ALMA Memo 461
The Calibration System revisited

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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 $P_{\rm sky}$ and when looking at a load $P_{\rm load}$, compared to the correlated signal measured by the correlator, $C_{\rm source}$:

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

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

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

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 $J_{\rm sky}$ is given by

$$\begin{aligned} J_{\rm sky} \;=\; & g_s(\eta J^s_{\rm m}(1-e^{-\tau_s}) + \eta J^s_{\rm bg} e^{-\tau_s} + (1-\eta) J^s_{\rm spill}) \\ & + g_i(\eta J^i_{\rm m}(1-e^{-\tau_i}) + \eta J^i_{\rm bg} e^{-\tau_i} + (1-\eta) J^i_{\rm spill}) \end{aligned} \tag{4}$$

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

$$J^j_{\rm x} = \frac{h\nu_j}{k} \frac{1}{e^{h\nu_j/kT_{\rm x}} - 1} \tag{5}$$

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

$$J_{\rm load} = g_s J^s_{\rm load} + g_i J^i_{\rm load} \tag{6}$$

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

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

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

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

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

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

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

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

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

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

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

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

When significant saturation is present, the appropriate equation is

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

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

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

where y is the desired precision (this is essentially Eq.64 of Appendix C in [Guilloteau, memo 423]). Using typical numbers ($y = 0.6\,\%$, $T_{\rm rec} + J_{\rm vane} \simeq 300$ 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

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

which translates into

$$P_{\rm sky}(1 + J_{\rm sky}A_{\rm sat}) = K_0(T_{\rm rec} + J_{\rm sky}) \tag{16}$$

$$P_{\rm v1}(1 + (f_1 J_{\rm load} + (1-f_1)J_{\rm sky})A_{\rm sat}) = K_0(T_{\rm rec} + f_1 J_{\rm load} + (1-f_1)J_{\rm sky}) \tag{17}$$

$$P_{\rm v2}(1 + (f_2 J_{\rm load} + (1-f_2)J_{\rm sky})A_{\rm sat}) = K_0(T_{\rm rec} + f_2 J_{\rm load} + (1-f_2)J_{\rm sky}) \tag{18}$$

This is a system with 4 unknowns (K_0, $T_{\rm rec}$ $J_{\rm sky}$ and $A_{\rm sat}$) 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.

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

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

$$\begin{aligned}P_{amb} &= \frac{K_0}{1 + J_{amb}/J_{sat}} (T_{rec} + J_{amb}) \\ P_{hot} &= \frac{K_0}{1 + J_{hot}/J_{sat}} (T_{rec} + J_{hot}) \\ P_{load} &= \frac{K_0}{1 + (f J_{amb} + (1 - f) J_{hot})/J_{sat}} (T_{rec} + f J_{amb} + (1 - f) J_{hot})\end{aligned} \tag{22}$$

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

$$\begin{aligned}P_{amb} &= \frac{K_0}{1 + J_{amb} A_{sat}} (T_{rec} + J_{amb}) \\ P_{hot} &= \frac{K_0}{1 + J_{hot} A_{sat}} (T_{rec} + J_{hot}) \\ P_{load} &= \frac{K_0}{1 + (f J_{amb} + (1 - f) J_{hot}) A_{sat}} (T_{rec} + f J_{amb} + (1 - f) J_{hot})\end{aligned} \tag{23}$$

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

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

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.

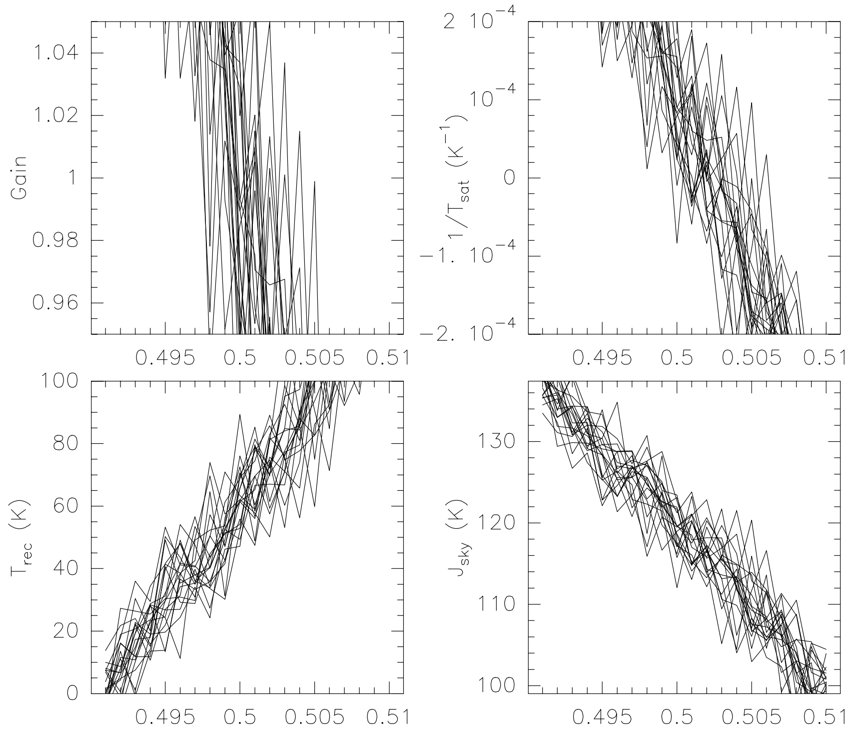

Figure 1: Expected dependencies of the receiver temperature (input value 60 K), gain (input value 1.00) and saturation value (input value 10^{-4}) as a function of the assumed value for the coupling coefficient f between the ambient and hot loads. The input value for f was 0.500.

Figure 1 gives the results under typical conditions ($T_{\rm rec} = 60$ K and $J_{\rm sat} = 10000$ K), for "reasonable" values of $J_{\rm amb} = 285$ K, $J_{\rm hot} = 385$ 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

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

obtained here for $J_{\rm sky} = 120$ 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 $A_{\rm sat}$ 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 $J_{\rm amb}$ and$J_{\rm hot}$ 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 $J_{\rm cold}$ 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 $A_{\rm sat}$.

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

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

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

From these figures, it is clear that measuring the gain (K(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 are required. The measurement equations are:

$$\begin{aligned}
P_{\rm sky} &= \frac{K_0}{1+J_{\rm sky}/J_{\rm sat}}(T_{\rm rec}+J_{\rm sky}) \\
P_{\rm amb} &= \frac{K_0}{1+J_{\rm amb}/J_{\rm sat}}(T_{\rm rec}+J_{\rm amb})
\end{aligned} \tag{26}$$

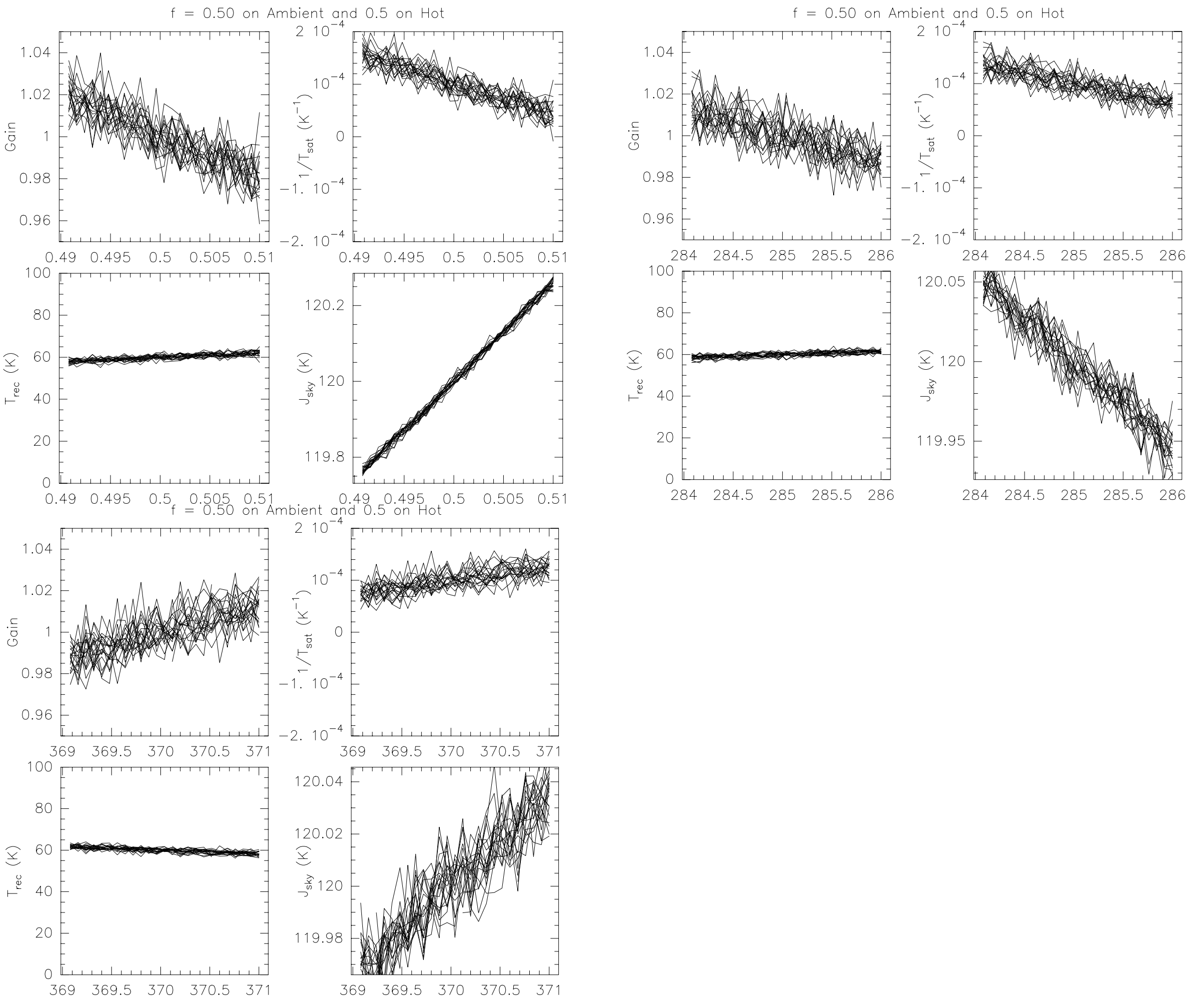

Figure 2: Expected dependencies of the receiver temperature (input value 60 K), gain (input value 1.00), saturation value (input value 10^{-4}), and effective atmospheric noise power (input value 120 K) as a function of the assumed value for the coupling coefficient f between the ambient (input value 0.5) and hot load, hot load temperature and (input value 370 K), and ambient load temperature (input value 283 K). A measurement noise of 0.1 K has been applied.

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

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

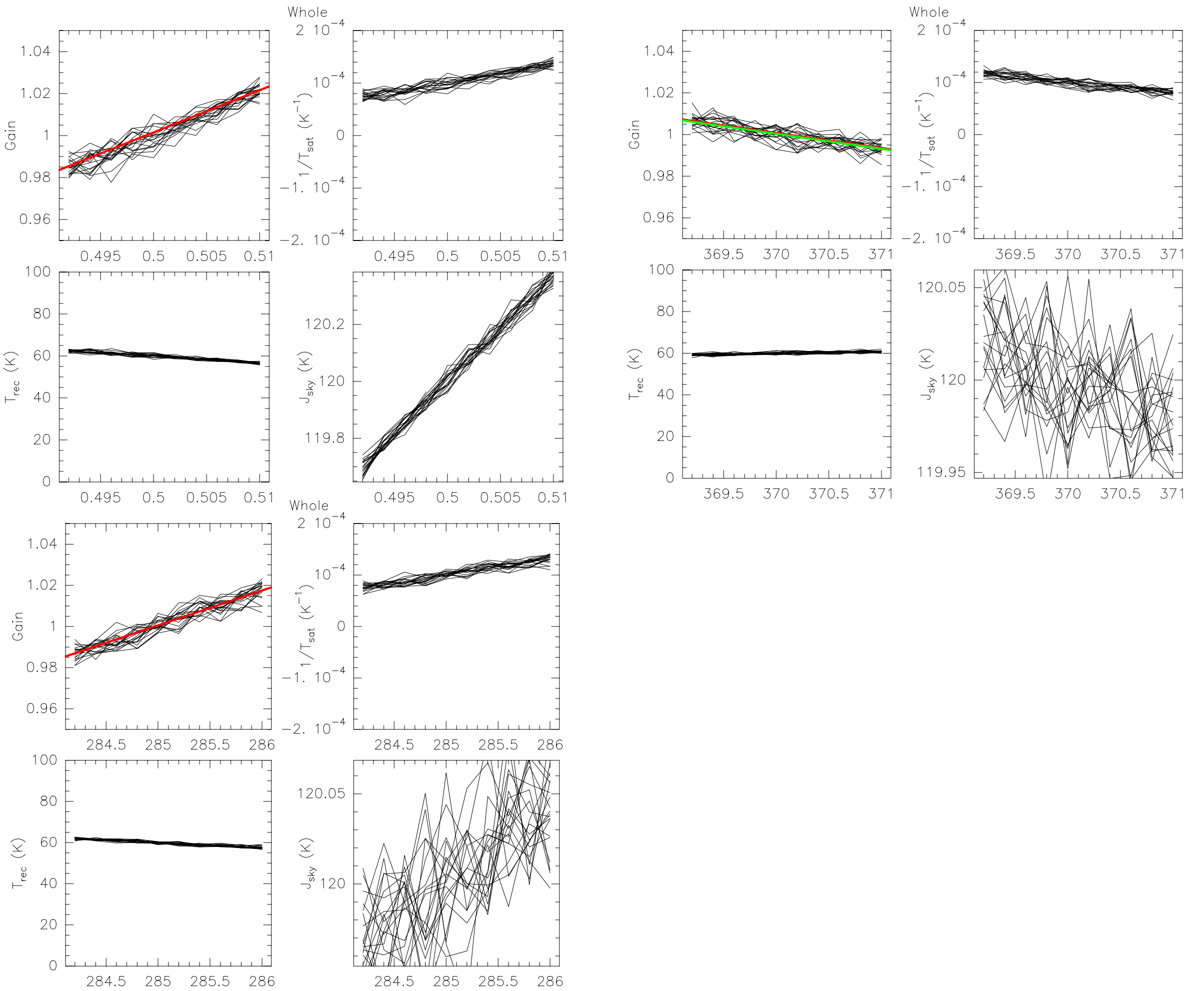

Figure 3: Expected dependencies of the receiver temperature (input value 60 K), gain (input value 1.00), saturation value (input value 10^{-4}), and effective atmospheric noise power (input value 120 K) as a function of the assumed value for the coupling coefficient f between the ambient (input value 0.5) and hot load, hot load temperature and (input value 370 K), and ambient load temperature (input value 283 K). A measurement noise of 0.1 K has been applied.

- 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 $J_{\rm sat}$. This can be derived from the equations 26: the precision on $1/J_{\rm sat}$ is essentially independent of $J_{\rm sat}$ for the range of values considered here, and is of order $2\ 10^{-5}$ for the level of errors mentioned above for f, $J_{\rm amb}$ and $J_{\rm hot}$.
- **Does** depend on the value of $J_{\rm sky}$. The precision actually degrades for larger values of $J_{\rm sky}$, by almost a factor of 2 for $J_{\rm sky}$ around 180 K, and a factor of 4 for $J_{\rm sky} \simeq 240$ K. This result is somewhat counter-intuitive, but derives from the fact we give the same weight to all measurements. When $J_{\rm sky}$ 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 $J_{\rm amb}$ and $J_{\rm load}$.

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 $J_{\rm sat}$ is a common number for all calibrations with a given tuning (as is most likely $T_{\rm rec}$). 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 $J_{\rm sky}$ 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 of the two feeds, so that the system could be used to help calibrating the polarization properties of ALMA.

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