Calibration -I
(in Radio Astronomy)

Ishwara Chandra CH

NCRA-TIFR

Acknowledgments:

Synthesis Imaging in Radio Astronomy – II: *Chapter 5*

Low Frequency Radio Astronomy (blue book): *Chapter 5*

Calibration and Advanced Radio Interferometry: *McKean, Garret, ASTRON*

Radio Astronomy: Lecture #9: *Dale E. Gary NJIT*

Calibration in Radio Astronomy: *Subhasis Roy*

Calibration: Wikipedia

Calibration is the comparison of measurement values delivered by a device under test with those of a calibration standard of known accuracy.

Calibration – general remarks

Calibration means estimating unknown parameters using known parameters, to recover the “**true”** values as close as possible.

Measured = TrueValue * X ; X can be due to instrument, scale, etc

This much is *that* much; **HOW** much is **THIS** much?

Seemingly simple, but needs to know several affecting factors during calibration –

In Radio Astronomy, calibration is required to remove instrumental and ionospheric effcts, mostly affects individual antennas -

For Calibration, one need to observe proper “***calibrators***” – OR

signal generators of known strength can also be used (not enabled in GMRT now)

What we measure

The basic equation for a synthesis array is

$$V(u,v) = \int \mathcal{A}(l,m)\, I(l,m)\, exp[-i2\pi(ul + vm)]\, dl\, dm$$ *(general)*

$$V_{ij}(t) = \int \mathcal{A}(l,m)\, I(l,m)\, exp[-i2\pi(u_{ij}(t)l + v_{ij}(t)m)]\, dl\, dm\ .$$

(for antenna pair)

where (l,m) are the direction cosines with respect to the phase center,

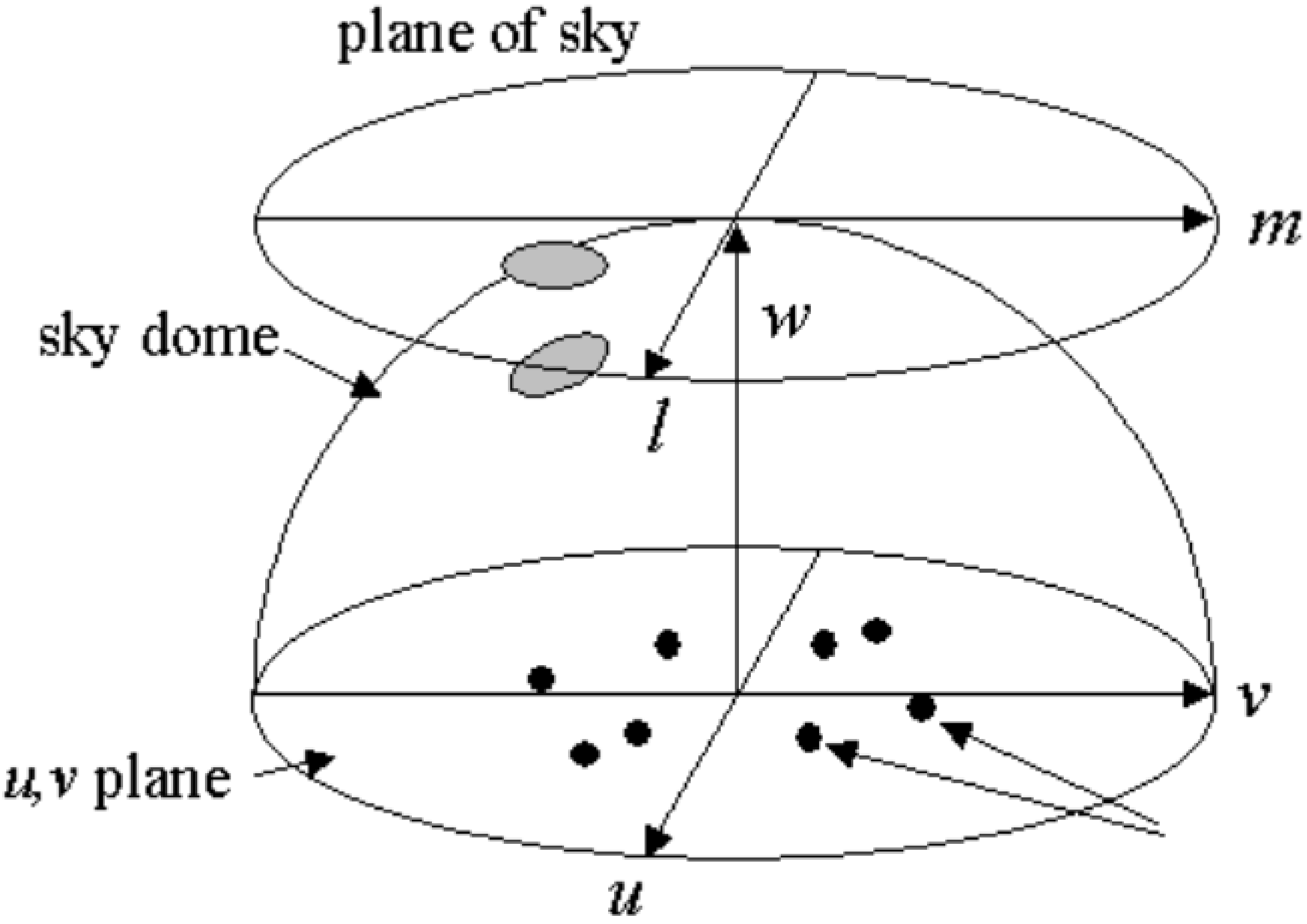
(u,v) are the projected baseline coordinates in wavelengths, $u = B_{l,\lambda}$, $v = B_{m,\lambda}$,

$V(u,v)$ is the true visibility evaluated at u, v,

$\mathcal{A}(l,m)$ is the normalized primary beam pattern (beam of a single antenna)

$I(l,m)$ is the brightness distribution of the source

Coordinate systems



More details in Jayaram's lecture.

What we measure

The basic equation for a synthesis array is

$$V(u,v) = \int \mathcal{A}(l,m)\, I(l,m)\, exp[-i2\pi(ul + vm)]\; dl\, dm$$ *(general)*

$$V_{ij}(t) = \int \mathcal{A}(l,m)\, I(l,m)\, exp[-i2\pi(u_{ij}(t)l + v_{ij}(t)m)]\; dl\, dm\ .$$

(for antenna pair)

where (l,m) are the direction cosines with respect to the phase center,

(u,v) are the projected baseline coordinates in wavelengths, $u = B_{l,\lambda}$, $v = B_{m,\lambda}$,

$V(u,v)$ is the true visibility evaluated at u, v,

$\mathcal{A}(l,m)$ is the normalized primary beam pattern (beam of a single antenna)

$I(l,m)$ is the brightness distribution of the source

true vs ***observed*** visibility

The signal is received by the antenna, gets processed by electronics and correlator – ***observed visibility, V'_{ij}*** **.**

The ***true*** and ***observed*** visibilities differ; the flux scale and phase will be arbitrary; also corruption due to RFI, receiver malfunction, ionosphere, etc.. Most of it is due to individual antennas, hence each antenna gain and phase needs to be calibrated.

During the measurement, one point source with known and constant flux is observed at the phase center – to determine *gain* and *instrumental phase*.

For N antennas, N(N-1)/2 baselines makes it easy to calculate

de-composing the ***observed*** visibility

$$\widetilde{V}_{ij}(t) = \mathcal{G}_{ij}(t)V_{ij}(t) + \epsilon_{ij}(t) + \eta_{ij}(t)\ ,$$

$$\begin{array}{rl} t & \text{is the time of the observation,} \\ \mathcal{G}_{ij}(t) & \text{is the baseline-based complex gain,} \\ \epsilon_{ij}(t) & \text{is a baseline-based complex offset, and} \\ \eta_{ij}(t) & \text{is a stochastic complex noise.} \end{array}$$

ε_{ij} and η_{ij} *should be small* compared to $G_{ij}(t)V_{ij}(t)$;

Noise term is reduced by integrating.

$G_{ij}(t,\nu)=G_{ij}(t).G_{ij}(\nu)$ – time and frequency for multi channel data

Closure phase and amplitude

Phase “corruptions” of antennas can be solved by closure phase.

A PHASE SENSITIVE INTERFEROMETER TECHNIQUE FOR THE MEASUREMENT OF THE FOURIER TRANSFORMS OF SPATIAL BRIGHTNESS DISTRIBUTIONS OF SMALL ANGULAR EXTENT

R. C. Jennison

(Communicated by A. C. B. Lovell)

(Received 1958 February 21)

Summary

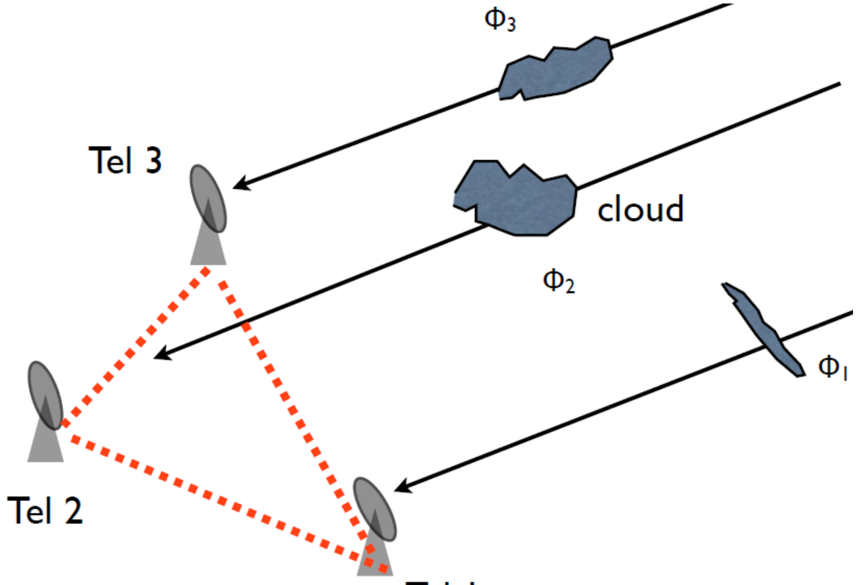
A method is described whereby the amplitude and phase of the complex Fourier transform of a spatial brightness distribution of small angular extent may be uniquely determined from a series of measurements with a triple

Closure phase and amplitude

The measured phase of the visibility for baseline ‘12’ is

$$\Phi_{12} = \varphi_{12} + \phi_1 - \phi_2$$

$$\Phi_{12} = \varphi_{12} + \phi_1 - \phi_2$$
$$\Phi_{23} = \varphi_{23} + \phi_2 - \phi_3 \qquad [2a]$$
$$\Phi_{31} = \varphi_{31} + \phi_3 - \phi_1$$



Clearly if we add these relations together:

$$\Phi_{12} + \Phi_{23} + \Phi_{31} = \varphi_{12} + \varphi_{23} + \varphi_{31} + (\phi_1 - \phi_1) + (\phi_2 - \phi_2) + (\phi_3 - \phi_3)$$

closure phase $= \varphi_{12} + \varphi_{23} + \varphi_{31}$

[2b]

Primary, Secondary and Bandpass Calibration

Mainly three types of calibration for *total intensity imaging*

Primary Calibration – to fix the flux scale ; stringent criteria – very stable flux and strong (3C48, 3C147 and 3C286)

Secondary Calibration (Phase calibration) – to correct for phases in the (near the) direction of target source; model slow gain change during long observations.

Bandpass Calibration – to calibrate channel to channel variation (*primary calibrator can double up as Bandpass Calibrator*)

(Prasun's lecture)

NCRA • TIFR

Selection of calibrators...

A *<u>primary calibrator</u>* should be

strong (*good SNR for each visibility*), (why?)

stable (*known and constant flux*) and (why?)

unresolved (*for all baselines*) source (why?)

A *<u>secondary calibrator</u>* should be

Close to target source (approximately same ionospheric patch)

stable (for the duration of observation), **unresolved** (for phase calibration)

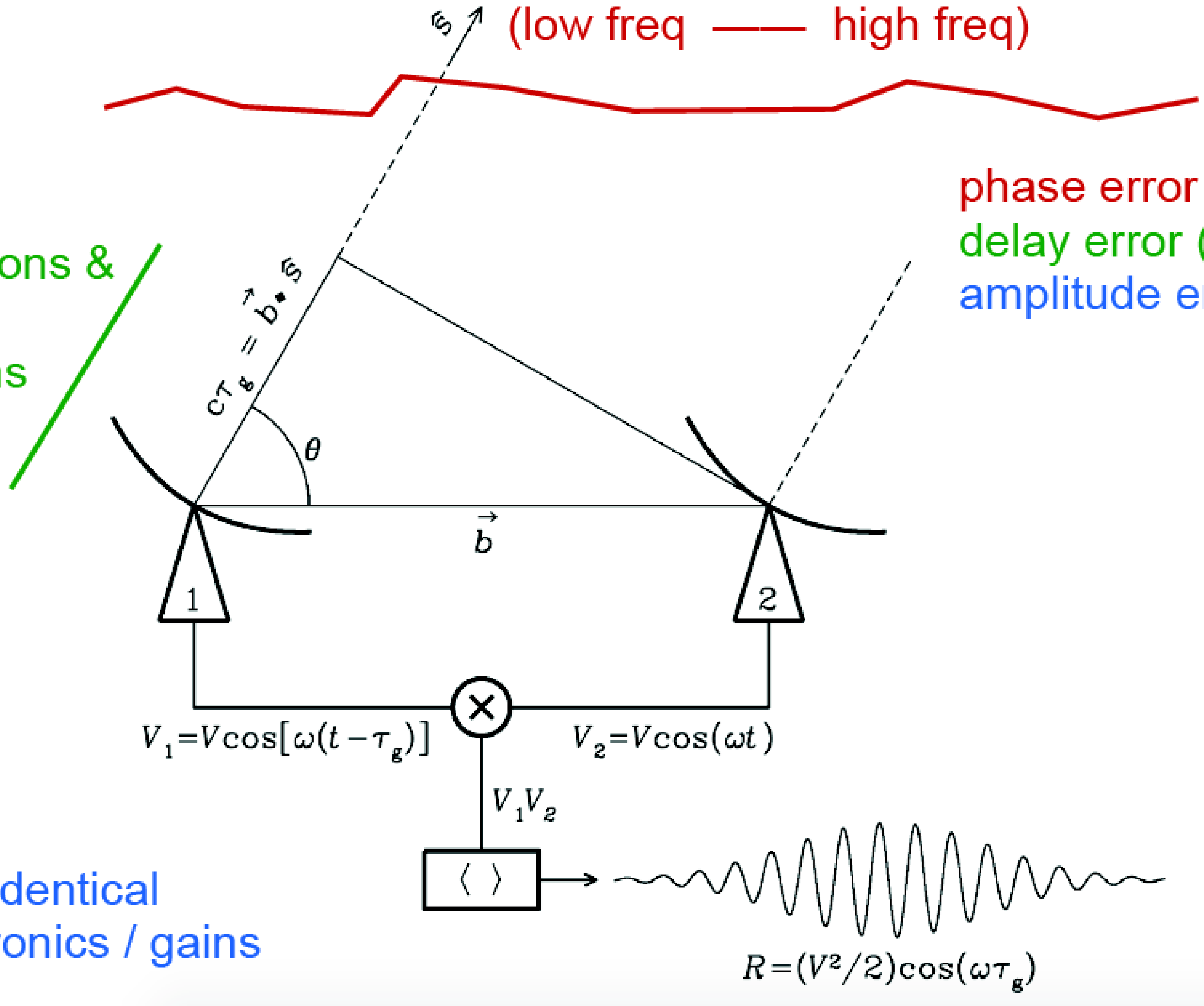
A ***<u>bandpass calibrator</u>*** should be strong and stable –
mostly primary calibrator doubles up.

Watch out for UV Limits while chosing calibrators!

Ionosphere+Troposphere
(low freq —— high freq)

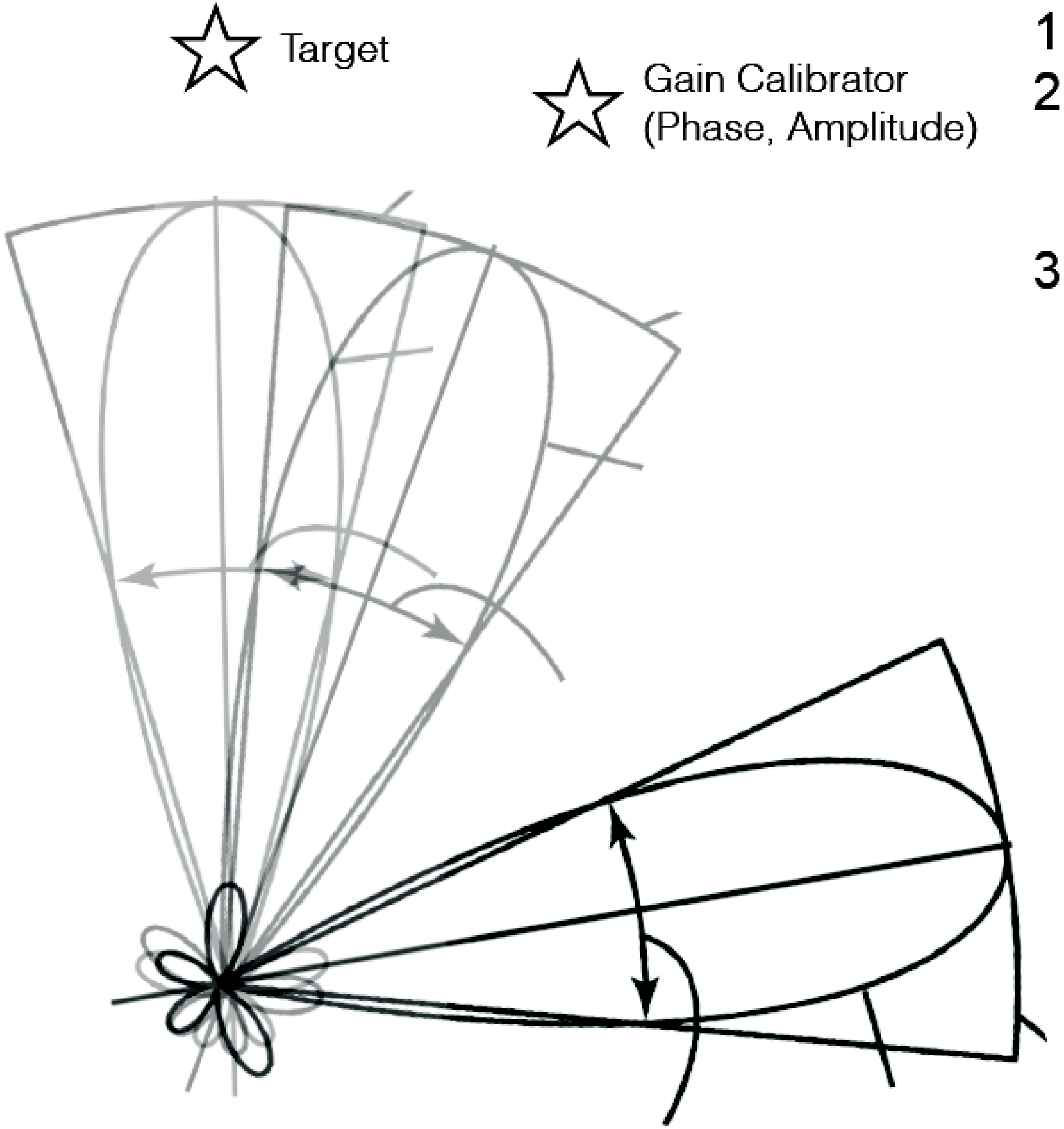
Bad positions & wide bandwidths

phase error ($\delta\omega t$)
delay error ($\delta\tau_g$)
amplitude errors (δV)



Non-identical electronics / gains

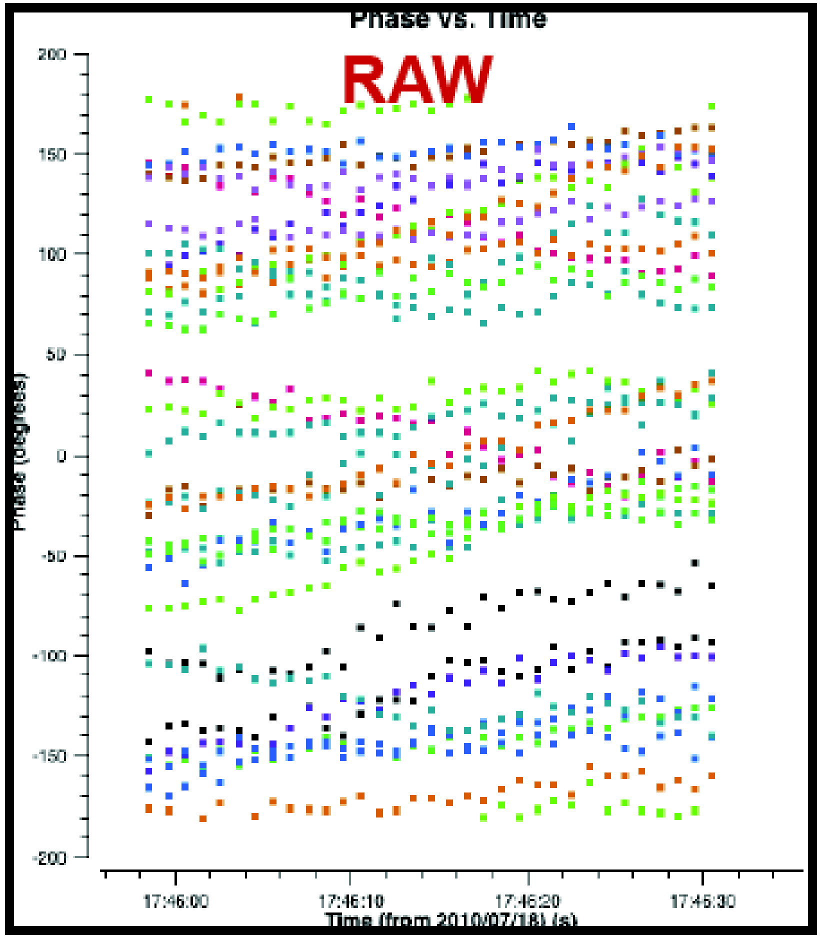
Solve for these issues using calibration

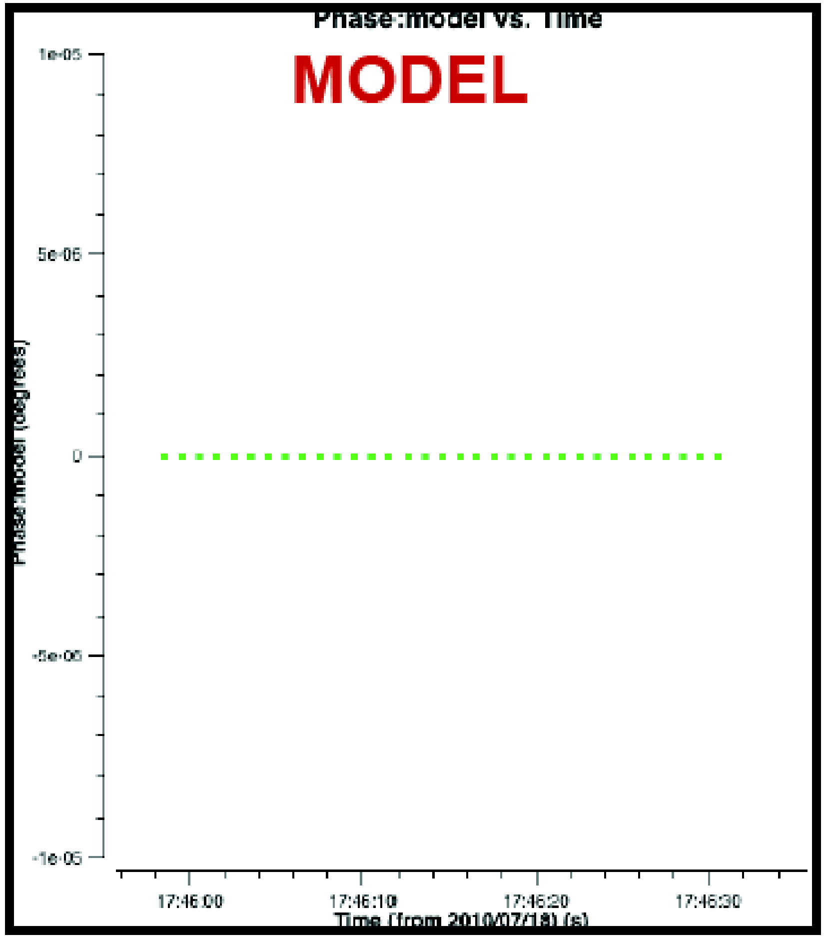


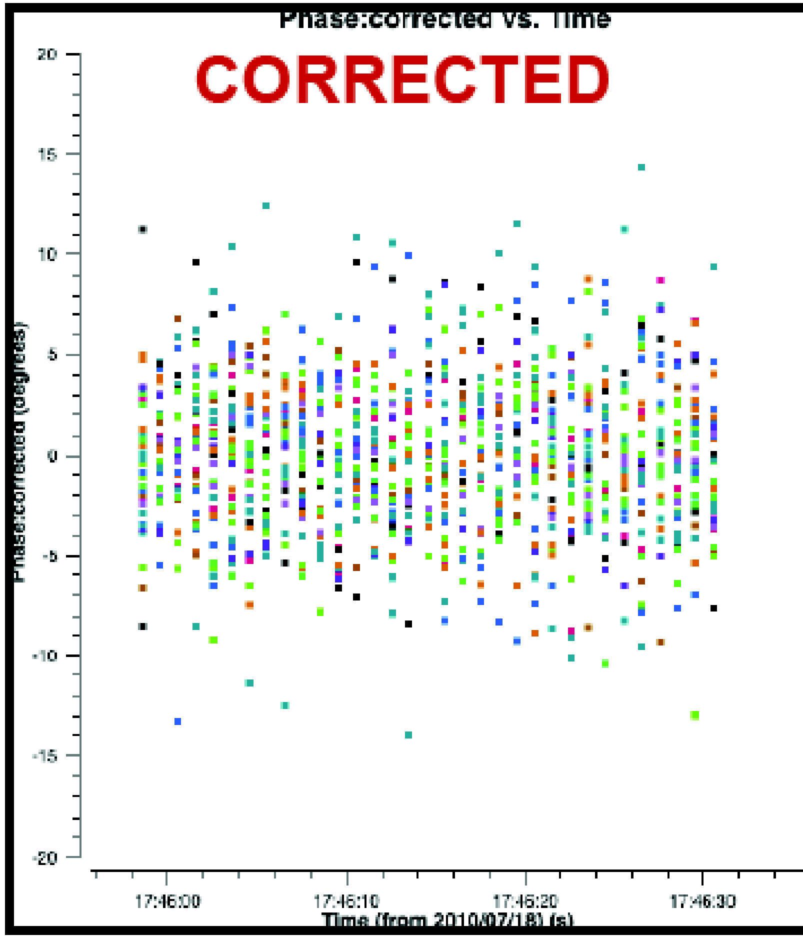
1. Observe **source**
2. Observe **calibrator** to measure gains (amplitude and phase) as a function of time.
3. Observe **bright calibrator** of known flux-density and spectrum to measure absolute flux calibration, band-pass and residual delays

Here is an observed visibility function (phase), the ideal visibility function and the calibrated data (after solving the G_{ij} in the the measurement equation).

Main source of phase error: Variable ionosphere or troposphere + electronics.

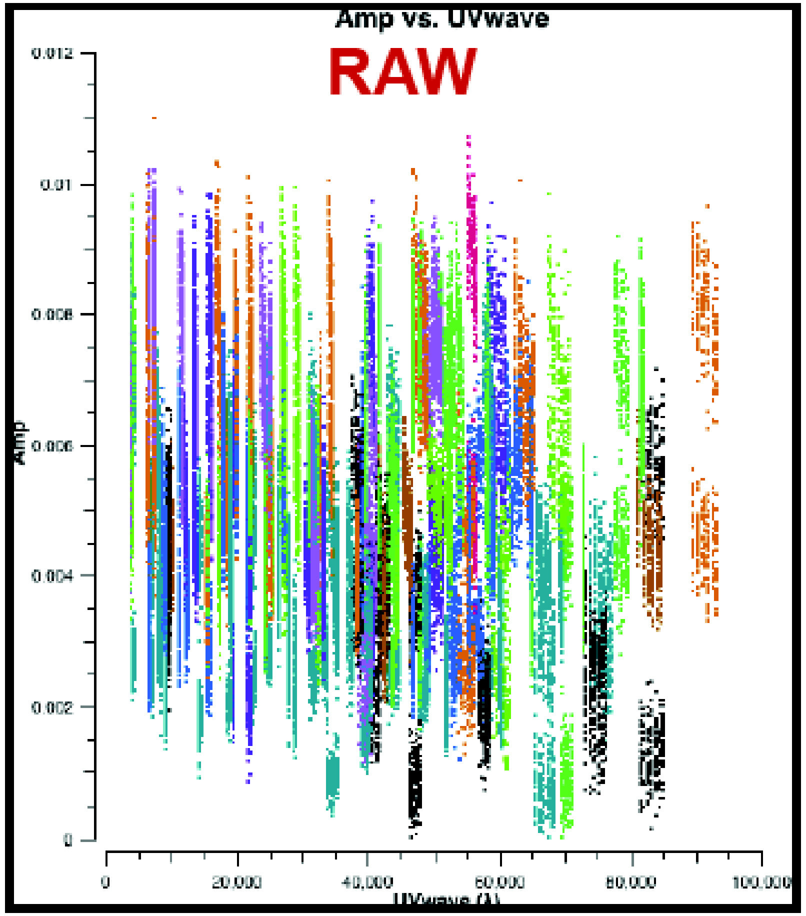


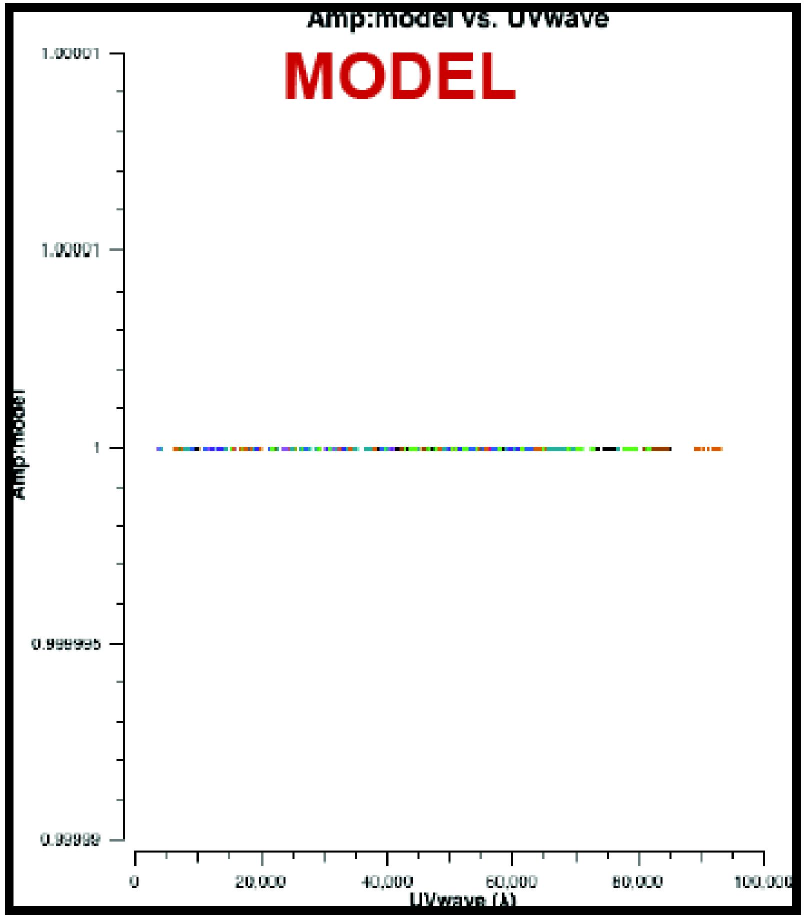


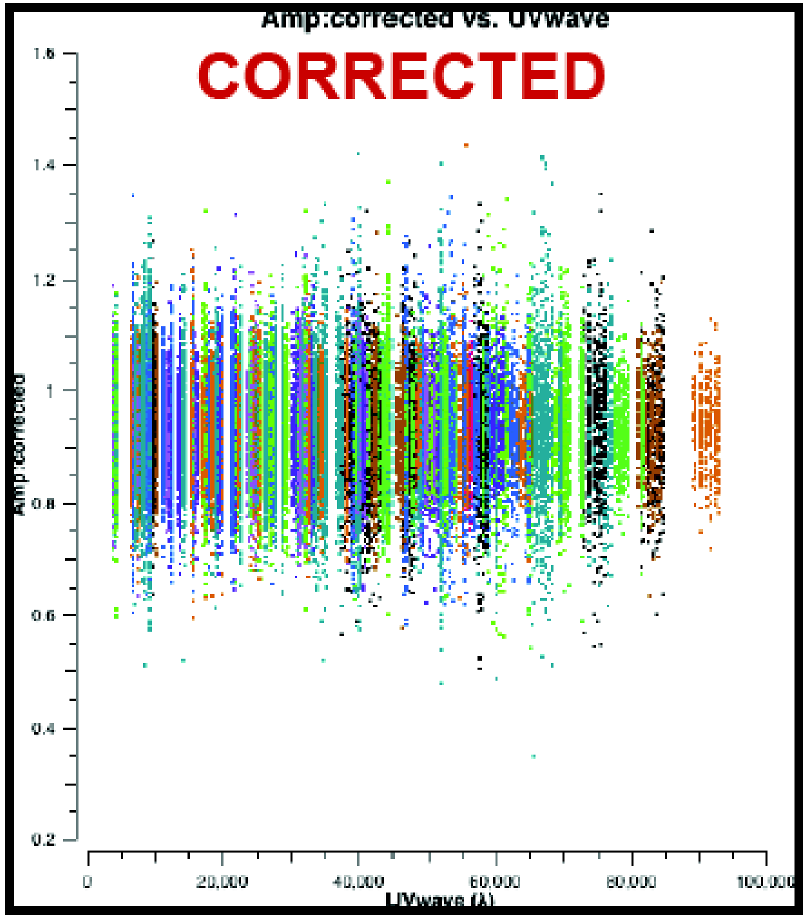


Here is an observed visibility function (amplitude), the ideal visibility function and the calibrated data (after solving the G_{ij} in the the measurement equation).

Main source of amplitude error: Variable gain in the amplifiers of the system.







Editing the data

- Data editing (flagging) is very important to remove bad data from severely corrupted data

- Amplitude and phase can vary independently in each channel

- Channel to channel variations likely (some channels would be bad due to narrow band RFI, for example)

Extreme caution in editing the source data ;
you may edit out a discovery!
(short spacing, for example)

Editing the data

How to differentiate between good and bad data?

Editing the data

How to differentiate between good and bad data?

For calibrator (stable, point source), phase and amplitude must be constant

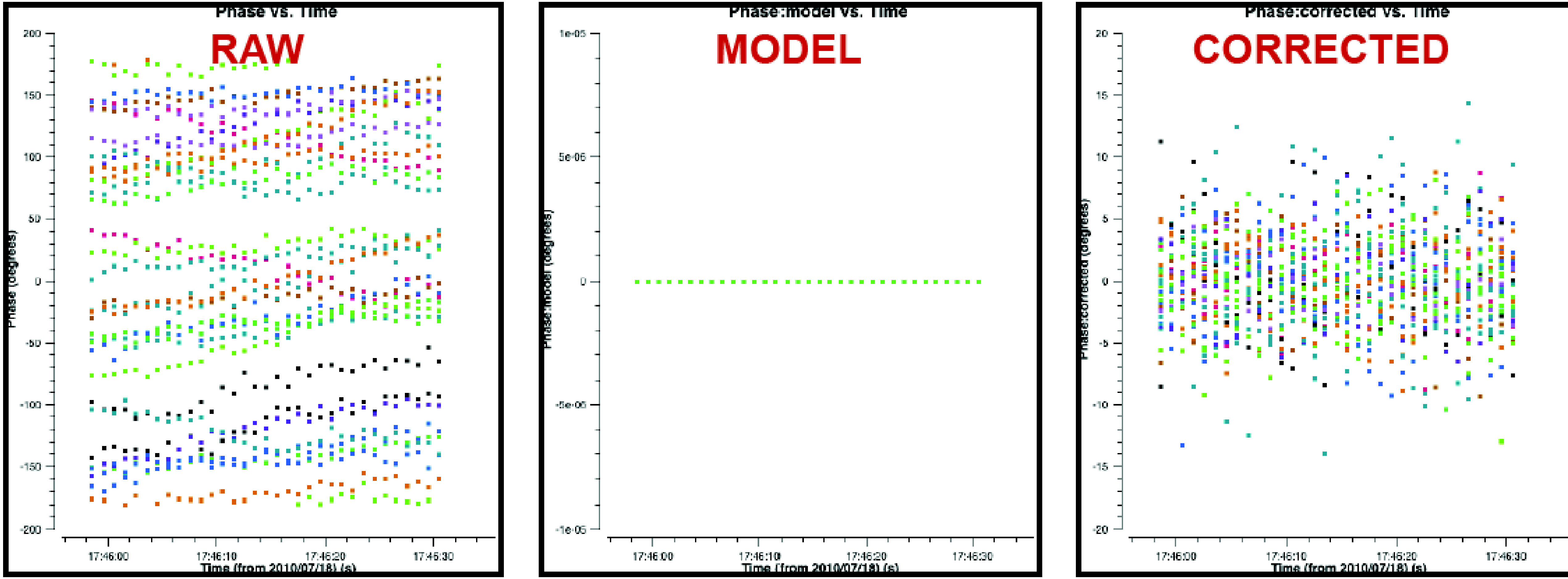
Before calibration, we do not know their values

The running differences should be close to zero!

Excellent parameter to check the quality of data (on calibrator)

Here is an observed visibility function (phase), the ideal visibility function and the calibrated data (after solving the G_{ij} in the the measurement equation).

Main source of phase error: Variable ionosphere or troposphere + electronics.



Editing the data

How to differentiate between good and bad data?

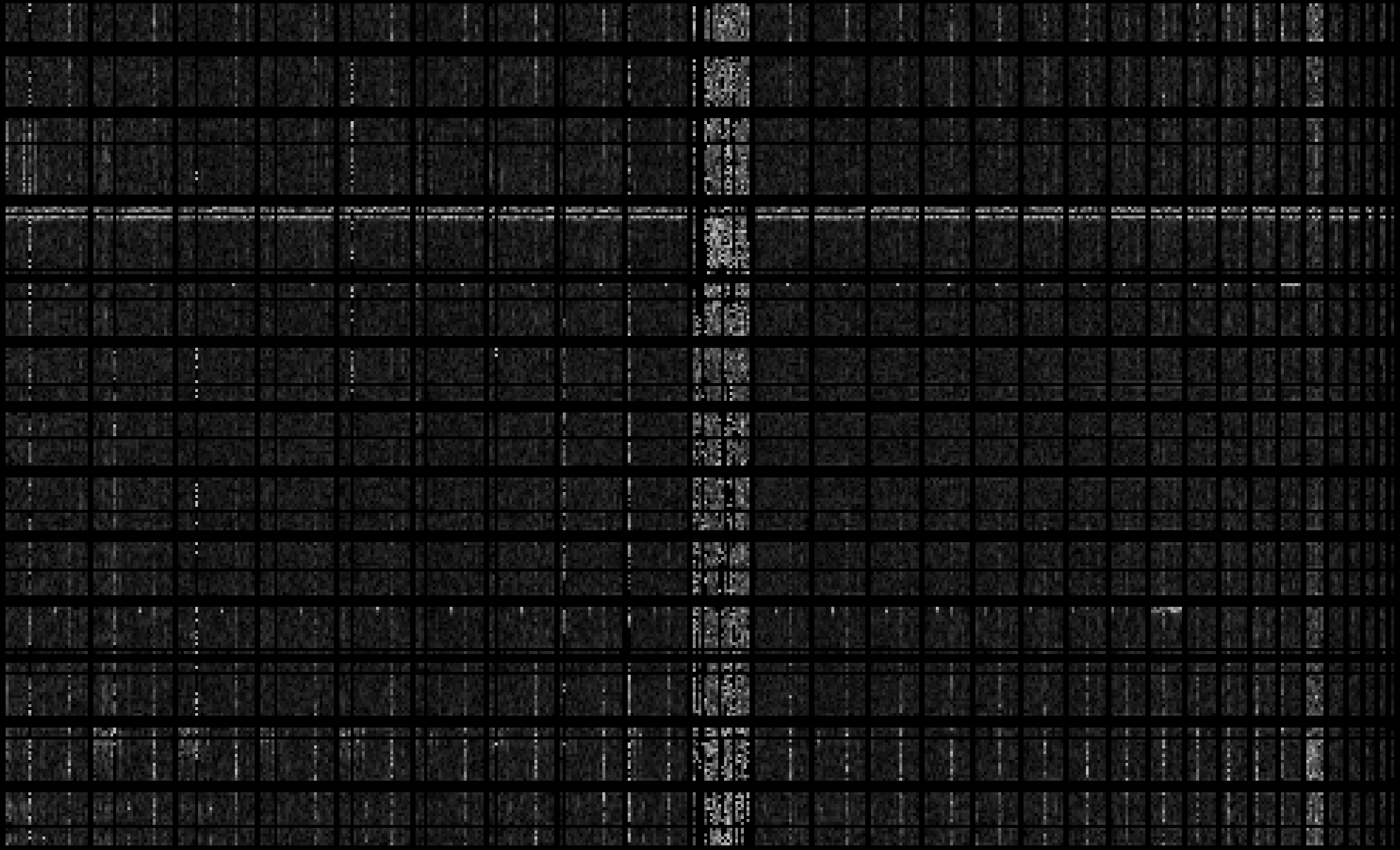
For calibrator (stable, point source), phase and amplitude must be constant

Before calibration, we do not know their values

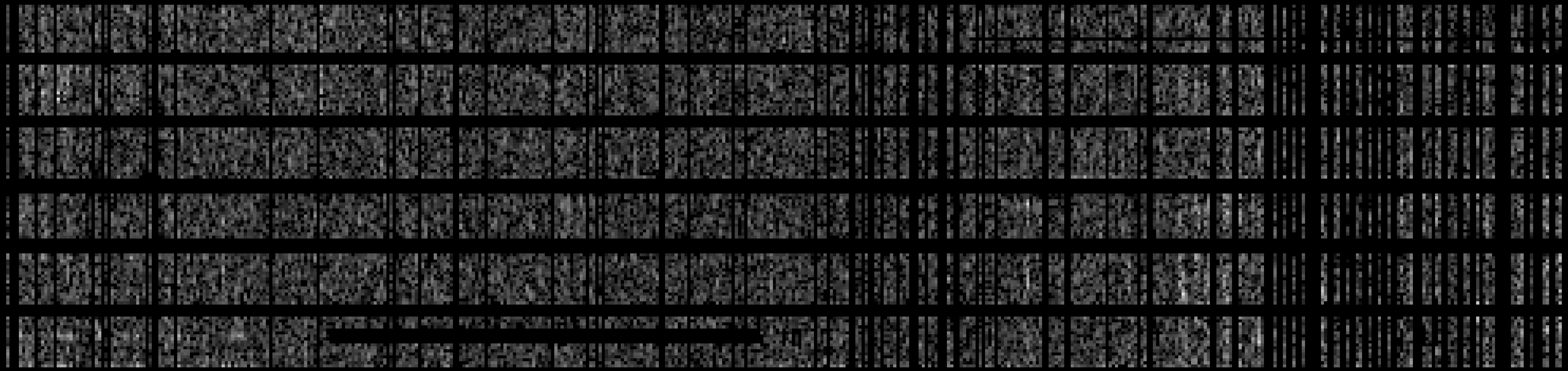
The running differences should be close to zero!

Excellent parameter to check the quality of data (on calibrator)

More on editing the data during tutorials..



AIPSTV - UNIX-5



E-CH ALL-IF LENGTH ALL-SOURCE SCAN 3 SHOW RR STOKES, FLAG RR

Primary Calibration

The purpose of ***primary calibration*** is to fix the flux scale;

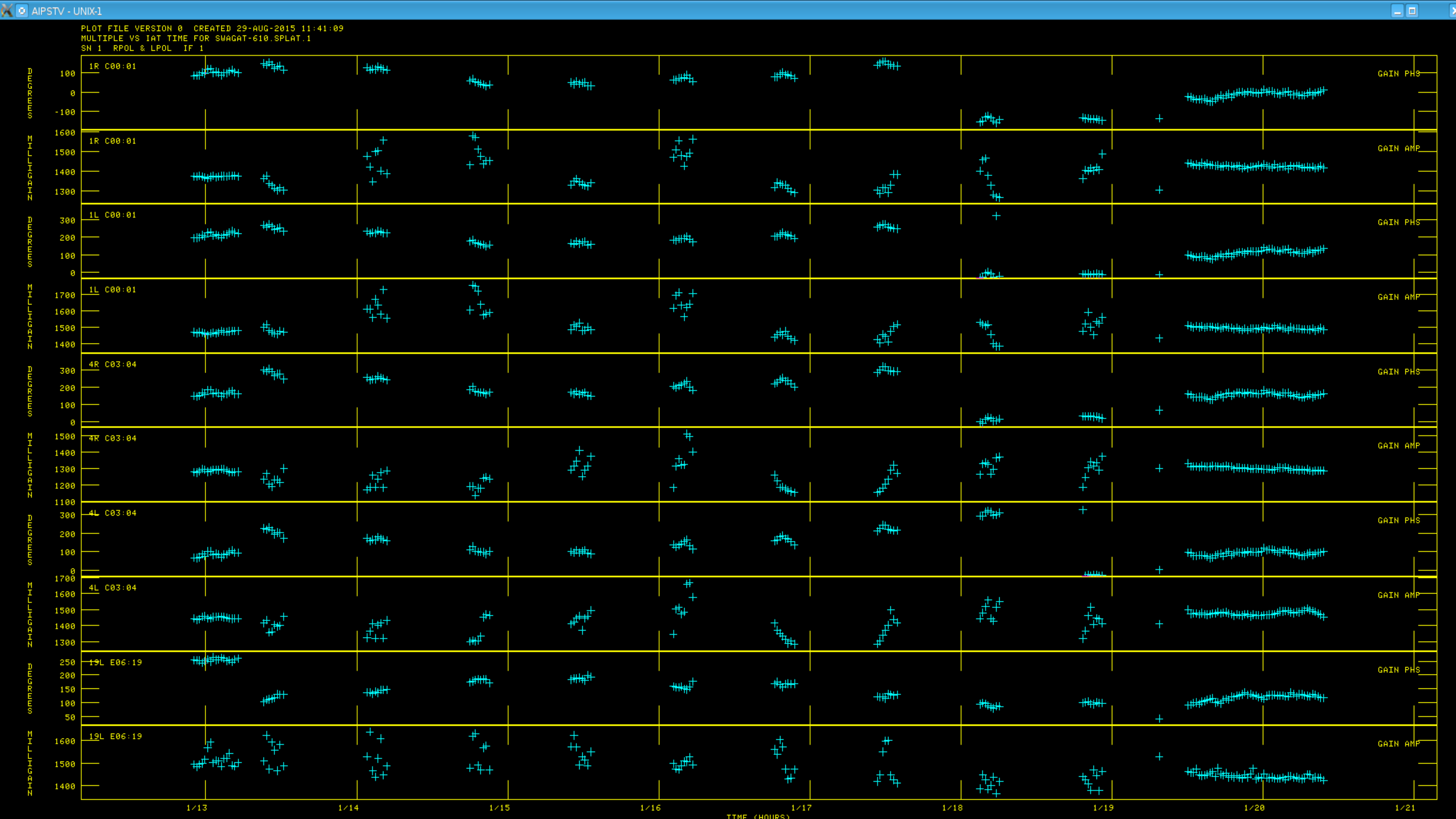
The correct expected flux should be loaded before running calibration tasks.

$$G_{ij}(t) = \mathcal{V}_{ij}(t)/S \qquad S = \text{flux of the point source}$$

Using closure amplitude and phase, antenna gain and will be computed..

Flux density "***S***" is known for primary calibrator

Note that $G_{ij}(t)$ is $G_{ij}(t)\ G_{ij}(\nu)$ for multi-channel data (bandpass calibration)



AIPSTV - UNIX-1
PLOT FILE VERSION 0 CREATED 29-AUG-2015 11:41:09
MULTIPLE VS IAT TIME FOR SWAGAT-610.SPLAT.1
SN 1 RPOL & LPOL IF 1
1R C00:01
GAIN PHS
1R C00:01
GAIN AMP
1L C00:01
GAIN PHS
1L C00:01
GAIN AMP
4R C03:04
GAIN PHS
4R C03:04
GAIN AMP
4L C03:04
GAIN PHS
4L C03:04
GAIN AMP
19L E06:19
GAIN PHS
19L E06:19
GAIN AMP
DEGREES
MILLIGAIN
1/13
1/14
1/15
1/16
1/17
1/18
1/19
1/20
1/21
TIME (HOURS)

Primary, Secondary and Bandpass Calibration

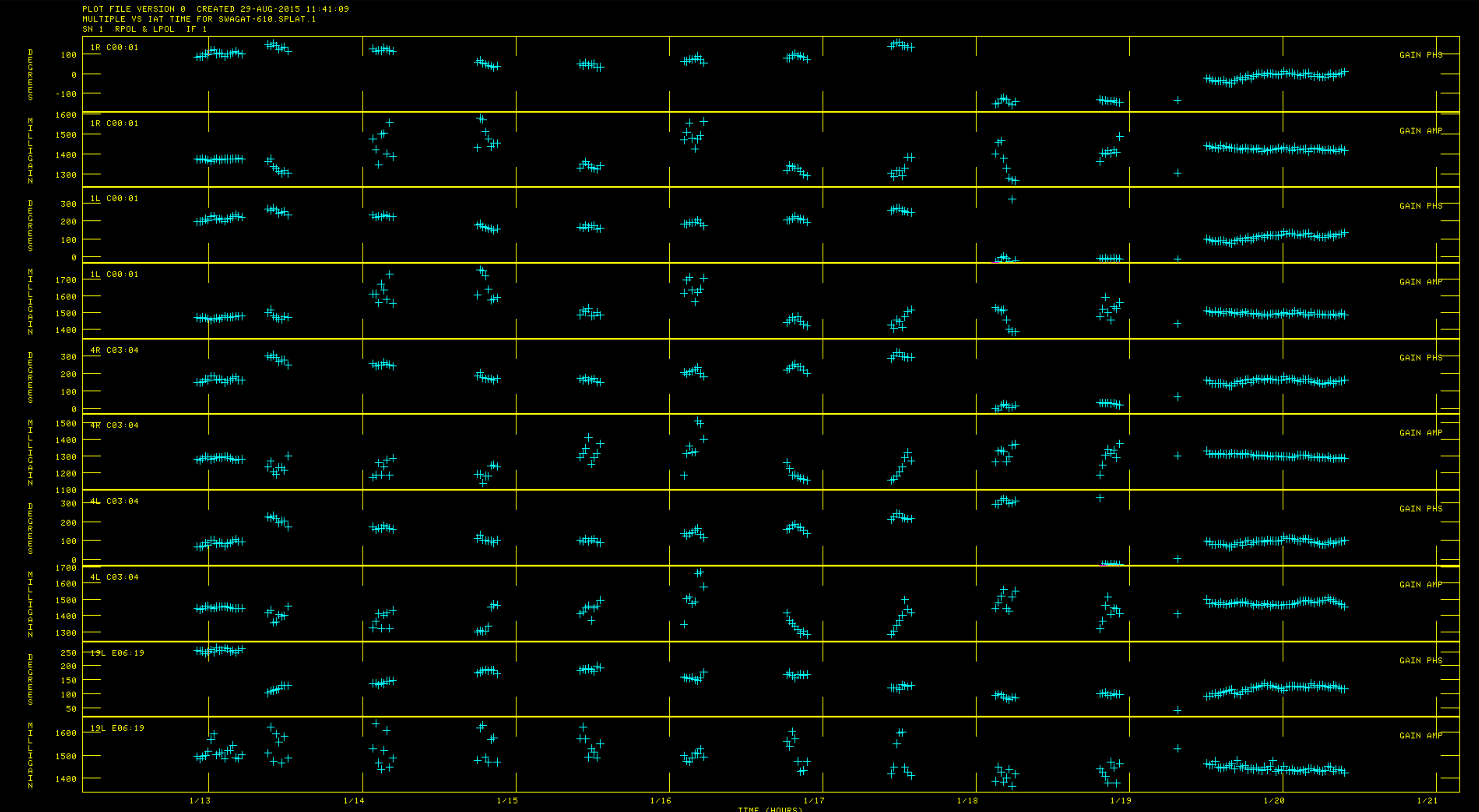
Secondary Calibration (phase calibration) –

- To transfer phase correction ***in*** the direction (***closer***, in practice) of the target
- To correct for the slow gain variation over time

Residual phase and gain corrections are carried out in '***self-calibration***'.

Self-calibration is a **MUST** at low radio frequencies

AIPSTV - UNIX-1



Primary, Secondary and Bandpass Calibration

Bandpass Calibration – to fix the variations across the band

$G_{ij}(t)$ is $G_{ij}(t)*G_{ij}(\nu)$ for multi-channel data

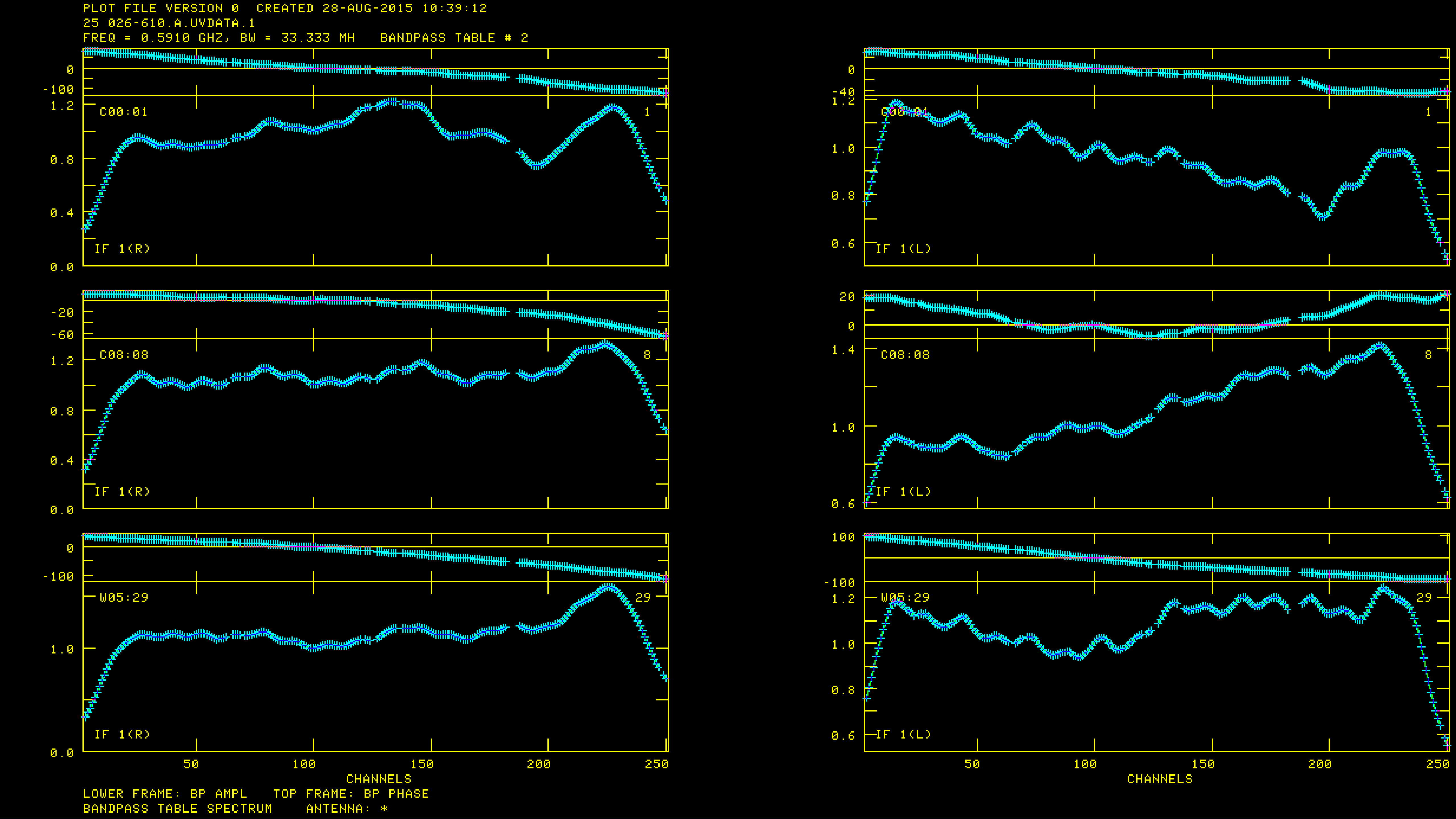
Computing $g(\nu)/g(\nu_0)$ and $\varphi(\nu)$ – $\varphi(\nu_0)$ for multi-channel data across the band is the bandpass calibration.

$$V'_{\mathrm{ij}}(t,\nu) = (g_i(t).g_i(\nu)).(g_j(t).g_j(\nu))^*.S$$

$$V'_{\mathrm{ij}}(t,\nu_0) = (g_i(t).g_i(\nu_0)).(g_j(t).g_j(\nu_0))^*.S$$

ν_0 is the Ref. chan.

$$V'_{\mathrm{ij}}(t,\nu) \div V'_{\mathrm{ij}}(t,\nu_0) = (g_i(\nu)/g_i(\nu_0)).(g_j(\nu)/g_j(\nu_0))^*$$


PLOT FILE VERSION 0 CREATED 28-AUG-2015 10:39:12
25 026-610.A.UVDATA.1
FREQ = 0.5910 GHZ, BW = 33.333 MH BANDPASS TABLE # 2
C00:01
IF 1(R)
IF 1(L)
C08:08
W05:29
CHANNELS
LOWER FRAME: BP AMPL TOP FRAME: BP PHASE
BANDPASS TABLE SPECTRUM ANTENNA: *

Determining Calibration Solutions

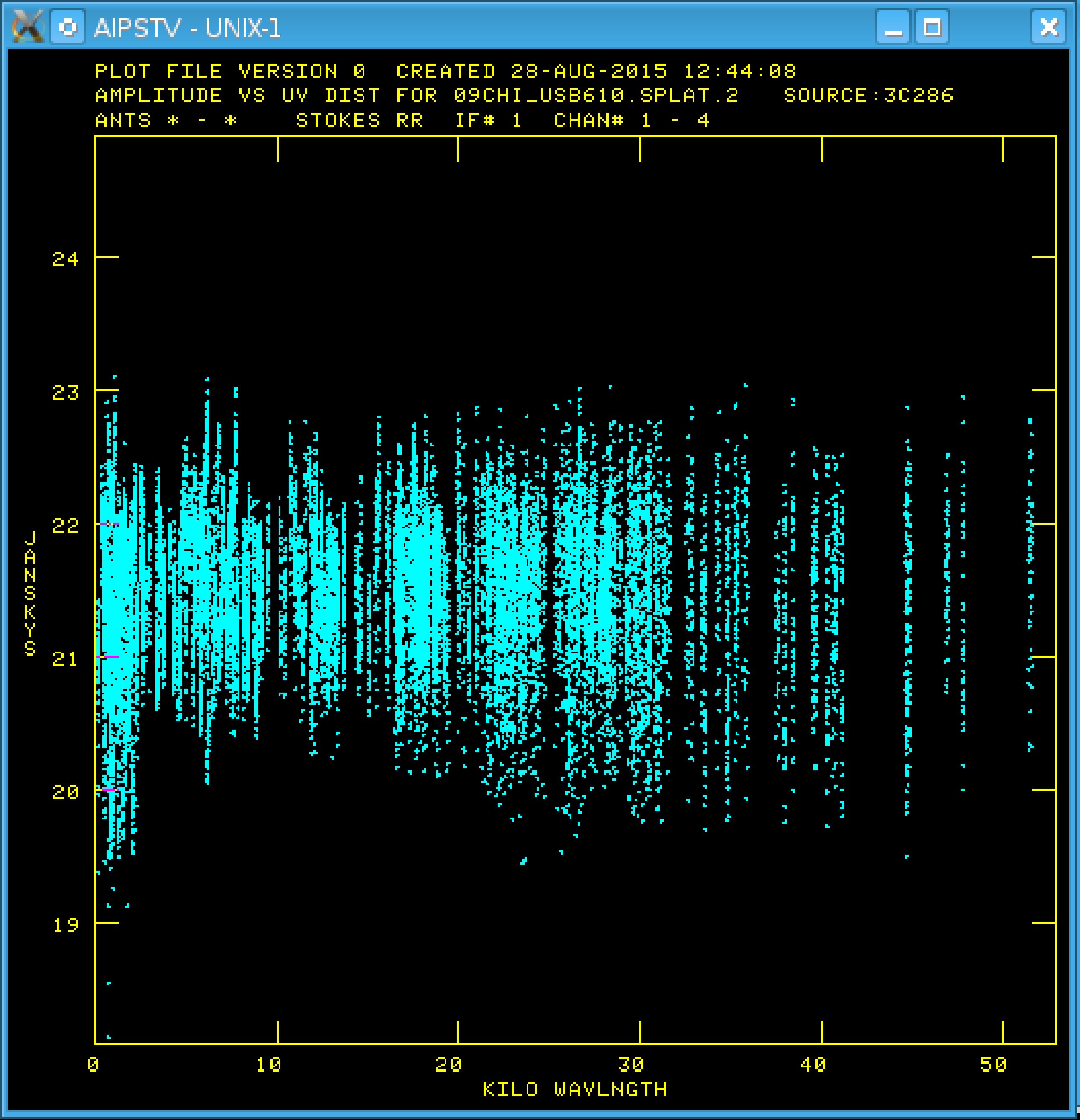
Single channel calibration ; then bandpass before channel collapse.

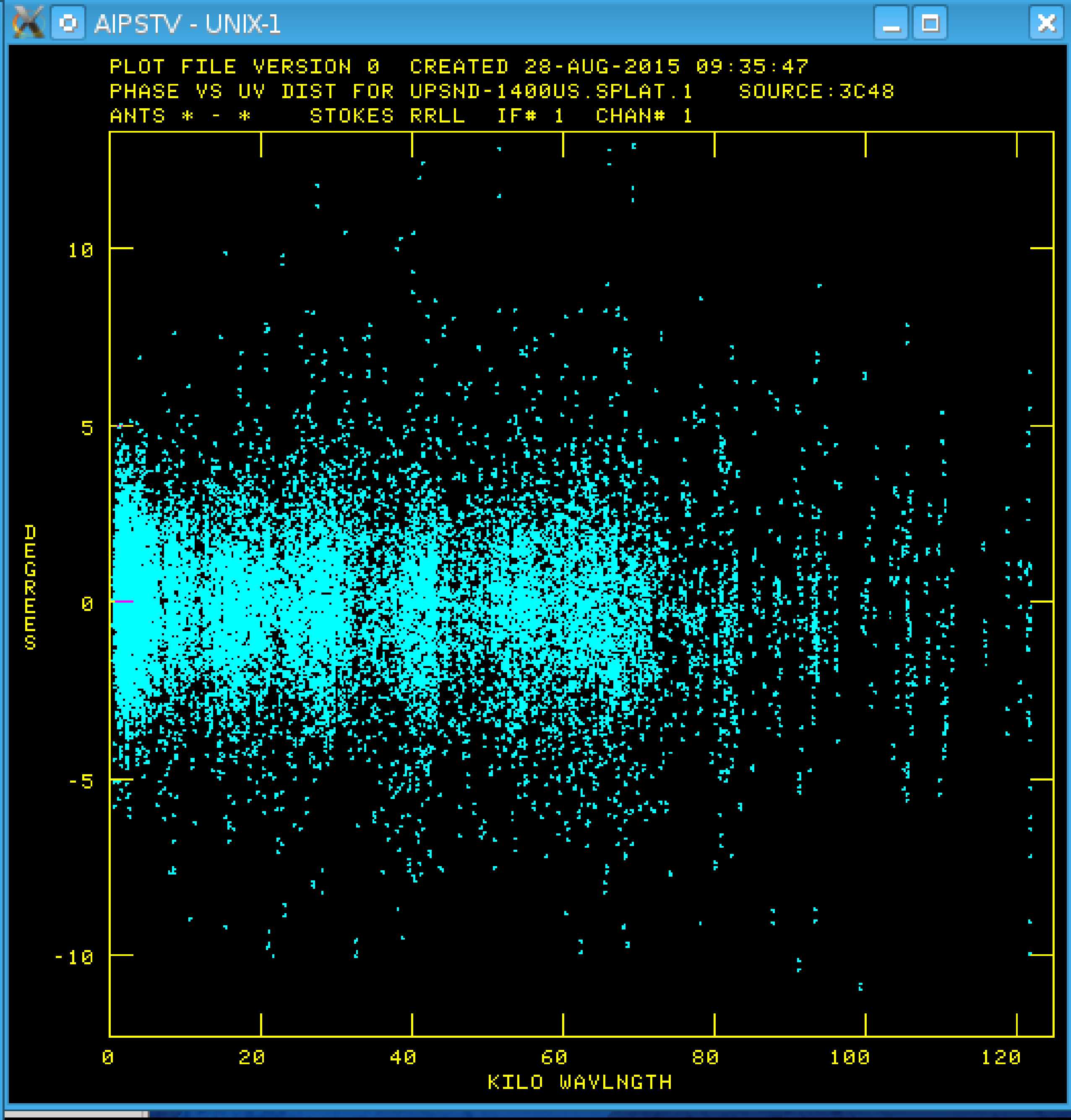
Check the solutions to ensure things are OK.

Since this is antenna gain and not baseline gain, all baselines need not be used.

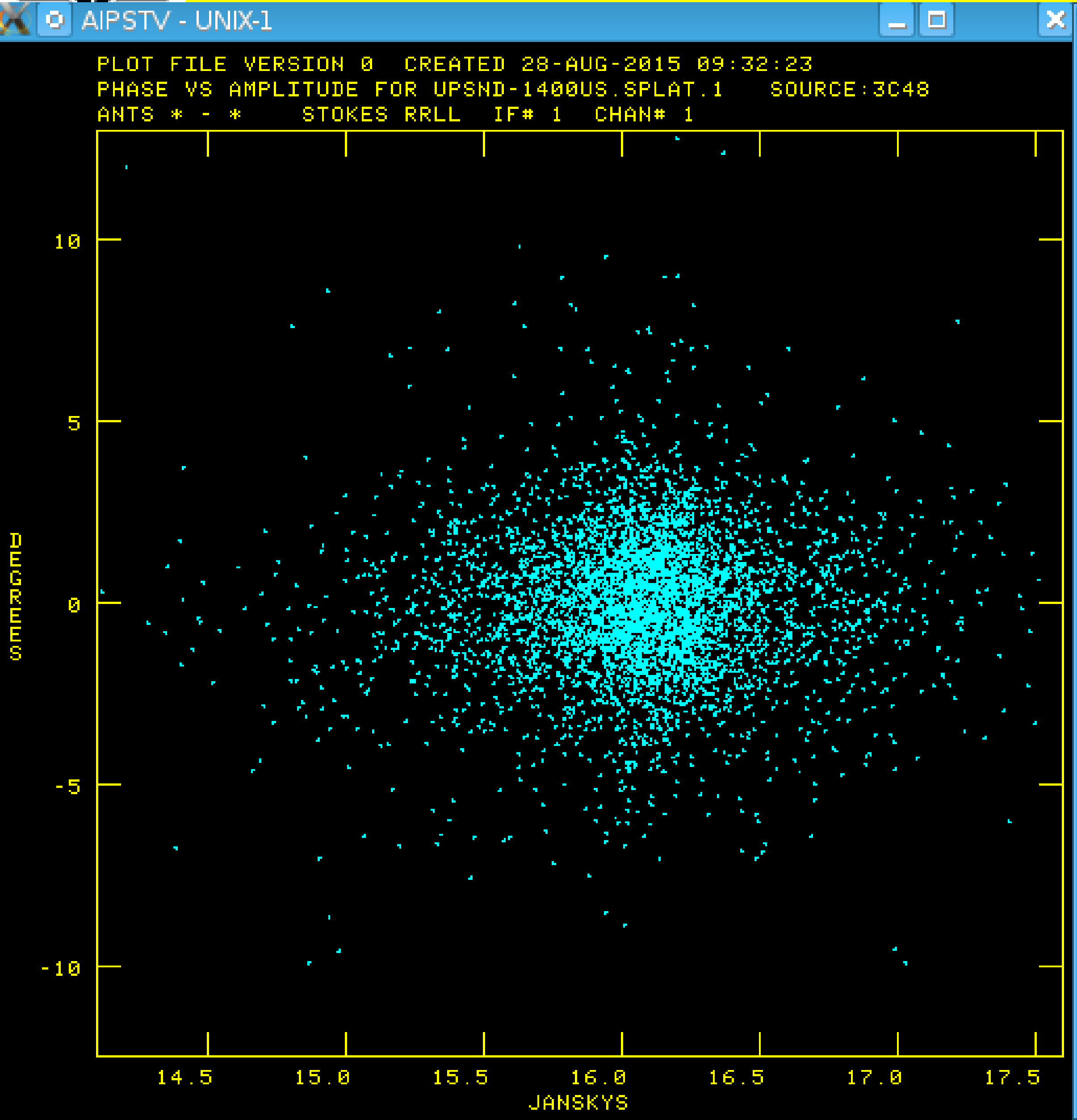
One (very) bad baseline can skew and after flagging one antenna, gain of all antenna may change..

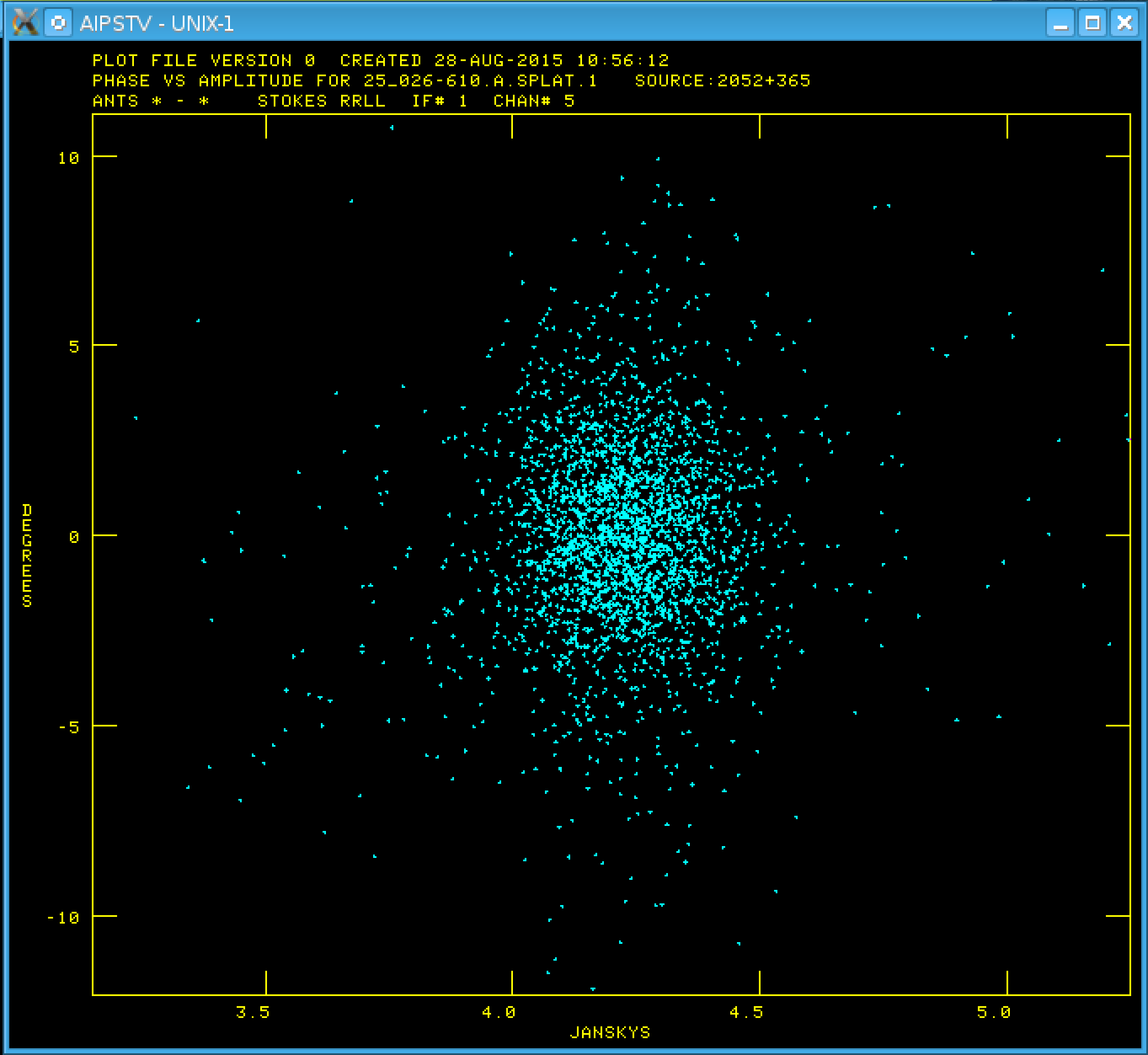
<u>More on this in tutorials..</u>


AIPSTV - UNIX-1
PLOT FILE VERSION 0 CREATED 28-AUG-2015 12:44:08
AMPLITUDE VS UV DIST FOR 09CHI_USB610.SPLAT.2 SOURCE:3C286
ANTS * - * STOKES RR IF# 1 CHAN# 1 - 4
JANSKYS
24
23
22
21
20
19
0 10 20 30 40 50
KILO WAVLNGTH


AIPSTV - UNIX-1
PLOT FILE VERSION 0 CREATED 28-AUG-2015 09:35:47
PHASE VS UV DIST FOR UPSND-1400US.SPLAT.1 SOURCE:3C48
ANTS * - * STOKES RRLL IF# 1 CHAN# 1
DEGREES
10
5
0
-5
-10
0 20 40 60 80 100 120
KILO WAVLNGTH

two-in-one plots (amp and phase)





NCRA • TIFR

Accuracy of Calibration

8 different observations spread across a month

setjy: 3C48 [I=32.181, Q=0, U=0, V=0] Jy @ 5.5005e+08Hz, (Perley-Butler 2017)
setjy: 3C48 [I=32.181, Q=0, U=0, V=0] Jy @ 5.5005e+08Hz, (Perley-Butler 2017)
setjy: 3C48 [I=32.181, Q=0, U=0, V=0] Jy @ 5.5005e+08Hz, (Perley-Butler 2017)
setjy: 3C48 [I=32.181, Q=0, U=0, V=0] Jy @ 5.5005e+08Hz, (Perley-Butler 2017)
setjy: 3C48 [I=32.181, Q=0, U=0, V=0] Jy @ 5.5005e+08Hz, (Perley-Butler 2017)
setjy: 3C48 [I=32.181, Q=0, U=0, V=0] Jy @ 5.5005e+08Hz, (Perley-Butler 2017)
setjy: 3C48 [I=32.181, Q=0, U=0, V=0] Jy @ 5.5005e+08Hz, (Perley-Butler 2017)
setjy: 3C48 [I=32.181, Q=0, U=0, V=0] Jy @ 5.5005e+08Hz, (Perley-Butler 2017)

Secondary calibrator:
fluxscale: 2302-373 : 5.05515 +/- 0.0395423
fluxscale: 2302-373 : 5.06486 +/- 0.0431466
fluxscale: 2302-373 : 4.97007 +/- 0.034872
fluxscale: 2302-373 : 4.97647 +/- 0.0274267
fluxscale: 2302-373 : 4.86727 +/- 0.025956
fluxscale: 2302-373 : 4.89262 +/- 0.0360364
fluxscale: 2302-373 : 4.90953 +/- 0.0097764
fluxscale: 2302-373 : 4.92557 +/- 0.0279088

Range: 4.86 to 5.06, end to end
OR   4.96 +/- 0.1   (~ 2%)

EXPECT small fluctuations like this due to various factors like elevation, SNR, etc

< 10% is acceptable

Tsys calibration - off and on galactic plane

The flux scale problem when observing close to galactic plane;

$T_{sys} = T_{rec} + T_{grnd} + T_{sky}$;

At 610 MHz, T_{rec}+T_{grnd} is 92K. T_{sky} away from galactic plane ~ 10K and near galactic plane can be a few hundred K.

The fringe strength is ~ Ta/T_{sys} ; can vary a factor of few (for Automatic Gain Correction ON). If not corrected, flux scale will be wrong by that order.

Subhasis's Lecture on "Observing in the Galactic Plane"

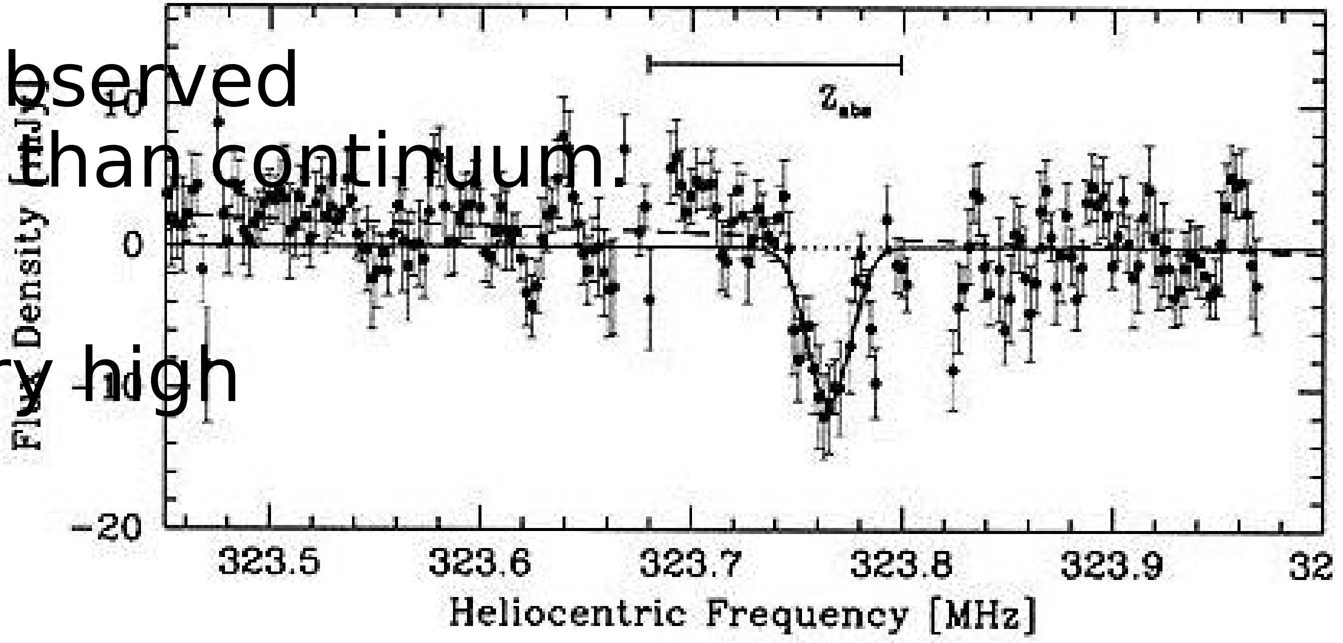
Spectral Line Calibration.

To detect emission or absorption at certain freq, with continuum on either side.

Exteremely good bandpass calibration is very important –

Bandpass calibrator should be observed
more frequently than continuum.

The SNR of bandpass should very high



Talk by Prasun Datta

Polarisation calibration

Parralactic angle (alt-az mount)

Position angle of polarization vector

Accurate estimate of polarisation leakage

Talk by Preeti Kharb

Other "Advanced" Issues

Wide band calibration ($\Delta\nu/\nu > 0.1$; sometimes 1!) *(Urvashi's talk)*

Antenna pointing changes during observations *(affects dynamic range; Ravi's talk)*

Beam rotation (non-circular beam)

Direction dependent phase correction (wide primary beam) *(Dharam's talk)*

Concluding Remarks

Most common types of calibration:-

Primary, Secondary, Bandpass and Polarization.

It is important to flag the bad data before calibration

Keep track of calibrator properties while observing and calibrating–

Even clean data without good calibrator is useless

The calibration is becoming more complex with upcoming facilities with large bandwidth, large field of view and high sensitivity.

'Self-calibration' *has revolutionised in* improving the image quality ***(Dwaraka's Talk)***

NCRA • TIFR