Atacama
Large
Millimeter
Array

# Amplitude Calibration Steps

ALMA-90.03.00.00-00x-A-SPE

2007–08–02

*Specification Document*

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*Change Record*

| Revision | Date | Author | Section/ Page affected | Remarks |
|---|---|---|---|---|
| 1 | 2005-06-29 | Robert Lucas | All | Initial Draft |
| 2 | 2005-07-11 | Jeff Mangum | All | Added some content to all sections |
| 3 | 2005-07-27 | Jeff Mangum | All | Added to "Conversion to $T_A^*$" section |
| 4 | 2005-08-11 | Jeff Mangum | All | Touched-up references |
| 5 | 2005-09-15 | Jeff Mangum | All | Minor edits |
| 6 | 2006-02-09 | Jeff Mangum | All | Added relative/absolute calibration |
| 7 | 2006-05-15 | Jeff Mangum | All | Added solar observations |
| 8 | 2006-05-25 | Jeff Mangum | All | Additions following internal review |
| 9 | 2007-02-17 | Jeff Mangum | All | Minor updates to some sections |
| 10 | 2007-08-02 | Jeff Mangum | All | Added timing diagram and touched-up sequencing |
| 11 | 2007-08-02 | Jeff Mangum | Appendices | Fixed error in Appendix A2 |

`$Id: AmpliCalStepByStep.tex,v 1.9 2007/08/02 11:09:32 jmangum Exp jmangum $`

# Contents

# 1 Goals

1. **Establish the $T_A^*$ scale** for ALMA observations, both in interferometry and single-dish mode, for continuum and spectral line data. Conversion to $T_A^*$ ensures that the main effects of variations of atmosphere absorption are taken out, so that emission from sources at different elevations can be compared. See [1] for details. Note that this is a *relative amplitude calibration* scale.

   As specified in [2] (SSR 2.3-R11) the visibilities are stored as cross-correlation coefficients. The option has also been taken to store the auto-correlations (recorded in all cases, both interferometry and single-dish) in similar units (see [3], [4], [5]). Thus the integral of the autocorrelation spectrum is 1.0 (the raw value of the zero-lag channel is kept too). We refer to this data as "raw data". However remember that the following corrections have already been applied:

   — correlator quantization correction,
   — WVR path length correction (optional)
   — residual delay error correction.

   Converting the raw data into $T_A^*$ data requires only multiplying by the system temperature $T_{SYS}$ for the proper observing frequency. This scaling factor is derived from measurements made with the relative amplitude calibration device (*c.* f. [1]).

2. **Convert $T_A^*$ into flux density units (janskys)**. This scale is appropriate for interferometric aperture synthesis and single-dish observation of point sources. Note that this is an *absolute amplitude calibration* scale. All measurements will ultimately need to be converted to flux density units.

   This step will remove the antenna gain, residual atmospheric antenna and receiver gain variations, receiver passbands, *etc.*

3. **Convert the $T_A^*$ into brightness temperature units**. This step is appropriate for single-dish observation of extended sources. Note that this is an *absolute amplitude calibration* scale.

# 2 Calibration Steps

## 2.1 Conversion to $T_A^*$ (Relative Amplitude Calibration) Scale

### 2.1.1 Relative Calibration Cycle Times

A single amplitude calibration system measurement will take $\sim$ 10 seconds. Relative amplitude calibration system measurements will need to be done every 5 to 30 minutes, where the shorter interval is necessary at the higher ALMA frequency bands.

### 2.1.2 Time Dependence Monitoring

As part of the standard phase calibration cycle (see Phase Calibration Example Document) a strong nearby phase calibrator will be measured at the target frequency at least every 10 minutes. These measurements can be used to track the relative amplitude calibration stability during an observing block.

#### 2.1.3 Relative Amplitude Calibration Sequence

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 $\sim$ 6dB 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.
   (d) For solar observations, the solar filter will be inserted between the receiver feed and the amplitude calibration device. All solar observation amplitude calibration measurements will be made with this solar filter inserted. Note that the current design of the solar filter will provide 13$\pm$3 dB of attenuation to the input signal, which will require $\lesssim$ 20 seconds of integration time on each calibration load to reach the required measurement precision.
4. Assume we have two loads at two temperatures $T_1$ and $T_2$: from the above steps one gets the true autocorrelation spectra $V_{\rm SKY}$, $V_1$, $V_2$, 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 $J_{\rm SKY}$, 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 $J_{\rm SKY}$. 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 $J_{{\rm M}s}$ and $J_{{\rm M}i}$ (the atmosphere source function in Kelvin), as well as $\tau_i$ and $\tau_s$ (the atmospheric optical depths), at the atmospheric frequency sampling, for the signal ($s$) and image ($i$) bands.
8. Calculate $T_{\rm CAL}$ at the atmospheric frequency sampling (see Appendix A).
9. Interpolate $T_{\rm CAL}$ to the observed frequency channels.
10. Calculate $T_{\rm SYS}$ for the observed frequency channels (see Appendix A).
11. Store results.
12. The scaling of the data to temperature units is then done by:

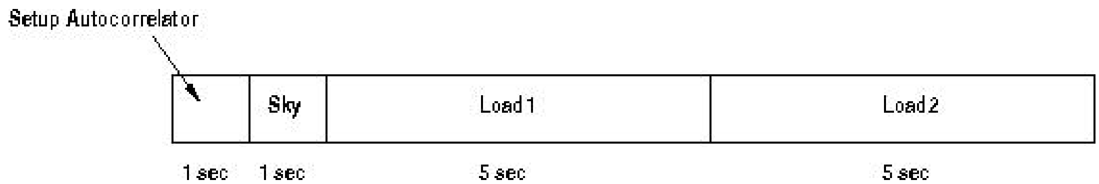


Figure 1: Relative amplitude calibration measurement timing diagram. Note that for solar observations the load measurements will be approximately 20 seconds in duration with the solar filter inserted.

(a) For autocorrelation data:

$$T_{\mathrm{A}} = \frac{\Delta V_{\mathrm{A}}}{V_{\mathrm{SKY}}} T_{\mathrm{SYS}}$$

here $\Delta V_{\mathrm{A}}$ is the observed change in autocorrelation spectra between source and reference position.

(b) For correlation data:

$$T_{\mathrm{A}} = r_{ij}\sqrt{T_{\mathrm{SYS}i} T_{\mathrm{SYS}j}}$$

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

*Note:* The formulas in [6] give $T_{\mathrm{CAL}}$ for the single load calibration, while the formulas in [1] do not explicitly derive $T_{\mathrm{CAL}}$. The definition of $T_{\mathrm{CAL}}$ can be extended to dual load calibration and refined to obtain a formulation which is easier to interpolate in frequency (by using an appropriate linear combination of the data from the two loads). See Appendix A for a derivation.

Figure 1 shows a "timing diagram" which describes a relative amplitude calibration measurement. Summarizing the supplementary (laboratory or otherwise) measurements needed for proper amplitude calibration calculation:

— Programable attenuator spectral response. Should have an initial (laboratory) measurement that is supplemented with regular (once per month) measurements of the spectral response using a strong source (*e.g.* Moon).

— Sideband gain ratio (measured interferometrically). Part of bandpass calibration.

— Sky coupling (measured from skydips).

## 2.2 Conversion to $T_{\mathrm{R}}$ or S (Absolute Amplitude Calibration) Scale

Conversion of the relative $T_{\mathrm{A}}^*$ amplitude scale to an absolute brightness temperature ($T_{\mathrm{R}}$) or flux (S) will be done in the "traditional" way. Measurements of astronomical objects whose fluxes are known or well-predicted by modelling are used to connect the absolute and relative amplitude scales. As the current state-of-the-art in amplitude calibration at millimeter and submillimeter wavelengths is generally larger than the 5% absolute calibration specification, the characterization of a set of absolute amplitude calibration standards will be an early and high-priority research project for the ALMA operation.

One of the first development projects that ALMA will pursue will be an adaptation of the absolute amplitude calibration scheme using interferometry proposed by Jim Gibson and Jack Welch (UCB RAL). See §B for a description of this next-generation absolute amplitude calibration system.

## References

[1] Mangum (2002), "Load Calibration at Millimeter and Submillimeter Wavelengths", ALMA Memo 434

[2] SSR Committee, ALMA Science Software Requirements and Use Cases, ALMA-70.10.00.00-002-I-SPE

[3] ALMA Calibration Plan (2006-09-06), SCID-90.03.00.00-007-A-PLA

[4] ALMA Calibration Specifications and Requirements (2005-09-26 Draft), ALMA-90.03.00.00-001-A-SPE

[5] Specifications and Clarifications of ALMA Correlator Details, Stephen Scott, 2003-01-29, AlmaCorr.pdf

[6] Bacmann & Guilloteau (2004), "Bandpass Calibration for ALMA", ALMA Memo 505

# A Expressions for $T_{\rm CAL}$ and $T_{\rm SYS}$

## A.1 Single Load

$$T_{\rm CAL} = (J_{{\rm M}s} - J_{{\rm BG}s}) + g e^{\tau_s - \tau_i}(J_{{\rm M}i} - J_{{\rm BG}i}) \quad (1)$$
$$+ e^{\tau_s}[(J_{{\rm SP}s} - J_{{\rm M}s}) + g(J_{{\rm SP}i} - J_{{\rm M}i})] \quad (2)$$
$$+ e^{\tau_s}/\eta_{\rm F}[(J_{{\rm L}s} - J_{{\rm SP}s}) + g(J_{{\rm L}i} - J_{{\rm SP}i})] \quad (3)$$

which can be rewritten as:

$$T_{\rm CAL} = (J_{{\rm M}s} - J_{{\rm BG}s}) + g e^{\tau_s - \tau_i}(J_{{\rm M}i} - J_{{\rm BG}i}) \quad (4)$$
$$+ \frac{e^{\tau_s}}{\eta_{\rm F}}[(J_{{\rm L}s} + gJ_{{\rm L}i}) - \eta_{\rm F}(J_{{\rm M}s} + gJ_{{\rm M}i}) - (1-\eta_{\rm F})(J_{{\rm SP}s} + gJ_{{\rm SP}i})] \quad (5)$$

and

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

## A.2 Dual Load

We have two loads 1 and 2 at different temperatures. We make a linear combination of 1 and 2 with weights $\alpha$ and $(1-\alpha)$, with the following definitions:

$$J_1 \equiv (J_{1s} + gJ_{1i}), \quad (7)$$
$$J_2 \equiv (J_{2s} + gJ_{2i}), \quad (8)$$
$$J_{{\rm L}s} = \alpha J_{1s} + (1-\alpha)J_{2s}, \quad (9)$$
$$J_{{\rm L}i} = \alpha J_{1i} + (1-\alpha)J_{2i} \quad (10)$$

We try to chose $\alpha$ so that $T_{\rm CAL}$ does not depend explicitly on $\tau$ by setting the term in [] in Equation 5 to 0 and substituting for $J_{{\rm L}s}$ and $J_{{\rm L}i}$:

$$\alpha J_1 + (1-\alpha)J_2 = \eta_{\rm F}(J_{{\rm M}s} + gJ_{{\rm M}i}) + (1-\eta_{\rm F})(J_{{\rm SP}s} + gJ_{{\rm SP}i}) \quad (11)$$

which is always possible. Then, our relation for $T_{\rm CAL}$ and $T_{\rm SYS}$ in a dual-load system becomes:

$$T_{\rm CAL} = (J_{{\rm M}s} - J_{{\rm BG}s}) + g e^{\tau_s - \tau_i}(J_{{\rm M}i} - J_{{\rm BG}i}) \quad (12)$$
$$T_{\rm SYS} = T_{\rm CAL}\frac{V_{\rm SKY}}{V_{\rm L} - V_{\rm SKY}} \quad (13)$$

with

$$V_{\rm L} = \alpha V_1 + (1-\alpha)V_2 \quad (14)$$

# B Next Generation Absolute Amplitude Calibration

The following is a description of the absolute amplitude calibration (conversion of $T_{\mathrm{R}}$ to S) scheme using interferometry proposed by Jim Gibson and Jack Welch (UCB RAL). Although not part of the baseline ALMA calibration plans, this system will be a high-priority development project for ALMA.

## B.1 The Single Antenna System

Figure 2 (top) shows the basic single antenna system with antenna effective area $A_i$, amplifier with system temperature $T_{sys_i}$ and gain $k_i$, including a-d converter and output autocorrelator. With an input antenna temperature, $T_{ant_i}$, the output is $O_i$.

$$O_i = k_i(T_{ant_i} + T_{sys_i}) \tag{15}$$

With two different known input antenna temperatures, $T_{i1}$ and $T_{i2}$, we get two outputs. $O_{1i}$ and $O_{2i}$. Their ratio, $Y_i = O_{2i}/O_{1i}$, gives the system temperature.

$$T_{sys_i} = \frac{Y_i T_{1i} - T_{2i}}{1 - Y_i} \tag{16}$$

The two measurements also give the amplifier gain factor,

$$k_i = \frac{O_{2i}}{T_{2i} + T_{sys_i}} \tag{17}$$

If antenna i is pointed toward a point source of flux S, the antenna temperature is $T_{ant_i} = (A_i/k_b)$ S, and the output is $O_i = k_i[T_{sys_i} + (A_i/k_b)S]$, Where $k_b$ is Boltzmann's constant, and $A_i$ is the antenna effective area.

## B.2 Interferometric Gain Calibration

In the array of antennas there is one small horn whose gain can be known to an accuracy of $\leq 1\%$. The goal is to transfer this gain to the other antennas, keeping that accuracy. All the system temperatures, $T_{sys_i}$, and amplifier gains, $k_i$, must be measured as described above, or in some equivalent manner. Here we assume that the amplifier passbands are identical and all the delays have been removed. It is further assumed that the interferometer correlator can provide both auto and cross correlations, so that the correlator gain factor is just the geometric mean of the individual autocorrelation gains. $k_{ij} = \sqrt{k_i * k_j}$ is known from the single antenna measurements above. Figure 2 (bottom) shows the block diagram for a pair of antennas in the array. The output when the pair is pointed at a point source of flux S is

$$O_{ij} = S\sqrt{A_i A_j} k_{ij} \tag{18}$$

To transfer the antenna gains we form the following rations.

$$\frac{O_{ki}O_{kj}}{O_{ij}} = \frac{\sqrt{A_k A_i} k_{ki} S \sqrt{A_k A_j} k_{kj} S}{\sqrt{A_i A_j} k_{ij} S} = A_k \frac{k_{ki} k_{kj}}{k_{ij}} S = A_k k_k S \tag{19}$$

The main point about getting the single antenna fluxes of the source is that we use the crosscorrelations between antennas to detect them, so that the result depends on the geometric means of the gains of the antennas in the pairs. The gain of the standard horn is typically 40 dB less than that of the other antennas in the array. If we were to measure the signal of the astronomical source directly with the horn antenna by itself, it would be too weak relative to the receiver noise to measure. In the crosscorrelation between the horn and one of the other array antennas, the signal is typically 20 dB greater, and it can be measured with good accuracy for strong sources such as the planets.

Let the standard gain horn be the k = 0 antenna. Then, for example, we can get a measurement of the point source flux from the following ratio.

$$\frac{O_{01}O_{02}}{O_{12}} = A_0 k_0 S \tag{20}$$

Since $A_0$ and $k_0$ are accurately known, we get an accurate flux for S from the above ratio. Now we can obtain the area of another antenna from another ratio of visibilities. For example,

$$\frac{O_{12}O_{13}}{O_{23}} = A_1 k_1 S \tag{21}$$

With S and $k_1$ known, we get area $A_1$ from this measurement. With the corresponding other ratios we get the gains of all the antennas. With care, we should get the areas of all the antennas with accuracies of the order of 1%. Another advantage of using the interferometer pairs for total flux measurements of the point source is that front-end drifts of single antennas are avoided.

Figure 1

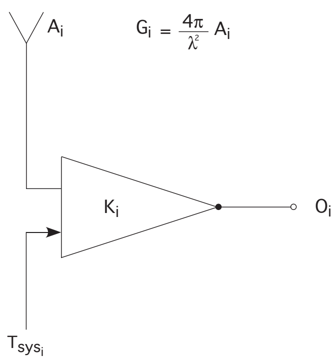


Figure 2

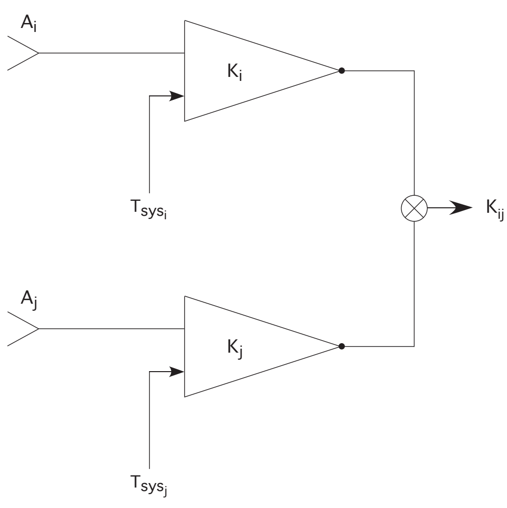


Figure 2: Top: basic single antenna system with antenna effective area $A_i$, amplifier with system temperature $T_{sys_i}$ and gain $k_i$, including a-d converter and output autocorrelator. Bottom: block diagram for a pair of antennas in the array. From Gibson & Welch.