PdBI data calibration

Frédéric Gueth

IRAM Grenoble

PdBI data processing

(1) What did happen at the Plateau

- Instrument calibrated
  - pointing, focus
  - antenna positions *
  - delays
- Raw data are writen in an **.ipb file**
- Calibration applied on-site:
  - **IF bandpass** (measured on noise diode)
  - **atmospheric absorption** ($\longrightarrow$ unit = Kelvin, not counts) *
  - **real-time atmospheric phase** correction

* can be corrected/modified off-line if necessary

PdBI data processing

(2) Off-line data calibration

- Four main steps
  - **RF bandpass**
  - **phase fluctuations vs. time**
  - **absolute flux calibration**
  - **amplitude fluctuations vs. time**
- Off-line calibrations are stored in a **.hpb file**

(3) After the data calibration: imaging

Calibration (CLIC) $\longrightarrow$ *uv*-table $\longrightarrow$ Imaging & Deconvolution (MAPPING)

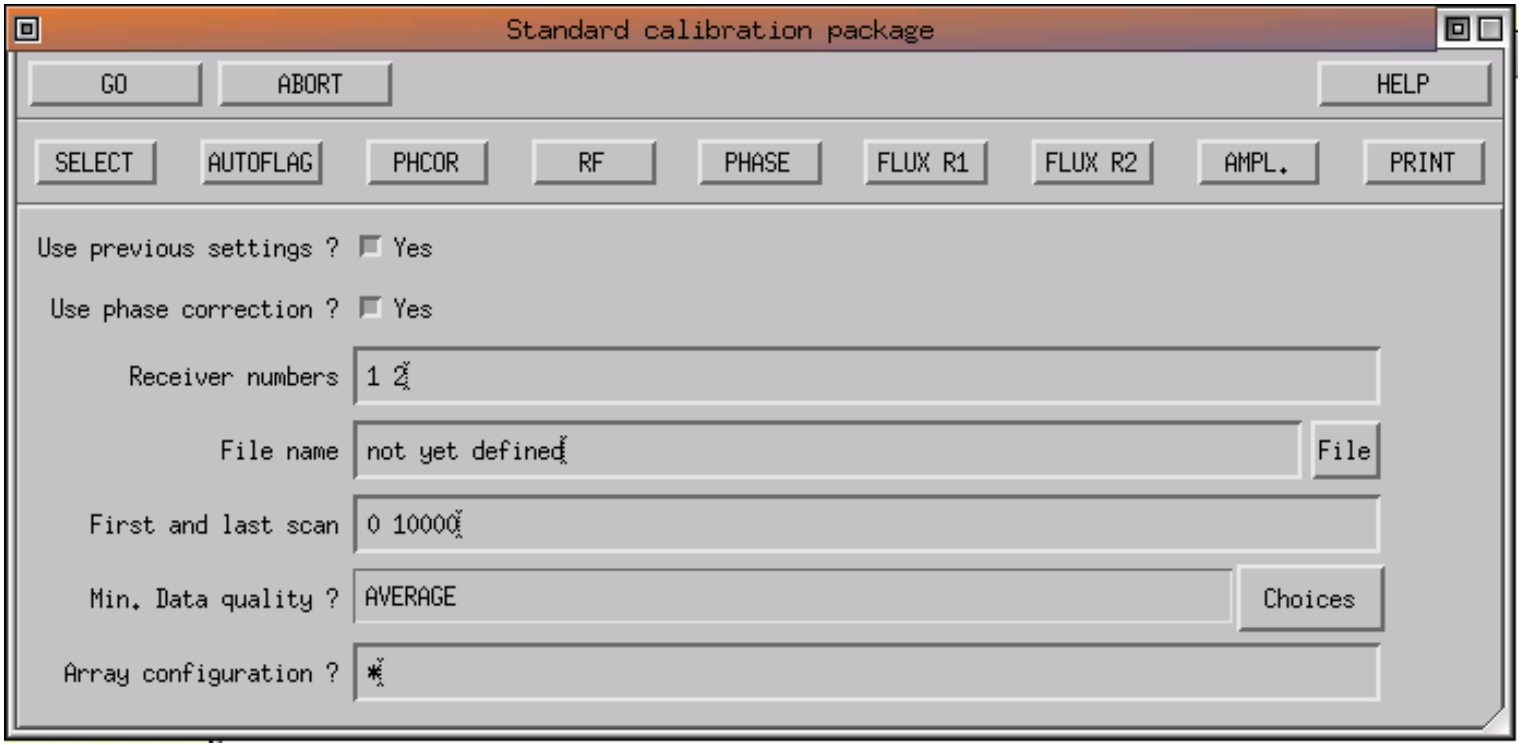
GILDAS

- **Data reduction package for millimeter astronomy** (interferometer and single-dish)
- Developed at IRAM and Observatoire de Grenoble
  - MPIfR, IEM–CSIC, Observatoire de Bordeaux, LERMA
- Collection of software sharing the same environment and scripting language (`SIC`)
  - **GREG** – Graphical library, image manipulation
  - **CLASS** – Single-dish spectra calibration
  - **CLIC** – PdBI calibration
  - **MAPPING** – PdBI imaging

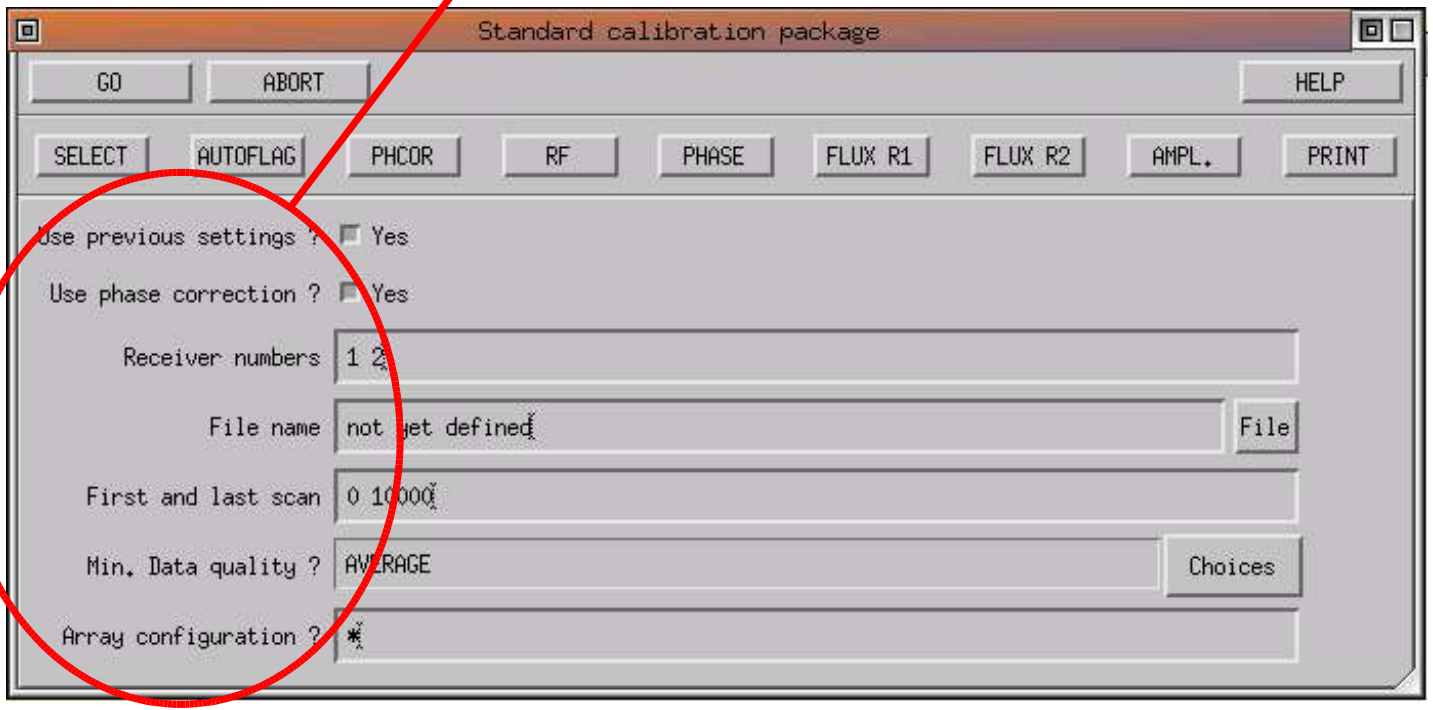
`http://www.iram.fr/IRAMFR/GILDAS`

`gildas@iram.fr`

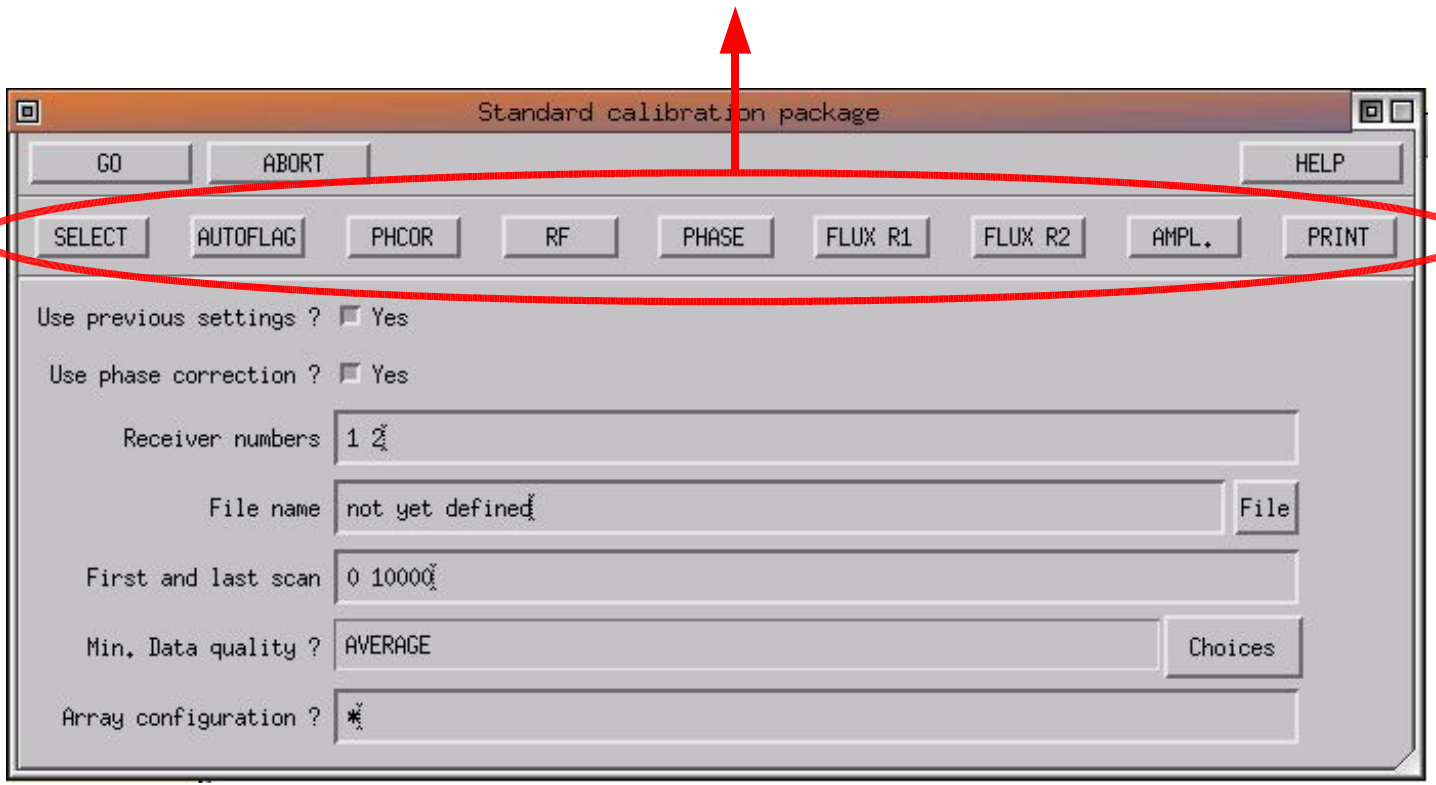
Standard PdBI calibration user interface



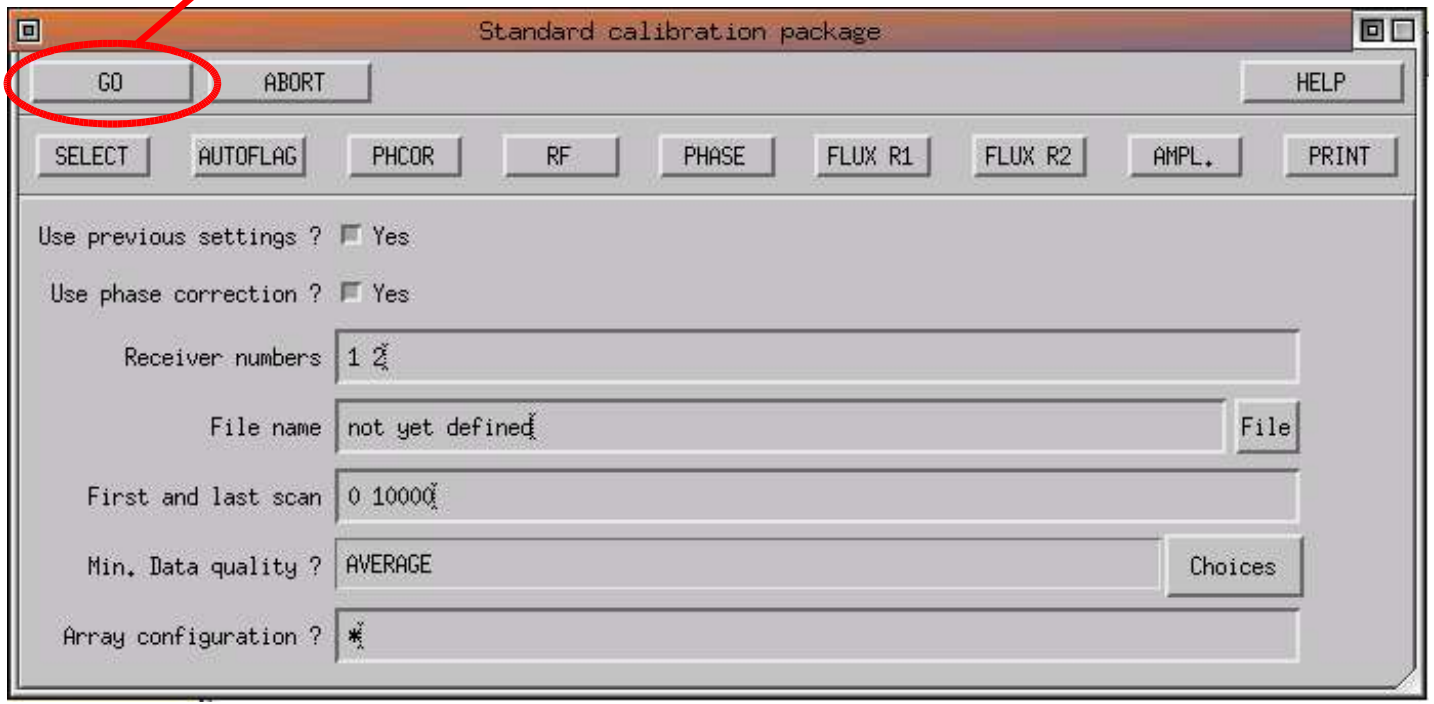
Input parameters to reduce an observation



One button per calibration step
The user can check/modify the results



All calibration steps in a row (pipeline)

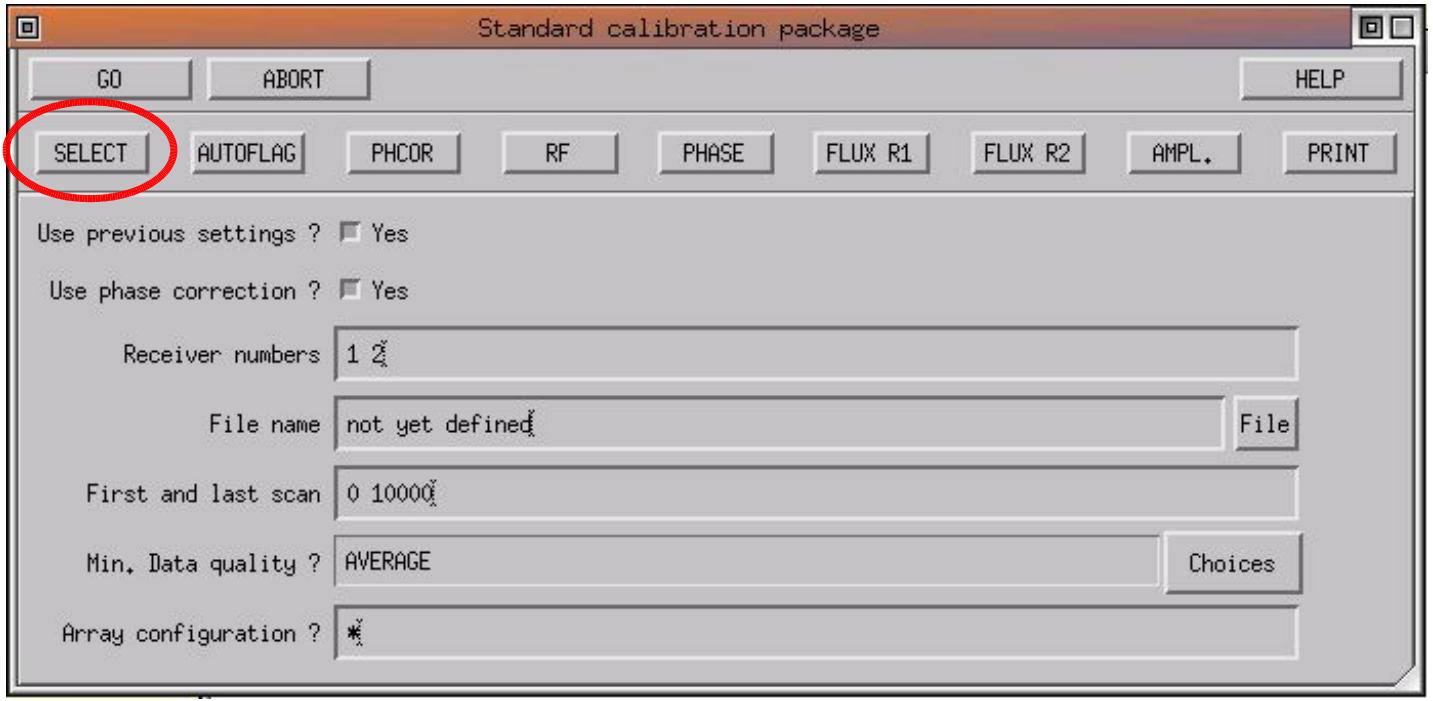


Input parameters

- `Use previous settings?` – In case the calibration was already done
- `Use phase correction?` – Use or not atmospheric phase correction: should always be **yes**
- `Receivers numbers` – Receiver **1** = 3 mm (85–115 GHz)
  Receiver **2** = 1 mm (210–245 GHz)
- `File name` – File to be calibrated
- `First and last scan` – To select only part of the data
- `Min. Data Quality?` – To select only part of the data
- `Array configuration?` – In case of configuration change

In most cases, only the file name must be entered

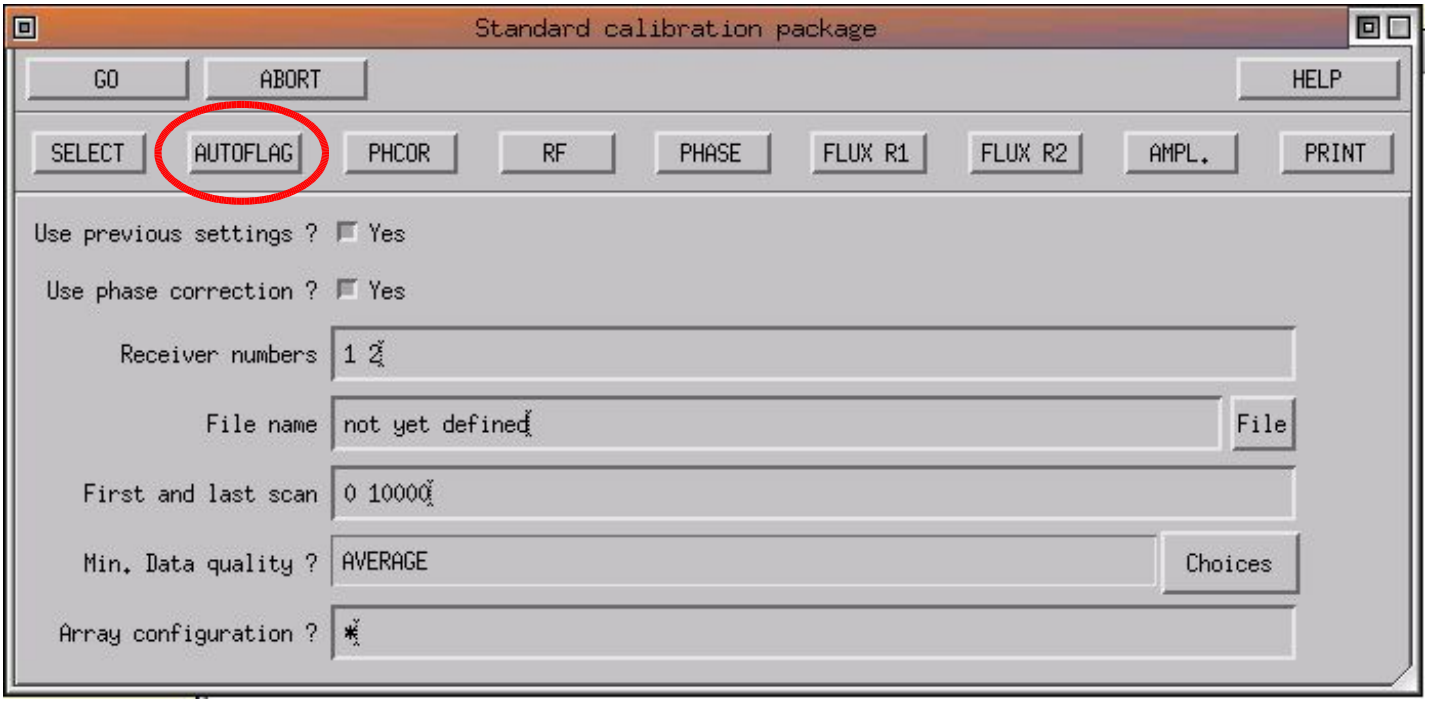
SELECT: Open the file



SELECT

- Open the file
- Basic checks, initializations of pipeline variables
- Automatic determination of the **receiver tuning (LSB/USB/DSB)**
- Detect possible **re-tuning of the receivers during the observations**
- Find the **bandpass calibrator** (= strongest quasar)

AUTOFLAG: Automatic flagging



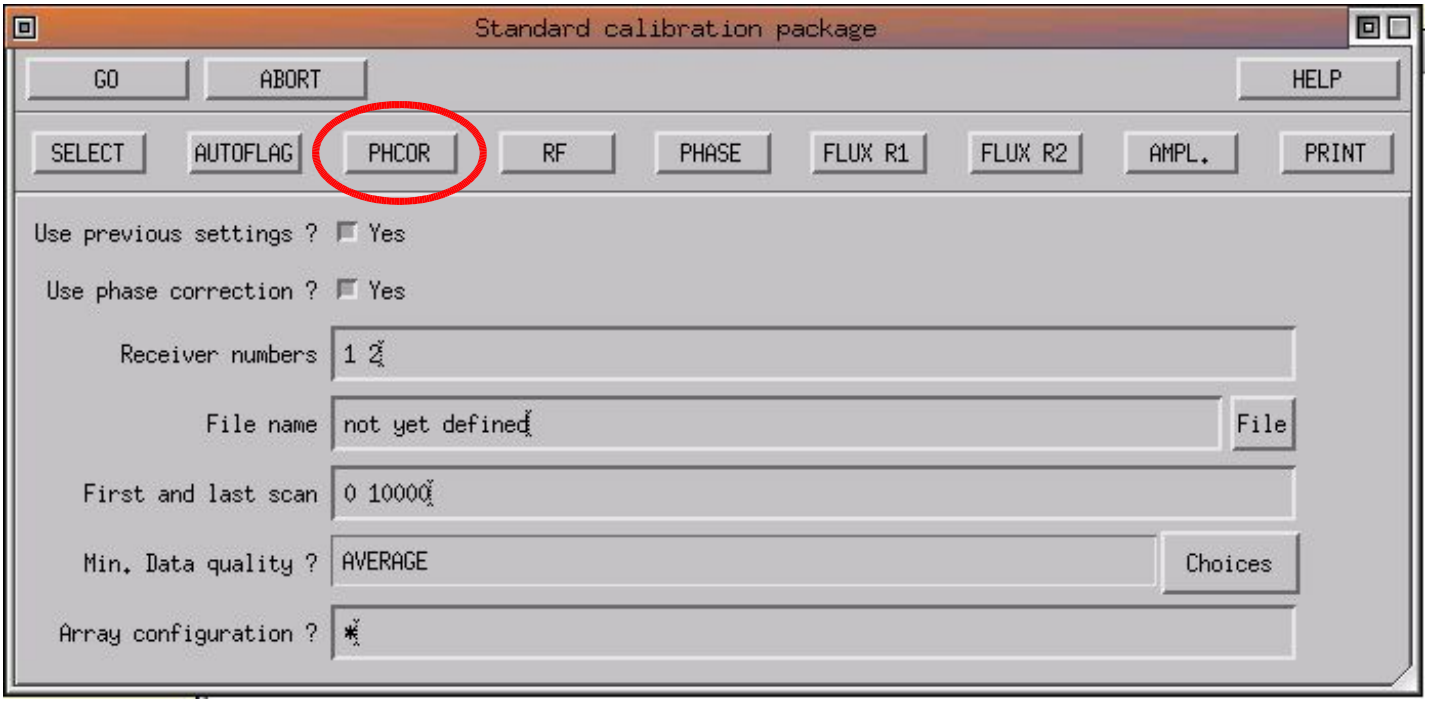
AUTOFLAG

- Instrumental problems are detected on site $\longrightarrow$ data are **flagged with keywords** (e.g. LOCK, L01, TSYS, ...)

- Off-line flagging of the data to **detect and flag possible corrupted scans**: loop on all scans and look for
  - timing error problems
  - wrong amplitude points *(not yet implemented)*

- Also: check observing date and warn for known problems at the time of the observations

PHCORR: Atmospheric phase correction



Atmospheric phase correction

- Water emission ⟶ Atmospheric model ⟶ Path length ⟶ Phase

- Water emission measurement
  - used to be based on **1 mm total power** measurements
  - now based on **22 GHz water vapour radiometers**

- Plateau de Bure real-time phase correction
  - applied to scan-averaged (∼1 min) data in the correlator
  - mostly a **correction of the amplitude decorrelation**
  - **both corrected and non-corrected data are stored in the file**

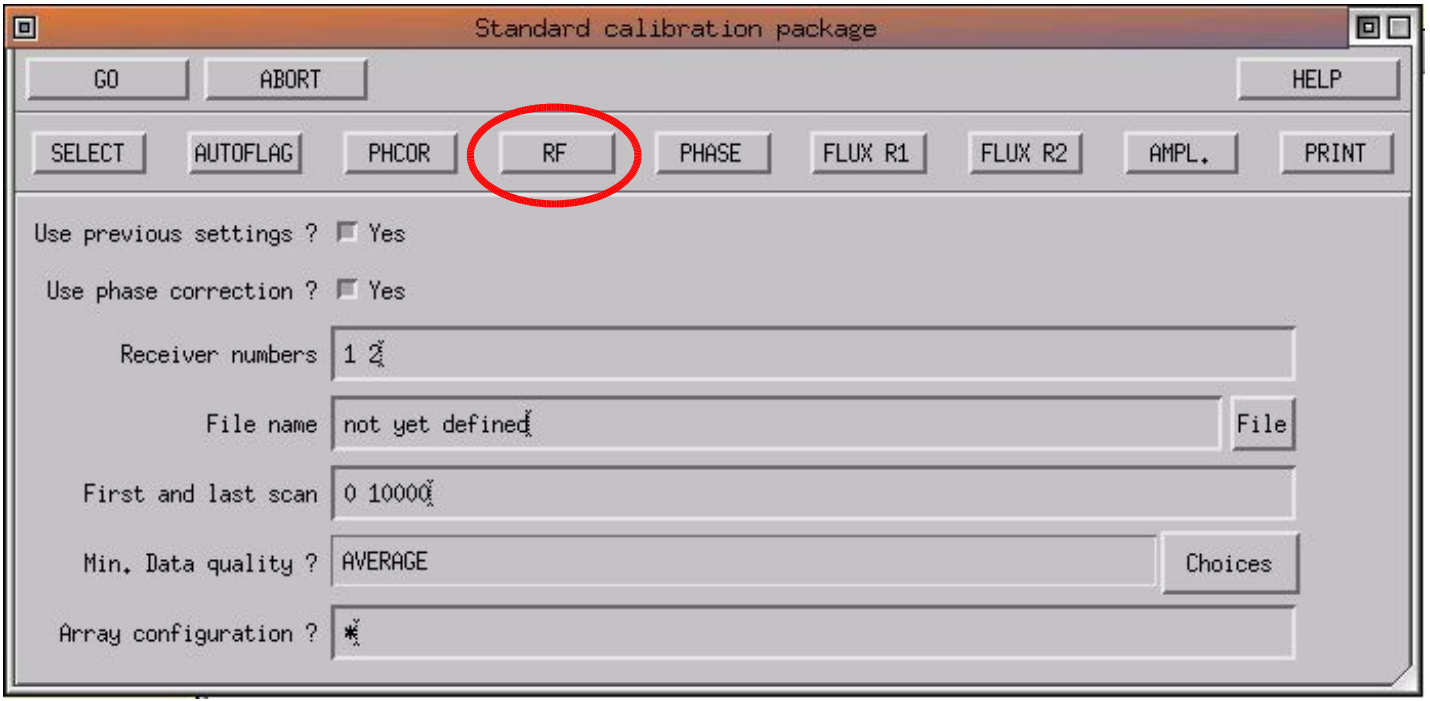
PHCORR

- For all calibrator measurements: **check whether the real-time atmospheric phase correction improves or the result or not**
  - compare corrected and uncorrected data for each scan
  - amplitude should be higher on the corrected data...
  - store antenna-based flag in each scan
- Test done at 3 mm, then used also at 1 mm
- Astronomical targets: the result obtained on the closest (in time) calibrator measurement is used
- In all further processing, the **phase correction is used only if it improves the result** (default behaviour of CLIC)

PHCORR – Example

```
Real-time atmospheric phase correction
Scans 1390 to 1390 : phase correction disabled (ant  1 2 3 4)
Scans 1403 to 1403 : phase correction disabled (ant  1 3 4)
Scans 1409 to 1425 : phase correction disabled (ant  1 3 4)
Scans 2075 to 2096 : phase correction disabled (ant  1 2 3 4)
Scans 2097 to 2097 : phase correction disabled (ant  1 4)

Ant. 1: real-time phase correction based on Total Power monitor
Ant. 2: real-time phase correction based on Total Power monitor
Ant. 3: real-time phase correction based on Total Power monitor
Ant. 4: real-time phase correction based on Total Power monitor
```

RF: RF Bandpass calibration



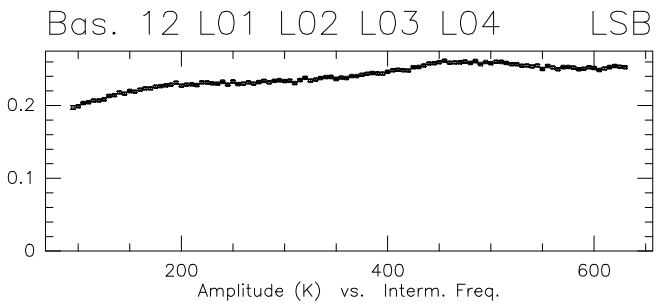
RF Bandpass calibration

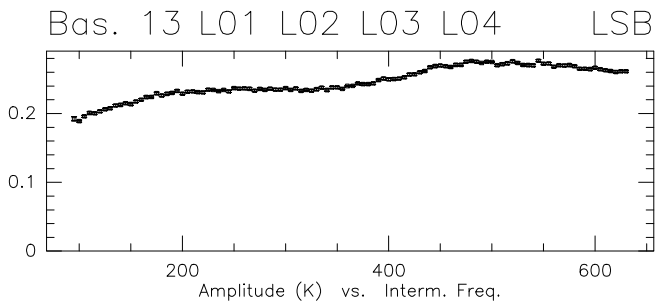
- Basic assumption: **the frequency- and time- variations are independant**
  - RF bandpass constant during the observations
  - RF bandpass mainly originates from the receiver $\longrightarrow$ must be re-calibrated after each re-tuning

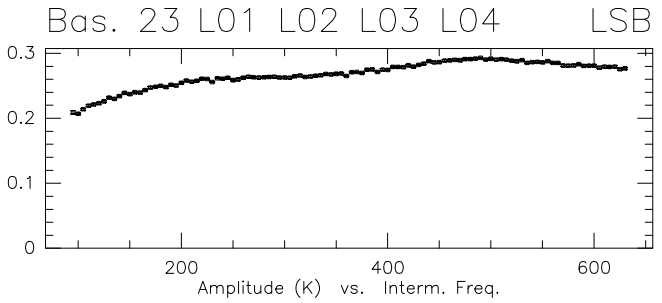
- Calibration method:
  - a **strong quasar** is observed at the beginning of each project (typically: 10–15 minutes)
  - **its phase must be zero, its amplitude must be constant $\longrightarrow$ fit a gain vs. frequency curve** to estimate the RF bandpass
  - correct all subsequent data for this bandpass

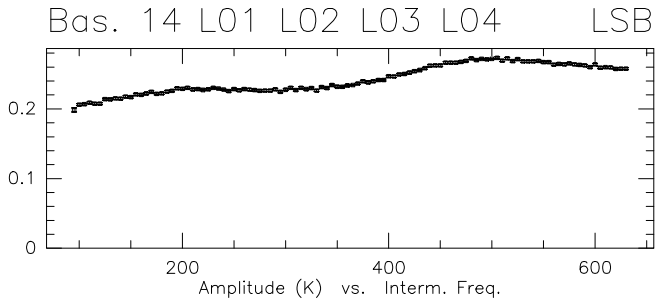
RF

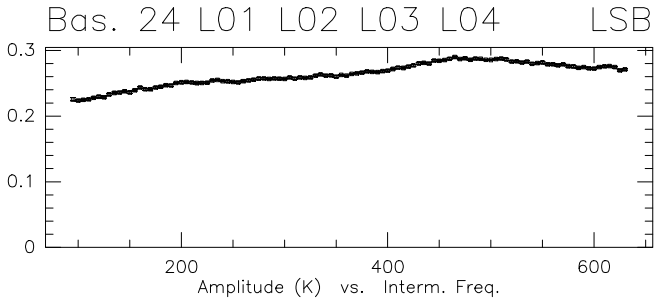
- Select the bandpass calibrator observations
- Self-calibration and average in time (improves SNR)
- Smooth to 5 MHz resolution (improves SNR)
- Solve for **antenna-based gain** (both amplitude and phase)
- Fit polynomial amplitude and phase vs. frequency curves
- Store calibration curves in all observations (calibrators + sources)
- **Do this calibration for:**
  - each scan range (receiver re-tuning)
  - 3 mm and 1 mm receivers
  - USB and LSB

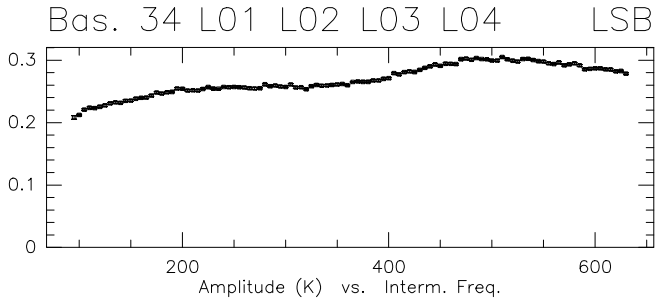

Bas. 12 L01 L02 L03 L04 LSB
0.2
0.1
0
200
400
600
Amplitude (K) vs. Interm. Freq.

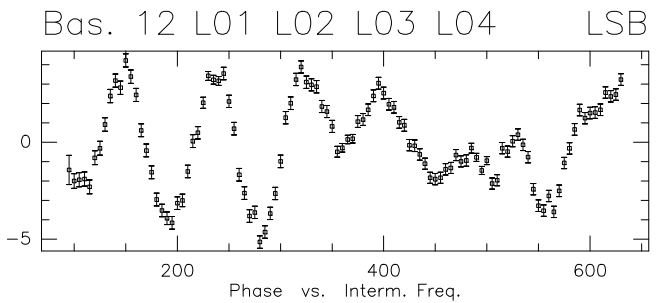

Bas. 13 L01 L02 L03 L04 LSB
0.2
0.1
0
200
400
600
Amplitude (K) vs. Interm. Freq.

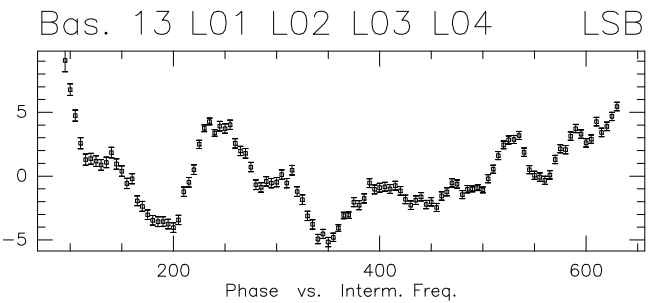

Bas. 23 L01 L02 L03 L04 LSB
0.3
0.2
0.1
0
200
400
600
Amplitude (K) vs. Interm. Freq.

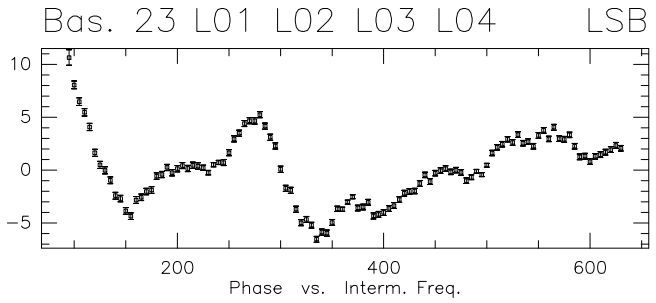

Bas. 14 L01 L02 L03 L04 LSB
0.2
0.1
0
200
400
600
Amplitude (K) vs. Interm. Freq.

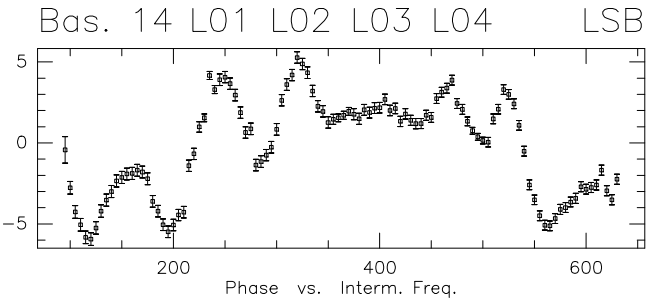

Bas. 24 L01 L02 L03 L04 LSB
0.3
0.2
0.1
0
200
400
600
Amplitude (K) vs. Interm. Freq.

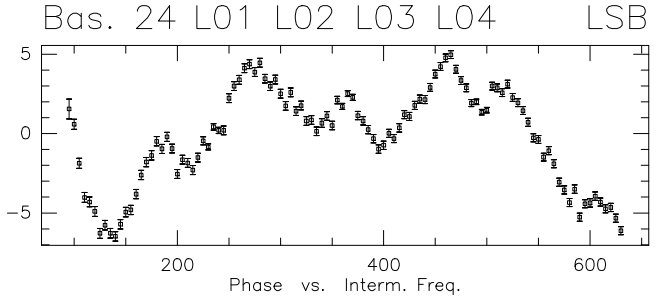

Bas. 34 L01 L02 L03 L04 LSB
0.3
0.2
0.1
0
200
400
600
Amplitude (K) vs. Interm. Freq.

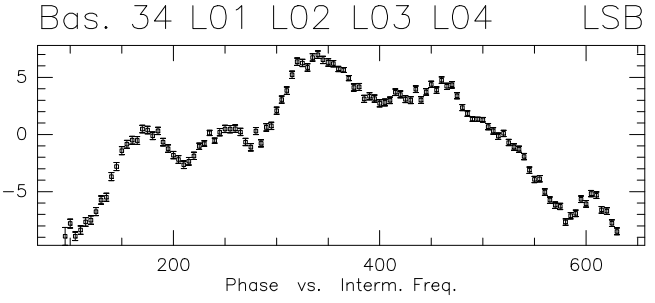

Bas. 12 L01 L02 L03 L04 LSB
0
−5
200
400
600
Phase vs. Interm. Freq.


Bas. 13 L01 L02 L03 L04 LSB
5
0
−5
200
400
600
Phase vs. Interm. Freq.


Bas. 23 L01 L02 L03 L04 LSB
10
5
0
−5
200
400
600
Phase vs. Interm. Freq.


Bas. 14 L01 L02 L03 L04 LSB
5
0
−5
200
400
600
Phase vs. Interm. Freq.


Bas. 24 L01 L02 L03 L04 LSB
5
0
−5
200
400
600
Phase vs. Interm. Freq.

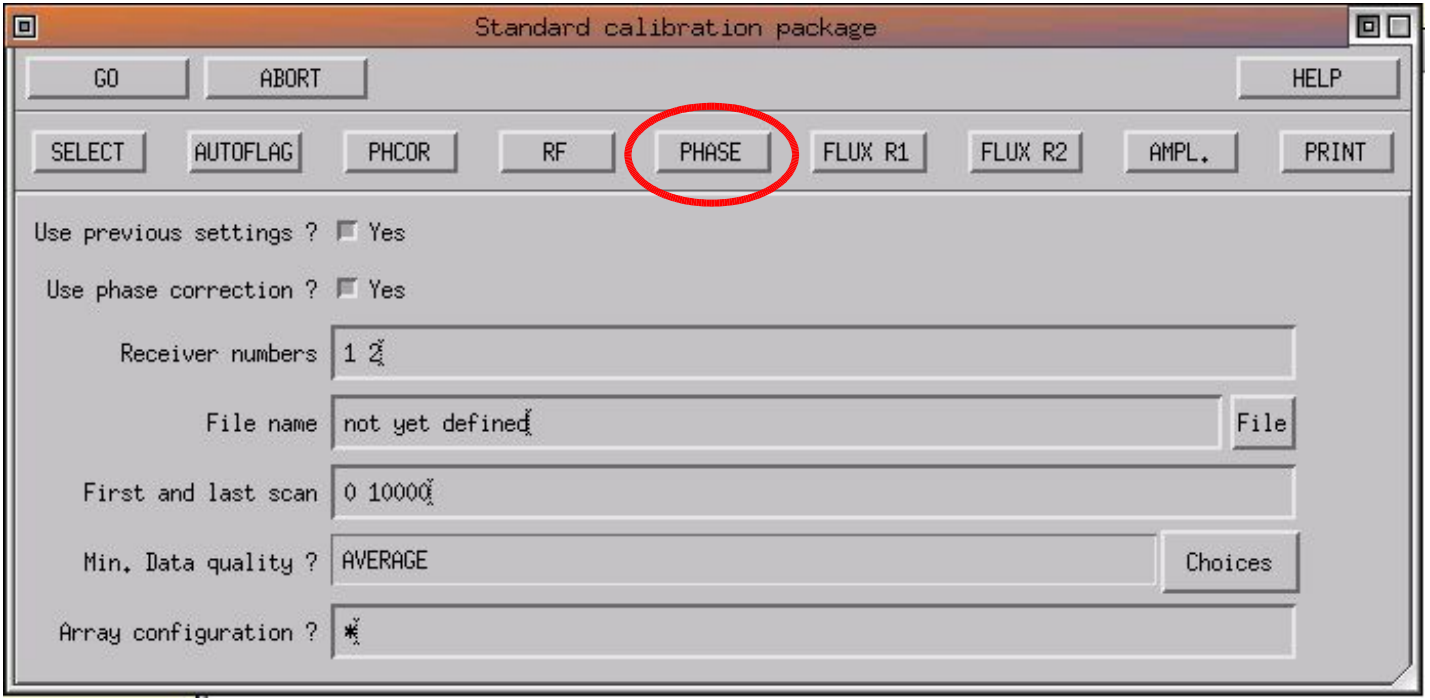

Bas. 34 L01 L02 L03 L04 LSB
5
0
−5
200
400
600
Phase vs. Interm. Freq.

Interactive mode

```
(...)
I-SOLVE_RF,[1361] Pha. Bas. 14  L01 L02 L03 L04 LSB rms:   1.006
I-SOLVE_RF,[1361] Pha. Bas. 24  L01 L02 L03 L04 LSB rms:  0.5631
I-SOLVE_RF,[1361] Pha. Bas. 34  L01 L02 L03 L04 LSB rms:  0.4665
LSB Bandpass Calibration for receiver 1:
Command was SOLVE RF 6 18 /PLOT
CLIC_3> SIC\PAUSE
CLIC_4>
```

- RF calibration very robust, no input usually required
- CO absorption in front of quasars $\longrightarrow$ usually does not affect the fit, no need to flag data

PHASE: Phase calibration



Phase calibration

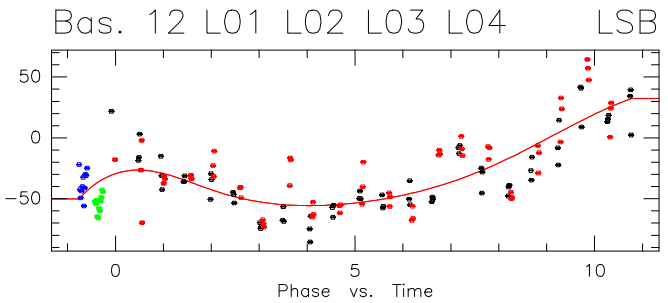
- Time dependence of the phase is caused by the atmosphere **and** the instrument (drifts, baseline errors)

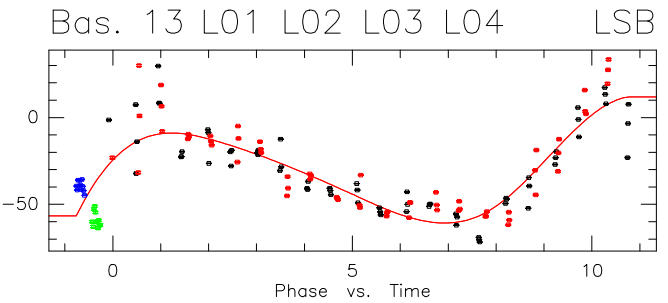
- Calibration method:
  - a point source calibrator (quasar) is observed every $\sim$ 20 minutes
  - **its phase must be zero $\longrightarrow$ fit a gain vs. time to the data to estimate the phase variations**
  - in practice: two calibrators are observed

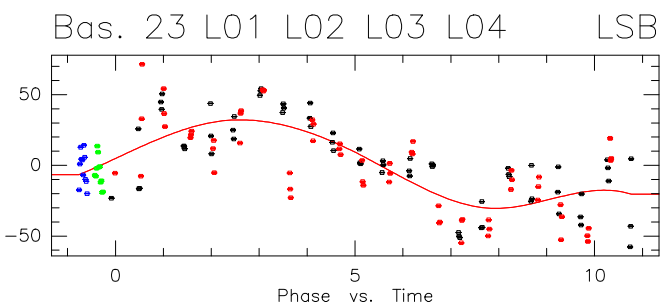
- **Phase transfer**
  - atmospheric fluctuation should scale with frequency
  - one can **use the 3 mm curve (highest SNR) to correct the 1 mm data**
  - the residual fluctuations at 1 mm must still be calibrated

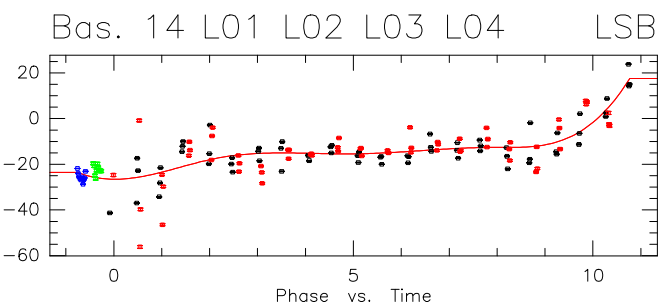
PHASE

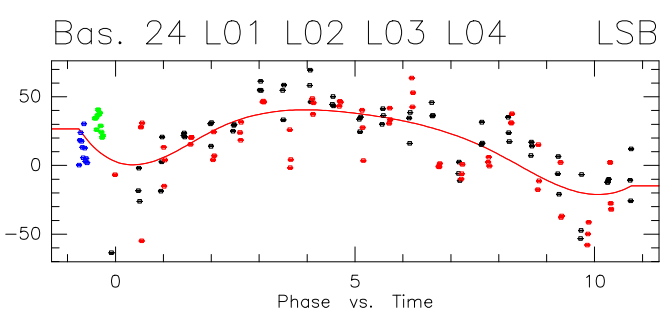
- Select the phase calibrator observations
- Find possible phase jumps (focus)
- Apply RF bandpass calibration
- **Receiver 2: apply Receiver 1 calibration, scaled by ratio of frequency (phase transfert)**
- Derive **antenna-based gain**
- Least-square fit of cubic splines (phase vs. time)
- Store calibration curves in all observations (calibrators + sources)

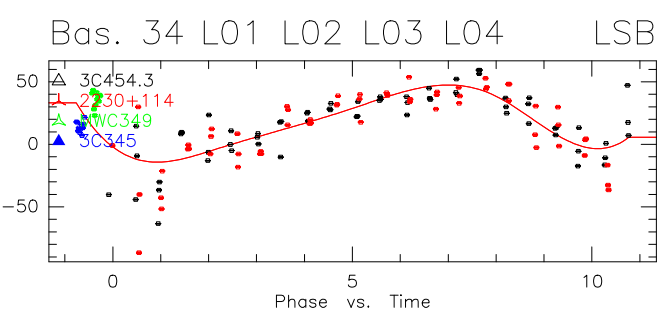

Bas. 12 L01 L02 L03 L04
LSB
50
0
−50
0
5
10
Phase vs. Time

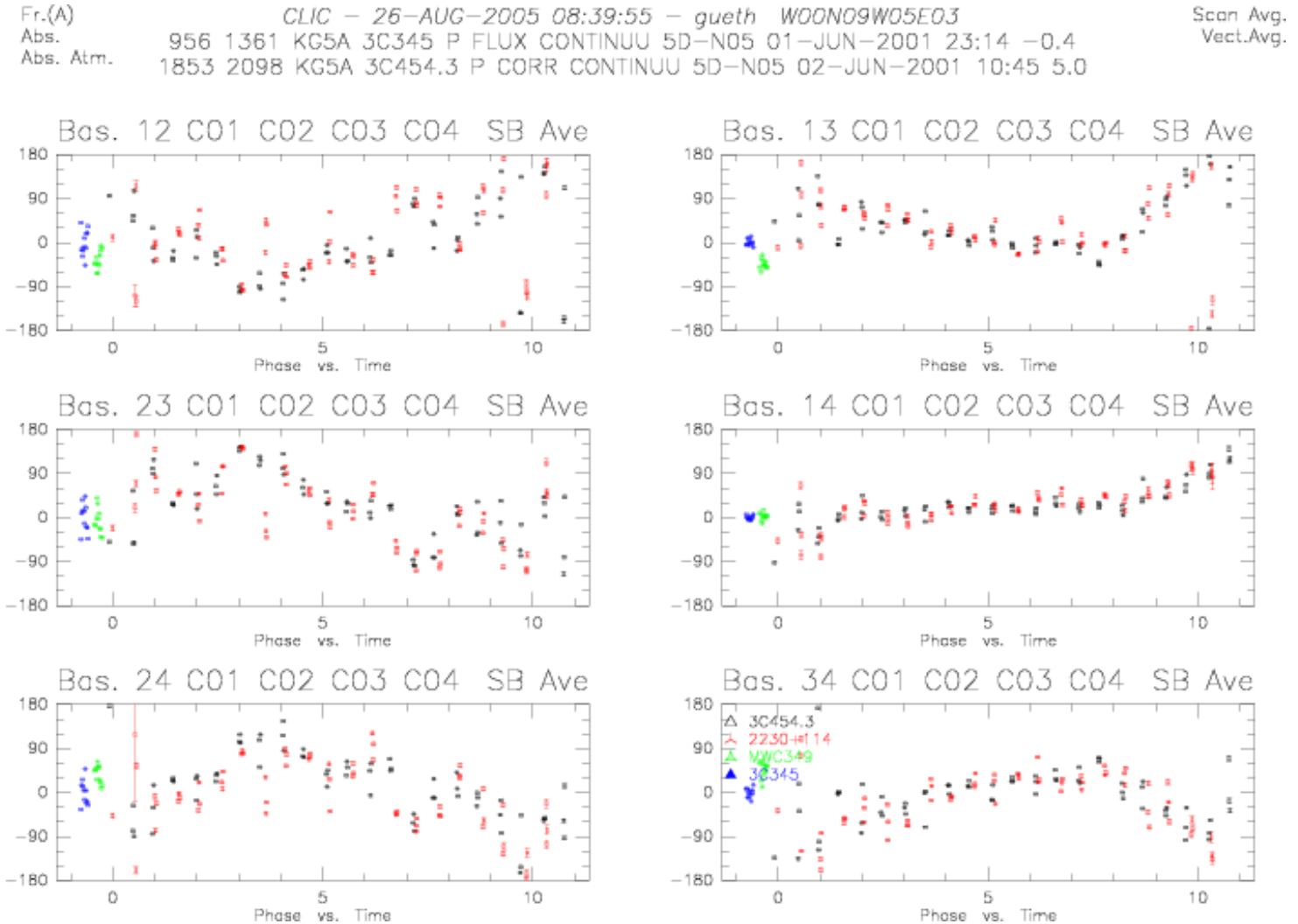

Bas. 13 L01 L02 L03 L04
LSB
0
−50
0
5
10
Phase vs. Time


Bas. 23 L01 L02 L03 L04
LSB
50
0
−50
0
5
10
Phase vs. Time

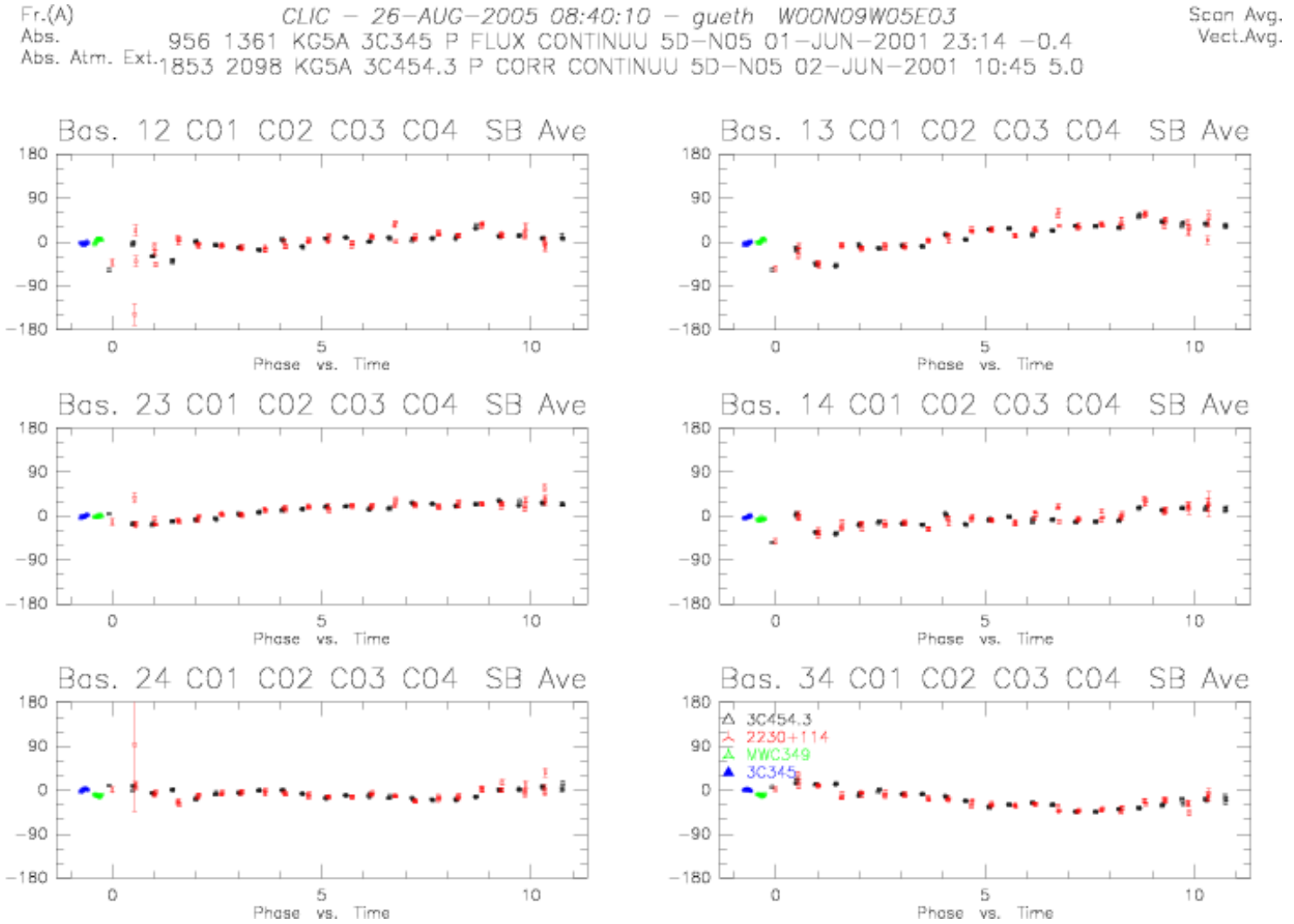

Bas. 14 L01 L02 L03 L04
LSB
20
0
−20
−40
−60
0
5
10
Phase vs. Time


Bas. 24 L01 L02 L03 L04
LSB
50
0
−50
0
5
10
Phase vs. Time


Bas. 34 L01 L02 L03 L04
LSB
3C454.3
2230+114
MWC349
3C345
50
0
−50
0
5
10
Phase vs. Time



230 GHz phase vs. time, no phase transfer

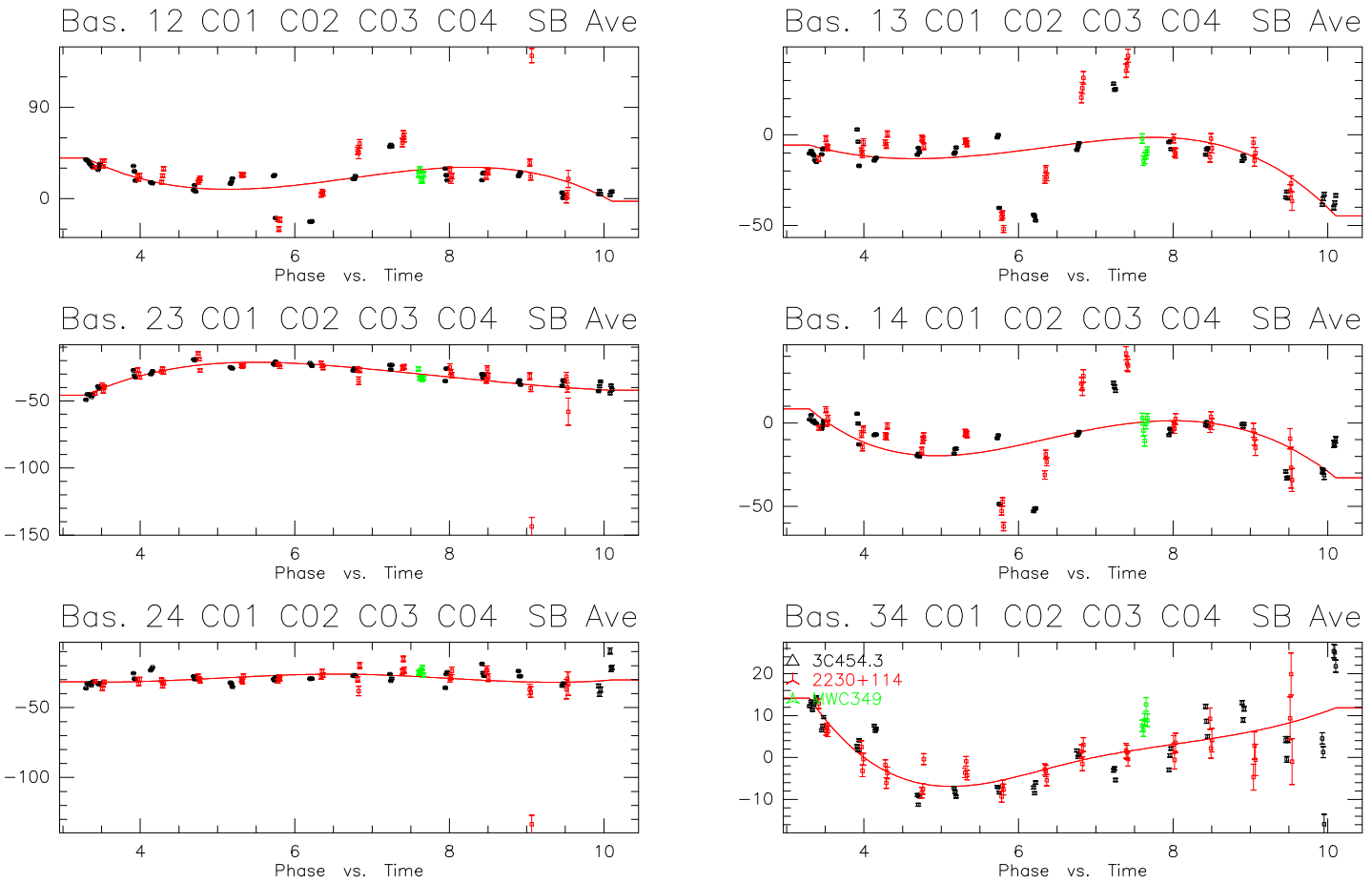


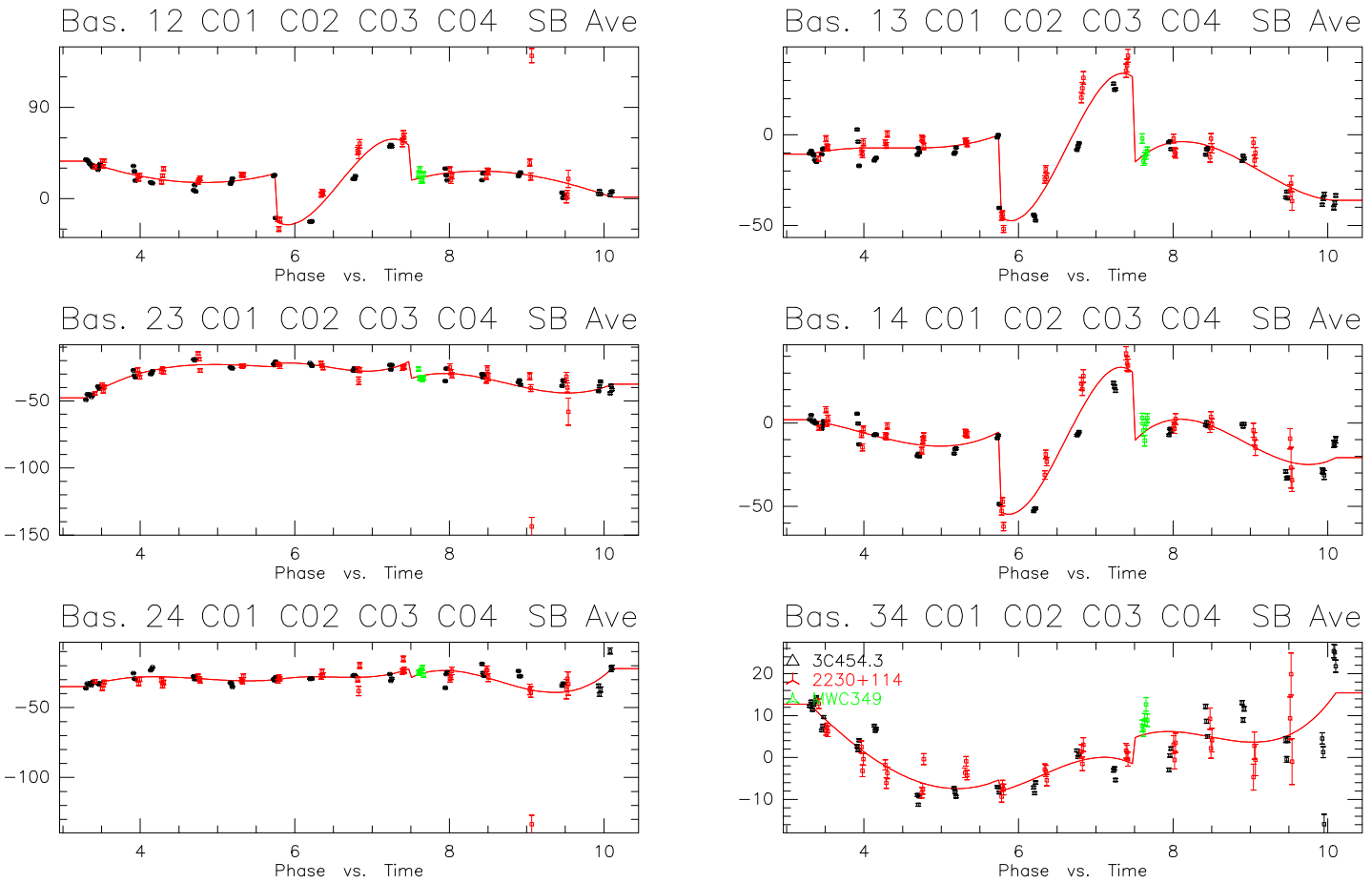
230 GHz phase vs. time, with phase transfer

Interactive mode

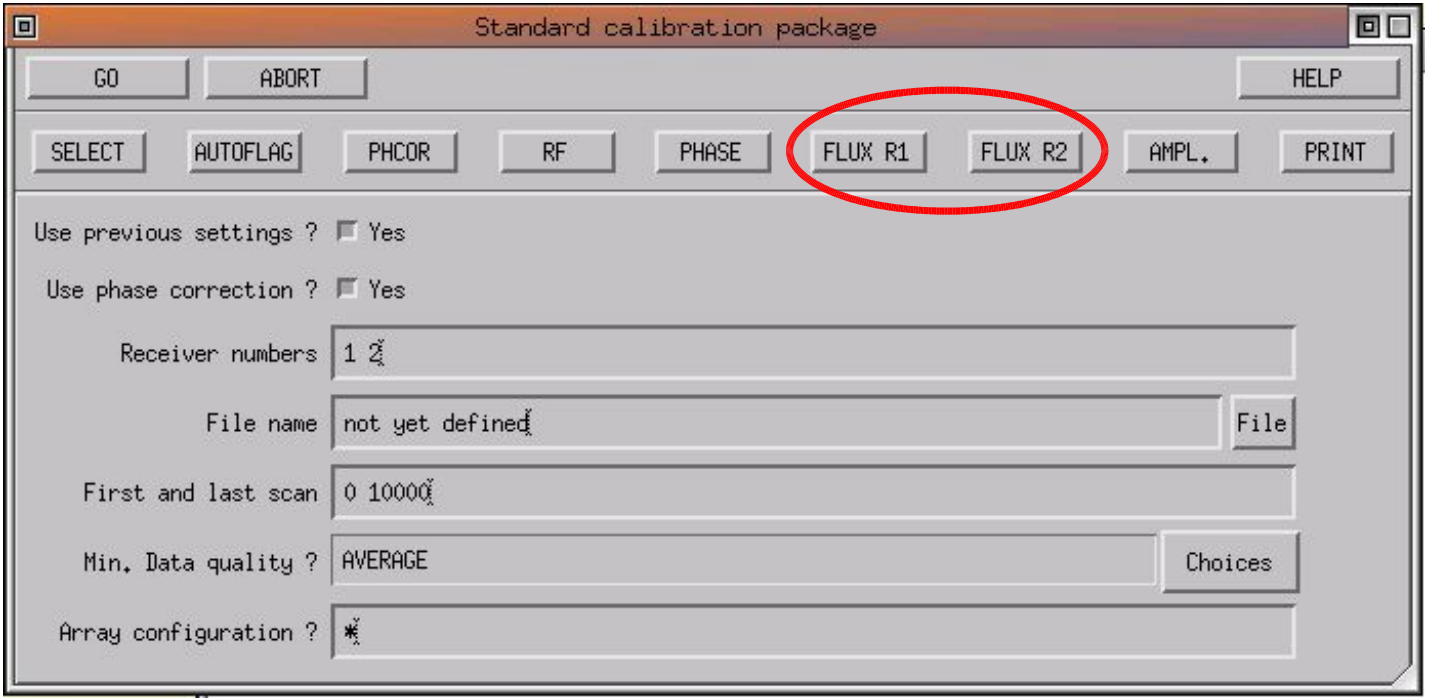
```
(...)
I-SOLVE_CAL,[2098] Pha. Bas. 14  C01 C02 C03 C04 LSB rms:    6.65 deg.
I-SOLVE_CAL,[2098] Pha. Bas. 24  C01 C02 C03 C04 LSB rms:   18.88 deg.
I-SOLVE_CAL,[2098] Pha. Bas. 34  C01 C02 C03 C04 LSB rms:   17.15 deg.
Phase calibration for receiver 1:
Command was SOLVE PHASE  /PLOT
You may try SOLVE PHASE  /PLOT  /BREAK 0 23.5
CLIC_3> SIC\PAUSE
CLIC_4>
```

- Potential problems
  - very noisy data (too weak calibrator)
  - strong drifts (baseline)
  - difference between the two phase calibrators (baseline)
  - phase jumps (focus) $\longrightarrow$ **SOLVE PHASE /BREAK**


Bas. 12 C01 C02 C03 C04 SB Ave
Bas. 13 C01 C02 C03 C04 SB Ave
Bas. 23 C01 C02 C03 C04 SB Ave
Bas. 14 C01 C02 C03 C04 SB Ave
Bas. 24 C01 C02 C03 C04 SB Ave
Bas. 34 C01 C02 C03 C04 SB Ave
Phase vs. Time
3C454.3
2230+114
MWC349


Bas. 12 C01 C02 C03 C04 SB Ave
Bas. 13 C01 C02 C03 C04 SB Ave
Bas. 23 C01 C02 C03 C04 SB Ave
Bas. 14 C01 C02 C03 C04 SB Ave
Bas. 24 C01 C02 C03 C04 SB Ave
Bas. 34 C01 C02 C03 C04 SB Ave
Phase vs. Time
3C454.3
2230+114
MWC349

FLUX: Flux scale calibration



Flux and Amplitude calibration

Backend counts $\longrightarrow$ Temperature (Kelvin) (Ta* scale)

- Done by chopper-wheel calibration at PdBI (every $\sim$20 minutes)
- Correct for
  - variation in electronic gains
  - variation of atmospheric absorption

Temperature (Kelvin) $\longrightarrow$ Flux (Jansky)

- Scaling by **antenna efficiency (Jy/K)**
- **Not sufficient for mm-interferometers**, because
  - amplitude loss due to decorrelation (phase noise)
  - variation of the antenna gain (pointing, focus, ...)

Flux and Amplitude calibration

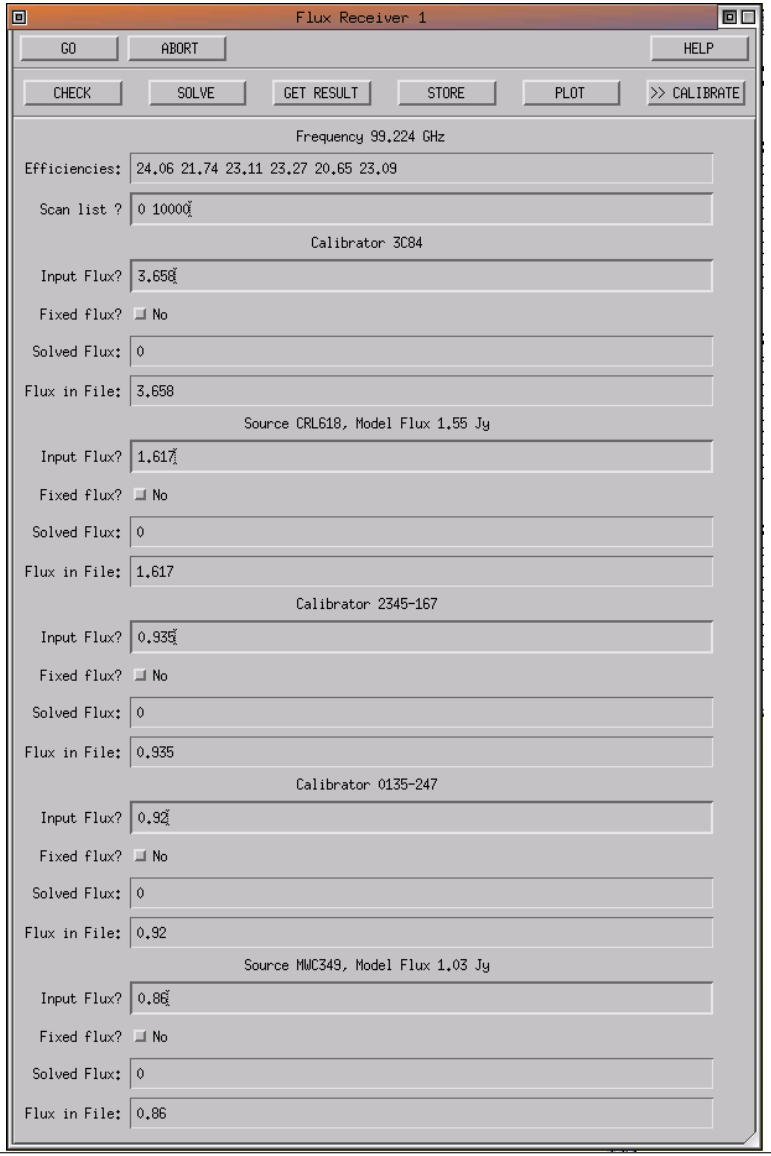
- **Need to do amplitude referencing to a point source** (quasar) to calibrate out the temporal variation of the antenna efficiency
- **Problem**: **all** quasars have varying fluxes and spectral indexes (several 10% in a few months)
- Consequence: amplitude calibration is done in three steps
  1. Atmospheric calibration on site (temperature scale)
  2. Find flux of quasars (`FLUX` button)
  3. Find temporal variation of amplitude (`AMPL` button)

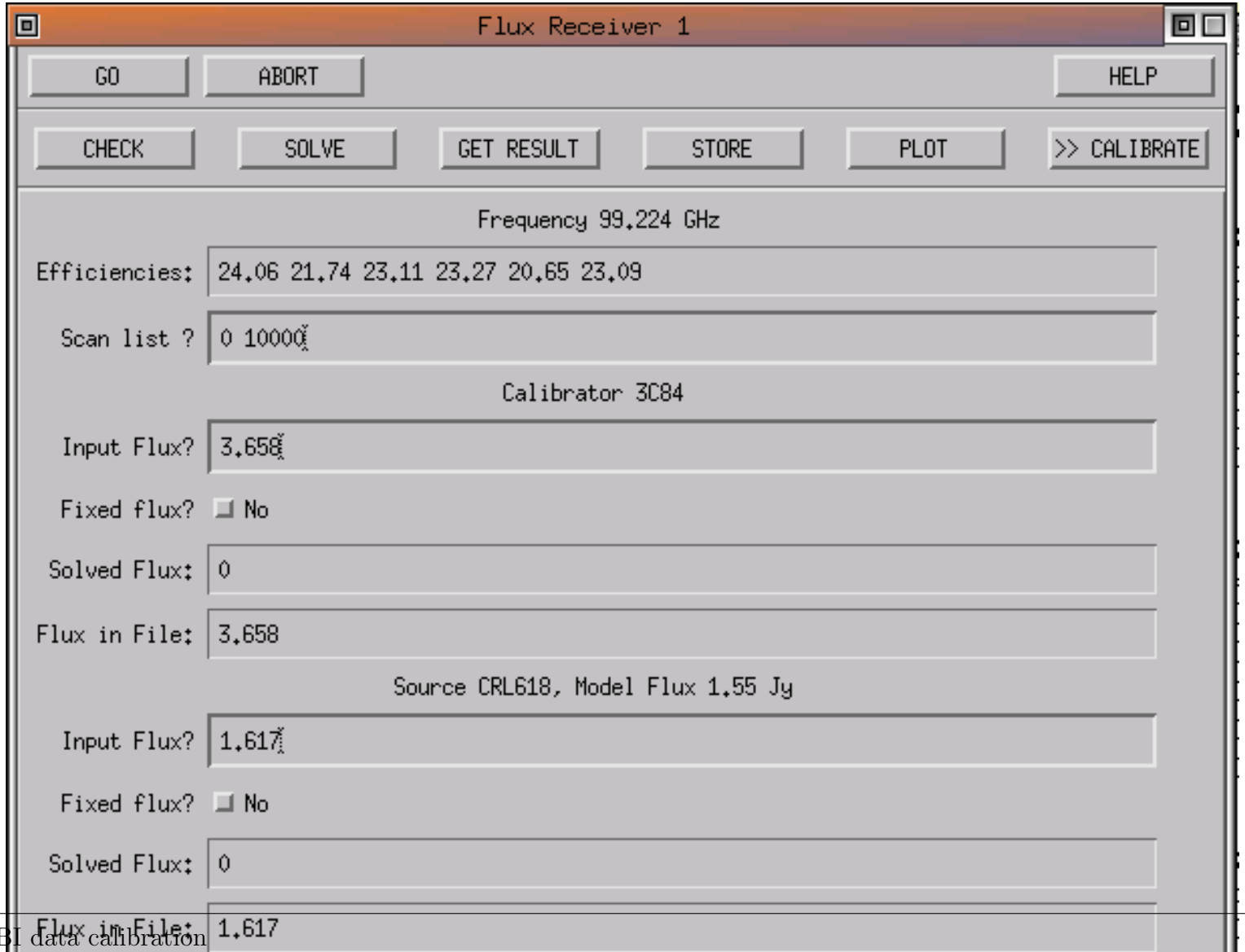
In most project, finding the absolute flux scale (2) is the most difficult step in the calibration

Step 2: Flux calibration

- Principle:
  - fix the flux of one or several **reference source(s)**
  - divide the measured temperature by this flux = antenna efficiencies (Jy/K)
  - apply antenna efficiencies to other sources to derive their flux

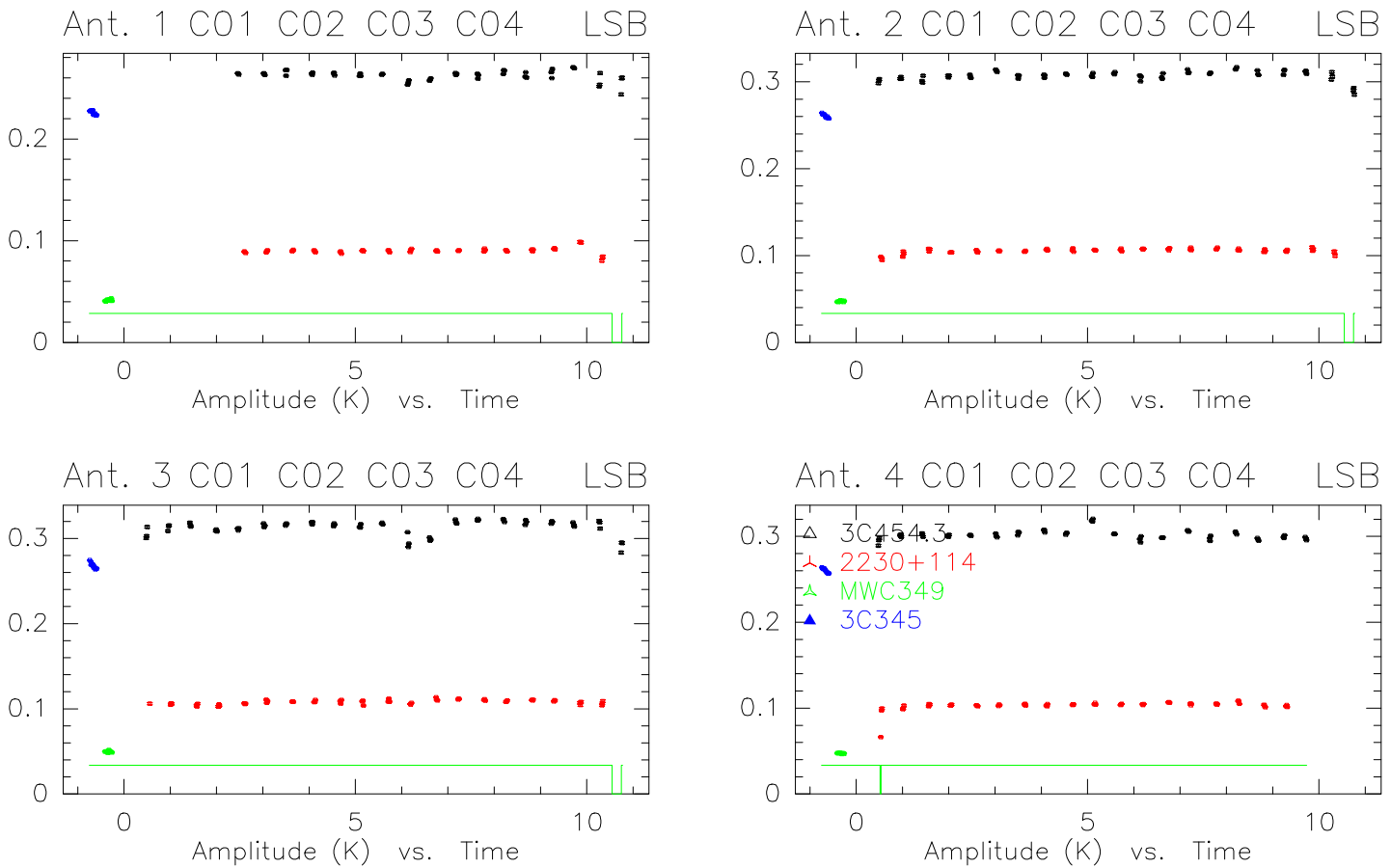
- Reference sources:
  - Planets are primary calibrators
  - **Strong quasars** (used as RF calibrator) have fluxes regularly measured against planets
  - **MWC 349**: $0.95\,(\nu/87)^{0.6}$ Jy
  - **CRL 618**: 1.55 Jy at 3 mm, 2 Jy at 1 mm
  - **MWC 349 and/or CRL 618 are observed in all projects**


Flux Receiver 1
GO
ABORT
HELP
CHECK
SOLVE
GET RESULT
STORE
PLOT
>> CALIBRATE
Frequency 99.224 GHz
Efficiencies: 24.06 21.74 23.11 23.27 20.65 23.09
Scan list ? 0 10000
Calibrator 3C84
Input Flux? 3.658
Fixed flux? No
Solved Flux: 0
Flux in File: 3.658
Source CRL618, Model Flux 1.55 Jy
Input Flux? 1.617
Fixed flux? No
Solved Flux: 0
Flux in File: 1.617
Calibrator 2345-167
Input Flux? 0.935
Fixed flux? No
Solved Flux: 0
Flux in File: 0.935
Calibrator 0135-247
Input Flux? 0.92
Fixed flux? No
Solved Flux: 0
Flux in File: 0.92
Source MWC349, Model Flux 1.03 Jy
Input Flux? 0.86
Fixed flux? No
Solved Flux: 0
Flux in File: 0.86


Flux Receiver 1
GO
ABORT
HELP
CHECK
SOLVE
GET RESULT
STORE
PLOT
>> CALIBRATE
Frequency 99.224 GHz
Efficiencies:
24.06 21.74 23.11 23.27 20.65 23.09
Scan list ?
0 10000
Calibrator 3C84
Input Flux?
3.658
Fixed flux?
No
Solved Flux:
0
Flux in File:
3.658
Source CRL618, Model Flux 1.55 Jy
Input Flux?
1.617
Fixed flux?
No
Solved Flux:
0
Flux in File:
1.617

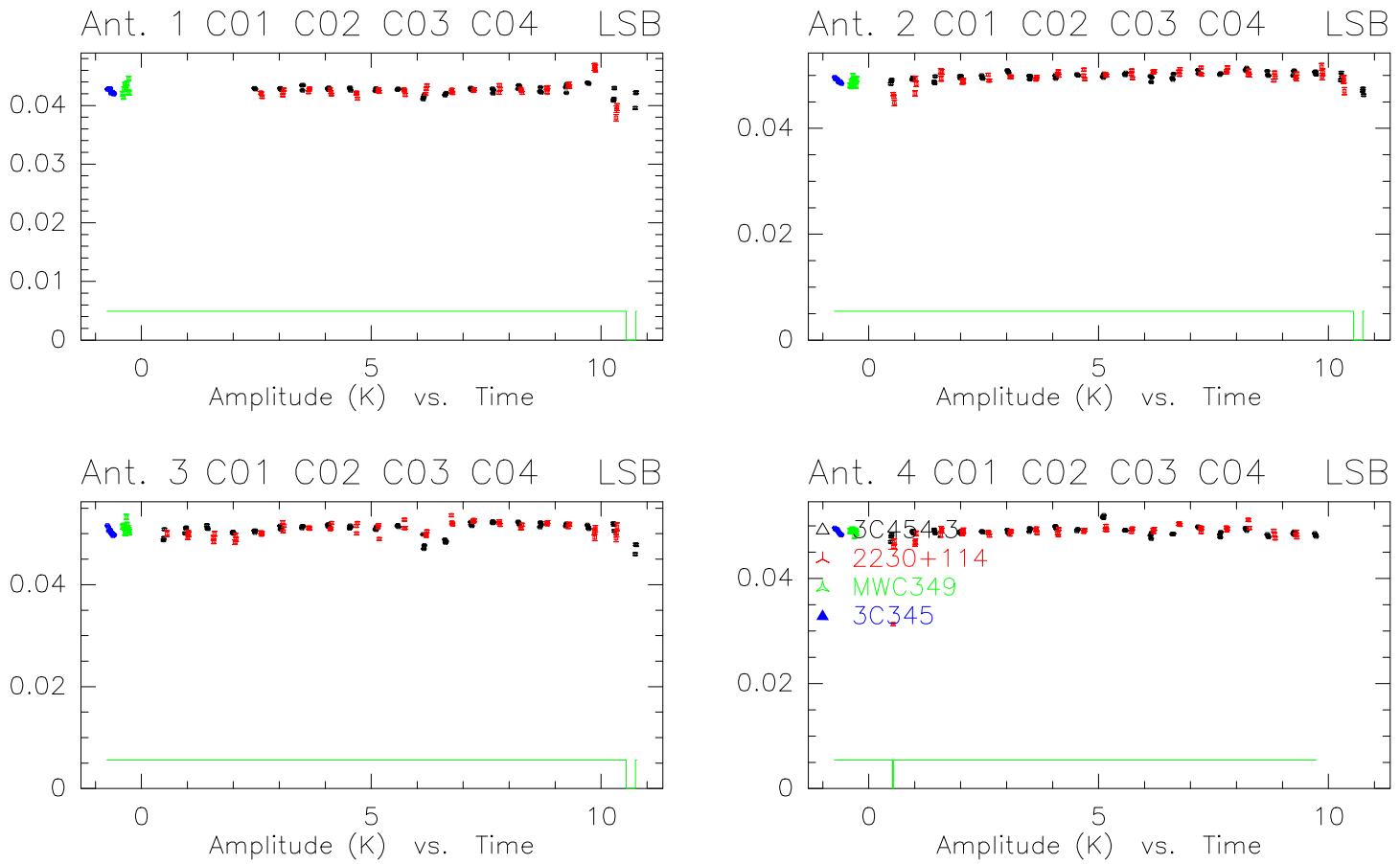
FLUX window

- `CHECK` – plot (inverse of) antenna efficiencies as a function of time using values currently in data file
- `SOLVE` – solve for the fluxes **using the selected reference sources**
- `GET RESULT` – accept the results
- `STORE` – store the fluxes in data file
- `PLOT` – plot (inverse of) antenna efficiencies as a function of time
- `>> CALIBRATE` – back to main calibration window


Ant. 1 C01 C02 C03 C04 LSB
Ant. 2 C01 C02 C03 C04 LSB
Ant. 3 C01 C02 C03 C04 LSB
Ant. 4 C01 C02 C03 C04 LSB
0
0.1
0.2
0.3
5
10
Amplitude (K) vs. Time
3C454.3
2230+114
MWC349
3C345

SOLVE FLUX

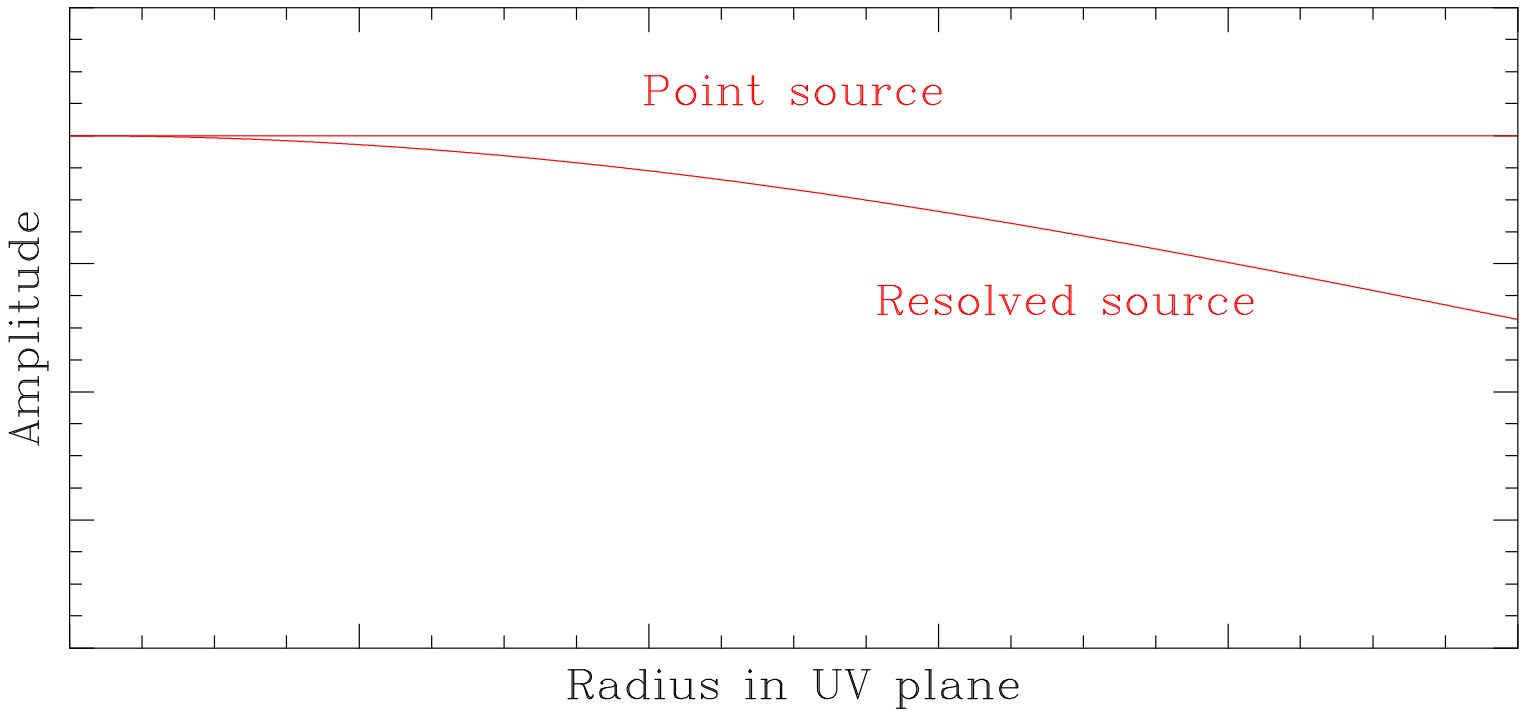
```
Flux and efficiency result for receiver 1 at 90.2 GHz:

                 in file            solve flux
              ---------------    ----------------
    3C345     read:    1.00 Jy   found:    5.32 Jy
   MWC349     read:    1.00 Jy   fixed:    0.97 Jy   (model:   0.97 Jy)
  3C454.3     read:    1.00 Jy   found:    6.16 Jy
 2230+114     read:    1.00 Jy   found:    2.12 Jy

 Antenna  1 (A1)    23.3 Jy/K   ( 0.94)
 Antenna  2 (A3)    20.6 Jy/K   ( 1.02)
 Antenna  3 (A4)    19.5 Jy/K   ( 1.07)
 Antenna  4 (A5)    20.5 Jy/K   ( 1.07)
```


Ant. 1 C01 C02 C03 C04 LSB
Ant. 2 C01 C02 C03 C04 LSB
Ant. 3 C01 C02 C03 C04 LSB
Ant. 4 C01 C02 C03 C04 LSB
0.04
0.03
0.02
0.01
0
5
10
Amplitude (K) vs. Time
3C454.3
2230+114
MWC349
3C345

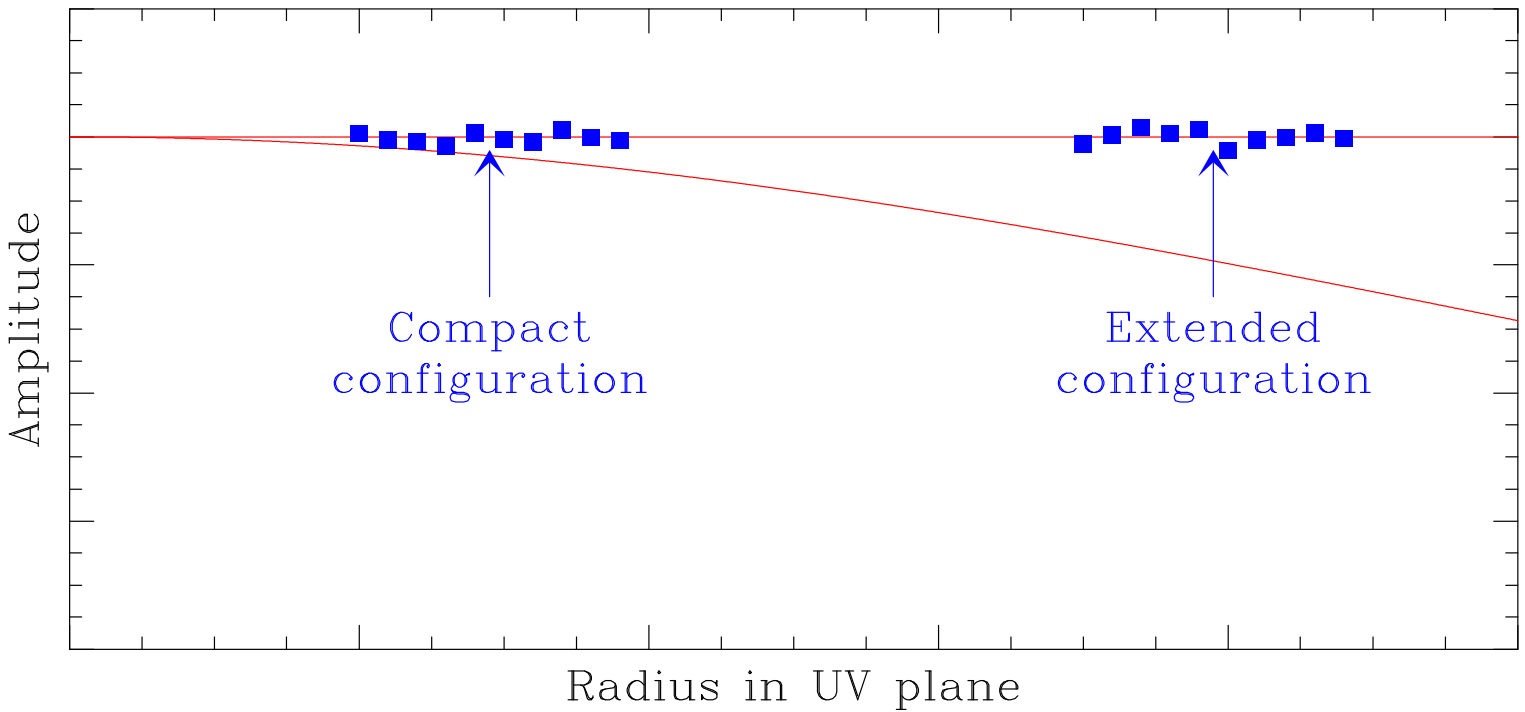
FLUX: recommended practices

- Ideally: select data that are close in time and that follow pointing/focus calibration
- Check the data quality of CRL 618 and MWC349 before using them as reference (may have been observed at low elevation)
- Check for the antenna efficiencies: cannot be better than **22 Jy/K at 3 mm, 35 Jy/K at 1 mm**
- **Cross-check flux calibration** between observations obtained within a short time interval (quasar fluxes are constant over a week)
- **A consistent flux calibration between observations is critical**
  - an error in the relative flux calibration between observations can mimic source structure
  - better have a wrong flux scale (scaling factor) than a wrong map (artefacts)

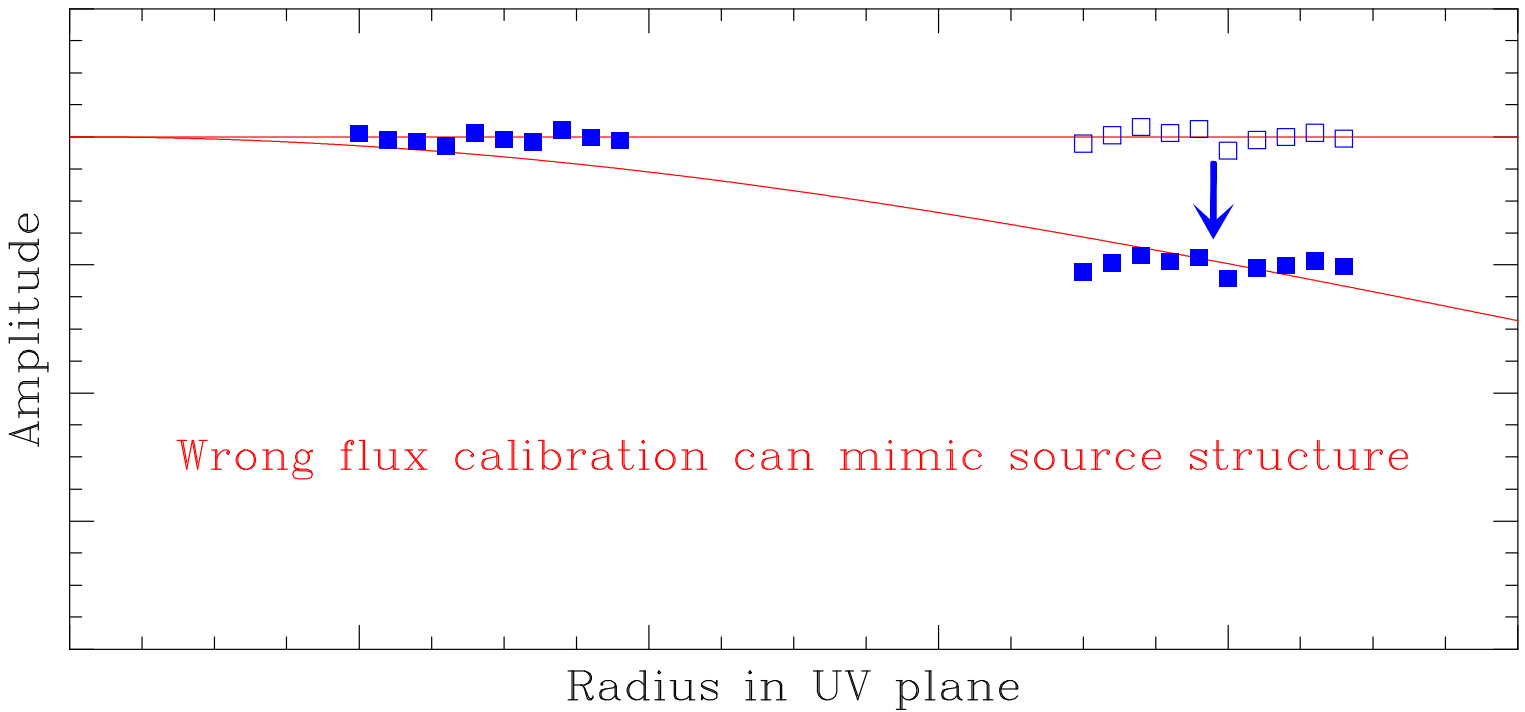
Flux calibration



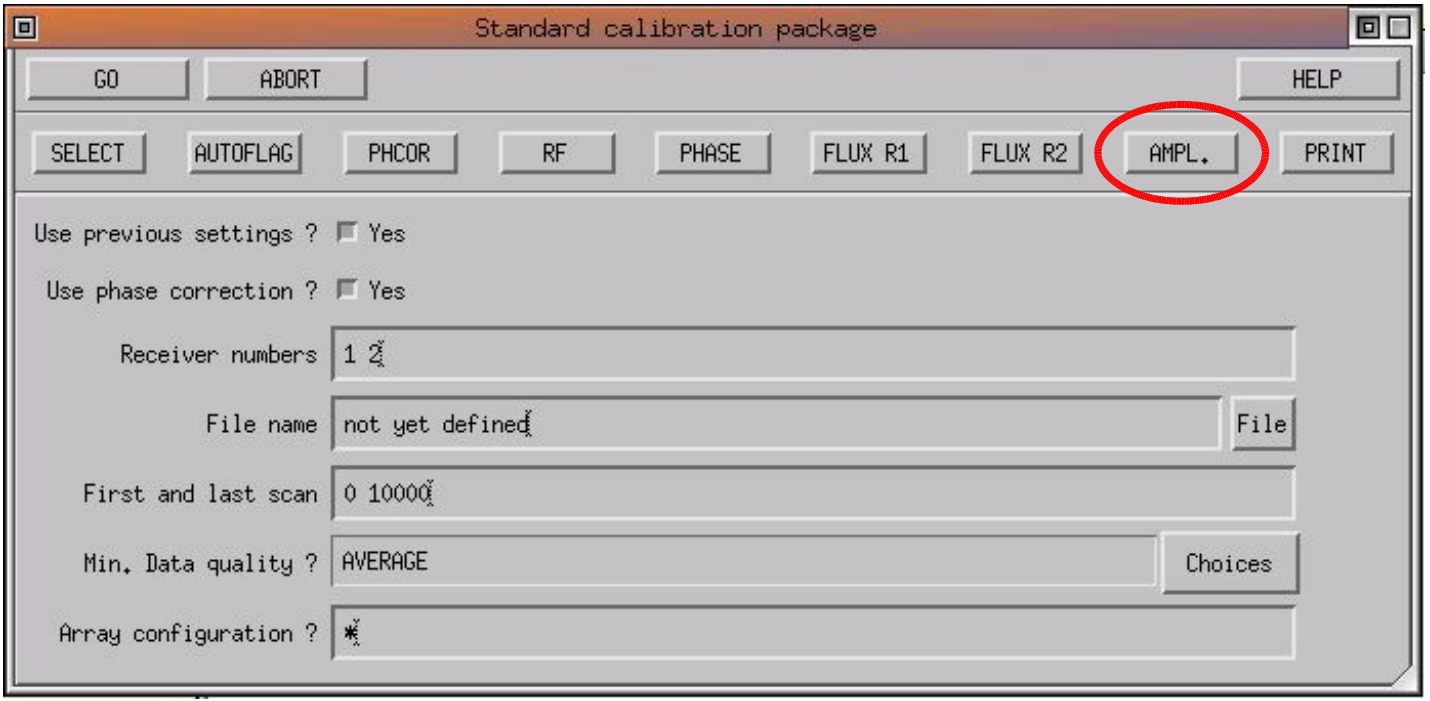
Flux calibration



Flux calibration

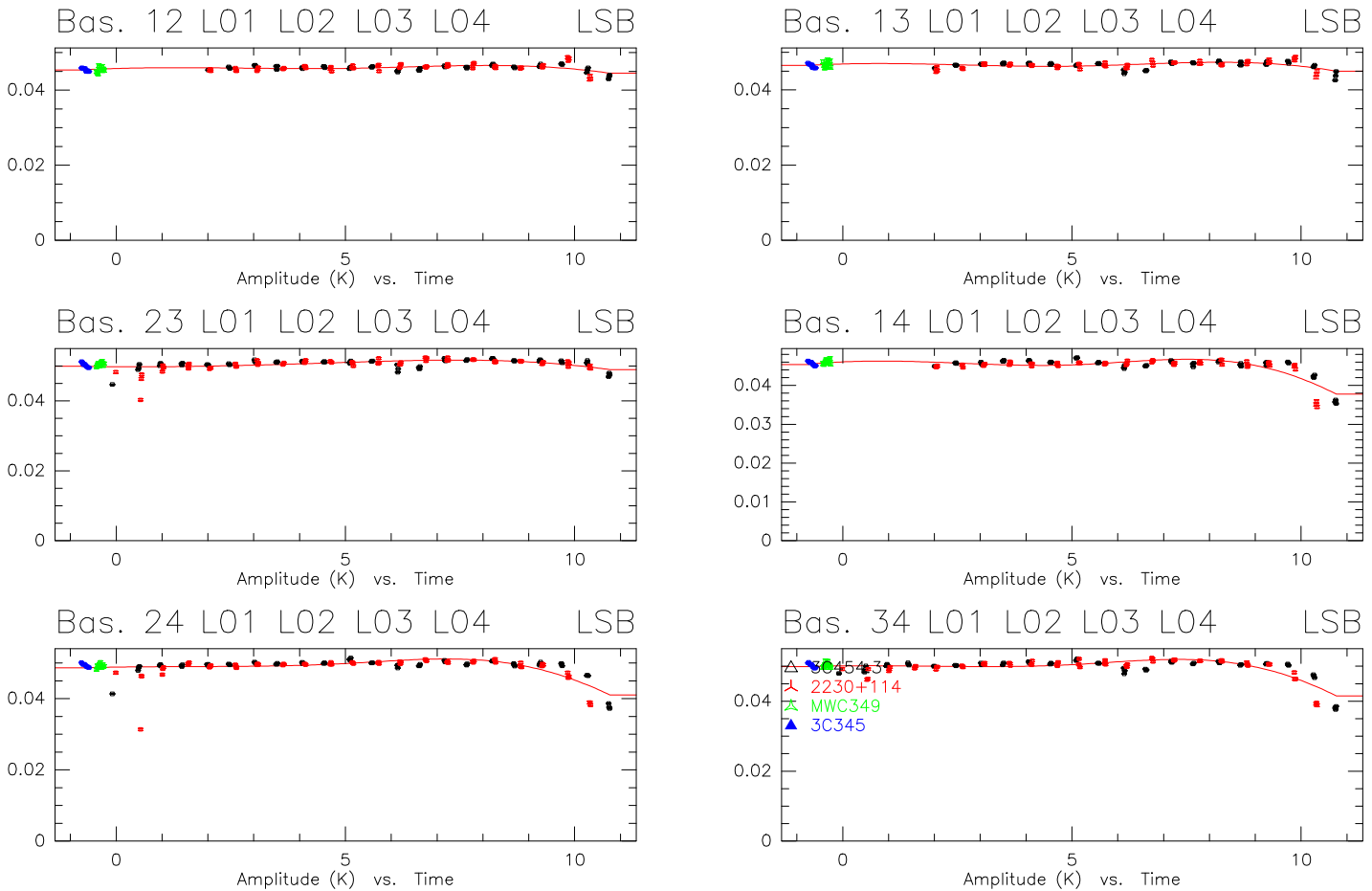


AMPL: Amplitude calibration



AMPL

- Select the phase calibrator observations
- Apply RF and PHASE calibration
- **Divide visibility amplitudes by source fluxes to have all calibrators on the same scale** (in K/Jy)
- Compute **antenna-based gain**
- Least-square fit of amplitude vs. time
- Store calibration curve in all observations (calibrators + sources)

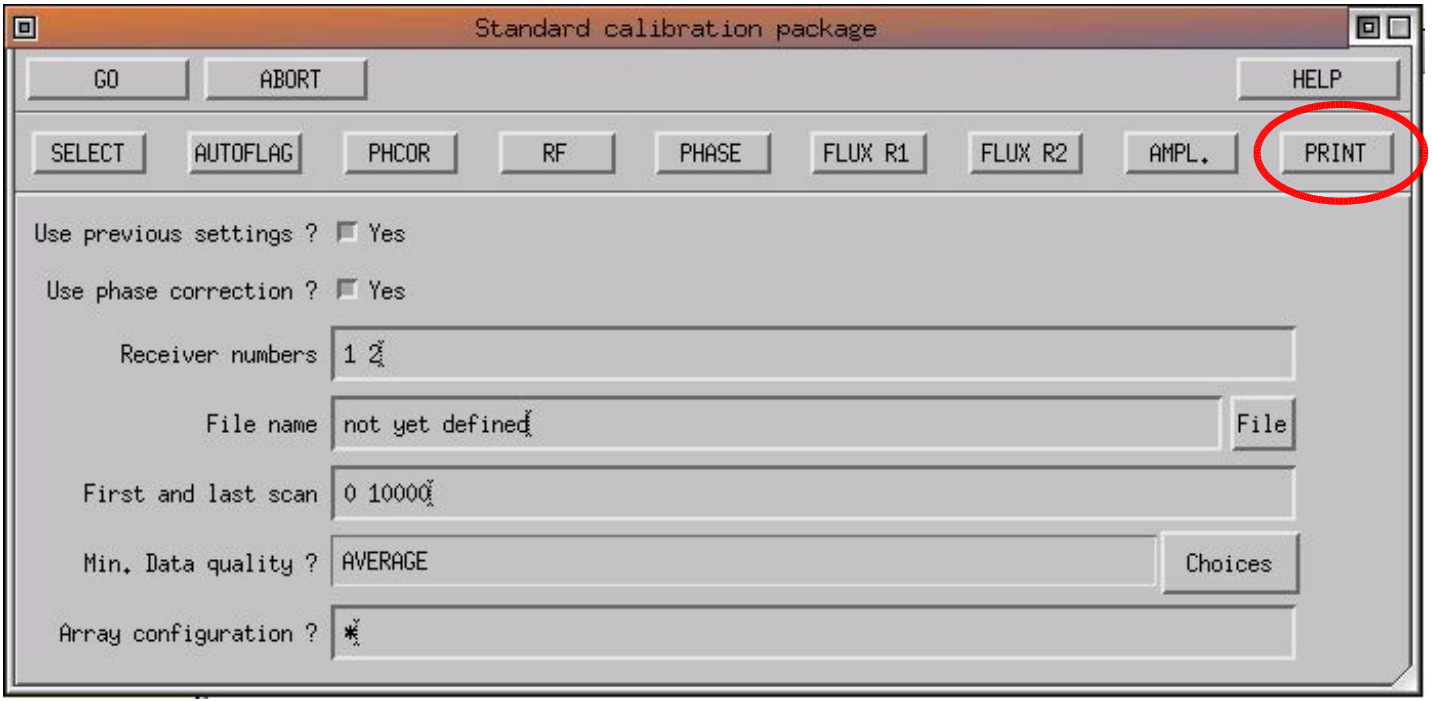

Bas. 12 L01 L02 L03 L04 LSB
Bas. 13 L01 L02 L03 L04 LSB
Bas. 23 L01 L02 L03 L04 LSB
Bas. 14 L01 L02 L03 L04 LSB
Bas. 24 L01 L02 L03 L04 LSB
Bas. 34 L01 L02 L03 L04 LSB
Amplitude (K) vs. Time
3C454.3
2230+114
MWC349
3C345

Interactive mode

```
(...)
I-SOLVE_CAL,[2098] Amp. Bas. 14  L01 L02 L03 L04 LSB rms:    5.70 %
I-SOLVE_CAL,[2098] Amp. Bas. 24  L01 L02 L03 L04 LSB rms:    2.84 %
I-SOLVE_CAL,[2098] Amp. Bas. 34  L01 L02 L03 L04 LSB rms:    3.04 %
Amplitude  calibration for receiver 1:
Command was SOLVE AMPLITUDE  /PLOT
You may try SOLVE AMPLITUDE  /PLOT  /BREAK 0 23.5
CLIC_3> SIC\PAUSE
CLIC_4>
```

- Potential problems
  - focus or pointing errors – strong amplitude loss or jumps
  - **amplitude noise is biased** – too weak calibrators may give wrong results
  - **decorrelation is baseline-based, fit is antenna-based** – too high decorrelation may introduce systematic errors on some baselines

PRINT: Print calibration report



Project KG5A Data File 01-jun-2001-kg5a
Observed on 02-JUN-2001 Configuration 5D-N05
(W00N09W05E03)

Automatic calibration report by CLIC @ x_calib

November 23, 2004

Scan range:	0 to 10000
Use R1 phases for R2:	YES
Self cal. phases R1→R2:	YES
Use phase correction:	YES (1mm)
Minimum quality:	AVERAGE
Auto. flag procedure:	NO

	Receiver 1	Receiver 2
Bandpass:	Excellent	Good
Phase:	Excellent	Poor
Seeing:	1.20″	–
Amplitude:	Good	Correct

1 Summary

1.1 Calibrators

Fluxes (Jy)	90.2 GHz		230.5 GHz		
3C345	5.32	*Computed*	3.12	*Computed*	
MWC349	0.97	*Fixed*	1.70	*Fixed*	*(Model = 0.97 1.7)*
3C454.3	6.16	*Computed*	4.49	*Computed*	
2230+114	2.12	*Computed*	1.17	*Computed*	

1.2 Efficiencies

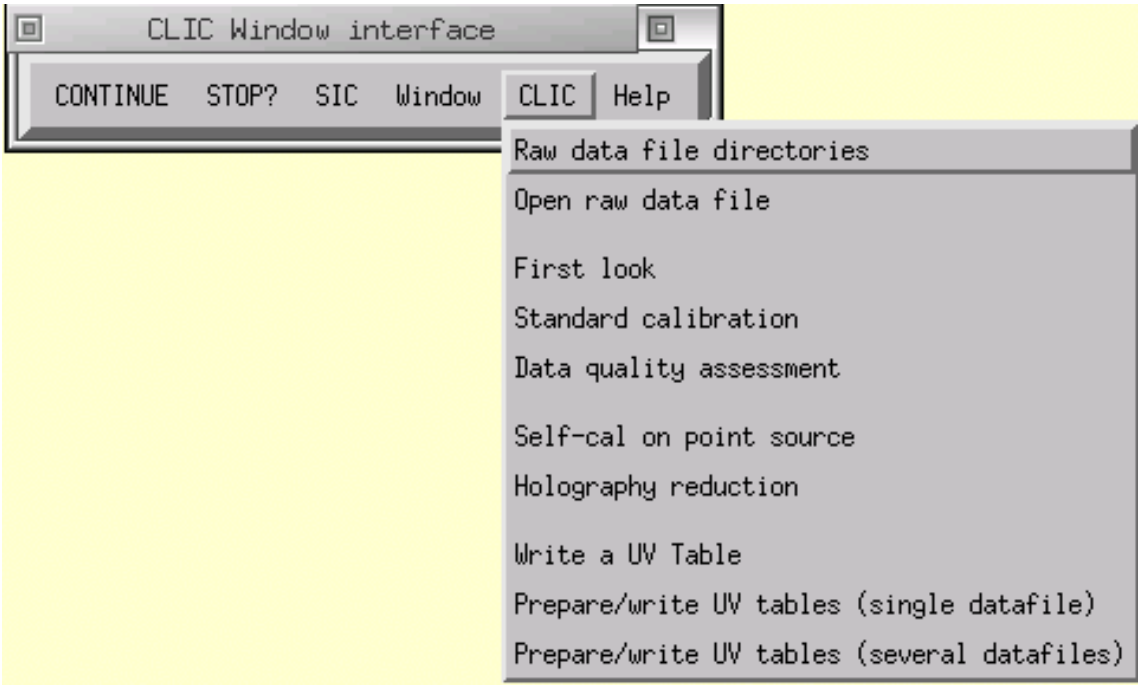
Radio seeing

- Phase fluctuations have different timescales:

< 1 min	**real-time atmospheric phase correction**
1 min – 1 hr	**radio seeing**
> 1 hr	**corrected by phase calibration**

- Phase noise translates into position errors: the flux of a point source is spread over a seeing disk
- Radio seeing is estimated by averaging **phase rms/baseline length** over all baselines (overestimation)
- Estimated at 3 mm only (because of phase transfert)
- Typically $0.2''$ to $1.5''$

Other tools

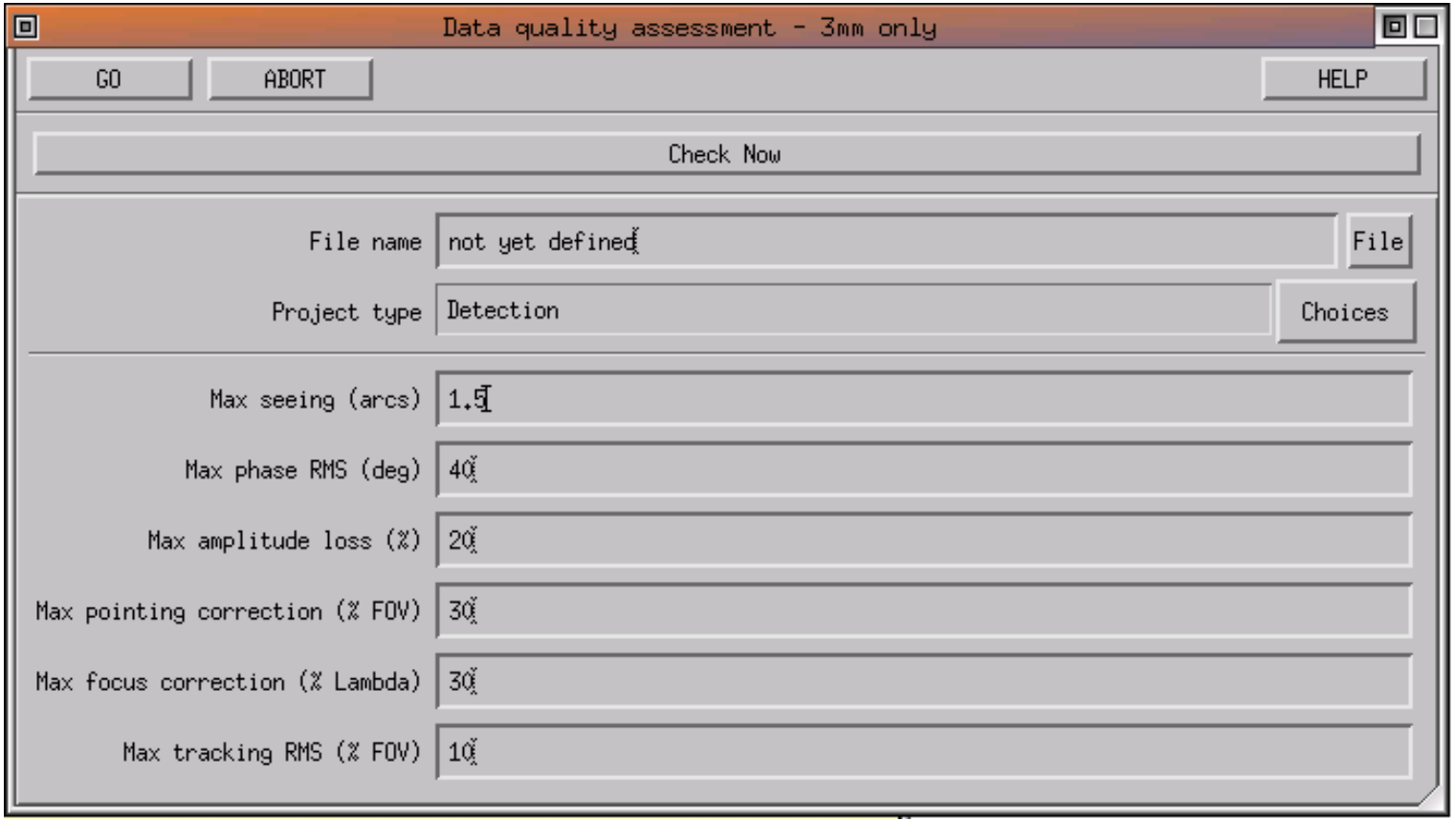

CLIC Window interface
CONTINUE
STOP?
SIC
Window
CLIC
Help
Raw data file directories
Open raw data file
First look
Standard calibration
Data quality assessment
Self-cal on point source
Holography reduction
Write a UV Table
Prepare/write UV tables (single datafile)
Prepare/write UV tables (several datafiles)

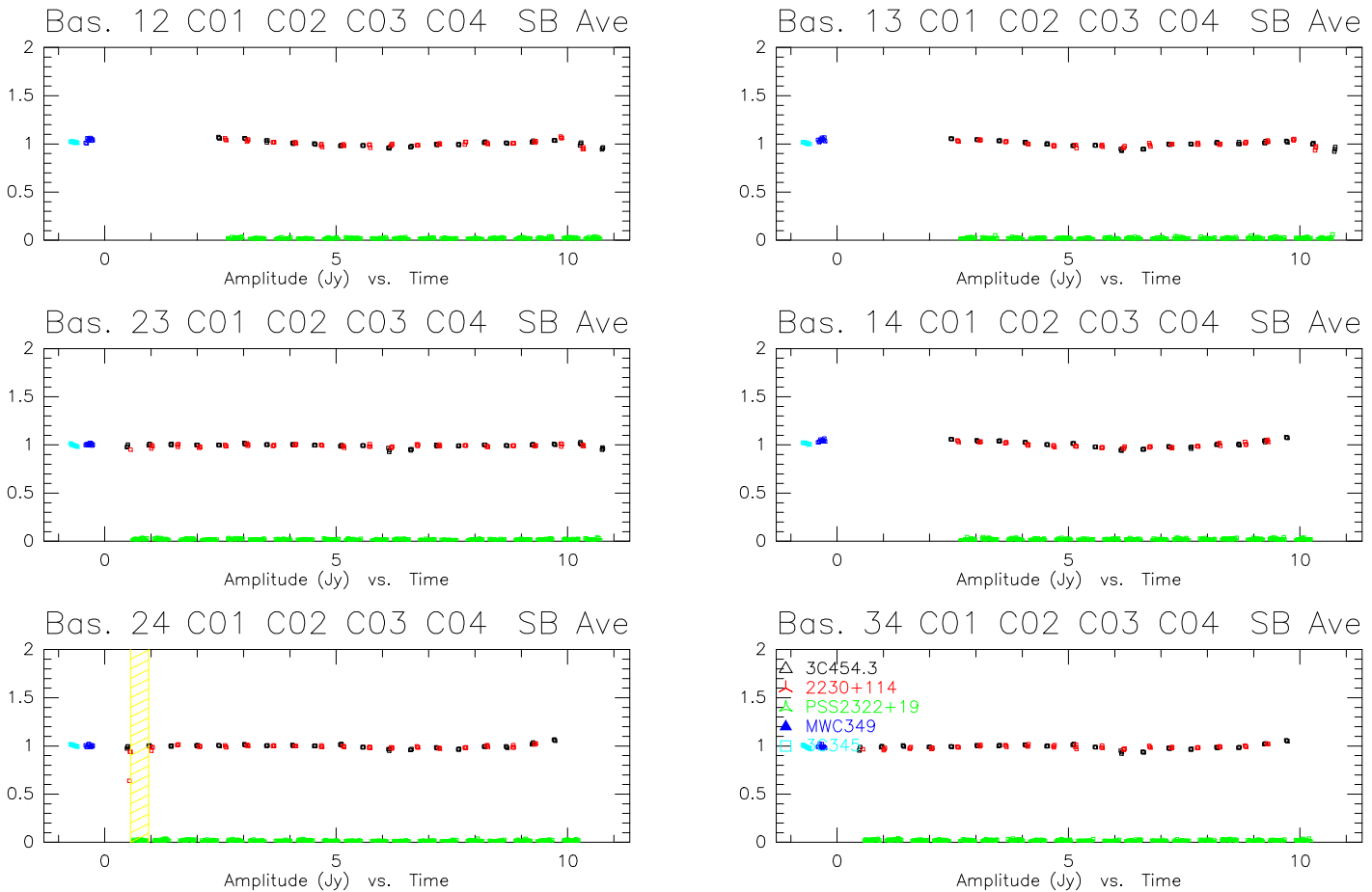
Other tools

- `Open raw data file` – create hpb file from ipb file
- `First look` – Basic checks of observing conditions: Tsys, Tracking, Pointing, Focus, Total Power, Water, etc...
- `Data quality assessment` – Select data to be used for imaging based on calibration results
- `Self-cal on point source` – self-calibration
- `Write a UV Table` – *uv*-table creation

- **PdBI Pipeline**
  - First Look + Calibration + Data quality assessment + UV Table
  - For internal use (IRAM staff) for the time being

Data quality assessment




Bas. 12 C01 C02 C03 C04 SB Ave
Bas. 13 C01 C02 C03 C04 SB Ave
Bas. 23 C01 C02 C03 C04 SB Ave
Bas. 14 C01 C02 C03 C04 SB Ave
Bas. 24 C01 C02 C03 C04 SB Ave
Bas. 34 C01 C02 C03 C04 SB Ave
Amplitude (Jy) vs. Time
3C454.3
2230+114
PSS2322+19
MWC349
3C345

CALIBRATION TUTORIALS

Thursday morning 9h–11h and 11h–13h