(continuum)

DATA ACQUISITION
&
CALIBRATION

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Foreword

An observation turns out to be successful when:

0. The weather/atmosphere is good (clear signal path)

1. The instrumentation performs according to specifications

2. The data acquisition goes smoothly

3. The software for the data analysis runs without problems

4. The observation ***has been*** *carefully planned (observe appropriate calibration sources! and often enough!)*

5. The user knows what she/he is doing during the data handling, and what kind of astrophysics can be derived from the “numbers” delivered by the experiment

Outline:

I. Setting the scene *[from antenna measurements to the interferometer; relevant parameters: baseline length, frequency, A,qφ, bandwidth, integration time and effects]*

II. Data structure *[what is a dataset]*

III. Principles of Calibration!

[amplitudes mean flux densities, phases mean position]
[the real world is full of corruption]

IV. Practical Calibration (little to do with III)

[finding problems and remedies: prevention is better than cure!]

Random concepts/facts relevant in (Technical) Radioastronomy:

Low energy photons, i.e. Wave formalism

Fraunhofer diffraction applies and HPBW ~ λ/D (monochromatic radiation!)

Synchrotron radio emission is polarized

Back/forth from/to the Fourier domain
(COMPLEX Visibility Function <FT> REAL Brightness Distribution)

Skip most of the details! There are appropriate textbooks:

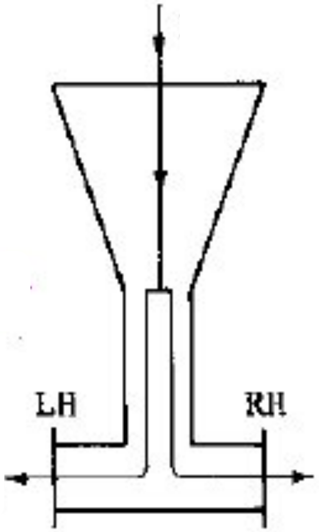
- *Rohlfs & Wilson: Tools of Radio Astronomy*
- *Thompson, Moran & Swenson: Interferometry and Synthesis in Radio Astronomy*
- *Various authors: NRAO Synthesis Imaging school(s)*
- *Felli & Spencer (eds)* Very Long Baseline Interferometry Tech. And Appl

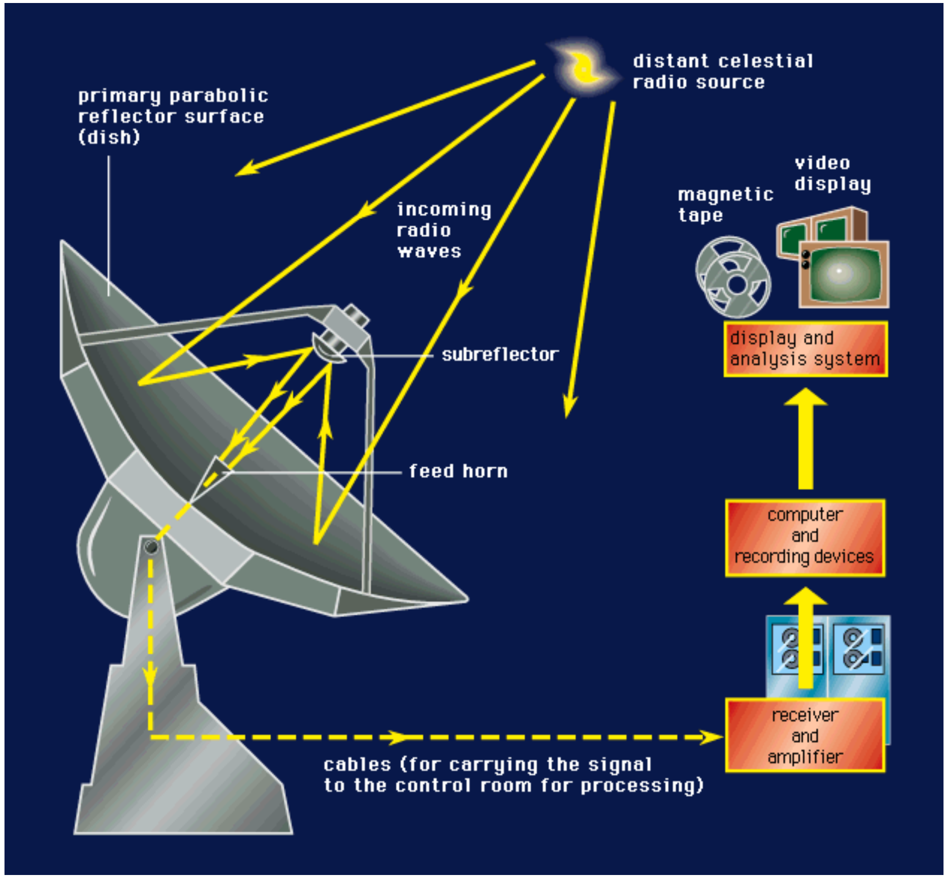
Let's have a “practical approach”

“From infinity….. to here!” (adapted from Buzz Lightyear, 1995)

Each antenna *(i^{th} single dish) measures a Voltage, i.e. the E field of the incoming monochromatic radiation is converted into V, to be sampled*

$$V^{i} = V_{o} \sin(\omega t + \phi)$$





http://www.almaobservatory.org/en/about-alma/how-does-alma-work

Everybody knows.... life is more complicated!

2 *hands / linears* for polarization *(together they fully sample incoming radiation)*

(R & L < == > X & Y)

$$V_L^i = V_L \sin\left(\omega t + \phi_L\right)$$
$$V_R^i = V_R \sin\left(\omega t + \phi_R\right)$$

.... well there is the noise as well!!!!

$$V_L^i = V_L \sin\left(\omega t + \phi_L\right) + n_L\left(t\right)$$
$$V_R^i = V_R \sin\left(\omega t + \phi_R\right) + n_R\left(t\right)$$

*We are **not** interested in most of the signal collected at each antenna [n(t)]*

Radio Interferometry:

the signals from two antennas _i and _j are (cross)CORRELATED
and this applies for ANY pair which can be made out of the whole array

$$V^{i} = V \sin\left(\omega t + \phi^{i}\right) + n^{i}(t)$$

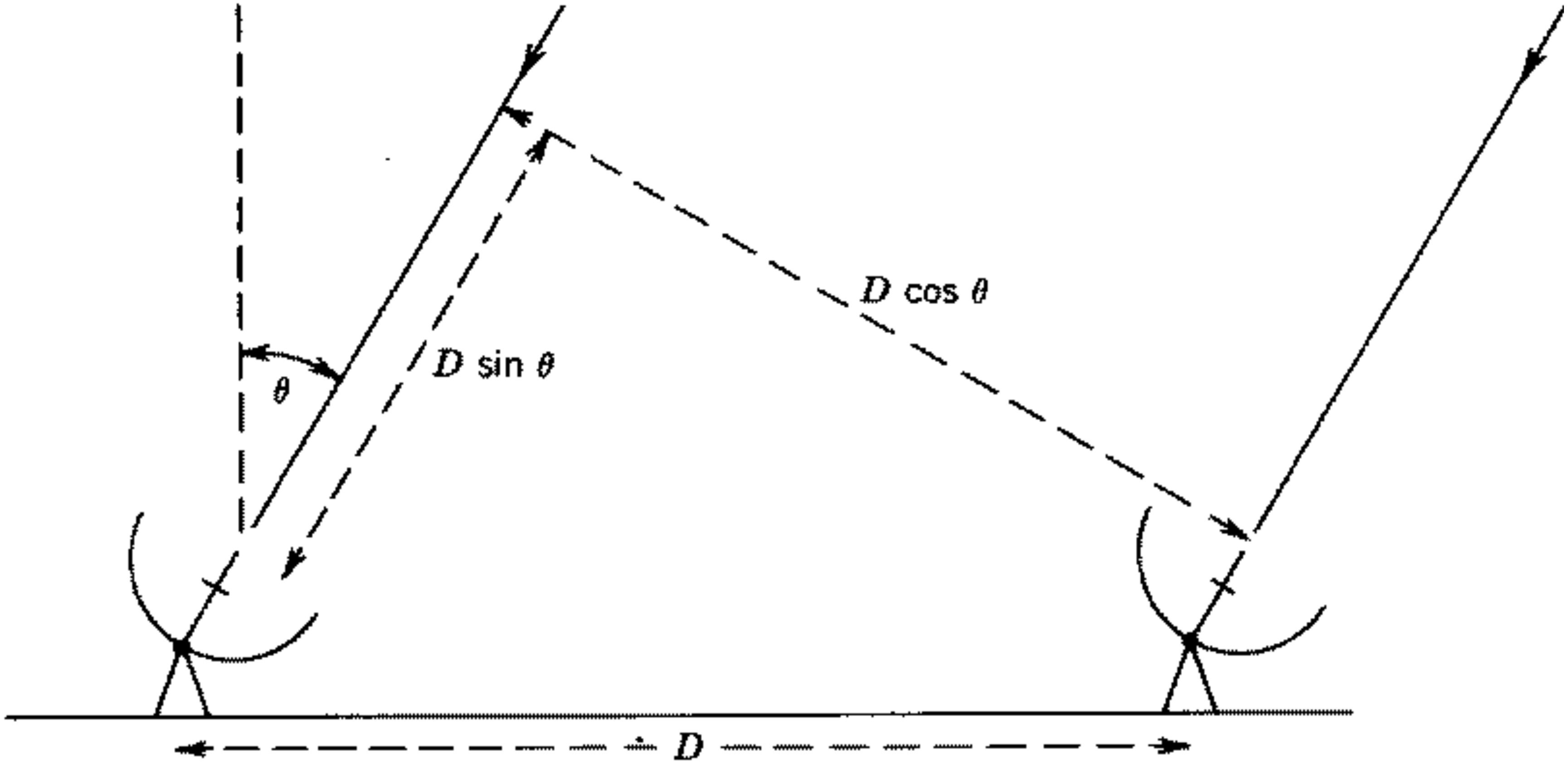
$$V^{j} = V \sin\left(\omega t + \phi^{j}\right) + n^{j}(t)$$

***N** antennas deliver* ***N(N-1)/2** independent combinations (measurements)*

radio Interferometry:

the signals from two antennas _i and _ j are (cross)CORRELATED

very, very far away source

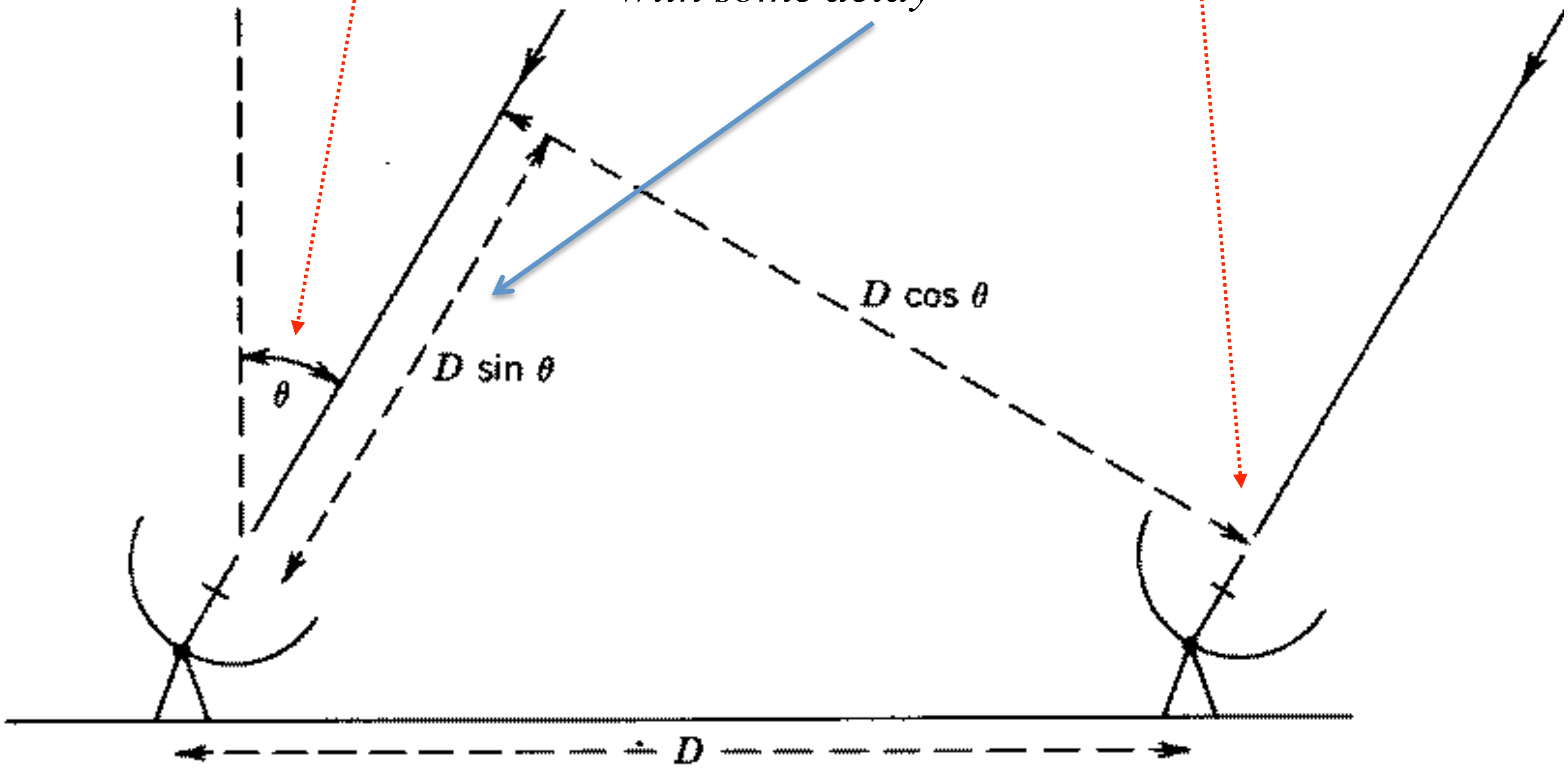


radio Interferometry:

the signals from two antennas _i and _ j are (cross)CORRELATED

$$V^i = V \sin\left(\omega t + \phi^i\right) + n^i\left(t\right)$$

$$V^j = V \sin\left(\omega t + \phi^j\right) + n^j\left(t\right)$$



wavefront gets in j

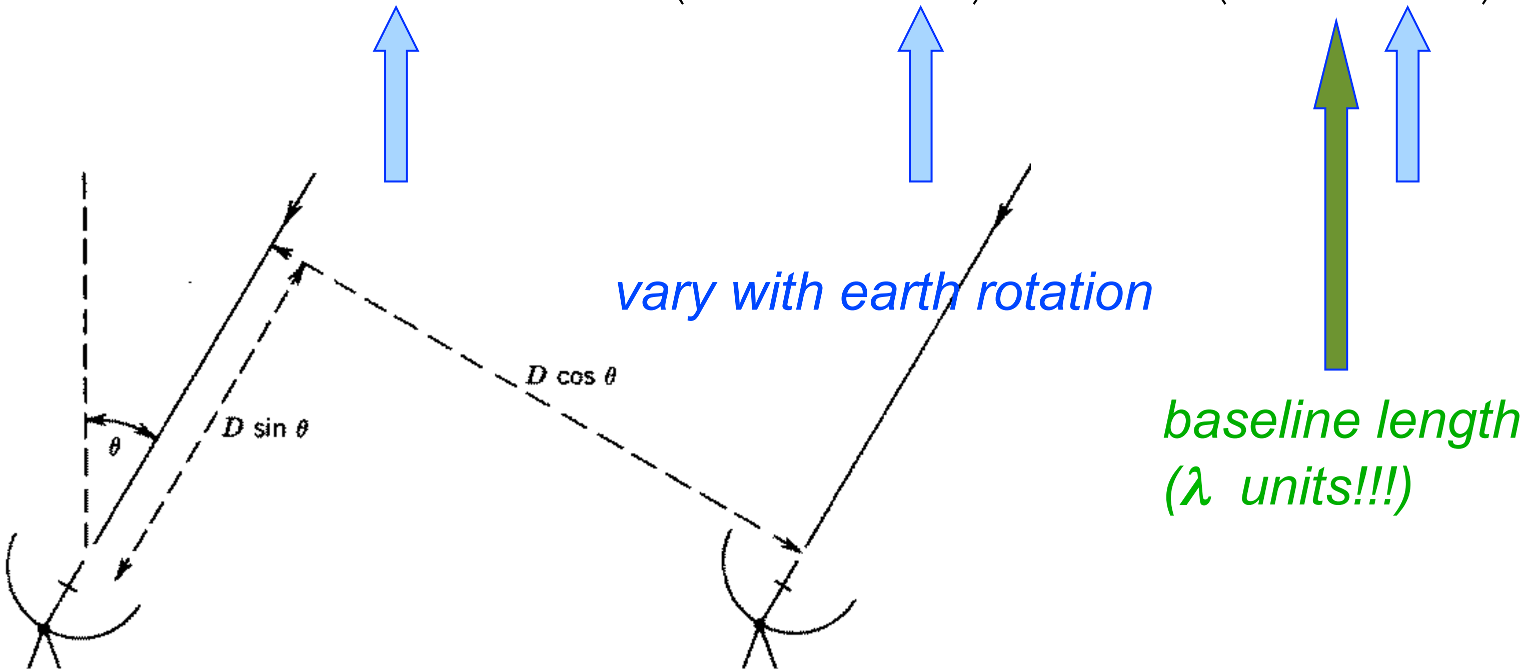
with some delay

The signal arrives at one of the antennas first and then, after τ_g , gets to the other. In case it gets into i first, then in j the signal is

$$\left(V^i V^j\right) = V^2 \quad \sin\left(\omega t + \phi^i\right) \quad \sin\left[\omega\left(t+\tau_g\right)+\phi^j\right]$$

after some (boring) algebra and approximations we obtain:

$$V^i V^j \approx V^2 \cos\left(\omega\tau_g\right) = V^2 \cos\left(2\pi\nu\frac{D}{c}\sin\theta\right) = V^2 \cos\left(2\pi\frac{D}{\lambda}\sin\theta\right)$$



vary with earth rotation

baseline length
(λ units!!!)

Indeed the CORRELATOR performs a more complicated operation (i.e. the true cross-correlation) to deliver VISIBILITIES:

$$V^{ij}\left(\tau_g\right) = \left(V^i V^j\right) = \lim_{T\to\infty} \int_{-T/2}^{T/2} V^i\left(t\right) V^{j*} \left(t+\tau_g\right) dt$$

In the (2-D) uv-plane each visibility samples the FT of the (2-D) $B(\theta,\phi)$

Modern correlators:
Are special computing devices
Handle and deliver a HUGE amount of data

Visibilities are:
Complex numbers (amplitude & phase), with ancillary information
Computed over the integration time = T

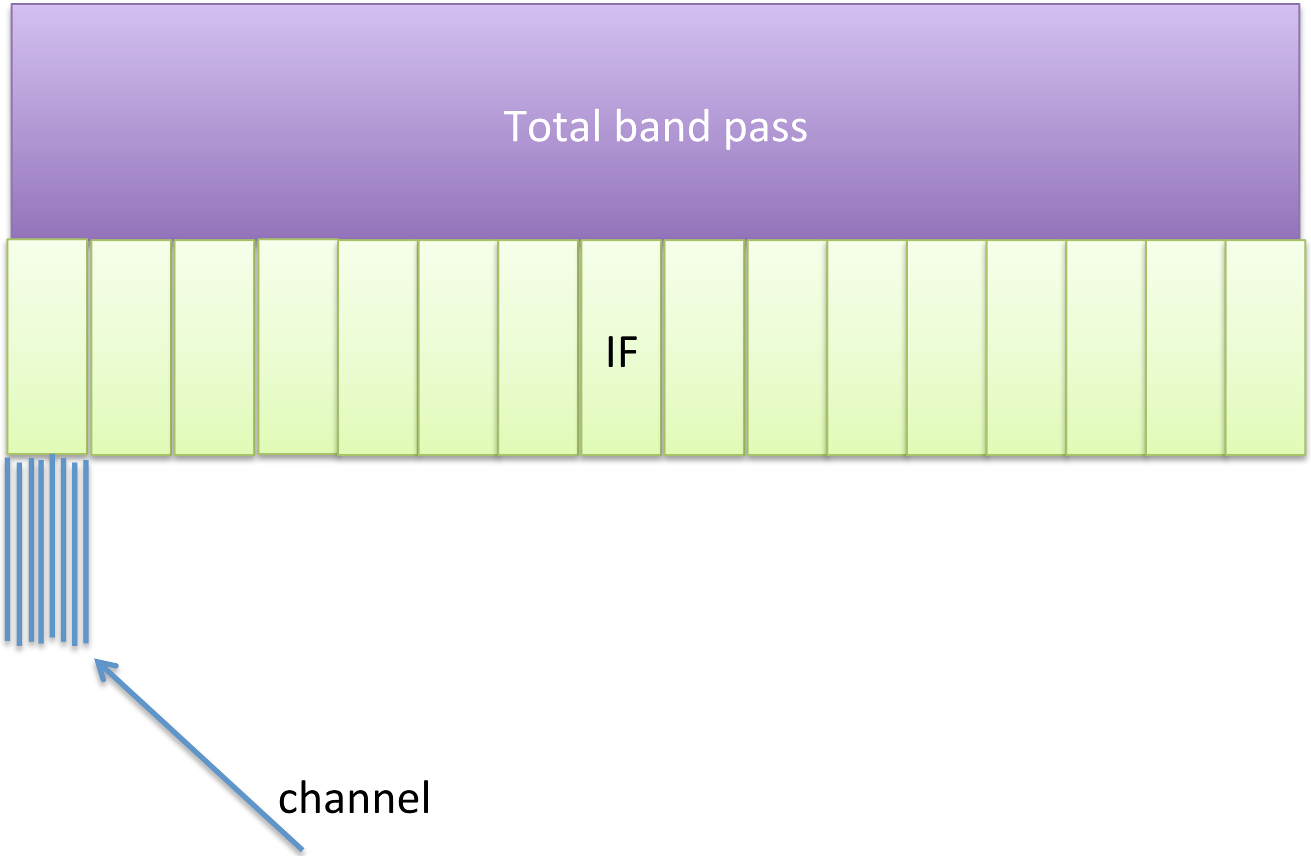
Q: What do we mean with the word ‘CORRELATOR’?

A: Lots of wires, boards, ~~fish’n~~ chips, …. power

http://www.almaobservatory.org/en/about-alma/how-does-alma-work

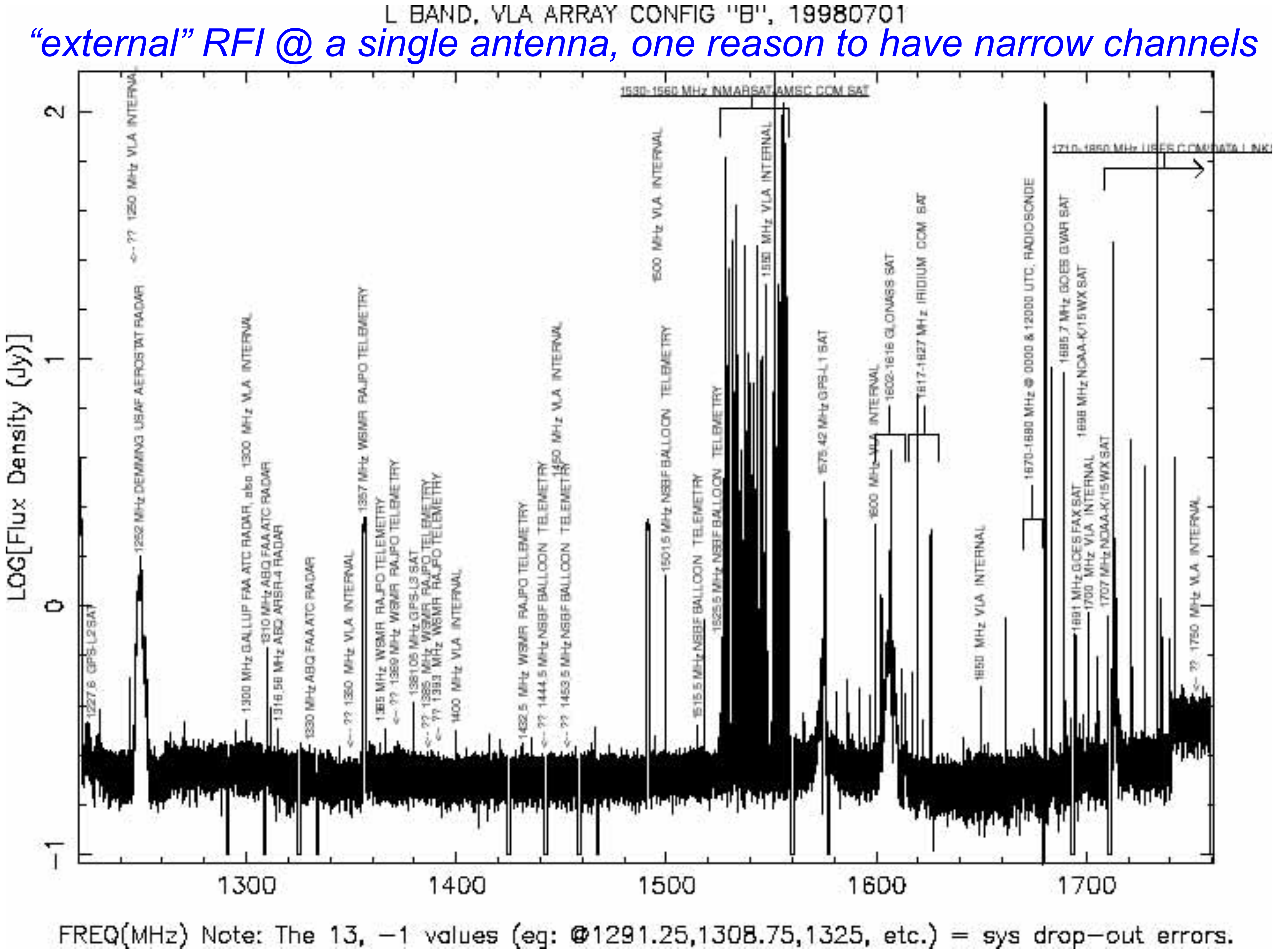
Provides an schematic idea of the correlator job

Basic structure of a dataset: (& some jargon)



The whole band is divided into **IF**s, which, in turn, are divided into **channel**s
The sampling is done for each hand (direction) of polarization (i.e. 2X)

“external” RFI @ a single antenna, one reason to have narrow channels



"Deep" radio images require sensitive continuum observations with:

Large bandwidths, often organized in sub-bands, in turn sliced into channels

Necessary to prevent (minimize) bandwidth smearing [radial]
*Allow an accurate **RFI** removal*

Long on-source times [(repeated) full tracks of the target(s)]
Short integration times prevent (minimize) time smearing [tangential]
Effective to remove time variable (intermittent) RFI

All this also allow to image wide fields [surveys!]
(large primary beams at low frequencies)
(a huge amount of significant pixels on the sky!)

Correlator throughput

Given an array made of N elements,

we have *N (N-1/2)* *baselines*

X 4 *either* *(**RR, LL, RL, LR** if full polarization mode – circular feeds)*

or *(**XX, YY, XY, YX** if full polarization mode – linear feeds)*

X sub-bands (IF) *(sensitivity requires large bandwidths, which are arranged into a number of sub-bands)*

X channels *(each sub-band is divided into a number of spectral channels, i.e. small widows in frequency, over which the data are averaged)*

X total observing time / integration time

Nowadays N is a few tens/hundreds/thousands, the number of sub-bands is a few tens, the number of channels can reach a few thousands, and the integration time is of the order of 1/a few sec. This makes A LOT of measurements!!!

*Each measurement/sample is a "**VISIBILITY**"*

(Nearly) Real interferometry(0)

Warnings:

The Visibility Function is not sampled in a uv-point, but it is rather averaged over an area (depending on integration time and bandwidth/frequency)
⇒ *this leads to image distortions known as smearing*

Old-type continuum datasets are nowadays out of date. Nonetheless still useful to understand how CALIBRATION works in practice

Modern datasets perform a sort of ***frequency synthesis****: the field of view may appear rather different across the observing bandwidth*

Many effects are (strongly) ***frequency dependent***
e.g. the ***FoV*** *is small / large at high / low frequencies*
and the data handling must take this into account

Each polarization – each channel - each IF need to be calibrated

More appropriate/specific presentations on this will be given by other lecturers!

Real interferometry(1)

*An interferometer samples the Visibility Function as **transmitted** by the **atmosphere** and the **instrumentation** (antenna, receiver, electronics, cables, correlator, etc.)*

$$V^{ij}_{obs} = V^{ij}_{true} G^{i} G^{j}$$

With a number of fair assumptions, CALIBRATION is the process to determine G^i aiming at transforming the observed quantities to the proper scale.

*All the quantities are **COMPLEX**, and therefore we need to find two values, **AMPLITUDE** and **PHASE**, for each antenna, polarization, sub-band, channel, ... possibly as a function of time*

Real interferometry (2) :

$$V^{ij}_{obs} = V^{ij}_{true} G^{i} G^{j}$$

The complex gain G can be generally split into two terms:

Amplitude a

Phase θ

and the new relationship can be written as:

$$A^{ij}_{obs} e^{i\theta^{ij}_{obs}} = A^{ij}_{true} a^{i} a^{j} e^{\left(i\theta^{ij}_{true} + \theta^{i} - \theta^{j}\right)}$$

Calibration means to find appropriate a and θ for the raw data, which are technically defined as "corrupted" (by various factors)

Therefore we have to fight this corruption by all means!!!

http://www.access-info.org/en/anti-corruption

http://www.aips.nrao.edu/install.shtml

http://casa.nrao.edu/casa_obtaining.shtml

http://www.astro.rug.nl/~gipsy

Real interferometric data:

$$V^{ij}_{obs} = V^{ij}_{true}\, G^{i} G^{j}$$

We need to know the true visibility in order to determine the complex gains

Simplest (ideal) case:

***Point-like** source of **known flux density** S, observed at the **centre of the field of view**, with nothing else around*

- ⇒ *ALL amplitudes are identical to S*
- ⇒ *ALL phases are 0 (zero)*
- ⇒ *Parallel hand polarization have to be considered*

warnings: the number of such ideal sources is ridiculously small (0)

sources (and FoV) are different as a function of

– frequency [high (10s GHz)/ low (a few 100s MHz)]

– interferometer (baseline length, also depends on frequency)

sources are often variable in both flux density and polarization

Let's try the simplest approach

*We can term the modification of the true signal into the observed measure as a **corruption** of the information carried out by the radiation.*

Basic assumption (1^{st} order)

*all the signal corruption can be determined and removed solving for an **element/antenna based correction***

Each element of the interferometer (both feeds on each antenna) will have a correction for

AMPLITUDE (t)
PHASE (t)

*to be applied (in combination) to ALL the measurements delivered by the correlator. **The product of corrections for each antenna will fix all the Visibilities on all baselines***

This operation MUST be done prior of Fourier inversion.

The complex gain G_i contains many components (along the signal path):

F = ionospheric Faraday rotation

T = tropospheric effects

P = parallactic angle (altaz-mounts)

E = antenna voltage pattern

D = polarisation leakage

J = electronic gain

B = bandpass response

K = geometric compensation

$$G^i = K^i B^i J^i D^i E^i P^i T^i F^i$$

*They are either **additive (phases)** or **multiplicative (amplitudes)**.*

*In most cases, **when performing calibration we can forget the origin of the contribution to be removed**. Some of them are specific (more relevant) to some observing modes/tools (VLBI, Spectral line, wide field) and of the observing frequency.*

Each term on the right has matrix form. The full matrix equation $\boldsymbol{G_i}$ is very complex,

Usually only need to consider the terms individually or in pairs, and rarely in open form

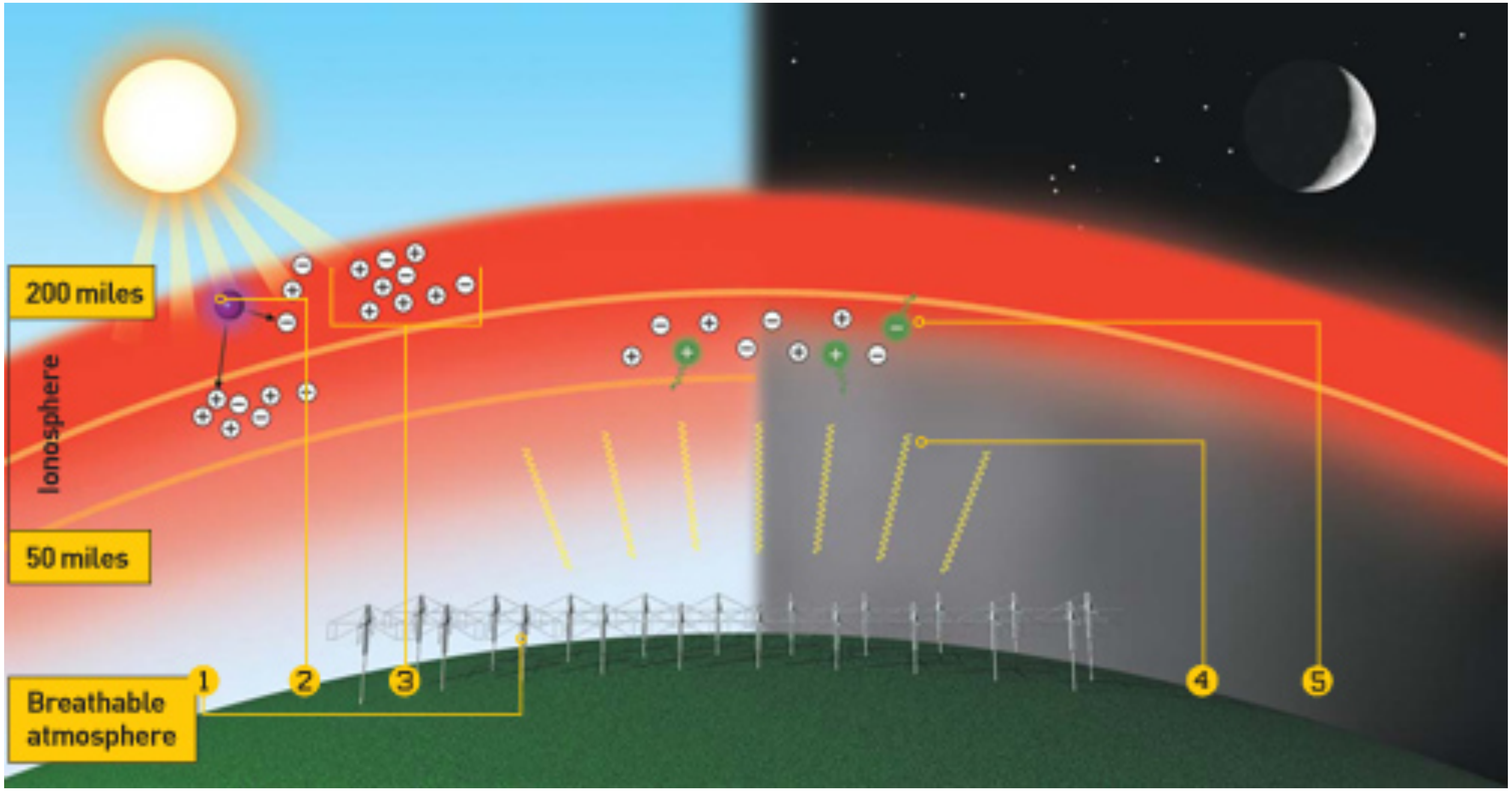
Existing software does the job (... more or less) but it is software....!

Ionospheric Refraction & Faraday Rotation F^{i}

ionosphere is inhomogeneous (t,θ), effects becoming more and more relevant as the observing frequency approaches the plasma frequency.

At low frequencies, in total intensity the effects are similar to the optical seeing (on longer timescale!)

Variable across the FoV



Ionospheric Faraday Rotation F^i

ionosphere is inhomogeneous:
- various directions have different refraction indices:
*It is **birefringent**:one hand of circular polarisation is delayed w.r.t. the other, introducing a phase shift:*

$$F^{RL} = e^{i\varepsilon} \begin{pmatrix} e^{i\Delta\Phi} & 0 \\ 0 & e^{-i\Delta\Phi} \end{pmatrix}; \quad F^{XY} = e^{i\varepsilon} \begin{pmatrix} \cos\Delta\Phi & -\sin\Delta\Phi \\ \sin\Delta\Phi & \cos\Delta\Phi \end{pmatrix}$$

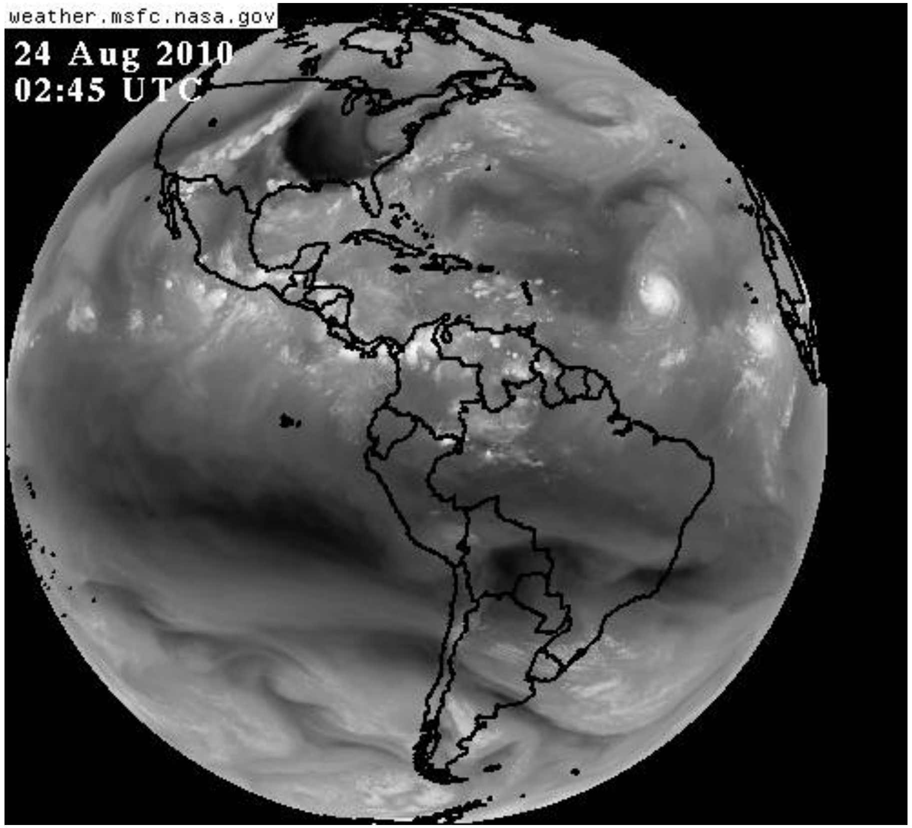
- *progressively relevant at long wavelengths (λ, λ^2) [@ 20cm $\Delta\phi$ could be tens of deg.)*
- *+ at solar maximum and at sunrise/sunset (high and variable TEC)*
- *Distant antennas have very different signal paths across the ionosphere (coherence length)*
- *Direction dependent within field-of-view*

$$\Delta\Phi \approx 812 \quad \lambda^2 \int B \,\text{�}\, n_e dl \quad rad \quad ; \quad \boxed{\varepsilon = n_e \lambda}$$

The Tropospheric contribution T^i

Troposphere causes poln-independent ***direction dependent*** *amplitude and **phase** variations due to emission/opacity and refraction*

$$T^{RL} = t \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$



- *+ relevant above ~15 GHz where water vapour (& oxygen, ...) absorbs/emits*
- *elevation dependent (path length across the troposphere) (gain curve!)*
- *Distant antennas are have very different signal paths across the troposphere*
- *May be critical on bad weather (Tsys and noise contribution, very short coherence time)*

The polarisation leakage D^i

Polarisers are not ideal (for circulars):
orthogonal polarisations are not perfectly isolated and mix
(similarly linear feeds are not perfect…..)

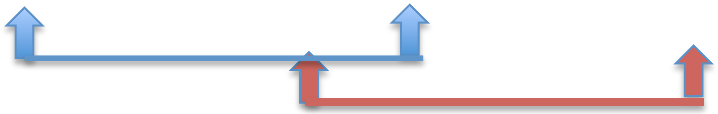
$$
\begin{aligned}
V_R^i &= V_R \sin(\omega t + \phi_R) + D_R V_L \sin(\omega t + \phi_L) \\
V_L^i &= V_L \sin(\omega t + \phi_L) + D_L V_R \sin(\omega t + \phi_R)
\end{aligned}
$$

- ***A geometric property of the feed design & frequency dependent***
- ***Rotates with the feed (telescope)*** *[Altaz .vs. Eq. mounts)*
- ***Vital for linear polarization imaging (RL & LR)*** *given that linear polarization in radio sources are generally small (a few percent or less….)*
- *Plays a role in very high dynamic range Stokes' I*
- *Good receivers may have D-terms of a few percent or less*

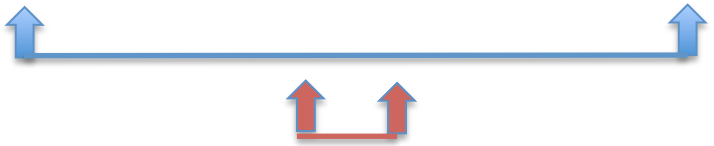
Is the polarisation leakage D^i important?

$$V_R^i = V_R \sin(\omega t + \phi_R) + D_R V_L \sin(\omega t + \phi_L)$$
$$V_L^i = V_L \sin(\omega t + \phi_L) + D_L V_R \sin(\omega t + \phi_R)$$

$$V_R^i V_R^j = (V_R^i + D_R^i V_L^i)(V_R^j + D_R^j V_L^j)$$



$$V_R^i V_L^j = (V_R^i + D_R^i V_L^i)(V_L^j + D_L^j V_R^j)$$



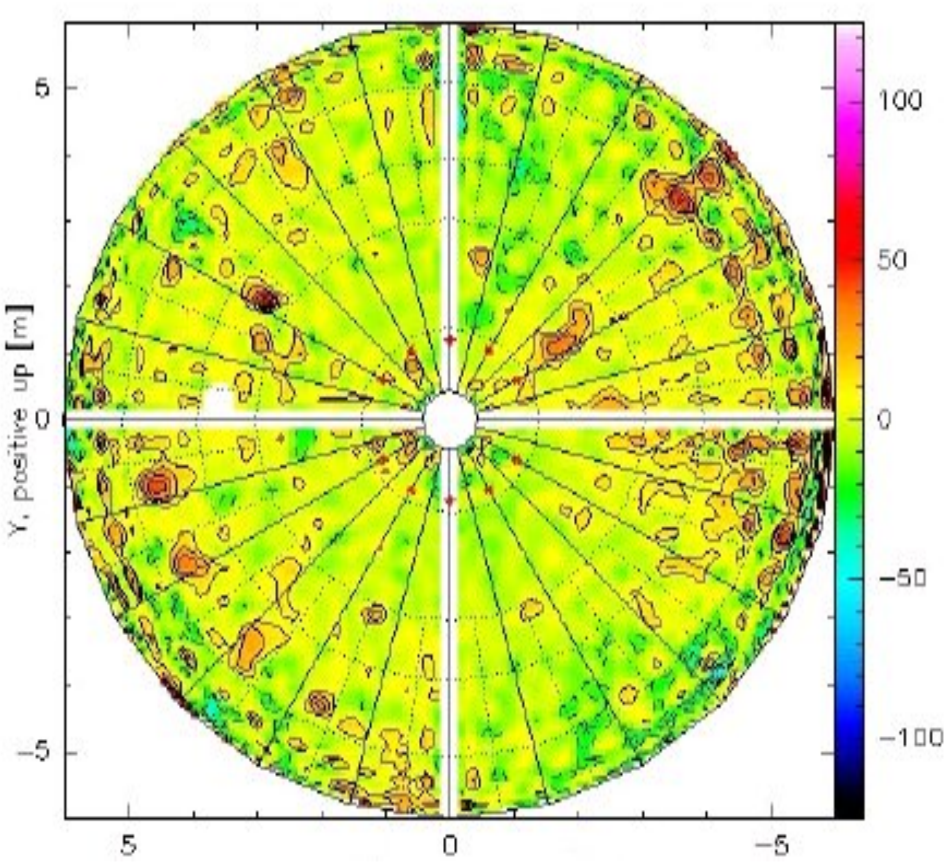
The Parallactic angle $\chi = P^i$

- *Alt – az antennas rotate during tracking (equatorial have a fixed orientation)*
- *Imply a rotation of the FoV and of the polarization response (intrinsic + leakage terms)*
- *use the feed rotation during the observation (i.e. change of the parallactic angle) to correct the instrumental polarization*

$$P^{RL} = \begin{pmatrix} e^{i\chi(t)} & 0 \\ 0 & e^{-i\chi(t)} \end{pmatrix} \; ; \quad P^{XY} = \begin{pmatrix} \cos\chi(t) & -\sin\chi(t) \\ \sin\chi(t) & \cos\chi(t) \end{pmatrix}$$

$$\chi(t) = atan\left(\frac{\cos(lat)\ \sin[HA(t)]}{\sin(lat)\cos(Dec) - \cos(lat)\sin(Dec)\cos[HA(t)]} \right)$$

The antenna voltage pattern E^i



- *Rotates with azimuth*
- *Related to elevation (gain curve)*
- *Individual antennas have direction dependent gains (non uniform illumination)*
- *Relevant when the full FoV (Primary Beam) is imaged (fields are wider and much more populated at low frequencies)*

The electronic antenna GAIN J^i

It accounts for most of amplitude and phase effects introduced by antenna electronics (amplifiers, mixers, digitizers, samplers, ...) and characteristics (collecting area, efficiency,....). ***It is the dominant term***

- *In practice in this term, many other effects (mentioned earlier) can be included*
- *No frequency dependence is deliberately considered (B^i)*
- *Can be considered the tribute to engineers: implies the need to convert to physical units.*

$$J^{RL} = \begin{pmatrix} j^R & 0 \\ 0 & j^L \end{pmatrix} \quad ; \quad J^{XY} = \begin{pmatrix} j^X & 0 \\ 0 & j^Y \end{pmatrix}$$

The bandpass response B^i

It represents the frequency-dependence of the performance of the whole system (mainly electronics)

- *It is dominated by the filter design and performance*
- *Disturbances introduced by spurious electronic behaviour (e.g. with temperature)*

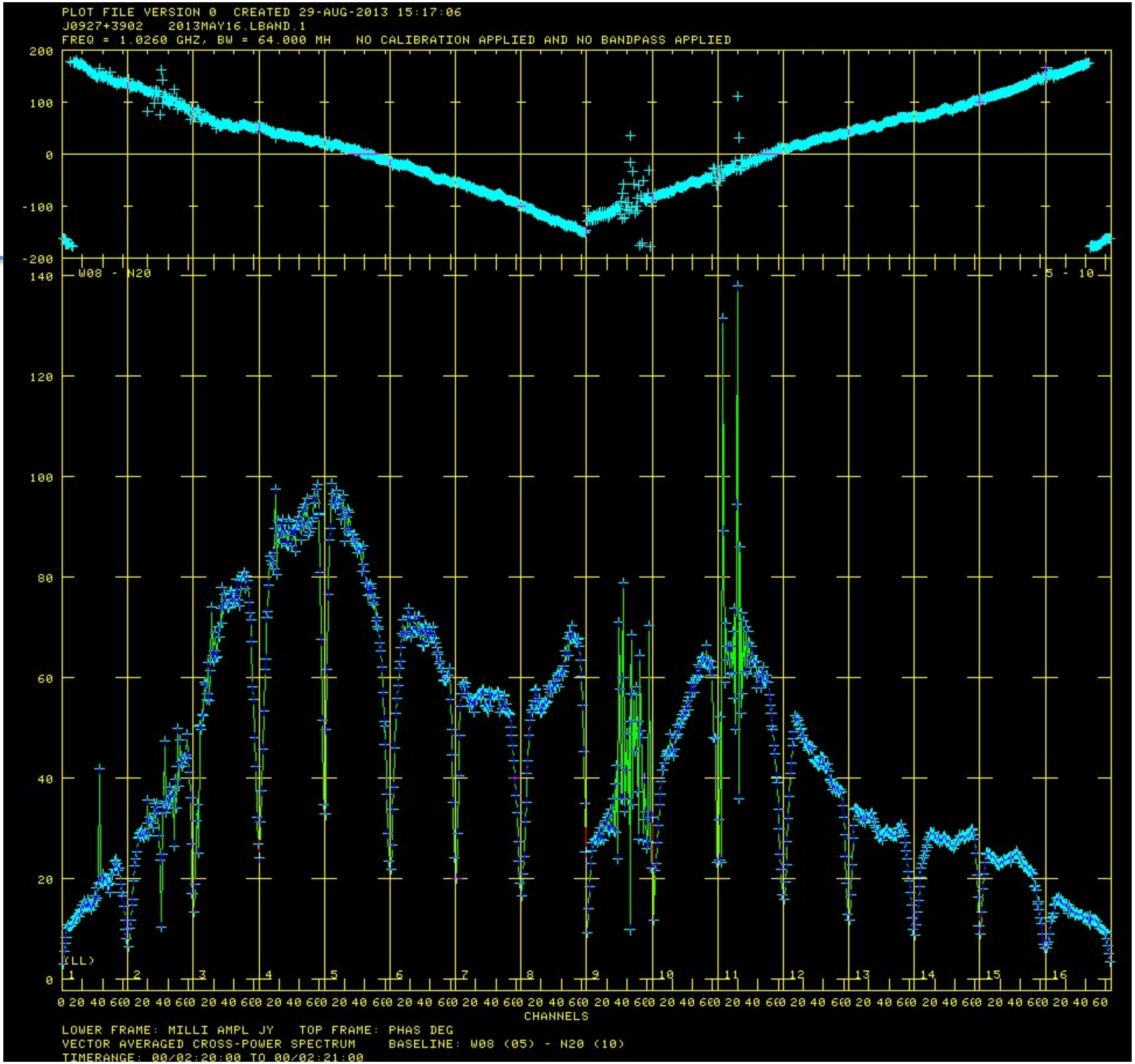
$$B^{RL} = \begin{pmatrix} b^R(\nu) & 0 \\ 0 & b^L(\nu) \end{pmatrix} \; ; \; B^{XY} = \begin{pmatrix} b^X(\nu) & 0 \\ 0 & b^Y(\nu) \end{pmatrix}$$

A strong (a good SNR per channel is necessary) calibrator, *possibly point-like*, ***observed by all the antennas***

Raw phases

Raw amplitudes

Frequency



```
PLOT FILE VERSION 0  CREATED 29-AUG-2013 15:17:06
J0927+3902   2013MAY16.LBAND.1
FREQ = 1.0260 GHZ, BW = 64.000 MH   NO CALIBRATION APPLIED AND NO BANDPASS APPLIED
```

```
LOWER FRAME: MILLI AMPL JY   TOP FRAME: PHAS DEG
VECTOR AVERAGED CROSS-POWER SPECTRUM   BASELINE: W08 (05) - N20 (10)
TIMERANGE: 00/02:20:00 TO 00/02:21:00
```

The geometric compensation K^i

The geometric model (antenna i, antenna j, source position) must be (ideally) perfect so that Synthesis Fourier Transform relation can work in real time; ***strong dependence on baseline length***

- *arises from uncertainties in antenna and source position (geodesy/astrometry)*
- *independent clocks and LO are a problem!*
- *specific of VLBI, gets worse with frequency*

$$K^{RL} = \begin{pmatrix} k^R & 0 \\ 0 & k^L \end{pmatrix} \quad ; \quad K^{XY} = \begin{pmatrix} k^X & 0 \\ 0 & k^Y \end{pmatrix}$$

Specific correlation and data handling techniques are necessary (Fringe Fitting) to recover residual errors. In general it is not relevant for "conventional interferometers" (EVLA, WSRT, GMRT, ATCA, MERLIN, ...)

End of principles of Calibration

From principles to real life

Hands on Real Calibration

Practical calibration: Prelude

Strong and point-like sources at the field centre have constant amplitudes w.r.t. baseline length and phase always 0.

- *Compare with correlated "raw" amplitudes and phases*
- *Derive "antenna based" solutions (for each polarisation, IF)*

Track phase and amplitude variations in time (on time scales shorter than the coherence time):

- *"Amplitude" & "Phase" variations should be smooth (within a few percent) with time*
- *Observe calibration sources every 10s of minutes at GHz frequencies (but beware of ionosphere!), or as short as every minute or less at high frequencies*

At the edges of the radio window (e.g. LOFAR, ALMA) the coherence time gets very short. Another calibration strategy may be necessary

VLBI is a different story…. *(different approach to get instrumental calbration)*

No point-like sources, other resources to measure antenna perfomance

Listen to Bob Campbell on thursday

Practical calibration: *standard continuum observation (1 channel)* ***Scene I***

Observe an unresolved and strong (isolated) source with known constant flux density (PRIMARY CALIBRATOR) [$S(\nu) = S_o F(\nu/\nu_o)$]

- *The number of such sources is* ***very very very*** *small. It is frequency dependent, and it is easier with interferometers with relatively short spacings.*
  Nowadays, source models allow calibration source resolved by the interferometer

- *Nearly impossible in VLBI*

- *At low frequencies the FoV is crowded! Other strong sources may contribute*

- *Nowadays source models are available, and allow also resolved calibrators*

- *They sample a LoS very far from that of the target, then inadequate for T and F*

They are intended to convert the "engineer" units to physical ones (Jy)

Practical calibration: Scene II

Observe an unresolved and strong source as close as possible to the target (SECONDARY CALIBRATOR) to take care of troposphere (and ionosph. FR)

- *The number of such sources quite comfortable. Still not they are not very well known at low and high frequencies*

- *Most of them are variable (blazars and FSRS), i.e. their flux density is unknown*

- *The closest to the target and the strongest ....the best is!*

- ***After the observation, have a look to the image of the calibrators!***

- ***By comparing the "average gain" solutions of the secondary C to that of the primary C, we measure the flux density of the secondary C***

Practical calibration: Scene III (scene stolen from Michiel Brentjens)

Observe an unresolved and strong source sampling a wide range of parallactic angles to determine instrumental polarization (POLARIZATION CALIBRATOR)

- *Geographic latitude of the interferometer and source declination deliver the parallactic angle coverage*

- *The R and L (X and Y) systems are dealt separately during the calibration implies a spurious rotation of the intrinsic polarization vector.*

- *A source with known polarization emission is necessary to determine the absolute orientation of the Electric polarization vector.*

MB will provide the audience with proper information!

Practical calibration: Scene IV (interlude)

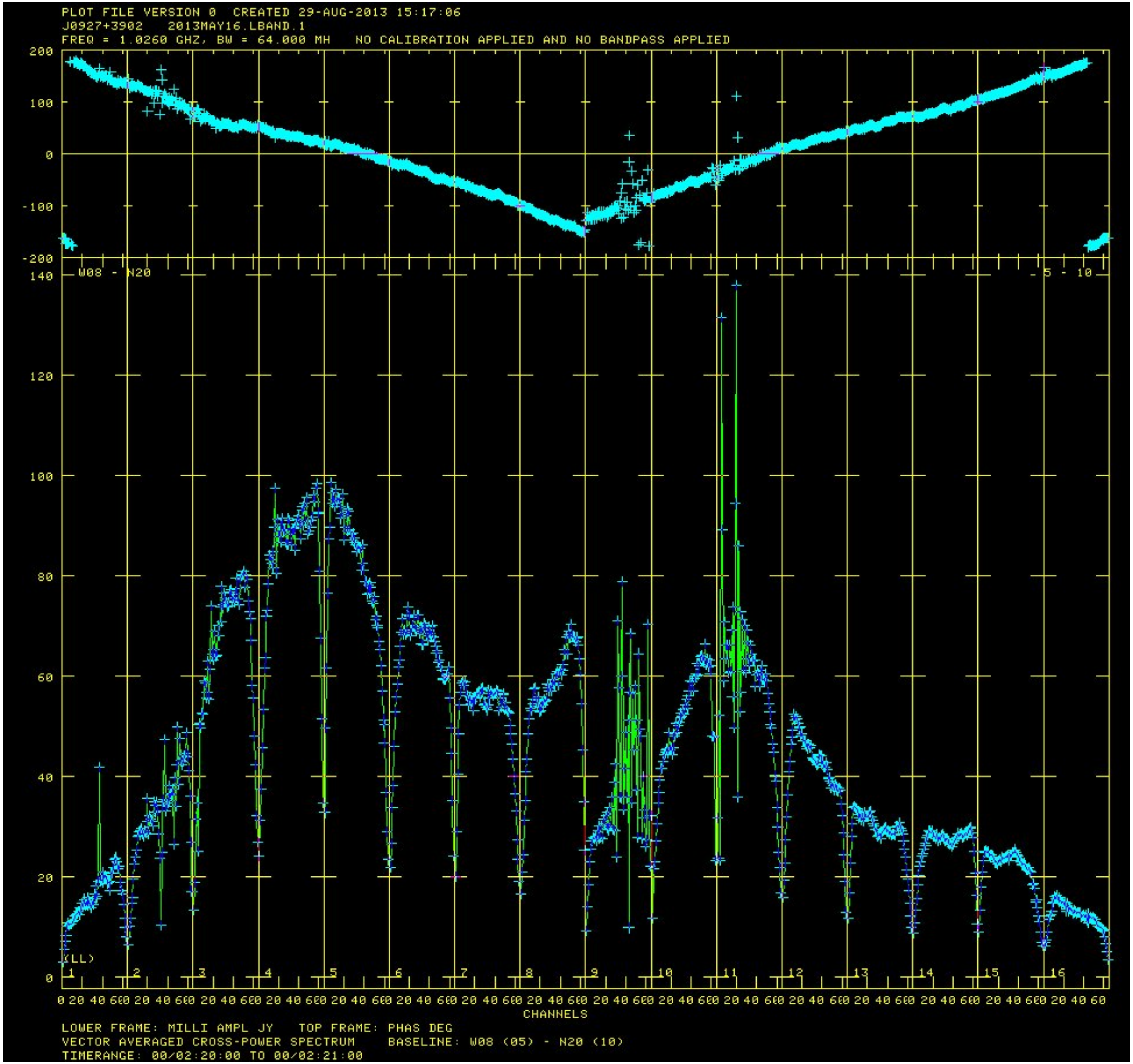
*In case of "spectral line" mode observations, do consider also a **calibrator for the band pass profile.***

It has to be point-like and strong (to have enough SNR over the single channels) and may need to be observed often enough to determine time variations

*The **bandpass profile is typical of each antenna/polarization**: it accounts for*

- *all filters along the signal path*
- *feed performance within its bandwidth*

Lecturers on spectral line interferometry will be more exhaustive.....


PLOT FILE VERSION 0 CREATED 29-AUG-2013 15:17:06
J0927+3902 2013MAY16.LBAND.1
FREQ = 1.0260 GHZ, BW = 64.000 MH NO CALIBRATION APPLIED AND NO BANDPASS APPLIED
200
100
0
-100
-200
140
W08 - N20
5 - 10
120
100
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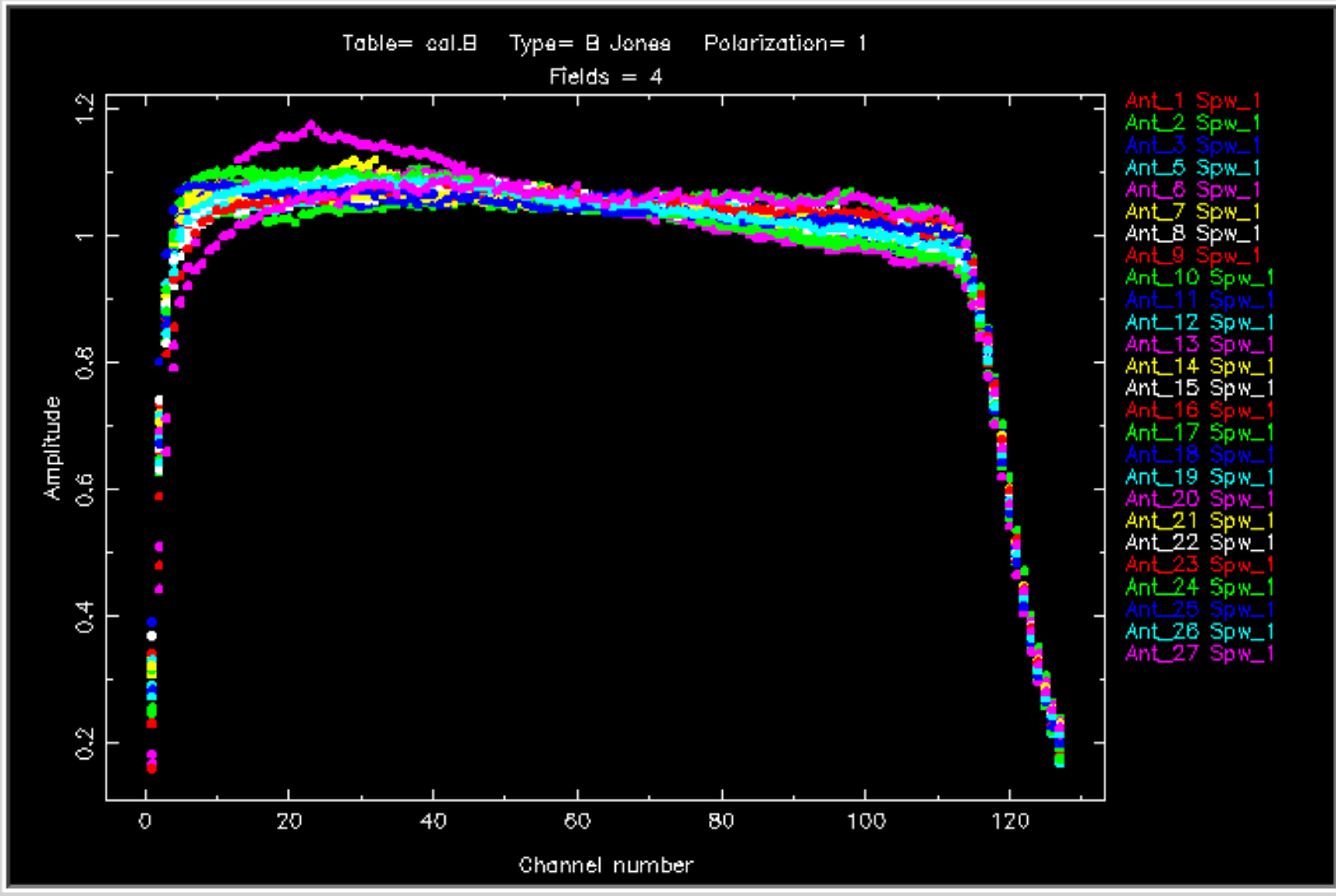
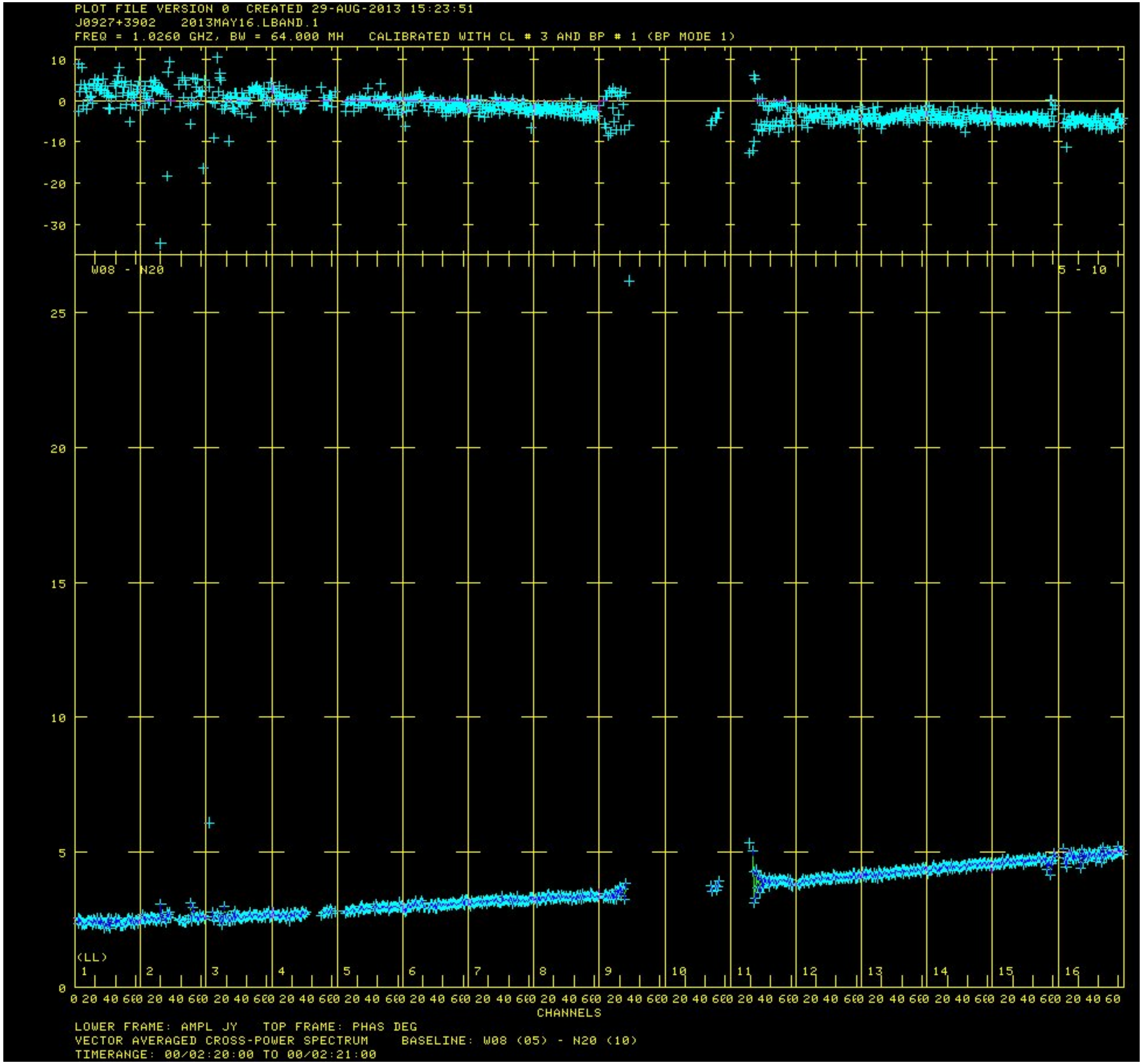
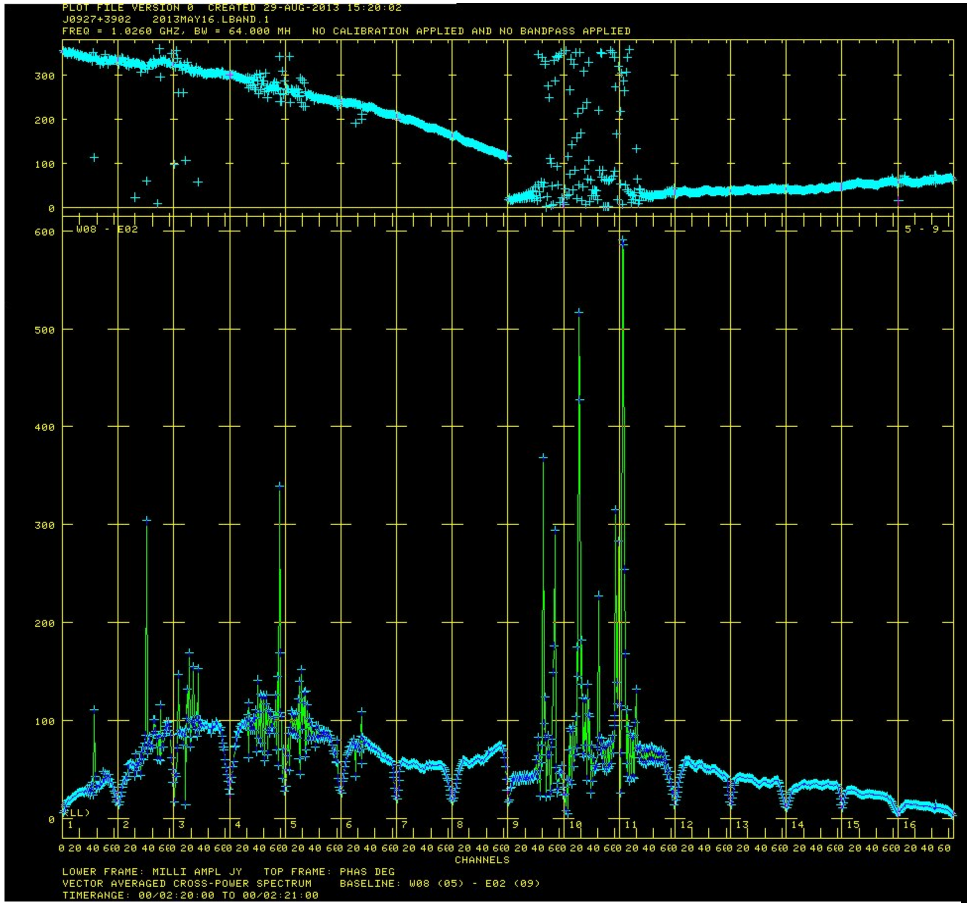
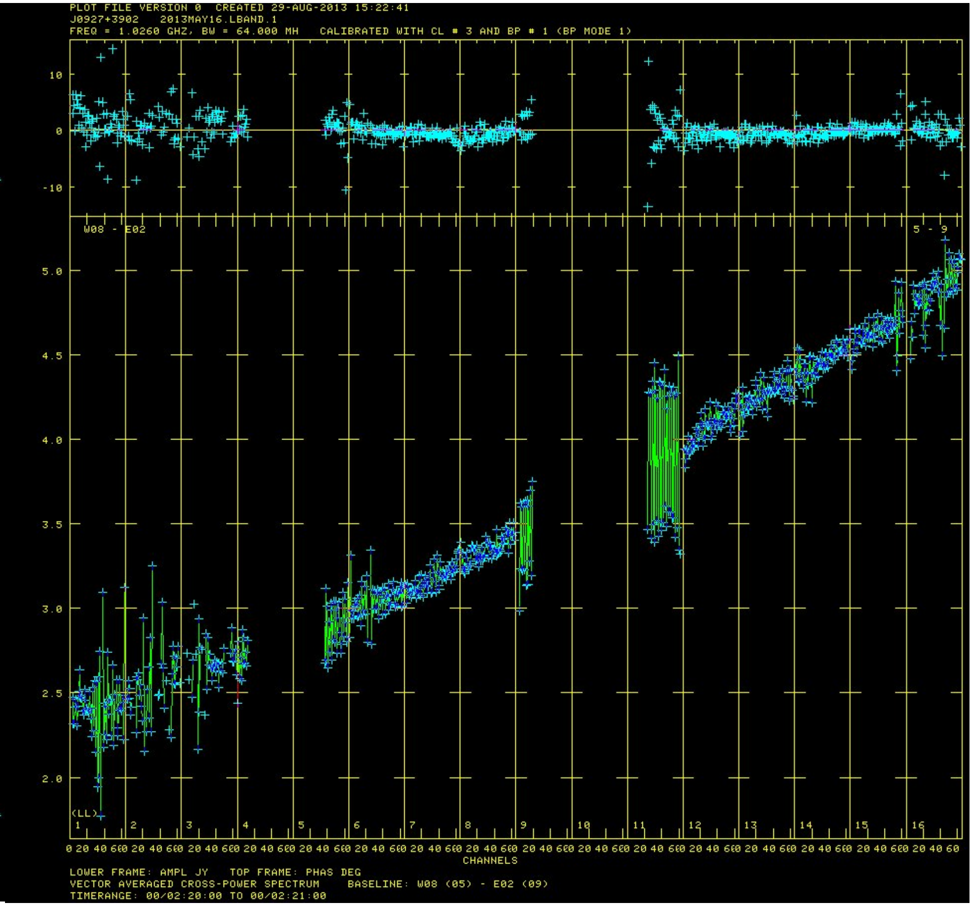
CHANNELS
LOWER FRAME: MILLI AMPL JY TOP FRAME: PHAS DEG
VECTOR AVERAGED CROSS-POWER SPECTRUM BASELINE: W08 (05) - N20 (10)
TIMERANGE: 00/02:20:00 TO 00/02:21:00

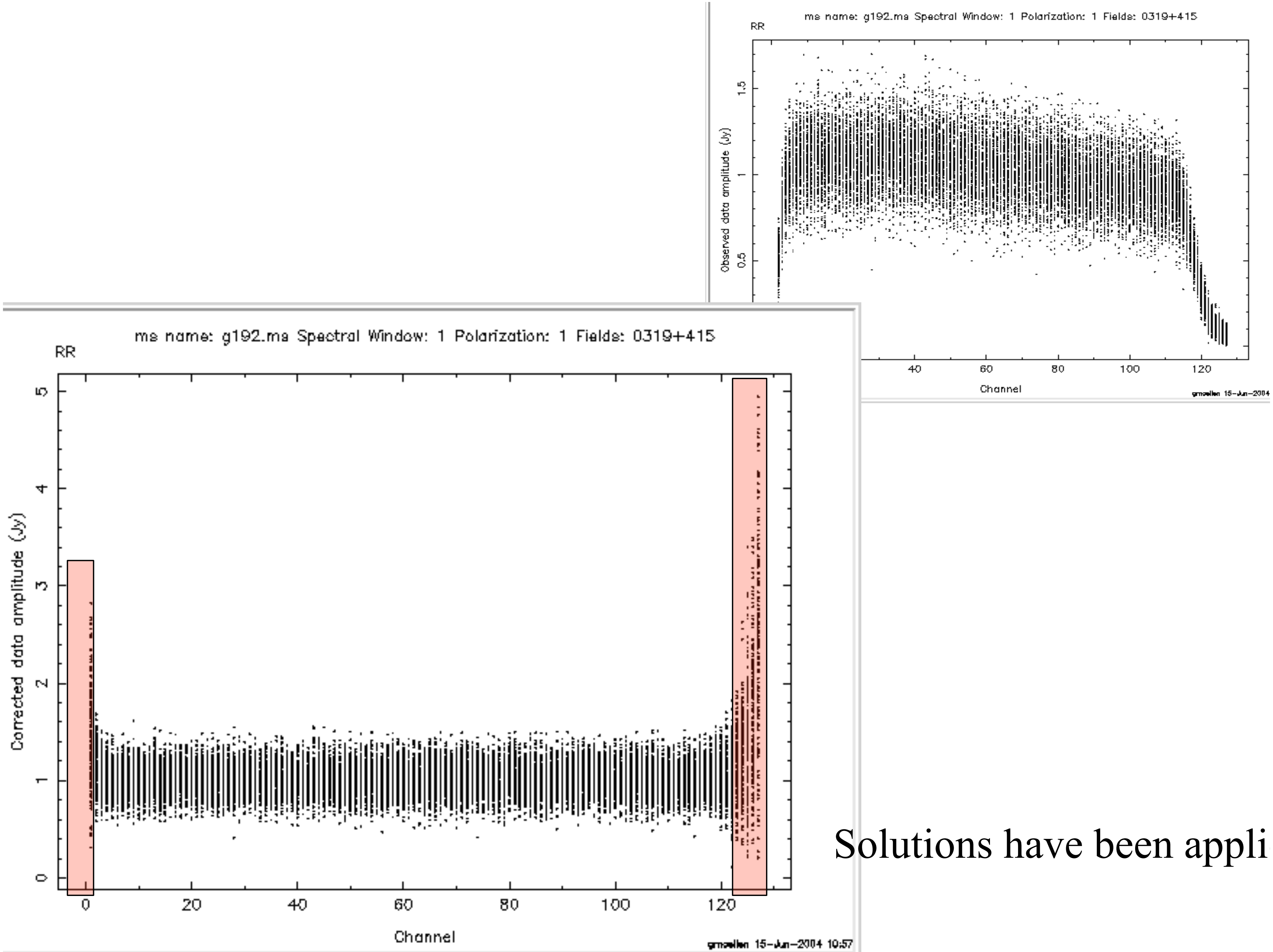
Normalised band bass profile: a solution for each CHANnel for each antenna




PLOT FILE VERSION 0 CREATED 29-AUG-2013 15:23:51
J0927+3902 2013MAY16.LBAND.1
FREQ = 1.0260 GHZ, BW = 64.000 MH CALIBRATED WITH CL # 3 AND BP # 1 (BP MODE 1)
10
0
-10
-20
-30
W08 - N20
5 - 10
25
20
15
10
5
0
(LL)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60
CHANNELS
LOWER FRAME: AMPL JY TOP FRAME: PHAS DEG
VECTOR AVERAGED CROSS-POWER SPECTRUM BASELINE: W08 (05) - N20 (10)
TIMERANGE: 00/02:20:00 TO 00/02:21:00


PLOT FILE VERSION 0 CREATED 29-AUG-2013 15:20:02
J0927+3902 2013MAY16.LBAND.1
FREQ = 1.0260 GHZ, BW = 64.000 MH NO CALIBRATION APPLIED AND NO BANDPASS APPLIED
300
200
100
0
W08 - E02
5 - 9
600
500
400
300
200
100
0
(LL)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60
CHANNELS
LOWER FRAME: MILLI AMPL JY TOP FRAME: PHAS DEG
VECTOR AVERAGED CROSS-POWER SPECTRUM BASELINE: W08 (05) - E02 (09)
TIMERANGE: 00/02:20:00 TO 00/02:21:00


PLOT FILE VERSION 0 CREATED 29-AUG-2013 15:22:41
J0927+3902 2013MAY16.LBAND.1
FREQ = 1.0260 GHZ, BW = 64.000 MH CALIBRATED WITH CL # 3 AND BP # 1 (BP MODE 1)
10
0
-10
W08 - E02
5 - 9
5.0
4.5
4.0
3.5
3.0
2.5
2.0
(LL)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60 0 20 40 60
CHANNELS
LOWER FRAME: AMPL JY TOP FRAME: PHAS DEG
VECTOR AVERAGED CROSS-POWER SPECTRUM BASELINE: W08 (05) - E02 (09)
TIMERANGE: 00/02:20:00 TO 00/02:21:00



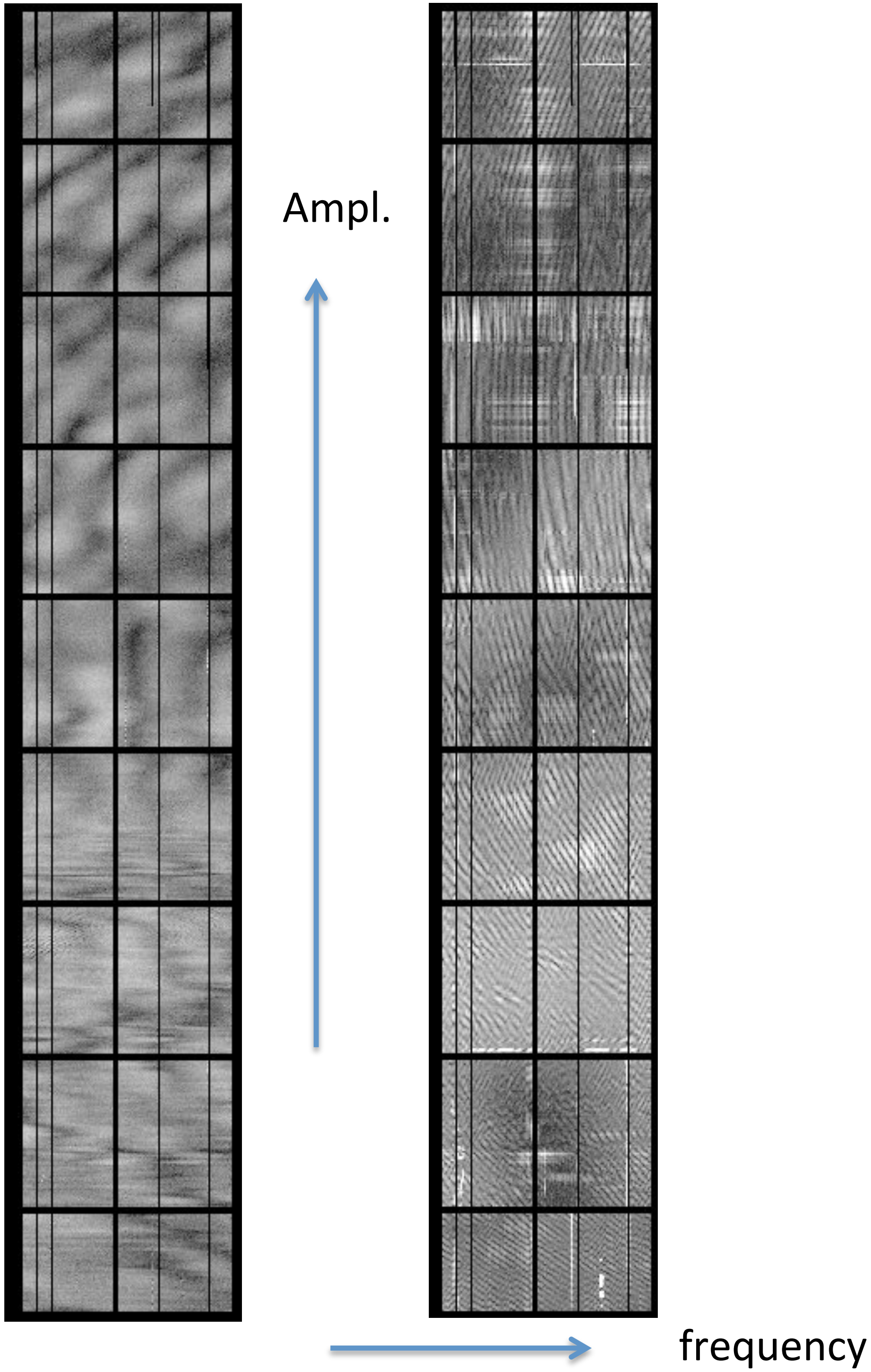
Solutions have been appli

Raw amplitudes:
Inspection of target data may help you as well

They are DIFFERENT wrt Calibrator data

Example: two baselines from a GMRT dataset at 330 MHz

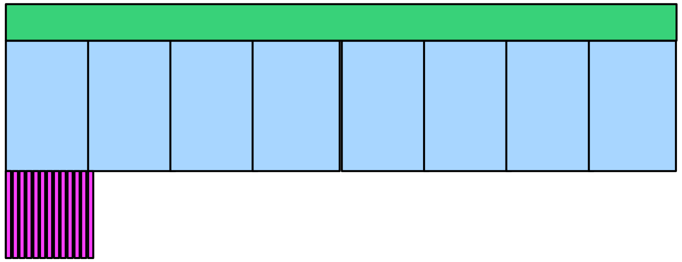
Short (left) and long (right) baselines



This slide has been deliberately repeated

Deep radio images implies sensitive continuum observations with:

Large bandwidths, often organized in sub-bands, in turn sliced into channels



Necessary to prevent (minimize) bandwidth smearing [radial]

Allow an accurate RFI removal

Long on-source times [(repeated) full tracks of the target(s)]

Short integration times prevent (minimize) time smearing [tangential]

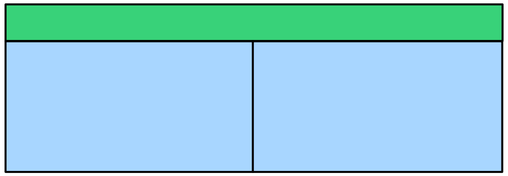
Effective to remove time variable (intermittent) RFI

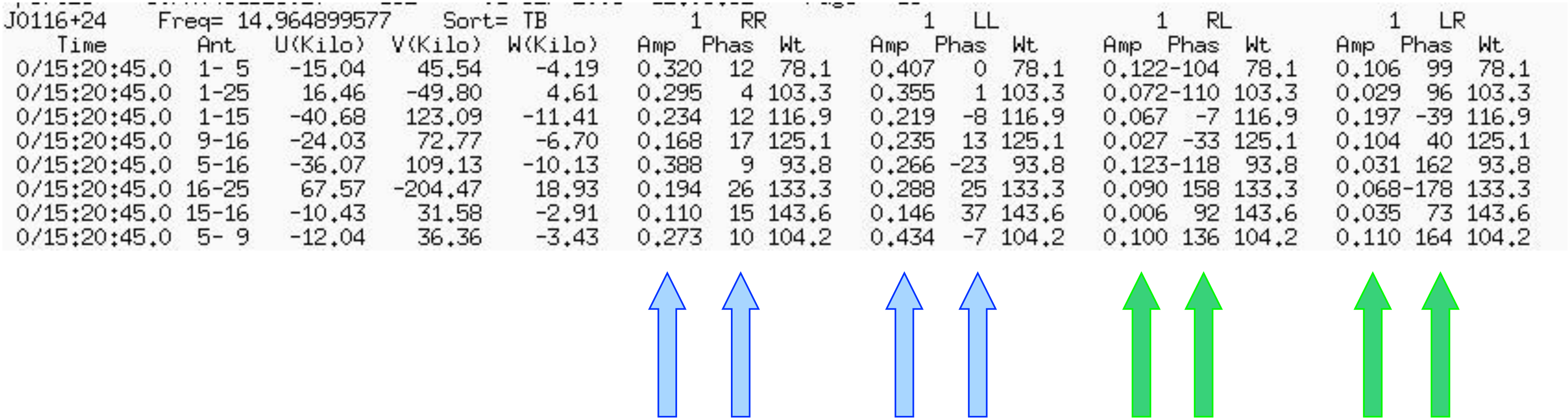
All this also allow to image wide fields [surveys!]

(large primary beams at low frequencies)

(a huge amount of significant pixels on the sky!)

Real interferometry:





```
J0116+24     Freq= 14.964899577     Sort= TB             1    RR                 1    LL                 1    RL                 1    LR
    Time          Ant   U(Kilo)  V(Kilo)  W(Kilo)   Amp  Phas   Wt       Amp  Phas   Wt       Amp  Phas   Wt       Amp  Phas   Wt
 0/15:20:45.0  1- 5  -15.04    45.54    -4.19   0.320   12   78.1   0.407    0   78.1   0.122-104   78.1   0.106   99   78.1
 0/15:20:45.0  1-25   16.46   -49.80     4.61   0.295    4  103.3   0.355    1  103.3   0.072-110  103.3   0.029   96  103.3
 0/15:20:45.0  1-15  -40.68   123.09   -11.41   0.234   12  116.9   0.219   -8  116.9   0.067   -7  116.9   0.197  -39  116.9
 0/15:20:45.0  9-16  -24.03    72.77    -6.70   0.168   17  125.1   0.235   13  125.1   0.027  -33  125.1   0.104   40  125.1
 0/15:20:45.0  5-16  -36.07   109.13   -10.13   0.388    9   93.8   0.266  -23   93.8   0.123-118   93.8   0.031  162   93.8
 0/15:20:45.0 16-25   67.57  -204.47    18.93   0.194   26  133.3   0.288   25  133.3   0.090  158  133.3   0.068-178  133.3
 0/15:20:45.0 15-16  -10.43    31.58    -2.91   0.110   15  143.6   0.146   37  143.6   0.006   92  143.6   0.035   73  143.6
 0/15:20:45.0  5- 9  -12.04    36.36    -3.43   0.273   10  104.2   0.434   -7  104.2   0.100  136  104.2   0.110  164  104.2
```

First of all have a look to the raw data.
Take your time at this stage. It may save a lot of time aftwerwards.

There are a number of tools to inspect the data. This is very relevant for calibration sources, and bring information valuable for target sources as well.

Inspections and editing of raw amplitudes on calibrators:

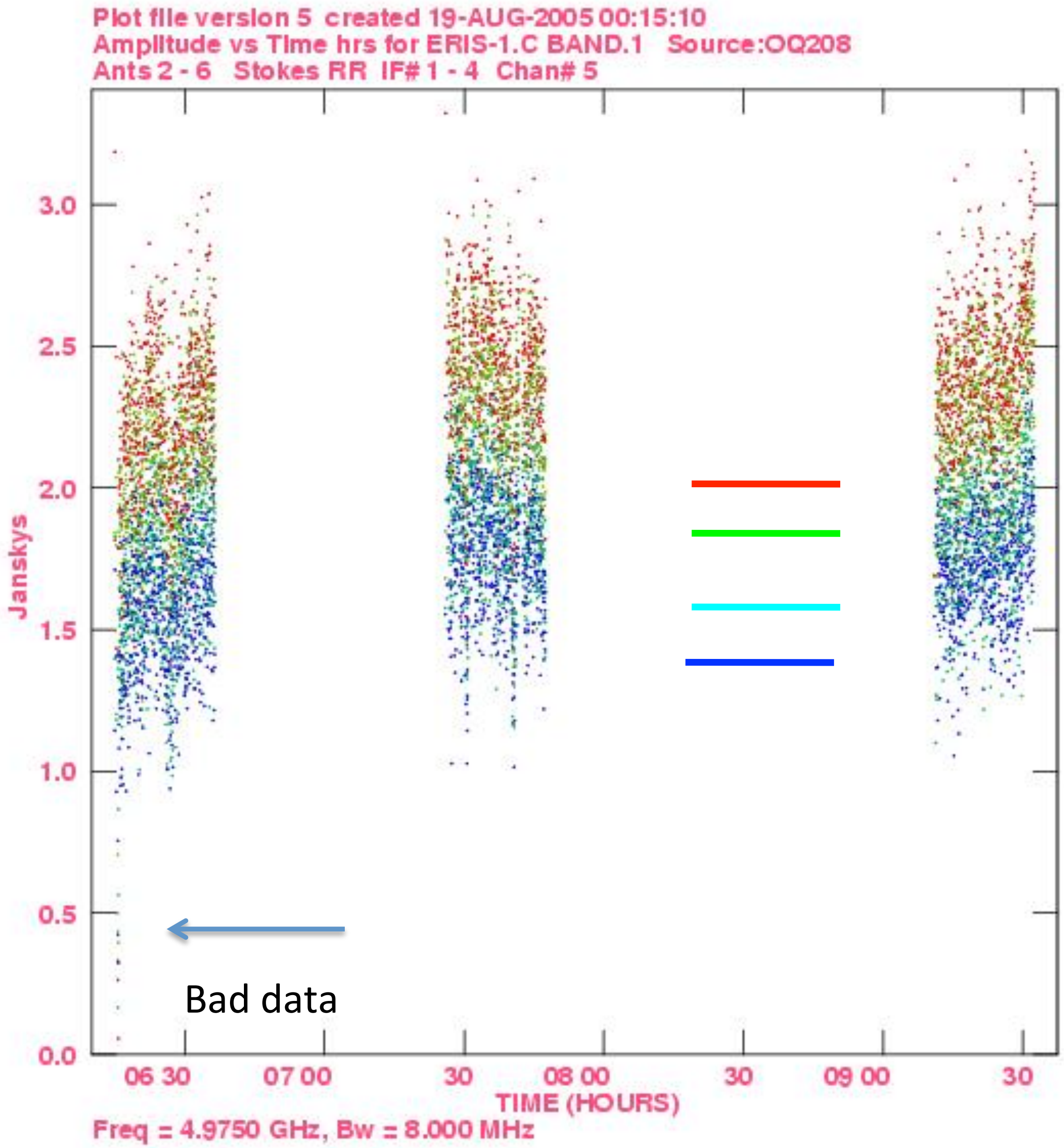
various tools: some are "automated", i.e.
- *no visual inspection, little brain usage*
- *incompatible with the "principal investigator" role*

may be useful to take care of the 0th order bad data

*Your brain, eyes and hands are very important (**it means you!**).*

A careful look to the calibration sources allow to learn a lot on what is the system performance on target data!

- *Channels/times with RFI*
- *Bad antennas*
- *Behaviour at start/stop scan times*



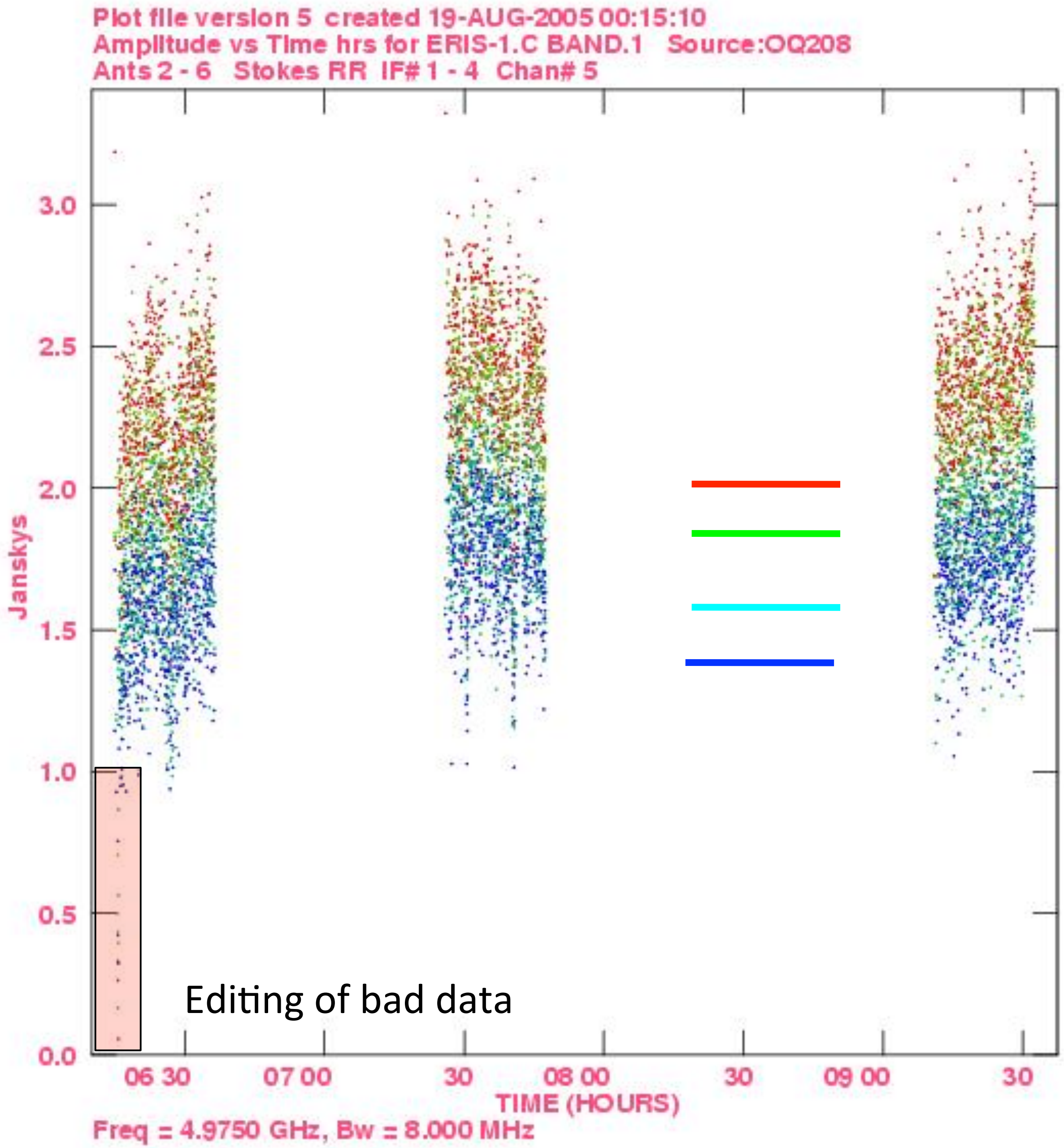
Bad data

RR amplitudes vs time

Example: a 2.4 Jy source

(pointlike on this baseline MC-JB)

Each IF is plotted with
a different colour (4)



Editing of bad data

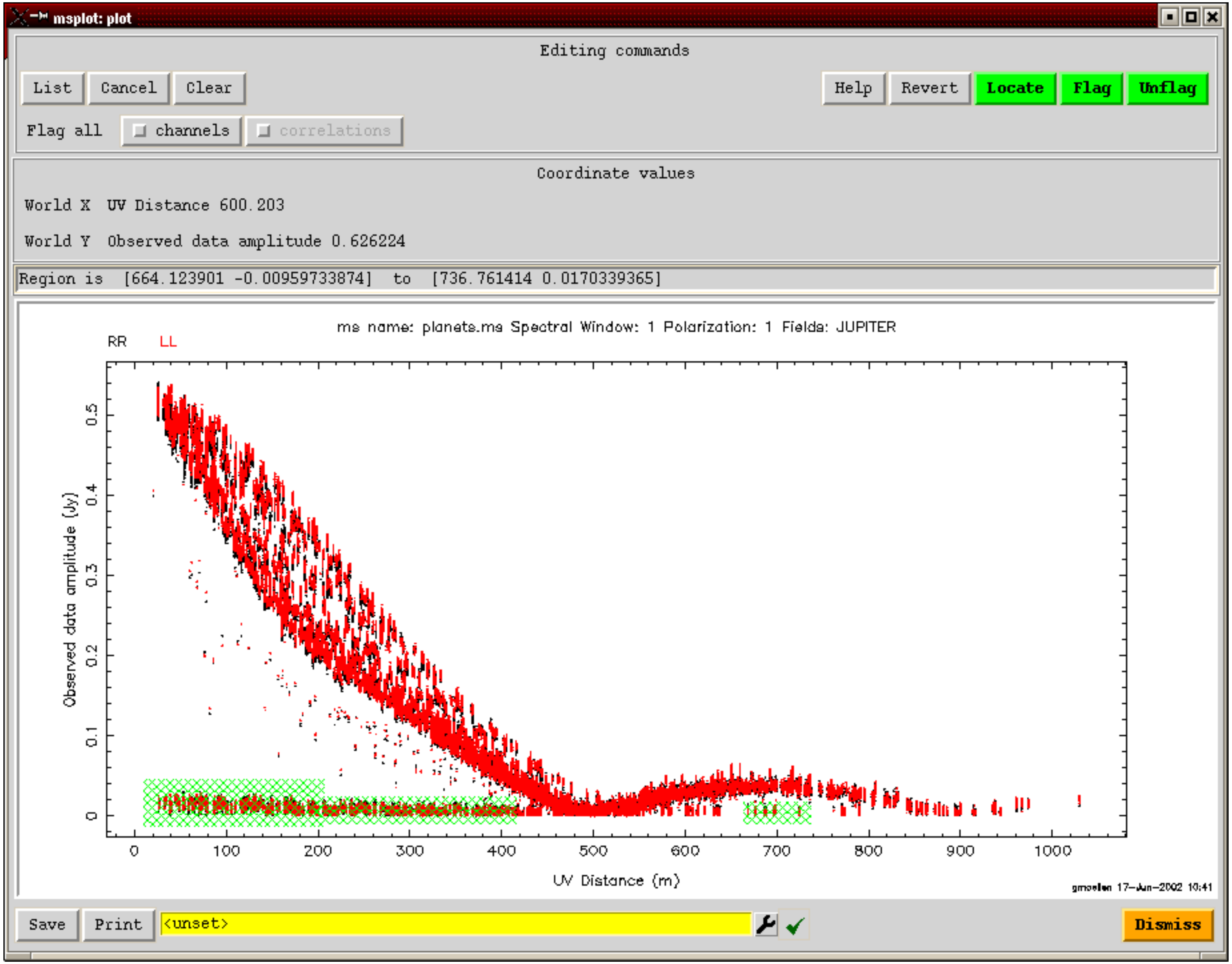
RR amplitudes vs time

Example: a 2.4 Jy source

(pointlike on this baseline MC-JB)

Each IF is plotted with
a different colour (4)

More examples of outliers: amplitude vs baselenlength.....



World X UV Distance 600.203

World Y Observed data amplitude 0.626224

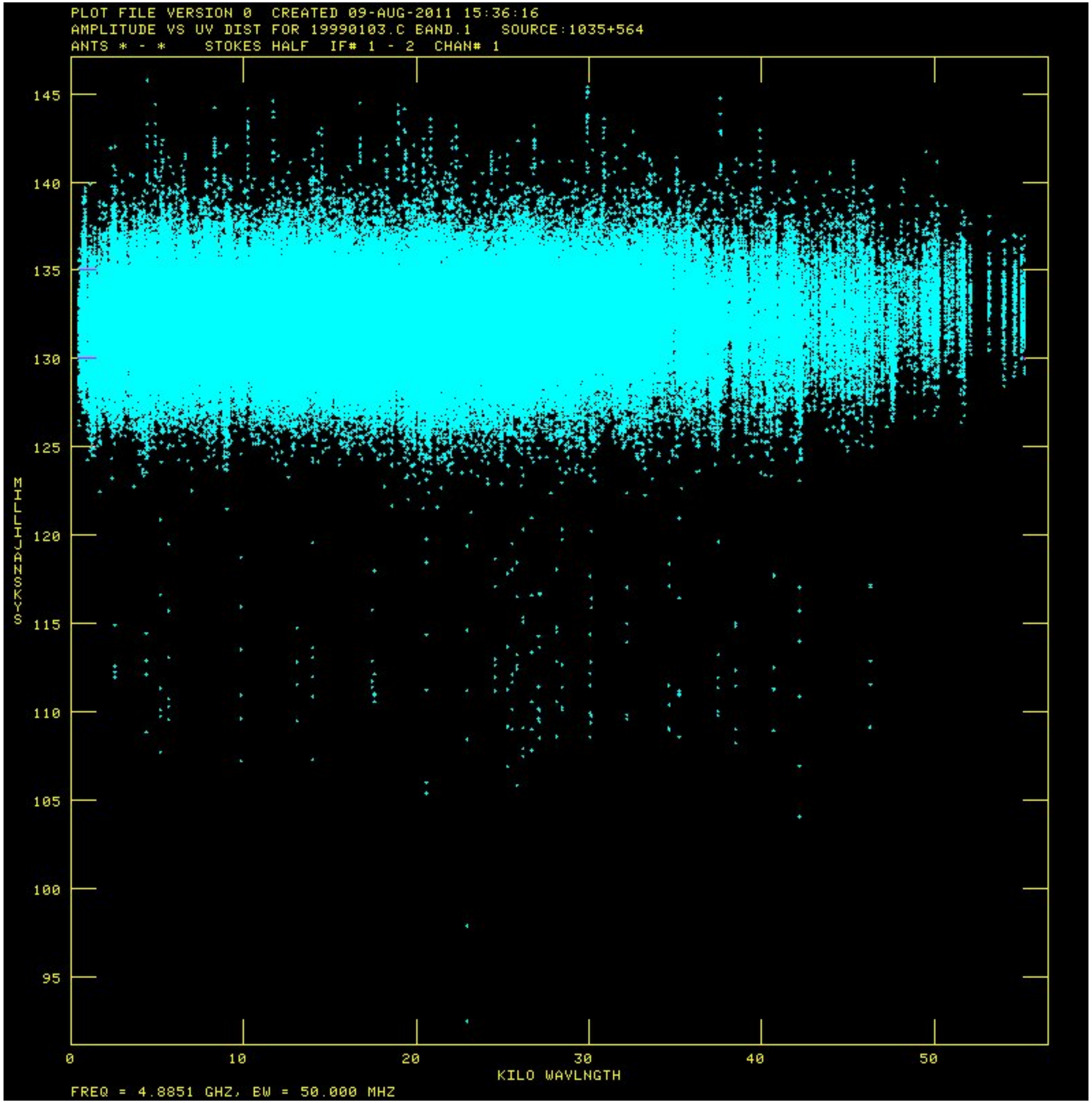
Region is [664.123901 -0.00959733874] to [736.761414 0.0170339365]

<unset>

Tutorial 1 (T1)
Secondary calibrator

RR, LL ; IF1 & IF2
Displayed

Raw Amplitudes
vs
Baselinelength

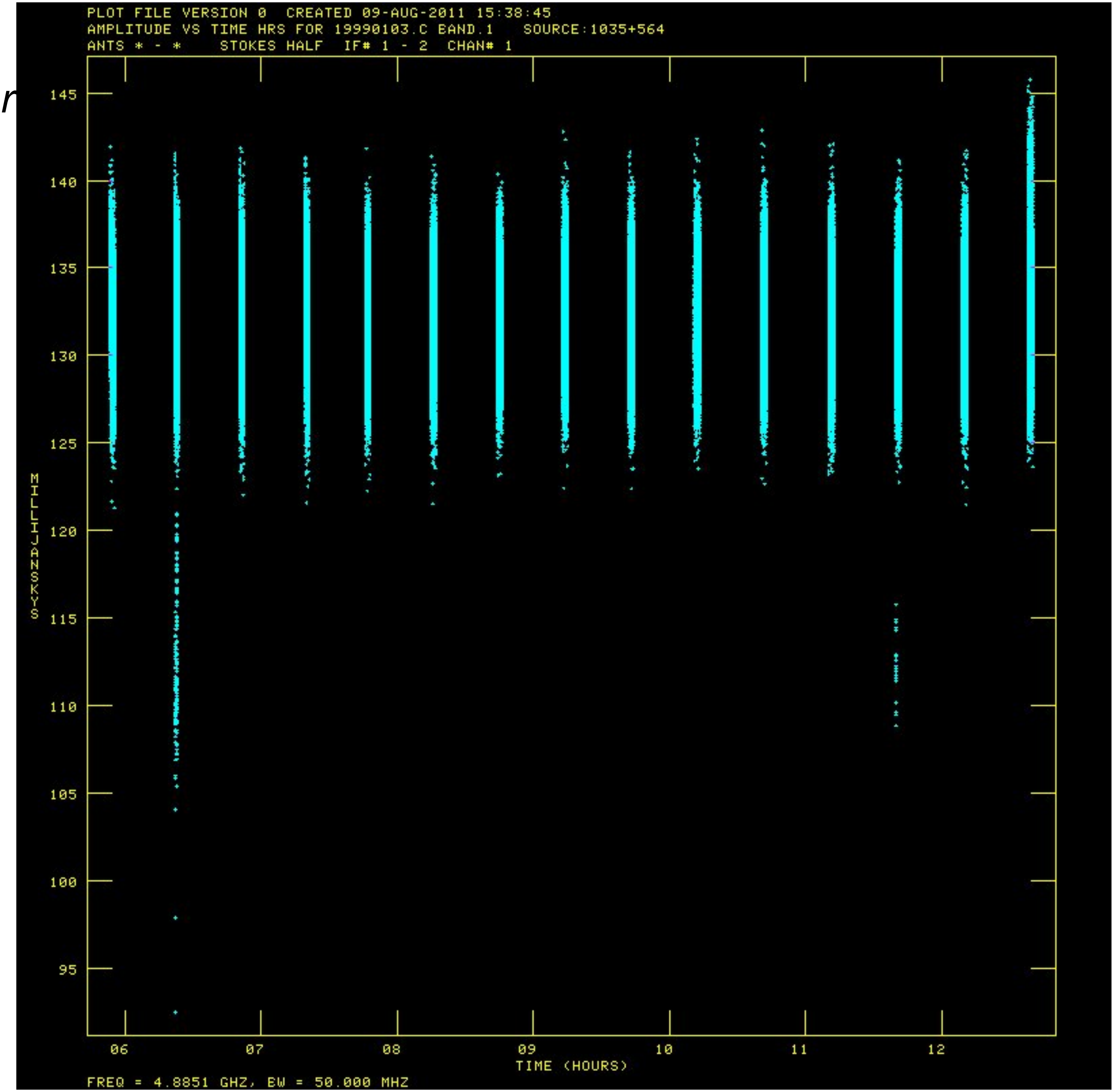


Tutorial 1 (T1)

Secondary calibrator

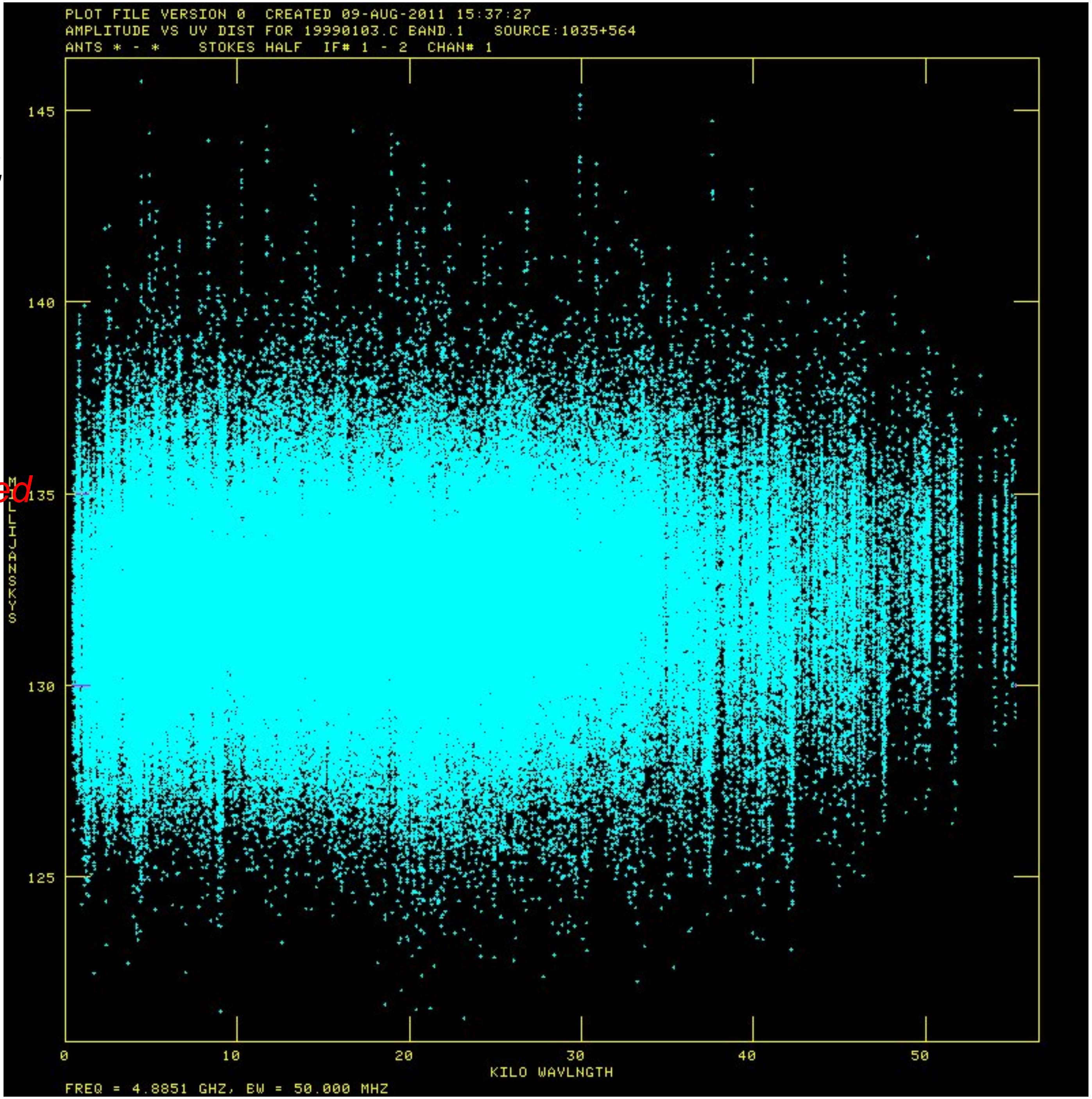
RR, LL ; IF1 & IF2
Displayed

Raw Amplitudes
vs
Time

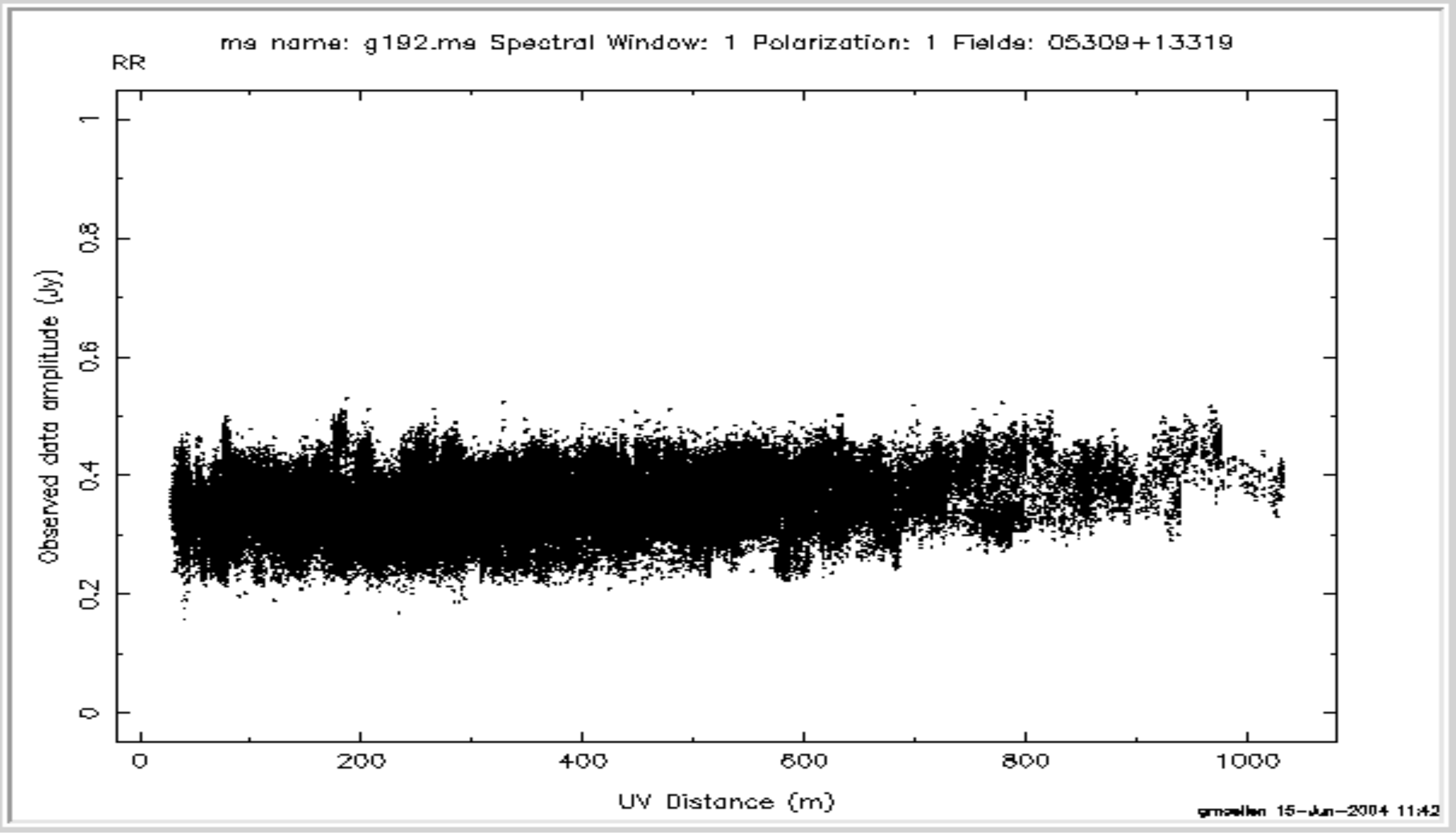


Tutorial 1 (T1)
Secondary calibrator,
raw amplitudes:
RR, LL ; IF1 & IF2
displayed

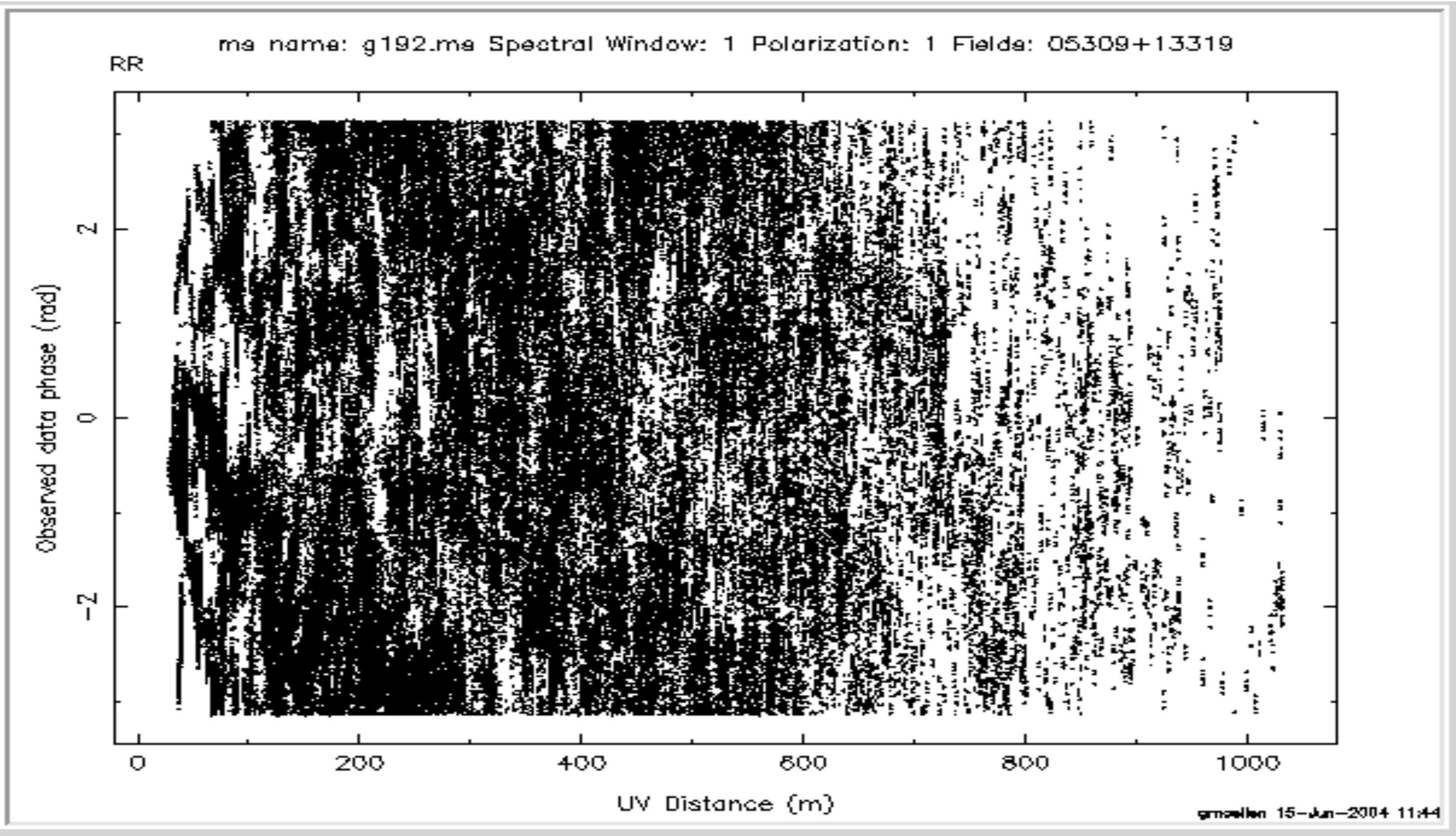
Once all the calibration sources are OK, proceed to the next step



Accurate inspection of the raw data: ***raw amplitudes .vs. baseline length***



Accurate inspection of the raw data: ***raw phases .vs. baseline length***



Fundamentals of interferometry:

Closure phase (3 baselines):

$$\varphi_{ij}^{obs} + \varphi_{jk}^{obs} + \varphi_{ki}^{obs} = \left(\varphi_{ij}^{true} + \theta_i - \theta_j\right) + \left(\varphi_{jk}^{true} + \theta_j - \theta_k\right) + \left(\varphi_{ki}^{true} + \theta_k - \theta_i\right)$$

Closure amplitude (4 baselines):

$$\left|\frac{V_{ij}^{obs} V_{kl}^{obs}}{V_{ik}^{obs} V_{jl}^{obs}}\right| = \left|\frac{J_i J_j V_{ij}^{true} J_k J_l V_{kl}^{true}}{J_i J_k V_{ik}^{true} J_j J_l V_{jl}^{true}}\right| = \left|\frac{V_{ij}^{true} V_{kl}^{true}}{V_{ik}^{true} V_{jl}^{true}}\right|$$

Aim of calibration:

FIND appropriate $\boldsymbol{\theta_i}$ *and* $\mathbf{J_i}$ *(solutions to be written in a SN table)*

The calibration information is organized in form of tables.

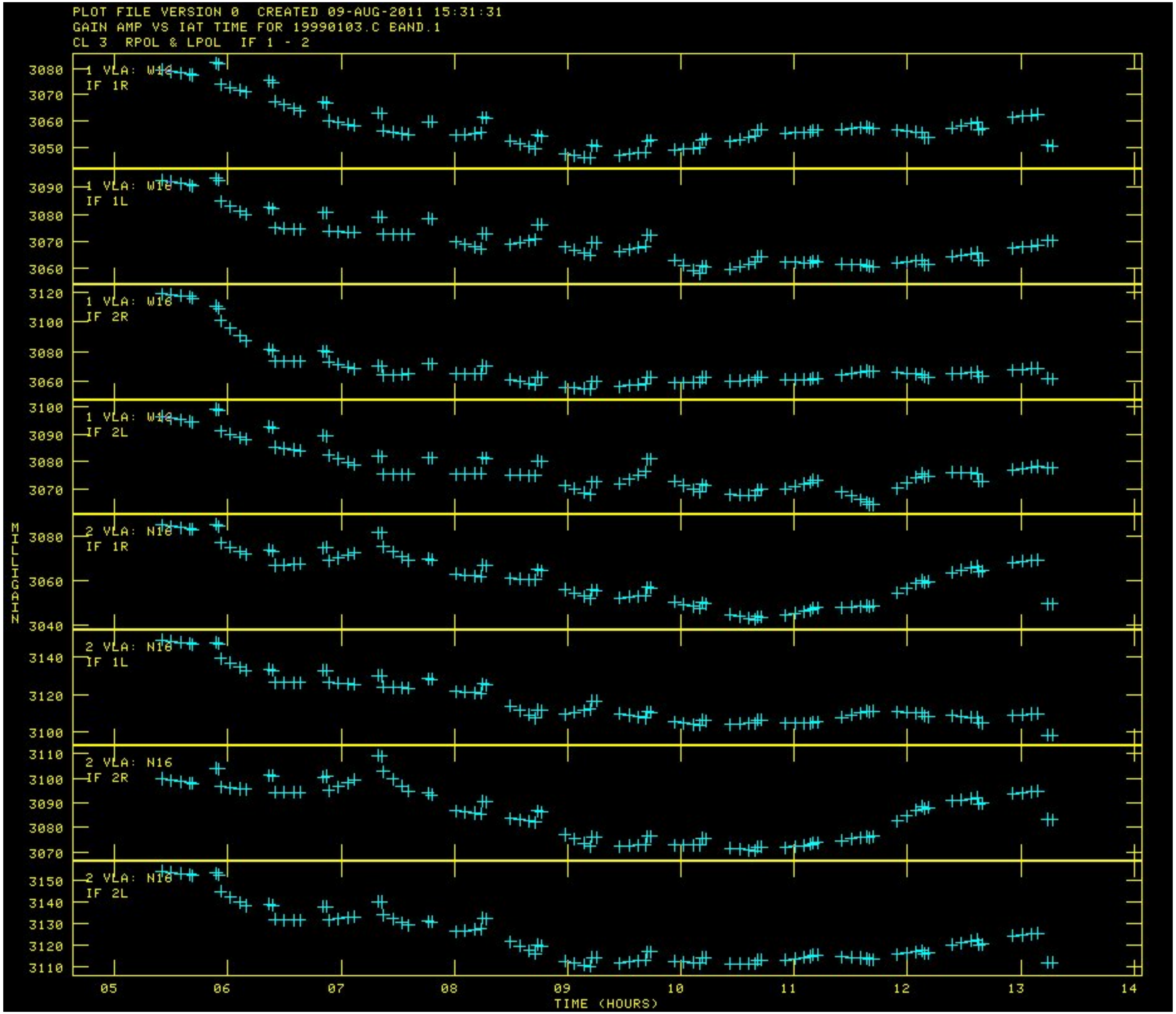
A suitable table applies (complex) corrections to the observed visibilities in order to obtain a data set in which (most of) the corruption to the signal has been removed.
*The most relevant are the **CL** table, the **BP** table and the **FG** table.*

These tables at various levels need to be inspected and validated by the user.

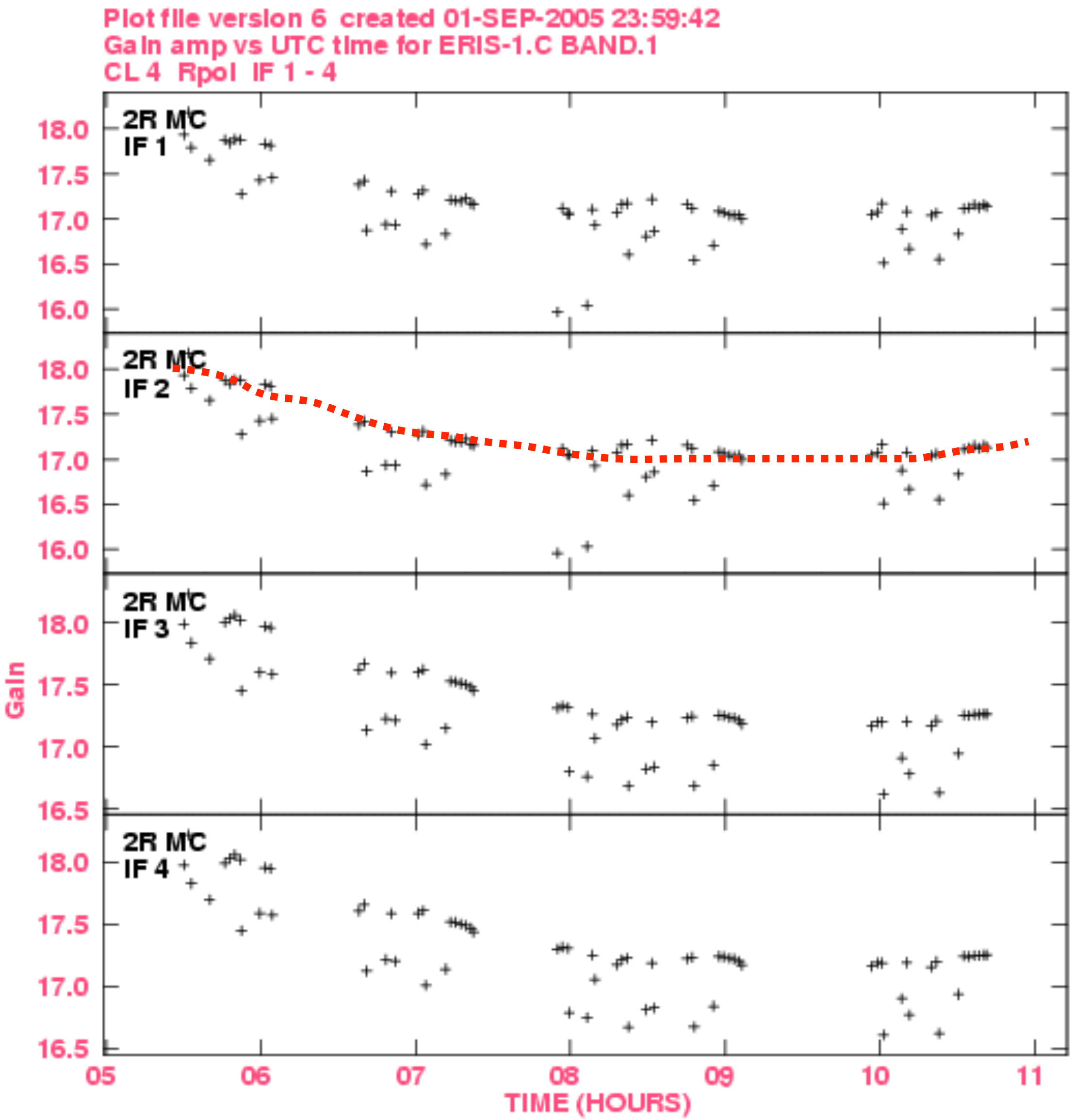
Finally they are applied to the data [i.e. to both primary and secondary calibration sources and finally to the target source(s)] to obtain the dataset after the “a – priori” calibration applied.

*At a later stage it is often necessary to refine this calibration with the **self-calibration** making use of the data of the targets.*

CL table


PLOT FILE VERSION 0 CREATED 09-AUG-2011 15:31:31
GAIN AMP VS IAT TIME FOR 19990103.C BAND.1
CL 3 RPOL & LPOL IF 1 - 2
1 VLA: W16
IF 1R
3080
3070
3060
3050
1 VLA: W16
IF 1L
3090
3080
3070
3060
1 VLA: W16
IF 2R
3120
3100
3080
3060
1 VLA: W16
IF 2L
3100
3090
3080
3070
2 VLA: N16
IF 1R
3080
3060
3040
2 VLA: N16
IF 1L
3140
3120
3100
2 VLA: N16
IF 2R
3110
3100
3090
3080
3070
2 VLA: N16
IF 2L
3150
3140
3130
3120
3110
MILLIGAIN
05
06
07
08
09
10
11
12
13
14
TIME (HOURS)

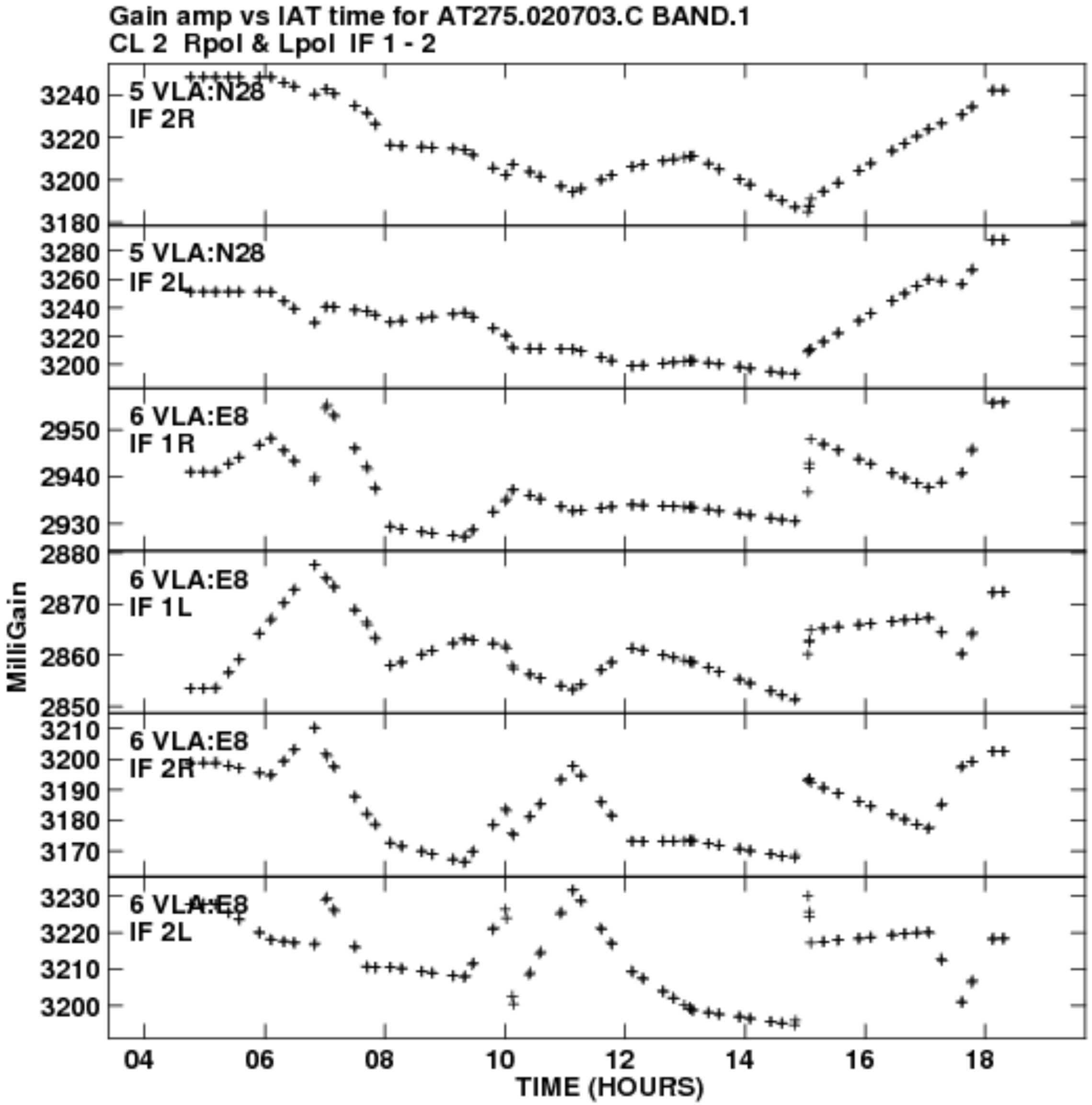
Example of *Amplitude* solutions (VLBI dataset)



Variations should be smooth and within a few percent

J_i from Tsys measurements at the telescope

Example of J_i solutions (2)

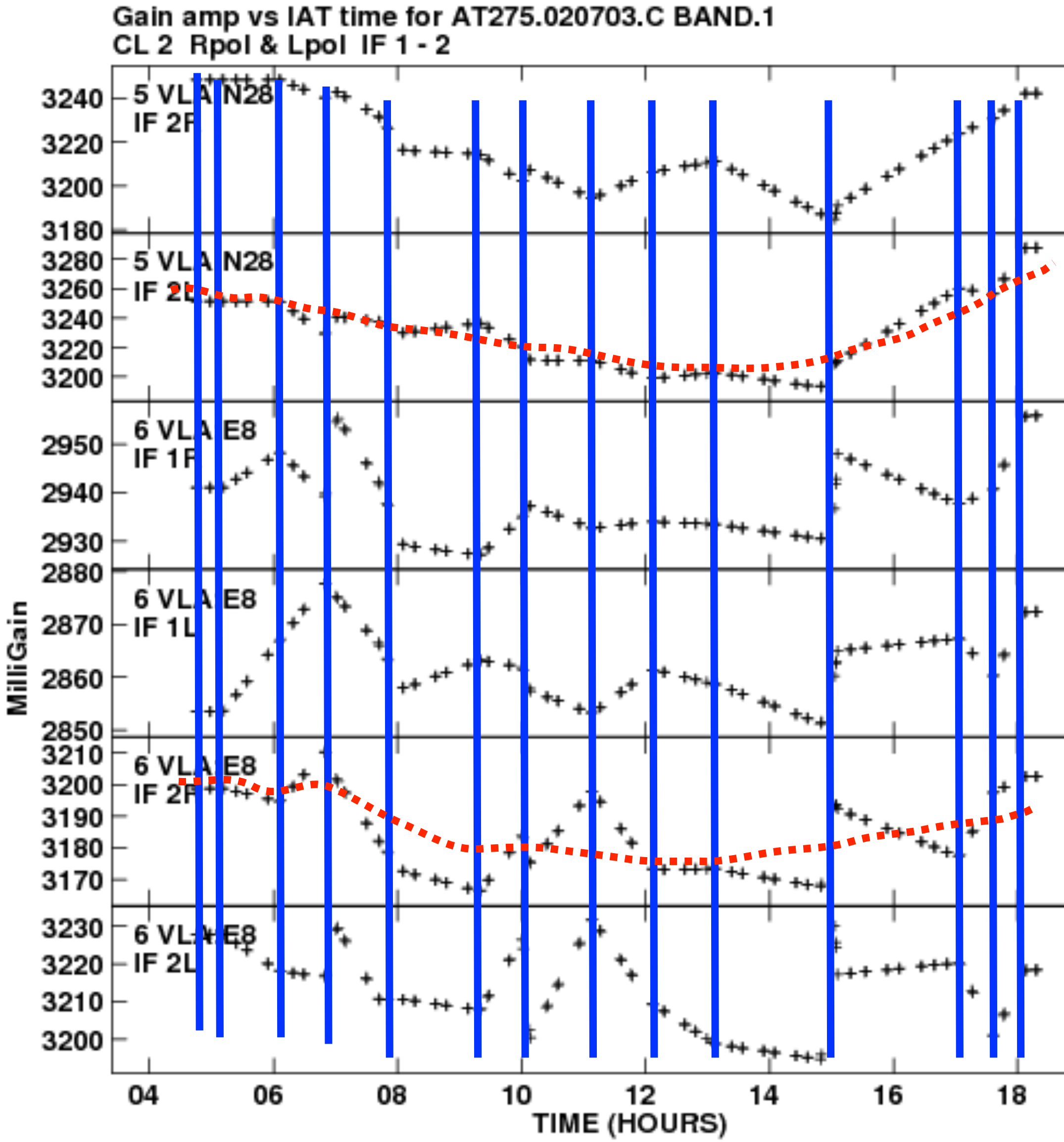


Variations should be smooth (??) and within a few percent

J_i derived from a flux density (primary) calibrator and a number of secondary (phase) calibrators.

No smoothing applied to J_i solutions

Example of J_i solutions (2)

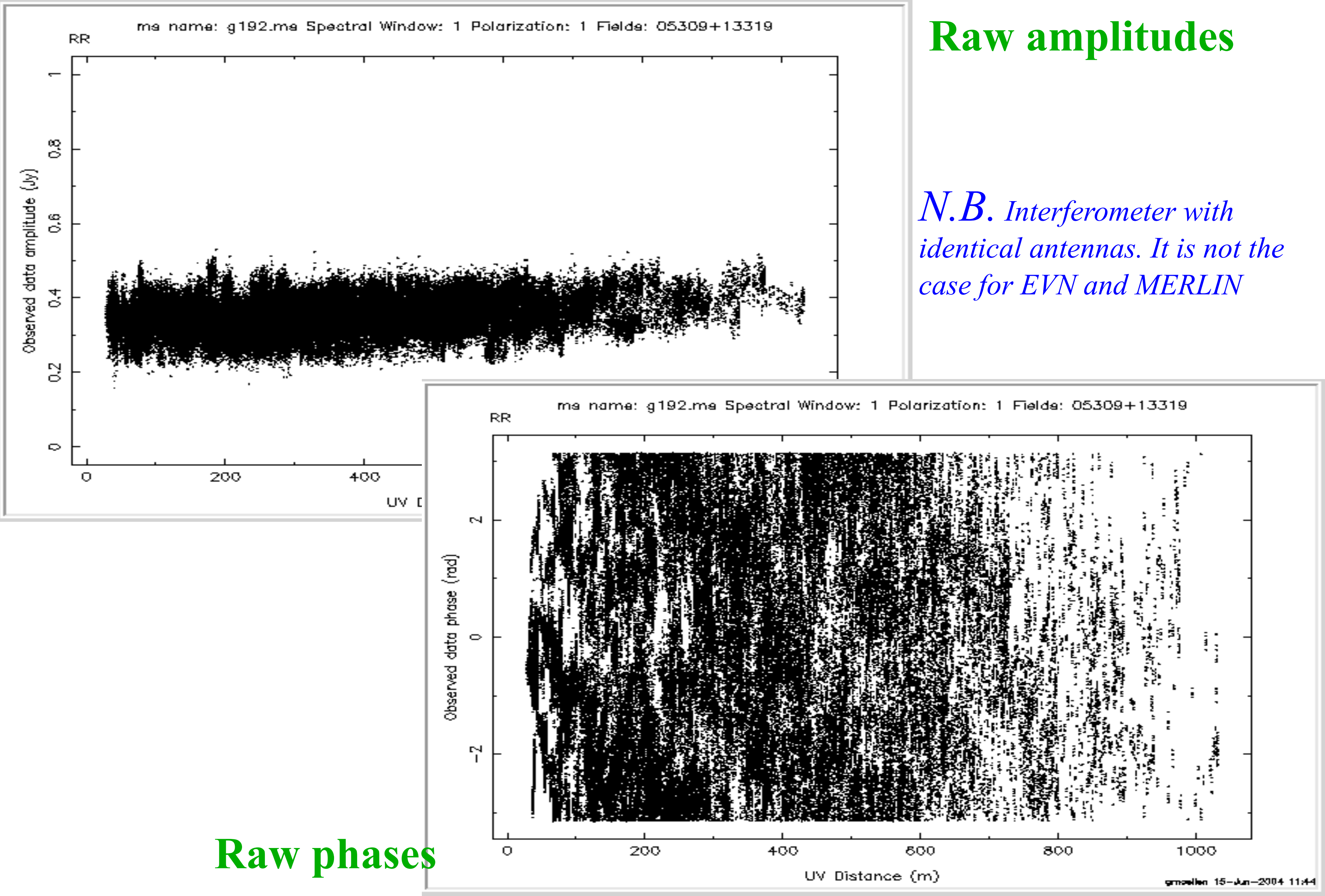


Variations should be smooth and within a few percent

J_i derived from a flux density (primary) calibrator and a number of secondary (phase) calibrators.

No smoothing applied to J_i solutions

Before calibration........



Raw amplitudes

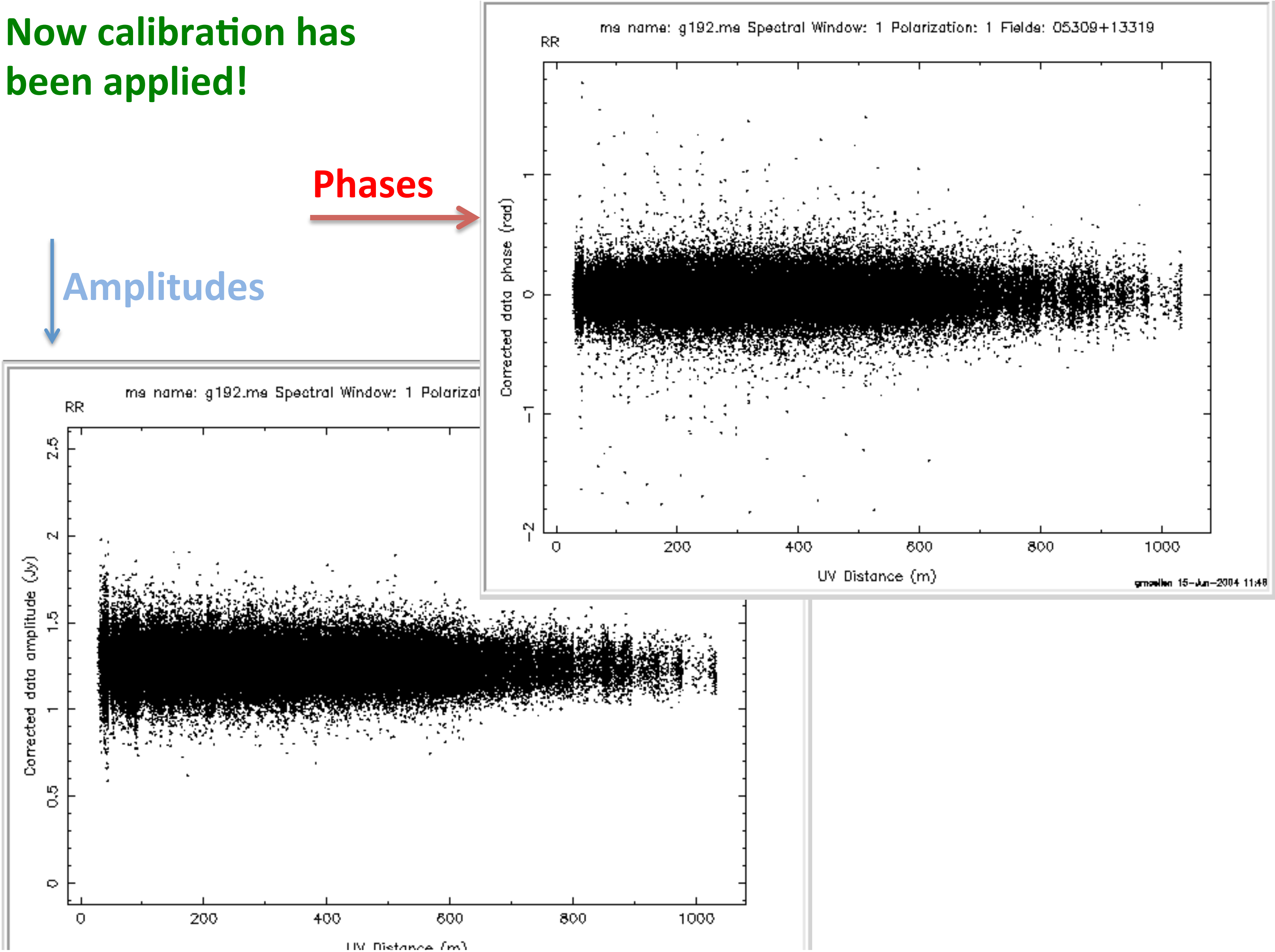
N.B. Interferometer with identical antennas. It is not the case for EVN and MERLIN

Raw phases

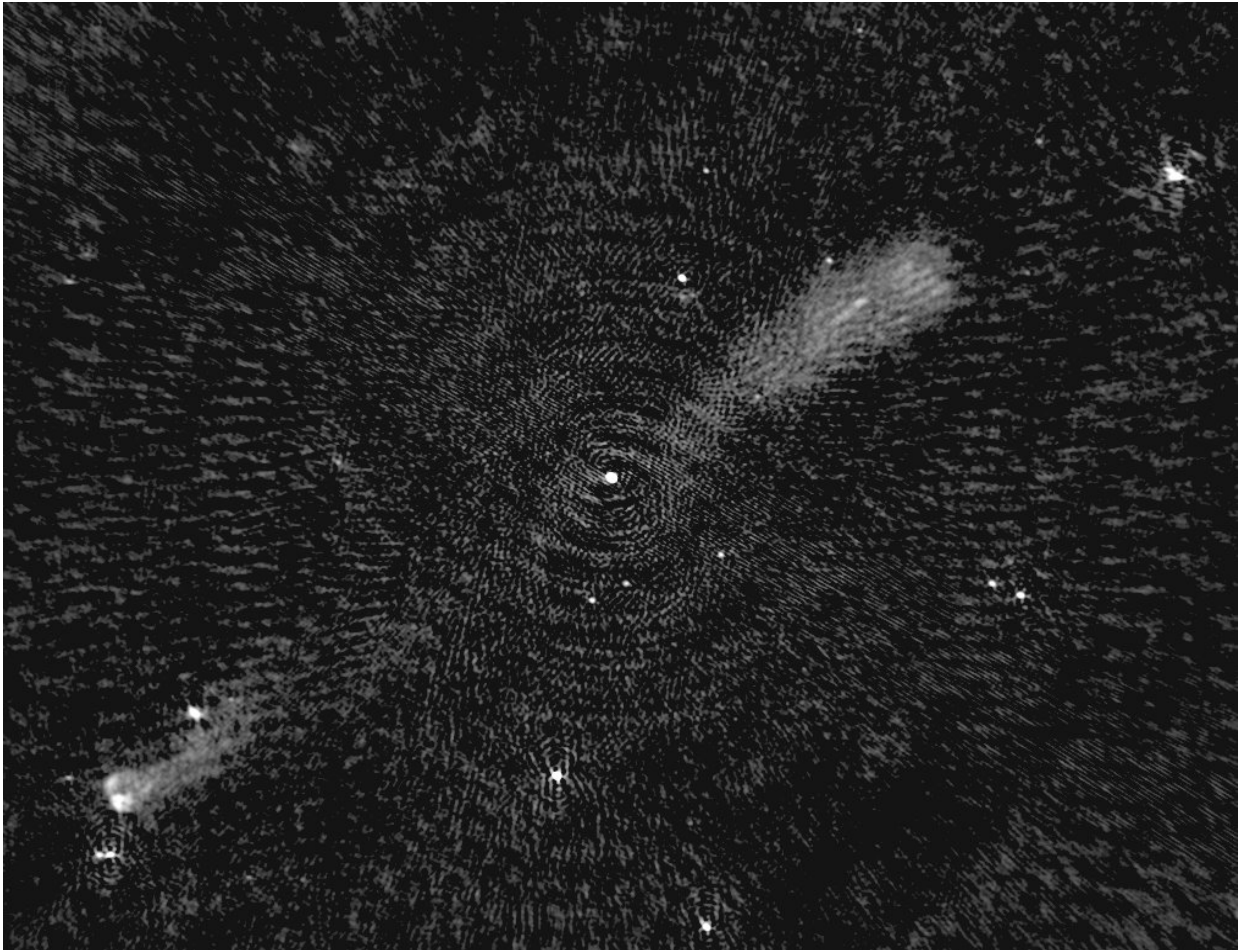
Now calibration has been applied!

Phases

Amplitudes



Mapping the calibrator(s)…… makes aware that they are ideal sources!



When A-PRIORI calibration is over.......

the data can now be coherently **averaged in frequency and in time** [in principle! (and when useful)]

The size of the UV data set is substantially reduced

speeds up all the subsequent data processing (imaging and self-calibration, further second-order editing, plotting, etc.)

may be dangerous, phases are likely to need further adjustment before averaging (true for weak targets)

A priori practical calibration summary/outcome/ recommendations

Planning the experiment (scheduling) is extremely important to make the calibration easy

- Observe (at least) one [pointlike] calibration source for the flux density scale (bandpass as well!)
- Observe (at least) one [pointlike] (phase) reference source close to the target object often enough to track phase (and gain) variations
- Observe (at least) one [pointlike] source for determining instrumental polarisation (a wide range of χ if polarised or unknown, it does not matter if it is not), if relevant
- Observe (at least) one source for the orientation of the polarisation vector, if relevant

Thinking **before**.......... a lot of time (and annoying work)can be saved **after**

One (may be more!) step(s) back (aka: what have we learned):

- **After observation, the initial data examination and editing is very important. The calibration process is much more efficient if bad data have properly been flagged out!**
  - Some real-time flagging occurred during observation (antennas off-source, LO out-of-lock, etc.). Any bad data left over?
    - **check operator's logs**
      - Pay attention to downtime reports, weather info, reports on RFI
    - **Directly inspect the raw data** (plot / print / display): remember that data on calibration sources should have high SNR, while data on target sources usually have low SNR and may appear noisy
  - Amplitude and phase should be continuously ***(smoothly)*** varying: **edit outliers**
  - Be conservative: those antennas/timeranges bad on calibrators are probably bad on weak target sources as well. **Edit them out!**
  - Distinguish between bad (hopeless) data and poor quality data.

    Some antennas may have significantly different amplitude response which may not be fatal; it may only need to be calibrated/readjusted