Amplitude Calibration
IRAM Plateau de Bure Interferometer

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Calibration compensates for imperfections and unknowns in the instrument use, including antenna defects (surface quality, focus), pointing errors, atmospheric transmission and fluctuations, receiver and backend gain and instabilities, etc...

This paper describes the way **OBS** (30-m or 15-m version) calibrates spectra, tries to assess the accuracy of the calibration factor, $Tcal$, under practical observing conditions, and then list precautions to take when observing.

Related information is available in

- IRAM Plateau de Bure Interferometer: OBS Users Guide
- CLIC: Continuum and Line Interferometer Calibration

Contents

1 Goal and Principle

1.1 Basic Equations

The `CALIBRATION` procedure goal is to convert backend counts into intrinsic surface brightness or flux density of the source. This conversion can be divided formally in two steps: correction for individual backend channel gains and receiver bandpass, and correction for atmospheric absorption and antenna gain.

Apart from putting the telescope into orbit, there is hardly any hardware fix which may help overcome the atmospheric absorption perfectly. Hence, the correction of atmospheric effects is difficult. The goal is to estimate properly the noise contribution from the atmosphere and the atmospheric transmission. **OBS** uses the standard chopper wheel technique to calibrate the backends and receiver gains.

This technique assumes the detector (receiver + IF cables + backend) is linear. Thus the detector counts, $Mean\_*$, are related to "effective temperatures" by

$$Mean\_load/K = Trec + T_{load} \tag{1}$$

when looking at any given load at a known (effective) temperature T_{load}. $Trec$ is the receiver noise temperature. On the sky,

$$Mean\_atm/K = Trec + T_{emi} \tag{2}$$

When looking at source of brightness T_B, one obtains

$$Mean\_source/K = Trec + T_{emi} + B_s * e^{-\tau} * T_B \tag{3}$$

where B_S is the appropriate antenna to source coupling factor, τ the atmospheric optical depth. Thus T_B can be derived from the counts introducing the "calibration temperature" $Tcal$ with

$$T_B = Tcal * \frac{(Mean\_source - Mean\_atm)}{(Mean\_load - Mean\_atm)} \tag{4}$$

and, in this simple case, Tcal would be given by

$$Tcal = (T_{load} - T_{emi})\frac{e^{\tau}}{B_s} \tag{5}$$

The basic equations presented above assume a pure single-sideband reception (or pure double-sideband on a continuum source). The system noise temperature is given by

$$Tsys = \frac{Tcal * Mean\_atm}{Mean\_load - Mean\_atm} \tag{6}$$

1.2 Atmospheric Model

Evaluating $Tcal$ thus requires to determine both T_{emi} and τ. Assuming the receiver temperature is known, the noise power received on the sky T_{emi} is given by

$$T_{emi} = \frac{(T_{load} + Trec) * Mean\_atm}{Mean\_load} - Trec \tag{7}$$

and is related to the sky emission temperature by

$$T_{sky} = \frac{T_{emi} - (1. - F_{eff}) * T_{cab}}{F_{eff}} \tag{8}$$

where the second formula corrects for the antenna coupling to the sky (F_{eff} is the forward efficiency). Strictly speaking, eq. (8) assumes that the rear sidelobes of the antenna look into the receiver cabin kept at a constant temperature T_{cab}, with low ohmic losses. T_{cab} can however be chosen as a weighted average of the focal cabin temperature and the outside temperature for all rearward losses.

In case of a double side-band receiver and single side-band signal, T_{sky} is a sum of the contribution of the two receiver bands weighted by the sideband gain ratio (gain in the image band divided by gain in the signal band).

$$T_{sky} = \frac{T_{sky\_s} + T_{sky\_i} * Gain\_i}{(1. + Gain\_i)} \tag{9}$$

and a similar equation for T_{emi}. Note that this assumes F_{eff} is identical in the two side bands.

To determine the opacity τ, the trick is to **model** the atmospheric emission to derive the transmission. There is some hope that it can work (at least in reasonably good conditions) because the transmission is dominated by a few constituants, among which only the water vapor varies significantly with time. Hence, if the atmosphere can be modelled by a small number of layers, it is possible to derive the transmission from the emission. The atmospheric model used (ATM, J. Cernicharo) is derived from a "Standard atmosphere" and the knowledge of the Atmospheric pressure P_{amb} and outside Temperature T_{amb} (and the altitude of the site). Together with the season in the year, these parameters give a good approximation of the physical temperature of the absorbing layers. By a minimization routine, with the amount of precipitable water vapor in millimeters as variable, the best model fitting the measured T_{sky} is found. Then, for each band (signal and image), the total zenith opacities are computed by summing the opacities due to Oxygen and Water, with a small empirical correction factor for other minor constituents.

The zenith opacities are used together with the elevation (number of air masses) to compute $Tcal$, the SSB scaling factor

$$Tcal = \frac{(T_{load} * (1. + Gain\_i) - T_{emi\_s} - Gain\_i * T_{emi\_i})}{B_s * e^{-Tau\_s * Air\_mass}} \tag{10}$$

where Tau_s is the zenith opacity in the signal sideband.

2 Calibration mode: COLD, AUTO, or TREC ?

Based on these equations, four modes of calibration are available: TREC, COLD, AUTO, and MANUAL.

2.1 No Nitrogen available : TREC Mode

This is what happens in **OBS** when used in TREC mode (specified by `OBS\SET CAL TREC`) and when you do a CAL command without the argument COLD. In this mode, the receiver temperature is used to determine the gain (conversion from counts to temperature) of the receiver.

With this method, the parameters which have to be specified are thus

- T_{load}, the hot load (also called chopper) temperature.
- T_{rec}, the receiver noise (DSB) temperature.
- P_{amb}, the external pressure.

- T_{amb}, the outside pressure.
- F_{eff}, the forward sky coupling efficiency.
- $Gain\_i$, the ratio of the gain in image band to that in the signal band.

plus a number of (semi) constant parameters (T_{cab}, site altitude, etc...). The elevation (and hence Air_mass) is read by the control program, as are the frequencies of the signal and image bands. All other parameters are derived by the calibration procedure.

The weather parameters may be supplied by the meteo station, specified by the `OBS\SET AMBIENT AUTO` command. If this automatic station does not work, you have to supply by hand P_{amb},T_{amb} and $Humidity$. This is done by the `OBS\SET AMBIENT P_amb T_amb Humidity` command. The $Humidity$ is not used for the calibration, but by the drive program for the refraction correction to the telescope pointing.

2.2 No Nitrogen available : AUTO mode

Another alternative is to assume that you know the water vapor content, either from a previous measurement and assuming the weather is stable, or from theoretical curves as a function of pressure, temperature and relative humidity. With the knowledge of the atmospheric parameters, the model predicts T_{sky} and Tau. In this mode, instead of $Trec$ above, you must supply $Water$ the amount of precipitable water vapor in millimeter. $Trec$ is then given by (from Eq. 7)

$$Trec = \frac{T_{load} * Mean\_atm - T_{emi} * Mean\_load}{Mean\_load - Mean\_atm} \tag{11}$$

This is what happens in **OBS** when used in AUTO mode (specified by `OBS\SET CAL AUTO`) and when you do a CAL command without the argument COLD.

2.3 CAL COLD calibration

This is the most complete calibration procedure, with the minimum number of assumptions. The first step is to measure the power detected by the receiver on the Sky, then on a warm load (the Chopper), then on a cold (liquid nitrogen) load, averaged over the channels of a specific backend. For a perfectly linear detector, the output power is proportional to the total input noise (Receiver + Load), hence the receiver temperature is simply given by

$$Trec = \frac{T_{load} * Mean\_cold - T_{cold} * Mean\_load}{Mean\_load - Mean\_cold} \tag{12}$$

Then, one can proceed as in TREC mode.

The description above refers to what happens when **OBS** when you use the CAL COLD command (in either TREC or AUTO mode).

2.4 MANUAL mode

The last (and worst) alternative is to specify all the atmospheric parameters. This is known as the MANUAL mode (specified by `OBS\SET CAL MANUAL` command). The sky emission is then computed from 4 parameters which are the atmospheric temperatures (T_{atm_s} and T_{atm_i}) and zenith opacities (Tau_s and Tau_i) in signal and image band respectively

$$T_{sky\_s} = T_{atm\_s} * (1. - e^{-Tau\_s * Air\_mass}) \tag{13}$$

$$T_{sky\_i} = T_{atm\_i} * (1. - e^{-Tau\_i*Air\_mass}) \qquad (14)$$

Outside temperature, pressure and humidity are not used for the calibration, although they are still necessary for the telescope pointing, and the water vapor content is no longer needed (you replace four independent parameters by a set of four other independent ones). $Tsys$ and $Trec$ are computed from Eqs. 6 and 11, so that the forward efficiency and gain image ratios are still required. For the calibration to be correct, it is however up to you to ensure that the values supplied are realistic at the frequency of your observations, and with the weather conditions you have...

This mode is just an "educated guess" for the atmospheric calibration, but it still corrects properly the relative gains of all the backend channels.

3 The temperature scale : "Beam Efficiency"

In Eq. 3, B_s is the antenna to source coupling factor, required to obtain a scale which corresponds to the **brightness** temperature of your source (which I presume is the only physical parameter which really interests you).

If you knew your source structure exactly, this factor could in principle be computed from the antenna radiation pattern. If the source is unresolved, it is customary to use the so-called "Main Beam Brightness" temperature scale, which would be the brightness temperature of a source just filling the main primary beam, hence using $B_s = B_{eff}$, the Beam efficiency. If the source extent is unknown, you would use $B_s = F_{eff}$, the Forward efficiency, pending further correction (T_A^* scale, with no direct relation with the brightness temperature of the source).

At the 30-m, B_s is called `B_Eff` in **OBS**, and it can be set using the `OBS\SET EFFICIENCY B_Eff F_Eff` command. (F_{eff} is also noted `F_Eff` in **OBS** manual). B_s is only a scaling factor in your temperature scale.

At Plateau de Bure, B_s is assumed equal to `F_eff`, because a secondary amplitude calibration is required.

4 The SKYDIP

In all the calibration modes, T_{sky} is derived from T_{emi} by correcting for the forward efficiency. Hence it is important to give correctly this forward efficiency. This efficiency can be measured using a skydip (command `OBS\SKYDIP`).

In a skydip, the total power on the sky is measured at various elevation. Since the sky brightness varies with the elevation, while the rearward losses are essentially constant, it is possible in a skydip to derive simultaneously the atmospheric transmission (i.e. the water vapor content, $Water$) and the forward efficiency F_{eff}. Provided $Trec$ is known (at all elevations), a skydip can be done. $Trec$ can be calculated from the gains on the Chopper and on the Cold Load when Nitrogen is available, or given by user input in TREC mode. In the first case, elevation dependent $Trec$ can be accounted for, while the second case require constant $Trec$.

5 Continuum Calibration

The description above assumes that the source signal comes only from the (so-called) *signal* sideband. This is of course not true for continuum radiation. If we neglect spectral index effects, one can derive the proper calibration of a continuum source from the description above. $Tcal$ should be multiplied by

$$\frac{1}{1 + Gain\_i * e^{(Tau\_s - Tau\_i)*Air\_mass}} \tag{15}$$

Similarly for spectral line observations, if you are interested in the image band, $Tcal$ should be multiplied by

$$e^{(Tau\_i - Tau\_s)*Air\_mass} / Gain\_i \tag{16}$$

6 Reduced Chopper Calibration

With modern sensitive receivers, the system noise under good weather conditions may be significantly lower than 300 K. Accordingly, measuring the total noise when looking at a warm load at 300 K requires a linear response of the whole detection system over a dynamic range greater than 2-3. This can be problematic.

There are several ways to bypass this limitation, for example

1. Using lower temperature (controlled or monitored) loads. This is probably the best, but it requires cooling devices somewhere.

2. If the receiver is linear, but not the backend, it is possible to place a switchable attenuator in the IF chain, preferably immediately after the conversion to IF frequency.

3. Covering partially the beam by the absorber, the other part still looking at the sky.

6.1 Partial Beam Coverage

This scheme has been implemented on Plateau de Bure, where the dynamic range of the detectors is relatively small (only 2 between optimum sensitivity and saturation). The only change from the standard equations presented before is the introduction of the "beam filling factor" or "calibration efficiency" C_{eff} in the output on the chopper (from Eq. (1-2))

$$Mean\_load/K = Trec + C_{eff} * T_{load} + (1 - C_{eff}) * T_{emi} \tag{17}$$

Algebra similar to that already exposed yields

$$Tcal = C_{eff} * \frac{(T_{load} - T_{emi}) * (1. + Gain\_i)}{B_s * e^{-Tau\_s*Air\_mass}} \tag{18}$$

just correcting $Tcal$ by an additional C_{eff} scaling factor.

In TREC mode, the sky emission is derived by

$$T_{emi} = \frac{(T_{load} + Trec) * Mean\_atm * C_{eff}}{Mean\_load - (1 - C_{eff}) * Mean\_atm} - Trec \tag{19}$$

and in AUTO mode, the receiver temperature may be derived by

$$Trec = \frac{C_{eff} * Mean\_atm * T_{load} - (Mean\_load - (1 - C_{eff}) * Mean\_atm) * T\_emi}{Mean\_load - Mean\_atm} \tag{20}$$

6.2 Attenuator

Using an attenuator just after the 1st IF conversion may be more convenient, because it then allows the backend to work at (almost) constant level. Let us assume an attenuation factor η (smaller than 1) is used on the chopper. Then

$$Mean\_load/K = \eta * (Trec + T_{load}) \tag{21}$$

and in TREC mode, the sky emission is given by:

$$T_{emi} = \frac{\eta * (Trec + T_{load}) * Mean\_atm}{Mean\_load} - Trec \tag{22}$$

while with a cold load, $Trec$ is given by

$$Trec = \frac{Mean\_cold * T_{load} - Mean\_load * T_{cold}}{Mean\_load - \eta * Mean\_cold} \tag{23}$$

T_B is now given by

$$T_B = e^{\tau} \frac{\eta}{B_s} (T_{load} + Trec) \frac{Mean\_sou - Mean\_atm}{Mean\_load} \tag{24}$$

7 Critical parameters, biases and errors

7.1 Low opacity approximation

To outline the relative importance of all parameters, I will now derive an approximate formula for the calibration factor $Tcal$ in the limiting (but frequent) case where the opacities are weak and equal in the image and signal bands.

$$T_{sky} = \tau * T_{atm} \tag{25}$$

where T_{atm} is the physical temperature of the absorbing layers. Thus

$$T_{emi} = F_{eff} * \tau * T_{atm} + (1 - F_{eff}) * T_{cab} \tag{26}$$

$$\tau = (T_{emi} - (1 - F_{eff}) * T_{cab})/(F_{eff} * T_{atm}) \tag{27}$$

$$Tcal = C_{eff} * (T_{load} - T_{emi})(1 + Gain\_i)/((1 - \tau) * B_s) \tag{28}$$

Eliminating τ gives

$$Tcal = C_{eff} \frac{(T_{load} - T_{emi}) * (1 + Gain\_i) * T_{atm} * F_{eff}}{B_s * (F_{eff} * (T_{atm} - T_{cab}) + T_{cab} - T_{emi})} \tag{29}$$

Although T_{cab} is a weighted average of the physical temperature of the cabin and the outside temperature, it is not very different from T_{load}. Hence we can simplify :

$$Tcal = C_{eff} \frac{F_{eff} * (1 + Gain\_i) * T_{atm}}{B_s * (1 - F_{eff} * \frac{T_{cab} - T_{atm}}{T_{cab} - T_{emi}})} \tag{30}$$

It is important to note that in this formula, T_{atm} is dependent mostly on the outside temperature and pressure (and site altitude of course), and weakly on τ because T_{atm} is the (physical) temperature of the absorbing layers. T_{emi} is the effective temperature seen by the antenna, and hence small compared to T_{cab}. The parameters are F_{eff}, B_{eff} and $Gain\_i$. Setting reasonable numbers :

$$T_{cab} = 290K,\ T_{atm} = 240K,\ T_{emi} = 50K, \text{ and } C_{eff} = 1,$$

yield

$$Tcal = \frac{240 * (1 + Gain\_i) * F_{eff}}{B_s * (1 - 0.2 * F_{eff})} \tag{31}$$

7.2 SKYDIP effects

Currently, T_{amb} (the outside temperature) is used instead of T_{cab} in Eq. 8. The effect of this assumption is intricate, because it is used also in the SKYDIP in which F_{eff} and $Water$ are both determined. If the atmospheric opacities are low, the sky brightness T_{sky} is a linear function of the number of airmass, and thus

$$T_{emi} = (1. - F_{eff}) * T_{cab} + F_{eff} * C^{te} * Water * Air\_mass \tag{32}$$

In this case F_{eff} is underestimated, because T_{amb} is usually *lower* than T_{cab}. An increase in $Water$ will compensate the lower value of the forward efficiency. If the opacities are sufficiently high, the linearity is no longer preserved, and the fit will be bad. However, for 20 K difference between T_{amb} and T_{cab}, the effect on F_{eff} is only 0.01 for F_{eff} around 0.90.

7.3 Derivatives

Another way to look at the critical parameters of the calibration is to analyse the partial derivatives of $Tcal$ with respect to the parameters.

7.3.1 Relative to $Trec$

$$\frac{\partial Tcal}{\partial Trec} = \frac{\partial Tcal}{\partial T_{emi}}\frac{\partial T_{emi}}{\partial Trec} + \frac{\partial Tcal}{\partial Tau}\frac{\partial Tau}{\partial Trec} \tag{33}$$

From Eq. (18)

$$\frac{\partial Tcal}{\partial T_{emi}} = \frac{Tcal}{T_{emi} - T_{load}} \tag{34}$$

and from Eq. (20)

$$\frac{\partial T_{emi}}{\partial Trec} = -1 + \frac{T_{emi} + Trec}{T_{load} + Trec} \tag{35}$$

thus

$$\frac{\partial Tcal}{\partial T_{emi}}\frac{\partial T_{emi}}{\partial Trec} = \frac{Tcal}{T_{load} + Trec} \tag{36}$$

For the second term, from Eq. (18)

$$\frac{\partial Tcal}{\partial Tau} = Air\_mass * Tcal \tag{37}$$

and from Eq. (27)

$$\frac{\partial Tau}{\partial Trec} = \frac{\partial Tau}{\partial T_{emi}}\frac{\partial T_{emi}}{\partial Trec} \tag{38}$$

$$\frac{\partial Tau}{\partial Trec} = \frac{1}{Air\_mass * T_{atm} * F_{eff}}\frac{\partial T_{emi}}{\partial Trec} \tag{39}$$

$$\frac{\partial Tcal}{\partial Tau}\frac{\partial Tau}{\partial Trec} = \frac{Tcal}{T_{atm} * F_{eff}}\frac{T_{emi} - T_{load}}{T_{load} + Trec} \tag{40}$$

giving finally

$$\frac{1}{Tcal}\frac{\partial Tcal}{\partial Trec} = \frac{T_{atm} * F_{eff} - T_{load} + T_{emi}}{F_{eff} * T_{atm} * (T_{load} + Trec)} \tag{41}$$

The typical numbers mentionned above, with $T_{load} = T_{cab}$, yield

$$\frac{1}{Tcal}\frac{\partial Tcal}{\partial Trec} = \frac{F_{eff} - 1}{F_{eff}}\frac{1}{T_{load} + Trec} \tag{42}$$

of the order of 3 10^{-4} per K. Note that this could be higher for higher opacities (hence higher T_{emi}).

7.3.2 Relative to $Tcab$

Taking Eq. (30), one may compute the derivative with respect to Tcab:

$$\frac{1}{Tcal}\frac{\partial Tcal}{\partial T_{cab}} = \frac{(T_{atm} - T_{emi}}{(T_{cab} - T_{emi}) * (T_{cab} - T_{emi} - F_{eff} * (T_{cab} - T_{atm})} \tag{43}$$

or with the numerical values in Eq. (31) about 3.6 10^{-3} per K.

7.3.3 Relative to F_{eff}

Again, from Eq. (30), assuming F_{eff} and B_{eff} are independent,

$$\frac{1}{Tcal}\frac{\partial Tcal}{\partial F_{eff}} = \frac{1}{F_{eff}} + \frac{1}{\frac{T_{cab} - T_{emi}}{T_{cab} - T_{atm}} - F_{eff}} \tag{44}$$

which is of the order of 1.4 for the numerical values in Eq. (31). The first term must be omitted if one assumes $B_s = F_{eff}$, and in this case the derivative is of the order of 0.26.

7.3.4 Relative to C_{eff}

$$\frac{\partial Tcal}{\partial C_{eff}} = \frac{Tcal}{C_{eff}} - \frac{Tcal}{T_{load} - T_{emi}}\frac{\partial T_{emi}}{\partial C_{eff}} \tag{45}$$

$$\frac{\partial T_{emi}}{\partial C_{eff}} = \frac{(T_{emi} + Trec)^2}{T_{load} + Trec} \tag{46}$$

$$\frac{1}{Tcal}\frac{\partial Tcal}{\partial C_{eff}} = \frac{1}{C_{eff}} - \frac{(T_{emi} + Trec)^2}{C_{eff}^2 * (T_{load} + Trec) * (T_{load} - T_{emi})} \tag{47}$$

7.3.5 Relative to η

$Tcal$ has a slightly different definition in this case, and

$$\frac{\partial Tcal}{\partial \eta} = \frac{Tcal}{\eta} + \frac{\partial Tau}{\partial \eta}\frac{\partial Tcal}{\partial Tau} + \frac{\partial Trec}{\partial \eta}\frac{\partial Tcal}{\partial Trec} \tag{48}$$

$$\frac{\partial Tau}{\partial \eta} = \frac{1}{T_{atm} * F_{eff}}\frac{\partial Temi}{\partial \eta} \tag{49}$$

$$\frac{\partial Temi}{\partial \eta} = -\frac{T_{emi} + Trec}{\eta^2} + \frac{\partial Trec}{\partial \eta}\frac{T_{emi} - T_{load}}{T_{load} + Trec} \tag{50}$$

In TREC mode, derivative with respect to $Trec$ must be omitted, and

$$\frac{1}{Tcal}\frac{\partial Tcal}{\partial \eta} = \frac{\eta * T_{atm} * Feff - T_{emi} - Trec}{\eta^2} \tag{51}$$

With a cold load, a corresponding equation could be derived using

$$\frac{\partial Trec}{\partial \eta} = Trec\frac{Trec - T_{cold}}{T_{load} - \eta * T_{cold} + (1-\eta) * Trec} \tag{52}$$

7.4 Results

Using the parameters used previously, and $C_{eff} = 0.5$, $\eta = 0.6$, and $Trec = 100$ K, we can make the following comparison of the variations of $Tcal$

Item	T_{cab}	$Trec$	F_{eff}	C_{eff}	η
Typical Error	2 K	10 K	0.01	0.02	0.02
Induced variation (in %)	0.7	0.3	1.3	2.0	-0.5

This shows that the maximum effect is from C_{eff} if this method is used, from F_{eff} otherwise. It also indicates that the "reduced chopper" calibration is not a good technique, but a switchable attenuator should be used instead.

7.5 Consequences

The most critical parameter of the calibration is the Forward Efficiency F_{eff}. This parameter is a function of frequency (antenna surface accuracy), but also of the receiver used (illumination) and of the *Focus* with a tendency to be too low if you are defocussed. If F_{eff} is underestimated, T_{sky} is underestimated (See equation 8 and note that T_{cab} is always greater than T_{emi} except in very bad sites...) and you may obtain anomalously low $Water$ vapor content, and vice-versa.

The sideband gain ratio *Gain_i* is also a critical parameter. *Gain_i* is not only a scaling factor as obvious in Eq. 8, but is also involved in the derivation of the atmospheric model since the contributions from the atmosphere in image and signal bands are considered. This effect will be important only if the opacities in both bands are significantly different, as for the J=1-0 line of CO.

On the 30-m telescope, because of the design of the cold load, T_{cold} is also a function of frequency and receiver (it varies from 87 K at 230 GHz to 116 K at 75 GHz). The values of T_{cold} are fairly well known by the receiver engineers : ask them...

8 Recommendations

Remember that you can measure all calibration parameters only if nitrogen is available, by the CAL COLD command.

8.1 30-m

Check the value of T_{cold} for each receiver used. If the weather is reasonably good, make a skydip (`OBS\SKYDIP` command) to measure the forward efficiency. In case of scattered clouds, you may prefer to rely on the preceding measurements of this parameter. In any case, the knowledge of the image band gain ratio, *Gain_i*, is essential. This is mostly a scale factor when signal and image opacities are similar, but this is not entirely true close to strong atmospheric absorption bands (e.g. at 115 GHz).

The observing strategy then depends on the weather and (or) receiver stability. Under good conditions (stable weather), you may calibrate with a CAL COLD from time to time, and use the derived value of the water vapor content for intermediate calibrations with a simple CAL AUTO. If the weather is not stable, but the receiver is, use a CAL TREC instead of the CAL AUTO. CAL COLD is always best since you can monitor both water vapor and receiver fluctuations.

Do not forget to focus (`OBS\FOCUS` command) the telescope for the receiver you are most interested in. Otherwise, the standard value of the beam efficiency will be wrong.

8.2 Interferometer

No cold load is available, so one has to rely on TREC for at least one receiver. *Gain_i* can be measured with the interferometer (3 antennas required) using a strong continuum point source (`OBS\GAIN command`).

This "single-dish" amplitude calibration is only a first step for interferometry. Additional degradation may come from phase noise. This degradation can be estimated from the amplitude of the phase calibrator (a quasar, usually). However, most quasars are variable sources, with typical time scales of months. Hence, flux referencing to a source of known flux is also necessary. Some quasars are regularly monitored to get the flux by comparison with planets and/or compact H_{II} regions. This secondary amplitude calibration allows the derivation of the true antenna efficiency (Jy/K conversion factor) at the time of observations.

8.3 Other problems

I have not mentionned pointing accuracy. This problem certainly limits the calibration accuracy in many circumstances. There is no perfect solution to that. Remember to set atmospheric parameters precisely for the refraction correction. Avoid checking the pointing on sources too far away from your object as most pointing errors are systematic effects in azimuth and elevation. The secondary calibration used at Plateau de Bure cancels to first order this problem, since pointing errors should be very similar on the phase calibrator and on the source, but correction for primary beam attenuation can not be applied properly in case of pointing problems.

There are a few circumstances which prevents any good calibration, such as anomalous refraction, high or time varying phase noise in interferometry, or gain losses due to thin partial ice or water coating on the dish surface. The main beam efficiency may drop by a factor 2 in the latter case, and anomalous refraction of more than 10" has been observed also. Unless you can monitor these effects by observing simultaneously a line of known intensity in your source, calibration will be impossible in any of these cases.