VLBI Data Analysis

Calibration, Edition and Fringe Fitting

Eduardo Ros[1,2] & Matthias Kadler[3,4]

1: U. Valencia, 2: MPIfR, 3: Dr. Remeis Obs. Bamberg, 4: ECAP

July 2nd, 2009
Multiwavelength Summer School

Calibrating and editing

- CALIBRATION: Removal of instrumental factors in the measurements
- Every physicist has to calibrate the instrument of measure being used
- EDITION: *no data are better than bad data*

Calibration - why? (i)

- Synthesis radio telescopes are not perfect (surface accuracy, receiver noise, etc.)
- Technical devices with different processes involved (frequency conversion, digital sampling, etc.)
- Control during the observation occasionally fails: calibration or edition of the data

Calibration - why? (ii)

- Scheduling and observing errors do occur (wrong source positions, slewing times different than expected, etc.)
- Atmospheric and space weather (ionosphere) conditions are not ideal
- RFI

Calibration methods

- Direct calibration:
  - Some parameters of the observations are known (geometry of the interferometer)
  - VLA: amplitude stability over 1%
  - VLBI: impossible
- Calibrator sources in the sky:
  - Calibration observing well-known objects
  - Monitoring of phase: phase-referencing
  - Monitoring of gain: determination of amplitudes
- Self-calibration

Instrumental effects, stable with time

- Antenna position coordinates: *geodetic values (ITRF)*
- Antenna pointing corrections: *pointing model elaborated at the telescopes*
- Zero-point setting of instrumental delays: *known by GPS values or another methods*

Stable effects during the observation

- Dry component of the atmospheric delay: *meteorological values*
- Antenna gain as a function of elevation: *gain curves determined at the telescopes*
- Shadowing of antennas by close ones: *at close elements (VLA), known at the scheduling*

Variable effects during the observation

- Variations at the system temperatures: *direct measurements and recording of the data*
- Phase variations in the local oscillator: *to be tracked*
- Wet component of the atmospheric delay: *determined with meteorological measurements, WVR*

What do we want and what do we get

- We want to obtain the visibility function, which has to be inverted to obtain the brightness distribution:

$$V(u,v) = \int I_\nu(x,y)\, e^{-i2\pi(ux+vy)} dx\, dy$$

- We obtain the correlation of the electric field (voltage) sampled at pairs of telescopes (baselines *ij*)

$$V_{ij}(t) = \left\langle x_i(t) e^{i\phi_i^{comp}} \cdot x_j^*(t) e^{-i\phi_j^{comp}} \right\rangle_t$$

The measured signal

- The net signal delivered by antenna *i*, $x_i(t)$, is a combination of the desired signal, $s_i(t,x,y)$, corrupted by a factor $J_i(t,x,y)$ and integrated over the sky, and noise, $n_i(t)$:

$$\begin{aligned} x_i(t) &= \int J_i(t,x,y) s_i(t,x,y)\, dxdy + n_i(t) \\ &= s_i'(t) + n_i(t) \end{aligned}$$

- $J_i(t,x,y)$ is the factor to be calibrated, it is antenna-based
- Sometimes, the effects contained in this term are irreversible and the data have to be edited

Correlation of signals

- The noise doesn't correlate:

$$
\begin{aligned}
\left\langle x_i \cdot x_j^* \right\rangle &= \left\langle (s_i' + n_i) \cdot (s_j' + n_j)^* \right\rangle \\
&= \left\langle s_i' \cdot s_j'^* \right\rangle + \left\langle s_i' \cdot n_j^* \right\rangle + \left\langle n_i \cdot s_j'^* \right\rangle + \left\langle n_i \cdot n_j^* \right\rangle \\
&= \left\langle s_i' \cdot s_j'^* \right\rangle \\
&= \left\langle \int J_i(t) s_i(t)\, dldm \cdot \int J_j^*(t) s_j^*(t)\, dldm \right\rangle \\
&= \left\langle \int J_i(t) J_j^*(t) s_i(t) s_j^*(t)\, dldm \right\rangle
\end{aligned}
$$

- Even if $n_i >> s_i$, the correlation isolates the desired signals

Calibration sequence (signal path)

- Faraday rotation
- Tropospheric effects
- Parallactic angle
- Antenna voltage pattern
- Polarization leakage
- Electronic gain
- Bandpass response

Ionospheric Faraday Rotation

- The ionosphere is birefringent, and one hand of the circular polarization is delayed wrt the other, introducing a phase shift:

$$\Delta\phi = 0.15\ \lambda^2 \int B_{\parallel} n_e ds\ \ \text{deg}$$

$$\lambda \text{ in cm},\ \ n_e ds \text{ in } 10^{14}\,\text{cm}^{-2},\ \ B_{\parallel} \text{ in G}$$

- Rotates the linear polarization position angle
- Important at long wavelengths, at sunrise or sunset, and at a maximum of solar activity
- Example:

$$TEC = \int n_e ds\ \sim 10^{14}\text{cm}^{-2};\, B_{\parallel} \sim 1\text{G};\, \lambda = 20\text{cm} \rightarrow \Delta\phi \sim 60^{\circ}$$

Troposphere

- Polarization-independent
- Amplitude effect: opacity
- Phase effect: refraction
- Effect: 2m (7ns) excess path length at zenith compared to vacuum
- Important at high frequencies, where water vapour absorbs and emits
- Correction: *water vapor radiometer, frequency switching?*

Parallactic angle

- Orientation of receiver with respect to the field of view
- Constant for equatorial telescopes
- Variable for alt-az

$$\chi(t) = \arctan\left(\frac{\cos(l)\sin(h(t))}{\sin(l)\cos(\delta) - \cos(l)\sin(\delta)\cos(h(t))}\right)$$

$$l = \text{latitude},\ h(t) = \text{hour angle},\ \delta = \text{declination}$$

- Rotates the position angle of linearly polarized radiation

Antenna voltage pattern

- Antennas have a direction-dependent gain
- Important for wide-field mapping (region of sky comparable or larger than λ/D
- Important at low frequencies

Polarization leakage

- Orthogonal polarizations are not completely isolated
- Feeds have a value of *d* of a few percent or less
- Frequency-dependent
- For RCP/LCP systems, the total intensity image is affected as ~*dQ*, *dU* (important only for high dynamic range imaging), and the linear polarization imaging is affected as ~*dI* (very important)

Electronic gain (i)

- Includes most of the amplitude and phase effects introduced by the electronics: amplifiers, mixers, quantizers, digitizers
- Dominates all the other effects
- Causes the scaling from engineering to radio astronomical units (Jy)
- Excludes frequency-dependent effects

Electronic gain (ii)

- Flux density observed for a given baseline:

$$S_{ij} = A_{ij} b \sqrt{\frac{T_{s_i} T_{s_j}}{K_i K_j}}$$

- A_{ij} is the measured visibility amplitude (raw correlation coefficient)
- Digitization losses: b
- K_i are the antenna sensitivities (K/Jy)
- T_{si} are the system temperatures in K

Electronic gain (iii)

- It is instructive to express the system temperature in terms of the system equivalent flux density, *SEFD*:

$$SEFD_i = \frac{T_{s_i}}{K_i}$$

- Examples at 5GHz:
  - *Jodrell Bank, 26m, SEFD=366 Jy*
  - *Effelsberg, 100m, SEFD=39 Jy*
  - *Noto, 32m, SEFD=220 Jy*
  - *VLBA antenna, 25m, SEFD=300 Jy*

Electronic gain (iv)

- Sensitivity of an interferometer:

$$\Delta S_{ij} = \frac{1}{\eta_s}\sqrt{\frac{SEFD_i \cdot SEFD_j}{2\Delta\nu\tau_{\mathrm{acc}}}}$$

- Electronic losses η_s
- $\Delta\nu$ is the observing bandwidth
- Accumulation time τ_{acc}

Bandpass response

- Frequency-antenna electronics
- The filters used to select the frequency passbands are not square
- Typically normalized

More effects…

- Errors in the geometric and the clock models, affecting the phase: solved by FRINGE-FITTING
- Baseline-based errors not included into antenna-based factors
  - Correlators are designed to prevent that
  - Averaging in time and frequency
  - Correlated noise (RFI)
  - Indistinguishable from source structure effects

Planning for good calibration: values provided by the observatory

- Antenna positions, earth orientation
- Clocks
- Antenna pointing, gains, voltage pattern
- Calibrator coordinates, flux densities, polarization properties

Planning for good calibration: absolute calibration

- VLBI: FORGET IT !

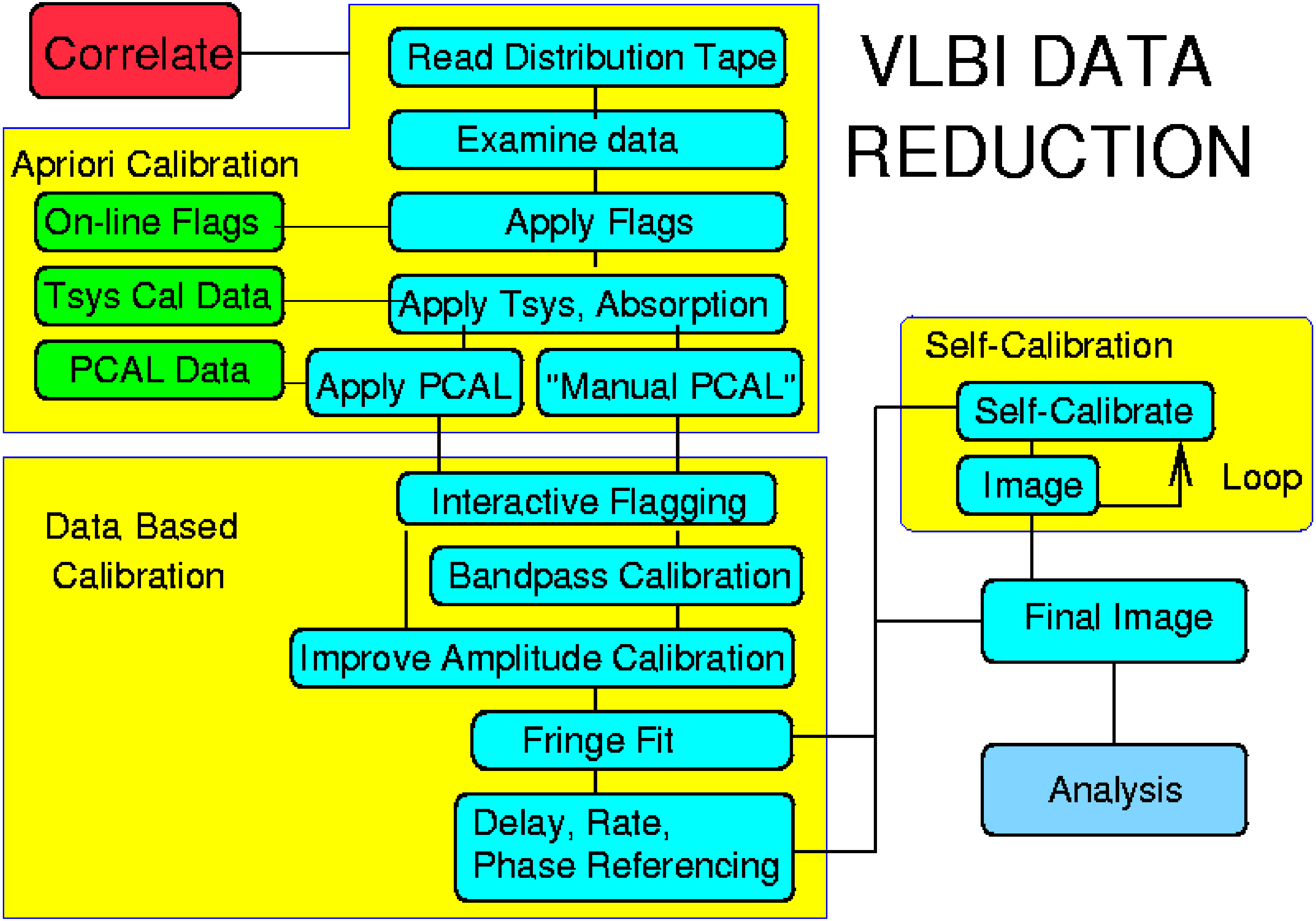
Planning for good calibration: cross-calibration

- Observe nearby point sources (predictable visibilities) and transfer solutions to target observations
- Observe a calibrator of known flux density
- Polarization observations:
    - Observe strong and unpolarized calibrators
    - Observe a broad range of parallactic angle

Radio Frequency Interference

- Originated from human beings
- Obscures natural emission in spectral line observations
- Adds to total noise power, making the amplitude calibration more difficult
- Can correlate between antennas close to each other
- Mitigation:
  - Electronic design in antennas
  - Choose interference-free frequencies
  - Observe continuum channels in spectral-line modes to edit bad channels

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

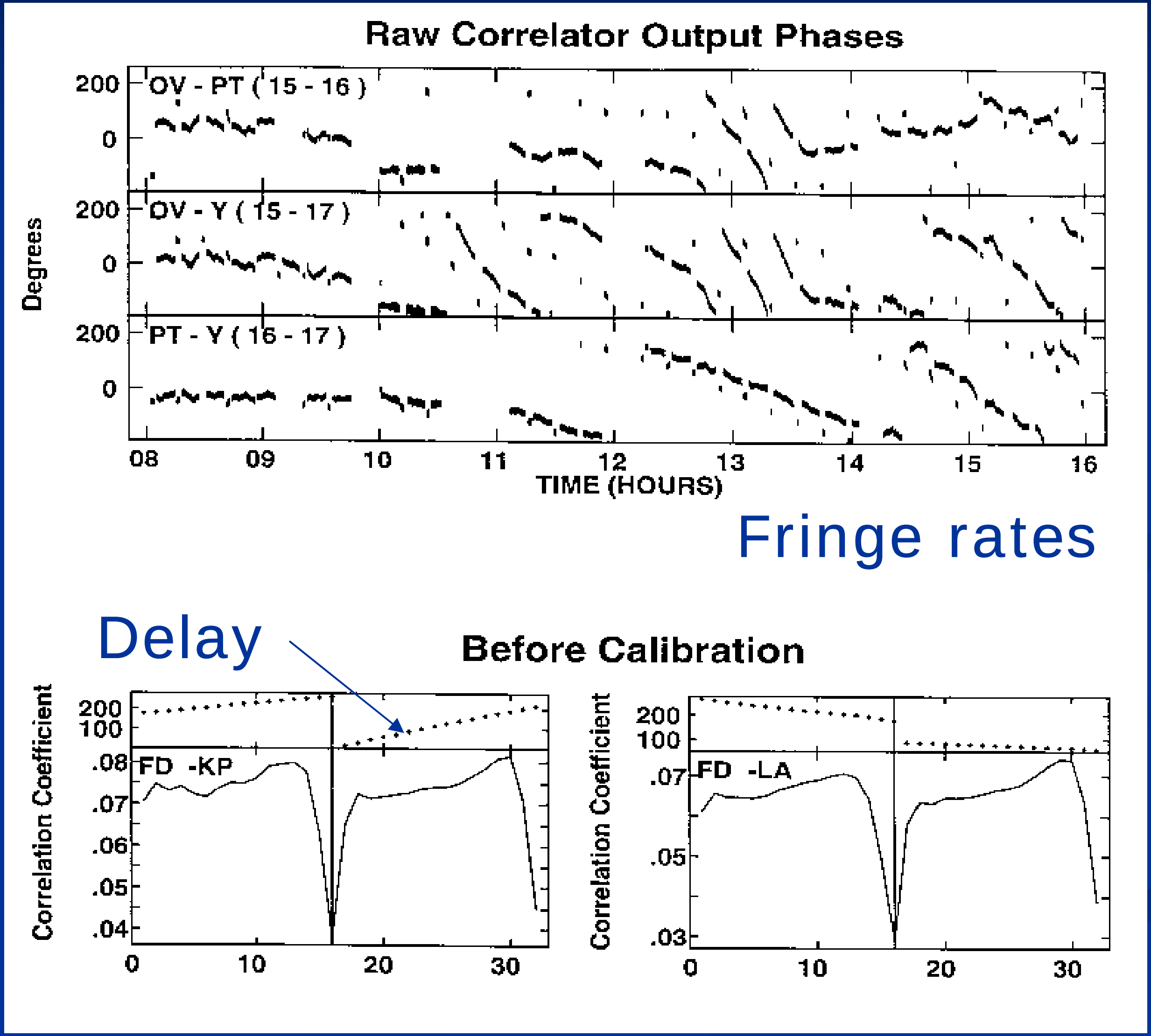
Image

Loop

Final Image

Analysis

Raw correlator output



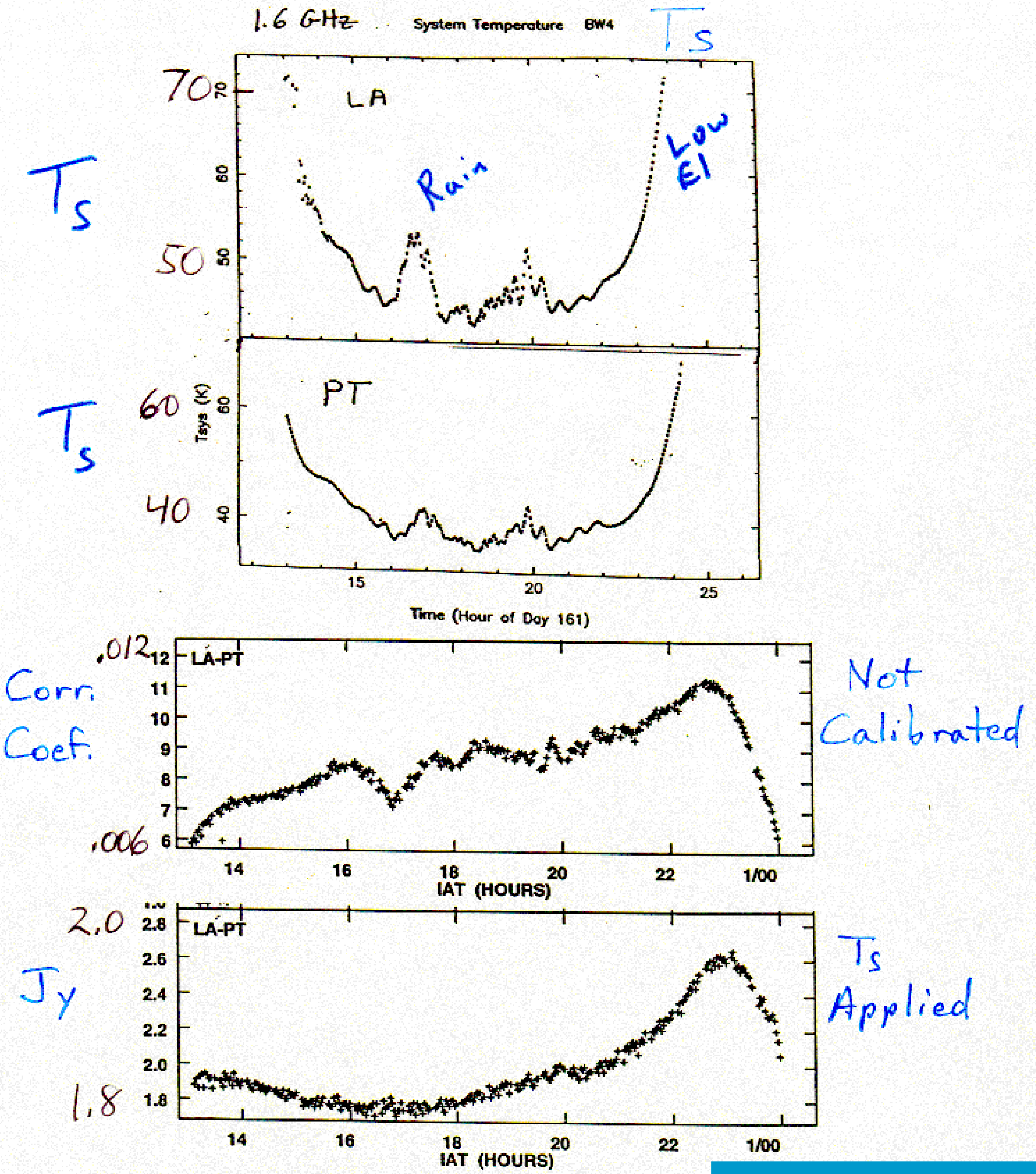
Fringe rates

Delay

Graphics by C. Walker

System temperature calibration

Rain and low elevation effects



Graphics by C. Walker

Digital sampling correction

- The use of 2-bit sampling causes a bias in the data due to digitization - can be estimated from the data itself and corrected
- Amplitude corrections not larger than 5%

Gain curve correction

VLBA gain curves, dependence of the antenna gain as function of elevation

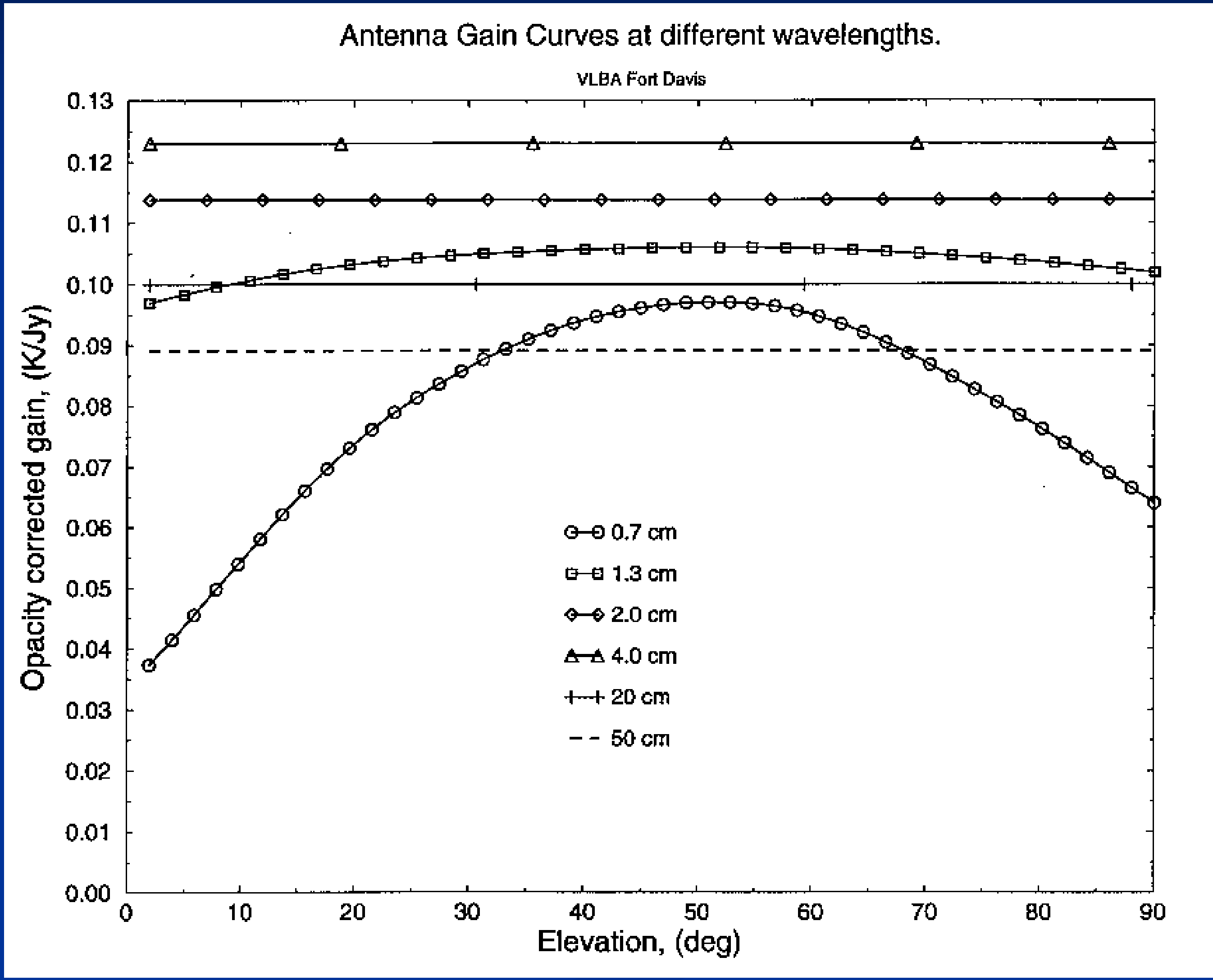
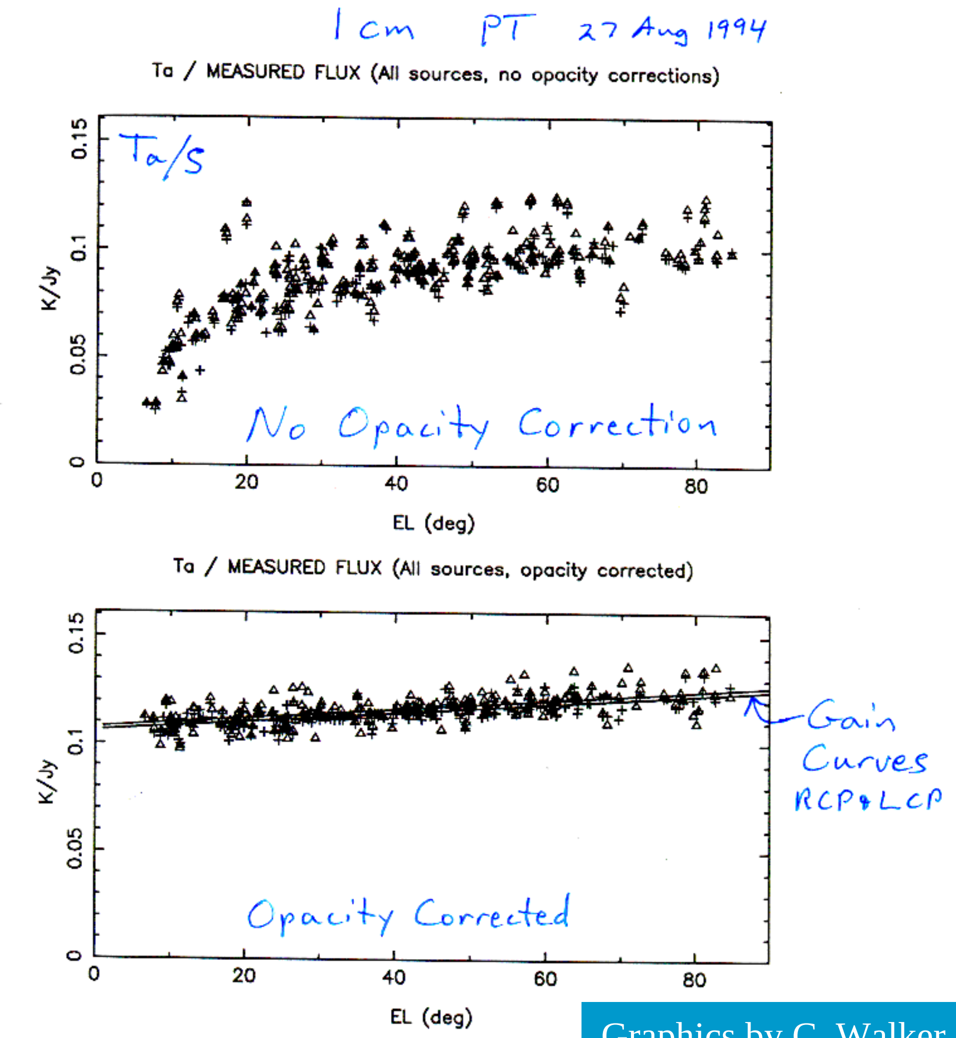


Image by C. Walker

Atmospheric opacity

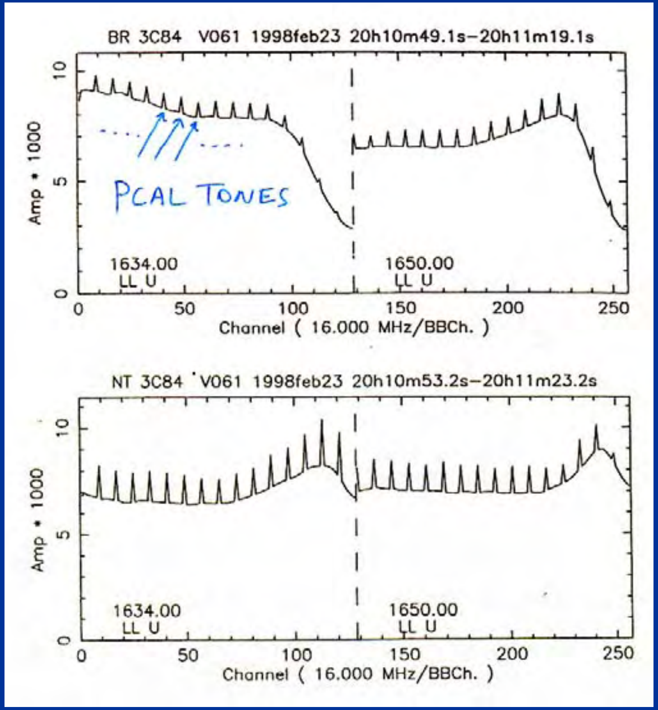
Absorption of the atmosphere



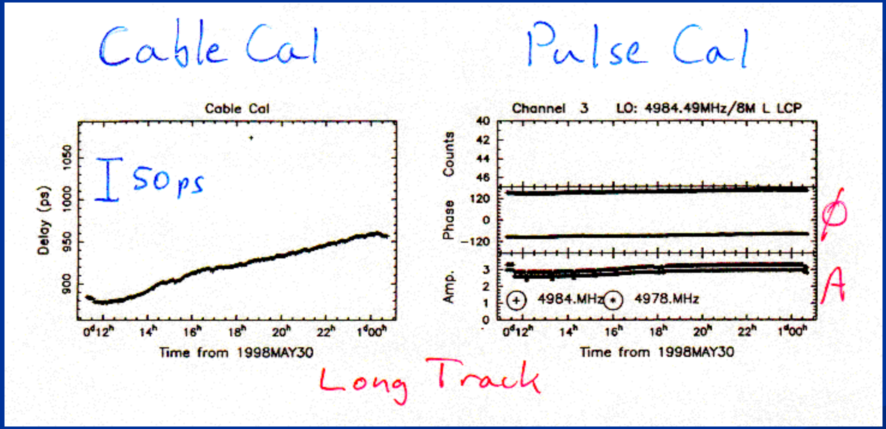
Graphics by C. Walker

Pulse cal system (i)

Correction of the instrumental phase shifts: pulse injection once per microsecond



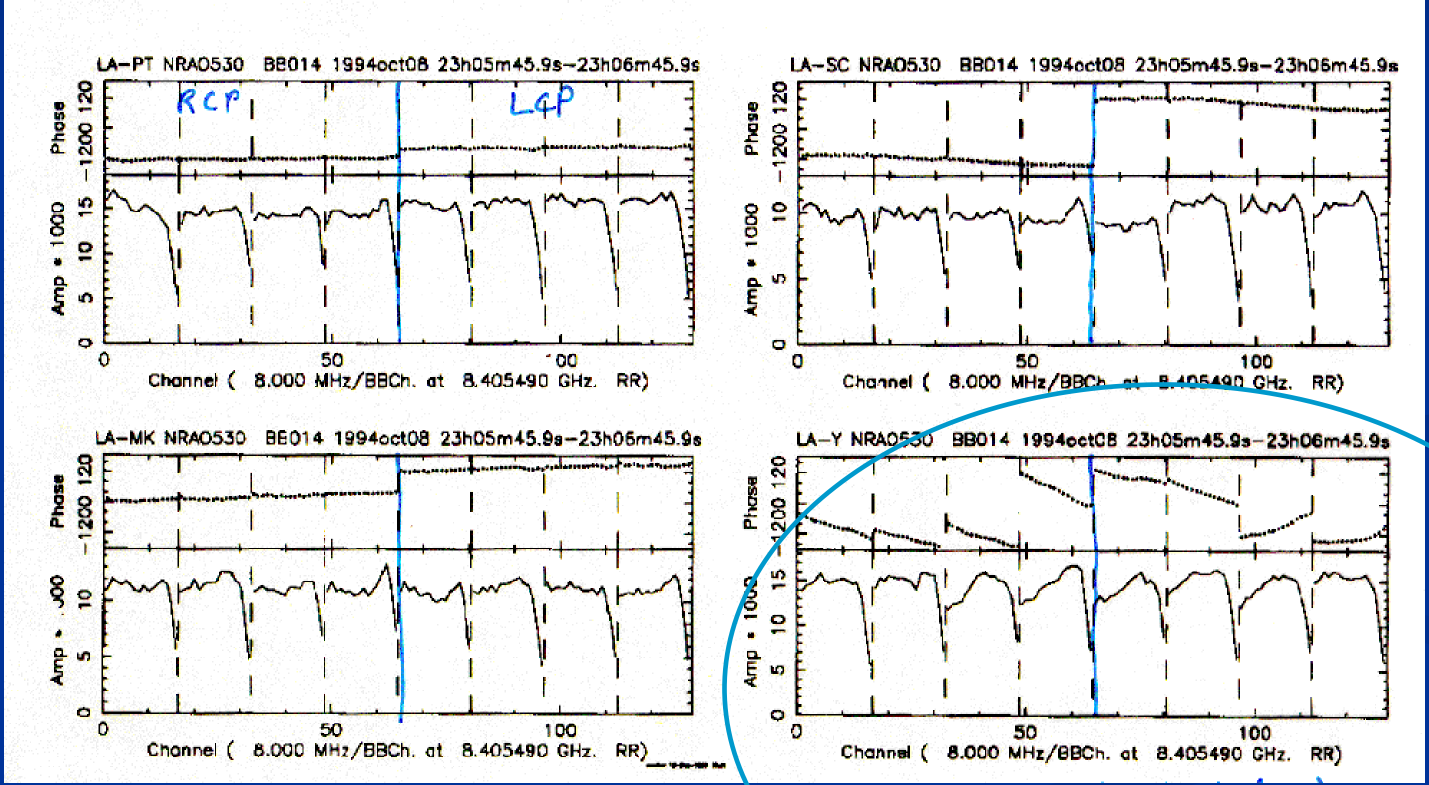
Pulse-cal tones



Monitoring of data

Graphics by C. Walker

Pulse cal system (ii)

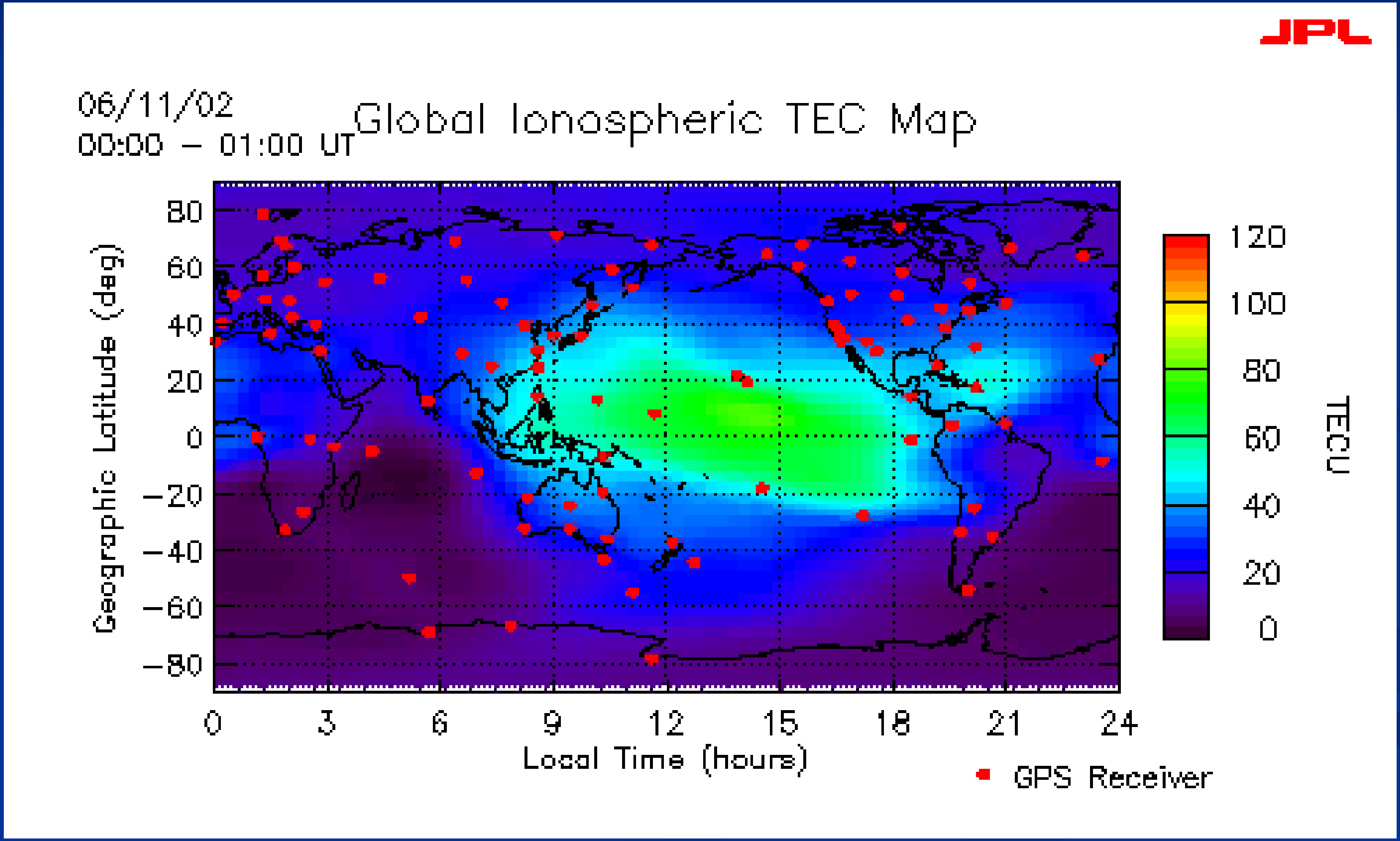


Data aligned with pulse-cal

VLA: no phase-cal, phases are not aligned

Graphics by C. Walker

Ionosphere


JPL
06/11/02
00:00 – 01:00 UT
Global Ionospheric TEC Map
Geographic Latitude (deg)
80
60
40
20
0
−20
−40
−60
−80
0
3
6
9
12
15
18
21
24
Local Time (hours)
120
100
80
60
40
20
0
TECU
GPS Receiver

Correction of parallactic angle

- Include the effect of the rotation of the receiver w.r.t. the sky in the phases
- Important in geodesy and in polarization observations

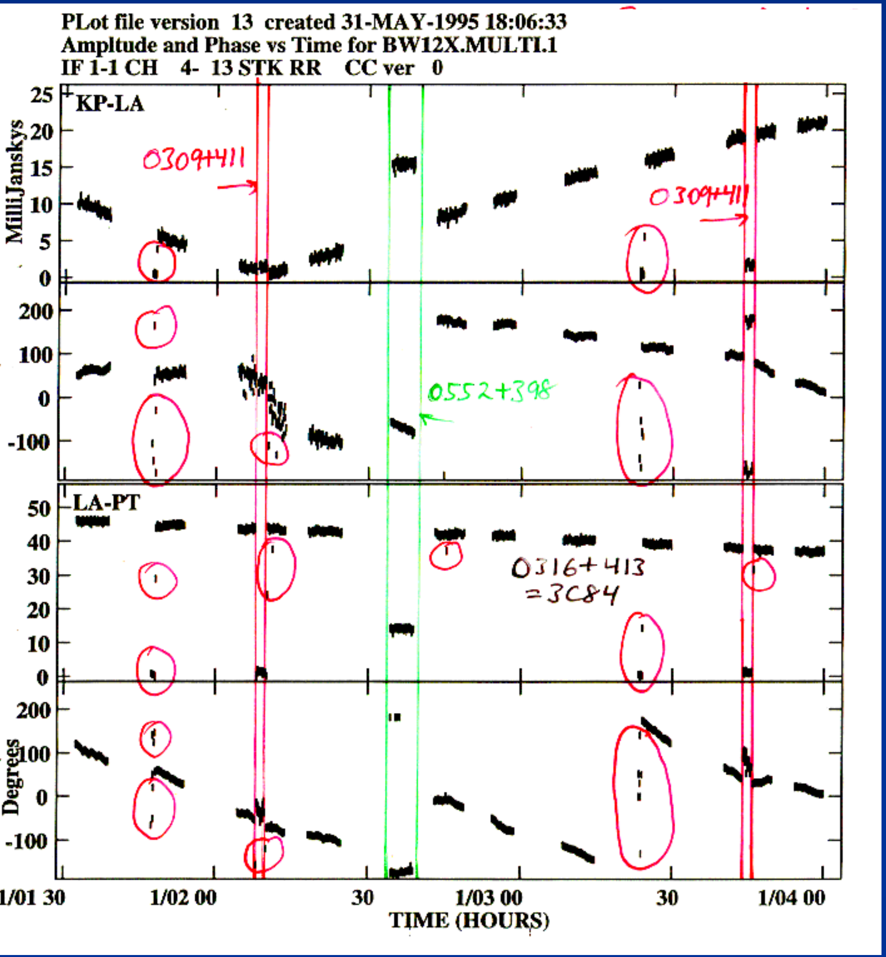
Editing bad data (i)

No data are better than bad data

- Automatic flagging of data: antenna off source, problems at synthesizers, low elevation
- Examining data: most of the causes of poor data are antenna-based
  - Weather
  - Bad playback
  - RFI
  - Bad automatic flagging

Editing bad data (ii)

Raw data, not edited



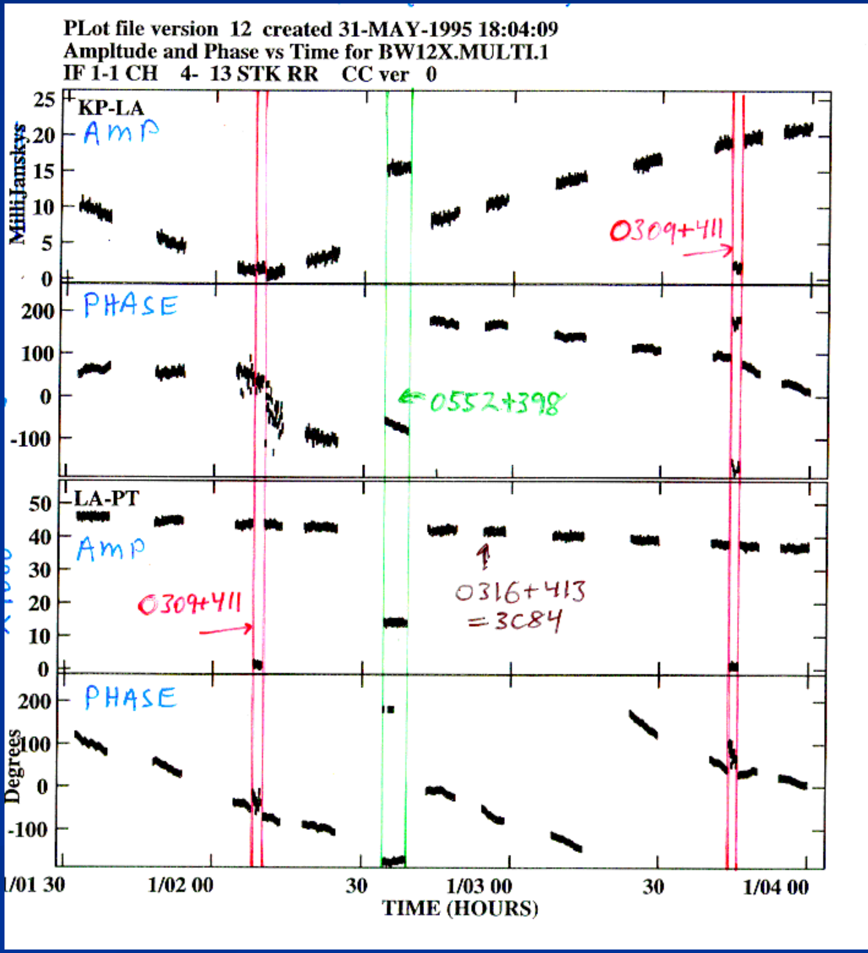
A

φ

A

φ

Edited data

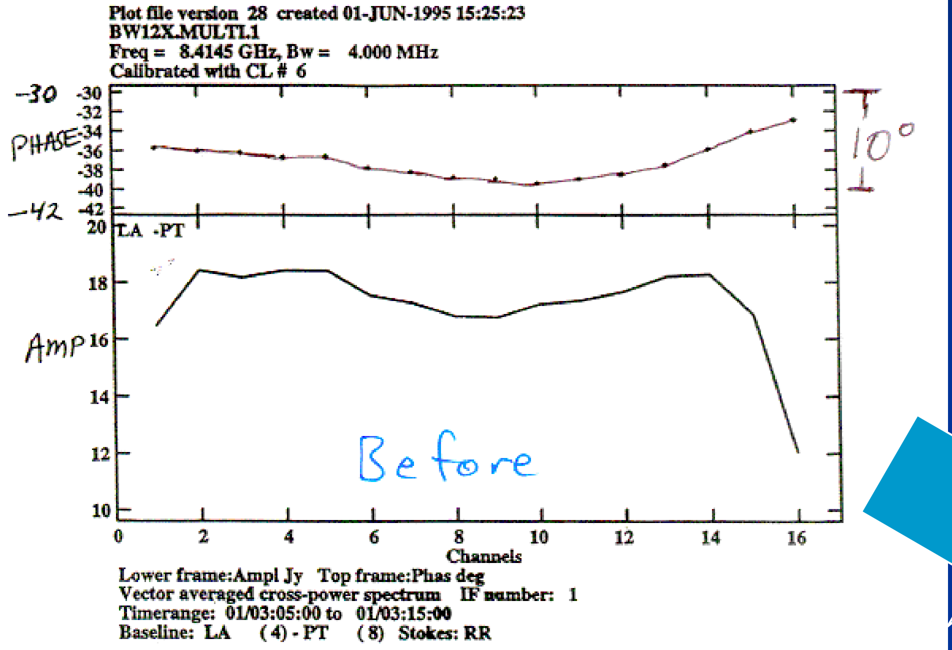


Graphics by C. Walker

Editing bad data (iii)

- Steps:
  - Check the performance of the antennas in the logs, and edit consequently
  - Removal of outliers and inconsistent data
  - Editing during the calibration, if insuperable difficulties appear
  - Editing during the imaging process, to improve the map quality

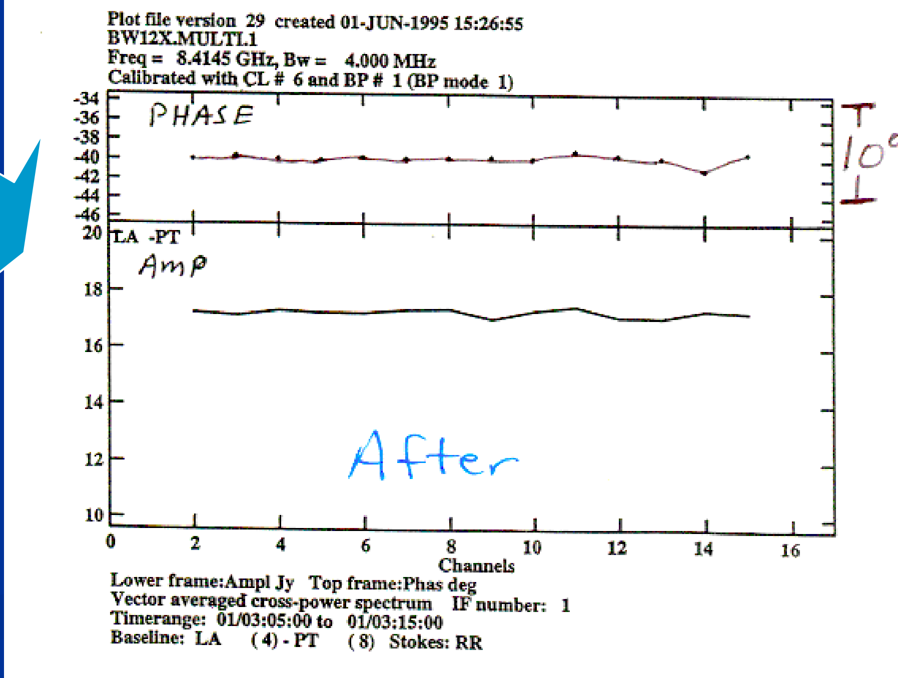
Bandpass calibration



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

“Self-calibration” in each channel



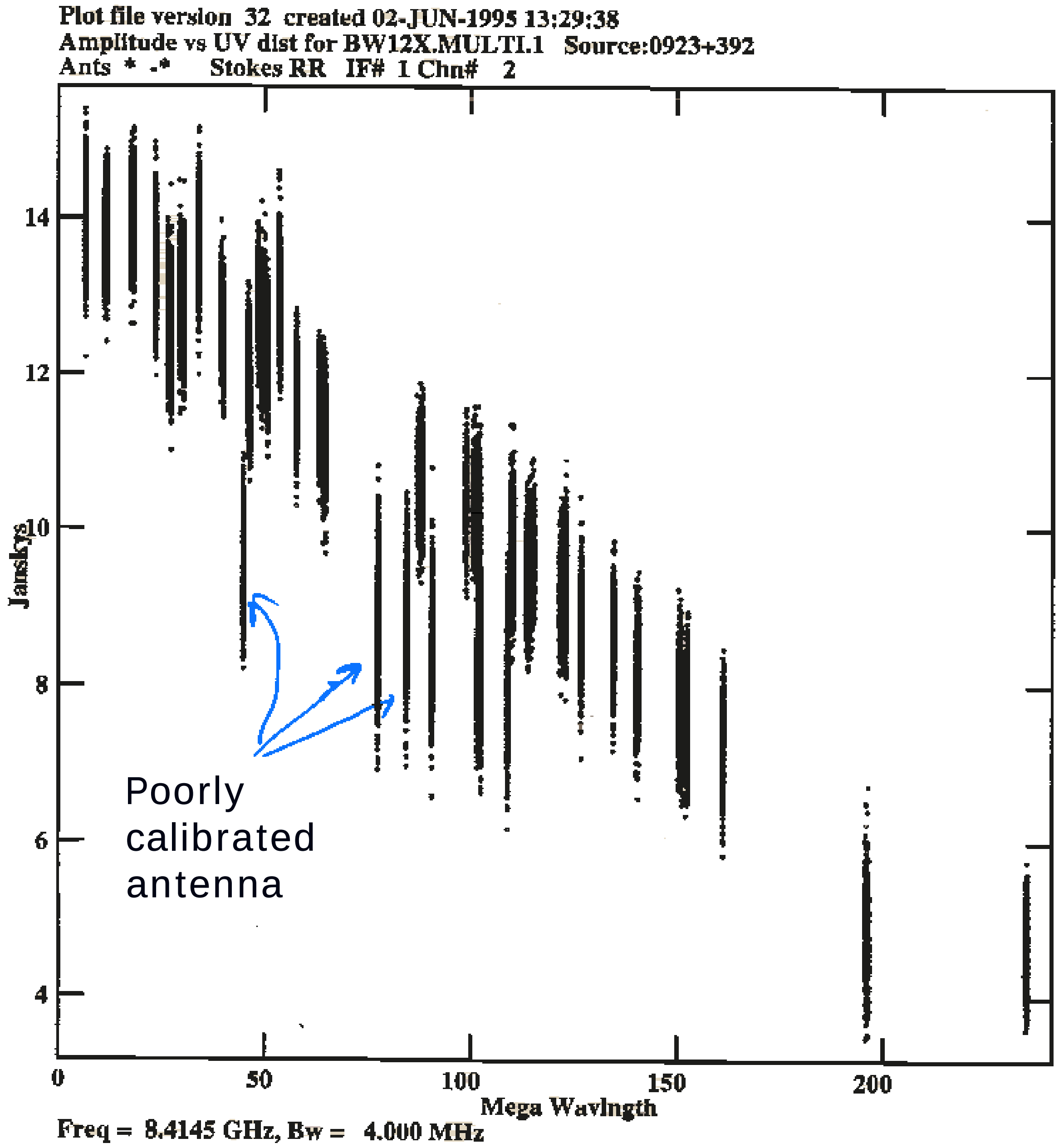
Plot file version 29 created 01-JUN-1995 15:26:55
BW12X.MULTI.1
Freq = 8.4145 GHz, Bw = 4.000 MHz
Calibrated with CL # 6 and BP # 1 (BP mode 1)

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

Needed for spectral line analysis

Graphics by C. Walker

Amplitude check



Poorly calibrated antenna

Visibility amplitude before mapping

Graphics by C. Walker

Fringe fitting (i)

- Raw correlator data have phase slopes in time (fringe rate) and frequency (delay)
- Fringe fit is self calibration with first derivatives in time and frequency
- When is done:
    - Fit one scan to align channels: *manual phase cal*
    - Used to allow averaging in frequency and time, with corrections for smearing, getting a higher SNR for astronomical purposes (imaging)
    - Used to get slopes in frequency for geodetic purposes (the delay is the main observable)

Fringe fitting (ii)

- Steps in the process:
  - FFT in 2D to estimate rates and delays to the reference antenna – search windows can be restricted
  - Least squares fit to the phases starting at the FFT estimate

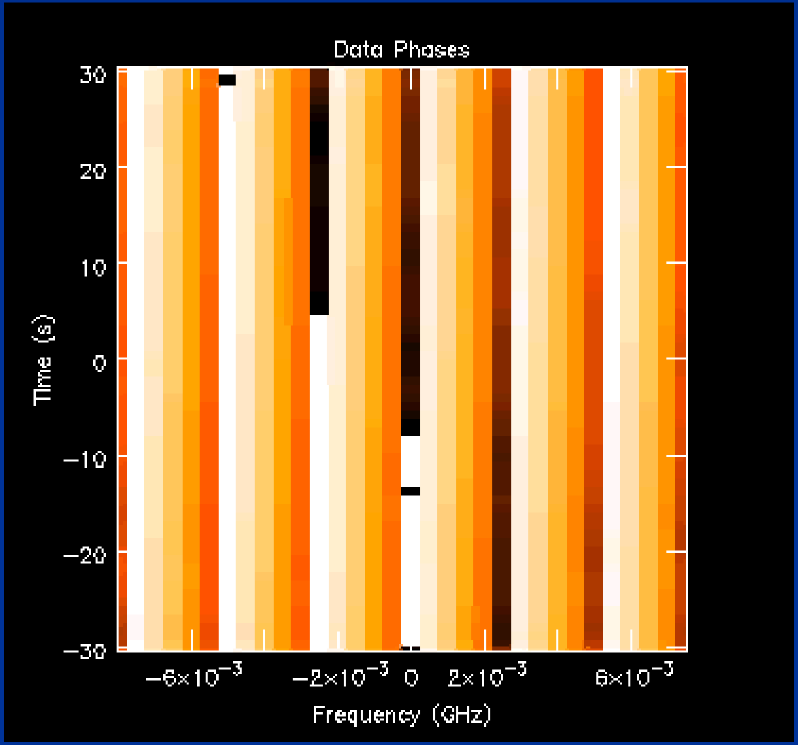
Fringe fitting (iii)

- Baseline-based fringe fitting
  - Not affected by poor source model
  - Used in geodesy
- Global fringe fitting
  - One phase, rate, and delay per antenna
  - All data used: high SNR
  - Source model allows improvement
  - Used for imaging

Fringe fitting (iv)

High SNR case

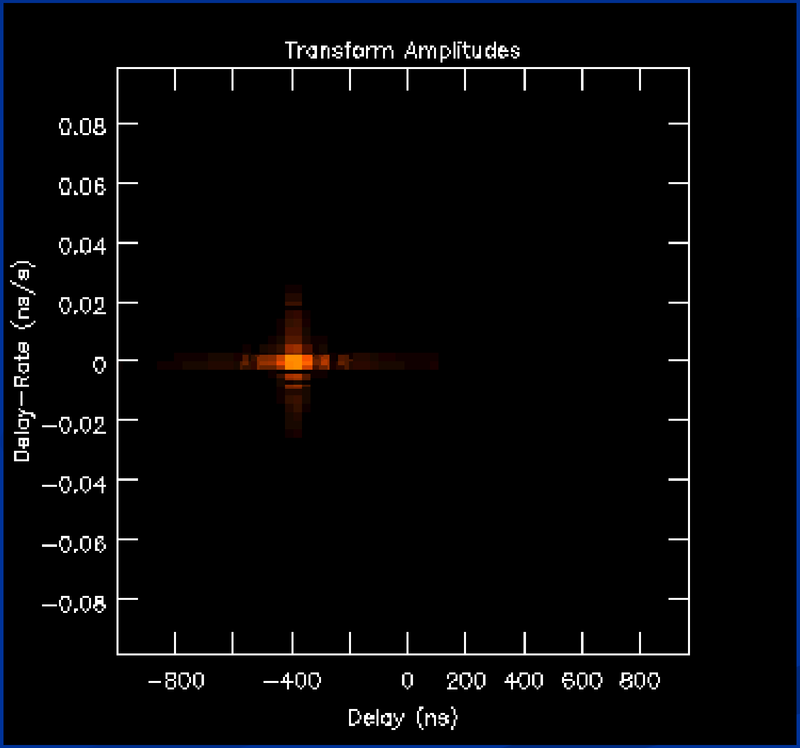
Input phase turns



Time

Frequency

Result of FFT



Fringe rate

Delay

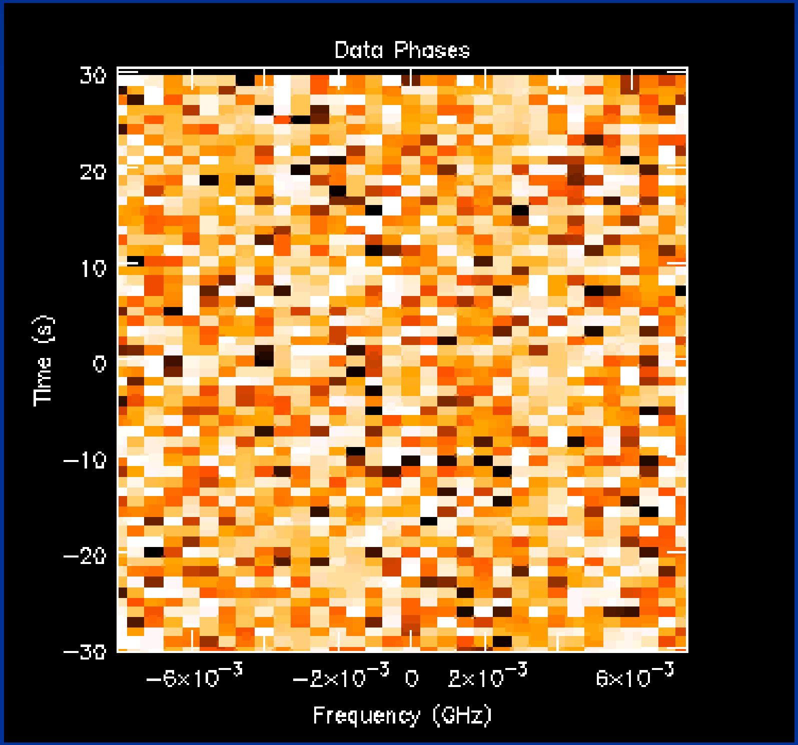
Graphics by C. Walker & G. Moellenbroc

Fringe fitting (v)

Low SNR case

Input phase turns

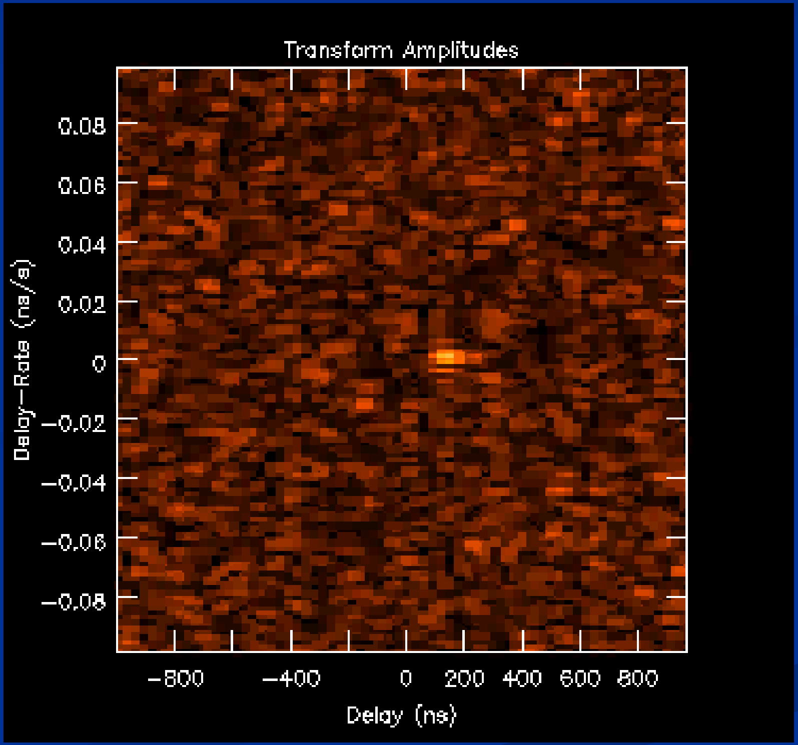
Time



Frequency

Result of FFT

Fringe rate

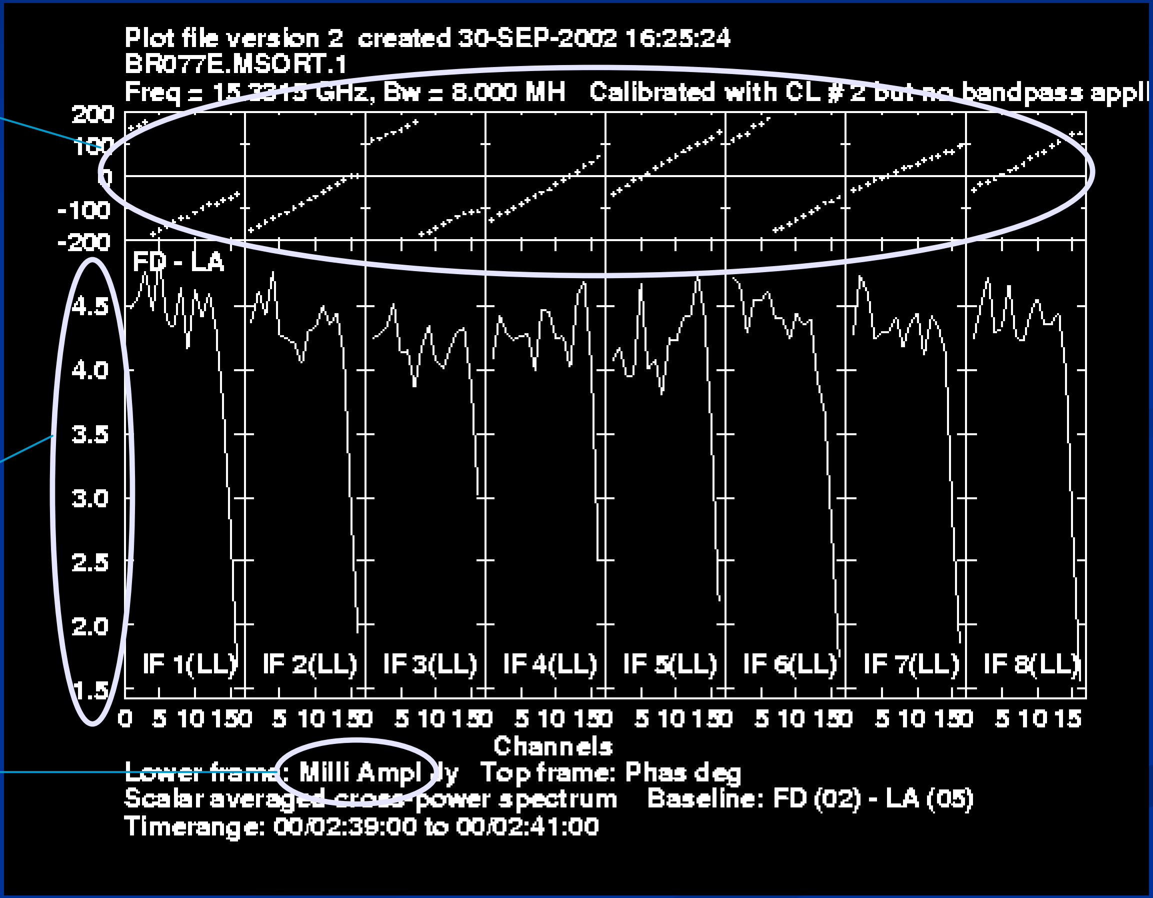


Delay

Images by C. Walker & G. Moellenbrock

Calibration step by step (i)

Phase slopes across each IF, offsets between IFs



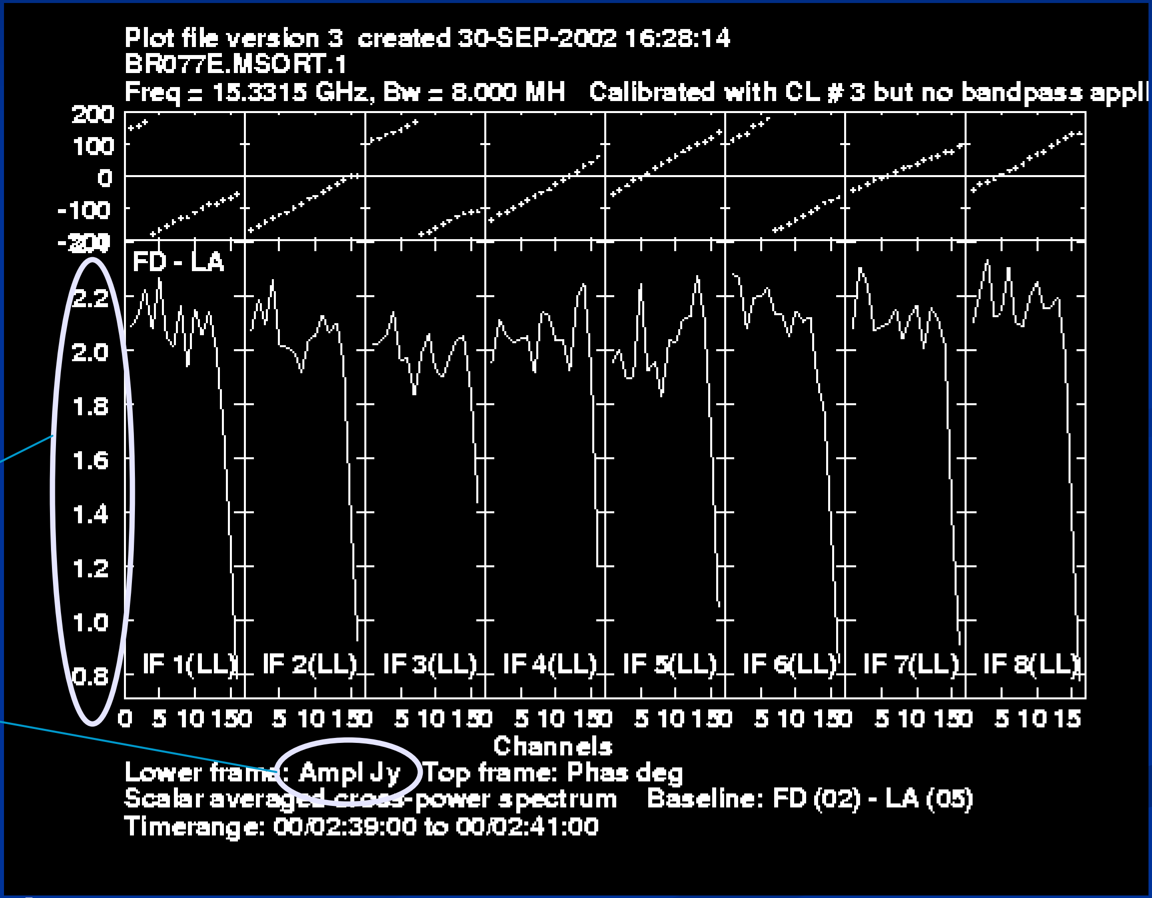
Plot file version 2 created 30-SEP-2002 16:25:24
BR077E.MSORT.1
Freq = 15.3315 GHz, Bw = 8.000 MH Calibrated with CL # 2 but no bandpass appli

Lower frame: Milli Ampl Jy Top frame: Phas deg
Scalar averaged cross-power spectrum Baseline: FD (02) - LA (05)
Timerange: 00/02:39:00 to 00/02:41:00

Uncalibrated amplitudes (correlation coefficients)

Raw data from the correlator

Calibration step by step (ii)

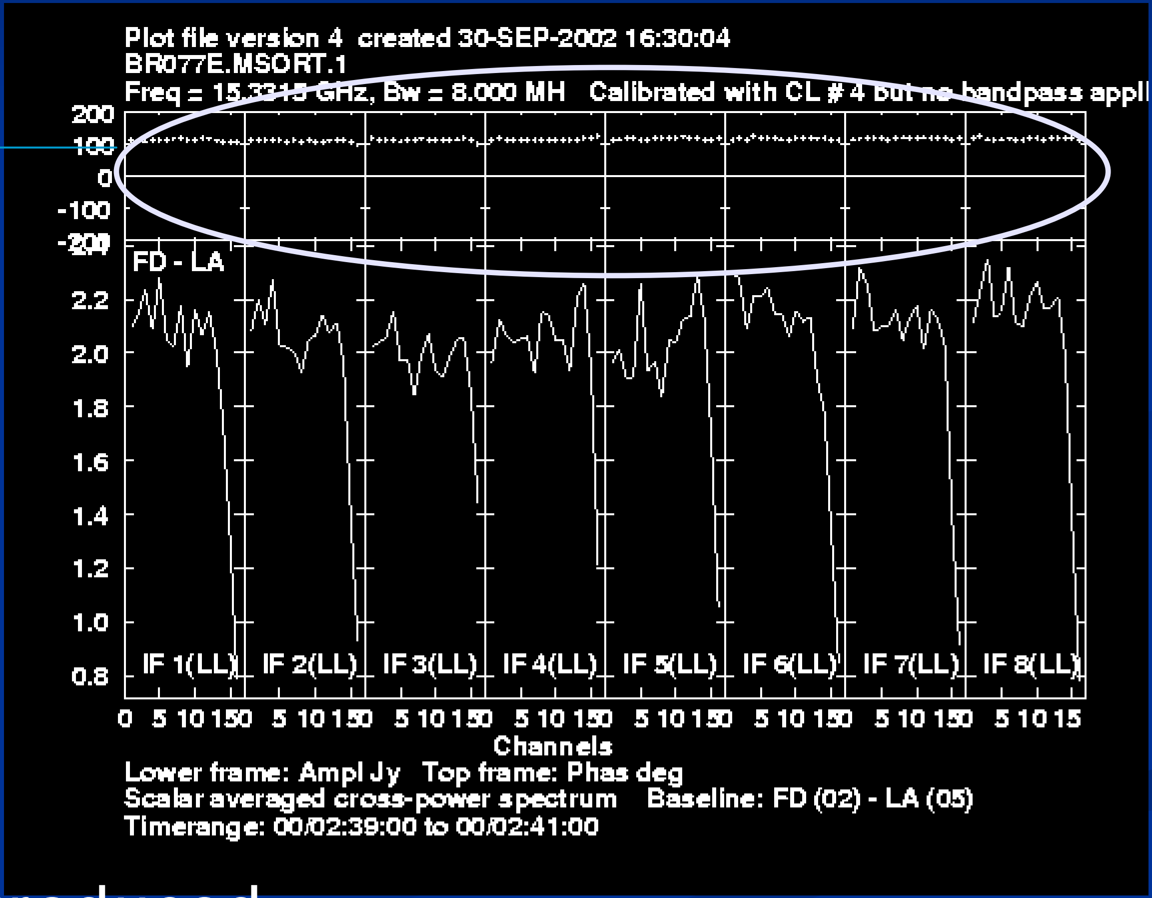


Calibrated amplitudes, in Jy

Amplitude calibration

Calibration step by step (iii)

No offsets between different IFs



Plot file version 4 created 30-SEP-2002 16:30:04
BR077E.MSORT.1
Freq = 15.3315 GHz, Bw = 8.000 MH   Calibrated with CL # 4 but no bandpass appl

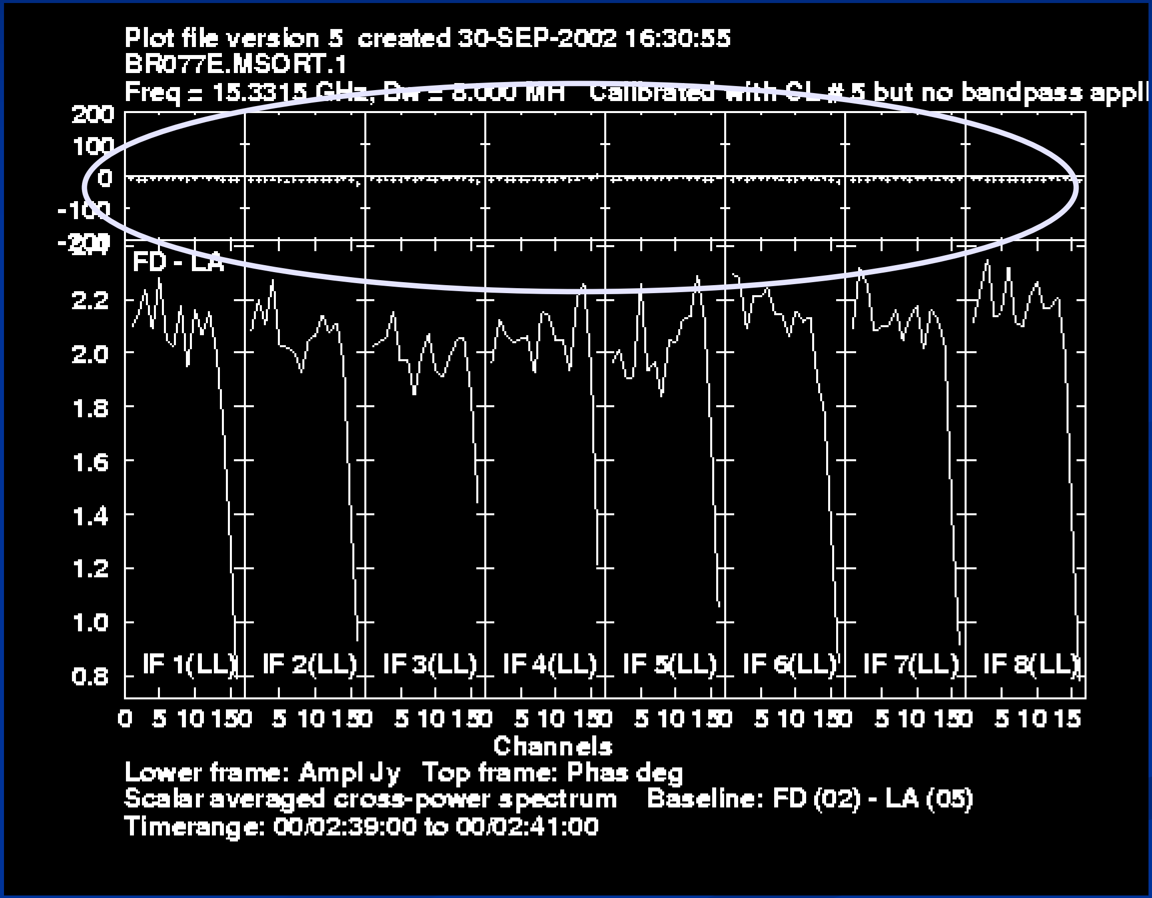
Lower frame: Ampl Jy   Top frame: Phas deg
Scalar averaged cross-power spectrum   Baseline: FD (02) - LA (05)
Timerange: 00/02:39:00 to 00/02:41:00

Phase calibration introduced

Calibration step by step (iv)

Solved for phase (equals zero) and delay (no slope).

<u>The data can be averaged in time and frequency. READY TO MAP!</u>



Fringe-fitting done

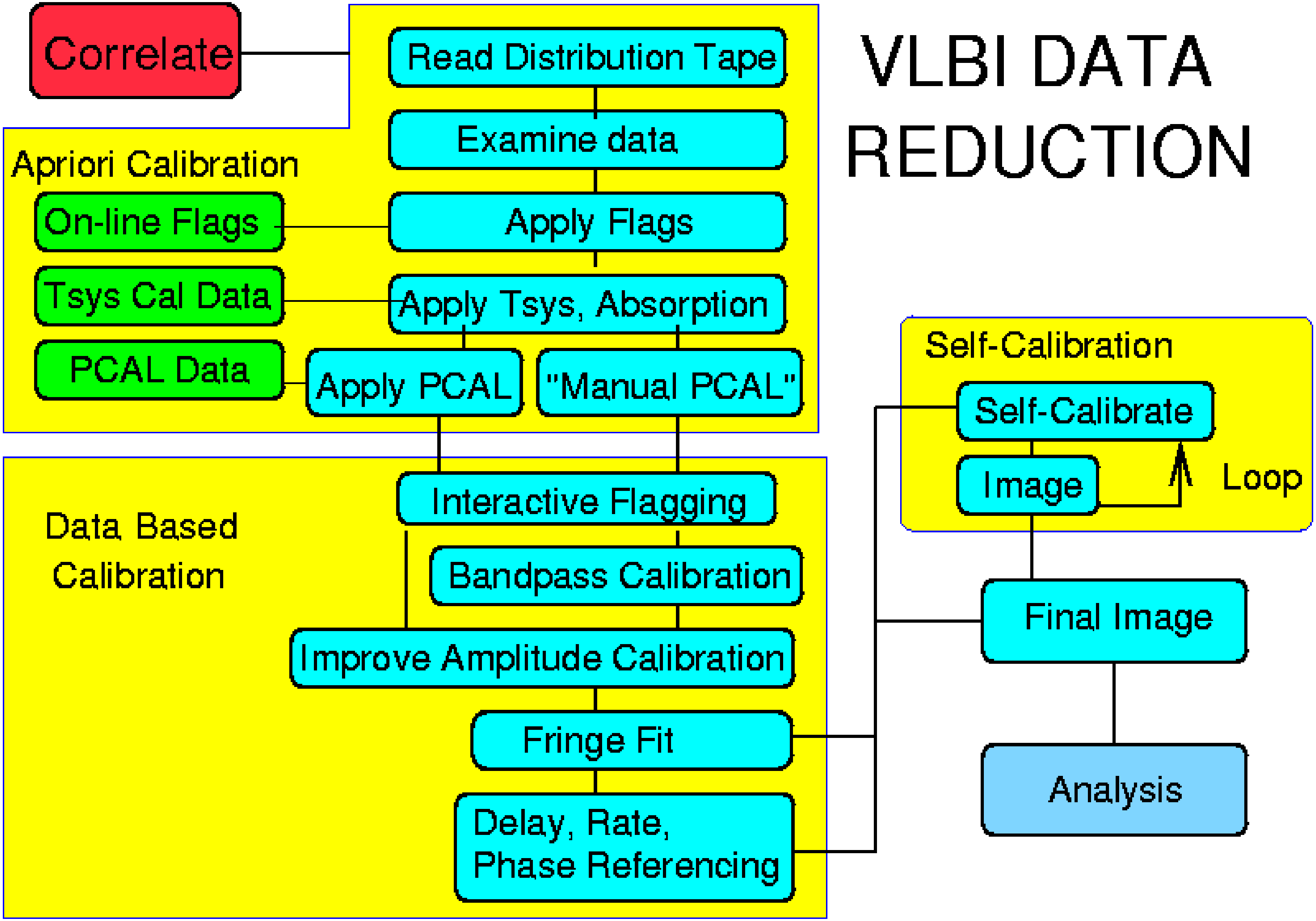
Polarization calibration

- Determination of the instrumental polarization: leakage factors at the antenna feeds, the so-called *D-terms*
- After fringe-fitting and self-calibration, use of a source model following the method described in Leppänen et al., AJ, 110, 2479 (1995) [multi-component similarity approximation]
- Absolute Electric Vector Position Angle (EVPA) calibration needed afterwards, comparing with a known, stable case (3C286, 3C138)

Astrometric/geodetic observations

- Use of the group delay using widely spread bandwidths
- Generally observing 2.3 and 8.4 GHz to remove ionosphere
- Solutions of data analysis:
  - Antenna and source positions
  - Earth orientation parameters (UT1-UTC, nutation, etc.)
  - Atmosphere and clock behavior
  - Accuracies better than 1 cm and 1 mas
- Geodesy: International VLBI Service

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

Credits

- Moellenbrock, 2002, Socorro Summer School, talk on *Calibration and Data Editing* (http://www.nrao.edu)
- Walker, 2002, Socorro Summer School, talk on *VLBI* (http://www.nrao.edu)
- *Synthesis Imaging in Radio Astronomy II*, by Taylor et al, ASP 180 (1999)
- *Very Long Baseline Interferometry, Techniques and Applications*, by Felly & Spencer, NATO ASI Series 283 (1989)
- *Interferometry and Synthesis in Radio Astronomy*, by Thompson et al., John Wiley & Sons, NY (1986)