ALMA Memo 461
The Amplitude Calibration System revisited

S.Guilloteau (IRAM / ESO), A.Bacmann (ESO)

September 16, 2003

Abstract

Different strategies of use of the polarization grids combined with two temperature loads for calibration are explored. It is shown that a system with an ambient load, a hot (100°C or so) load, and a semi-transparent grid with 50 % transmission allows to reach a 1 % accuracy on the receiver gain even in presence of saturation. The best precision requires a device which offers the 5 major combinations: Sky, Sky+Ambient, Sky+Hot, Ambient, Hot. If saturation is negligible, the system can be used as a standard dual load calibration device, with better accuracy.

1 Introduction

Preliminary tests of the semi-transparent vane calibration scheme proposed for ALMA have shown difficulties in achieving even 5 % accuracy, with time variations of unknown origin. Similar problems are found in the dual-load device on subreflector, where frequency dependence of the coupling factor was found to reach 30 %, while time variations were of order 10 %. [Mangum memo 318] has shown that two loads are useful at submm wavelengths to provide the highest calibration accuracy. At mm wavelengths, a single load can give similar precision, but receiver saturation is a potentially serious issue.

Accordingly, it is important to re-explore the possibilities for calibration in order to reach the highest possible (absolute) calibration accuracy. A possibility is to use polarization grids, which are very accurate, broad band, predictable devices, as tools to build semi-transparent systems. By controlling the grid orientation, the transmission can be controlled and adjusted to the appropriate level.

2 Basic Equations

We use here the formalism developed in [Moreno & Guilloteau, memo 372] and [Guilloteau, memo 423]. The calibration can be derived from the output powers measured by the receiver on the sky P_{sky} and when looking at a load P_{load}, compared to the correlated signal measured by the correlator, C_{source}:

$$
\begin{aligned}
P_{\text{sky}} &= K(P_{\text{sky}})(T_{\text{rec}} + J_{\text{sky}}) \\
P_{\text{load}} &= K(P_{\text{load}})(T_{\text{rec}} + J_{\text{load}}) \\
C_{\text{source}} &= K(P_{\text{sky}})g_s\eta e^{-\tau}T_A
\end{aligned}
\tag{1}
$$

The coefficient $K(P)$ incorporates possible non linearity of the detector (receiver + amplifiers + backend). J_{load} is the effective temperature of the load. In case a semi-transparent device is used, its effective temperature J_{vane} can be expressed as

$$J_{\text{vane}} = f J_{\text{load}} + (1 - f) J_{\text{sky}} \tag{2}$$

where f is the fraction of the beam filled by the load, and η the forward efficiency. g_s and g_i are the normalized signal and image gain of the receivers $g_s + g_i = 1$. Note that, in terms of image to signal gain ratio, g,

$$g_s = 1/(1 + g) \quad \text{and} \quad g_i = g/(1 + g) \tag{3}$$

The sky emissivity J_{sky} is given by

$$\begin{aligned} J_{\text{sky}} &= g_s(\eta J_{\text{m}}^s(1 - e^{-\tau_s}) + \eta J_{\text{bg}}^s e^{-\tau_s} + (1 - \eta) J_{\text{spill}}^s) \\ &+ g_i(\eta J_{\text{m}}^i(1 - e^{-\tau_i}) + \eta J_{\text{bg}}^i e^{-\tau_i} + (1 - \eta) J_{\text{spill}}^i) \end{aligned} \tag{4}$$

where τ_j is the sky opacity (at the current elevation) and

$$J_{\text{x}}^j = \frac{h\nu_j}{k} \frac{1}{e^{h\nu_j/kT_{\text{x}}} - 1} \tag{5}$$

is the Rayleigh-Jeans equivalent temperature of a black body at T_{x} at frequency ν_j. j takes values s or i for signal or image bands respectively. J_{m} is the effective atmospheric temperature (source function), J_{bg} the cosmic background, and J_{spill} the spillover. Similarly, the effective load temperature J_{load} is

$$J_{\text{load}} = g_s J_{\text{load}}^s + g_i J_{\text{load}}^i \tag{6}$$

A major limitation of the calibration accuracy is the possible saturation of the receiver when looking at a warm load (or at the sky...). Using antenna temperatures to express the power levels, the receiver saturation can be expressed as

$$K(T_{\text{ant}}) = \frac{K_0}{1 + (J_{\text{ant}}/T_{\text{sat}})} \tag{7}$$

Note that in Eq.7, J_{ant} is not T_{ant}, but the **input equivalent noise temperature**, and should in principle not incorporate the self-generated noise from the receiver. Thus, $T_{\text{ant}} = T_{\text{rec}} + J_{\text{ant}}$, provided T_{rec} is measured at the entrance of the mixer.... . By extension, we shall note $K(T) = K(J)$. Practical values for ALMA receivers are

$$T_{\text{sat}} \simeq 20000 \left(\frac{\nu}{100 \text{ GHz}} \right)^2 \text{ K} \quad \text{for band 3 and 6} \tag{8}$$

$$T_{\text{sat}} \simeq 1300 \left(\frac{\nu}{100 \text{ GHz}} \right)^2 \text{ K} \quad \text{for band 7 and 9} \tag{9}$$

Saturation is maximal at the lowest frequencies in each band. For band 3 at 84 GHz, $T_{\text{sat}} = 14000$ K, leading to a saturation of 2.1 % on an ambient load. For band 7 at 275 GHz, $T_{\text{sat}} = 9700$ K and the saturation would be 3.1 % on an ambient load.

Dual Load Calibration Solving for the calibration problem requires to derive the receiver gain at the effective input power of the receiver, i.e. to determine

$$G = K(J_{\text{sky}}) = \frac{K_0}{1 + J_{\text{sky}}/J_{\text{sat}}} \tag{10}$$

In addition, of course, other parameters like the atmospheric transmission (in the dual load calibration mode) will need to be determined too.

Single Load Calibration For the a single-load calibration with a semi-transparent vane of coupling f, the measurement equations are

$$
\begin{aligned}
P_{\text{sky}} &= K(P_{\text{sky}})(T_{\text{rec}} + J_{\text{sky}}) \\
P_{\text{vane}} &= K(P_{\text{vane}})(T_{\text{rec}} + fJ_{\text{load}} + (1 - f)J_{\text{sky}}) \\
C_{\text{source}} &= K(P_{\text{sky}})\eta e^{-\tau} T_A
\end{aligned}
\tag{11}
$$

If $K(P)$ is assumed constant, this is a one-load calibration method, for which the source antenna temperature is given by

$$
T_A = fT_{\text{cal}} \frac{C_{\text{source}}}{P_{\text{vane}} - P_{\text{sky}}}
\tag{12}
$$

where T_{cal} is the single-load calibration temperature (See Memo 423, Eq.17).

When significant saturation is present, the appropriate equation is

$$
T_A = fT_{\text{cal}} \frac{C_{\text{source}}}{\frac{K(J_{\text{sky}})}{K(J_{\text{vane}})} P_{\text{vane}} - P_{\text{sky}}}
\tag{13}
$$

Calibration to the required accuracy implies that f should be known to at least the same accuracy, but also that $\frac{K(J_{\text{sky}})}{K(J_{\text{vane}})} P_{\text{vane}} - P_{\text{sky}}$ be estimated to the appropriate precision. In [Guilloteau, memo 423], it was demonstrated that, if saturation correction was not used, this required $K(J_{\text{vane}})$ to be essentially the unsaturated gain $K(0)$ (see Appendix B, Eq.56). If saturation correction is applied, the error δa on $A_{\text{sat}} = 1/T_{\text{sat}}$ should be less than

$$
\delta a \leq \frac{y}{T_{\text{rec}} + J_{\text{vane}}}
\tag{14}
$$

where y is the desired precision (this is essentially Eq.64 of Appendix C in [Guilloteau, memo 423]). Using typical numbers ($y = 0.6\,\%$, $T_{\text{rec}} + J_{\text{vane}} \simeq 300$ K), implies $\delta a \leq 2\,10^{-5}$ K^{-1}.

3 Single Load with Two Semi-transparent vanes

If we calibrate with two semi-transparent vanes, the equations are

$$
\begin{aligned}
P_{\text{sky}} &= K(P_{\text{sky}})(T_{\text{rec}} + J_{\text{sky}}) \\
P_{\text{v1}} &= K(P_{\text{v1}})(T_{\text{rec}} + f_1 J_{\text{load}} + (1 - f_1)J_{\text{sky}}) \\
P_{\text{v2}} &= K(P_{\text{v2}})(T_{\text{rec}} + f_2 J_{\text{load}} + (1 - f_2)J_{\text{sky}})
\end{aligned}
\tag{15}
$$

which, using Eq.**??**, translates into

$$
\begin{aligned}
P_{\text{sky}}(1 + J_{\text{sky}} A_{\text{sat}}) &= K_0(T_{\text{rec}} + J_{\text{sky}}) \tag{16} \\
P_{\text{v1}}(1 + (f_1 J_{\text{load}} + (1 - f_1)J_{\text{sky}})A_{\text{sat}}) &= K_0(T_{\text{rec}} + f_1 J_{\text{load}} + (1 - f_1)J_{\text{sky}}) \tag{17} \\
P_{\text{v2}}(1 + (f_2 J_{\text{load}} + (1 - f_2)J_{\text{sky}})A_{\text{sat}}) &= K_0(T_{\text{rec}} + f_2 J_{\text{load}} + (1 - f_2)J_{\text{sky}}) \tag{18}
\end{aligned}
$$

This is a system with 4 unknowns (K_0, T_{rec} J_{sky} and A_{sat}) and 3 measurements. Accordingly, this system does **NOT** allow to measure one of the parameters.

We can subtract Eq.16 from Eqs.17-18, and obtain

$$
\begin{aligned}
(P_{v1} - P_{sky})(1 + A_{sat}J_{sky}) + A_{sat}P_{v1}f_1(J_{load} - J_{sky}) &= K_0 f_1(J_{load} - J_{sky}) \\
(P_{v2} - P_{sky})(1 + A_{sat}J_{sky}) + A_{sat}P_{v2}f_2(J_{load} - J_{sky}) &= K_0 f_2(J_{load} - J_{sky})
\end{aligned}
\tag{19}
$$

which, provided J_{sky} is known, is a linear system in A_{sat} and K_0. If the saturation is negligible $A_{sat} = 0$, the system becomes

$$
\begin{aligned}
P_{v1} - P_{sky} &= K_0 f_1(J_{load} - J_{sky}) \\
P_{v2} - P_{sky} &= K_0 f_2(J_{load} - J_{sky})
\end{aligned}
\tag{20}
$$

i.e., it is obviously degenerate in K_0 and J_{sky}, and strictly equivalent to a **one** load measurement only. Hence, such a system cannot replace a two-load system, and cannot provided an estimate of J_{sky}.

In the general case, we also have to assume we know J_{sky} to calibrate. In this case, we obtain a linear system in K_0 and A_{sat}

$$
\begin{aligned}
K_0 f_1(J_{load} - J_{sky}) - A_{sat}(J_{sky}(P_{v1} - P_{sky}) + f_1 P_{v1}(J_{load} - J_{sky})) &= P_{v1} - P_{sky} \\
K_0 f_2(J_{load} - J_{sky}) - A_{sat}(J_{sky}(P_{v2} - P_{sky}) + f_2 P_{v2}(J_{load} - J_{sky})) &= P_{v2} - P_{sky}
\end{aligned}
$$

whose solution is

$$
\begin{aligned}
A_{sat} &= \frac{f_1(P_{v2} - P_{sky}) - f_2(P_{v1} - P_{sky})}{-f_1(J_{sky}(P_{v2} - P_{sky}) + f_2 P_{v2}(J_{load} - J_{sky})) + f_2(J_{sky}(P_{v1} - P_{sky}) + f_1 P_{v1}(J_{load} - J_{sky}))} \\
K_0 &= \frac{f_1 P_{v1}(P_{v2} - P_{sky}) - f_2 P_{v2}(P_{v1} - P_{sky})}{-f_1(J_{sky}(P_{v2} - P_{sky}) + f_2 P_{v2}(J_{load} - J_{sky})) + f_2(J_{sky}(P_{v1} - P_{sky}) + f_1 P_{v1}(J_{load} - J_{sky}))}
\end{aligned}
\tag{21}
$$

4 Three Loads with Saturation Correction

A possible calibration scheme is to use three loads of different temperatures. This allows in principle to derive the 3 parameters of the calibration equations: T_{rec}, K_0 and J_{sat}. One of the implementation of such a scheme is a system with one ambient load ($J_{load} = J_{amb}$, one hot (or cold) load ($J_{load} = J_{hot}$), and a removable polarization grid which can allow to feed an arbitrary combination of the two loads ($J_{load} = f J_{amb} + (1 - f)J_{hot}$, with f between 0 and 1).

The measurements are given by

$$
P_{amb} = \frac{K_0}{1 + J_{amb}/J_{sat}}(T_{rec} + J_{amb})
\tag{22}
$$

$$
P_{hot} = \frac{K_0}{1 + J_{hot}/J_{sat}}(T_{rec} + J_{hot})
$$

$$
P_{load} = \frac{K_0}{1 + (f J_{amb} + (1 - f)J_{hot})/J_{sat}}(T_{rec} + f J_{amb} + (1 - f)J_{hot})
$$

The system can be inverted, but this is quite cumbersome in analytic form. We can solve it using a simple minimization scheme, after re-writing it in the following way

$$
P_{amb} = \frac{K_0}{1 + J_{amb}A_{sat}}(T_{rec} + J_{amb})
\tag{23}
$$

4

$$P_{\text{hot}} = \frac{K_0}{1 + J_{\text{hot}} A_{\text{sat}}} (T_{\text{rec}} + J_{\text{hot}})$$

$$P_{\text{load}} = \frac{K_0}{1 + (f J_{\text{amb}} + (1-f) J_{\text{hot}}) A_{\text{sat}}} (T_{\text{rec}} + f J_{\text{amb}} + (1-f) J_{\text{hot}})$$

where $A_{\text{sat}} = 1/J_{\text{sat}}$ to get a more stable form. We are interested in finding the derivatives of our 3 unknowns, T_{rec}, K_0 and A_{sat} as function of the three input parameters, J_{amb}, J_{hot} and f. The sky temperature can then be derived from

$$P_{\text{sky}} = \frac{K_0}{1 + J_{\text{sky}} A_{\text{sat}}} (T_{\text{rec}} + J_{\text{sky}})$$

To reproduce noise, the measurement errors were taken to be 0.1 K. Since the total power represents about $350 - 450$ K on the loads, this implies a short term stability of $2 - 3 \; 10^{-4}$, and a noise equivalent bandwidth of 20 MHz.
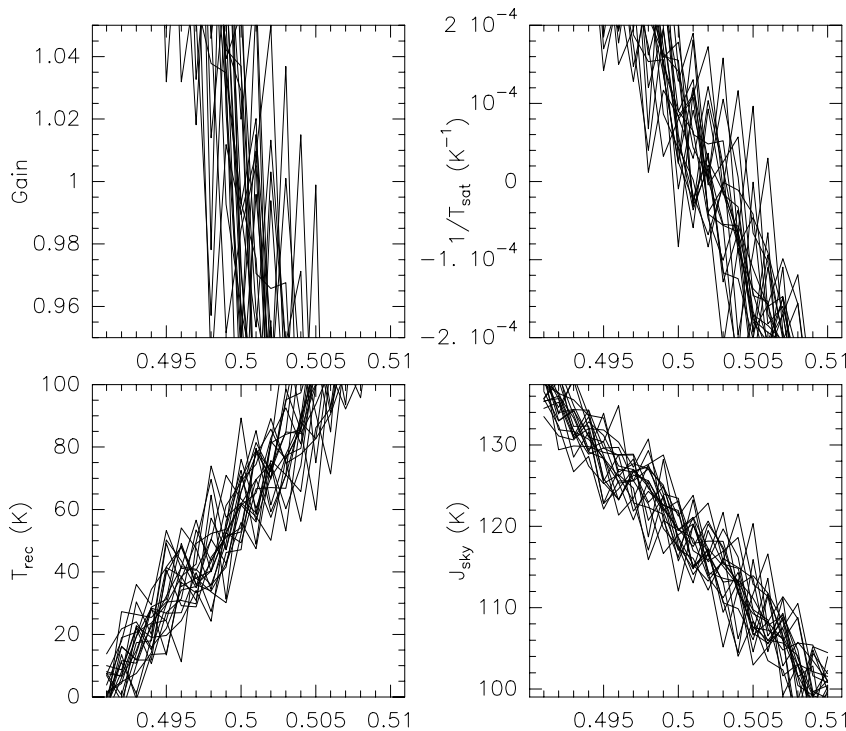

Figure 1: Expected dependencies of the receiver temperature (input value 60 K), gain (input value 1.00) and saturation value (input value 10^{-4}) as a function of the assumed value for the coupling coefficient f between the ambient and hot loads. The input value for f was 0.500.

Figure 1 gives the results under typical conditions ($T_{\text{rec}} = 60$ K and $J_{\text{sat}} = 10000$ K), for "reasonable" values of $J_{\text{amb}} = 285$ K, $J_{\text{hot}} = 385$ K and $f = 0.5$. The gain which is plotted is actually not K_0 but the gain at the input power received when looking at the sky, as appropriate

$$K_{sky} = \frac{K_0}{1 + J_{\text{sky}} A_{\text{sat}}} \tag{24}$$

obtained here for $J_{\text{sky}} = 120$ K. It is absolutely clear from Fig.1 that to obtain a 1% precision on calibration, the coupling coefficient f should be known to the unrealistic precision of 0.02 %... Note that this result can be equivalently derived from the need to known G to 1 % in the two load method, or to know A_{sat} to about $2\,10^{-5}$ when using saturation correction in a one load method (see Eq.14). Measurement errors (noise and short term stability) even are a serious issue with this technique. The dependencies on the knowledge of the temperatures J_{amb} and J_{hot} is less critical (a precision of 1 K would be just sufficient).

The situation improves slightly (precision on f of 0.13 %) when using a cold load J_{cold} instead of an ambient one, but not sufficiently. Accordingly, **a scheme with two loads and an intermediate coupling between them is not sufficiently accurate to correct for saturation**. Attempting to correct for saturation may actually be worse than ignoring it in some cases, since the form of the saturation allows for negative values of A_{sat}.

5 Semi Transparent Vane with Two Loads

Rather than using 3 loads with known effective temperatures, another scheme is to use a semi transparent vane, coupled alternately with an ambient and a hot load, and one of the two loads coupled completely to the receiver.

The measurements are given by

$$
\begin{aligned}
P_{\text{sky}} &= \frac{K_0}{1 + J_{\text{sky}}/J_{\text{sat}}}(T_{\text{rec}} + J_{\text{sky}}) \quad (25)\\
P_{\text{amb}} &= \frac{K_0}{1 + J_{\text{amb}}/J_{\text{sat}}}(T_{\text{rec}} + J_{\text{amb}})\\
P_{\text{vamb}} &= \frac{K_0}{1 + (f J_{\text{amb}} + (1-f)J_{\text{sky}})/J_{\text{sat}}}(T_{\text{rec}} + f J_{\text{amb}} + (1-f)J_{\text{sky}})\\
P_{\text{vhot}} &= \frac{K_0}{1 + (f J_{\text{hot}} + (1-f)J_{\text{sky}})/J_{\text{sat}}}(T_{\text{rec}} + f J_{\text{hot}} + (1-f)J_{\text{sky}})
\end{aligned}
$$

This is an even more cumbersome system than previously, with 4 unknowns (T_{rec}, J_{sat}, K_0, and J_{sky}), 3 parameters (J_{amb}, J_{hot}, and f), and 4 measurements. We apply the same minimization technique as before to derive the sensitivity of K_0 and J_{sky} to the uncertainties in the 3 parameters. The results are given in Fig.2.

From these figures, it is clear that measuring the gain ($K(\text{sky})$) to 1 % precision requires knowledge of f to about 1 % precision in this scheme. It is also clear that this can be done only for a gain stability of order $3\ 10^{-4}$, unless repeated measurements are averaged together.

An interesting problem is how stable is this result as function of the receiver saturation.

6 Optimum Setup

It is conceivable to design a system which allows to obtain any of the 6 combinations (Sky, Sky+Ambient, Sky+Hot, Ambient, Hot, Ambient+Hot), but the measurement in presence of saturation only requires 4 of these. An important question is which combination provides the best estimate of the calibration? To measure saturation, the widest possible sampling of the saturation curve seems appropriate. This implies a priori that the Sky and the Hot load should be included. Also, better results will be obtained with hotter loads. This leaves 3 possibilities for the rest:
- Sky+Hot and Ambient
- Sky+Hot and Sky+Ambient
- Sky+Ambient and Ambient
When only one load is used through the semi-transparent vane, the results are quite sensitive to the absorption coefficient of this vane. Accordingly, the overall combination Sky, Sky+Ambient, Sky+Hot, Hot gives the best accuracy. It is also the least sensitive to the receiver instabilities. However, if one also wishes to use a Single load calibration in order to benefit from its advantages, the ability to observe directly the Ambient load is important. Thus, ideally, 5 setups
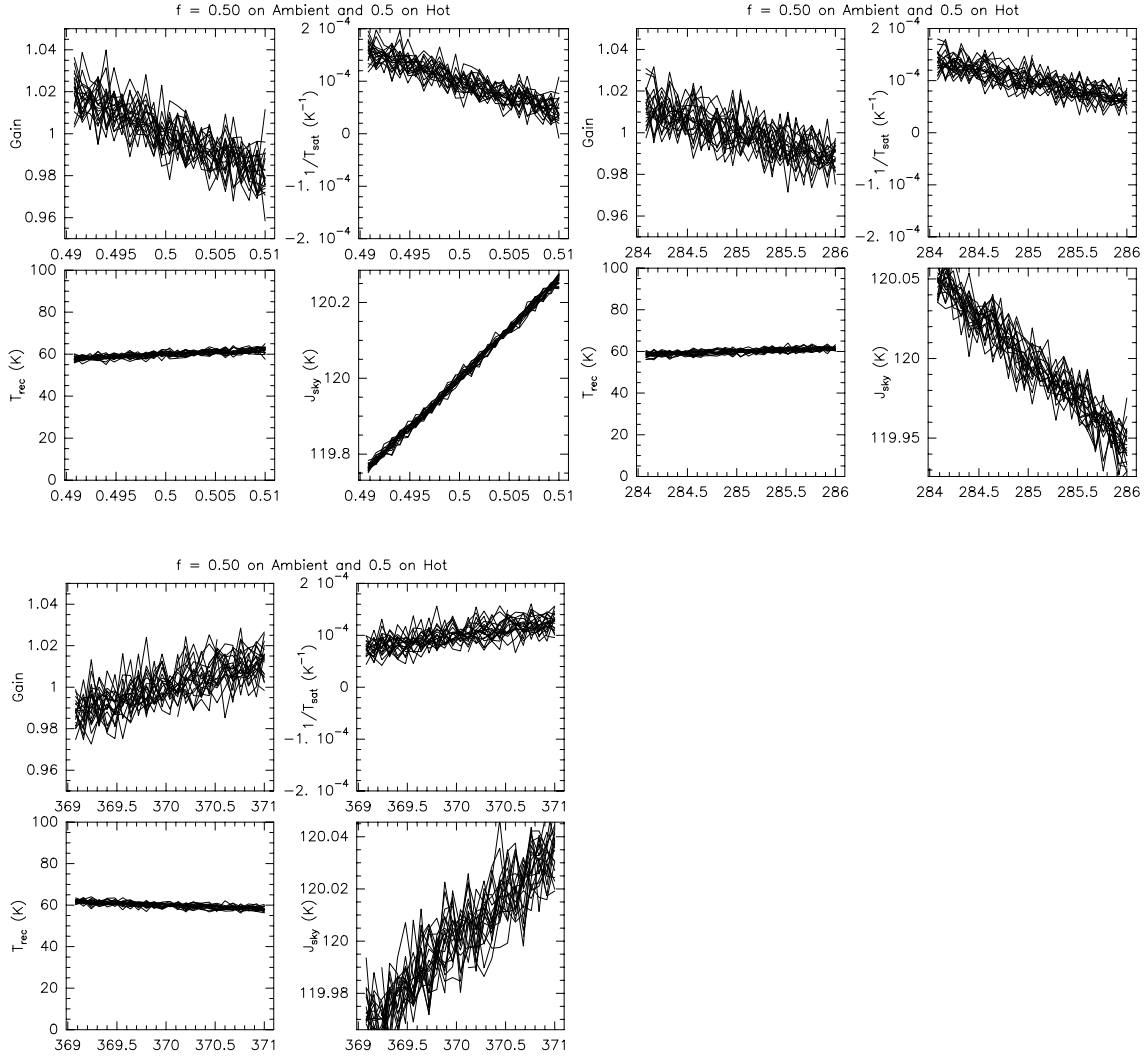
Figure 2: Expected dependencies of the receiver temperature (input value 60 K), gain (input value 1.00), saturation value (input value 10^{-4}), and effective atmospheric noise power (input value 120 K) as a function of the assumed value for the coupling coefficient f between the ambient and hot load (top left corner, input value for $f = 0.5$) , hot load temperature (top right corner, input value 370 K), and ambient load temperature (bottom left corner, input value 283 K). A measurement noise of 0.1 K has been applied.

are required. Using Eq.25 and adding a measurement *vhot* with the vane coupling the Sky and Hot load, the measurement equations are:

$$P_{\mathrm{sky}} \quad = \quad \frac{K_0}{1 + J_{\mathrm{sky}}/J_{\mathrm{sat}}}(T_{\mathrm{rec}} + J_{\mathrm{sky}}) \qquad (26)$$

$$P_{\mathrm{amb}} \quad = \quad \frac{K_0}{1 + J_{\mathrm{amb}}/J_{\mathrm{sat}}}(T_{\mathrm{rec}} + J_{\mathrm{amb}})$$

$$P_{\mathrm{hot}} \quad = \quad \frac{K_0}{1 + J_{\mathrm{hot}}/J_{\mathrm{sat}}}(T_{\mathrm{rec}} + J_{\mathrm{hot}})$$
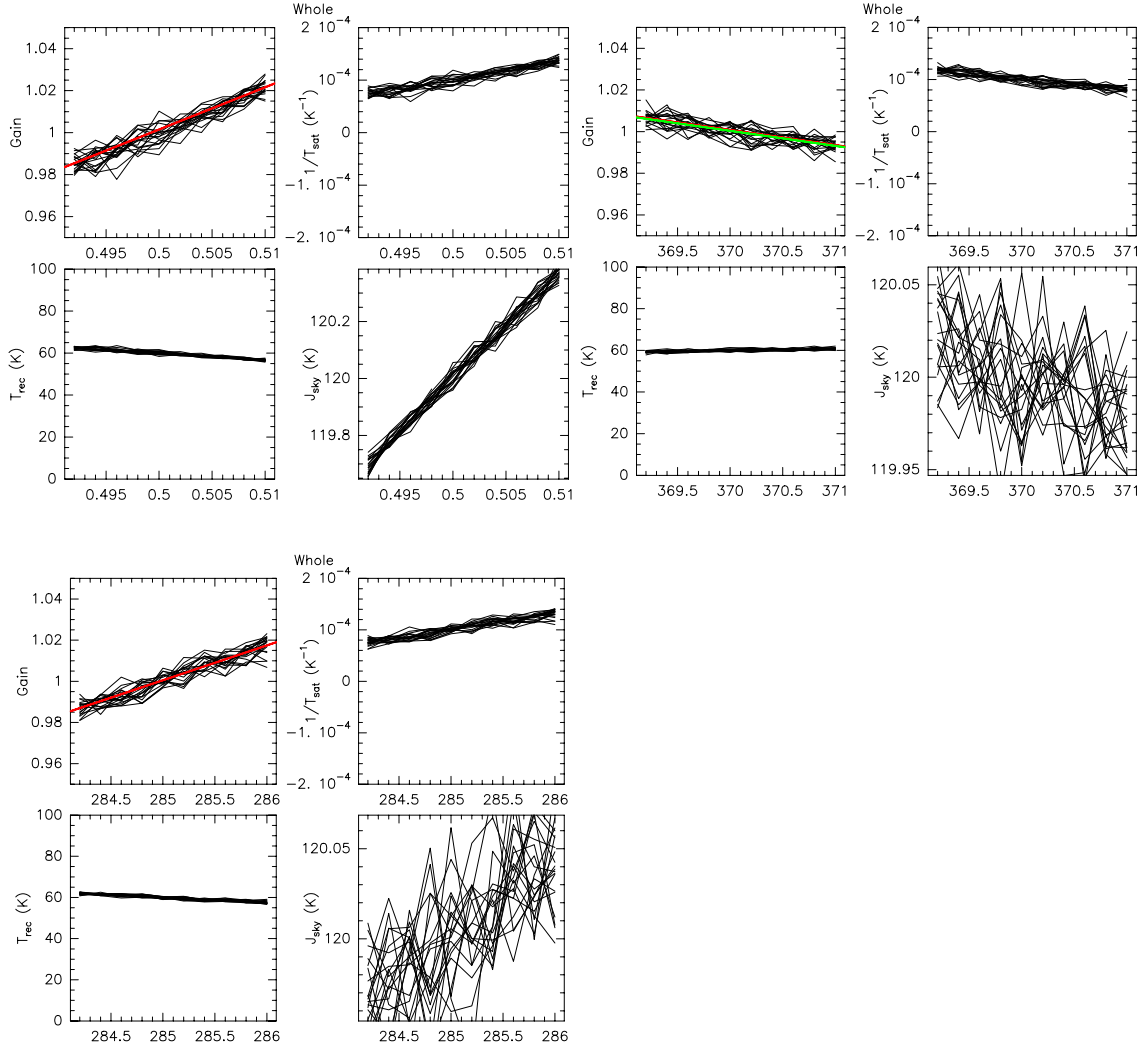
Figure 3: Expected dependencies of the receiver temperature (input value 60 K), gain (input value 1.00), saturation value (input value 10^{-4}), and effective atmospheric noise power (input value 120 K) as a function of the assumed value for the coupling coefficient f between the ambient and hot load (top left corner, input value $f = 0.5$), hot load temperature (top right corner, input value 370 K), and ambient load temperature (bottom left corner, input value 283 K). A measurement noise of 0.1 K has been applied.

$$P_{\text{vamb}} \quad = \quad \frac{K_0}{1 + (fJ_{\text{amb}} + (1-f)J_{\text{sky}})/J_{\text{sat}}}(T_{\text{rec}} + fJ_{\text{amb}} + (1-f)J_{\text{sky}})$$

$$P_{\text{vhot}} \quad = \quad \frac{K_0}{1 + (fJ_{\text{hot}} + (1-f)J_{\text{sky}})/J_{\text{sat}}}(T_{\text{rec}} + fJ_{\text{hot}} + (1-f)J_{\text{sky}})$$

The combined precision when the 5 positions are used is summarized in Figure 3. This indicates that:

- The coupling fraction f should be known to within 0.008, i.e. 1.6 % precision
- The Ambient temperature should be known with better than 0.3 K
- The Hot load temperature should be known with better than 0.6 K

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- Measurement errors should not significantly exceed 0.1 K, i.e. the gain stability should be better than $3\,10^{-4}$ on the measurement timescale. If not, several measurements must be averaged together to get the required precision.

In addition, the precision of the measurement:

- does **not** depend on the value of J_{sat}. This can be derived from the equations 26: the precision on $1/J_{\mathrm{sat}}$ is essentially independent of J_{sat} for the range of values considered here, and is of order $2\,10^{-5}$ for the level of errors mentioned above for f, J_{amb} and J_{hot}.

- **Does** depend on the value of J_{sky}. The precision actually degrades for larger values of J_{sky}, by almost a factor of 2 for J_{sky} around 180 K, and a factor of 4 for $J_{\mathrm{sky}} \simeq 240$ K. This result is somewhat counter-intuitive, but derives from the fact we give the same weight to all measurements. When J_{sky} gets larger, the differences between the semi-transparent vanes and the loads becomes smaller, which results in a loss of precision.

The 5 steps measurement system can be used in a more precise way when **a priori** knowledge of the saturation level can be used. If the saturation is negligible, the best is to ignore the measurement with the semi-transparent device, and only consider the direct measurement. A gain in accuracy by a factor of 4 is then expected for the same precision on the input parameters J_{amb} and J_{load}.

In the above discussion, we have not considered absorption coefficient f significantly different from 0.5. This is because we consider an instrumental setup which allows to calibrate both polarization states simultaneously. Since we are using a polarization grid to modulate the transmission, the only common solution is for $f = 0.5$. Other values of f could only be obtained by rotating the grid between the measurements for each polarization, adding significant complexity to the system.

The optimal use of such a 5-position system will require more studies, in particular on the averaging methods to be used since J_{sat} is a common number for all calibrations with a given tuning (as is most likely T_{rec}). A significant gain in precision is expected when all measurements obtained when observing a single source are averaged together (a posteriori), leaving only K_0 and J_{sky} as variable parameters.

Mechanical setups offering these 5 positions appear feasible (M.Carter, private communication). In addition, it may be possible to rotate the polarization grid, thus modulating in a different way the input to the two feeds, so that the system could be used to help calibrating the polarization properties of ALMA.

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