Very Long Baseline Interferometry

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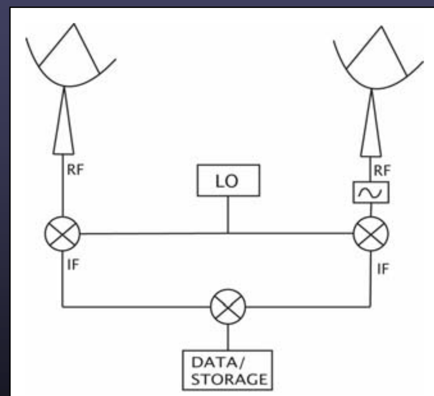
Outline

- What is VLBI?
- What is VLBI good for?
- How is VLBI different from connected element interferometry?
- What issues do we need to consider in VLBI observations?

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

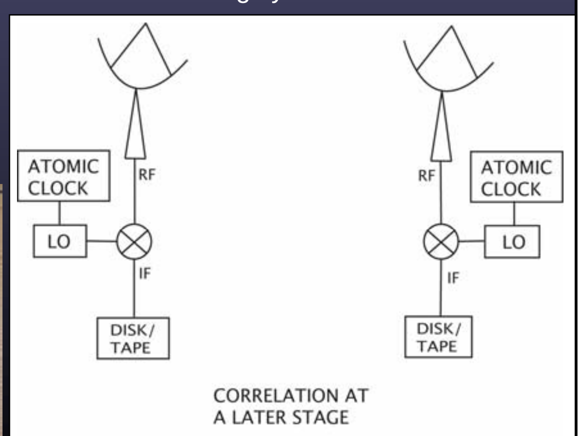


Connected elements:
done via cables

VLBI versus connected elements

- In VLBI there are no IFs or LOs connecting the antennas
- Instead accurate time standards and a recording system is used

Mark 5 recording system

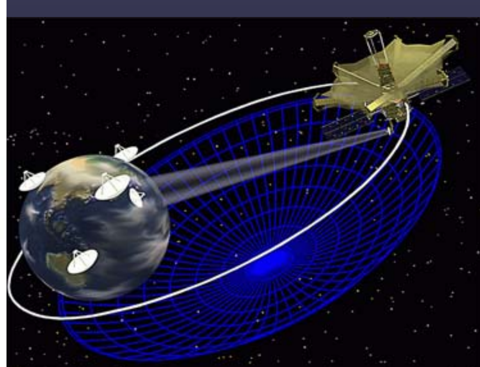


VLBI correlators

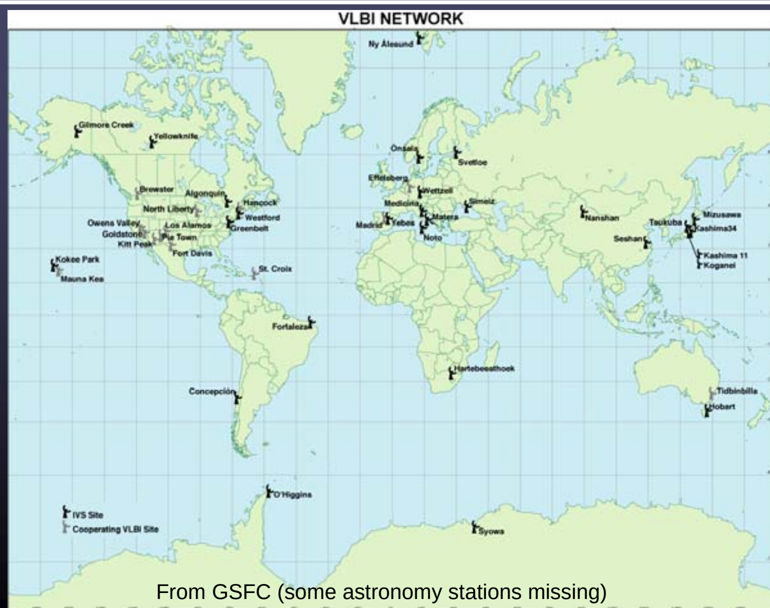
- The correlation is not real-time but occurs later on
- Disks/tapes shipped to the correlators
- Examples are the VLBA and the JIVE correlator

What is VLBI good for?

- 'Very Long Baselines' implies high angular resolution ($\theta \sim \lambda/B$)
- The Very Long Baseline Array (VLBA) 0.1 - 5 mas



Global VLBI stations



From GSFC (some astronomy stations missing)

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

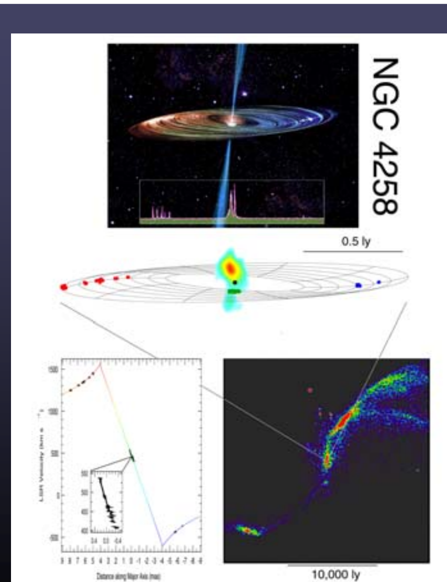


Image courtesy: L. Greenhill

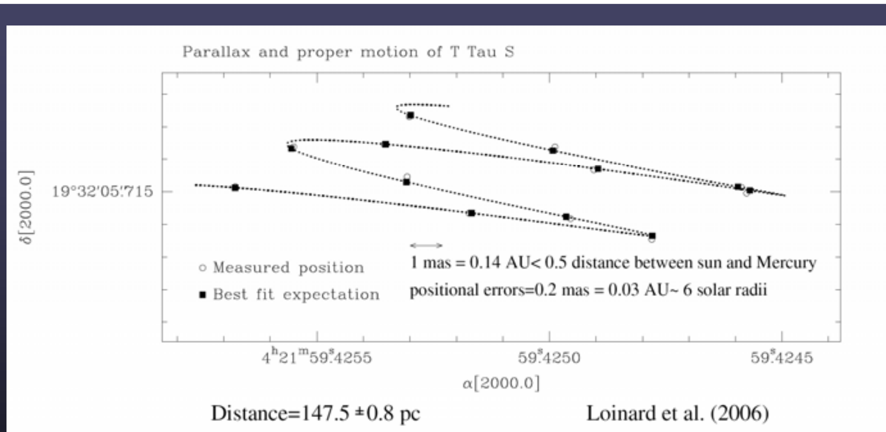
The SS433 movie

- X-ray binary with precessing relativistic jet
- Daily snapshot observation with the VLBA at 20 cm for 40 days (~1/4 of precession period).

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

Mioduszewski, Walker, Rupen & Taylor

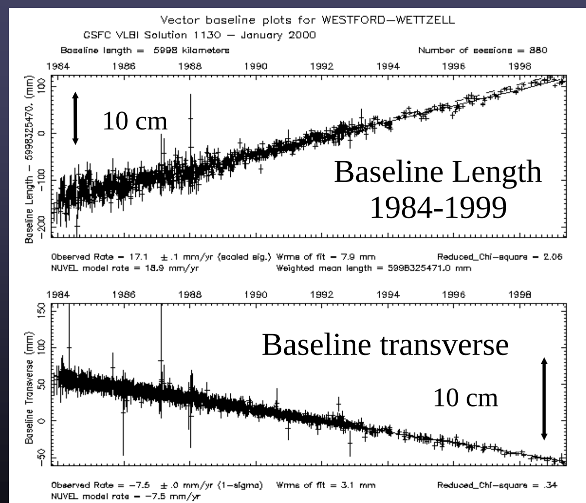
Astrometry



- 12 epochs of observations on T Tauri Sb
- This has driven down the distance error to 0.8 pc

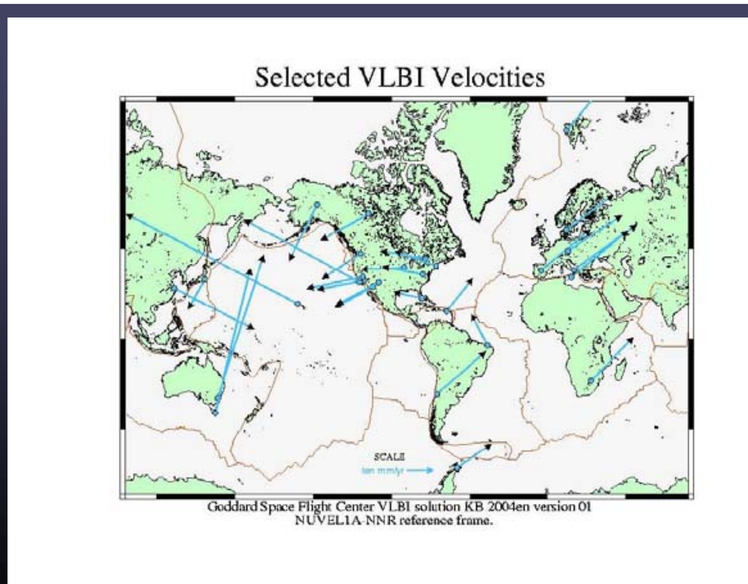
Image courtesy: A. Mioduszewski, L. Loinard

Distance from Germany to Massachusetts



GSFC Jan. 2000

Plate tectonics



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 stabilities varies between telescopes
  - Model uncertainties due to inaccurate source positions, station locations, and Earth orientation, which are difficult to know to a fraction of a wavelength

  - *Solve by fringe fitting*

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

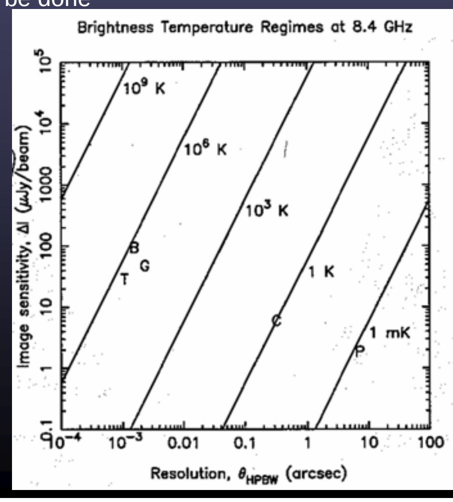
  - *Solve by using T_{sys} and gains to calibrate amplitudes*

- Only sensitive to limited scales
  - Structure easily resolved out

  - *Solve by including shorter baselines (MERLIN, VLA)*

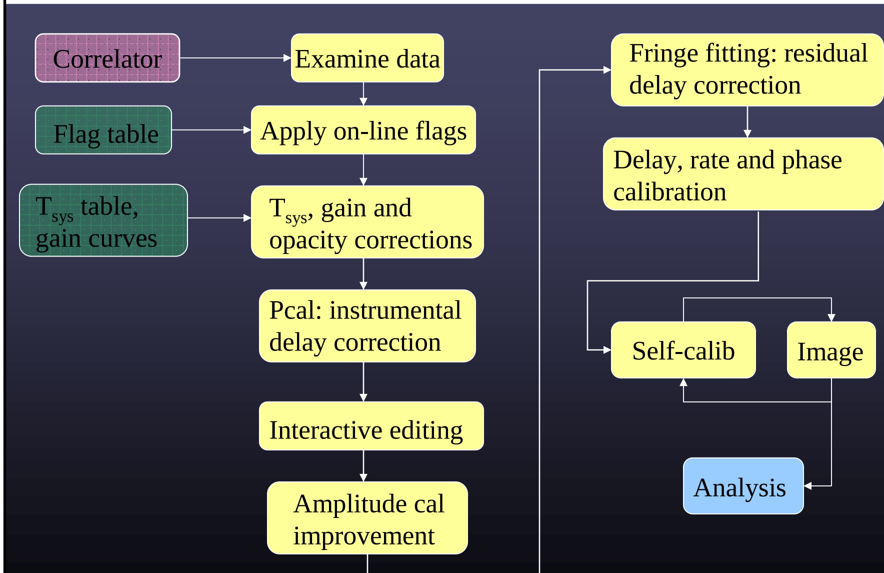
Differences VLBI and connected interferometry (continued)

- Only sensitive to non-thermal emission processes ($T_{b,min} \propto \theta^{-2}_{HPBW}$)
  - 10^6 K brightness temperature limit
  - Limits the variety of science that can be done
- To improve sensitivity
  - Use bigger telescopes (HSA)
  - For continuum, use a higher data rate (wider bandwidth), MkV (disk based recording) can reach 1GBps



Chapter 9 in the book

VLBI data reduction path - continuum



Signal flow in a VLBI system

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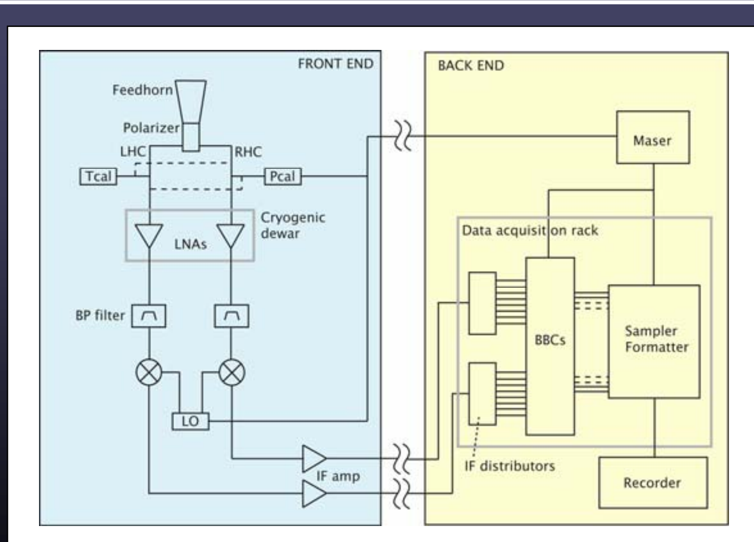

The task of the correlator

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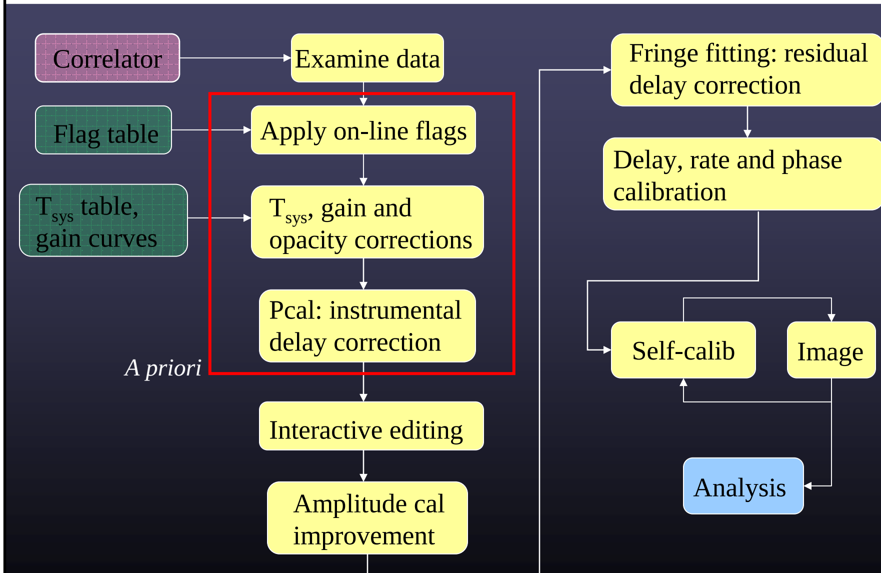
- Main task is to cross multiply signals from the same wavefront
  - Antennas at different distances => delay
  - Antennas move at different speed => rate
- Offset estimates removed using a geometric model
- Remaining phase errors normally dominated by the atmosphere
- Write out data

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 1998.

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

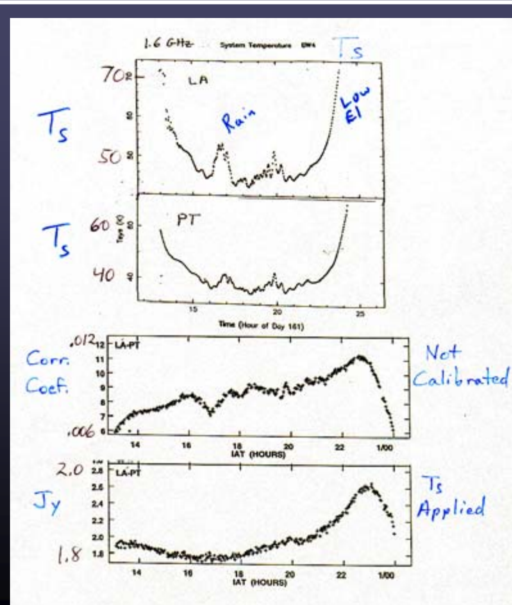
$$S_{cij} = \rho \frac{A}{\eta_s} \sqrt{\frac{T_{si} T_{sj}}{K_i K_j e^{-\tau_i} e^{-\tau_j}}}$$

- 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

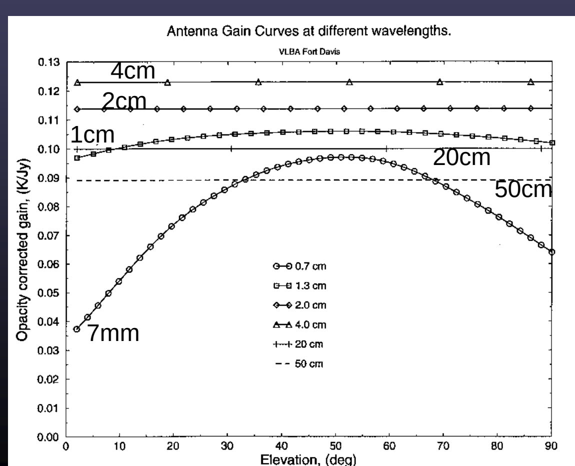
Upper plot: increased T_{sys} due to rain and low elevation

Lower plot: removal of the effect.



VLBA gain curves

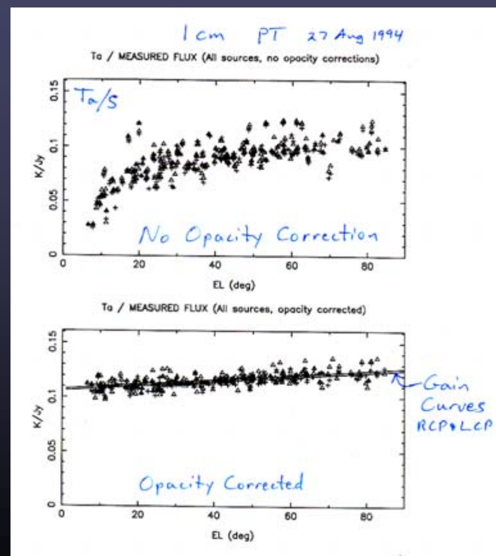
- Caused by gravitationally induced distortions of antenna
- Function of elevation, depends on frequency



Atmospheric opacity correction

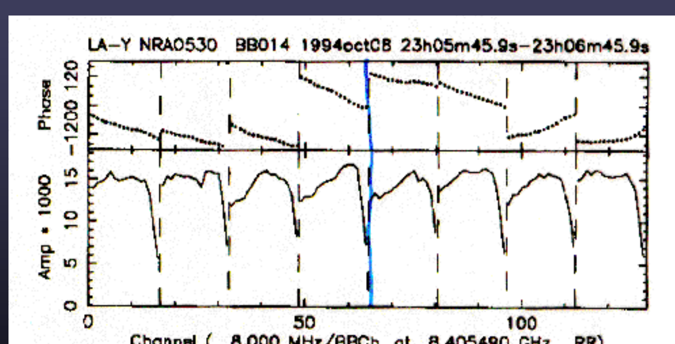
- Corrections for absorption by the atmosphere
- Can estimate using T_s - T_r - T_{spill}

Example from VLBA single dish pointing data



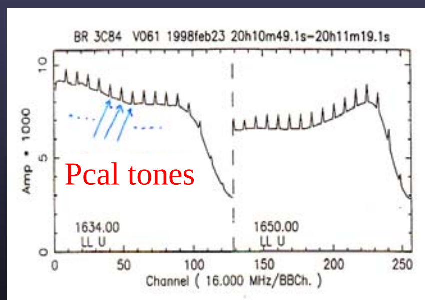
Instrumental delays

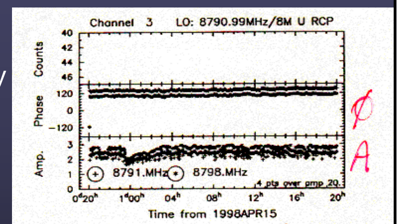
- Caused by different signals paths through the electronics in the separate bands



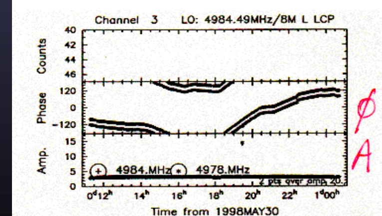
The pulse cal

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



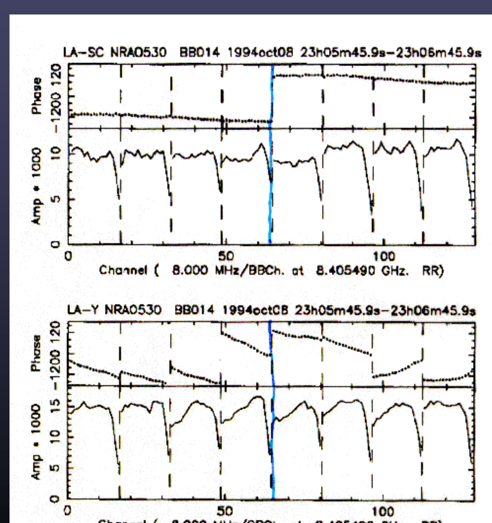


Pulse cal monitoring data



Corrections using Pcal

- Data aligned using Pcal
- No Pcal at VLA, shows unaligned phases



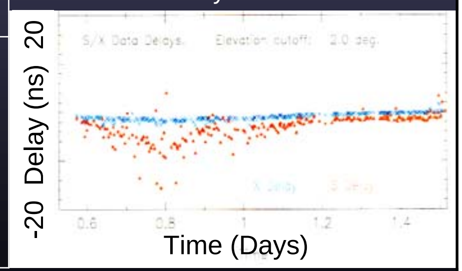
Ionospheric delay

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

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

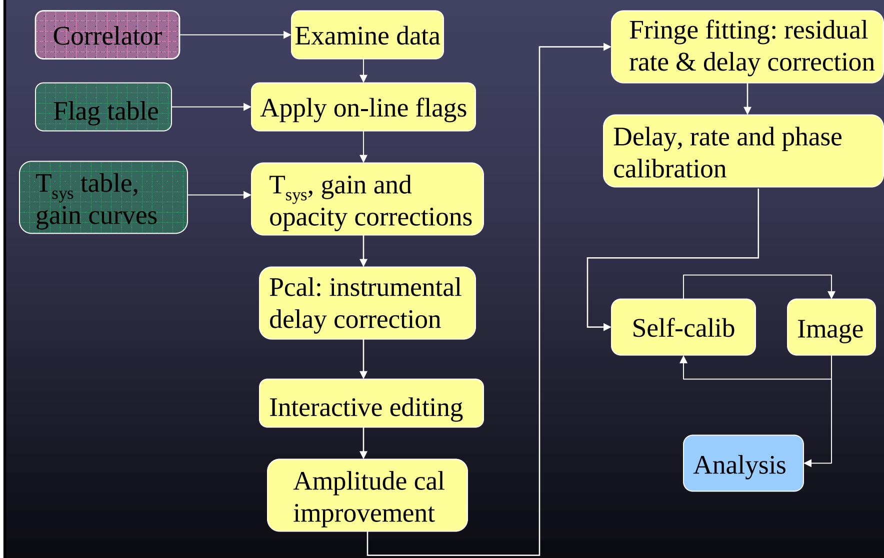


GPS based ionospheric models

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

Ionosphere map from iono.jpl.nasa.gov

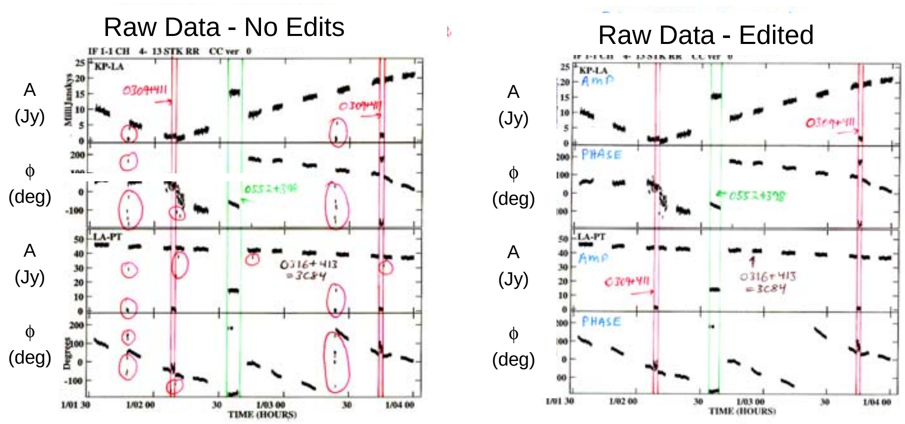
VLBI data reduction path - continuum



Editing

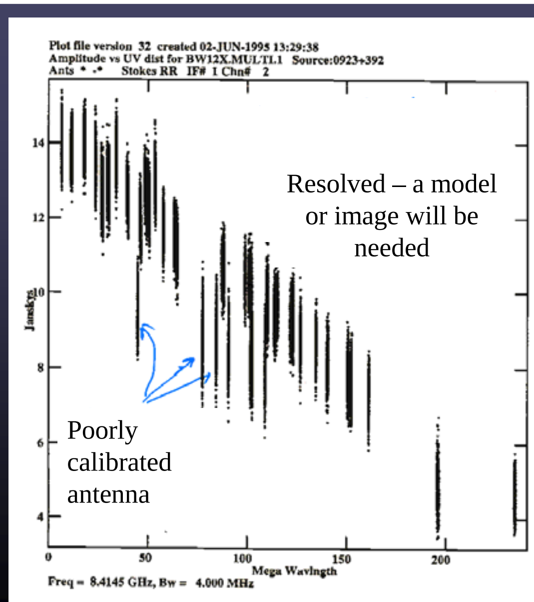
- Flags from on-line system will remove most bad data
  - Antenna off source
  - Subreflector out of position
  - Synthesizers not locked
- Final flagging done by examining data
  - Flag by antenna (most problems are antenna based)
  - Poor weather
  - Bad playback
  - RFI (may need to flag by channel)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

Editing example

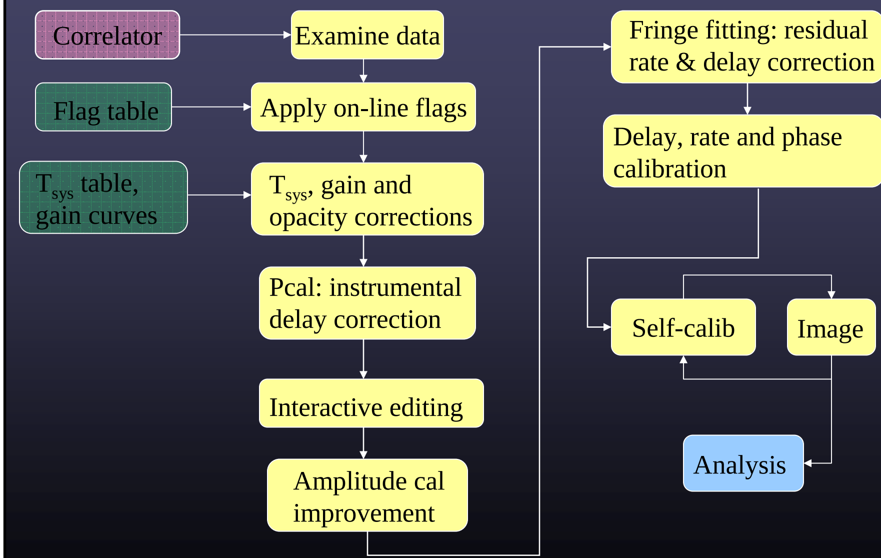


Amplitude check source

- 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

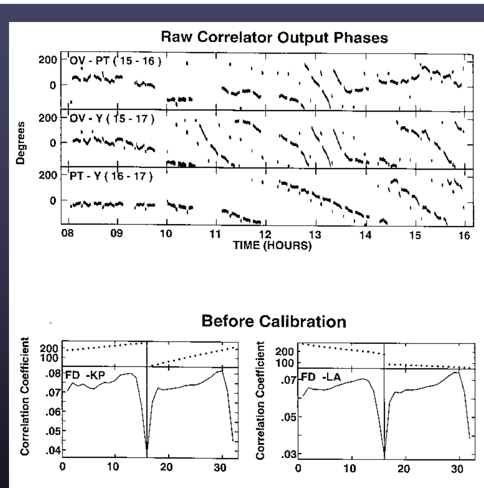


VLBI data reduction path - continuum



Phase errors

- Raw correlator output has phase slopes in time and frequency
- Caused by imperfect delay model
- Need to find delay and delay-rate errors



Fringe fitting

- For astronomy:
  - Remove clock offsets and align baseband channels ("manual pcal")
  - Fit calibrator to track most variations
  - Fit target source if strong
  - Used to allow averaging in frequency and time
    - Allows higher SNR self calibration (longer solution, more bandwidth)

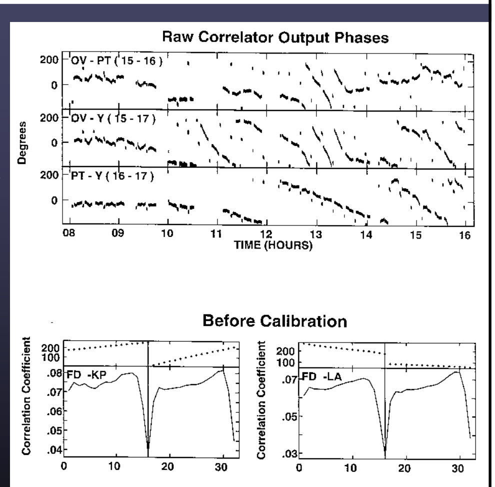
- For geodesy:
  - Fitted delays are the primary "observable"
  - Correlator model is added to get "total delay", independent of models

Residual rate and delay

- Interferometer phase $\phi_{t,\nu} = 2\pi\nu\tau_t$

- Slope in frequency is "delay"
  - Fluctuations worse at low frequency because of ionosphere
  - Troposphere affects all frequencies equally ("nondispersive")

- Slope in time is "fringe rate"
  - Usually from imperfect troposphere or ionosphere model



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"

- Fringe fit is self calibration with first derivatives in time and frequency

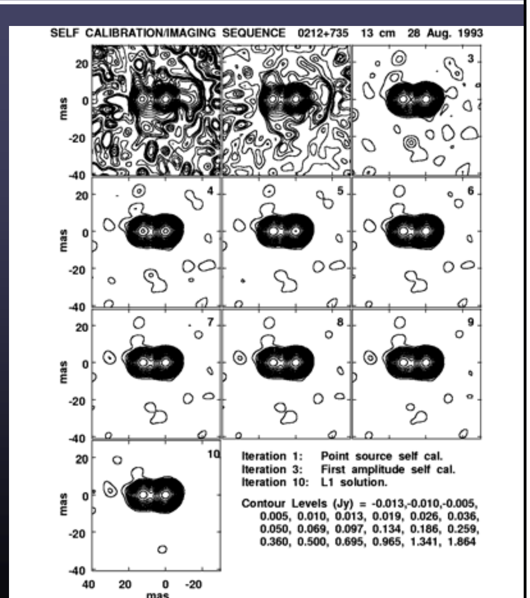
Fringe fitting: how

- Usually a two step process
  1. 2D FFT to get estimated rates and delays to reference antenna
     - Use these for start model for least squares
     - Can restrict window to avoid high sigma noise points
  2. Least squares fit to phases starting at FFT estimate

- Baseline fringe fit
  - Fit each baseline independently
  - Must detect source on all baselines
  - Used for geodesy.
- Global fringe fit (like self-cal)
  - 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 sequence

- Iterative procedure to solve for both image and gains:
  - Use best available image to solve for gains (start with point)
  - Use gains to derive improved image
  - Should converge quickly for simple sources
- Does not preserve absolute position or flux density scale



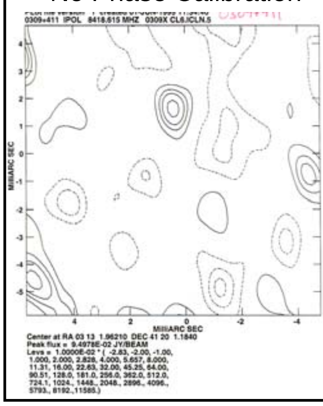
Phase referencing

- 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
    - 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)
  - Used by about 30-50% of VLBA observations

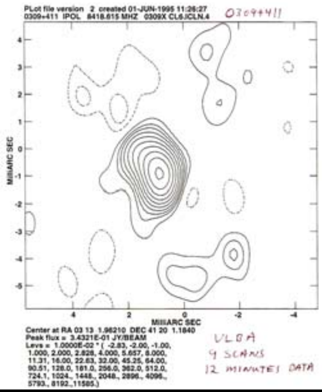
Phase referencing/self cal example

- 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

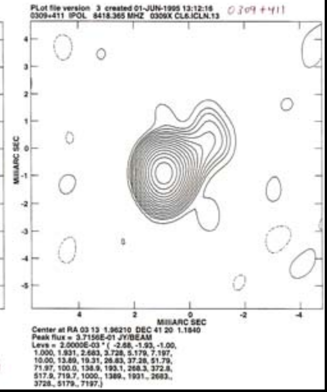
No Phase Calibration



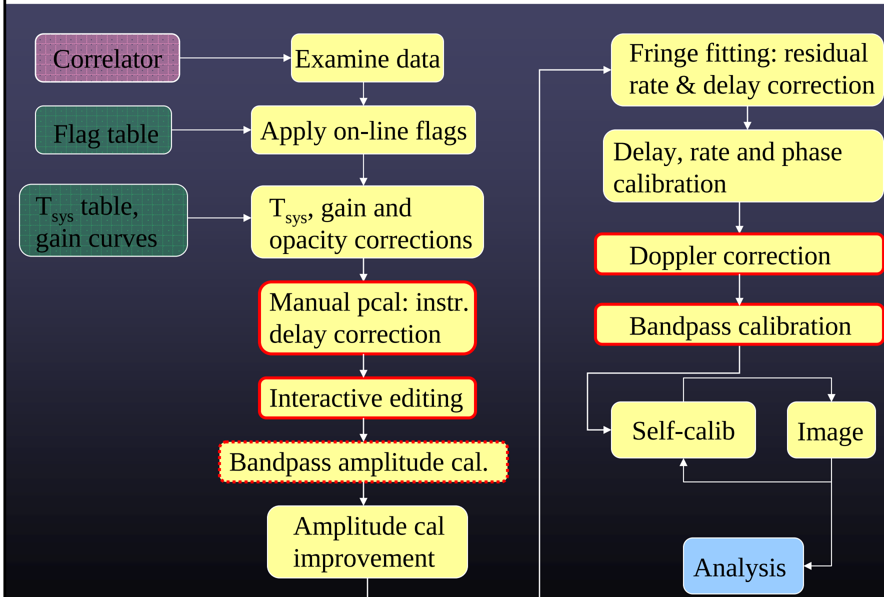
Reference Calibration



Self-calibration



VLBI data reduction path - spectral line

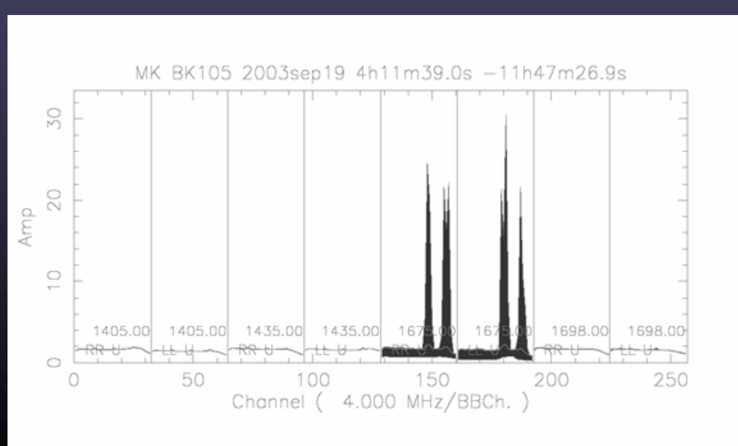


Manual Pcal

- 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

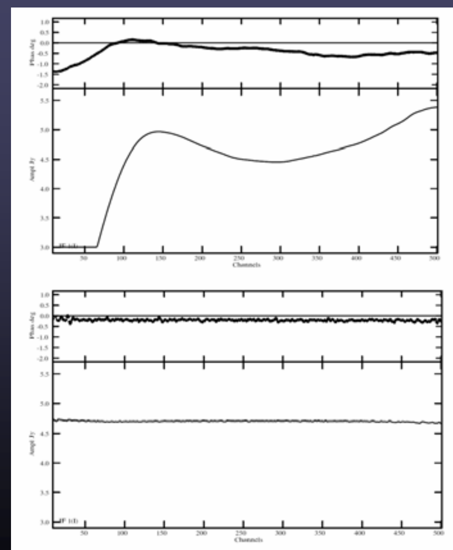
Editing spectral line data

- No difference from continuum, except for that a larger number of channels allow for RFI editing



Bandpass calibration: why

- 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



Bandpass calibration: how

- Best approach to observe a strong, line-free continuum source (bandpass calibrator)
- Two step process:
  1. Amplitude bandpass calibration before Doppler corrections
  2. Complex bandpass calibration after continuum (self-)cal on bandpass cal.

  – After final continuum calibration (fringe-fit) of the calibrators, good cross-correlation continuum data exists
  – The bandpass calibrator must be calibrated so its visibility phase is known - residuals are system
  – Use the bandpass calibrator to correct individual channels for small residual phase variations
  – Basically a self-cal on a per channel basis

Additional spectral line corrections

- Doppler shifts:
  - Without Doppler tracking, the spectra will shift during the observations due to Earth rotation.
  - Recalculate in AIPS: shifts flux amongst frequency channels, so you want to do the amplitude only BP calibration first
- Self-cal on line:
  - can use a bright spectral-line peak in one channel for a one-channel self-cal to correct antenna based temporal phase and amplitude fluctuations and apply the corrections to all channels

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.
- What angular resolution is needed for your science? Will determine choice of array.
- Will you be able to probe all important angular scales? Include shorter baselines?
- Can you reach the required sensitivity in a decent time?

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
- Leave occasional gaps for tape readback tests (2 min)
- For non-VLBA observations, manage tapes
  - Tape passes and tape changes
  - With Mark5, only worry about total data volume

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