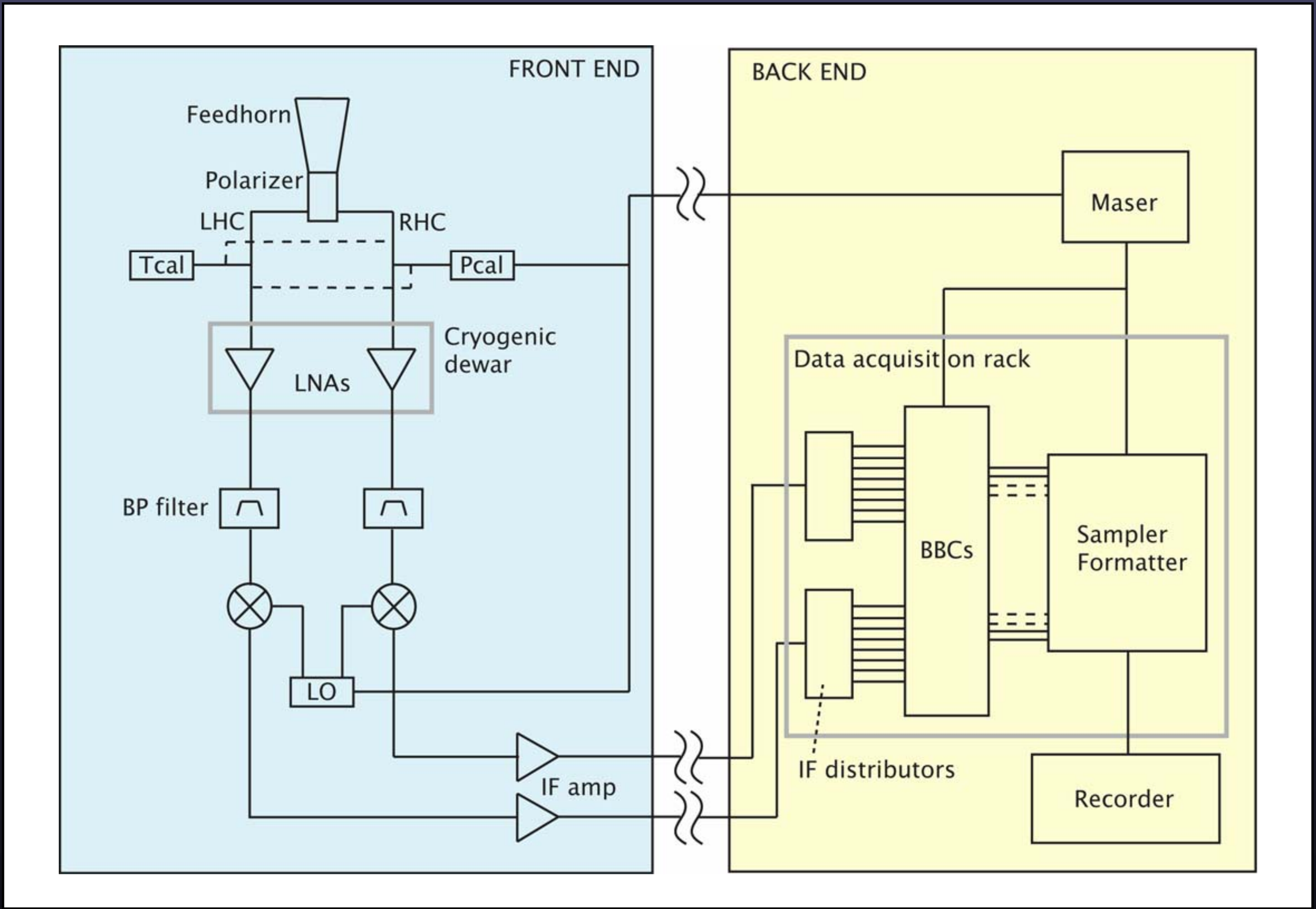
- Baseline sweeps out ellipse in u,v plane with time.
- BW governs radial extent of u,v swath.
- Averaging in time/BW erases sky structure.

Field of View

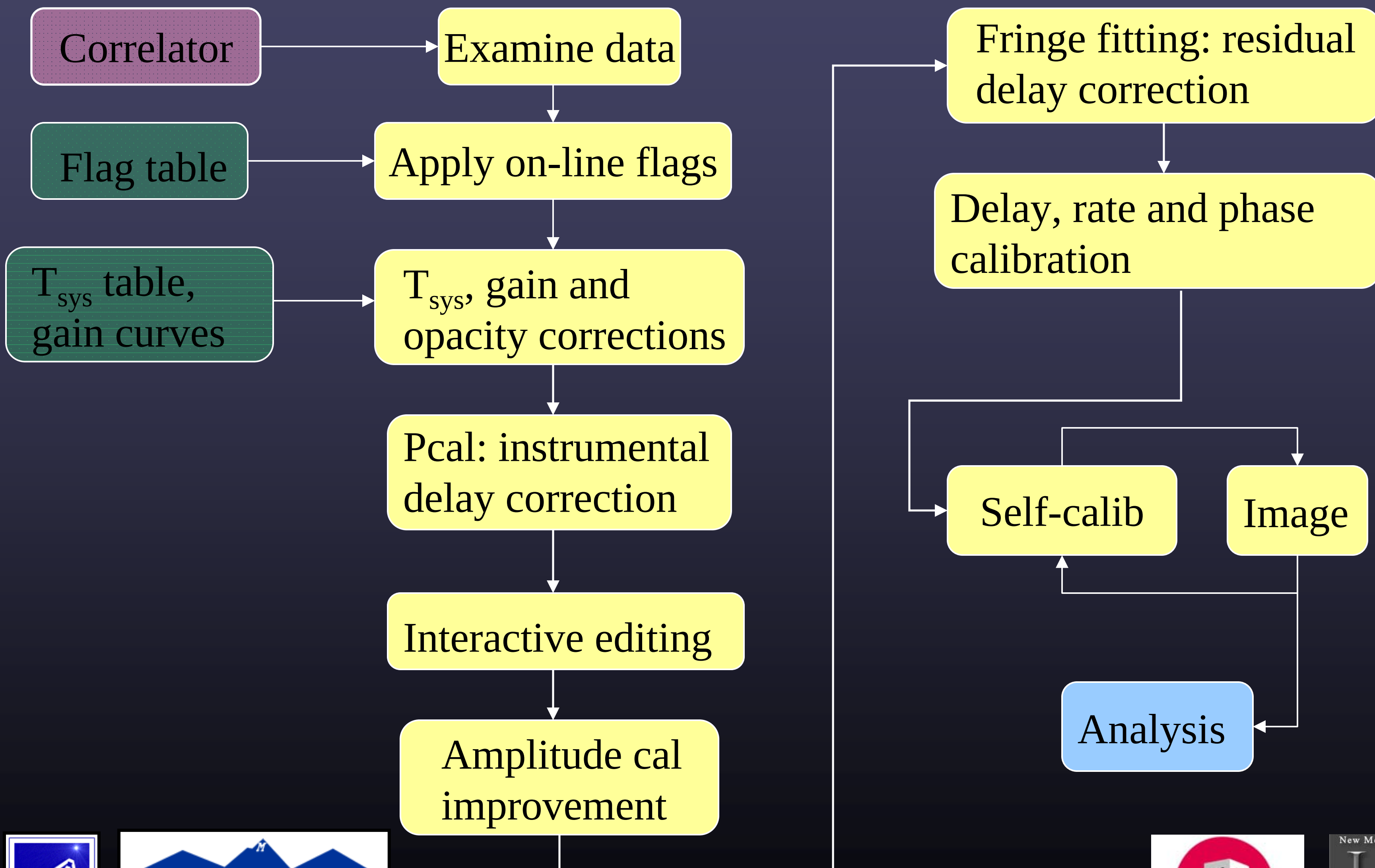


- Field of view limited by correlator parameters.
- For wide field of view, need small time and frequency intervals.
- Averaging in time and frequency does not treat all baselines equally - distortion.
- Critical for VLBI
- See lecture 18 in book.

Signal flow in a VLBI system



VLBI data reduction path - continuum



The task of the correlator

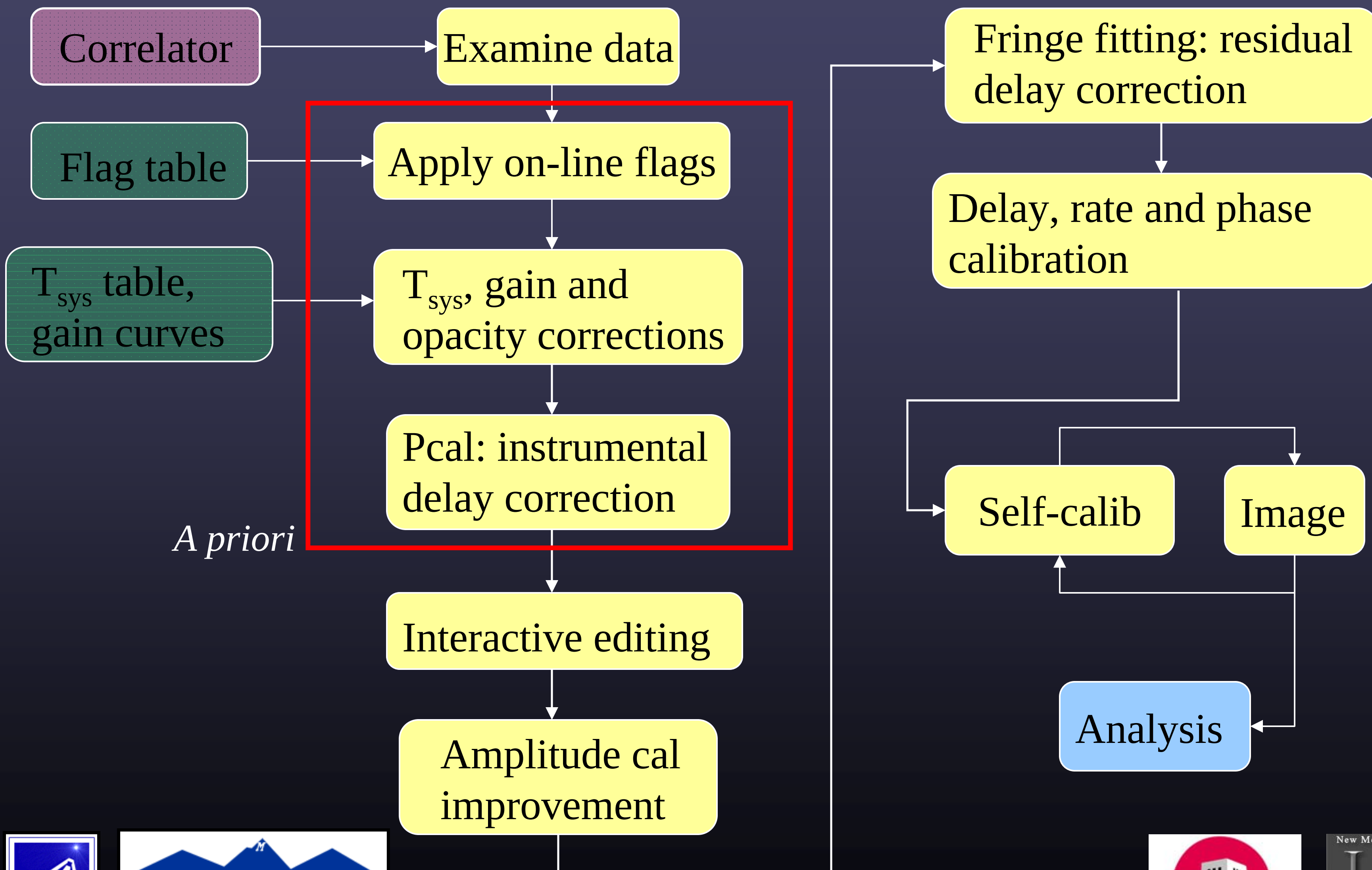
- Main task is to cross multiply signals from the same wavefront
  - Antennas at different distances => delay
  - Antennas move at different speed => rate
- Offset estimates removed using a geometric model
- Remaining phase errors normally dominated by the atmosphere
- Write out data

The VLBA delay model

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

Adapted from Sovers, Fanselow, and Jacobs, Reviews of Modern Physics, Oct 1…98.

VLBI data reduction path - continuum



Apriori editing

- Flags from the on-line system will remove bad data from
  - Antenna not yet on source
  - Subreflector not in position
  - LO synthesizers not locked

VLBI amplitude calibration

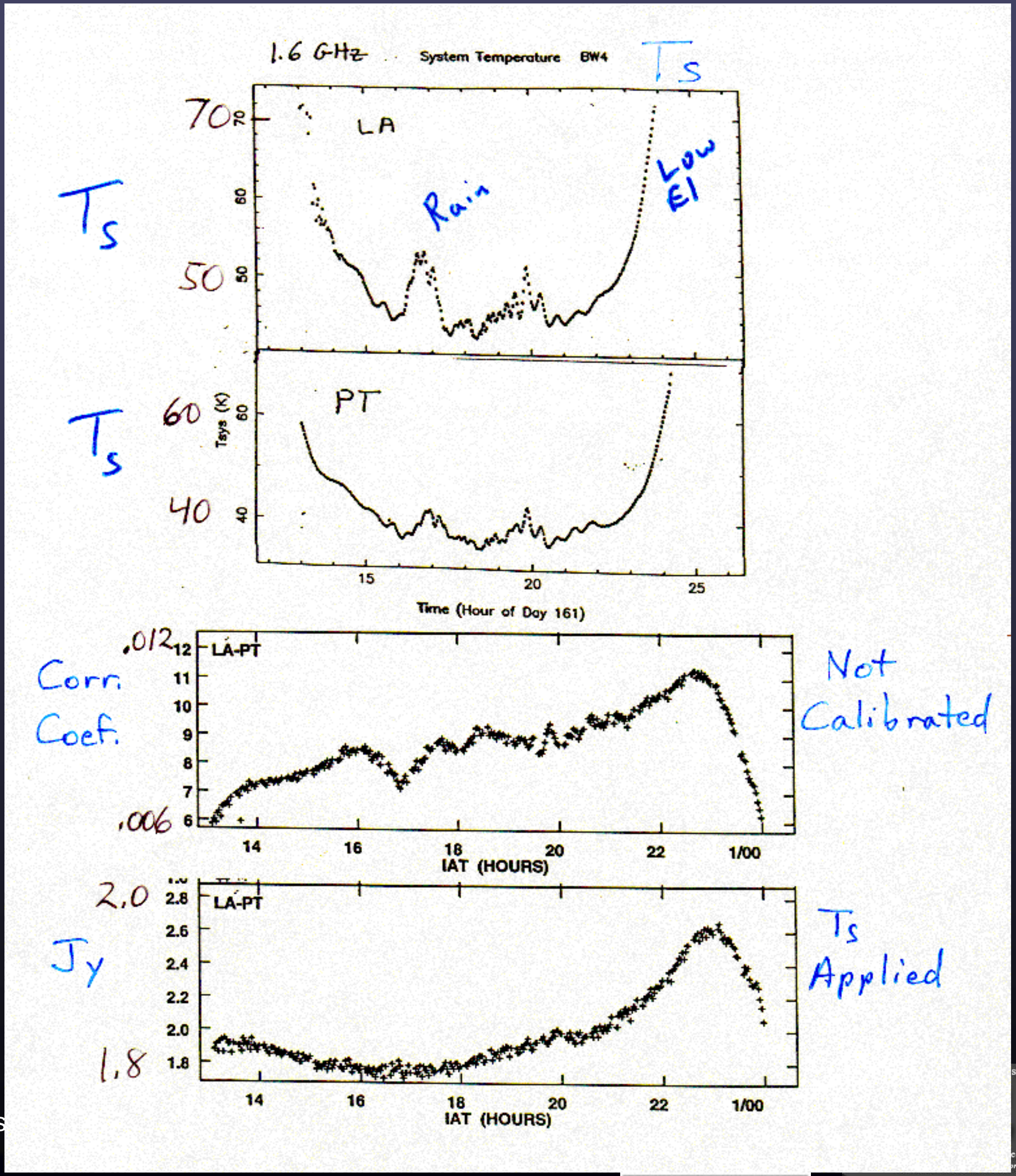
$$S_{cij} = \rho \frac{A}{\eta_s} \sqrt{\frac{T_{si} T_{sj}}{K_i K_j e^{-\tau_i} e^{-\tau_j}}}$$

- 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

Calibration with system temperatures

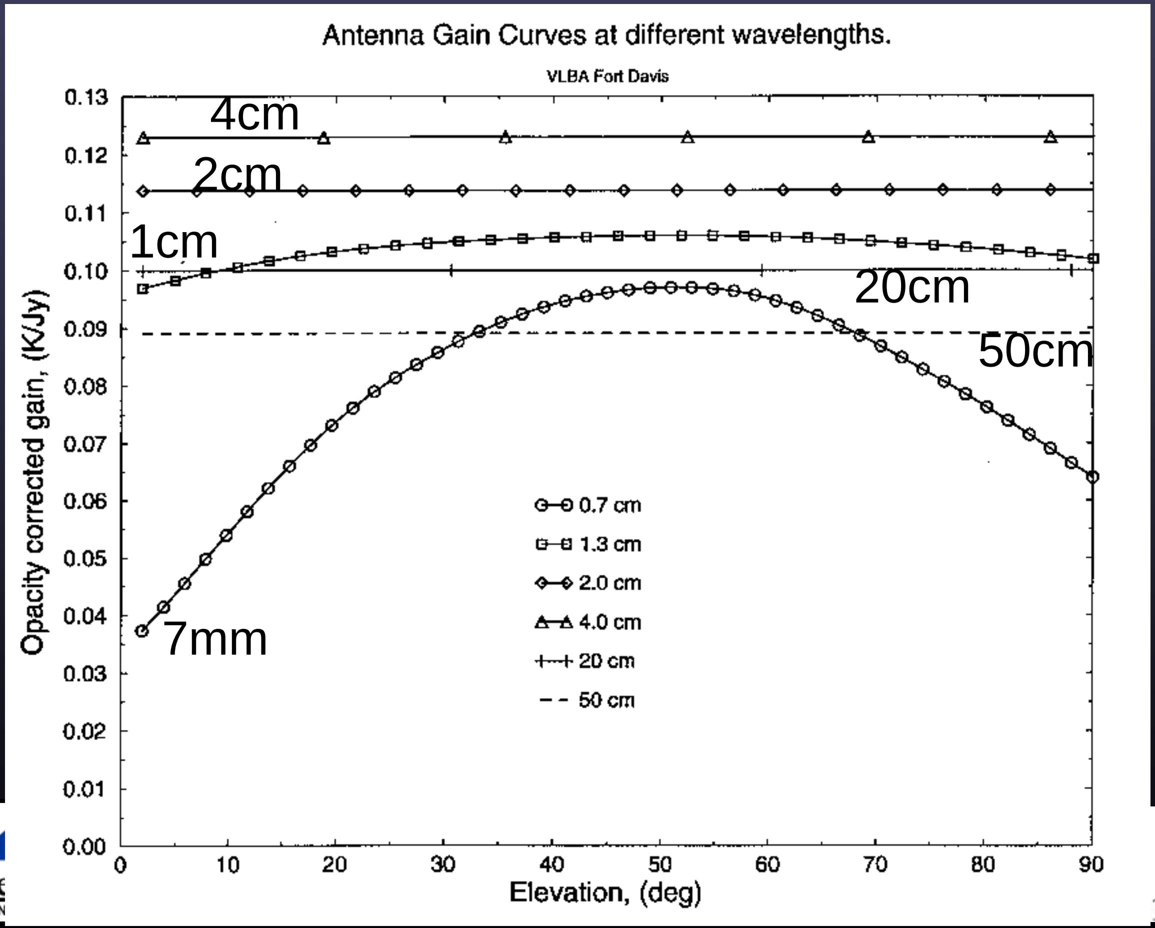
Upper plot: increased T_{sys} due to rain and low elevation

Lower plot: removal of the effect.



VLBA gain curves

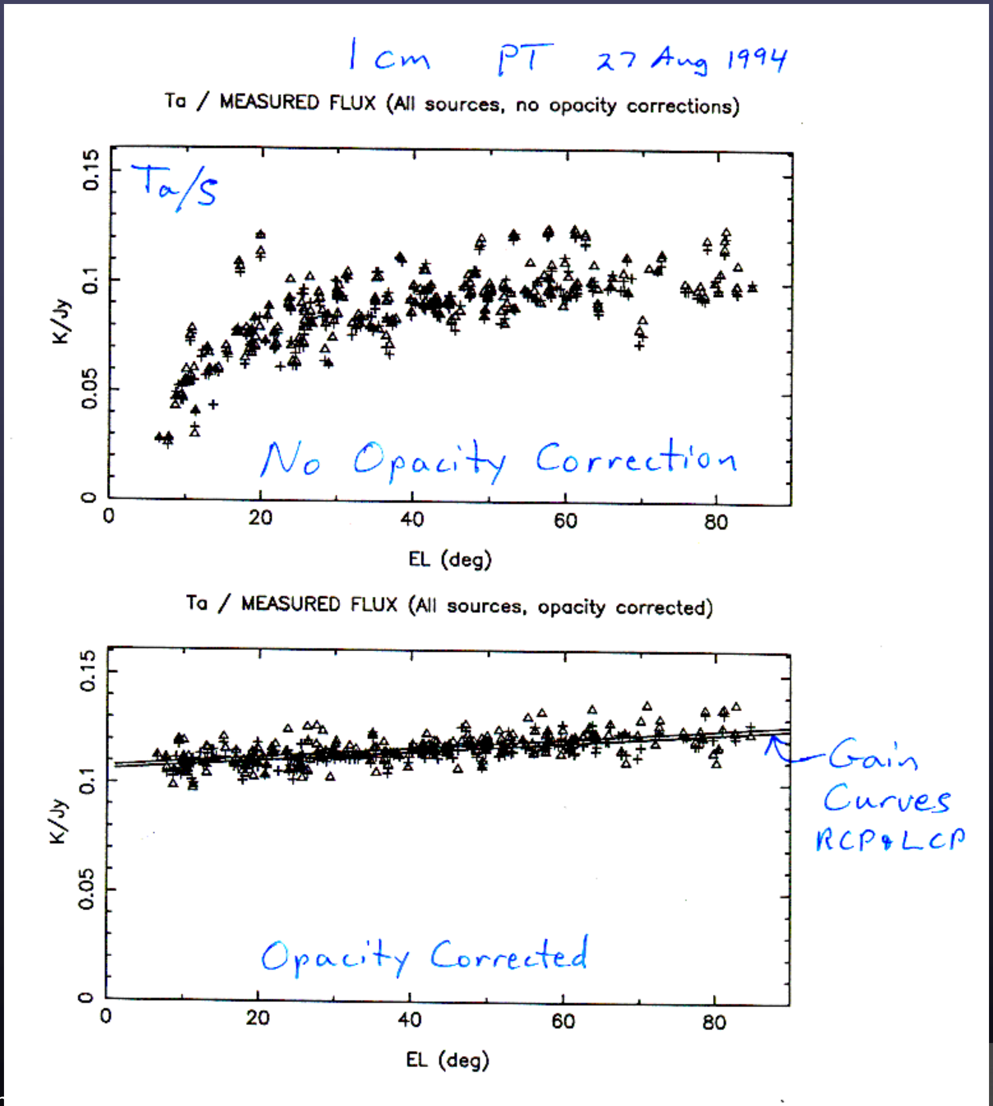
- Caused by gravitationally induced distortions of antenna
- Function of elevation, depends on frequency



Atmospheric opacity correction

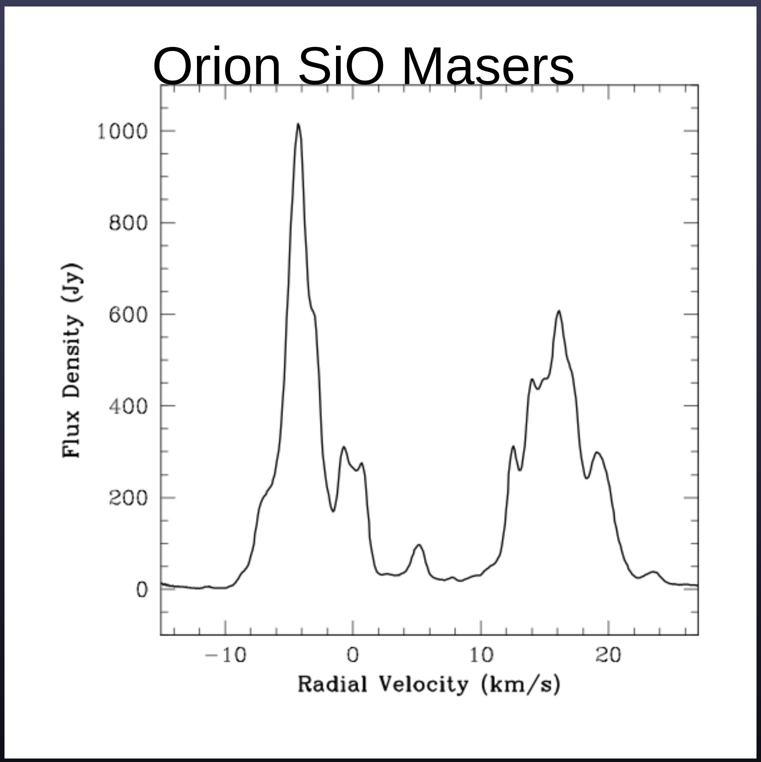
- Corrections for absorption by the atmosphere
- Can estimate using T_{sys} - T_{rec} - T_{spill}
- Want to de-couple gain curve from opacity.

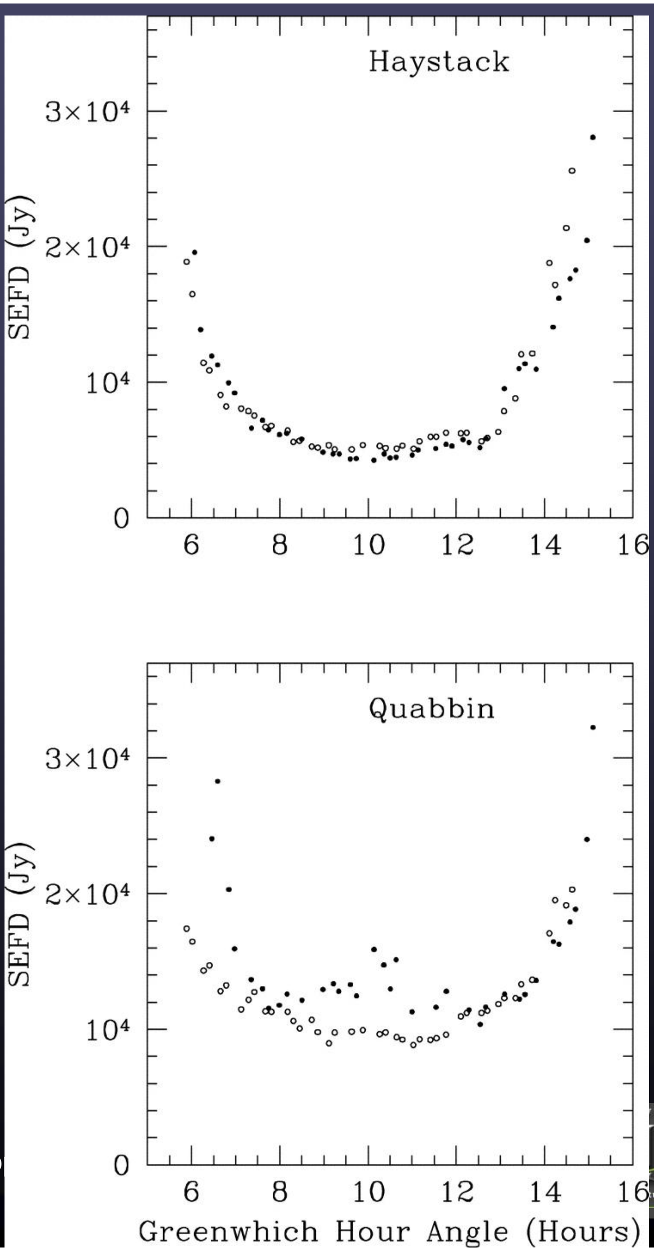
Example from VLBA single dish pointing data



Spectral Line VLBI: A special case

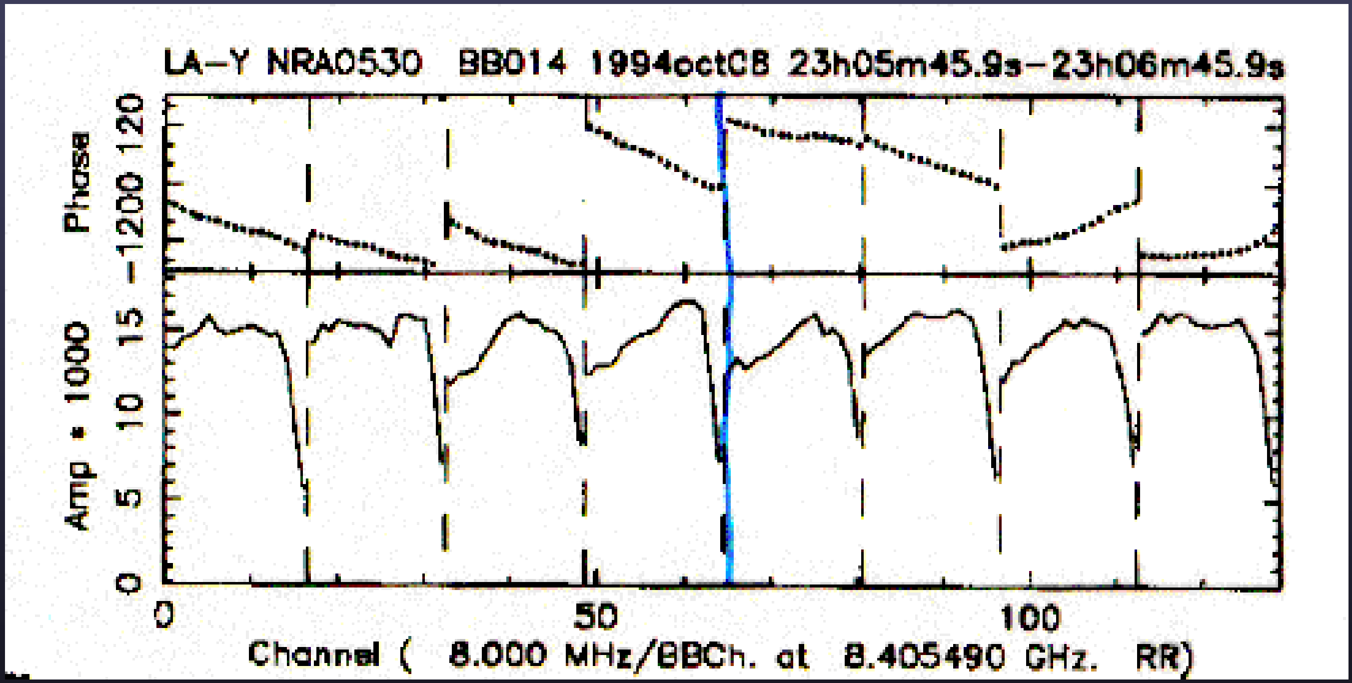
- Can obtain excellent relative amplitude cal from spectral fitting.
- Select a template spectrum, then compare all other times and antennas to the template.
- Takes care of pointing errors.





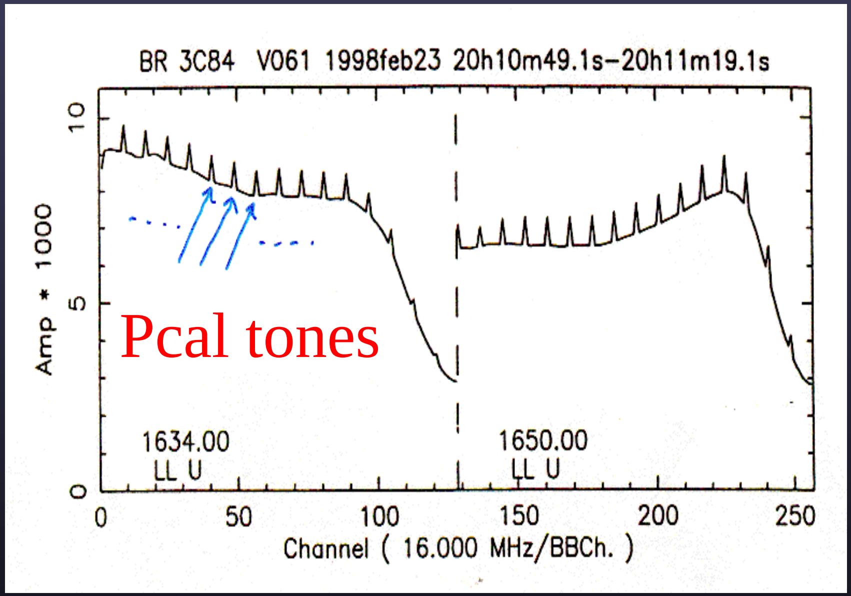
Instrumental delays

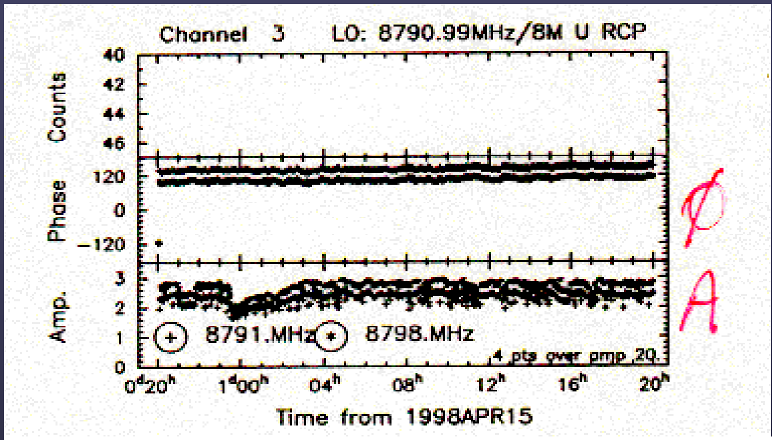
- Caused by different signals paths through the electronics in the separate bands
- Must be corrected to integrate over entire band.



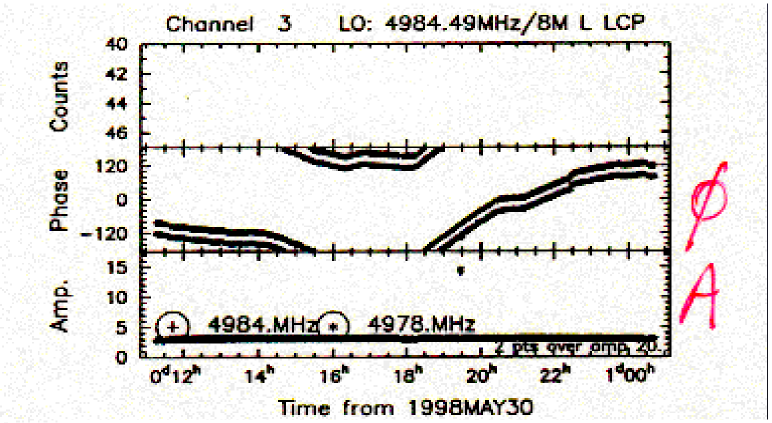
The pulse cal

- Corrected for using the pulse cal system (continuum only)
- Tones generated by injecting a pulse every microsecond





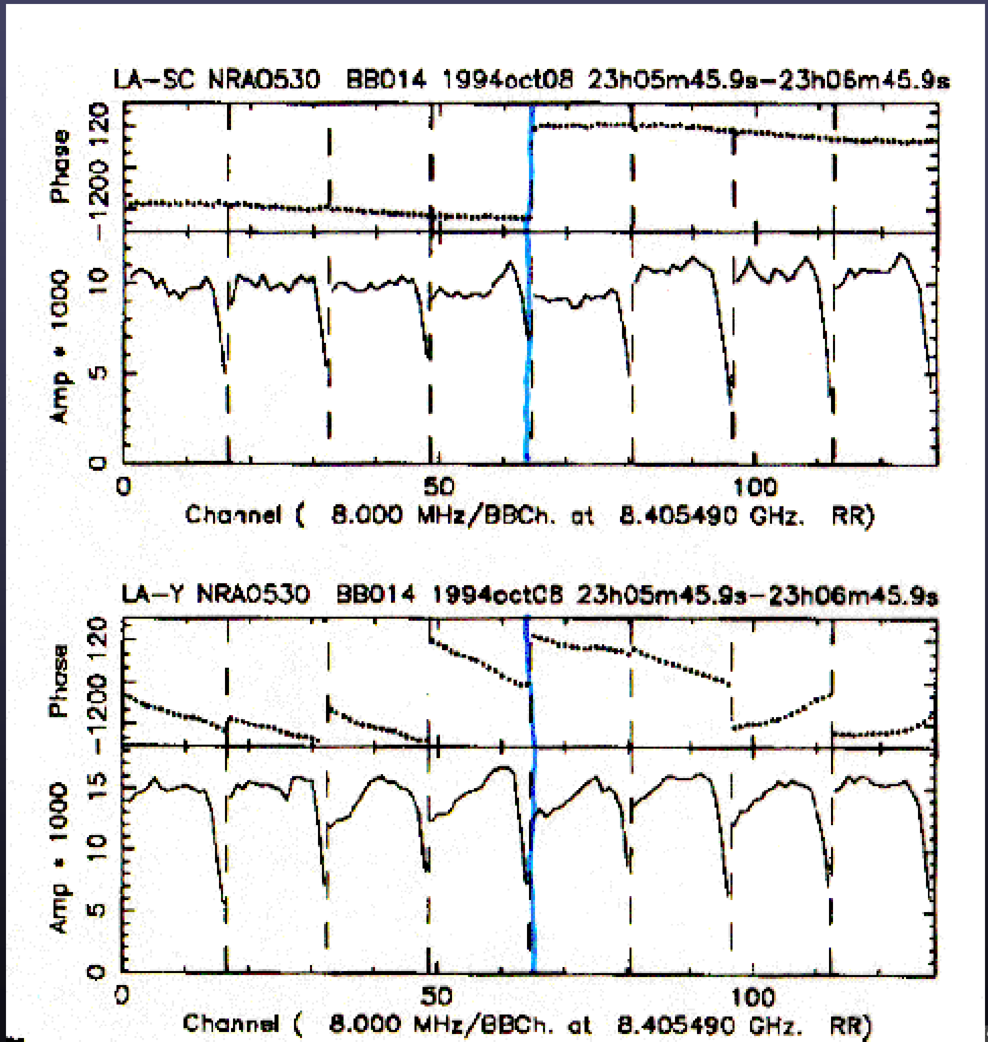
Pulse cal monitoring data



Corrections using Pcal

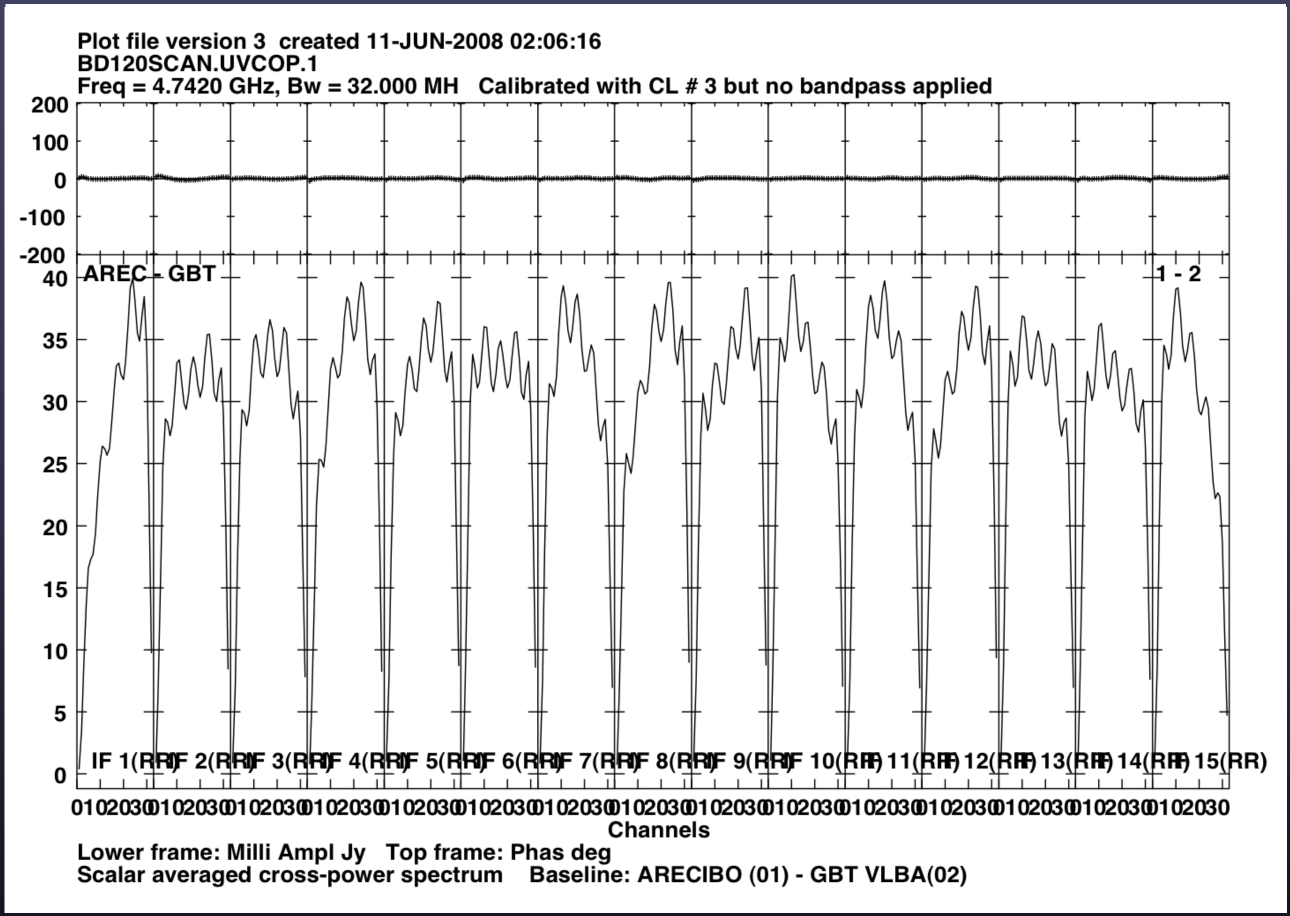
- Data aligned using Pcal

- No Pcal at VLA, shows unaligned phases

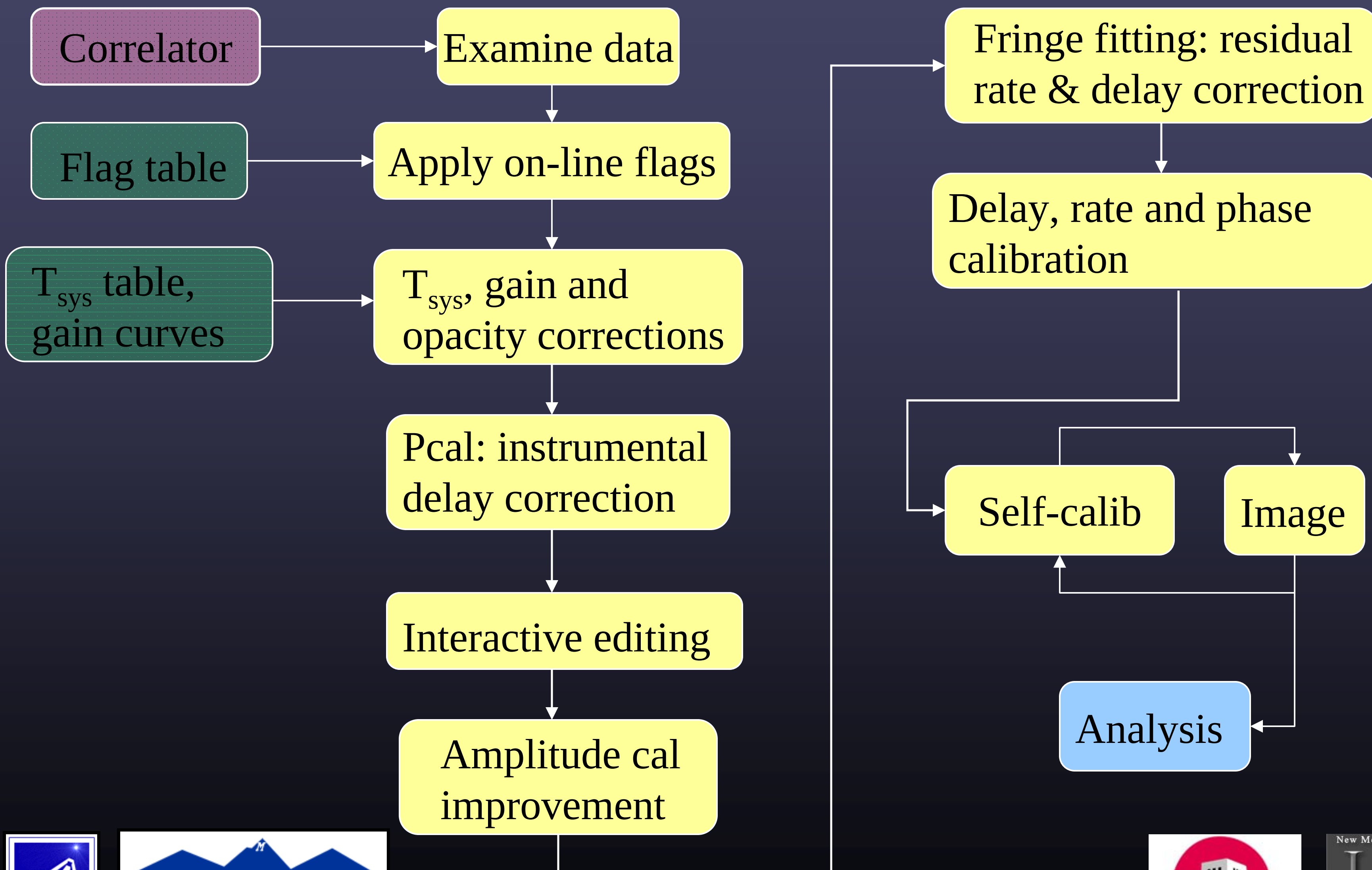


No phase offsets in new digital VLBI backends.

- Digital Backends use Polyphase Filterbanks
- Phase between channels well determined.
- Channels line up in phase, but still need bandpass corrections.
- 1.92 Gb/s
- High sensitivity!



VLBI data reduction path - continuum



Editing

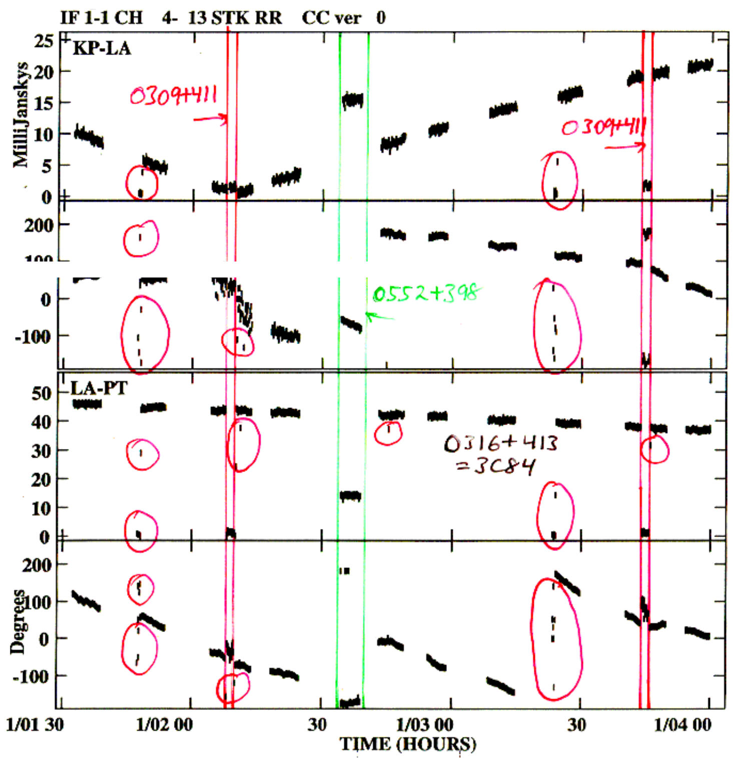
- Flags from on-line system will remove most bad data
  - Antenna off source
  - Subreflector out of position
  - Synthesizers not locked

- 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

Editing example

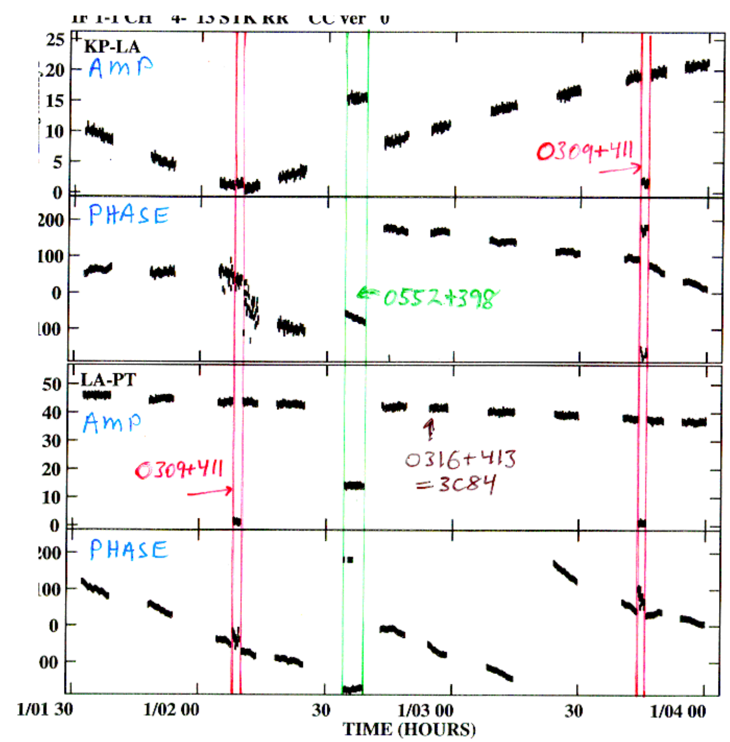
Raw Data - No Edits

A (Jy)
ϕ (deg)
A (Jy)
ϕ (deg)



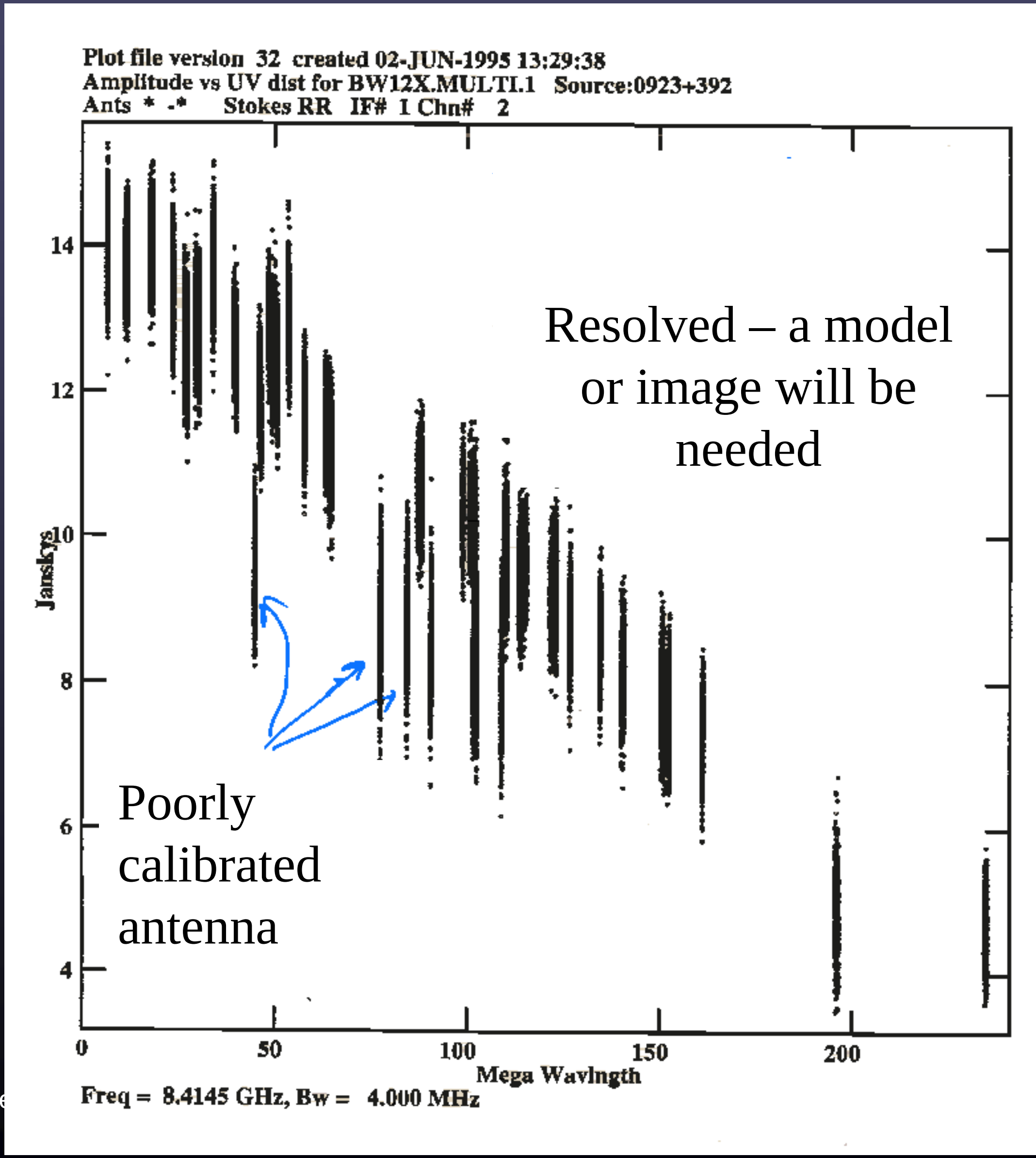
Raw Data - Edited

A (Jy)
ϕ (deg)
A (Jy)
ϕ (deg)

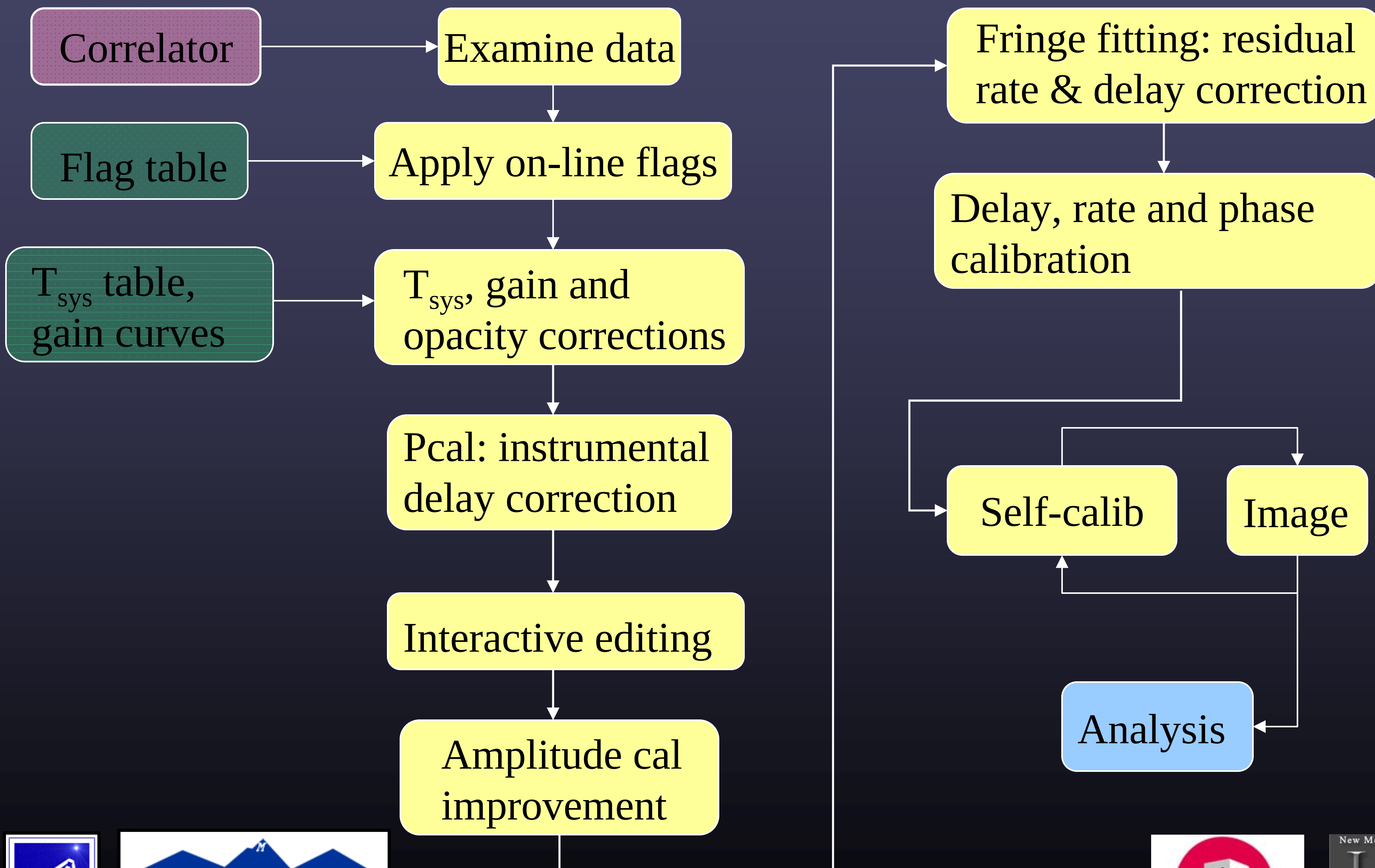


Check Amplitude Cal

- Typical calibrator visibility function after apriori calibration
- One antenna low, perhaps due to poor weather
- Resolved => need to image
- Use information to fine tune the amplitude calibration

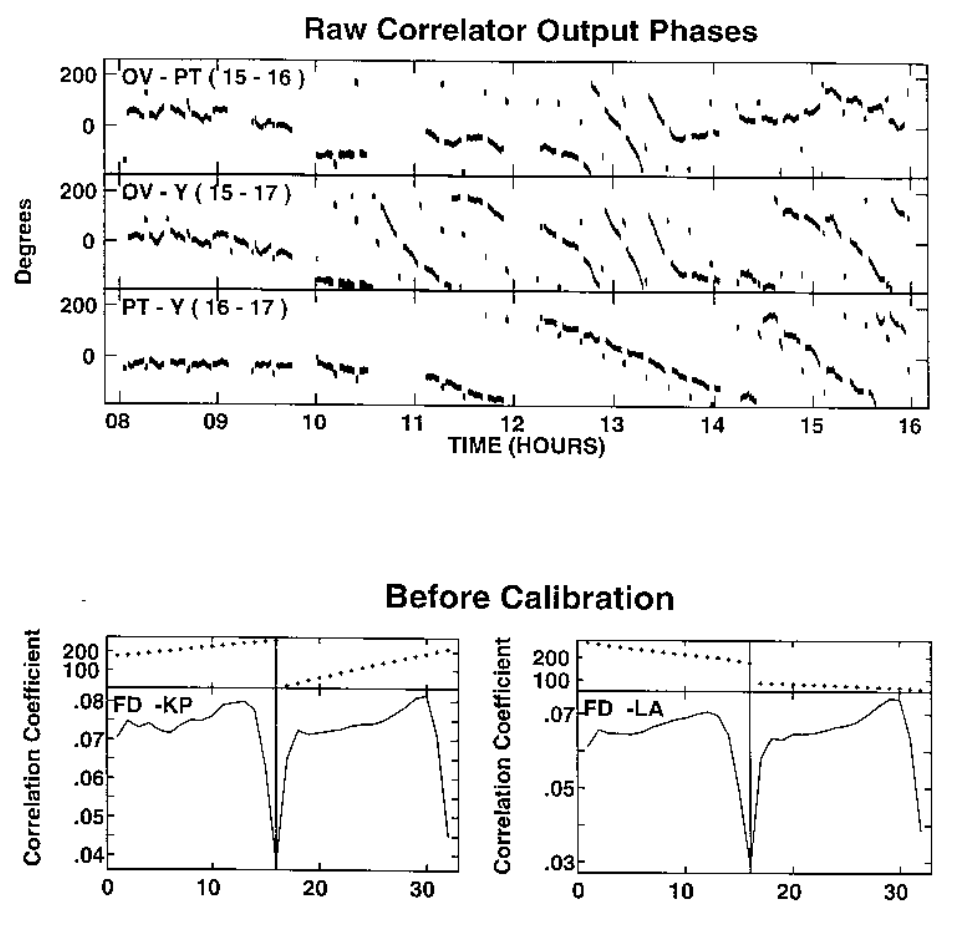


VLBI data reduction path - continuum



Fringe Fitting: Phase errors

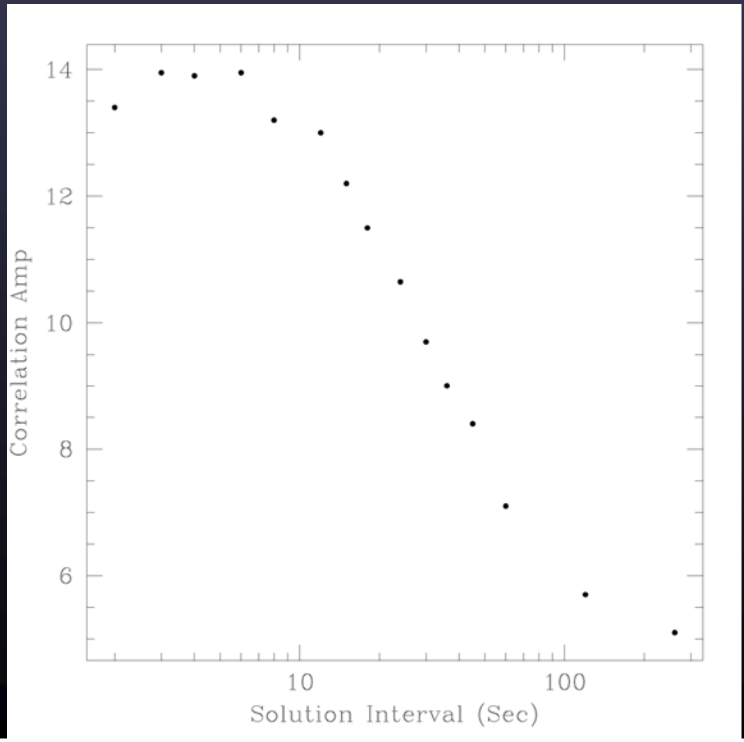
- Raw correlator output has phase slopes in time and frequency
- Caused by imperfect delay model and time dependent atmospheric effects, and also clocks that are fast/slow… (even temperature sensitive synthesizers under an air conditioning vent!!)
- Need to solve for slopes to average data in time and frequency.



Fringe fitting theory

- Interferometer phase $\phi_{t,\nu} = 2\pi\nu\tau_t$
- Phase error $d\phi_{t,\nu} = 2\pi\nu d\tau_t$
- Linear phase model $\Delta\phi_{t,\nu} = \phi_0 + (\delta\phi/\delta\nu)\Delta\nu + (\delta\phi/\delta t)\Delta t$

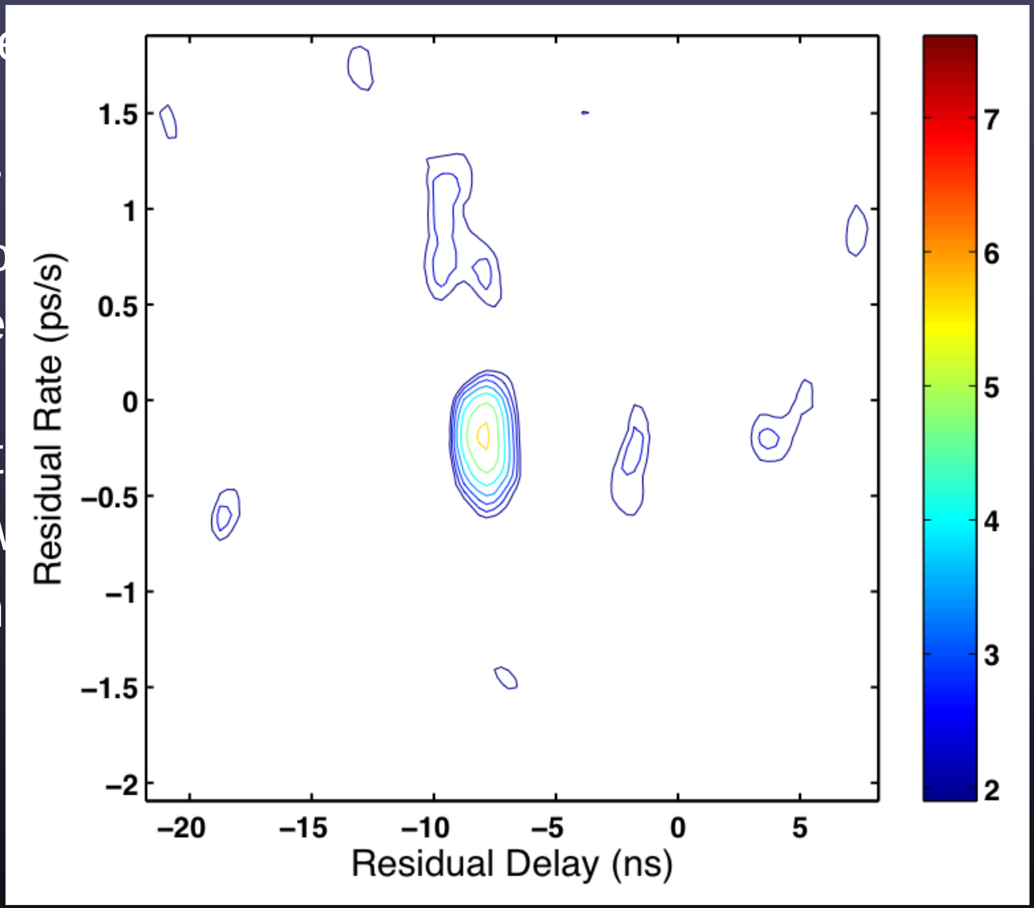
- Determining the delay and rate errors is called "fringe fitting" or "fringe searching".
- Set solution interval according to coherence time: fringe rate changes with time!



129 GHz

Fringe fitting: how

- Usually a two step process
  1. 2D FFT to get estimate
     antenna
  2. Output from correlator
     – FFT over spectral po
     – FFT over time (corre
       fringe rate.
     • Use these for start
     • Can restrict windov
  3. Least squares fit to ph



Phase referencing: faint targets and astrometry

Use source nearby to target to get fringe solutions - apply to target.

- Nodding calibrator (move antennas)
- In-beam calibrator (separate correlation pass)
- Multiple calibrators for most accurate results – get gradients

Need to calibrate often: 5 minute on/off cycle for 1-5GHz, 10 sec for 43GHz

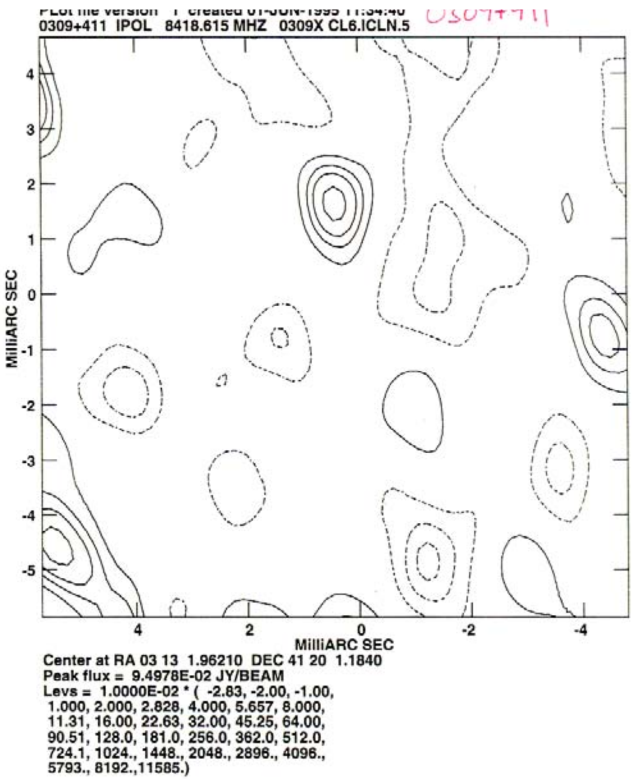
Need calibrator close to target (< 5 deg for low freq., within 1 degree for 43/86GHz)

Used by about 30-50% of VLBA observations

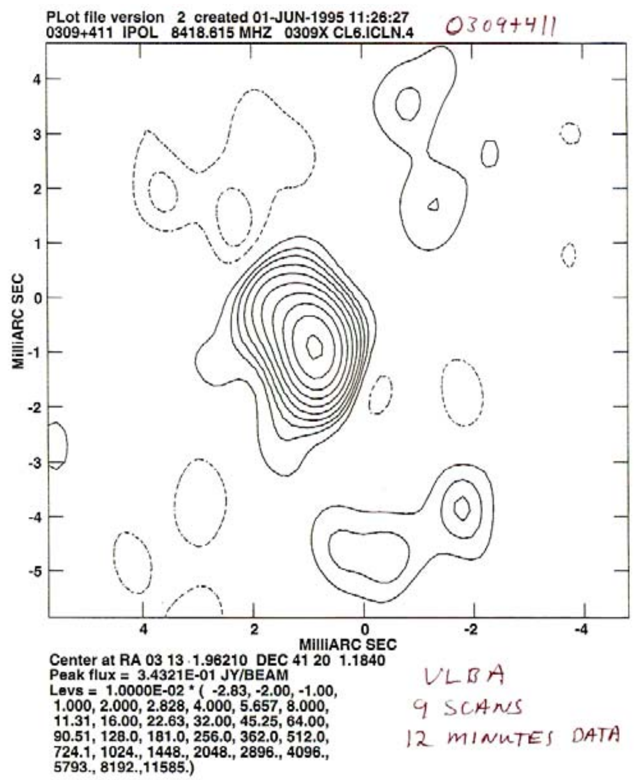
Phase referencing/self cal example

- No phase calibration: source not detected
- Phase referencing: detected, but distorted structure (target-calibrator separation probably large)
- Self-calibration on this strong source shows real structure

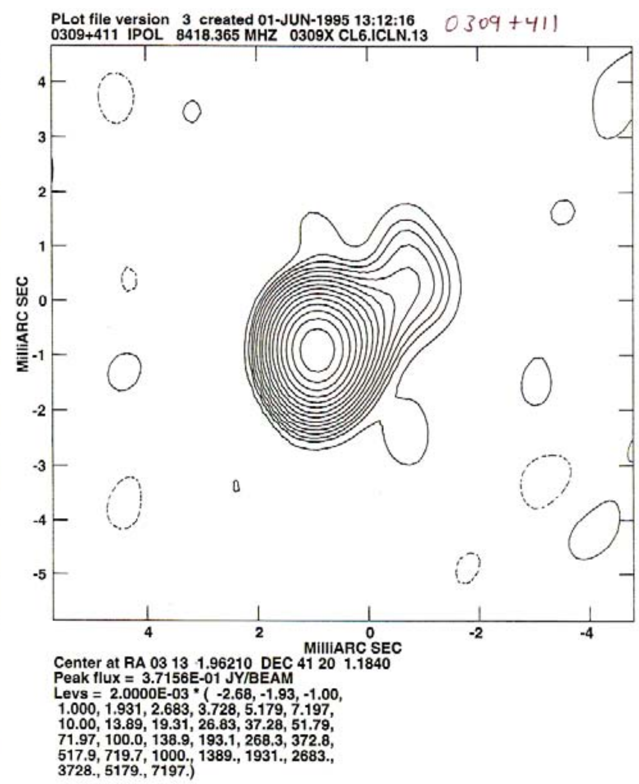
No Phase Calibration



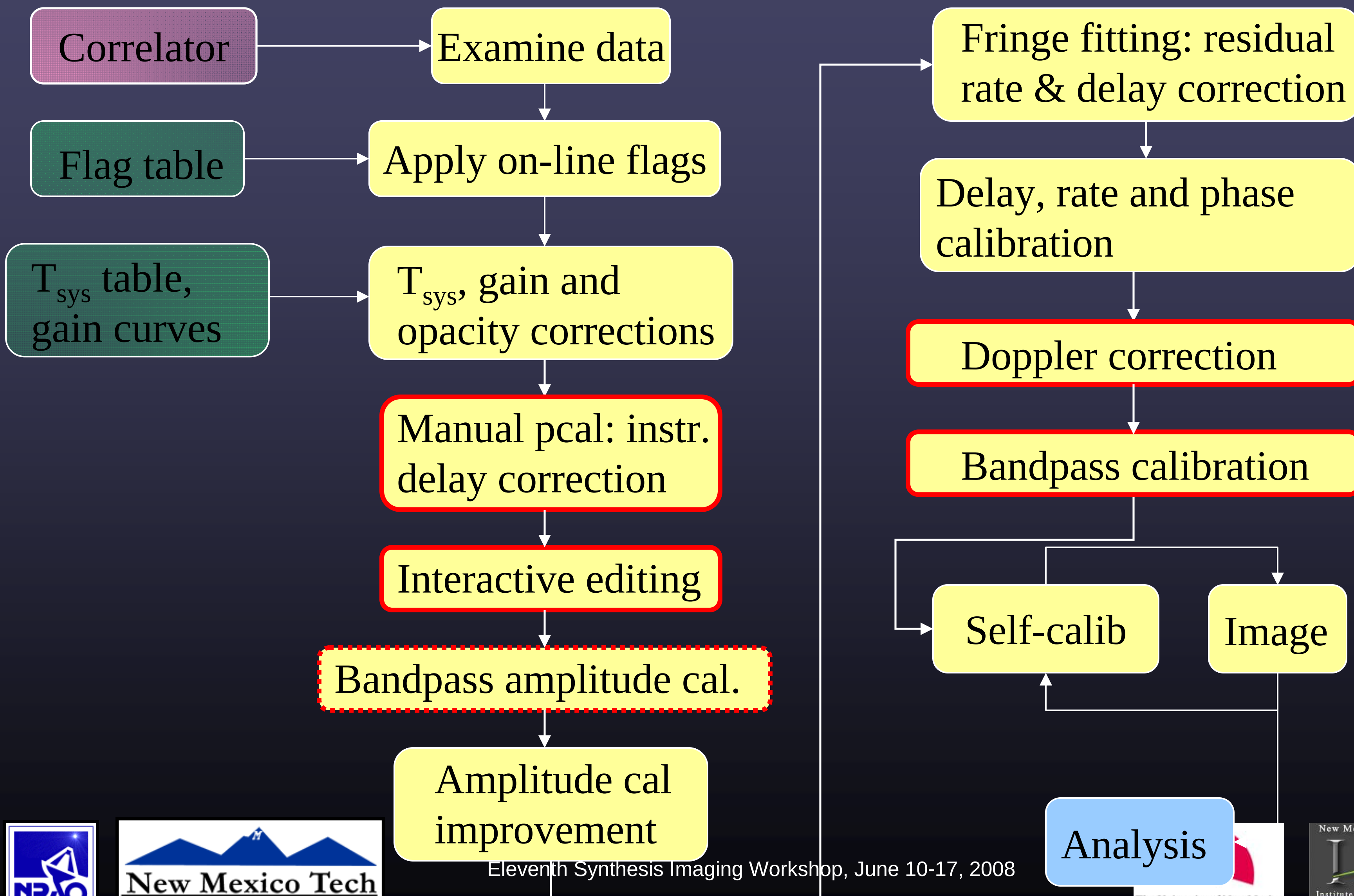
Reference Calibration



Self-calibration



VLBI data reduction path - spectral line

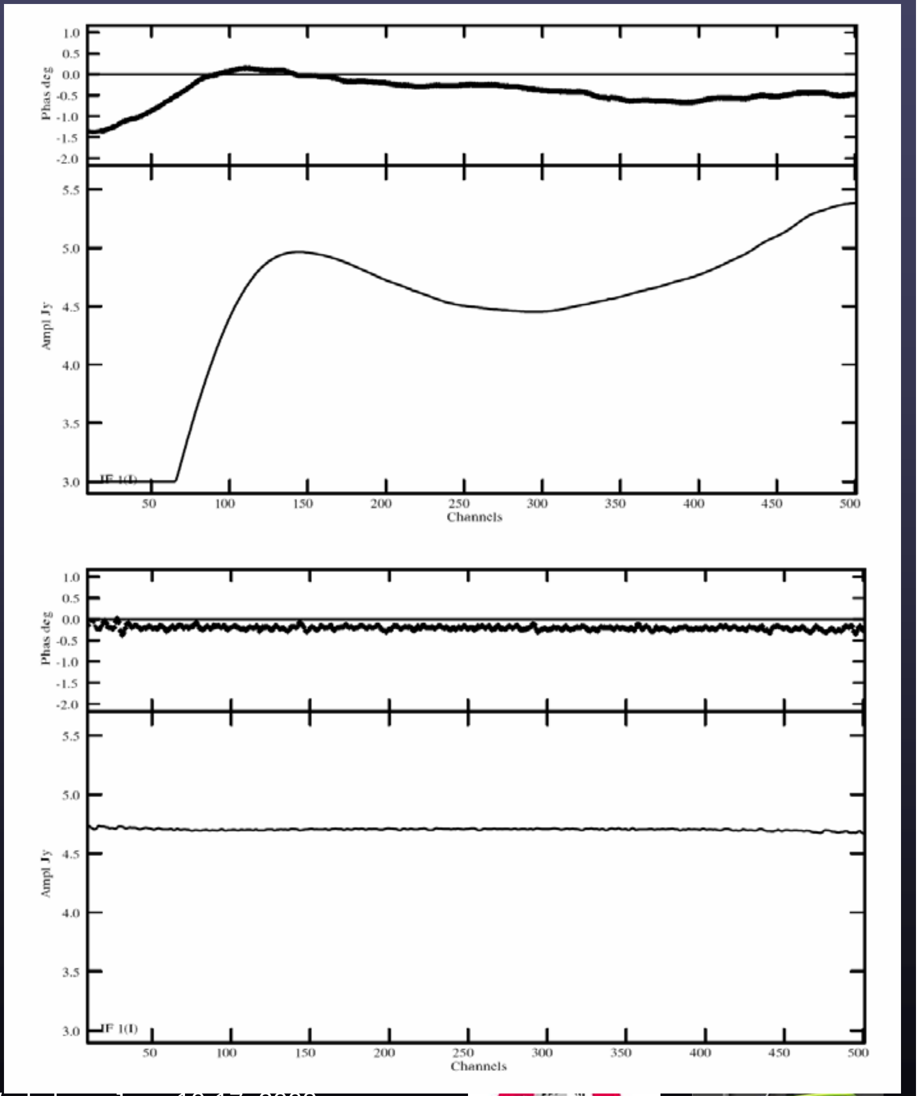


Manual Pcal

- Cannot use the pulse cal system if you do spectral line
- Manual Pcal uses a short scan on a strong calibrator, and assumes that the instrumental delays are time-independent
- In AIPS, use FRING instead of PCAL

Bandpass calibration

- Complex gain variations across the band, slow functions of time
- Needed for spectral line calibration
- May help continuum calibration by reducing closure errors caused by averaging over a variable bandpass
- Use observations of continuum source to derive bandpass table.



Additional spectral line corrections

- Dopp
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- Self-c
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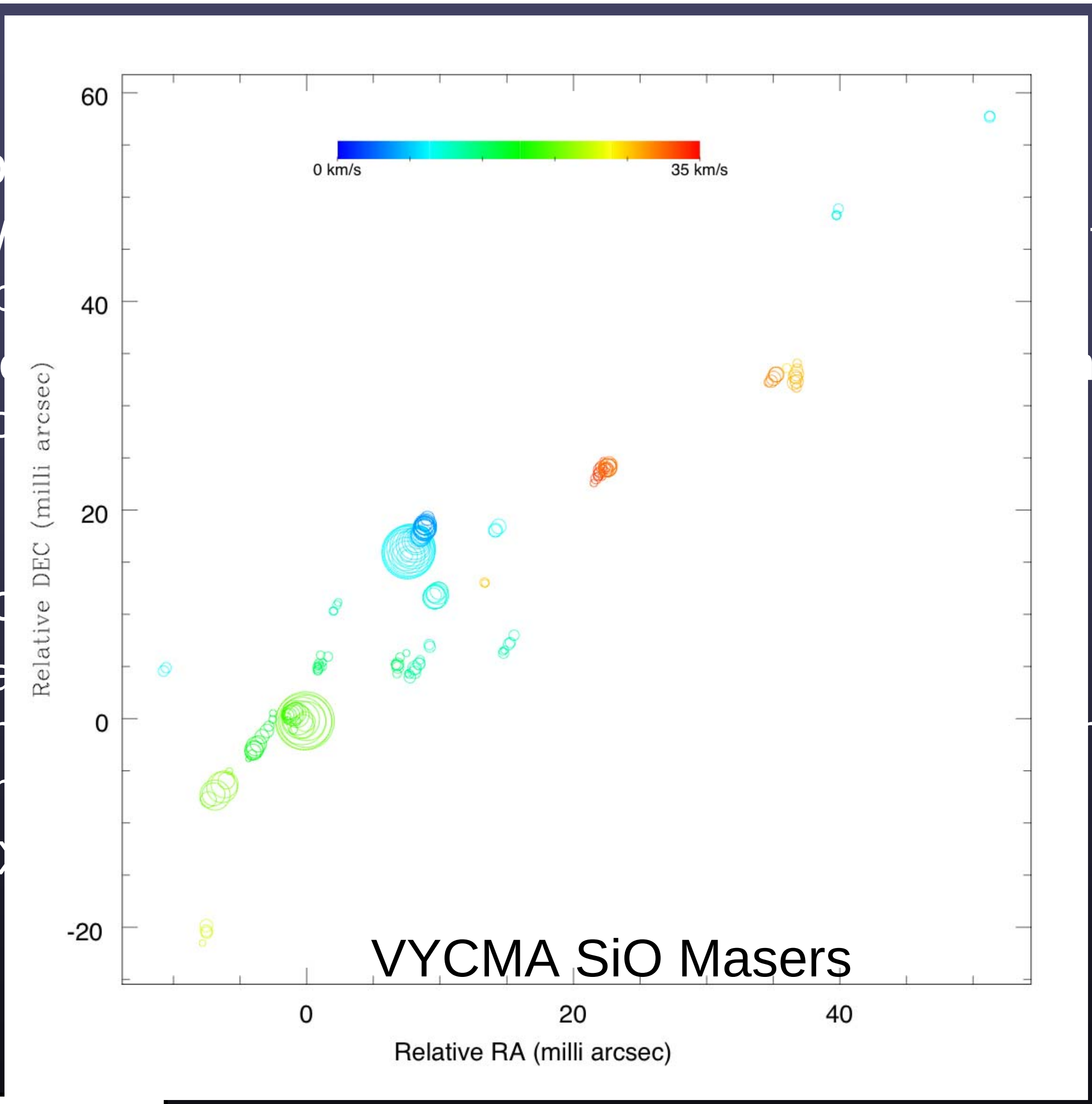
  - EX



Preparing observations

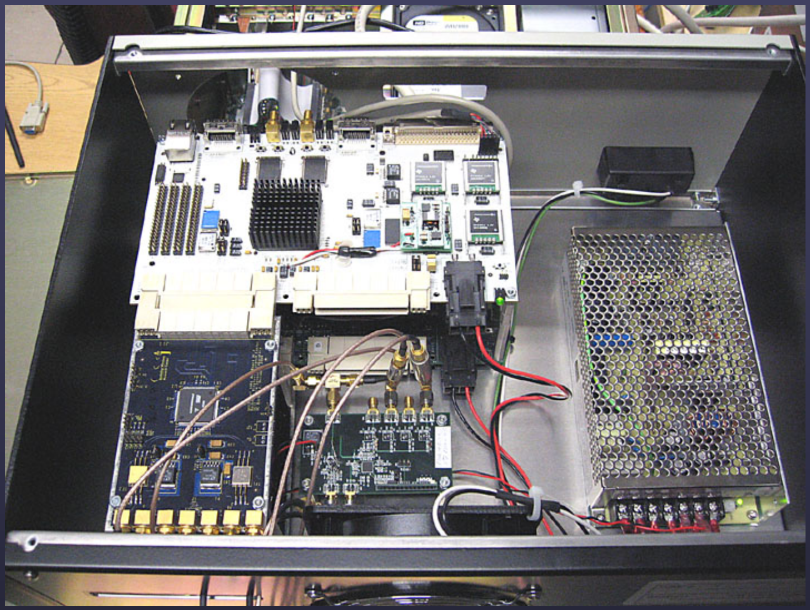
- Know the flux density of your source (preferrably from interferometry observations)
- For a line target, is the redshifted frequency within the available receiver bands? Different arrays have different frequency coverage. How wide is the line - set BW of channels.
- How wide a field of view do you require?
- Will you be able to probe all important angular scales? Include shorter baselines?
- What are your sensitivity requirements: can you reach desired map noise levels ?

Scheduling hints

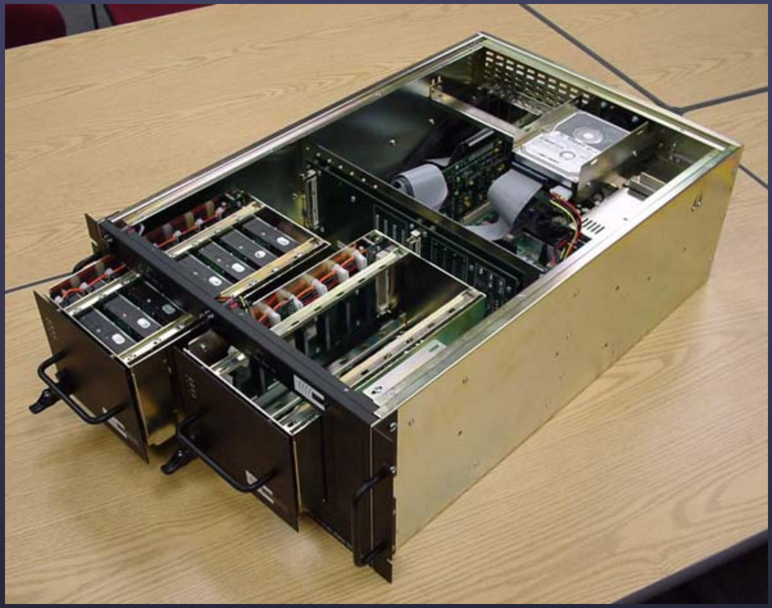
- PI provides the detailed observation sequence
- The schedule should include:
  - Fringe finders (strong sources - at least 2 scans)
  - Amplitude check source (strong, compact source)
  - If target is weak, include a delay/rate calibrator
  - If target very weak, use phase referencing
  - For spectral line observations, include bandpass calibrator
- Consider correlation parameters: analysts will want to know
  - Correlator averaging time.
  - Number of spectral points.
  - Polarization

New 4Gb/s VLBI System

Digital Backend (DBE)



Digital Recorder (Mark5)



- Total cost $40-50K per station.
- x16 in BW over current VLBA sustainable rates.
- Equivalent to replacing VLBA with 50m antennas.
- Planned VLBA/HSA 4Gb/s upgrade by early 2009: x4 in sensitivity over current VLBA sustainable rate.

Summary

- VLBI is not fundamentally different from connected element interferometry
- A few additional issues to address when observing and reducing data
- VLBI provides very high angular resolution and position accuracy
- VLBI set to experience big jump in sensitivity with exciting new science possibilities.