IRAM NOEMA
Data Reduction CookBook

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Version 5.0

This document describes how to reduce NOEMA observations and gives some ideas to perform first analysis and imaging. Sect. 1 explains how to get started, from planning your trip to Grenoble to having a project account. The standard procedure to calibrate NOEMA data with the CLIC software package is described in Sect. 2. A few instructions to start the data analysis with the MAPPING software package are given in Sect. 3. A theoretical description of the calibration as well as a description of the extended pipeline (or AoD) `First Look` report are annexed in Apps. A and B respectively.

Documentation
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1. IRAM

Related information is available in:

- IRAM NOEMA: Introduction
- IRAM NOEMA: OBS Users Guide
- IRAM NOEMA: Atmospheric Calibration
- CLIC: Continuum and Line Interferometric Calibration
- MAPPING: Imaging and Deconvolution of Aperture Synthesis Data
- MIS: Millimeter Interferometry Simulation Tools
- GREG: Graphical Possibilities
- SIC: Command Line Interpretor

Contents

1 Getting started

1.1 Preparing your travel

The day by day execution of Plateau de Bure projects can be followed at `http://www.iram.fr/IRAMFR/PDB/project.html`. The status of the observations of each project can be checked at `http://www.iram.fr/IRAMFR/PDB/ ongoing.html`. The *scientific secretary* informs the project principal investigator on the completion of his/her program and on the steps to follow to organize the travel to IRAM Grenoble, where the data reduction is normally carried out. By following these instructions, you should get in contact with your *local contact*[1] or with your collaborator at IRAM (who is the project local contact) to find some convenient dates for both of you. Remote data reduction is possible in exceptional cases, after agreement with the local contact and thereby with the *scientific coordinator*.

For most projects a week at Grenoble is enough to finish the data calibration and perform first analysis. An experimented astronomer may need less time. We recommend to spend one day on data analysis after calibration, so that we can help if there are difficulties and return back to data calibration if needed. You are invited to consult with your local contact before deciding on the duration of your stay. To avoid overbooking the computer facilities, no more than two groups are accepted simultaneously. You should consult the visitor list before discussing dates with the local contact. You will tell the scientific secretary on the agreed dates as soon as possible, so that she can book a computer, and may help in hotel booking and in other questions related to your visit. Visits must be announced at least two weeks in advance. You can consult the conditions for financial support for visiting astronomers at `http://www.iram.fr/IRAMFR/PDB/bure_mission.html`. Finally, note that IRAM is closed from Friday 6pm to Monday 8am.

1.2 Working on the IRAM computers

As soon as you arrive at IRAM Grenoble, an account is created for your project. Project accounts are in general allocated for a period of two weeks and are automatically removed at the end of that period (with no archiving or warning). You should get in contact with your local contact in case you need more time.

At your arrival a computer at the IRAM terminal room is booked for the reduction of your project. Your local contact will provide some information on the computer directories, download the raw data and have a first look with you at the calibration procedure.

[1] A local contact is assigned to each A and B-rated project which does not have in-house collaborator. He/She assists you in the preparation of observing procedures and in the data reduction.

Project accounts contain a README file, the `reports`, `calib` and `maps` directories and the `tmp -> /scratch/xxxx/` link. In README you will find a description of the account directories and some other helpful information. The `reports` directory contains the calibration results obtained by the *pipeline*[2], sometimes also those from an improved calibration by the *astronomer on duty (AoD)*[3], and AoD's notes to help with the calibration (Sect. 2.1). The data calibration is, by default, performed in the `calib` directory, further data analysis in `maps`.

In order to download the project raw data, the command `getproj` must be executed in the shell prompt. The data are stored in the scratch directory linked by tmp, and are visible from all CLIC sessions launched on the computer where `getproj` was executed.

By default the GILDAS daily version is used. You can execute "`gagiram` mmmyy" (mmm = month, yy = year) to switch to a previous GILDAS release.

At the end of the calibration you may want to save a copy of the project account. Reduced data can either be transferred via `scp` to your home institute or archived on DVDs. From the account home the command "buildDVD ." allows you to burn in a DVD all the things there contained. Note that the `IPB` data files are in the scratch of the assigned computer and so by keeping the default distribution they are not saved in the DVD. Finally, it is strongly recommended to check the integrity of the recorded data before the account expires.

[2]Pipeline normally refers to the automatic calibration taking place at Bure, which is afterwards verified, sometimes also improved, by the astronomer on duty.

[3]Astronomer on Duty taking care of the NOEMA observations and of the first data calibration

2 Data Calibration with CLIC

CLIC is the software to calibrate NOEMA data. The calibration of most projects is carried out with a few interactive procedures and widgets provided within CLIC, so most astronomers do not need to know much about CLIC commands. We recommend however to have a look in the CLIC manual[4] at the following commands: `help`, `file`, `find`, `list`, `plot`, `set x` and `set y`. During the calibration you will become familiar with others, e.g. `solve`. In general we recommend to read the CLIC manual to have a deeper understanding of the calibration possibilities.

In some of the following sections, paragraphs written with *italic* fonts are aimed to solve problems that may appear in the calibration. You can skip these paragraphs in a first reading.

2.1 NOEMA pipeline and AoD notes

In the project account, the `reports` directory contains the first calibration results produced or revised by the AoD (Sect. 1.2). The gzipped postscript and ascii files report on the calibration. Particularly those whose names include `-pipe` result from the automatic data reduction or pipeline (Sect. 1.2). You will get familiar with the calibration reports in Sects. 2.4, 2.5 and 2.6. The AoD performing the observations evaluates the data quality and calibration, and may write notes in the ascii file of extension `note`. It is recommended to read the notes relative to each track before starting its calibration. The files of extension `hpb`, so-called *header* files, store the parameters derived from the calibration.

Having a look at the automatic reports before starting the calibration may be useful, mainly for an experimented astronomer. They can be used, for instance, to decide on the first track to calibrate, likely the one with the best flux calibration. In addition, note that the AoD at Bure performs a comprehensive analysis of the observations, and his/her notes (in the `note` file) may be useful to identify problems, which perhaps are visible in some of the plots of the `First Look` report (see Sect. 2.5 and App. B). Recommendations concerning the calibration might also be added to the AoD notes.

Nowadays the `pipeline` is distributed with every release of `GILDAS`, although it can only be used with data obtained later than January 2007. You just need to type "`@pipeline 'project_name' 'date'` " and the pipeline will be launched, producing outputs very similar to those obtained at the observatory. It has become usual among NOEMA users to start the data calibration by launching the `pipeline`. If this first calibration is not satisfactory, the analysis of the `pipeline` report, with the help of the AoD notes and the local contact, allow improving easily the data calibration. Anyway, we recommend to have a critical look at the `pipeline` output protocols before making use of the `hpb` files. Particularly, it is known that the `Data Quality Assessment` procedure

[4]available on-line at `http://www.iram.fr/ IRAMFR/GILDAS/`

launched at the end of the calibration often flags out more data than actually needed. If you plan to recalibrate all or parts of the calibration from the `pipeline`-produced `hpb` file, we recommend first to remove all the `Data Quality Assessment` flags by using the following commands:

```
file both 'file_name.hpb'
find
store flag redu /ant all /reset
store flag redu /base all /reset
```

At the end of the new calibration you can use the `Data Quality Assessment` procedure (Sect. 2.7) to flag the undesirable data according to the needs of your project.

2.2 How the data look like

Let us assume that we are already looking at the data, in CLIC. After typing in CLIC `find` and later `list` we will see, e.g.:

```
60 7684 QA12 3C454.3      P CORR CO10     6Cq-N17      12-NOV-2007 21:58  2.9
61 7685 QA12 3C454.3      P CORR CO10     6Cq-N17      12-NOV-2007 21:59  2.9
62 7686 QA12 3C454.3      P CORR CO10     6Cq-N17      12-NOV-2007 22:00  2.9
```

where each line corresponds to an observation *subscan*[5]. Each subscan contains the following information:

```
- First column: Observation number
- Second column: Scan number
- Third column: Project name
- Fourth column: Source name
- Fifth column: Type of source (O=object, P=phase calibrator)
- Sixth column: Type of scan procedure
- Seventh column: Line name
- Eighth column: Array configuration, i.e. antenna positions
- Nineth column: Date
- Tenth column: UT time
- Eleventh column: Hour angle
```

The usual observational procedures (column sixth) and characteristics are:

```
CORR: cross-correlation; 1 subscan (ss) is obtained per scan
GAIN: cross-correlation to measure the sideband rejection; 1 ss
FOCU: focus measurements in all the antennas; 5 ss
POIN: interferometric pointing in all the antennas; 2 ss
```

[5]A *subscan* (which is a scan partition) is the shortest acquisition for which spectral information is stored. Frequency-averaged acquisitions are stored for each second, and are known as *records*

```
FLUX: cross-correlation to measure the flux; 1 ss
IFPB: IF passband calibration, by observing a noise diode; 2 ss
AUTO: autocorrelation; 1 ss
CALI: atmospheric calibration, autocorr. on SKY, HOT [COLD] load; 2 [3] ss
SKYD: sequence of autocorrelations to calibrate the 22 GHz receivers; 12 ss
```

By using the mentioned procedures, a typical sequence of observations is:

```
- Receiver tuning followed by a sideband gain measurement
- Radio frequency passband calibration on a bright source
- Acquisitions on at least a flux calibrator, MWC 349 if possible
- Check the pointing and focus on the predefined phase calibrator(s)
- Possibly a flux measurement on this calibrator(s)
- Cross-correlations on the phase calibrator(s)
- Cross-correlations on source
```

About 3 minutes are spent on each phase calibrator, some more time if pointing and focus are performed, every $\sim$ 23 minutes on source. Pointing and focus are normally repeated every two transitions of $\sim$ 23 minutes on source. `IFPB`, `AUTO` and `CALI` scans are obtained before correlations to calibrate the observations in real time (see Sect. A.3).

2.3 Getting started with CLIC

Just type CLIC in the shell prompt, and click on the CLIC widget shown in Figure 1 to have the menu.

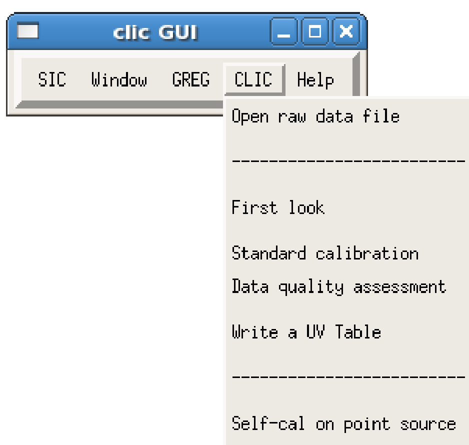


Figure 1: CLIC menu

In the following sections we describe the steps to follow in order to calibrate a standard project, following the options listed from top to bottom in the CLIC menu.

2.4 Open raw data file

The data obtained at Plateau de Bure are stored in files of extension `IPB`. The parameters derived from the calibration are stored in files of extension `hpb` (or *header* files). A naked version of these files can be created with the option `Open raw data file` (Figure 2) in the CLIC menu (Figure 1).

First of all, the location of the raw data (`IPB` files) must be defined, either by clicking in `RAW DATA DIRECTORIES` (see Figure 2) or within the `.gag.dico` gildas file. In the IRAM project accounts (see Sect. 1.2) the location of the raw data is already predefined. A raw data file must be selected among the `Project_Date` choices. `OPEN and FIND` opens this file and proposes a standard name for the output file. `CREATE HEADER FILE` creates a `hpb` file ready to calibrate the data in antenna-based mode. By default `Mode` (in the widget) is NEW, and so a new `hpb` file is created each time. By selecting OLD, visibilities can be added to an existing `hpb` file, which is very convenient if observations were contiguous in time.

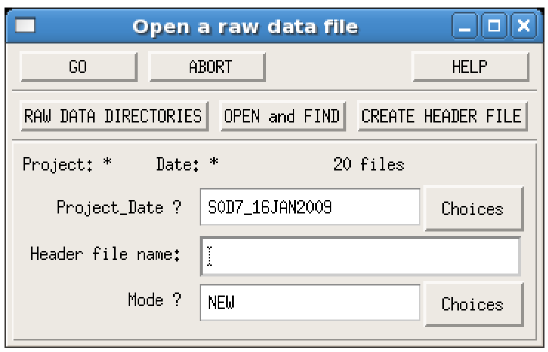


Figure 2: `Open raw data file`, in the CLIC menu.

In this and the following widgets there are at the top the options `GO` and `ABORT`. `GO` is aimed to run all the options proposed as clickable buttons, from left to right, with no stop. In general, its use is only recommended for the `First Look` (see Sect. 2.5). `ABORT` closes the widget and returns to the parent widget.

As mentioned in Sect. 2.1, the `hpb` files resulting from the NOEMA pipeline calibration are given in the directory `reports`. We recommend not to use them to create the final *uv*-tables since, for the time being, they were not created with this purpose and so may include severe flags or artifacts due to a further AoD analysis.

2.5 First Look

To have a look at the conditions in which the observations were obtained click on the `First Look` in the CLIC menu (Figure 1). An extended version of the `First Look` is used by the AoD and by the pipeline procedure (see App. B).

An `hpb` file name is needed to start with the `First Look` widget (see Figure 3). The scan range can also be specified. By default all the scans are taken into account (i.e. from `0` to `10000`). The receiver with which the source(s) was observed is determined by clicking on `Select`.

`Select` is also necessary to assess the presence of data, and to define variables needed in the following calibration steps. The options from `Meteo` to `Water` can be clicked with no defined order. Each of them creates one or two plots and then pauses waiting for a "`continue`", in the CLIC prompt, in order to save the displayed plots in postscript files. `Print` combines all these postscript files in a file called show-'date'-'projectname'.ps, including also a description of the observational setup and a detailed scan list.

This package is actually not interactive since it does not admit an input other than "`continue`". With `GO` we can therefore obtain the same result as by clicking through the buttons, from `Select` to `Print`. It is recommended to check the `First Look` report to identify instrumental features, errors, verify weather conditions, etc. This information becomes particularly relevant to take adequate decisions in case of calibration difficulties.

Note that all the plots created with the `First Look` are presented for *physical antennas*[6], while the calibration procedures refer to *logical antennas*[7]. Sometimes the AoD refers in his/her notes to physical antennas, but note that all the CLIC commands refer to the logical ones. In the section 1.2 of the calibration report (see Sect. 2.1 and 2.6), efficiencies are presented for logical antennas, the equivalent physical numbers are shown into parenthesis.

Select, in addition to selecting the used receiver(s), adopts default settings for data presentation, reports on the amount of correlations obtained, defines scan ranges between tunings by looking at the `gain` scans, reports on the used baselines and antennas, on the array configuration, on the used calibrators and their fluxes, and the tuned band. `Select` also introduces in the widget the option to select telescope configuration if that changed during the observations. Information is given in the line of commands, which is specially relevant for calibration (as shown in Figure 4).

Meteo provides information on the atmospheric conditions at the time of the observations: Ambient temperature (in K), relative humidity (%), pressure (mbar) and the mean and maximum wind speed (m/s).

[6]Each NOEMA antenna has a reference number that identifies it, from 1 to 6 corresponding to the order in which they were built. When we refer to the antennas by using this reference number, we call them physical antennas.

[7]CLIC uses a numbering for the antennas proper to each observation, going from 1 to the number of used antennas. We refer to logical antennas when we use their reference number in CLIC. Note that the logical antennas differ from the physical ones if the array has less than 6 antennas and the missing antennas are not the last ones.

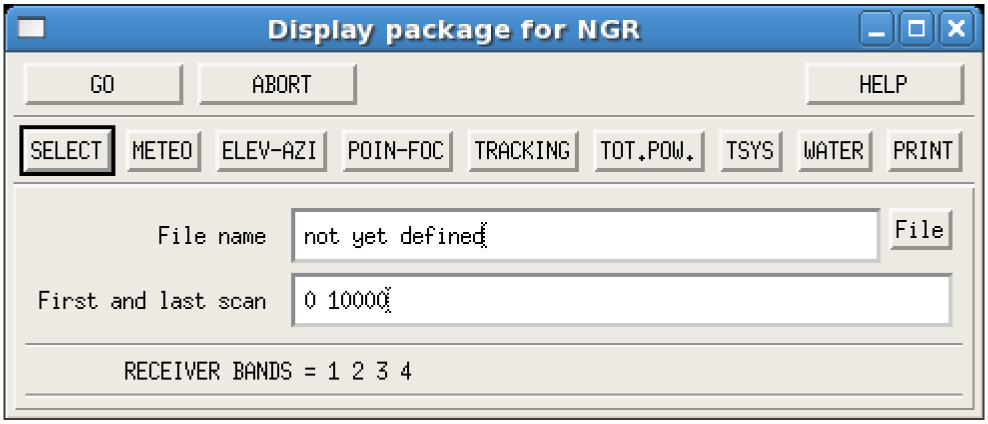


Figure 3: `First Look`, in the CLIC menu

Elev-Azi plots the elevation and azimuth of each scan, so that we can see the relative position of a source with respect to the calibrators.

Poin-Foc presents the pointing corrections (in arc seconds) in azimuth and elevation, and the focus corrections (in mm) per antenna. Note that pointing and focus measurements are performed typically every $\sim$ 50 min (i.e. every two transitions on source)

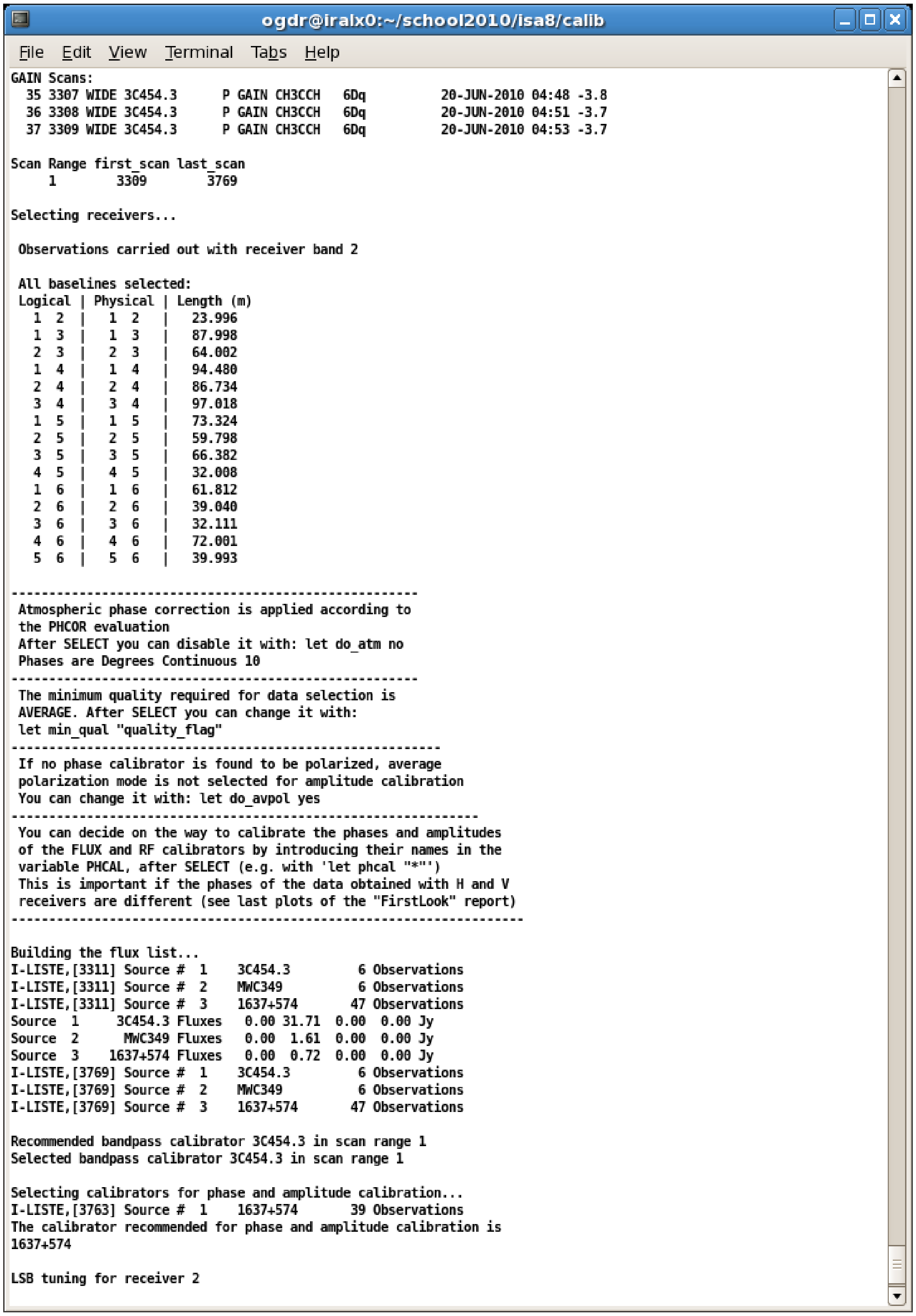
Tracking shows the rms of the tracking variations (in arc seconds) in azimuth and elevation.

Tot. Pow. displays the total power (in K) obtained per *correlator input*[8].

Tsys plots the system temperature (in K) along the track, for the tuned and the rejected band. Note that after January 2007 all receivers installed at Plateau de Bure are operated in single side-band mode. A plot is created per correlator input[8].

Water shows the values derived for the water vapor pressure (in mm) by modeling the atmospheric behavior from the data obtained with the astronomical receivers. The water vapor pressure (`WVR` H_2O) obtained from the 22GHz receivers is also shown. Note that the

[8] There are two correlators at the observatory: 1) The Narrow-band correlator accepts two 1 GHz input signals, from the 4 GHz band obtained per polarization. Narrow inputs refer to the two 1GHz-bandwidth signals entering into the narrow-band correlator, which correspond to quarters of the receiver bands. The astronomer decides on the configuration of the eight spectral units of the narrow-band correlator within the two selected Narrow inputs. 2) The Widex correlator is composed of four units, each one accepting 2 GHz bandwidth. Units 1 and 3 and units 2 and 4 are placed consecutively to cover a bandwidth of 3.8 GHz respectively in the IF of H and V polarization receivers. Widex inputs correspond hence to the four Widex units)



```
ogdr@iralx0:~/school2010/isa8/calib
File  Edit  View  Terminal  Tabs  Help
GAIN Scans:
  35 3307 WIDE 3C454.3      P GAIN CH3CCH   6Dq         20-JUN-2010 04:48 -3.8
  36 3308 WIDE 3C454.3      P GAIN CH3CCH   6Dq         20-JUN-2010 04:51 -3.7
  37 3309 WIDE 3C454.3      P GAIN CH3CCH   6Dq         20-JUN-2010 04:53 -3.7

Scan Range first_scan last_scan
     1        3309        3769

Selecting receivers...

 Observations carried out with receiver band 2

 All baselines selected:
 Logical | Physical | Length (m)
   1  2  |    1  2   |   23.996
   1  3  |    1  3   |   87.998
   2  3  |    2  3   |   64.002
   1  4  |    1  4   |   94.480
   2  4  |    2  4   |   86.734
   3  4  |    3  4   |   97.018
   1  5  |    1  5   |   73.324
   2  5  |    2  5   |   59.798
   3  5  |    3  5   |   66.382
   4  5  |    4  5   |   32.008
   1  6  |    1  6   |   61.812
   2  6  |    2  6   |   39.040
   3  6  |    3  6   |   32.111
   4  6  |    4  6   |   72.001
   5  6  |    5  6   |   39.993

------------------------------------------------------
 Atmospheric phase correction is applied according to
 the PHCOR evaluation
 After SELECT you can disable it with: let do_atm no
 Phases are Degrees Continuous 10
------------------------------------------------------
 The minimum quality required for data selection is
 AVERAGE. After SELECT you can change it with:
 let min_qual "quality_flag"
---------------------------------------------------------
 If no phase calibrator is found to be polarized, average
 polarization mode is not selected for amplitude calibration
 You can change it with: let do_avpol yes
--------------------------------------------------------------
 You can decide on the way to calibrate the phases and amplitudes
 of the FLUX and RF calibrators by introducing their names in the
 variable PHCAL, after SELECT (e.g. with 'let phcal "*"')
 This is important if the phases of the data obtained with H and V
 receivers are different (see last plots of the "FirstLook" report)
--------------------------------------------------------------------

Building the flux list...
I-LISTE,[3311] Source #  1    3C454.3         6 Observations
I-LISTE,[3311] Source #  2    MWC349          6 Observations
I-LISTE,[3311] Source #  3    1637+574       47 Observations
Source  1     3C454.3 Fluxes   0.00 31.71  0.00  0.00 Jy
Source  2      MWC349 Fluxes   0.00  1.61  0.00  0.00 Jy
Source  3    1637+574 Fluxes   0.00  0.72  0.00  0.00 Jy
I-LISTE,[3769] Source #  1    3C454.3         6 Observations
I-LISTE,[3769] Source #  2    MWC349          6 Observations
I-LISTE,[3769] Source #  3    1637+574       47 Observations

Recommended bandpass calibrator 3C454.3 in scan range 1
Selected bandpass calibrator 3C454.3 in scan range 1

Selecting calibrators for phase and amplitude calibration...
I-LISTE,[3763] Source #  1    1637+574       39 Observations
The calibrator recommended for phase and amplitude calibration is
1637+574

LSB tuning for receiver 2
```

Figure 4: Information given in the line of commands after `Select`, in the `First Look` and the `Standard Calibration` sections.

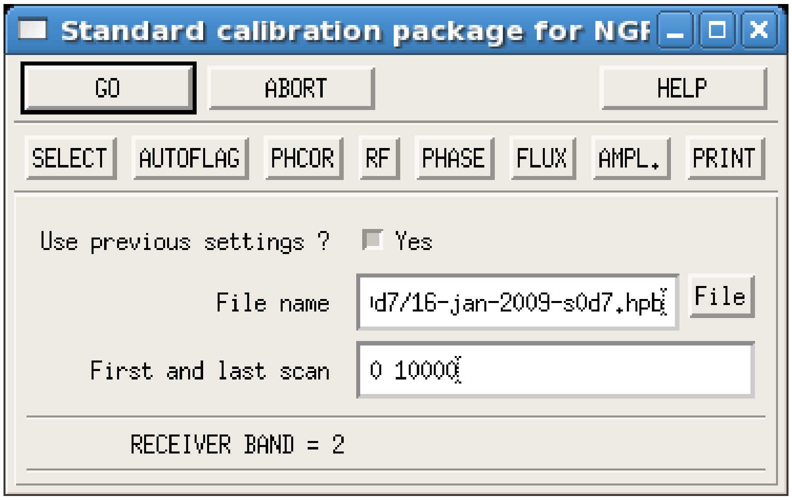


Figure 5: `Standard Calibration`, in the CLIC menu

22GHz receivers are only sensitive to water vapor, while the astronomical ones permit to obtain a rough estimate of the water in the atmosphere, including liquid water. A plot is created per correlator input[8].

Print combines all the plots in a file of name show-'date'-'projectname'.ps.

AoD or pipeline First Look: The astronomer on duty carrying out the observations performs a deeper analysis of the data. The file created by the AoD `First Look` includes more technical plots, related to receiver calibration, bandpass stability, correlator tweaks, 22 GHz receivers, cables transporting the synthesizer signals, etc (briefly described in App. B). The AoD may include remarks in the project `note` file (see Sect. 2.1) if the inspection of these plots reveals problems to be considered in the calibration.

2.6 Standard Calibration

This tool is designed to calibrate a standard NOEMA project. The name of the `hpb` (*header*) file must be specified in the `Standard Calibration` widget (Fig. 5) to start. A limited scan range can be selected to perform a complete or partial calibration. By default all the scans are considered. The receiver band used in the observations is determined by clicking on `Select`.

The calibration must be done by clicking on the proposed steps from left to right. `Select` is so needed at first, and also before repeating any part of the calibration. The last option `Print` combines all the postscript files created of each calibration step in a single file called 'date'-'projectname'.ps. This package is an interactive tool which pauses for an input from the astronomer. It is not recommended therefore to click on the `GO` (see Sect. 2.4).

The option `Use previous settings` (in the widget; Fig. 5) permits to adopt settings coming from a previous calibration of the selected `hpb` file, with respect to the atmospheric phase correction, scan ranges, selected bandpass calibrator, etc.

Finally, note that all the plots created within the `Standard Calibration` are presented for logical antennas, which are sometimes different from the physical ones shown in the `First Look` outputs (see Sect. 2.5 and App. B).

2.6.1 Select

It selects the used receiver band(s), establishes defaults for data presentation, reports on the amount of correlations obtained, scan ranges between tunings, array configuration(s), lists the physical baselines and antennas, builds a first flux list and reports on the tuned band. In addition, it defines internal variables which are later used by the calibration procedures.

The procedure also selects the RF calibrator, at first the brightest observed source, otherwise that selected in a previous RF calibration. The selection is reported in the line of commands, as shown in Figure 4. Sometimes, because of technical problems or to improve sensitivity, another calibrator must be considered. In those cases "let band_source *'a_new_calibrator'* " must be typed in CLIC to select *'a_new_calibrator'*.

`Select` deduces which are the phase calibrators observed alternatively with the source, hence suitable to calibrate phase and amplitude evolution in time. The names of the selected calibrators are stored in the variable `phcal`. You can decide about the content of `phcal` as follows: "let phcal '*calibrator1*' '*calibrator2*' ... ". Note that "let phcal '*' " should be selected if the (frequency averaged) phases from the H and V polarization receivers are not identical, which for instance can be seen in the `RF phases` plot in the `First Look` (see more details in Sect. 2.6.5).

By default, the atmospheric phase corrections derived from the 22GHz receivers are used according to the `PhCor` evaluation (see Sect. 2.6.3). However, sometimes it is recommended (by the `Autoflag` procedure or by the AoD) not to use the phase corrections, for instance due to problems with the 22GHz receivers. "let do_atm no" allows ignoring the atmospheric phase corrections.

Several gain ranges: From time to time, the `Select` procedure pauses to inform on the presence of different gain ranges, i.e. scan intervals with different tuning characteristics. The RF calibration is then performed independently for each gain range (i), and a calibrator is so assigned to the variable "band_source[i]" for each range. When the procedure pauses, `continue` should be typed in the line of commands to continue.

2.6.2 Autoflag

Different verifications are performed in all the obtained scans, which are flagged if anomalies are identified. For instance, `Autoflag` checks that the timing of the acquisitions is correct. It also verifies that no source data are surrounded only by flagged calibrator acquisitions, which for instance may happen if an antenna is shadowed. A message is given for information if problems are found, reporting about introduced flags.

Warnings, periods of observational peculiarities: If the observations were obtained in periods with special conditions or difficulties, a message is shown to inform about it and about the possible consequences in the calibration.

2.6.3 PhCor

`PhCor` compares the amplitude of each scan with and without atmospheric phase correction. The phase correction is only adopted when it reduces the phase decorrelation within each scan. Note that the spectral units, L01 to L12, do not store information on time scales smaller than a scan, while the continuum units, C01 to C12, do so; two streams of data are so stored at Bure for each L0i and C0i unit, respectively with and without atmospheric phase correction.

A green line on the bottom of the plot produced during the flux calibration (see Figure 9) shows, when being above zero, the scans for which the program `PhCor` activates the atmospheric phase correction.

In addition, this procedure checks for interferences in the WVR channels, if it was not done before (for instance by the pipeline).

Note that the data are not corrected for atmospheric decorrelation if "let do_atm no" was selected (see Sect. 2.6.1).

At the end, a procedure is launched to verify if the phase calibrators are polarized, setting the variable `do_avpol` accordingly (see Sect. 2.6.7) to define the amplitude calibration mode.

2.6.4 RF calibration

The goal is to measure the receiver bandpass (RF) to calibrate the source data. For this, a bright calibrator is observed for some minutes. By default, in a first calibration the procedure `Select` selects the brightest observed source for the RF calibration. The selected RF calibrator can be changed by modifying the variable "band_source" as explained in Sect. 2.6.1. If several gain ranges are found, an independent RF calibration is performed for each range.

The procedure pauses to propose fits for amplitudes and phases for each correlator input (as shown in Figure 6); by default the solutions for the Narrow correlator inputs are obtained with "solve rf 12 20 /plot", where "12" is the polynomial degree to fit amplitudes and "20" for phases (higher degrees are used for the Widex correlator units).

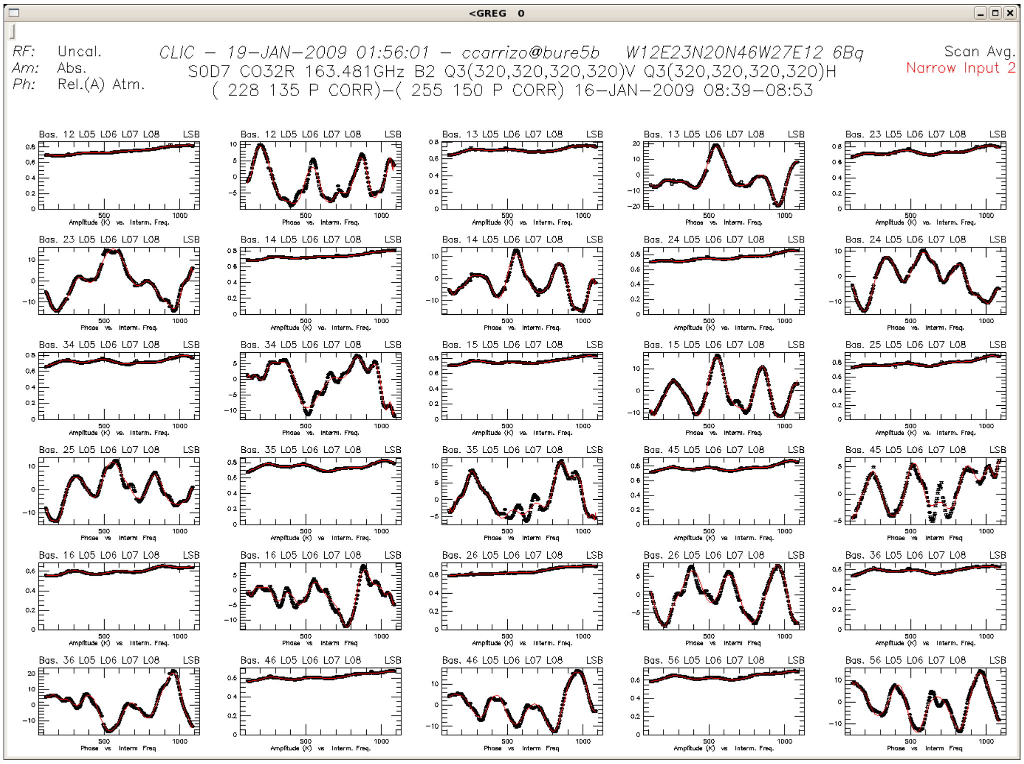


Figure 6: Example of the RF calibration of data obtained for the second Narrow correlator input

Changing the polynomial degrees with respect to the ones proposed by the automatic procedure rarely improves the RF calibration. In the pause, "continue" (or "c") should be typed to accept the solution and store the calibration parameters in the `hpb` file.

Sometimes the fit of the bandpass looks poor with deviations of a few degrees (in phase) or a few percents (in amplitude) between the measured data and fits are observed. For the time being there are no simple means to reduce these small differences. In general, they have no influence on the results.

Sometimes the procedure crashes (when fitting) because the data of an antenna is flagged. Two solutions exist: (1) Mask (see point 2 in Sect. 2.6.10) shadow, saturati[on] or redu[ction] flags to use these data for the RF calibration if the signal to noise ratio is good enough. (2) Select another calibrator by typing "let band_source 'a_new_calibrator' " as indicated in Sect. 2.6.1.

If delays are observed (constant slope in phases vs. frequency for one or more antennas) we may correct for it to decrease the phase decorrelation within scans. By using the commands "solve delay /plot" and "modify delay" we can correct for this (see Sect. 2.6.9).

Differences in the LO1ref frequencies result in frequency offsets in the RF amplitude profiles.

If the AoD (through the project notes) informs you on the presence of a big LO1ref jump (which is often linked to cable phase jumps) we recommend to calibrate the RF with the strongest phase calibrator observed cyclically with the source, for which the source LO1ref frequency was properly considered.

2.6.5 Phase calibration

In most projects we observe, alternatively to the source(s), one or two phase calibrators, for which 'ideal' phases (without instrumental contribution) are known to be zero for all the baselines. The track of these phases allows us to measure and remove possible instrumental contributions. The phase fittings for the calibrators observed cyclically with the source (set by `Select`, Sect. 2.6.1) are obtained with the command "solve phase /plot". Breaks and jumps can be introduced in the fit with the option "solve phase /break *'break_degree' 'break_time'* ". *Break_degree* is the order of the polynomial derivative that is discontinuous at the break point, the sharpest one being 0. *Break_time* is the UT time (h) at which the break should happen. (See two examples of phase calibration in Figure 7.) The option "/weight" can be used to take into account the weight ($\sim$ SNR) of the different calibrators, and "/polynomial" to impose polynomials of a given degree (the last option is incompatible with the use of breaks). More information can be found in the CLIC manual, or by typing "help solve phase" in CLIC. The procedure pauses after proposing a fit. A previous solution can be removed from the plot with "clear seg" to try a new one. A solution is accepted by entering "c" in the line of commands. The phases are calibrated independently for each polarization, and stored in the `hpb` file at the end of the procedure.

The choice of phase calibrators used to calibrate the source phases and amplitudes is performed by `Select` (see Sect. 2.6.1). If you disagree with the choice, it can be modified with "let phcal '*list_of_calibrators*' ". The phases and amplitudes of the calibrators not included in this '*list_of_calibrators*' are self-calibrated. Note that if the frequency-averaged phases from H and V polarization receivers are not equal (which for instance can be seen in the `RF phases` plot, see Sect. B) self-calibration should be avoided, and hence "let phcal '*' " should be entered after `Select` (Sect. 2.6.1).

If due to some poor data obtained in a limited time interval, the fit fails in other interval in which the phases seem well constrained, we can divide the phase calibration in two parts, by specifying the scan intervals in the main calibration widget. We should just pay attention that no source data remains uncalibrated between the two selected intervals.

From time to time the procedure crashes because too many calibrator data are flagged for an antenna or baseline. To find a proper solution for the other baselines we can just mask (see point 2 in Sect. 2.6.10) whichever the flags, solve the phases for all baselines, and reset at the end these masks. Verify at the end that the source data that were calibrated with flagged calibrator data are not used.

If the data obtained for a calibrator are too bad, and are not needed in the calibration, we can flag them as indicated in Sect. 2.6.10.

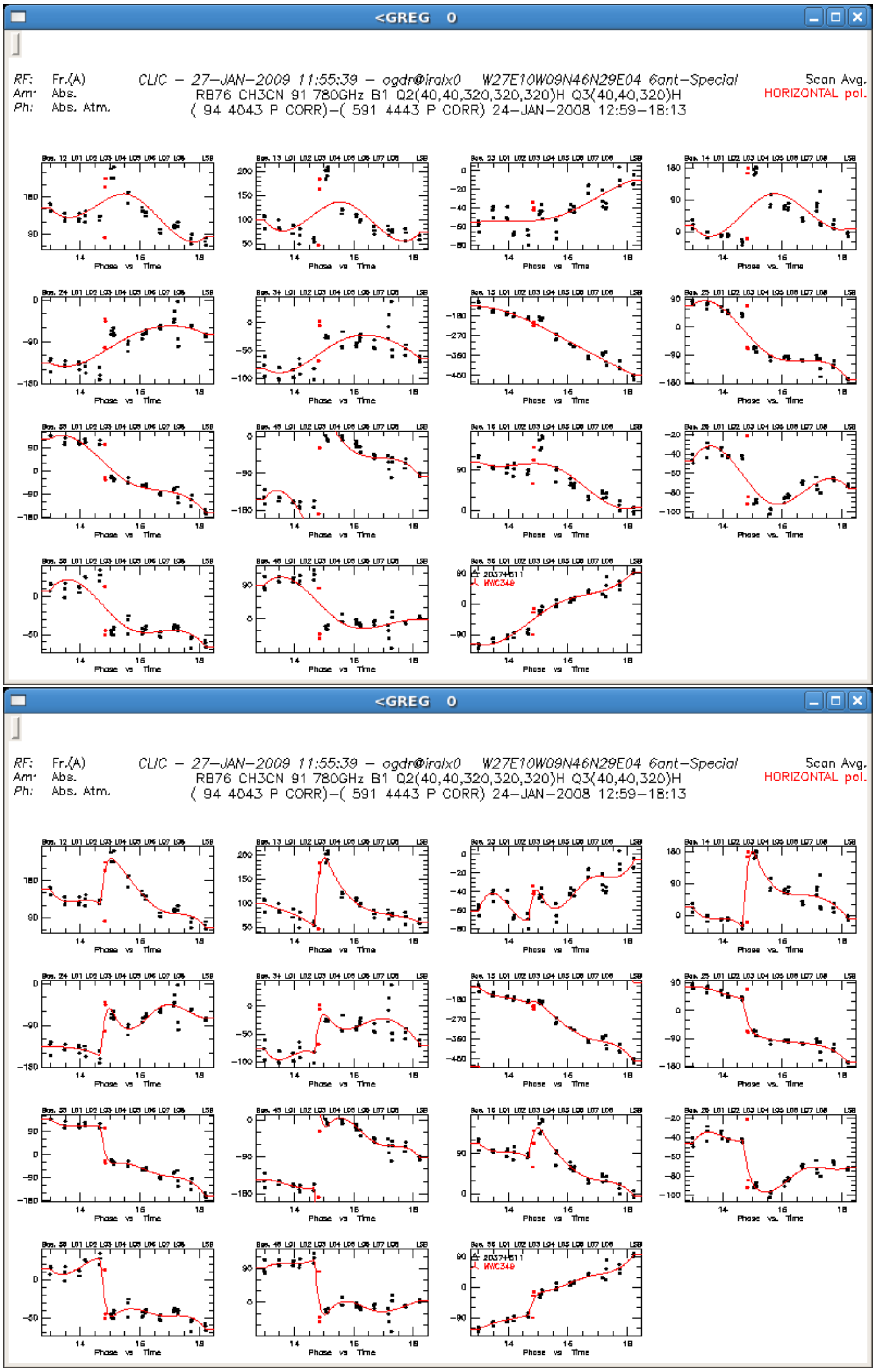


Figure 7: Example of the phase calibration of data obtained for the horizontal polarization. The command "solve phase /plot" was used in the first plot, "solve phase /plot /break 1 14.7 3 15.2" was used in the second one. The introduction of sharp breaks in the phase calibration should always result from an analysis of the reasons for such phase jumps.

2.6.6 Flux calibration

When clicking on `FLUX` (in the CLIC menu; Fig. 1) a widget similar to the one shown in Fig. 8 is opened. The flux calibration is an iterative process in which the known flux of one or more calibrators is fixed to determine the efficiencies (Jy/K) of the antennas, which are then used to estimate the flux of the other calibrators. When a flux is fixed, `SOLVE` derives efficiencies and fluxes. `GET RESULT`, `STORE`, and `PLOT` store the solved flux densities and plot the amplitudes scaled by the derived fluxes (in K/Jy). These scaled amplitudes correspond to the inverse of the antenna efficiencies, that, in an ideal project, should remain constant and equal to their nominal values.

The amplitudes obtained for a calibrator often vary along the track due to effects of a changing atmosphere or instrumental problems. Antenna efficiencies should be estimated by considering the best data ranges. Observational glitches, data obtained with bad pointings or focus measurements, or limited intervals of bad data should not be considered. If for an observed polarization amplitude oscillations on a 24 hour scale are observed, this is often an indication of that the emission is polarized. Having H and V polarizations is needed to confirm the presence of polarized emission. (The degree of polarization of the NOEMA phase calibrators is evaluated and archived at the observatory, and so can be checked by your local contact if needed.) Anyway, there is nothing to do in the flux calibration with respect to this. The `Scan List` option permits to select the scan ranges to be considered in the calculation of fluxes and efficiencies. After `PLOT`, scan numbers can be determined by using the command "cursor" and clicking on the display (an example is shown in Figure 9).

All the calibrators observed during the track are shown in this widget. Currently the main flux calibrator is MWC 349, which is observed in most of the projects; when included, a flux is proposed to be fixed, as we can see in Fig. 8. Its use must be however considered by checking the quality of the observed correlations: i.e. correlations on MWC 349 showing a big scatter in amplitude should not be considered unless they are representative of the track observing conditions. The other calibrators, the one used to calibrate the RF and also the phase calibrators, can be used in this process. Their flux may be known from other tracks observed close in time. Note also that we monitor the flux of the brightest calibrators. Your local contact can provide you this information, and also an estimate of the right efficiencies with a reasonable accuracy. For example, for a track observed in good conditions the expected efficiencies for the different antennas should range from 20 to 25 Jy/K, from 25 to 32 Jy/K, and from 32 to 45 Jy/K for receiver bands 1, 2, and 3 respectively. Values much larger than those expected should be well explained by the observational conditions. Efficiencies significantly smaller are not possible.

By properly using this method, the absolute calibration obtained is typically precise to less than 10% at 3mm and $\sim 20\%$ at 1mm. Special attention should be payed to the relative flux calibration between different tracks; normally the different tracks provide

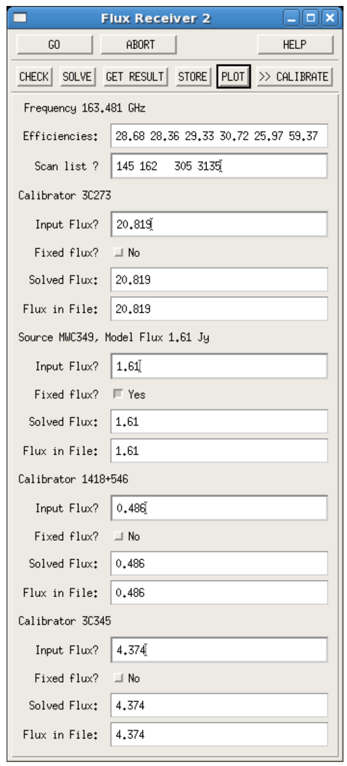


Figure 8: Flux Calibration widget, showing on top the solved antenna efficiencies. Note that these are characteristics of the antennas, and the different values obtained between antennas should be well understood by the AoD at the time of the observations and likely also by your local contact. For instance, the low efficiency of A6 at the moment of these observations was due to a polluted injected LO signal; a new LO box was installed in A6 just after these observations. In the second row we define the scan intervals to be considered in the flux calibration.

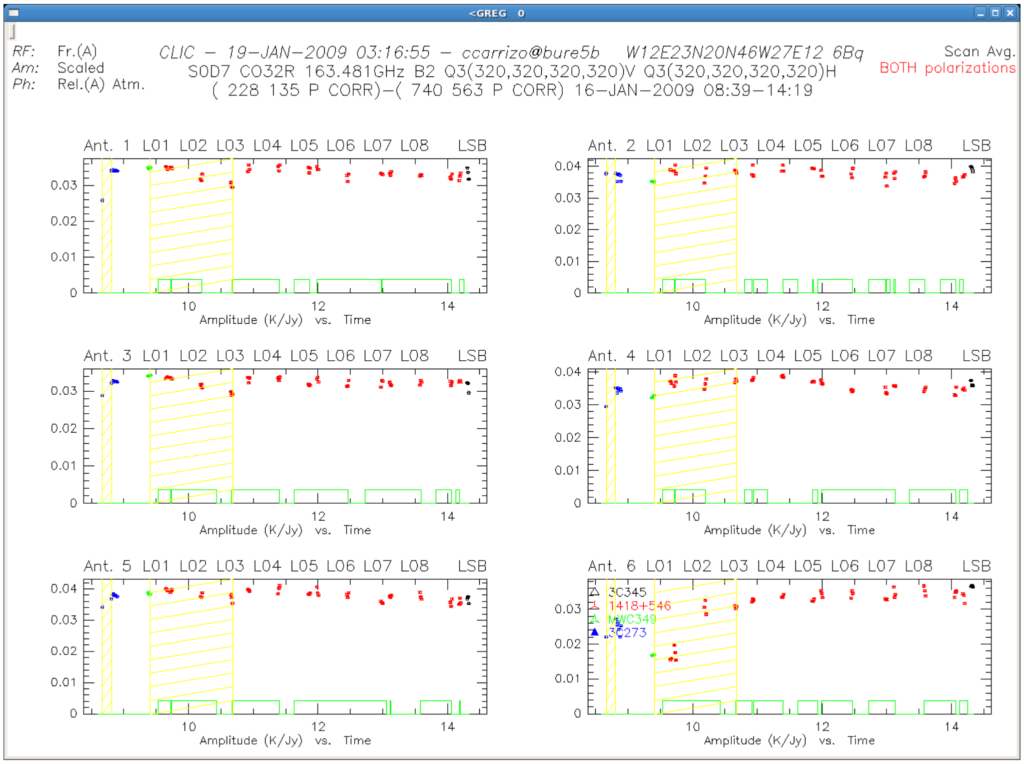


Figure 9: Flux Calibration plot, showing the amplitudes scaled by the solved fluxes. Note that the amplitudes from both Narrow correlator inputs are averaged in this plot.

complementary information in the *uv*-plane, and so a wrong relative flux calibration can be interpreted as source structure.

As mentioned in Sect. 2.6.3 the green lines at the bottom of the plots show, when being above zero, the regions in which the atmospheric phase correction is applied as resulted from `PhCor`.

Note finally that the option `CHECK`, at the top of the FLUX calibration widget (Fig. 8), permits to obtain a solution by fixing a reference calibrator and ignoring scans of quality below a certain threshold. This may be used as a first try, a second iteration is often needed (after storing the first one). A solution is stored with `GET RESULT` and `STORE`, and a new `PLOT` should be created accordingly.

The flux calibration is performed by averaging the amplitudes from all the spectral units, i.e. from all the correlator inputs[8]*, H and V polarizations. Delays (see Sect. 2.6.4 and 2.6.10) result in flux losses due to that phases are frequency averaged. To correct for remaining delays you should follow the instructions given in Sect. 2.6.9. Also, as mentioned in Sect. 2.6.5, differences in the (frequency averaged) phases from H and V polarization receivers introduce amplitude losses* *in the flux calibration for the RF and flux calibrators. See Sect. 2.6.5 to correct for this effect. Note anyway that either the presence of delays or polarization differences are rare, since the standard NOEMA observing procedures correct for them at the very beginning of each track.*

If flagged data are masked, such masks should be reset before the flux calibration. Since fluxes are solved by averaging the data of all the spectral units, we may not be able to identify problems coming from some flagged data from, for example, one of the narrows.

2.6.7 Amplitude calibration

The amplitude calibration is similar to the phase calibration in its concept: fitting and removing the amplitude changes observed in the calibrators along the track. The command to be used is "solve amplitude" with the same options as for the phase calibration, in Sect. 2.6.5. Scaled amplitudes are plotted, so we can verify that the flux calibration, in relative terms, was correct.

Sometimes we find complementary (between polarization V and H) variations of the amplitudes in time, indicating that the calibrator emission is polarized (see Figure 10). The amplitudes of both polarizations should be then averaged to cancel such variations (see Figure 11). By typing in the line of commands "let do_avpol yes" the amplitude calibration is performed in the average mode. At the end of the `PhCor` procedure an assessment on the polarization of the phase calibrators is performed (if not done before, for instance by the pipeline), and the variable `do_avpol` is set accordintly.

The amplitude calibration procedure presents similar characteristics and problems to those described for the phase calibration, in the paragraphs with italic-fonts in Sect. 2.6.5.

In addition, pointing and focus problems do often result in amplitude losses, mainly at higher frequencies, when the primary beam is smaller. A proper fit of the amplitudes affected by these problems may allow to correct for it; note that this is only valid if the source emission is expected to be centered and compact. We should also consider the proximity of the source to the calibrator(s).

2.6.8 Print

`Print` combines all the postscript files created at each step of the calibration to produce a file named 'date'-'projectname'.ps. In its first pages the calibration quality is summarized, including resulting efficiencies and flux densities, and the rms of the RF, phase and amplitude calibrations.

2.6.9 Usual difficulties

Baselines

Sometimes, during the observations of a project, a good baseline model (a precise determination of the antenna positions) is not available. This introduces typical phase drifts that are often well identified by an experienced astronomer (see Figure 12). Normally the AoD reports on this in the project `notes` and often proposes a baseline solution

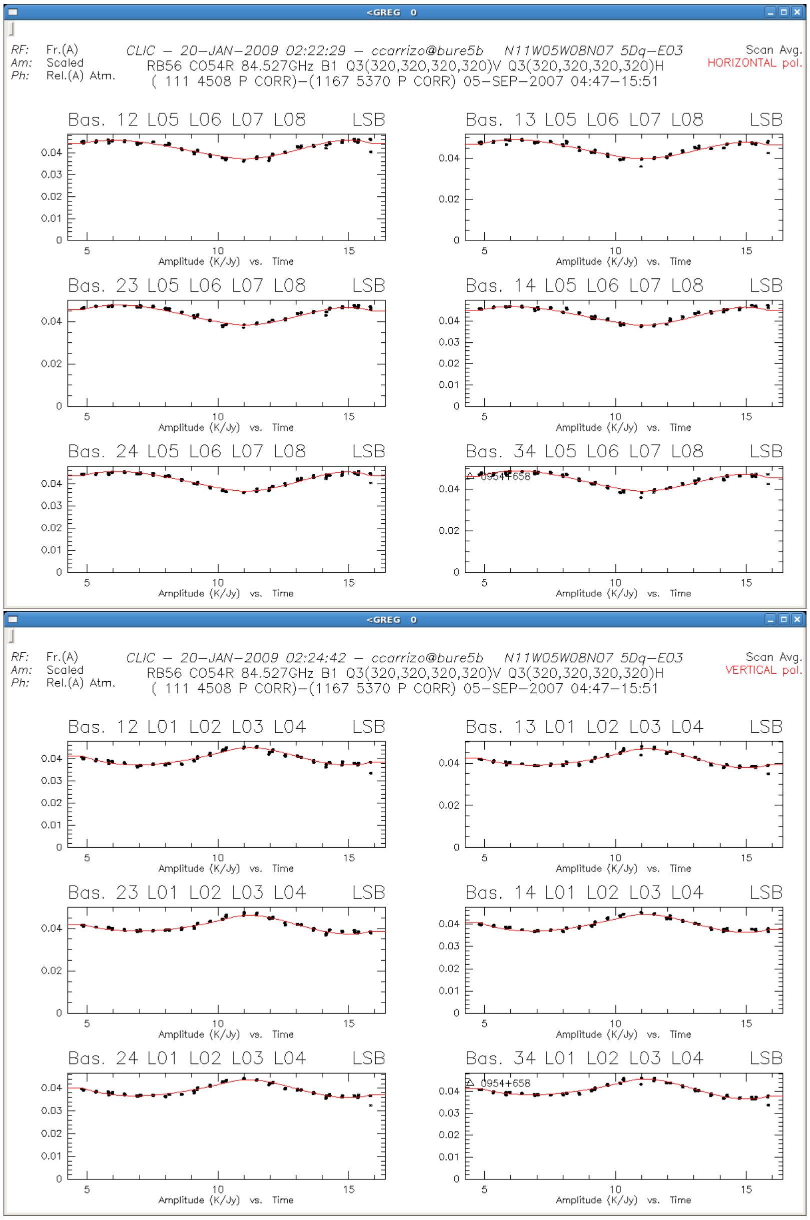


Figure 10: Example of the standard amplitude calibration, performed independently for the V and H polarization receivers. In this example the calibrator emission is found to be polarized. The option “let do_avpol yes” will allow repeating the amplitude calibration by averaging the calibrator emission for both polarizations, as shown in Figure 11.

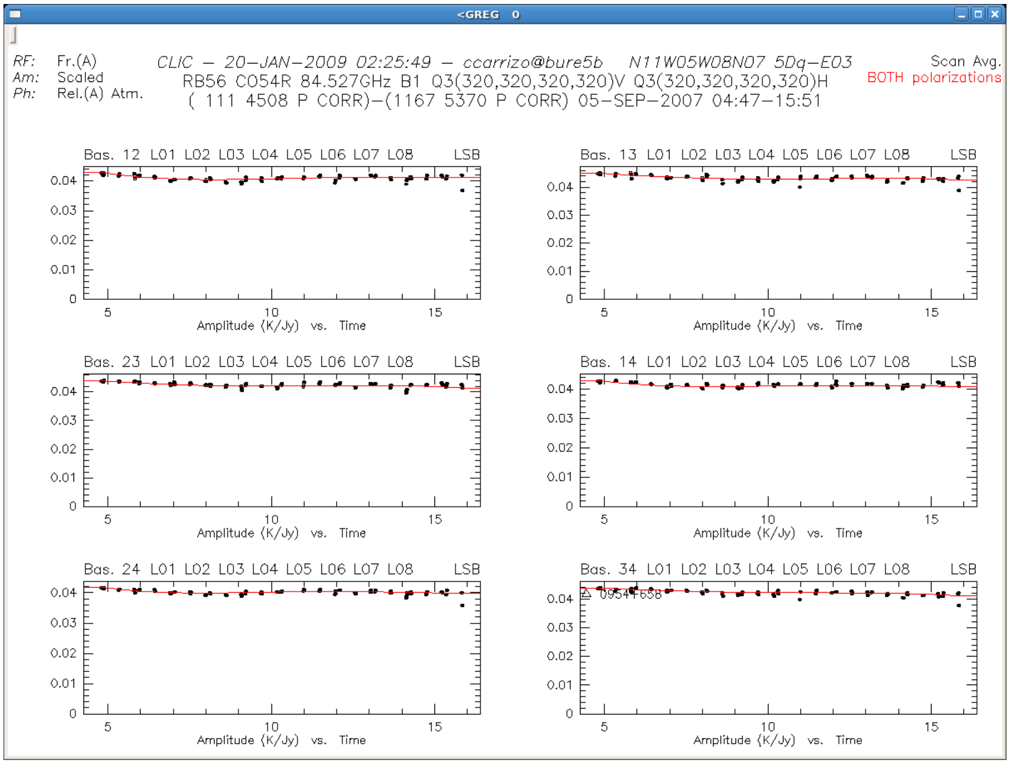


Figure 11: Example of the amplitude calibration in the average mode, i.e. by averaging the emission of V and H polarization receivers.

obtained hours or days later. Baseline solutions obtained close to each track are given in the directory `baselines`. Otherwise, they can be provided by the local contact. To apply a baseline model, "set /def" and "find" should be entered at first in CLIC, followed by the command "modify antenna 1...2...3...4...5...6.../offset 99" as proposed by the best baseline model, either found in the in the AoD notes or in the `baselines` directory. Note that this command refers to logical antennas, which should be well identified within the solution if the number of antennas is smaller than six. Verify with your local contact if any doubt.

Delays

As mentioned in Sect. 2.6.4, sometimes data must be corrected for delays (see Figure 13). To determine the delays we first select a polarization (with "set polar ..") and then plot phases (with "set y phase") vs. the if1 frequency (or band frequency, with "set x if1"), preferably after selecting antenna-mode (with "set antenna all"). Delays are determined with "solve delay /plot /print" for each polarization. To enter a solution, all

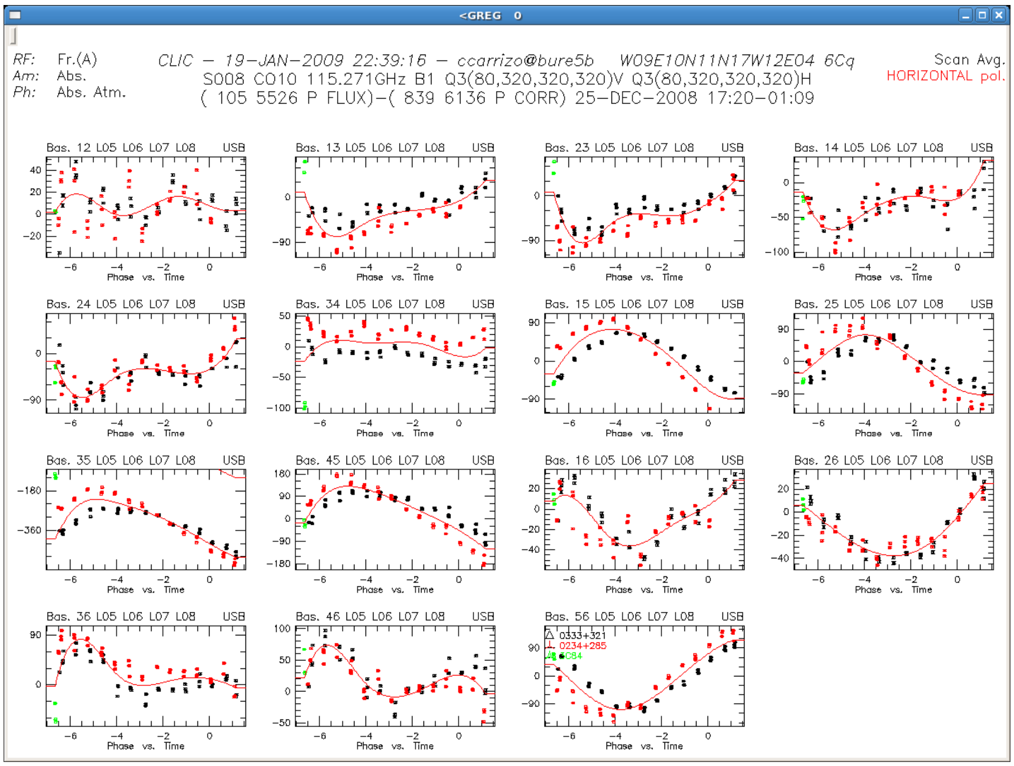


Figure 12: Example of phases affected by a 'baseline' problem. The separation of the phases obtained for the two phase calibrators as well as the large phase drifts are characteristics of a wrong baseline model. In this case, the position of antennas 3 and 5 were wrong in $\sim$ 5mm.

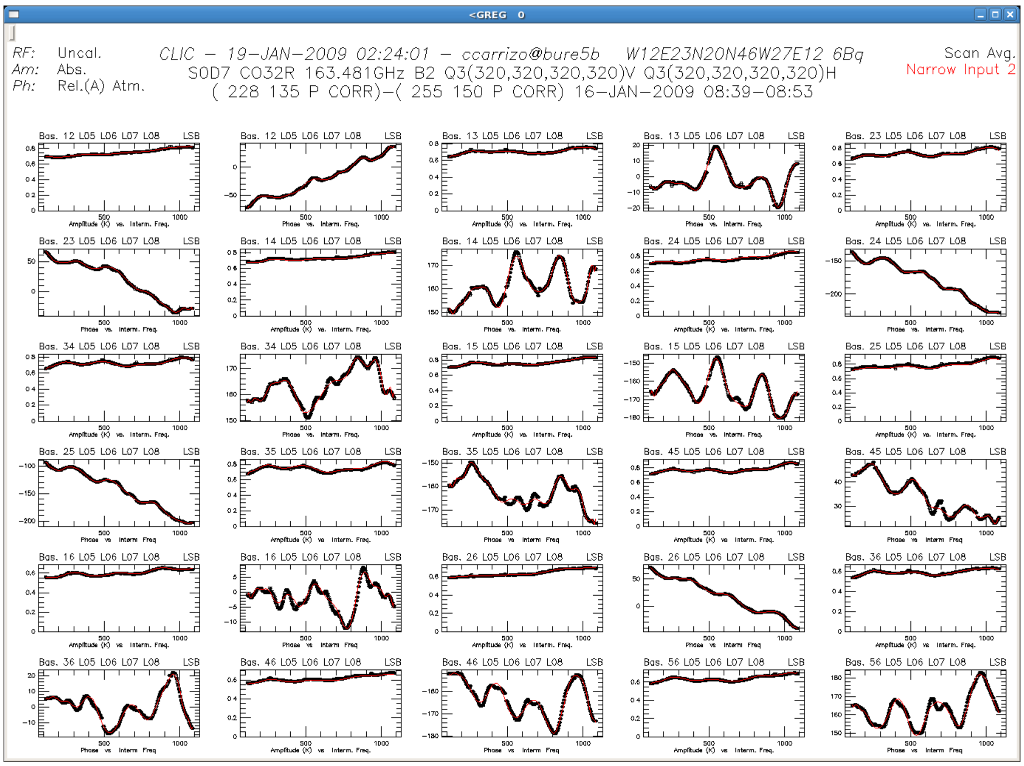


Figure 13: Example of a RF calibration where we can appreciate a remaining delay in the baselines including A2. Delays can be solved with the commands “solve delay” and “modify delay” (see Sect. 2.6.9).

concerned scans must be selected with "find" and then the command "modify delay ..." must be typed, as proposed by the solution. After correcting delays the RF calibration must be repeated.

Note that, for the time being, the continuum units are not corrected offline for delays. If delays are modified, we advise using spectral units (instead of continuum ones) at each step of the calibration process.

Atmospheric Phase Correction

By default the atmospheric phase correction derived from the 22GHz receivers is applied according to the results obtained with the `PhCor` procedure. We can however remove it by typing "let do_atm no" in the line of commands before performing any calibration. If a previous calibration was already carried out applying the atmospheric phase correction, the option `no` must be also selected in `Use previous settings`. The whole calibration must be then repeated. On the upper-left corner of each data plot we can see *Ph: Abs./Rel(A). Atm*, where *Atm* reports on the presence of the atmospheric phase correction (according to `PhCor`).

See additional information in Sect. 2.6.3.

Several telescope configurations

If a track includes observations with different telescope configurations, for example if an antenna was removed during the observations, after clicking on `Select` the different configurations will appear in the main calibration widget. The calibration must be perform independently for each configuration. `Use previous settings` is then set off.

2.6.10 FAQ

• *How to proceed to repeat a calibration step?* If you want to repeat a part of the calibration, you do not need to repeat all the calibration steps happening before, but those taking place later according to the scheme here described. Note that clicking on `Select` (within the `Standard Calibration` widget) is always recommended before repeating any calibration step, in order to have proper settings.

• *How can I mask flagged data?* Sometimes procedures crash because a lot of data of an antenna or baseline are flagged. We can verify the kind of flags with the command "list /flag". We can mask them with the command "mask *flag_label* /ant *i*" (or "/baseline *ij*"). For example, "mask shadow /ant 3" would mask the flags of antenna 3 (logical) due to shadowing. Masking flags without a clear understanding of what it means is not recommended. However, masking certain calibrator flags may be convenient in some cases (see Sect. 2.6.4, 2.6.5 and 2.6.7). If flagged data are masked in some part of the calibration, the masking should be reset with "mask /reset" (e.g. "mask shadow /ant 3 /reset") at the end of the calibration step.

• *Is there any command in* CLIC *that refers to physical antennas?* No. The physical antenna numbers are just shown in the plots of the `First Look` procedures, because the command "plot /physical" is the default there. Otherwise, all CLIC commands and procedures use the logical numbers for antennas. This must be taken into account if AoD notes refer to physical antennas, or when applying a new baseline model in observations with an incomplete array.

• *How can I flag data?* After selecting the data to be flagged with "find", you can use the command "store flag *flag_label* /ant *i*" (or "/baseline *ij*"). We can also delete them by changing their quality with the command "store quality 9 /ant *i*" (or "/baseline *ij*"). Please, ask your local contact if any doubt.

For example, the following commands would allow flagging correlations obtained with all antennas on a source of name starting by 1823, between the scans 234 and 250, with the label "redu":

```
CLIC> find /proc corr flux /sou 1823* /scan 234 250
CLIC> store flag redu /ant all
```

2.6.11 Other calibration procedures

Baseline-based calibration

Sometimes we have difficulties to have antenna-based calibration solutions. In almost all the cases this can be solved by finding the origin of the problem, often due to the presence of corrupted data. If the difficulties are found to be due to baseline-dependent problems, for instance related to the correlator, to the atmosphere, etc, it may be better to calibrate in baseline-based mode. In that case the `hpb` file must be created by using the CLIC command "copy header base" instead of "copy header antenna" (the default in Sect. 2.4). The baseline-based solution can be then obtained by defining "set rf/ phase/ amplitude baseline" before solving and storing. Antenna-based solutions can be also stored in these `hpb` files by using "set rf/ phase/ amplitude antenna", followed by solve and store. Note that the last solution stored is the one considered by default. Get in contact with your local contact for a more detailed explanation if needed.

Self-calibration

Self-calibration can be performed by selecting "Self-cal on point source" in the CLIC menu (Fig. 1), with a procedure similar to that here described for a "Standard Calibration" that includes also the source correlations.

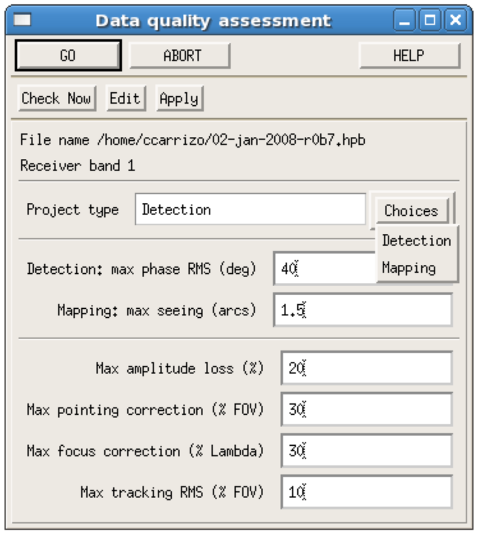


Figure 14: `Data Quality Assessment`, in the CLIC menu

2.7 Data quality assessment

An assessment of the quality of the calibrated data can be performed by selecting in the CLIC menu (Fig. 1) the option `Data quality assessment` (see Fig. 14). This procedure creates a `clic` procedure to flag data not satisfying predefined quality criteria. By default two different criteria are adopted to assess the data quality, depending if the project aim is detecting or mapping source emission. In the first case, the criterion is just the phase stability. In the second, data whose phase stability results in a `seeing` larger than the maximum defined in the widget are not considered. The adopted thresholds to assess the quality of the amplitude and phase calibrations change with the receiver band. The considered limits to evaluate the quality of pointing, focus and tracking are defined in relation with the primary beam and the wavelength. Plots are created to identify with shadowed areas the data of poor quality according to the limits defined in the widget (Fig. 14). Histograms presenting a statistical analysis of the data quality are created at the end.

By clicking on `Check Now` a `clic` procedure is created to flag the data shown in shadowed areas of the plots. It is to the user to `Apply` or not this procedure. The option `Edit` permits to modify the procedure before applying it.

2.8 *UV*-Table Creation

A *uv*-table with calibrated source visibilities can be created by selecting "Write a UV Table" in the CLIC menu (Fig. 1). A widget similar to the one shown in Fig. 15 is opened.

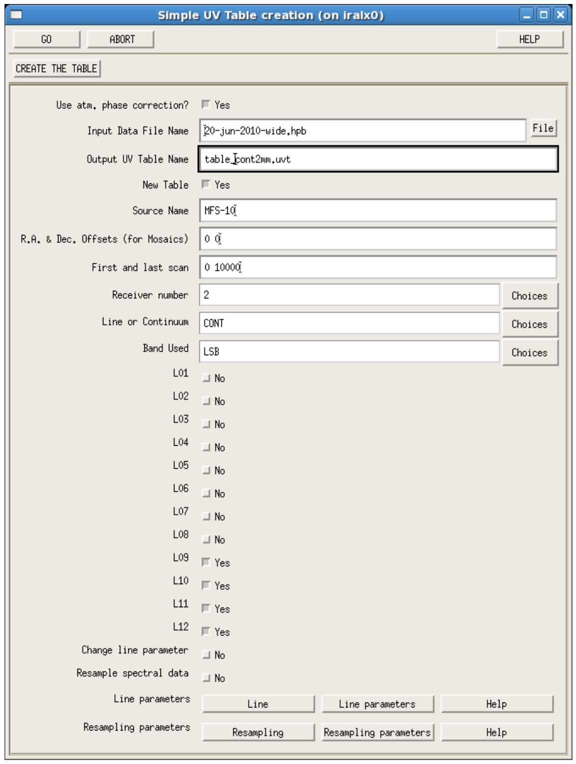


Figure 15: `Write a UV Table`, in the CLIC menu.

The `hpb` file name, table name (with no extension), source name, receiver band, tuned side band and table mode (with spectral -`LINE`- or without spectral -`CONT`- information) are to be specified. In the widget, the atmospheric phase correction must be disabled if it was not taken into account in the calibration. The rest frequency can be redefined, as well as the table resampling for the `LINE` mode. A *uv*-table is newly created if the option `New Table` is set `on`; visibilities are added to an existing *uv*-table if the option `New Table` is set `off`.

This procedure creates (or includes) the selected calibrated source visibilities into the specified *uv*-table, but also creates (or updates) a `clic` procedure, which can be executed by entering "@mytable-table.clic" in CLIC to produce the same table (of name "mytable" in this example). Editing a script to create tables (the file "mytable-table.clic" in our example, see Fig. 16) is easy and likely faster than filling in all the options available in the widget to create tables. This `clic` procedure defines the `hpb` file, calibration and table settings, selects the correlations on source, and finally uses the CLIC command "table", possibly with the options "/resample" and "/frequency". In the CLIC menu there exist other more complex procedures to create tables, but likely none of them is as fast and flexible as editing table scripts is.

Particularly for mosaics a table must be created for each observed offset, all of them with a generic common name followed by an offset number (an example is shown in Fig. 16). The imaging MAPPING procedures (presented in Sect. 3) will so recognize the mosaic and properly proceed with the imaging.

2.9 Calibrating and/or merging with data previous to 2007

2.9.1 CLIC backwards compatible

The current versions of CLIC are backwards compatible and hence can be also used to calibrate data obtained before 2007, when a new generation of receivers was installed at Plateau de Bure (see also Sect. 2.9.5).

2.9.2 uv-tables obtained before 04/2004

The format of the *uv*-tables changed in March 30, 2004. The MAPPING command "uvt_convert" updates the *uv*-tables' format to be treated with a recent `GILDAS` version and particularly to mix the old tables with recent data.

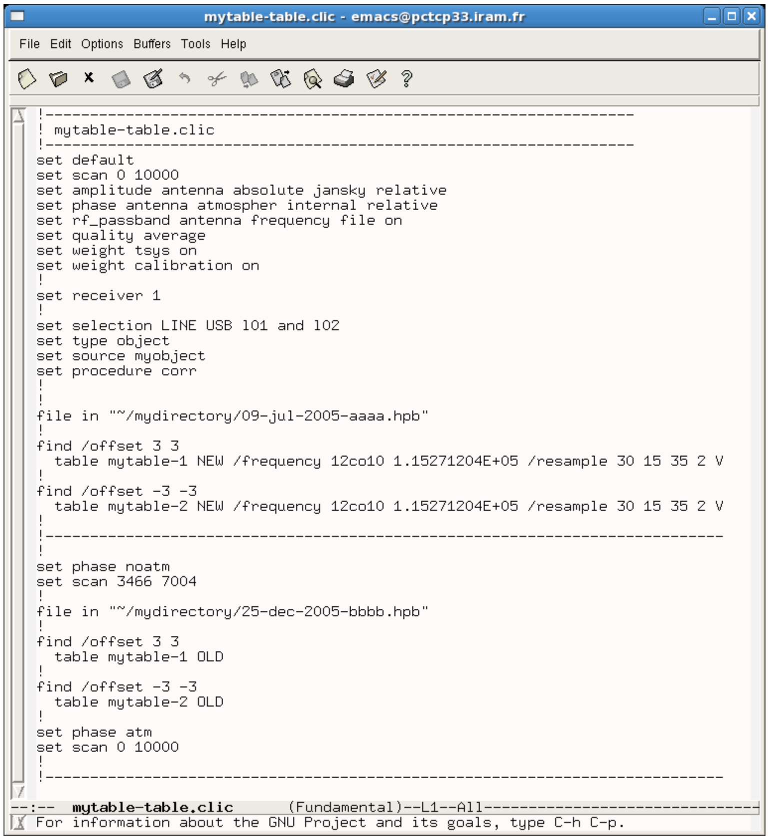
2.9.3 Merging old and new data

In order to merge old and new data the best is likely to create the *uv*-tables from the old and the new hpb files, with the same CLIC version dated later than April 2004, as described in Sect. 2.8: 1) Using the widget to create a table or just to add visibilities in a previous table by setting on or off the option `New table` (see Fig. 15). 2) Editing a table script and using the command `table` with the options `new` and/or `old` as shown in Fig. 16, depending if the table is to be created or if just visibilities from a second data set are added.

Otherwise, *uv*-tables can be merged with the procedure "run uv_merge" either in CLIC or in MAPPING, provided they have the same spectral setup. Contact your local contact if your situation does not correspond to any of the mentioned cases.

2.9.4 Continuum projects between 11/2005 and 01/2007

In November 25, 2005, prototypes of the new generation of receivers were installed on antenna 6, while the other antennas continued observing with the old receivers. This situation remained until January 2007, when all antennas were equipped with new receivers. As a consequence, for those projects observed with DSB tuning the creation of continuum tables from all baselines except for those with antenna 6 should be made by using both bands, but the baselines with antenna 6 should just include the tuned band (pure SSB). Note that this affects all 1mm continuum projects, where the tuning was DSB by default with the old receivers.




```
!--------------------------------------------------------------------
! mytable-table.clic
!--------------------------------------------------------------------
set default
set scan 0 10000
set amplitude antenna absolute jansky relative
set phase antenna atmospher internal relative
set rf_passband antenna frequency file on
set quality average
set weight tsys on
set weight calibration on
!
set receiver 1
!
set selection LINE USB 101 and 102
set type object
set source myobject
set procedure corr
!
!
file in "~/mydirectory/09-jul-2005-aaaa.hpb"
!
find /offset 3 3
  table mytable-1 NEW /frequency 12co10 1.15271204E+05 /resample 30 15 35 2 V
!
find /offset -3 -3
  table mytable-2 NEW /frequency 12co10 1.15271204E+05 /resample 30 15 35 2 V
!
!------------------------------------------------------------------------------
!
set phase noatm
set scan 3466 7004
!
file in "~/mydirectory/25-dec-2005-bbbb.hpb"
!
find /offset 3 3
  table mytable-1 OLD
!
find /offset -3 -3
  table mytable-2 OLD
!
set phase atm
set scan 0 10000
!
!------------------------------------------------------------------------------
--:--  mytable-table.clic      (Fundamental)--L1--All-------------------------------
For information about the GNU Project and its goals, type C-h C-p.
```

Figure 16: Script to create *uv*-tables for a mosaic of two points, as edited by emacs. Note that for the data of the second day the same settings adopted but for the atmospheric phase correction and the considered scan range.

To create continuum tables we recommend: First, storing in the *uv*-table the data coming from all the antennas for the band tuned in antenna 6. Second, storing the visibilities obtained for the other band, ignoring antenna 6 data. For example, for a project LSB tuned in antenna 6, but DSB in the others, we would proceed as follows:

```
set band lsb
table table_name
set band usb
mark data /ant 6
table table_name /nocheck scan
```

2.9.5 Very Old Projects

The calibration of very old projects (older $\sim$ 1995) is likely not possible with widgets because of the many big changes over the years. Consult the SOG (at sog@iram.fr) if needed.

3 First Instructions for Data Analysis with MAPPING

MAPPING is the GILDAS software package to image and analyze NOEMA data. The tools described here are complex procedures built over simple MAPPING commands. We recommend to look at the MAPPING manual to have a deeper understanding of imaging and deconvolution concepts and of the command functionalities.

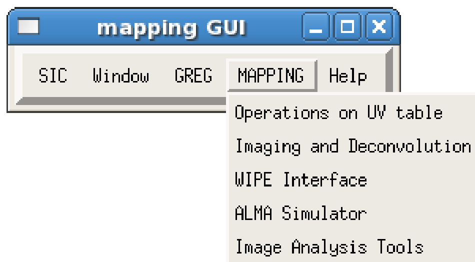


Figure 17: MAPPING menu.

The menu shown in Fig. 17 leads to two main sections, `Operations on` UV`-tables` and `Imaging and deconvolution`. In the widgets resulting from the selection of these options (Figs. 18 and 21) the left column lists the procedures to be run, their control parameters can be edited by clicking on the related button in the central column, help is displayed by pushing on the right buttons. At the bottom of all the "Parameters" widgets (see e.g. Fig. 19 and 20) there are the options `GO` and `DISMISS`. `GO` executes the procedure with the specified parameters, `DISMISS` closes the widget.

In the below sections, the paragraphs starting with *At the prompt:* describe how to run the same procedures through the command line instead of through the widgets. While this possibility exists for all the widget functionalities, information is given for some of them. In general, typing"`go` *procedure_name*" is needed to call MAPPING procedures. To modify the control parameters "`let` *variable_name value*" is used. Their content can be checked with "`input` *procedure_name*" or by typing "`exam` *variable_name*". The name and a short description of the control variables can be found by clicking where the values for parameters are requested, in the widgets.

In addition, a few variables are used by (almost) all the procedures. You can also define their values directly at the prompt. For instance "`let name` ..." is used to define the generic name (without extension) of your table or image, "`let first` ..." to define the first channel to be considered, "`let last` ..." to define the last one.

3.1 Operations on UV table

By clicking in the MAPPING menu (Fig. 17) on `Operations on` UV `table` the widget presented in Fig. 18 is opened. There, by clicking on the buttons in the column on the left, we run the corresponding procedures, some of them described below. We strongly recommend to look at the adopted parameters (in the central column) before executing them.

The main procedures related to the analysis of the data in the *uv*-plane are described in the following sections:

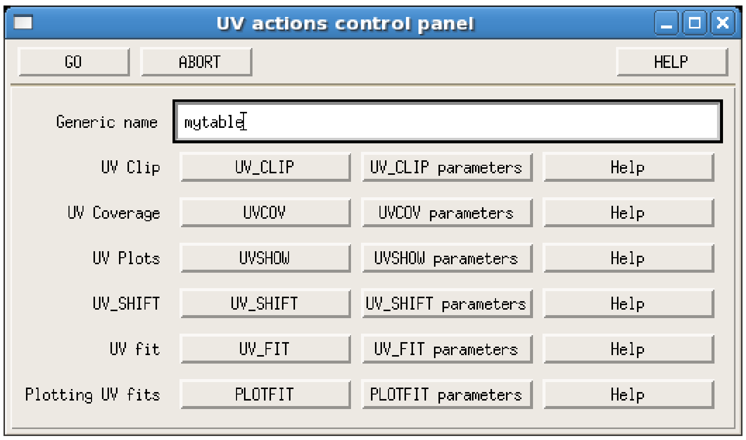


Figure 18: Operations on *UV* table, from the MAPPING menu.

3.1.1 UVSHOW

UVSHOW plots the *uv*-data. By default amplitudes vs. *uv*-radii are presented, for all visibilities and spectral channels. The `UVSHOW parameters` widget (see Fig. 19) permit to select the visibility's characteristic (amplitude, real part, weight, etc.) to plot. By default the different tracks are plotted with different colors. Plotting a model fitted by UVFIT is possible by clicking in the corresponding option.

At the prompt:
Procedure: `go uvshow`

Some variables:

```
let ytype amp
let ytype weight
let xtype radius
let xtype time
let uvshow%fit no/yes
let uvshow%zero yes/no
let uvshow%track yes/no
```

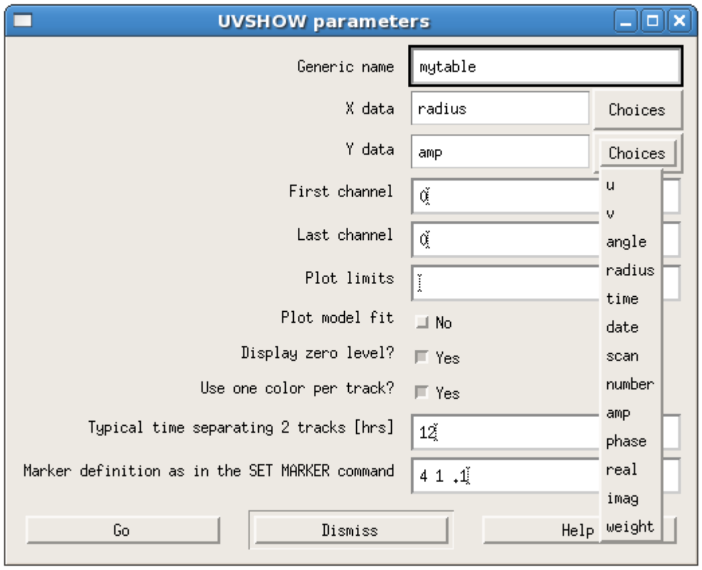


Figure 19: UVSHOW parameters, to plot the UV-data.

3.1.2 UVSHIFT

Procedure to shift the phase center of a UV-table. Absolute or relative coordinates can be introduced. The position angle of the reference axes (which is then considered by the plotting procedures) can also be changed.

At the prompt:
Procedure: `go uv_shift`

3.1.3 UVFIT

Procedure to fit the obtained uv-data with the Fourier Transform of the following functions (see Fig. 20): a point, a circular Gaussian, an elliptical Gaussian, a circular disk, an elliptical disk, a circular or elliptical ring, an exponential brightness distribution, a distribution proportional to radius^{-2}, and a distribution proportional to radius^{-3}. Some parameters can be fixed by defining them in the option `Parameters`. They are the offset R.A., offset Dec and flux for a point function, offset R.A., offset Dec, flux and diameter for c_gauss, offset R.A., offset Dec, flux, major and minor diameter and position angle for e_gauss, offset R.A., offset Dec, flux and diameter for c_disk, offset R.A., offset Dec, flux, major and minor diameter and position angle for e_disk, offset R.A., offset Dec, flux, inner diameter and outer diameter for a ring, offset R.A., offset Dec, flux and diameter for the functions called expo, power-2 and power-3.

The fitted function can be subtracted in a residual table (of extension uvfit) that later can be plotted with UVSHOW (Sect. 3.1.1).

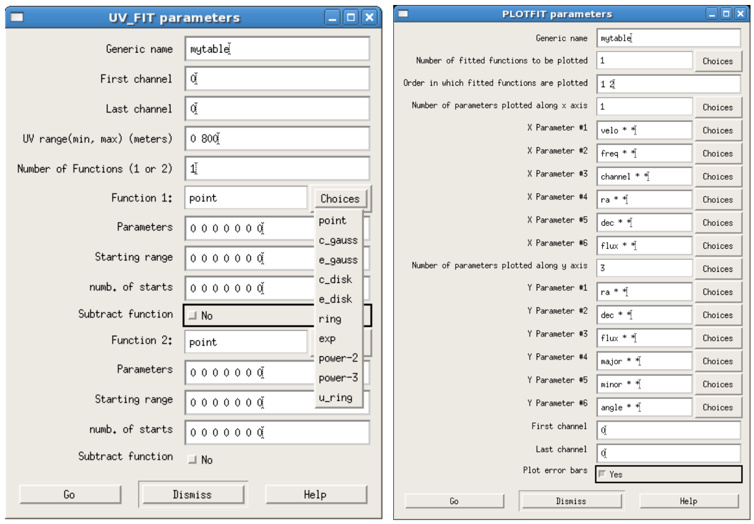


Figure 20: *Left:* UV_FIT parameters, to fit the *UV*-data with the Fourier Transform of simple functions. *Right:* PLOTFIT parameters, to plot the fitting results obtained with UVFIT.

3.1.4 PLOTFIT

PLOTFIT is aimed to plot the results of UVFIT. The number of parameters to plot (see Fig. 20) is to be defined if larger than 3. By default it presents the position of the center of the fitted function, R.A. and Dec, and the flux at each velocity. Several options are available for each fitting. Error bars are plotted by default.

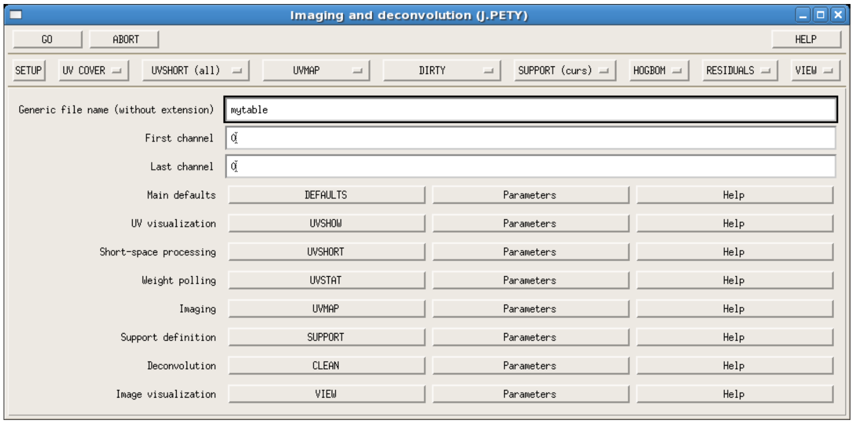


Figure 21: Imaging and deconvolution, from the MAPPING menu.

3.2 Imaging and deconvolution

By clicking in the MAPPING menu (Fig. 17) on `Imaging and deconvolution` in the widget presented in Fig. 21 is opened. The menus at the top of Fig. 21 permit to run some of the most used procedures. The list of options presented below in the widget (Fig. 21) allow us to execute the same procedures (on the left) and modify the corresponding parameters (at the center).

3.2.1 SETUP

`SETUP` performs a first check of the data related to a common *generic name*[9], and reports on possible consistency problems if mosaics or short-spacing data. Short-spacing tables to be merged with interferometric data are supposed to have the same generic name with the extension `tab`. For mosaics, all the fields must keep a common generic name followed by *-i* for each field *i*; just the generic name should be then specified in the imaging procedures. From this initial inspection of the data, map and pixel sizes are recommended and later used by default in the imaging process.

3.2.2 UVSHORT

Four steps are proposed in UVSHORT (setup, table, merge and clean) to merge interferometric and single-dish data. The compatibility of both data sets is checked, a *uv*-table is created from the single-dish data, both data sets are merged and imaged in order to verify the consequences on the beam. A `uvt` table is created with the resulting merged

[9] Generic name refers to the table name without extension, and, for mosaics, without the offset specification (see Sect. 2.8).

data. The default UVSHORT parameters are well adapted for merging NOEMA and 30m-telescope data.

We recommend to use the procedure `UVSHOW` (see Sect. 3.1.1) to verify the merged *uv* data, and particularly to verify that the flux calibration is not incompatible. For example, by plotting amplitude versus *uv* radius we can check the flux of both data sets at their interface, i.e. at a *uv* radius of 15m (for the NOEMA array).

3.2.3 UVMAP

Procedure to compute a dirty map (with extension `lmv`) and beam (with extension `beam`) from *uv*-tables. For mosaics a unique dirty image is created, as well as individual ones for each field. UVMAP estimates which are the best values for pixel and map sizes. We recommend to use them. By default images are created by using natural weights for the visibilities. Uniform weights can be defined in the widget (see Fig. 22), but indeed correspond to robust weighting.

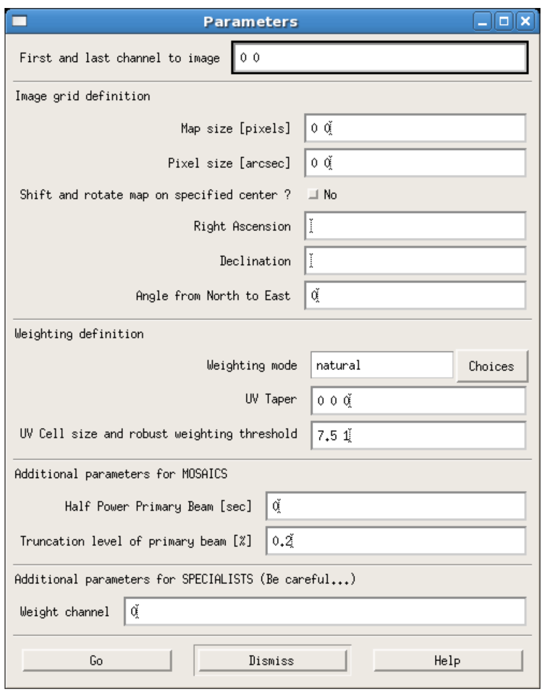


Figure 22: UVMAP parameters, to create a dirty (`.lmv`) image.

UVSTAT weight/taper The advantages and inconveniences of modifying the weights from natural to robust are quantified, and numbers are shown by UVSTAT in mode `weight`. The advantages and inconveniences of tapering can be verified with UVSTAT in mode `taper`.

DIRTY/BEAM/PRIMARY/WEIGHTS at the top of the imaging widget (Fig. 21) are aimed to plot the results from UVMAP, that is "mytable"`.lmv`, "mytable"`.beam`, and, if mosaicing, also "mytable"`.lobe` and "mytable"`.weight`.

At the prompt:
Procedure: `go uv_map`

To plot:
Procedure: `go bit`

Some variables:
```
let type lmv
let type beam
let first 7
```

3.2.4 SUPPORT

Procedure to define polygons inside which the CLEANing procedure will look for CLEAN components. A common polygon can be defined for all the channels, or one polygon per channel. Polygons can be defined with the cursor or by introducing the needed parameters to define elliptical or rectangular supports. All these possibilities can be easily identified in the SUPPORT widget.

At the prompt:
Procedure: `go support`

Some variables:
```
let support%oneperplane yes/no
let support%kind cursor/ellipse/rect
```

3.2.5 CLEAN

It identifies in the dirty map CLEAN components and convolve them with a deduced synthetic beam. Different CLEANing methods can be used. HOGBOM and CLARK are recommended for being the most robust (see `MAPPING` manual for details). By using `SUPPORT`s the search for CLEAN components can be restricted to the areas where the source is known to be (when the variable `myclean%support`=yes, see Sect. 3.2.4). The criterion to stop the search for CLEAN components within the residual map can be modified by changing the `Stopping criteria` options in the CLEAN parameters widget (Fig. 23). By default no supports are used in a first CLEANing of a dirty map, but can be defined for later CLEANing. The option to CLEAN with supports can also be set on or off in the CLEAN parameters widget. By default the flux accumulated in the identified CLEAN components is shown (if `myclean%show`=yes), and stored in a file of name including `-cct`.

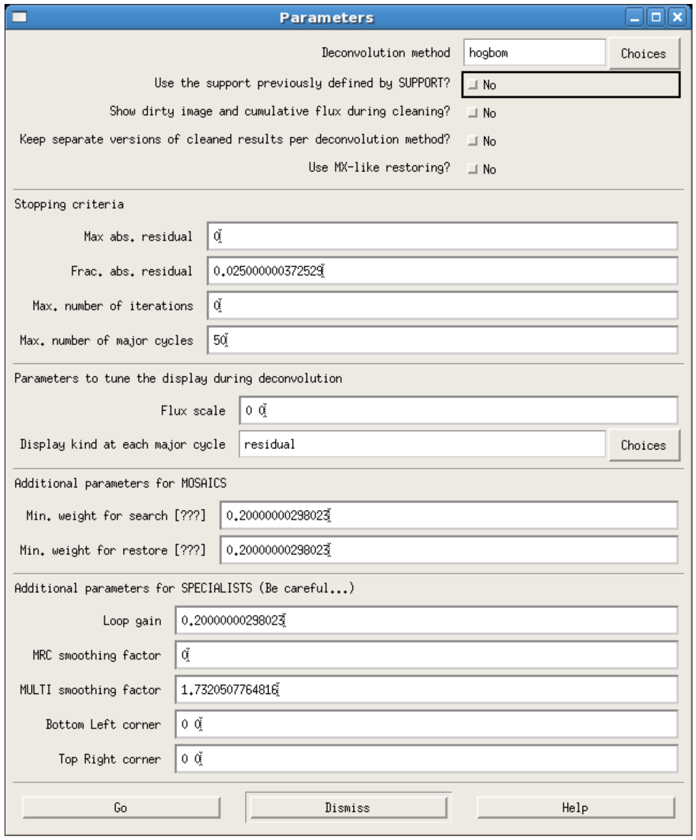


Figure 23: Clean parameters, to identify CLEAN components and convolve them with the deduced synthetic beam.

HOGBOM/CLARK/others at the top of the imaging widget permits CLEANing by using the defined parameters.

RESIDUALS/CLEAN/CCT at the top of the imaging widget plots the resulting residuals (stored in a file of extension `.lmv-res`), the CLEANed image (in a file of extension `.lmv-clean`) or the found CLEAN components (in a file of extension `.lmv-cct`).

At the prompt:
Procedure: `go clean`

Some variables:
```
let method hogbom/clark
let myclean%show yes/no
let myclean%support yes/no
let niter 1500
let ares 1e-3
```

To plot*:*
Procedure: `go bit`

Some variables:
```
let type lmv-clean
let first 23
let last 45
let type lmv-res
```

3.2.6 VIEW

Procedure to plot resulting images and cubes. VIEW plots the averaged image, a selected channel, the line profile obtained from a certain position, and the integrated line profile. Ranges and channels to plot, and areas and pixels for which profiles should be shown, are selected by clicking on each plot with the mouse. Typing `h` anywhere in the plotting window displays help information on the terminal. BIT presents the images obtained for all the spectral channels (within the specified first and last channels)

VIEW/BIT at the top of the imaging widget permits selecting the procedure to plot.

At the prompt:
Procedure: `go view`

Procedure: `go bit`

Some variables:
```
let type lmv-clean
let first 23
let last 45
let size 50
let spacing 3e-3
```

A Appendix: Calibration Principles

An "ideal" interferometer samples the Fourier transform of the sky brightness multiplied by the antenna beam pattern; these samples are called **visibilities**. In practice, because of noise, imperfections, sampling, and other effects, several terms perturb the visibilities to produce the true output of a "real" interferometer. The goal of the calibration is to identify and estimate all the important instrumental and atmospheric effects and apply appropriate corrections to recover the true visibilities.

A.1 Standard Decomposition of Visibilities

For any given complex number Z, let us call PZ its phase, AZ its amplitude, and Z^* its complex conjugate. The observed visibility $V_{ijk}(t)$ is a complex number representing the amplitude and phase of the signal detected on baseline ij, from spectral channel k, at time t,

$$V_{ijk}(t) = AV_{ijk}(t).\exp(-i.PV_{ijk}(t)) \tag{1}$$

This visibility is the Fourier transform of the product of the primary beam patterns of the antennas and the brightness distribution of the observed source, sampled at the point $(u(t), v(t))_{ij}$ corresponding to baseline ij at time t,

$$V_{ijk}(t) = FT(B_i(x, y, x_0 + x_i, y_0 + y_i)B_j^*(x, y, x_0 + x_j, y_0 + y_j)I(x, y, k))(u, v)_{ij} \tag{2}$$

where

- FT is the Fourier Transform operation, x, y are integration parameters,
- $I(x, y, k)$ is the brightness distribution of the source at frequency k,
- $B_i(x, y, x', y')$ is the voltage pattern of antenna i pointed in direction (x', y'),
- (x_0, y_0) is the pointing direction of the antennas,
- (x_i, y_i) is the pointing error of antenna i, and
- $(u, v)_{ij}$ are the projected coordinates of baseline ij, in wavelength units.

If we further assume that all antennas are equal, their pointing errors are negligible, their beam shape does not depend on the pointing direction, and the fractional bandwidth is small ($\delta\nu/\nu << 1$), this equation reduces to

$$V_{ijk}(t) = FT(P(x, y)I(x, y, k))(u, v)_{ij} \tag{3}$$

where $P(x, y)$ is the power beam pattern of the antennas.

The antennas, receivers, cables, and correlators all introduce additional modifications to this visibility. These perturbations can be formally decomposed into

$$V_{ijk} = A_i A_j^* S_{ik} S_{jk}^* C_{ijk} R_{ijk} + O_{ijk} + N_{ijk} \tag{4}$$

where

- A_i is the complex gain of antenna i (amplitude and phase),
- S_{ik} is the complex gain of channel k for antenna i,
- C_{ijk} is the complex gain of channel k for correlator entry ij,
- R_{ijk} is the theoretical visibility of the source,
- O_{ijk} is a non random error on channel k for correlator entry ij. These errors have various origins, such as finite bandpass, bandpass mismatch between antennas i and j, etc...), and
- N_{ijk} is a random error due to detection noise.

Provided the design of the interferometer system is adequate, the terms appearing in this decomposition have the following properties:

- $N_{ijk}(t)$ is normally distributed with known variance.
- O_{ijk} is negligible with respect to N_{ijk}. We will assume $O_{ijk} = 0$ in the following discussion.
- $C_{ijk}(t)$ is only weakly time dependent. This factor is introduced essentially by analog filters in the correlator and residual (constant) delay offsets between subbands; it may depend strongly on k.
- $S_{ik}(t)$ is only weakly time dependent. This factor is introduced by receivers and IF cables. The frequency (k) dependence is weak.
- $A_i(t)$ depends on antenna pointing (amplitude only), focus (amplitude and phase), and on atmosphere (amplitude and phase).

Let $W = V - O - N = V - N$ to first order. Here, $PN_{ijk}(t)$ is a random phase and $AN_{ijk}(t)$ has known variance, $<AN>$. Then

$$PW_{ijk}(t) = PA_i(t) + PS_{ik}(t) - PA_j(t) - PS_{jk}(t) + PC_{ijk}(t) + PR_{ijk}(t) \tag{5}$$

$$PW_{ijk}(t) = PV_{ijk}(t) + PD_{ijk}(t) \tag{6}$$

where

- PA_i is the instrumental phase on antenna i
- PS_{ik} is the relative phase of channel k for antenna i
- PC_{ijk} is the relative phase of channel k for correlator entry ij, independent of the PS_{ik}
- PR_{ijk} is the source phase on baseline ij for channel k. $R_{ijk}(t)$ only depends on ij through the coordinates of antennas i and j, via $(u(t), v(t))_{ij}$.
- PD_{ijk} is a phase noise introduced by measurement noise N_{ijk}

Then, to first order,

- PC_{ijk} can be measured independently, and is only weakly time dependent,
- PS_{ik} is constant, providing the receiver is not retuned,
- PA_i is time variable, on many different timescales, and
- PD_{ijk} has known variance, depending on $W_{ijk}/\texttt{<}AN\texttt{>}$.

Similar relations can be expressed for the intensities:

$$AW_{ijk}(t) = AA_i(t).AS_{ik}(t).AA_j(t).AS_{jk}(t)).AC_{ijk}(t).AR_{ijk}(t) \tag{7}$$

and

$$AW_{ijk}(t) = AV_{ijk}(t) + AD_{ijk}(t) \tag{8}$$

where

- AA_i is the gain of antenna i (including effects due to atmospheric absorption, focus, receiver gain, pointing, etc...),
- AS_{ik} is the relative gain of channel k for antenna i,
- AC_{ijk} is the relative gain of channel k for correlator entry i, j, measured independently from AS_{ik},
- AR_{ijk} is the Source intensity on baseline ij. $AR_{ijk}(t)$ depends on ij only through antenna coordinates.
- AD_{ijk} has known variance $\texttt{<}AN\texttt{>}$.

The purpose of calibration is to determine as best as possible these various functions, taking advantage of the time independence of some parameters, and of the weak chromaticity of the atmosphere.

A.2 Baseline versus Antenna based calibration

Although many of these calibration parameters are antenna based, CLIC is able to keep simultaneously two values for these parameters: an antenna-based value and a baseline-based value. Whenever an antenna-based calibration function is computed (i.e. a part of the A_i, or of the S_{ij}), CLIC offers the possibility of solving for an antenna-based or a baseline-based function. In general, solving for antenna based parameters should be preferred, since this mode offers less free parameters (so that they are better constrained) and uses a priori knowledge of the instrument (e.g. the phase closure relations). However, in some cases, well-identified baseline-related problems make it difficult to calibrate in antenna-based mode, so it may be needed to look for baseline-based solutions, mainly for amplitude or phase calibration.

A.3 Plateau de Bure Online Calibration

Some of the mentioned terms are partially estimated on real time so that the stored visibilities are already corrected from their contribution. Specific OBS commands, a dedicated `GILDAS` software package (`RDI`) and some CLIC `procedures` are used to produce and reduce the following scans:

- `CALI`: Each scan consists of two or three subscans, obtained by the OBS command `CALIBRATE`. They are used to measure the atmospheric transmission and receiver temperature, converting backend counts in antenna temperature outside atmosphere (which is a factor in AA_i, excluding pointing and focus terms).
- `IFPB`: Two subscans are obtained by the OBS command BANDPASS, which switches the correlator entries to a common noise source. Thus all the AC_{ijk} and PC_{ijk} are measured, except for a residual delay (visible as a constant phase slope with respect to frequency) due to path differences between the noise source and the antenna connections to the correlator.
- `GAIN`: This procedure allows measuring the sideband gain ratio of the receivers, by looking at a strong cosmic source (in practice, only AI_i is computed, although the phase term PI_i could also be derived). Since this ratio only depends on the receiver tuning, in particular on the backshort tuning, a `CALIBRATE` scan is made just after tuning modifications.

Results from `CALI` and `IFPB` observations are applied to the data by the automatic data compression job. Corrections from tuning modifications are introduced in OBS by the operator just after `GAIN`, at the beginning of the observations. Therefore, in principle, amplitude errors should only be due to phase noise, pointing and focus errors.

A.4 Offline Calibration; the rules of the game

The purpose of the offline calibration (carried out when the acquisition process is ended at the observatory) is to estimate as precisely as possible all the various terms of Equation 4. The basic principle is to measure the visibilities of sources with known (spatial and frequency) structure, in practice continuum point-like sources (called calibrators), which flux (so b_{ijk}) is also known or can be deduced. By simple division, the product $A_i.A_j^*.S_{ij}.S_{ij}^*$ is determined at the time intervals in which these calibrators are observed, and interpolated for the intermediate times in which the project source is. The signal to noise ratio of the calibrator measurements is the main limiting factor in this process.

Another important limitation concerns the validity of the interpolations used to predict the values of the calibration factors on the studied sources. It is desirable to estimate the quality of these predictions, and to ignore data which for any reason may deviate substantially from the predictions (for example due to instrumental problems, strong atmospheric variations, etc).

B Appendix: Pipeline or AoD First Look

The `First Look` report created by the `pipeline` is much longer than what is available under the CLIC `First Look` widget (Sect. 2.5). This report provides detailed and critical information of system performance to the AoD. It shows hence various technical aspects which may be difficult to interpret by non-trained astronomers. Here we briefly describe the content of these plots.

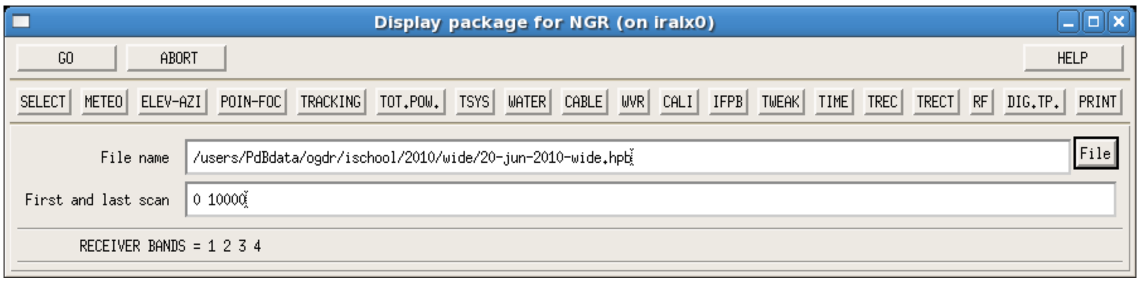


Figure 24: Pipeline or AoD `First Look` widget

Summary: The first page of the `First Look` report shows the correlator setup, for the Narrow-band and Widex correlator units[8], and the number of correlations obtained on each source. Warnings are often included, and are mainly addressed to the AoDs for technical assessment.

Meteorogical data: See details in Sect. 2.5. The verification of the wind speed is particularly important for AoDs if tracking problems are found in the "Elevation and Azimuth" plot.

Elevation and Azimuth: See description in Sect. 2.5. Colored lines are included to mark flagged scans or records (seconds). Deep blue lines refer to flags due to antenna shadowing, red to correlator unit flags, solid pale blue lines to `DATA` (correlator related) flags, dashed pale blue lines to tracking problems, green to phase lock losses, yellow to doppler or time issues, and pink to outliers in the system temperature, pointing problems or user or pipeline flagged data. More details about the flags can be found in "Flag data List" paragraph presented below.

Pointing and Focus corrections: See description in Sect. 2.5. Colored lines are included if pointing or focus corrections change by more than 30% the size of the primary beam or wavelength, respectively.

Antenna Tracking Errors: See description in Sect. 2.5. Problems are often related to strong wind. It may happen, though it remains very rare, that large tracking errors indicate a technical problem. This monitoring is particularly important to foresee interventions by the technical staff in NOEMA antennas.

22GHz monitors present the results obtained in time from the 22GHz receiver in each antenna. The first three plots show the counts obtained in each of the three channels of the 22GHz receivers. They are combined to produce the 'triple' values, which are used to model the atmosphere, disentangle between water vapor and droplets, and predict the atmospheric phase fluctuations by which the interferometric data are affected. This is then used to reduce of phase decorrelation within each scan. Derived water vapor amounts are displayed in the 'Water Monitoring' plots. The given ambient temperatures are obtained by sensors placed close to the 22GHz receivers. Peltier Temperatures are directly related to the receiver performance, and should remain within the plot limits.

CALI scans vs time plots show the time evolution of the `CALI` autocorrelation scans, which can consist of two (on the hot load and sky respectively) or three (on the cold load, hot load and sky) subscans. Measurements on the cold load are typically performed every ~ 50 min, and are used to derive and monitor receiver temperatures. Differences between antennas are normally linked to receiver attenuations, and differences between units are often linked to correlator tweaks. In correct weather conditions, the sky autocorrelations show a constant value because the signal variations due to airmass change is compensated by correlator tweaking. This tweaking effect is however visible in the autocorrelations on the loads. (Note that Widex tweak levels change in large steps.) Strong variations in the input signal often result in changes in the tweak values, and accordingly in the `CALI` autocorrelations.

IFPB scans vs time plots present the time evolution of the amplitudes of the `IFPB` correlations obtained on the noise source (see Sect. 2.2). Absolute amplitude values change from unit to unit, depending on the IF phase delay. As the noise diode provides a constant input, `IFPB` amplitudes should remain constant along a track. Sharp variations in the tweak levels (for instance due to bad weather) can however result in changing amplitudes of the IFPB scans, due to tweaking adjustment effects.

Tweak levels vs time plots show the tweak levels for each of the Narrow correlator units, per correlator sub-band. Values remaining constant (in correct weather conditions) in time correspond to the `IFPB` scans, tweak values change with the airmass for the other acquisitions.

Monitoring the time, UTC, NTP and PPS. The monitoring of the time synchronization signals is important as it is essential to stop fringes, ensure a good pointing, etc. This plot helps us to monitor differences in time between the UTC (from the maser-synchronized GPS) and NTP ([GPS-]synchronized NTP) times, as well as time offsets between hardware clocks (PPS used by the correlator from maser-synchronized GPS time) and software synchronized events (NTP).

Receiver Temperatures in the IF plots present the receiver temperature computed along the IF bandwidth from one of the first `CALI` scans including a cold load acquisition (often called 'cal-cold' scan). Different colors are used to identify the different correlator inputs. These plots shows better than any other the presence of parasites and tuning features. Particularly, marks are included to identify the known system parasites (from the IF processor at 6300, 4500 MHz, and at 3 and 4 times the LO1ref local oscillator frequencies). Dotted lines represent the values stored in the data header, computed by the online `RDI` software.

Receiver Temperatures vs Time plots display the evolution of the mean receiver temperature values averaged over the correlator-input[8] bands. They should not change by more than a few K in projects with stable tunings. Tunings affected by strong parasites may show changing receiver temperatures. An intervention from the frontend group may happen as a consequence of the information extracted from these plots.

Dewar Temperature plots show the temperatures measured at various stages in the cryostat.

Observing List summarizes the sequence of obtained scans. `CALI` and `IFPB` acquisitions are ignored in this list.

Flagged data List shows all the flagged records and scans. It should be consistent with the color marks in the 'Elevation-Azimuth' plots.

Total Power vs time: See description in Sect. 2.5. Values are presented per each calibration unit (which correspond to correlator inputs[8]): Two Narrow Quarters and four Widex units. Moderate differences (of a few K) in the values from the different units are due to the different covered frequency ranges.

Cable Phase plots present the phase delays (in degrees) produced at the Master Frequency level by the cables in their movements, mostly due to antenna tracking, for the used and unused bands. Colored lines mark changes that could result in phase variations larger than 30^o. Significant changes in the LO1ref local oscillator frequencies are also displayed in grey lines.

System Temperatures vs time: See description in Sect. 2.5. Plots are shown per calibration unit.

Water Vapor vs time: See first description in Sect. 2.5. A plot is created per calibration unit. A differential plot is created to compare the results obtained from all the antennas. Pale blue lines in the WVR H_2O plots mark the update of the 22GHz receiver calibration by the online software.

RF phases plots compare the phases obtained per correlator input in the (IF1) frequency band. Remaining phase delays can be identified in these plots. One plot is created for the first correlation scan at the project start, another for the last correlation scan at the project end. Note that if the (frequency averaged) phases from H and V polarization receivers are not equal, "let phcal '*' " should be entered after `Select` (see Sects. 2.6.1 and 2.6.5).

Amplitudes for Narrow and Widex correlator inputs: Comparison of the signal level obtained from all the correlator inputs[8] (or calibration units), which -in principle- should be almost identical. Uncorrected delays result in amplitude differences among the correlator units, which become particularly important between the Widex and the Narrow-band correlator units. Delays can be identified in the `RF phases` and the `RF calibration` plots, and the data can be corrected for them by following the instructions in Sect. 2.6.9.