IRAM Plateau de Bure Interferometer
Calibration CookBook

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This document describes the calibration software for the IRAM Plateau de Bure Interferometer.

Related information is available in:

- IRAM Plateau de Bure Interferometer: Users Guide
- IRAM Plateau de Bure Interferometer: Foreign Commands
- IRAM Plateau de Bure Interferometer: Trouble Shooting Guide
- IRAM Plateau de Bure Interferometer: Frequency Setup
- IRAM Plateau de Bure Interferometer: Atmospheric Calibration
- CLIC: Continuum and Line Interferometer Calibration
- GreG: Grenoble Graphic

Revision history

- V 3.0: New computers and Motif interface
- V 2.0: Antenna based calibration

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1 Project Calibration in 10 Steps

1. Your project number, e.g. x999, will be used as "username" for all data files. Use this account to log on IRAUX1.

2. Download your data using the following commands

```
$ load_project x999
$ load_x999
```

3. Read the x999.note file

4. Create the calibration files

```
$ CLIC @ PR:DEFINE
Wait for Menu Bar, Hold the ''CLIC'' Menu
Select ''Raw Data File''
```

5. For each calibration file, calibrate using

```
$ CLIC @ PR:DEFINE
Wait for Menu Bar, Hold the ''CLIC'' Menu
Select ''Standard Calibration''
```

6. Save the calibration (and optionally data) files on optical disk. Also save the Postscript logs for archive.

```
$ load_don 1 ipb
$ cp *.hpb *.IPB *.ps ~/don_ipb/
$ unload_don
```

7. Make the UV tables. Create CLIC command procedures to do so: **never** rely on interactive typing for this stage. Then, delete the calibration and data files.

```
$ rm *.hpb *.IPB *.ps
```

8. Make the images

```
$ GRAPHIC INPUT
Wait for Menu Bar, Hold the ''Program(s)'' Menu
Select ''Interferometric Data Display''
Activate UV_MAP, CLEAN and DISPLAY for each UV data set
```

9. Save the UV tables, images and ancillary files used

```
$ load_don 1 map
$ cp *.uvt *.lmv* *.beam *.clic *.graphic ~/don_map/
$ unload_don
```

10. Write up your article (optional).

2 Introduction

Long after you read the "Introduction to the IRAM PdBI" to prepare an observing proposal, calibrating interferometric data will be your first *real* contact with the IRAM Plateau de Bure Interferometer (PdBI).

You will need to become familiar with interferometry concepts and to use the **CLIC** program to calibrate these data. This document sums up the theoretical and pratical steps in data calibration. We outline and justify a "streamline" receipe that can be followed in all "standard" cases.

3 Principles

An "ideal" interferometer samples the Fourier transform of the sky brigthness 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 calibration is to identify and estimate all the important instrumental effects and apply appropriate corrections to recover the true visibilities.

3.1 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 obsrved 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.
- $(u, v)_{ij}$ 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 $W_{ijk}/<AN>$.

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 part of this term,
- 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 $<AN>$.

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.

3.2 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, it may often be interesting to look at the baselines based solutions. Both methods are illustrated in this document.

3.3 Sideband Separation

The PdBI is able to detect and separate signals from both the Upper and Lower sidebands of the receivers. These two bands can be considered to define two different sets of k *sky frequencies*. Alternatively, we can also assume that k is an index to *intermediate frequency*. In this representation, Equation 4 is split in two similar equations for the Signal and Image band of the receiver, and becomes after adding superscript b (for Signal or Image band)

$$V_{ijk}^b = A_i^b (A_j^b)^* S_{ik}^b (S_{jk}^b)^* C_{ijk} R_{ijk}^b + O_{ijk}^b + N_{ijk}^b \tag{9}$$

A simplification occurs in this representation because the correlator based error C_{ijk} is independent of b. For a small IF frequency (1.5 GHz) as compared to the observing frequency, the effects of pointing and focus on the antenna gain terms do not depend on the sideband b. The atmospheric transmission does depend on the sideband (specially at the edge of strong telluric lines like the Oxygen band), but the phase fluctuations are not very chromatic. For this purpose of atmospheric transmission, it is convenient to extract the receiver sideband gain ratio I_i (image over signal, averaged over the receiver bandwidth) from the antenna gain:

$$V_{ijk}^S = A_i A_j^* S_{ik}^S (S_{jk}^S)^* C_{ijk} R_{ijk}^S + N_{ijk}^S \tag{10}$$

$$V_{ijk}^I = I_i I_j^* A_i A_j^* S_{ik}^I (S_{jk}^I)^* C_{ijk} R_{ijk}^I + N_{ijk}^I \tag{11}$$

where superscripts S and I stand for Signal and Image bands respectively.

Provided the receiver is not retuned, and in the (very good) approximation of non chromatic atmospheric phase fluctuations, I_i is a constant in time. Small variations in the amplitude may happen because of imperfect atmospheric calibration.

3.4 Plateau de Bure Real-time Calibration

For the PdBI, some terms are (partially) estimated in almost real time, using specific **OBS** command (and the associated `procedures` in **CLIC** which can be used ass selection criterium): `CALIBRATE (CALI)`, `BANDPASS (IFPB)`, and `GAIN (GAIN)`.

- `CALI`
  This procedure consists in two subscans obtained by **OBS** command `CALIBRATE`. It measures the atmospheric transmission and receiver gain, converting backend counts in antenna temperature outside atmosphere (a factor in AA_i, excluding pointing and focus terms).

- `IFPB`
  This procedure consists in two subscans obtained by **OBS** command BANDPASS, in which the correlator entries are switched to a common noise source. Thus all the AC_{ijk} and PC_{ijk} can be measured, except for a residual delay (visible as a constant phase slope as function of frequency) due to path differences between the noise source and the antenna connections to the correlator.

- `GAIN`
  This procedure measures 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, and in particular on the backshort tuning, it need not be repeated frequently.

Results from `CALI` and `IFPB` observations are automatically applied to the data by the automatic data compression job. `GAIN` results are usually specified manually by the operator before proceeding with observations. After these two calibrations are applied, amplitude errors can only be due to phase noise, pointing and focus errors.

3.5 The Rules of the Game

The purpose of the post-real time calibration is to estimate as precisely as possible all the various terms of Equations 10 and 11. The calibration receipes described in this document are based entirely on their relative importance and behaviour (time and frequency dependence).

The basic principle is to measure the visibilities of sources of known (spatial and frequency) structure, in practice continuum point sources of known flux F for which $W^b_{ijk} = F$. By simple division, the product $A_i.A_j^*.S_{ij}.S_{ij}^*$ is determined at some time intervals, then interpolated at other times and applied to the sources to be studied.

The signal to noise ratio for these measurements may be the limiting factor, especially for the S_{ik} terms since the bandwidths of the spectral channels are narrow. It is then necessary to take full advantage of the low time or low frequency dependence of all factors to optimize the signal to noise ratio on all determinations.

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 (instrumental problems, strong atmospheric variations, etc...). This part of the calibration is often called “editing”.

4 Starting

Six HP workstations (IRAUX1 to IRAUX6), are available at the IRAM headquarters:

- IRAUX1 is a workstation dedicated to Plateau de Bure data reduction. It is an HP-735 model with 24 GBytes of storage for data analysis, a DAT drive, and a magneto-optical disk drive with removable disks of 1.3 GBytes each for archiving of the project results.
- IRAUX6 is another dedicated workstation for Plateau de Bure data reduction. It is similar to IRAUX1, except for the processor, a J280 PA-8000 based model, about twice faster than IRAUX1.
- IRAUX2 is the general server for all network processes.
- IRAUX3 serves for system development.
- IRAUX4 is used for VLBI, 30-m data reduction, and by IRAM astronomers as a general purpose machine. It has an optical disk drive for disks of 650 Mbytes each, and a DAT drive.
- IRAUX5 is used for software development and by IRAM astronomers as a general purpose machine. It has an optical disk drive for disks of 650 Mbytes each.

In practice, only IRAUX1 and IRAUX6 should be used. Be careful to connect to the right machine, in order to avoid network disk access as much as possible. The consoles can be used as an X-Terminal: log-on and then create X-terminals on IRAUX1 or IRAUX6 as appropriate by clicking on the right-most mouse button and selecting iraux1 (or iraux6) in the menu. For optical disks, see below.

4.1 Optical Disks

The HP computers IRAUX1, IRAUX4, IRAUX5 and IRAUX6 have removable optical disk drives. IRAUX1 and IRAUX6 can read disks of 1.3 GBytes (the "yellow" disks) and 650 Mbytes, while IRAUX4 and IRAUX5 can only read the 650 MBytes one. These optical disks are double-faced. To prevent handling errors (confusion between projects for example), the disks have a project identifier and are initialized with one face "reserved" for CLIC data ("ipb" face) and the second one for maps ("map" face). Before being accessible to the user, the optical disk must be software mounted using the commands:

```
   $ load_don ipb iraux1    ! or iraux6, for the ''ipb'' side,
or
   $ load_don map iraux1    ! or iraux6, for the ''map'' side,
```

Once finished with data handling, the optical disk must be dismounted before unloading, using the command

```
   $ unload_don
```

The "unload_don" command fails if any active process is still working on the optical disk, or has one of the optical disk directory has working directory. Logoff any process, and move to the home directory before using this command.

Please reserve IRAUX1 and IRAUX6 drives for 1.3 GBytes "yellow" disks. If the drive on your peculiar machine is used, you can mount a disk on the other drives from IRAUX1, using command

```
   $ load_don map iraux5
or $ load_don ipb iraux6
```

but the disk will be mounted in "ReadOnly" mode. If you need write access, log on the other computer and work from there.

4.2 Getting Started

If you have any problem with the system, contact (in priority order) 1) your local contact, 2) Patrick Dumontroty (system manager) or 3) Alain Perrigouard (computer division leader), 4) Roberto Neri, 5) Stephane Guilloteau.

First get an account and an optical disk for the HP computer. The account name is a project number, e.g. X999. Contact R.Neri or S.Guilloteau for this. Once your account is set, you must download your data from the bure archive, which is either on DAT tapes or on CDROMs.

4.3 Finding and Gathering Data

For recent projects (since late 1992, i.e. projects archived from the HP workstation at Bure), we keep on-line a list of the DAT and CDROM contents. The lists of DAT contents looking like that:

```
 Archive number  1
 ------------------
-rw-rw-rw-   1 guillote astro     308736 Oct 14 14:51 12-jan-1993-.ipb
-rw-rw-rw-   1 guillote astro     818688 Oct 14 14:51 12-jan-1993-c018.ipb
-rw-rw-rw-   1 guillote astro     496640 Oct 14 14:51 12-jan-1993-test.ipb
-rwxr-xr-x   1 guillote astro      68331 Oct 14 11:41 12-jan-1993.log-obs
-rwxr-xr-x   1 guillote astro      14901 Oct 14 11:41 12-jan-1993.log-rdi
-rwxr-xr-x   1 guillote astro       1749 Oct 14 11:41 12-jan-1993.log-red

 Archive number  2
 ------------------
-rw-rw-rw-   1 guillote astro     866816 Oct 14 14:52 13-jan-1993-.ipb
-rw-rw-rw-   1 guillote astro   31393280 Oct 14 14:52 13-jan-1993-c018.ipb
-rw-rw-rw-   1 guillote astro      59904 Oct 14 14:52 13-jan-1993-test.ipb
-rwxr-xr-x   1 guillote astro     142489 Oct 14 11:41 13-jan-1993.log-obs
-rwxr-xr-x   1 guillote astro      83965 Oct 14 11:41 13-jan-1993.log-rdi
-rwxr-xr-x   1 guillote astro       4754 Oct 14 11:41 13-jan-1993.log-red
```

etc...

The file naming convention is such that the data file names is composed of the date (e.g. `13-jan-1993`), a minus sign (-), and the project name (e.g. `c018`), with a file extension `.ipb`. The log files (`*.log-*`) are interesting to have a detailed log of what happened during the observations.

For CDRom's, the naming convention is slightly different, to be compatible with ISO standards. File names are upper cases, 8 characters, 3 character extensions (IPB, OBS or RDI). The first character is the year code (A for 1990, B for 1991, etc...), the second character the month code (in hexa: 1 January, 2 March, A October, etc...), the next 2 characters the date in the month, and the last 4 the project name. CLIC automatically translates the "long" naming convention into "short" names if needed. For example H110G028.IPB translates into 10-jan-1997-g028.ipb.

Your own project can be easily located using the command

```
 find_project x999
```

where `x999` is your project number. This produces an output like:

```
[07-feb-1997]   07-feb-1997-g067.ipb      221225472 bytes -> DAT:    198
[10-feb-1997]   10-feb-1997-g067.ipb      120860160 bytes -> DAT:    198
[20-feb-1997]           H220G067.IPB      217222144 bytes -> CDROM: 1001
[25-mar-1997]           H325G067.IPB      138128896 bytes -> CDROM: 1018
[31-mar-1997]           H331G067.IPB      226795520 bytes -> CDROM: 1020

Project requires diskspace for 879 Mbytes of raw data
Available local diskspace is 873 MBytes

File g067.list created
```

The command `load_project` creates a procedure which will download automatically the project data files, provided you mount the appropriate DAT(s) and/or CDRom(s) when asked for. The DATs and CDRoms are in a cabinet in the computer room. The list of all observations performed is available on the Web.

Only some of the above facilities are available for old projects. For older data, there are several binders in the IRAM library to help you find out what days your project was observed and which tapes contain your data. The Summary binder contains a daily list of the interferometer configuration, projects observed, and sequence numbers of the archive tapes where the data is stored. The Scanlists binders contain daily lists of each scan observed. The Tape Contents and Cassette Contents binders contain lists of all the files archived on tapes and 8mm video cassettes, respectively. Copies of the telescope operators' observing logs and on-duty astronomers' observing reports are also kept in the library.

Once the "raw data" is loaded, you have to created the calibration files from it. At this stage, you also want to concatenate contiguous data in a unique header file (i.e. to avoid the arbitrary splitting occuring at midnight). To do that, start CLIC, and then use the following CLIC commands

```
FILE OUT B2.HPB NEW   ! Open an output file. Use long name like
                      ! W12E24N20.HPB if you prefer (but this is tedious)
SET PROCEDURE *       ! All type of data for completeness
SET TYPE *            ! Objects and calibrators.
SET SCAN * *          ! Any and all scans.
FILE IN 01-JAN-1994-X999.IPB   ! Daily archive file.
FIND                  ! Select the scans, and
COPY HEADER           ! Copy the HEADER only to the output file
FILE IN 02-JAN-1994-X999.IPB   ! Now repeat this as needed.
FIND                  ! Select the scans, and
COPY HEADER           ! Copy the header only.
...
FILE IN B2.IPB        ! Read the file just created.
LIST IN/OUT B2.SCANLIST       ! List what's in the file.
LIST IN/SHORT/OUT B2.SHORTLIST    ! Long and summary format
EXIT
```

In case of problems or special cases, you may have to select your data based on other critera than the project number: a range of scan numbers, for instance. With the Window environment, you can also select the `‘‘Raw Data File’’` menu to do this (almost) automatically.

Data can then be copied to optical (now or later, when calibration is finished) Mount the optical disk:

```
$ load_don ipb    ! Software load the optical disk
$ cd don_ipb      ! Move to /users/project/x999/don_ipb directory
$ cp ~/data/*.hpb .     ! copy the *.hpb header files on the optical disk
$ cp ~/data/*.IPB .     ! copy the *.IPB data files too
```

The example above assumed you have been working in a directory named `/users/project/x999/data` for data reduction.

5 A First Look at the Data

5.1 Identifying the Observations: Who is Who ?

First, you can get more informations about the quality of your observations on the `x999.note` file. This file, written on the site by the astronomer on duty, contains a brief history of each observing run. Problems encountered, weather conditions, etc.. are mentionned. It is also convenient to have the observing procedure of your project: `setup-x999.obs`. In order to retrieve these files which are located on the Bure machines, ask your local contact.

Then before starting any calibration or editing, you must of course look at the data. A scanlist is an essential tool. Produce it using command `LIST/OUPUT Filename` and print the listing. But a summary list produced by `LIST/SHORT/OUTPUT` is usually enough because its gives all the fundamental steps of the observations:

```
1457_1459 EA21 3C454.3     P GAIN CO-ISO   w00w05e03    20-AUG-1994  -1.4_ -1.4
1460_1461 EA21 3C454.3     P GAIN CO-ISO   w00w05e03    20-AUG-1994  -1.2_ -1.2
1462_1464 EA21 3C454.3     P GAIN CO-ISO   w00w05e03    20-AUG-1994  -1.1_ -1.1
1465_1476 EA21 3C454.3     P CORR CO-ISO   w00w05e03    20-AUG-1994  -1.0_  -.9
1477_1479 EA21 3C84        P POIN CO-ISO   w00w05e03    20-AUG-1994  -5.2_ -5.2
1482_1482 EA21 0415+379    P FLUX CO-ISO   w00w05e03    20-AUG-1994  -5.9_ -5.9
1483_1485 EA21 0415+379    P CORR CO-ISO   w00w05e03    21-AUG-1994  -5.9_ -5.9
1486_1507 EA21 V773_TAU    O CORR CO-ISO   w00w05e03    21-AUG-1994  -5.8_ -5.4
1508_1513 EA21 0415+379    P CORR CO-ISO   w00w05e03    21-AUG-1994  -5.5_ -5.4
1514_1535 EA21 LKCA_3      O CORR CO-ISO   w00w05e03    21-AUG-1994  -5.3_ -5.0
...........
2162_2167 EA21 W3OH        P CORR CO-ISO   w00w05e03    21-AUG-1994  -2.0_ -2.0
```

In this short list, atmospheric calibration (named `CALI`) and passband calibration of intermediary frequency (named `IFPB`) are omited because they are systematically done before starting a cross-correlation `CORR`.

The scanlist written above contains the following informations:

```
- First column: Scan number
- Second column: Project name
- Third column: Source name
- Fourth column: Type of source (O=object, P=phase calibrator)
- Fifth column: Type of observation
- Sixth column: Line name
- Seventh column: Configuration, i.e. antenna positions on the stations
- Eighth column: Date
- Nineth column: Hour angle interval.
```

The type of observations (column five) can be:

```
GAIN: a cross-correlation in order to measure the sideband ratio
CORR: a cross-correlation
FOCU: a simultaneous focus measurement on each antenna
POIN: an interferometric pointing on all antennas
FLUX: a flux measurement
CALI: an atmospheric calibration (autocorelations on SKY and HOT load)
```

```
IFPB: an IF passband calibration (done using the noise diode)
AUTO: an autocorrelation alone
HOLO: an holography measurement
```

In the above example, the sequence of the observations (which is typical) was the following:

```
 - From 1457 to 1464: Receiver tuning and sideband gain measurements
 - From 1465 to 1476: Radio frequency passband calibration on 3C454.3
 - From 1477 to 1479: Check of the pointing before starting integration
(after pointing, the focus may also be checked)
 - Scan 1483 : flux measurement of the calibrator.
 - From 1482 to 1485: First phase calibration
 - From 1486 to 1507: First cross-correlation on first source...
 - From 1508 to 2161: ... Project ...
 - From 2162 to 2167: cross-correlation on W3OH for flux calibration
```

Here the data to calibrate start with the scan 1465, i.e. the last GAIN measurement. The command `SET SCAN 1485 *` will permit to select the good scans. It is useful to calibrate simultaneously the data POIN, GAIN and CROSS. For example, the POIN on 3C84 will help for flux estimate. Cross-correlation on W3OH will be used as a check on the flux calibration because the flux of this HII region is well known between 80 and 115 GHz and not resolved on the shortest baselines (i.e. $B < 100$ m). CRL618 and MWC349 are also used for this purpose.

5.2 Some Intrumental Effects

Looking at the AMPLITUDE and PHASE versus TIME gives lots of informations. Here is a list of some problems you can easily understand by comparing the evolution of the amplitude and phase.

- Decreasing amplitude on some baseline
  The pointing is becoming bad on one antenna (or more). Look at the scanlist and identify the position of the pointing in between the cross-correlations. Usually after the next pointing scan the problem must disappear. If you need to check it, select the next pointing scan and use the command `SOLVE POINT/PLOT` to determine the pointing corrections, see CLIC Manual for details.

- Amplitude drops to zero and the phase is completely random
  The phase-lock is open on one receiver (or more). If this is confirmed, these data must be flagged on the source.

- Phase jump while the amplitude stays almost constant
  A focus has been done and corrections have been applied on one antenna (or more). Look at the scanlist and identify the focus. Use the command `SOLVE FOCUS/PLOT` to determine the correction values. Do not forget that the phase jump is twice the focus correction (optical way). For example, if there is a correction in the subreflector position of 0.1 mm on Antenna 1, the phase jump on the corresponding baselines is about $\frac{4\pi}{\lambda} \times \frac{180}{\pi} \times 0.1 \sim 24^o$. Focus phase jumps must be properly taken into account in the phase calibration curve. In this case, you have to calibrate the phase using the command `SOLVE PHASE/BREAK var1 var2` (see details in CLIC manual).

- Smooth phase slope while the amplitude stays constant
  Instrumental thermal drifts due to sun or day-night effects induce such behaviour. During an observing run of several hours, it is normal to see them and one major goal of the relative phase calibration is to correct this effect. Drifts of 10^o per hour are not uncommon, depending on weather conditions (wind, sun, etc...).

  However, should the drift appear quasi-sinusoidal, or exceed 90^o peak to peak, it may originate in a baseline error. This may happens when baselines were measured after your project was performed. For details about this problem, see section 9 and 10. Note that at first order, residual baselines errors are cancelled by the phase calibration. This is why it is of prime importance to use a phase calibrator as near as possible from your source.

6 Calibrating: Basic Steps

Before calibrating data, one must read carefully this section. It gives the basic and fundamental informations you need to know in order to calibrate properly and efficiently the data. In fact, in standard projects (i.e. more than 90 % of the cases), the experiment shows that a really careful reading of this section permits to avoid most of the time lost by people.

- Radio Frequency Passband Calibration
- Phase Calibration
- Amplitude Calibration
- Flux Calibration

You should also look at section "A Safe Method" for a practical way to guarantee that you have indeed done what you wanted.

6.1 Radio Frequency Passband

The correlator passband (Intermediate Frequency passband) has already been calibrated in the quasi real time processing, so the next step is to calibrate the receivers passband (RF passband), i.e. to compute the S_{ik}. To improve the sensitivity, this should be done with data where the time dependence of the phase is small or has already been calibrated. The optimum way, actually used by the "automatic" calibration procedure, is to self-calibrate the phase on the calibrator before averaging in time to get the RF passband.

Typical RF calibration errors (given by the command `SOLVE RF`) are a few ^{o} of phase, and a few % of amplitude.

6.2 Phase Calibration

The goal here is to measure the PA_i factors as a function of time. Maximum sensitivity is required, so the continuum correlator is used to determine these phases, possibly in DSB mode if the phase calibrator is really weak.

Since the measured phases are interpolated by *continuous* functions of time, the 2π ambiguities in phase must be resolved before. Any other discontinuity must also be identified (phase lock problem, focus change, etc...). See the section 4 and 7 for details.

Phase data as function of time should be plotted, and a `SOLVE PHASE/PLOT` command will determine the phase functions. Several options are possible, in particular discontinuities can be specified; see CLIC manual for details. If the fit is satisfactory, these functions should be stored in the data file using the `STORE PHASE` command.

6.3 Amplitude

In the real-time processing, only receiver gain and atmospheric transmission have been calibrated. Remaining terms affecting the effective antenna gain (in K/Jy), such has pointing errors, focus errors, and decorrelation due to atmospheric phase noise and oscillator phase jitter must also be compensated for. Amplitude calibration involves interpolating the time variations of the antenna gains measured with the phase calibrator, assuming its flux is known.

This is done by plotting the `SCALED` amplitude for calibrators as function of time, then fitting a curve through it. Discontinuities (breaks) can be introduced at appropriate times if needed.

6.4 Antenna Gain and Flux Scale

The antenna gains (in K/Jy) are simply the ratios of the measured visibilities of a point source (in units of antenna temperature, as obtained after real-time calibration) to the flux of the source. Unfortunately, most phase calibrators are time variable sources, and have frequency dependent fluxes. The IRAM staff regularly monitors the fluxes of the bandpass calibrators at 2 frequencies. The flux of your phase calibrators at your observing frequency is not generally known at the time of observations. It must be derived by bootstrapping from measurements of sources of known fluxes.

To properly bootstrap the fluxes, measurements should be as close in time as possible (to ensure reasonably equal phase noises), and preferrably pointing scans (`POIN`) should be used to correct for possible pointing errors. Of course, the focus should not have changed between the measurements, and atmospheric calibration should be good. In this case, the antenna gains are identical for the flux calibrator and the source(s) whose fluxes must be measured.

Sources of known flux are specified using the `SET FLUX Source Value` command. After the data have been selected, the `SOLVE FLUX` command calculates the antenna gains. Then the `STORE FLUX` command stores the fluxes for all selected scans.

More details about flux measurement are available in the "Flux Measurement" documentation. Bad determinations of the flux scales can create important artefacts on the final images. This determination is particularly tricky: consult IRAM staff.

7 Calibrating: Strategies

7.1 DSB versus Separate Sideband Calibration

CLIC can store independant calibration curves (phase and antenna) for the LSB and USB, but can also work in a mode where a single curve is stored using command

```
STORE PHASE or AMPLITUDE /BAND DSB or USB or LSB
```

Each case may have its own advantage and drawbacks:

- Separate Sideband Calibration
  This is the default mode, but it does not preserve the relative phase (and/or amplitude) of the two sidebands. On the other hand, it allows to correct for time variations of this receiver gain ratio and relative phases. Note that atmospheric phases are not chromatic (to first order), so that these relative phases are purely instrumental.

- DSB mode
  This works only when the above gain ratio and relative phases are constant in time. In case

the observations were done with double sideband tuning, this mode is more sensitive. This may be an important advantage for example for CO J=1-0 observations, where the system noise is high and calibrators are weak.

- LSB or USB mode
  When nearly single-sideband tuning was used (e.g. LSB where high rejection is possible), the noise in the image sideband may be too high to allow proper calibration. DSB calibration is not optimum either, since it is more noisy than the LSB calibration. Applying the LSB calibration is then the best way to recover the USB band (should it contain anything useful...).

  USB mode is also more effective than DSB or separate sideband calibration for the 3 mm receivers above 110 GHz, where the sideband rejection is 5-6 dB.

In practice, we recommend to check whether the relative phases of the two sidebands significantly differ. If no, DSB or LSB calibration depending on receiver tuning is best. If yes, this also implies that the RF calibration is time dependent: more thorough work is required... Be sure the variation is really significant: a small bias is better than a larger noise...

7.2 EXTERNAL versus INTERNAL phase calibration

For the 1.3 mm receivers, there are two ways of calibrating the phase: either `INTERNAL` or `EXTERNAL`. `INTERNAL` phase calibration is just what is done for the 3 mm receiver: the measured phased if fit by a continuous curve. However, because of higher phase noise at 1.3 mm (both thermal and atmospheric), 2π ambiguities are more frequent and more difficult to resolved. One can use instead the `EXTERNAL` phase calibration, in which phase derived from the 3 mm receiver is first removed (with correction for the frequency difference), and then a residual phase offset between receivers is fit.

There are still two ways to compute the `EXTERNAL` phase calibration. In the first mode, the "standard" 3 mm calibration curve is stored as external phase reference curve. The fit on the residual 1.3 mm phase thus incorporates atmospheric fluctuations: the derived phase noise is representative of the atmosphere, but the phase difference between both receivers is not measured in an optimum way. In the second mode, a "self-calibration" derived from the 3 mm data is stored as external phase reference curve. The fit on the residual 1.3 mm phase no longer includes any atmospheric noise. The phase difference between both receivers is thus measured in an optimum way.

Switching between `EXTERNAL` and `INTERNAL` calibrations is done using command

```
SET PHASE INTERNAL      or   SET PHASE EXTERNAL
```

Both solutions can be stored independently in the .IPB file.

7.3 Antenna Based Calibration

The three basic steps, RF passband, phase and amplitude calibration can be performed independently using antenna based or baseline based parameters. Switching between the two modes is done using commands

```
SET RF ANTENNA          or   SET RF BASE
SET PHASE ANTENNA       or   SET PHASE BASE
SET AMPLITUDE ANTENNA   or   SET AMPLITUDE BASE
```

Both solutions can be stored independently in the .IPB file. Note that one can combine an antenna based phase calibration with a baseline based RF calibration for example.

Antenna based calibration normally provides better results, because it reduces the number of unknown and preserve closure relations. The antenna based calibration has a few minor limitations and *a priori* unusual features

- Only one group of subbands and one band can be calibrated at once. To calibrate both sidebands, proceed in sequence.
- Data must be plotted *per baseline*, and fits are displayed per baseline also; these displayed functions are the product of the baseline based fitted functions. Although this may look odd at first view, it is the best way to adjust the antenna based parameters.
- As a side effect, 2π phase ambiguities can be partially resolved by antenna base calibration, but it still helps to use `SET PHASE CONTINUOUS`.

Antenna based calibration is the default, and is strongly recommended. Switching to baseline-based calibration should only be performed in very peculiar cases.

8 Editing

8.1 What is Editing ?

"Editing" is identifying and removing the bad data from the data set. CLIC offers several ways to do that: scan selection, *tagging* data with a quality indicator, selective *flags* associated to the individual components of the array (antenna pointing, phase lock, correlator, etc...).

Whatever tool the astronomer uses, keeping a history of the calibration and editing steps is important. We emphasize the need to maintain a history procedure detailing all the scan selections and flagging events, with enough comments to understand the reasons for these events. A good complement to this procedure is a listing of all the observations where the same events are detailed in comments inserted at the appropriate place.

8.2 Flagging and Tagging

Flags are discussed in detail in the **CLIC** manual. Remember the differences between a `Flag` (permanent problem indicator), a `Mask` (temporarily ignore some flags), and a `Mark` (temporarily set some flags). The `STORE FLAG` command is the preferred way to flag data. The index must have been defined before. The `FLAG` and `UPDATE` commands are only used in case of record based flagging.

If a whole scan is bad for all correlator subbands and all baselines, it is easier to *tag* it using command `TAG` with a poor quality indicator. The scan will then be totally ignored if an appropriate quality level is specified with the `SET QUALITY` command.

As for scan selection, we highly recommend you keep an accurate log of the flagging in a `.CLIC` procedure.

9 Calibration: The Automatic Package

An "automatic" calibration procedure following the above rules has been written to streamline the calibration process. Except for flux calibration, it is *really* "automatic". The procedure is launched by typing `@ PR:DEFINE`, which activates a menu-bar on the screen.

Figure 1: Menubar for CLIC

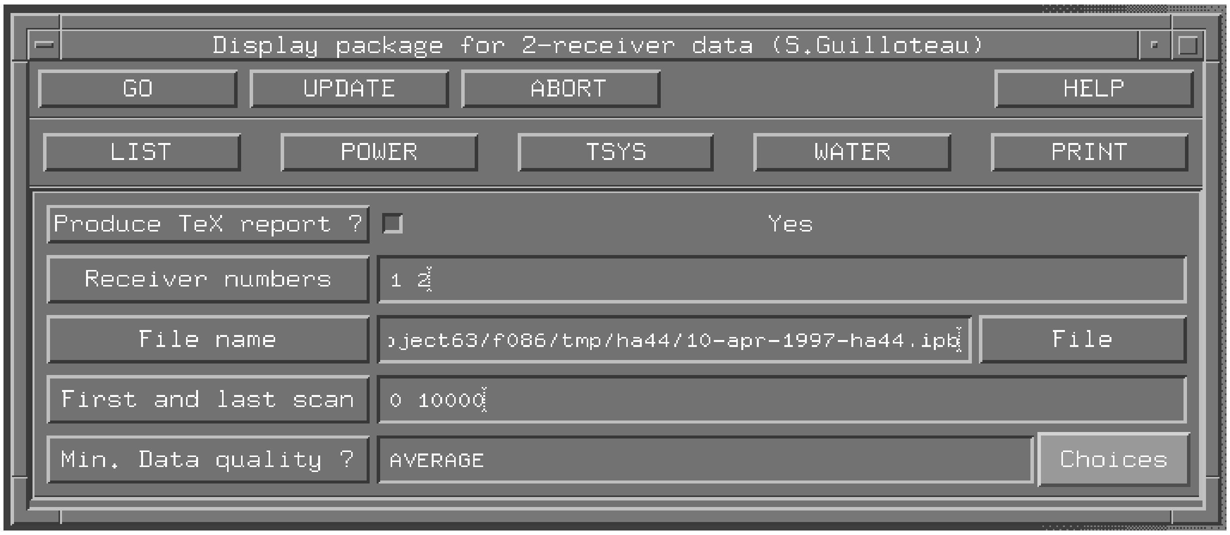

Figure 2: Interface for data summary

Press and hold the mouse button the `CLIC` item. A sub-menu appears, allowing to launch interface windows for calibration and display. Several options appear:

```
File
Raw Data File
First look
Standard calibration (2 receiver)
Simple checks
Holography reduction
```

Move down to your selected choice and release the button. A new window interface will be launched

9.1 First look

The "`first look`" window is designed to plot some basic data, which may be useful before going into calibration.

- `LIST` will select scans, produce scan lists, and a plot showing `TIME, ELEVATION, HOUR_ANGLE` as function of scan number.
- `TOTAL` does a plot of total power vs time.
- `TSYS` does a plot of system temperature vs time.

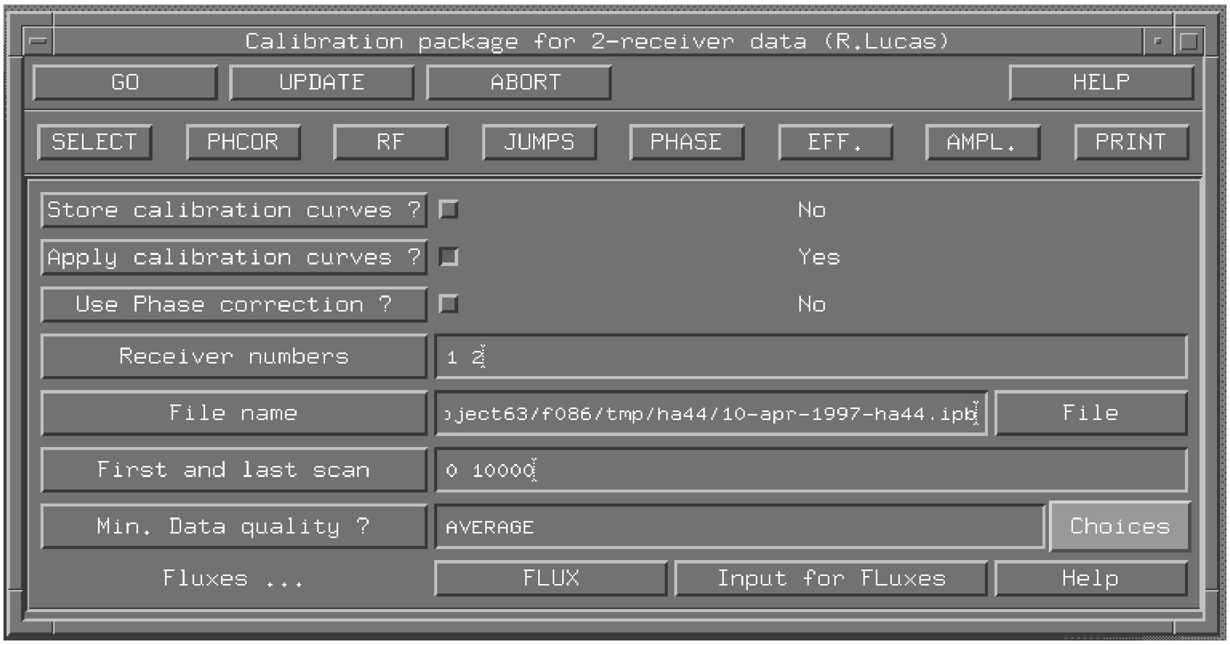

Figure 3: Interface for dual-frequency calibration

- `WATER` does a plot of water vapor vs time.
- `PRINT` concatenates all plots and scan lists in .tex file, and produces a Postscript report from it.

Button `GO` can be used to do automatically all steps in sequence, without any manual intervention.

9.2 Calibration

By selecting the `2-receiver` item, a new window interface appears:

- `SELECT` selects data file and scans.
- `PHCOR` computes atmospheric phase correction.
- `RF` computes the RadioFrequency passband.
- `JUMPS` identifies possible phase and amplitude discontinuities.
- `PHASE` computes the phase calibration curve
- `EFF.` computes the mean telescope efficiencies, and derives flux density of secondary calibrators from the bandpass calibrator.
- `AMPL.` computes the amplitude calibration curve.
- `PRINT` prints a text summary (filename.sum) and optionally a PostScript summary with all plots.

Calibration normally proceeds by doing all steps in sequence, from left to right (i.e. SELECT, PHCOR, RF, JUMPS, PHASE, EFF., AMPL.) and then using PRINT to get the summary. Button GO can be used to do it automatically, without any manual intervention. This may be a good starting point.

While steps SELECT, PHCOR, RF, JUMPS, PHASE are in principle straightforward, steps EFF. and AMPL. require proper adjustement of the flux density scale. This is done by the sub-procedure FLUX described in next section. PRINT can be done at any time, although it is only essential for a final summary. PRINT gives a rather detailed report, including phase noise, amplitude stability, estimate of seeing, etc.... However, these results are reset to unknown for each SELECT operation.

9.3 Flux density calibration

For amplitude calibration, the dual-frequency calibration procedure uses the flux density of the quasars which are stored in the data (header) file. The stored values may not necessarily be accurate, and usually require better determination. The FLUX button allows to switch to a different menu for better flux density scale calibration.

After selection of the receiver, a new window appears with the list of flux for the phase and amplitude calibrators of the project. The window contains 4 command buttons:

- Solve which solves the unknown fluxes from sources with fixed flux.
- Get Result which accepts the solution from the last Solve
- Store which stores the accepted values into the data file.
- Plot which plots the efficiency curve as function of time.
- Calibrate which switches back to the main calibration procedure.

For each calibrator, 4 lines appear

- Input flux the value used as input for the Solve button.
- Fixed flux a logical variable indicating whether the Input flux value should be used as input, or not, by the Solve button
- Solved flux the flux determined by the last Solve action.
- Flux in file the flux stored in the data file.

The last two items are displayed for information, but cannot be modified directly by the user. They can only be modified through the Solve Get Result and Store buttons of the command window.

Once the user is satisfied with the Flux in file values, button Calibrate can be used to come back to the main calibration procedure.

Iteration for steps EFF. and AMPL. is usually required after adjustment of the calibrator flux densities. PRINT can be done at any time, although it is only essential for a final summary. PRINT gives a rather detail report, including phase noise, amplitude stability, estimate of seeing, etc.... However, these results are reset to unknown for each SELECT operation.

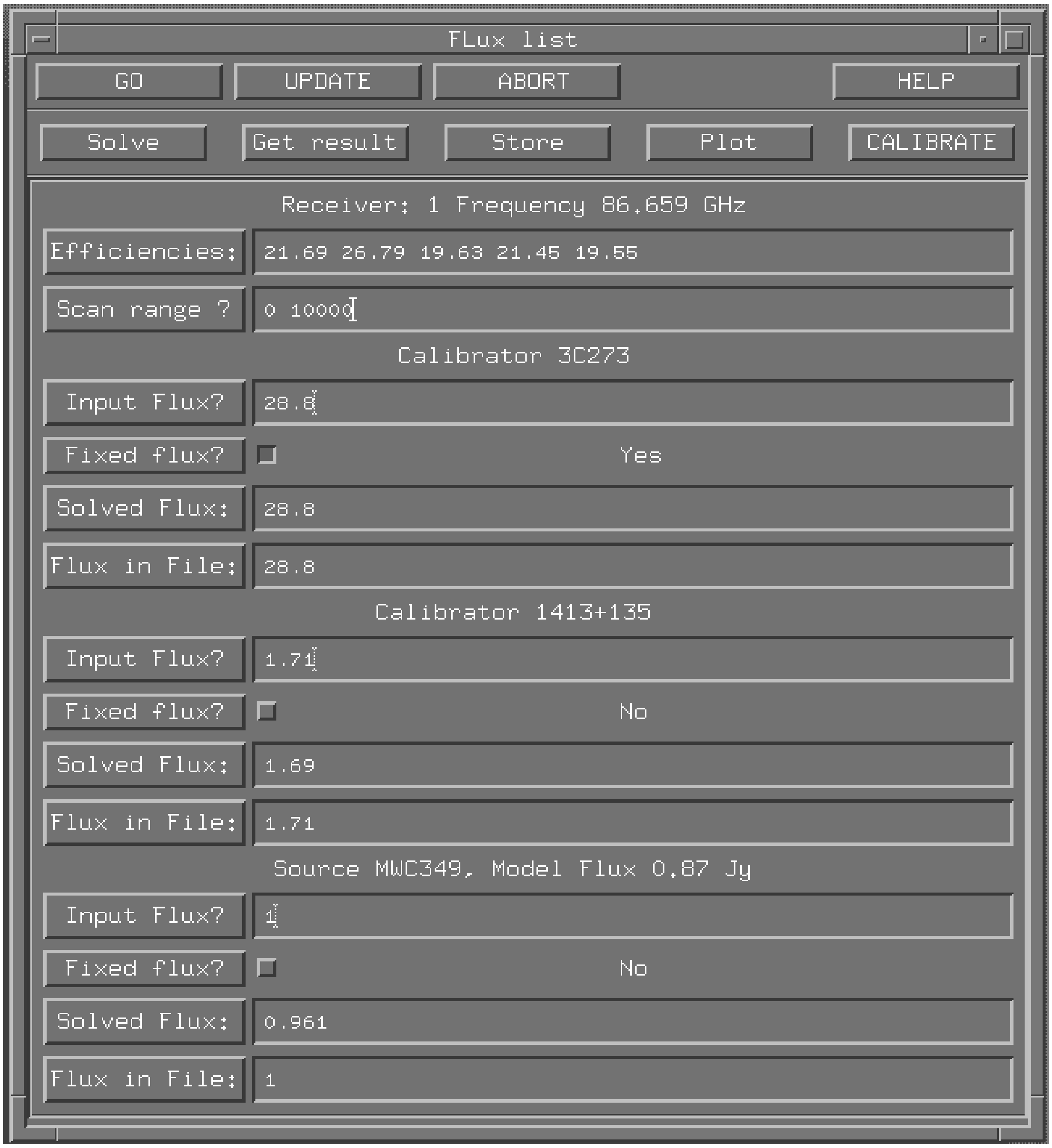

Figure 4: Interface for dual-frequency calibration

9.4 Some Checks

The following procedure helps to check the quality of the calibration.

```
! Define parameters for checks
CLIC\SET DEF
SET BASE 12 13 23 ! 3 antennas used in this example, see above.
SET SUB L01 TO L06
FIND/SOUR 3C84 /PRO COR
SET PHASE RELATIVE
SET AMPLITUDE RELATIVE
SET RF ON FREQUENCY
SET Y AMPLITUDE PHASE
SET PLOT HISTO
SET PLOT BARS

! CHECK 1) Amplitude and Phase versus Time
SET X TIME
PLOT
```

The Phase must be centered around 0.0 ^{o} and the amplitude must be equal to the calibrator flux (in the previous example 4.8 Jy).

```
! CHECK 2. Amplitude and Phase versus I_FREQ
SET X I_F
PLOT
```

On each baseline, the phase curve must be flat and centered around 0.0 (point-like source). The amplitude must be flat and equal to the product $Flux(Jy) \times Phase(DecorrelationTerm)$. The phase decorrelation term is equal to $exp(-\delta\Phi^2/2)$ where $\delta\Phi$ is the phase noise measured on each baseline by the command `SOLVE PHASE`. According to the previous example, the amplitude must be around ~ 4.2, ~ 4.4 and ~ 4.5 Jy for baselines B12, B13 and B23 respectively.

10 Dirty tricks: Back to Real-time

If you ever encounter these problems, *consult an expert.*

10.1 Baselines

In principle, baseline calibration was done before the observations. Under special circumstances, however, the operator and on-duty astronomer at Plateau de Bure may decide to postpone baseline determination until later. In such a case, the data must be corrected for the new baseline values before any instrumental phase calibration can be performed, because a wrong baseline implies a wrong prediction of the calibrator and source phases as a function of time.

This modification can be done on compressed data using the `MODIFY BASELINE` command.

10.2 Atmospheric calibration

This calibration may have been done using bad parameters (e.g. wrong Trec or Forward Efficiency or receiver gain ratios). Since all the measurement results are kept, it is possible to recompute a new solution. This can be done using the `ATMOSPHERE` command, after specifying the new input parameters using the `SET ATMOSPHERE` command.

11 Appendix

11.1 Old Projects: Loading and Gathering Data

Projects started before December 27, 1992 have to use the VAX and Exabyte tapes to recover the original data. The procedure is outlined below (so that we can remember it) but **do NOT do it yourself, ask your local contact, please**.

To restore data from tape to disk, log on to the IRAM04. From the HP computers, press the rightmost mouse button to display a menu of connection to various computers. Select IRAM04 and log in under your project account. Allocate and mount the Exabyte drive named MUB0: and restore the save sets of names `COMP_Date.BCK` where `Date` is a date like `30JUN90`, using the following commands

```
$ ALLOCATE MUB0:
$ BACKUP/NOASSIS/LOG/NOCRC MUB0:COMP_Date.BCK []
```

The data will be written on your login directory, IPB$DISK:[X999], where X999 is your account name (project number usually). Once finished, put the Exabyte tape back in the cabinet. Logoff from IRAM04.

Then, from the HP, use the following CLIC commands to gather the data

```
FILE OUT B2.IPB NEW   ! Open an output file. Use long name like
                      ! W12E24N20.IPB if you prefer (but this is tedious)
SET PROJECT X999      ! Select on your project number basis
SET PROCEDURE *       ! All type of data for completeness
SET TYPE *            ! Objects and calibrators.
SET SCAN * *          ! Any and all scans.
FILE IN IPB$DISK:[X999]01-JAN-1991.IPB   ! Daily archive file.
FIND                  ! Select the scans, and
COMPRESS 30 5         ! Copy them to the output file, with 30 sec time
                      ! integration
FILE IN IPB$DISK:[X999]02-JAN-1991.IPB   ! Now repeat this as needed.
FIND                  ! Select the scans, and
COMPRESS 30 5         ! Copy them to the output file, with 30 sec time
...
FILE IN B2.IPB        ! Read the file just created.
LIST IN/OUT B2.SCANLIST       ! List what's in the file.
LIST IN/SHORT/OUT B2.SHORTLIST    ! Long and summary format
EXIT
```

In case of problems or special cases, you may have to select your data based on other critera than the project number: a range of scan numbers, for instance. Once you have collected the data, remove the daily data file using the following command:

```
rm /ipb_disk/x999/*.ipb
```

A header file can also be created after this stage.