



**Atacama
Large
Millimeter
Array**

Dual Load Amplitude Calibration in ALMA

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ALMA Memo

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1 Introduction

The purpose of this memo on amplitude calibration describe how we use the dual load system that has been implemented for amplitude calibration. The main motivation for using two loads was first to make sure that we could correct for non linearity. I attempt to show here that having two loads allows to have a more efficient method to correct for variations of atmosphere optical depths with time and frequency.

2 Formalism

The basic observation of the sky, loads, and source, following the notations of [5], give:

$$V_{\text{SKY}} = K \times (T_{\text{REC}} + J_{\text{SKY}}) \quad (1)$$

where J_{SKY} is the Rayleigh-Jeans equivalent temperature of the sky, seen by the receiver horn,

$$V_{\text{L}} = K \times (T_{\text{REC}} + J_{\text{L}}) \quad (2)$$

where J_{L} is the Rayleigh-Jeans equivalent temperature of the load.

Signal from astronomical source:

$$V_{\text{A}} = K \times (g_s \eta_{\text{F}} e^{-\tau_s} T_{\text{A}}) \quad (3)$$

System noise:

$$T_{\text{SYS}} = \frac{e^{\tau_s}}{g_s \eta_{\text{F}}} (T_{\text{REC}} + J_{\text{SKY}}) \quad (4)$$

where J_{SKY} is:

$$J_{\text{SKY}} = g_s [\eta_{\text{F}} (J_{\text{Ms}} (1 - e^{-\tau_s}) + J_{\text{BG}} e^{-\tau_s}) + (1 - \eta_{\text{F}}) J_{\text{SPs}}] + g_i [\eta_{\text{F}} (J_{\text{Mi}} (1 - e^{-\tau_i}) + J_{\text{BG}} e^{-\tau_i}) + (1 - \eta_{\text{F}}) J_{\text{SPi}}] \quad (5)$$

2.1 Single Load Calibration

In the single load technique (as old as millimeter-wave radioastronomy, see [6]) the difference between the sky and the calibration measurement is used to scale the measured signal:

$$T_{\text{A}} = T_{\text{CAL}} \frac{V_{\text{A}}}{V_{\text{L}} - V_{\text{SKY}}} \quad (6)$$

where T_{CAL} is given by (**check**)

$$\begin{aligned} T_{\text{CAL}} = & (J_{\text{Ms}} - J_{\text{BGs}}) + g e^{\tau_s - \tau_i} (J_{\text{Mi}} - J_{\text{BGi}}) \\ & + e^{\tau_s} [(J_{\text{SPs}} - J_{\text{Ms}}) + g (J_{\text{SPi}} - J_{\text{Mi}})] \\ & + e^{\tau_s} / \eta_{\text{F}} [(J_{\text{Ls}} - J_{\text{SPs}}) + g (J_{\text{Li}} - J_{\text{SPi}})] \end{aligned}$$

which can be rewritten more simply as:

$$T_{\text{CAL}} = (J_{\text{Ms}} - J_{\text{BGs}}) + g e^{\tau_s - \tau_i} (J_{\text{Mi}} - J_{\text{BGi}}) + \frac{e^{\tau_s}}{\eta_{\text{F}}} [J_{\text{Ls}} + g J_{\text{Li}} - \eta_{\text{F}} (J_{\text{Ms}} + g J_{\text{Mi}}) - (1 - \eta_{\text{F}}) (J_{\text{SPs}} + g J_{\text{SPi}})] \quad (7)$$



For simplicity consider a single side band system ($g_i = 0; g_s = 1$):

$$T_{\text{CAL}} = (J_{\text{M}} - J_{\text{BG}}) + \frac{e^\tau}{\eta_{\text{F}}} [J_{\text{L}} - \eta_{\text{F}} J_{\text{M}} - (1 - \eta_{\text{F}}) J_{\text{SP}}] \quad (8)$$

as J_{L} and J_{M} are not very different, T_{CAL} is only weakly dependent on the optical depth of the atmosphere.

The ‘classical’ way to calibrate is then to get τ from a skydip done once in a while and compute T_{CAL} using 7. An improved way is to determine τ from a standard atmosphere model, in which the water content is obtained from equation 5 (one has to assume T_{REC} known).

2.2 Dual Load Calibration

We have two loads 1 and 2 at different temperatures. For some telescopes (like the Pico Veleta 30m and the Palteau de Bure array of IRAM), we have a cold load and an ambient temperature load. For ALMA we will have an ambient load and a warm load (about 80 degrees C).

2.2.1 Context

At present for IRAM telescopes we use the two loads differently:

- The two loads are used to measure T_{REC} . Then J_{SKY} can be deduced from the sky emission. Then the best-fit water content is found from atmosphere modelling. This allows calculating T_{CAL} and/or T_{SYS} .
- The ambient load emission is then used as a reference, as in equ. 6 (30m), or T_{SYS} is used to scale the correlation factor (Bure).

In these schemes we have a problem with new large bandwidths. We have to calculate T_{CAL} or T_{SYS} for many channels as their variation with frequency is appreciable. Also in case of fast time variations of the water contents (poor weather) the atmosphere model must be run frequently to follow the variations of the atmosphere emission.

In [5], the two load method is viewed as an absolute calibration method (there is no need to know the receiver temperature T_{REC} as in the single-load method), but the calibration used is the difference between the two loads. T_{CAL} becomes:

$$T_{\text{CAL}} = \frac{(1 + g)e^\tau}{\eta_{\text{F}}} (J_{\text{L2}} - J_{\text{L1}}) \quad (9)$$

which is very simple but heavily dependent on the optical depth (exponentially), hence on its changes with frequency and time. This is not suitable for accurate calibration, as pointed by the authors. The main advantage on the single load calibration, i.e. having a ‘first order’ cancellation of the dependence on τ , is lost.

2.2.2 Proposed method

The proposal here is to use the two loads as a refinement of the single load method, only improving on its advantages.

We make a linear combination of the two load measurements, with weights α and $(1 - \alpha)$, we get:

$$V_{\text{L1}} = K \cdot (T_{\text{REC}} + J_{\text{L1}}) \quad (10)$$

$$V_{\text{L2}} = K \cdot (T_{\text{REC}} + J_{\text{L2}}) \quad (11)$$

$$V_{\text{L}} = \alpha V_{\text{L1}} + (1 - \alpha) V_{\text{L2}} = K \cdot (T_{\text{REC}} + J_{\text{L}}) \quad (12)$$



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where

$$J_L = \alpha J_{L1} + (1 - \alpha) J_{L2} \quad (13)$$

If we use this linear combination of the two loads as the only load in the single-load calibration, we may attempt to choose α such that T_{CAL} (eq 7) is independent of the optical depth, by solving the equation:

$$J_{L_s} + gJ_{L_i} - \eta_F(J_{M_s} + gJ_{M_i}) - (1 - \eta_F)(J_{SP_s} + gJ_{SP_i}) = 0 \quad (14)$$

or

$$J_L = \eta_F(g_s J_{M_s} + g_i J_{M_i}) - (1 - \eta_F)(g_s J_{SP_s} + g_i J_{SP_i}) \quad (15)$$

introducing the averages:

$$J_M = g_s J_{M_s} + g_i J_{M_i}; J_{SP} = g_s J_{SP_s} + g_i J_{SP_i}$$

we obtain the simple expression for α :

$$\alpha = \frac{\eta_F J_M + (1 - \eta_F) J_{SP} - J_{L2}}{J_{L1} - J_{L2}} \quad (16)$$

while

$$T_{\text{CAL}} = (J_{M_s} - J_{BG_s}) + g e^{\tau_s - \tau_i} (J_{M_i} - J_{BG_i}) \quad (17)$$

The system temperature T_{SYS} is obtained by:

$$T_{\text{SYS}} = T_{\text{CAL}} \frac{V_{\text{SKY}}}{V_L - V_{\text{SKY}}} \quad (18)$$

with

$$V_L = \alpha V_1 + (1 - \alpha) V_2$$

and the scaling of spectra obtained by

$$T_A = T_{\text{CAL}} \frac{V_A}{V_L - V_{\text{SKY}}}$$

or equivalently by:

$$T_A = T_{\text{SYS}} \frac{V_A}{V_{\text{SKY}}} \quad (19)$$

The nice result here is that both quantities involved as intermediate steps, i.e. α and T_{CAL} , are very much independent of the optical depth. The only atmospheric quantity involved are J_M , which is the Raileigh-Jeans equivalent physical temperature of the atmosphere averaged on the line of sight, and, for T_{CAL} , the difference in optical depth between the image and signal bands.



2.3 Receiver Temperature

The obvious method to calculate T_{REC} is to use directly the two load measurements and derive the value in the usual way. The issue here is the loss of precision due to the low value of the receiver temperature in the lower bands ($\sim 50\text{K}$) and the high values of the load temperatures ($\sim 300\text{K}$ and $\sim 380\text{K}$). This implies a multiplication of errors (Todo: equation) where a 1K error on the hot load equivalent temperature is multiplied by a factor of ~ 4 .

If we have a good model of the atmospheric emission we can alternatively use the sky as a cold load (in band 3 and good observing conditions its radiation temperature is typically 10K).

(equation)

Finally we can combine the three measurements (sky, ambient and hot loads) to investigate for nonlinearity in the receiving chain; saturation is expected in the mixer in some bands.

(equation for 3-load measurement)

2.4 Saturation effects

TODO :

error in T_{rec} and T_{sys} due to saturation.

2.5 Observing Procedure

2.5.1 Current implementation

At this point the above method is implemented in ALMA:

- The loads and the sky are observed with the same level settings of the IF chain, using the autocorrelations measured in TDM mode (dual polarization, 128 channels in each 2GHz baseband, giving a resolution of 15.625 MHz). This is done by executing the `AtmCalTarget`.
- T_{SYS} is evaluated using equation 18 for each channel frequency in all basebands, at the time of the `AtmCalTarget` execution, and stored in the `SysCal` table of the ASDM. In the determination of T_{SYS} :
 - the forward coupling efficiency is a band-dependent value measured using skydips. Currently default values are used [*table*]
 - the optical depths in the signal and image bands are determined from the ATM model, using the water content that fits the current WVR data.
 - the sideband gain ratio is obtained from the most recent sideband gain ratio measurements; if no measurement was done a default value for the current band is used. [*table*]
- In Casa the T_{SYS} values are interpolated in time and frequency to scale data according to equation 19.

2.5.2 Future Improvements

- For `AtmCals` it is not required to measure the loads each time and for each source. The change of gain between the attenuator setting used for the loads and further observations can be determined by observing the sky with the two attenuator settings, in sequence. Then updates of T_{SYS} are made by a simple observation of the sky emission, without reobserving the loads and without changing the attenuation levels.



2.5.3 Discussion

- Do we need on-source or off-source Tsys ?
- How well can we correct for atmospheric lines?
- How often do we need to measure Tsys?
- Effect of offsets in samplers. These offsets introduce a constant autocorrelation signal in all lags and thus a zero frequency signal in the autocorrelation spectra; due to the 1/2 channel shift and the windowing function a 1/f signal is added.
 - estimate current effect
 - in principle can be removed using correlations.

3 Conversion to T_A^* scale

1. Set up (autocorrelation). One needs to set the programmable attenuators to be sure the correlator is working at optimum sensitivity. This is done by optimizing the value of the unscaled channel zero count for each baseband, or by using the sampler statistics.
2. Observe the sky (autocorrelation). Integration time of 1 sec at most.
3. Observe one or two loads at known temperature (autocorrelation). Requirements:
 - (a) Must be observed with the same configuration and integration time.
 - (b) To avoid problems with exceeding the dynamic range of the correlator, when observing the hottest load attenuation of ~ 6 dB must be inserted in the IF, using the programmable attenuators.
 - (c) The spectral response of the attenuators need to be measured previously (*i.e.* in the laboratory before delivery and as part of a receiver maintenance schedule). More frequent, but less accurate, calibration of the spectral response of the attenuators can be made by observing a strong source (*i.e.* the Moon). To avoid interference by atmospheric transmission during these measurements, a relatively transparent frequency range should be chosen for these measurements.
4. Assume we have two loads at two temperatures T_1 and T_2 : from the above steps one gets the true autocorrelation spectra V_{SKY} , V_1 , V_2 , by:
 - (a) multiplying the autocorrelation functions by the recorded channel zero values and
 - (b) dividing by the spectral response of the attenuations inserted in the IF.
5. Using the known load (equivalent) emissions, the sky coupling factor (deduced from skydips), the sideband gain ratios (separately measured interferometrically), we calculate the observed atmosphere Rayleigh-Jeans equivalent brightness J_{SKY} , for selected spectral channels (these could be e.g. subband averages). This ‘atmosphere frequency sampling’ is expected to be every 100 MHz.
6. Using the ATM atmospheric model, one finds the best model parameters that reproduce J_{SKY} . Usually this means deducing only the precipitable water vapour content.

Note: for ALMA it could be that using the absolute value from the WVR data is better. This is TBD as the WVR is primarily designed for determining the water vapour fluctuations.
7. Using the current atmospheric parameters (derived from a nearby weather instrumentation installation), calculate J_{M_s} and J_{M_i} (the atmosphere source function in Kelvin), as well as τ_i and τ_s (the atmospheric optical depths), at the atmospheric frequency sampling, for the signal (s) and image (i) bands.



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8. Calculate T_{CAL} at the atmospheric frequency sampling.
9. Interpolate T_{CAL} to the observed frequency channels.
10. Calculate T_{SYS} for the observed frequency channels.
11. Store results.
12. The scaling of the data to temperature units is then done by:

- (a) For autocorrelation data:

$$T_A = \frac{\Delta V_A}{V_{\text{SKY}}} T_{\text{SYS}}$$

here ΔV_A is the observed change in autocorrelation spectra between source and reference position.

- (b) For correlation data:

$$T_A = r_{ij} \sqrt{T_{\text{SYS}i} T_{\text{SYS}j}}$$

This scaling will actually be done in the *aips++* filler (or any other software that needs to access the data in temperature units).

References

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