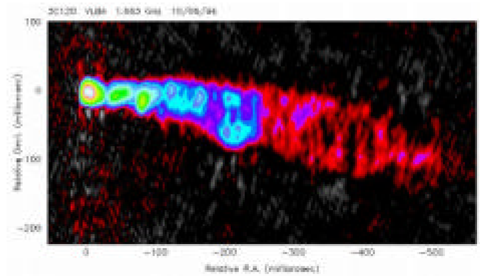
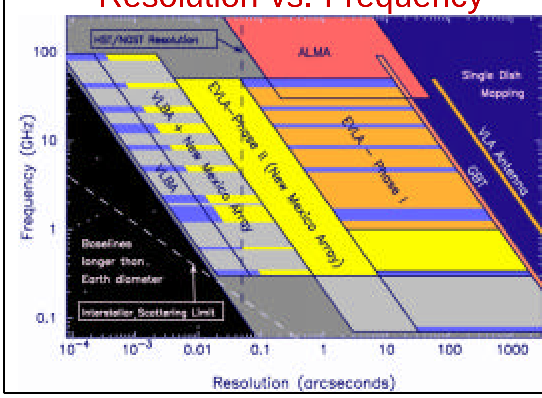
VLBI



What is VLBI?
(Very Long Baseline Interferometry)

- Radio interferometry with unlimited baselines
  - For high resolution – milliarcsecond (mas) or better
  - Baselines up to an Earth diameter for ground based VLBI
  - Can extend to space (HALCA)
- Traditionally uses no IF or LO link between antennas
  - Atomic clocks for time and frequency– usually hydrogen masers
  - Tape recorders for data transmission
    - Disk based systems under development
  - Delayed correlation after tapes shipped
  - Real time over fiber is a long term goal
- Can use antennas built for other reasons
- Not fundamentally different from linked interferometry

Resolution vs. Frequency



THE QUEST FOR RESOLUTION

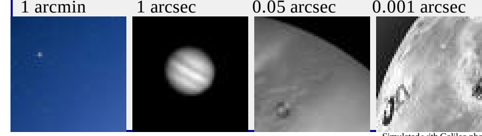
Resolution = Observing wavelength / Telescope diameter

Angular Resolution	Optical (5000A) Diameter	Instrument	Radio (4cm) Diameter	Instrument
1′	2mm	Eve	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

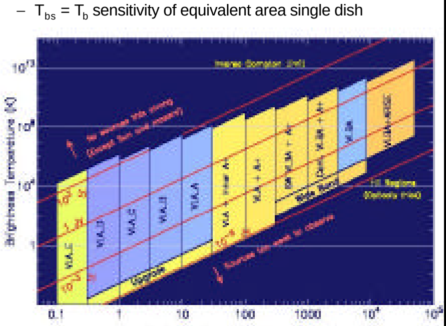
Brightness Temperature Sensitivity

- T_b sensitivity = $T_{bs} \times$ Filling Factor
  - T_{bs} = T_b sensitivity of equivalent area single dish

Filling factor $\propto 1/D^2$ so VLBI can only see very "Bright" sources

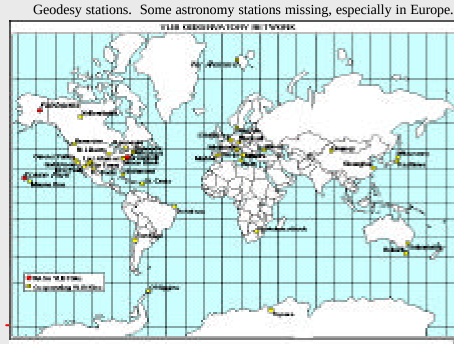
Independent of frequency

Density of sources much greater at low flux density



GLOBAL VLBI STATIONS

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

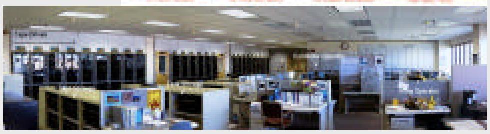


The VLBA

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

National Radio
Astronomy Observatory

A Facility of the
National Science
Foundation



VLBI SCIENCE SAMPLES

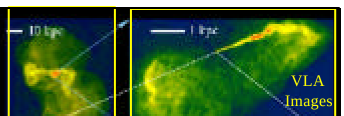
CAPABILITY	EXAMPLE SCIENCE
High resolution continuum	Jet formation
Movies and polarization	Jet dynamics and magnetic fields
Phase referencing to detect weak sources	Detect survey sources, distinguish starbursts from AGN
Phase referencing for positions	Accurate proper motions
High resolution spectral line	Accretion disks and extra galactic distances
Spectral line movies	Stellar environments
Geodesy and astrometry	Plate motions, EOP, reference frames

M87

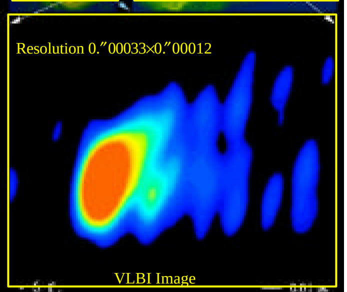
Base of Jet

43 GHz Global VLBI

Junor, Biretta, & Livio
Nature, 401, 891



VLA Images



Black Hole / Jet Model

Resolution 0.″00033×0.″00012

VLBI Image

3C120 43 GHz VLBA Movie

Gómez et al. Science 289, 2317

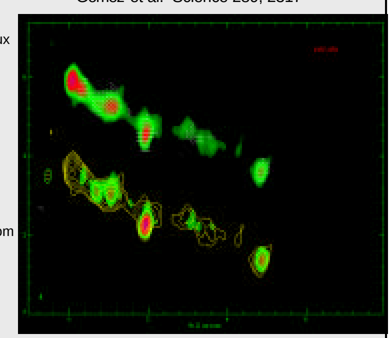
Bottom:
- Contours of intensity
- Color shows polarized flux

Top:
- Color shows intensity
- Lines show B vectors

Resolution ~0."0005

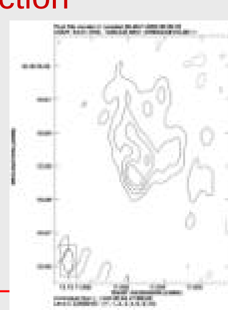
One image / Month

Intensity and polarization variations suggest jet-cloud interaction
- Between 2 and 4 mas from core (~8 pc)
- Cloud would be intermediate in mass between broad and narrow line clouds.



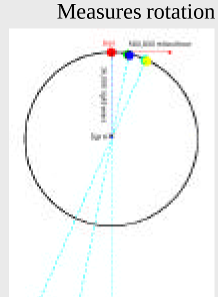
AGN or Starburst?
Weak source detection

- Would like to distinguish AGN from starbursts in surveys etc.
- Starburst will have brightness temperature too low to detect
  - VLBI detection implies it is an AGN
- Example from VLBA+EB+GBT
  - Phase referencing
  - 1.4 GHz
  - Peak 104 μJy. Total 1.2 mJy
  - RMS noise 10 μJy
  - From Fomalont (survey observations)

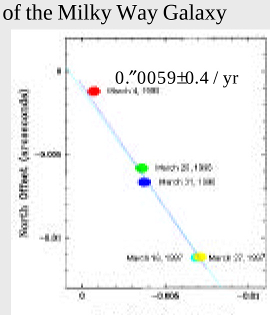


MOTIONS OF SGRA*

Measures rotation of the Milky Way Galaxy

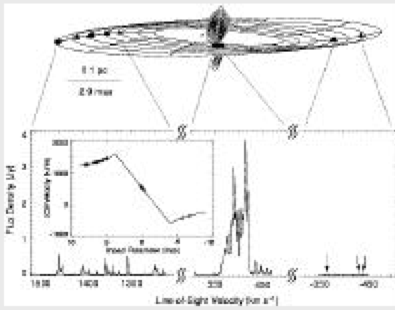


Reid et al. 1999, Ap. J. 524, 816



The Black Hole in NGC 4258

- H_2O masers in edge-on accretion disk
- Clear Keplerian rotation
- Orbit speed from Doppler shifts of masers
- Central mass from orbit speed and radius
- Distance from transverse angular motion or acceleration of central masers



Central mass = 3.6×10^7 solar mass (Miyoshi et al. Nature 373, 127)
Distance = $7.2 \pm 0.3 \pm 0.5$ Mpc (Herrnstein et al. Nature 400, 539)

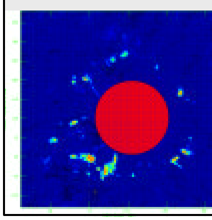
SiO Masers in TX Cam

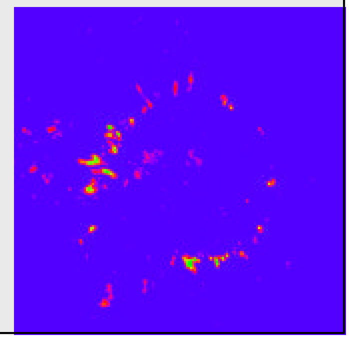
Mira variable (Pulsating star)

VLBA 43 GHz, two week intervals

Full velocity and polarization information available

Diamond and Kemball



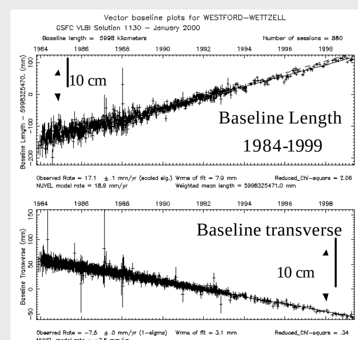


GEODESY and ASTROMETRY

- 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

PLATE MOTIONS
GERMANY to MASSACHUSETTS

- Note improvement of errors over time
- Plate motion is clear
- Possible annual effects starting to show
- From GSFC VLBI group - Jan 2000 solution



DATA REDUCTION
VLBI vs LINKED INTERFEROMETRY

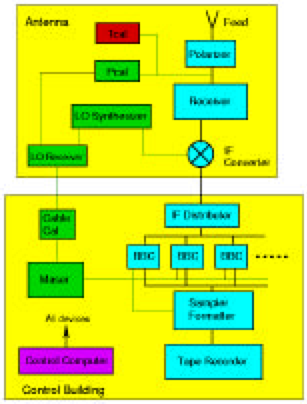
- VLBI is not fundamentally different from linked interferometry
- Differences are a matter of degree
  - Separate clocks allow rapid changes in instrumental phase
  - Independent atmospheres give rapid phase variations and large gradients
    - Different source elevations exacerbate the effect
  - Sources bright enough to be both easily detectable and compact to VLBI are small, highly energetic, and variable
    - There are no flux calibrators
    - There are no polarization position angle calibrators
    - There are no good point source amplitude calibrators
  - Model uncertainties are can be large
    - Source positions, station locations, and the Earth orientation are difficult to determine to a small fraction of a wavelength
  - Often use antennas not designed for interferometry. Not very phase stable

VLBI Data Reduction
Unique Aspects

- Schedule fringe finder observations (Helps correlator operations)
- Correct instrumental phases with pulse calibration tones
- Correct high delay and phase rate offsets with fringe fit
- Phase referencing requires short throws and fast cycles
- Calibrate flux density using telescope a priori gains
- Calibrate polarization PA using near concurrent observations on a short baseline instrument
- Image calibrators
- Strong source imaging usually based on self calibration with very poor starting model

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 (32 track)
  - Record
  - Also keep time and stable frequency
- Other systems conceptually similar



VLBI CORRELATOR


JIVE Correlator

- Read tapes
- 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
- FX: FFT then cross multiply spectra (VLBA)
- XF: Cross multiply lags. FFT later (JIVE, Haystack, VLA …)
- Accumulate and write data to archive
- Some corrections may be required in postprocessing
  - Data normalization and scaling (Varies by correlator)
  - Corrections for clipper offsets (ACCOR in AIPS)

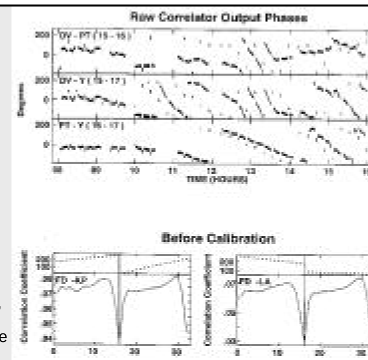
THE DELAY MODEL

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

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

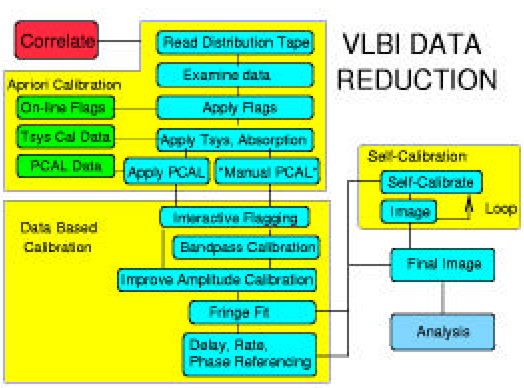
Item	Approx Max	Time scale
Zero order geometry.	6000 km	1 day
Nutation	~ 20"	< 18.6 yr
Precession	~ 0.5 arcmin/yr	years
Annual aberration.	20"	1 year
Retarded baseline.	20 m	1 day
Gravitational delay.	4 mas @ 90° from sun	1 year
Tectonic motion.	10 cm/yr	years
Solid Earth Tide	50 cm	12 hr
Pole Tide	2 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

Raw Residual Data from Correlator



- Significant phase changes with time (fringe rates)
- Significant phase slopes in frequency (delays)
- Can contain bad data, although that not shown in this example

VLBI DATA REDUCTION



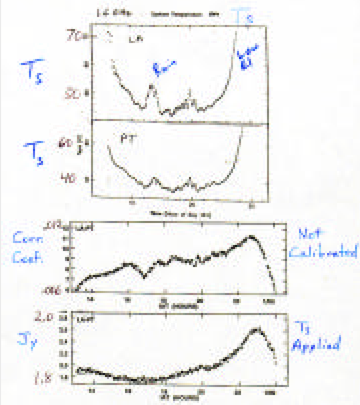
VLBI Amplitude Calibration

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

- S_{cij} = Correlated flux density on baseline i - j
- r = Measured correlation coefficient
- A = Correlator specific scaling factor
- h_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^{-t} = Absorption in atmosphere plus blockage
- Note T_s/K = *SEFD* (System Equivalent Flux Density)

Calbration with Tsys

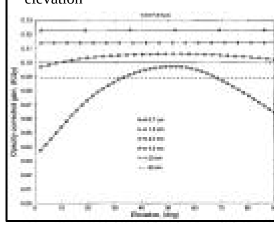
Example shows removal of effect of increased Ts due to rain and low elevation



Gain curves and Opacity correction

VLBA gain curves

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

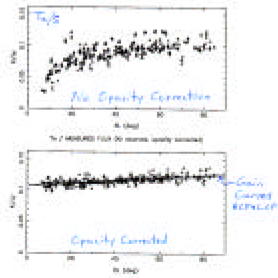


Atmospheric opacity

Correcting for absorption by the atmosphere

Can estimate using Ts – Tr – Tspill

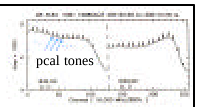
Example from single -dish VLBA pointing data



Pulse Cal System

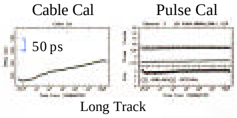
Tones generated by injecting pulse once per microsecond

Use to correct for instrumental phase shifts

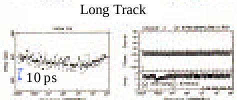


Monitor data

Cable Cal   Pulse Cal

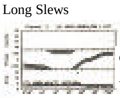


Long Track



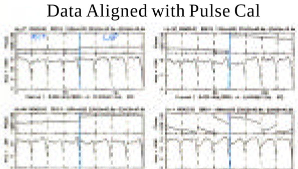
Geodesy – Long Slews

At c, 1 ps = 3mm



Long track at non-VLBA station

Data Aligned with Pulse Cal

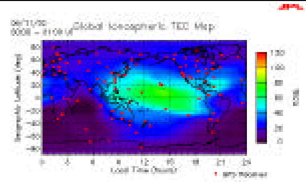


No PCAL at VLA

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)

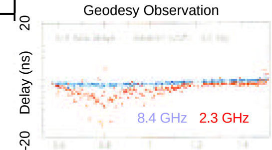


Ionosphere map from iono.jpl.nasa.gov

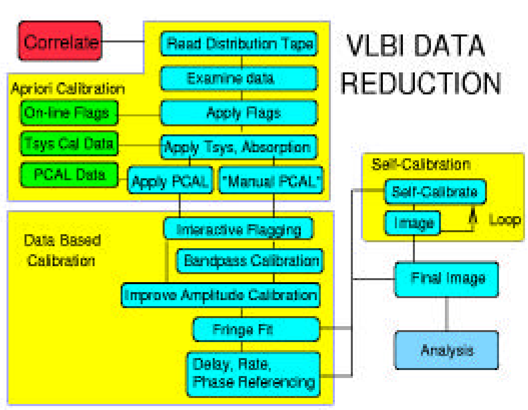
Maximum Likely Ionospheric Contributions

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

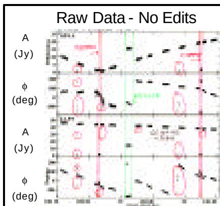


VLBI DATA REDUCTION

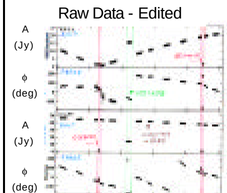


EDITING

Raw Data - No Edits



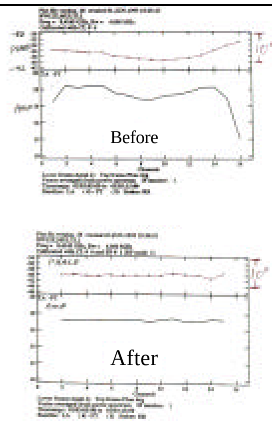
Raw Data - Edited



- 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
  - Best to flag antennas - nearly all causes of poor data are antenna based
  - Poor weather
  - Bad playback
  - RFI (May need to flag by channel)
  - On-line flags not perfect

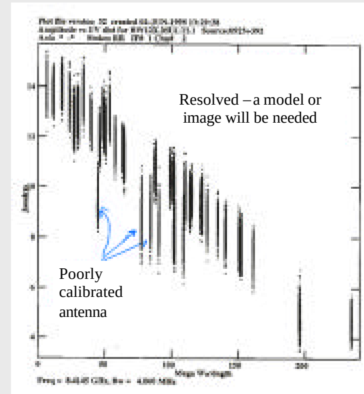
Bandpass Calibration

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



Amplitude Check Source

Typical calibrator visibility function after a priori calibration but before fine tuning with model



FRINGE FITTING: WHAT and WHY

- Raw correlator output has phase slopes in time and frequency
  - Slope in time is "fringe rate"
    - Fluctuations worse at high frequency because of water vapor
  - Slope in frequency is "delay" (from $\phi = \nu\tau$)
    - Fluctuations worse at low frequency because of ionosphere
- Fringe fit is self calibration with first derivatives in time and frequency
- For Astronomy:
  - Fit one or a few scans to "set clocks" and align channels ("manual pcal")
  - Fit calibrator to track most variations (optional)
  - Fit target source if strong (optional)
  - Used to allow averaging in frequency and time
  - Used to allow higher SNR self calibration (longer solution)
  - Allows corrections for smearing from previous averaging
- For geodesy
  - Fitted delays are the primary "observable"
  - Slopes fitted over wide frequency range ("Bandwidth Synthesis")
  - Correlator model is added to get "total delay"

FRINGE FITTING: HOW

- Usually a two step process
  - 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 (like self cal)
  - One phase, rate, and delay per antenna
  - Best SNR because all data used
  - Improved by good source model
  - Best for imaging

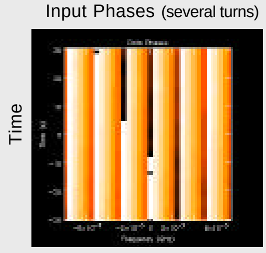
FRINGE FITTING EXAMPLE: HIGH SNR CASE

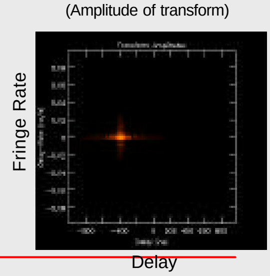
Movies made by George Moellenbrock using AIPS++

Source is easily seen in one integration time / frequency channel

Input Phases (several turns)

Result of fringe fit FFT (Amplitude of transform)





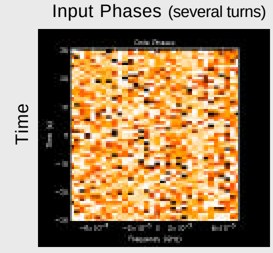
FRINGE FITTING EXAMPLE: LOW SNR CASE

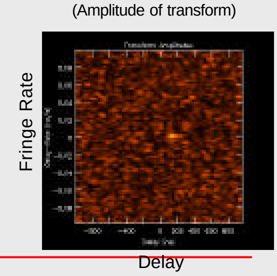
Movies made by George Moellenbrock using AIPS++

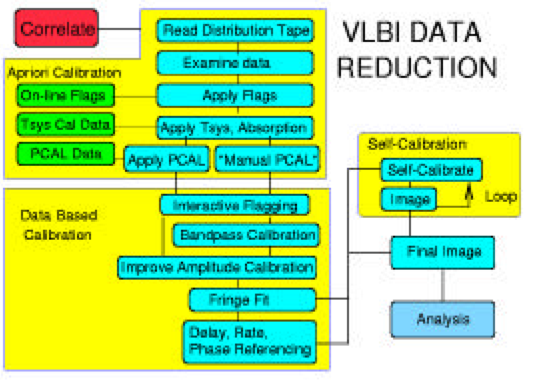
Source cannot be seen in one integration time / frequency channel

Input Phases (several turns)

Result of fringe fit FFT (Amplitude of transform)





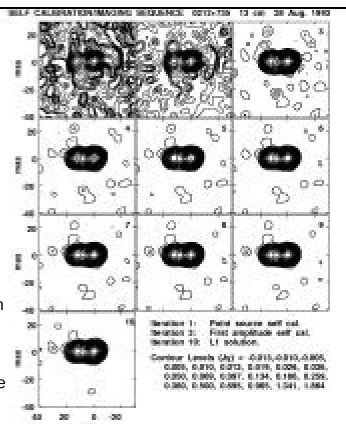


Self Calibration Imaging

- Can image even if calibration is poor or nonexistent
- Possible because there are N gains and N(N-2)/2 baselines
  - Can determine both source structure and antenna gains
  - Need at least 3 antennas for phase gains, 4 for amplitude gains
  - Works better with many antennas
- Iterative procedure:
  - 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
- Does not preserve absolute position or flux density scale
  - Gain normalization usually makes this problem minor
- Historically called "Hybrid Mapping". Based on "Closure Phase".
- 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
- Vary parameters between iterations
  - Taper, robustness, uvrange etc
- Try to reach thermal noise
  - Should get close

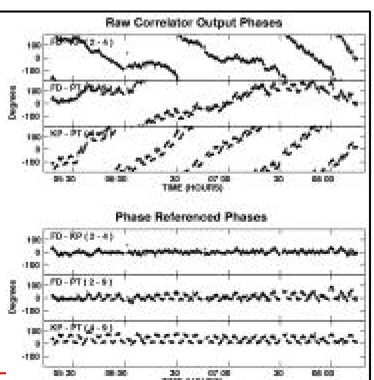


PHASE REFERENCING

- Use phase calibrator outside target source field
  - Nodding calibrator (move antennas)
  - In-beam calibrator (separate correlation pass)
  - Multiple calibrators for most accurate results
- Very similar to VLA calibration but:
  - Geometric and atmospheric models worse
    - Affected by totals between antennas, not just differentials
    - Model errors usually dominate over fluctuations
    - 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

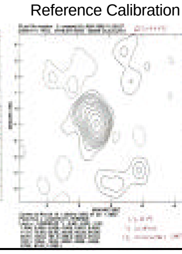


Phase Referencing Example

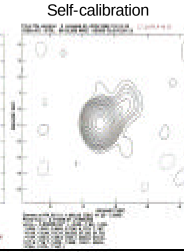
1. With no phase calibration, source is not detected (no surprise)
2. With reference calibration, source is detected, but structure is distorted (target-calibrator separation is probably not small)
3. Self-calibration of this strong source shows real structure

No Phase Calibration

Reference Calibration



Self-calibration



GEODETIC and ASTROMETRIC OBSERVATIONS

- Use group delays from wide spanned bandwidths
  - Use “totals” with correlator model added back in
- Use 2.3 and 8.4 GHz (S/X) to remove ionosphere
- Can do global fits to all historical geodesy data
- Fits include:
  - Antenna and source positions
  - Earth orientation (UT1-UTC, nutation, …)
  - Time variable atmosphere and clocks
  - Many other possible parameters
  - Accuracy is better than 1 mas for source position and 1cm for antenna positions
- Observing by service groups, often using dedicated antennas

SCHEDULING

- PI provides detailed observation sequence
- Include fringe finders (strong sources - at least 2 scans)
- Include amplitude check source (compact source)
- If target 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, include polarization calibrators
  - Get good paralactic angle coverage on one to get instrumental terms
  - Observe absolute position angle calibrator
- Leave occasional gaps for tape readback tests (2 min)
- For non-VLBA observations, manage tapes (passes and changes)

FUTURE DEVELOPMENT

- Use GPS tropospheric delays for calibration
- Use water vapor radiometers for calibration
- Use improved ionosphere models when available (especially 3D)
- Regular use of multi-frequency synthesis (MFS)
- Use pulse cal for Tsys measurement; for polarization PA calibration
- Push to higher frequencies
- More use of large antennas (GBT, EB, Arecibo, Y27)
- Develop robust automated imaging procedures
- Technical push to wider bandwidths and real time
- Fill in shorter baselines
  - MERLIN/VLBI integration in Europe; EVLA/VLBA integration in US
- Future space projects
- Big sensitivity increase with long baselines of SKA