The ALMA Sensitivity Calculator

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www.almascience.org

User Support:

For further information or to comment on this document, please contact your regional Helpdesk through the ALMA User Portal at **www.almascience.org** . Helpdesk tickets will be directed to the appropriate ALMA Regional Center at ESO, NAOJ or NRAO.

Revision History:

Version	Date	Editors
0.1	March 2011	Andy Biggs

Contributors

The ALMA Sensitivity Calculator is primarily the work of Hiroshi Yatagai (NAOJ), with contributions from Alan Bridger (UK ATC), Andy Biggs (ESO), Harvey Liszt (NRAO), Leonardo Testi (ESO) and Joe Schwarz (ESO).

Contributors’ Logos

In publications, please refer to this document as:
Author/Editor, Year, Complete Title, Version #, ALMA

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1 Introduction

The main tool for calculating the sensitivity of ALMA is the ALMA Sensitivity Calculator (ASC), formerly known as the Exposure Time Calculator. This is a Java application that is contained within the ALMA Observing Tool (OT) and which can be used as a pop-up tool with which the user can experiment with various sensitivity options, but which is also used by the OT to calculate how much time will be required to achieve the goals of the project. It is also available online as a Java applet located at the ALMA Science Portal[1].

This document aims to provide a full description of what the Sensitivity Calculator actually does.

2 User Interface

The main way that a user interacts with the Calculator is through a GUI in the OT or via a Java applet on a web page - both are essentially identical. By entering various parameters, the time required to achieve a particular sensitivity (in either Jy or K) can be calculated, or vice versa. The inputs that affect the sensitivity or time are given below.

- Source declination – this is used to calculate the maximum elevation of the observation and thus the minimum airmass i.e. the ASC assumes that the source is transiting.
- Observing frequency – this sets the receiver temperature, antenna efficiency and the atmospheric opacity.
- Bandwidth per polarization – this otherwise straightforward parameter should be set to 8 GHz for continuum observations and to the channel width for spectral line.
- Water vapour column density – i.e. precipitable water vapour (PWV). The user is able to enter one of seven octile values or the calculator will set this automatically depending on the frequency entered. It does this in the following way
  - $\nu < 163$ GHz – 6th octile (2.748 mm)
  - $163 \geq \nu < 275$ GHz – 5th octile (1.796 mm)
  - $275 \geq \nu < 500$ GHz – 4th octile (1.262 mm)
  - $\nu \geq 500$ GHz – 2nd octile (0.658 mm)
- Number of anntenas – the ASC currently defaults to the values for Early Science, namely 16 12-m antennas and none from the ALMA Compact or Total Power arrays.
- Angular resolution – this affects the time estimates when sensitivities are specified in temperature units. The calculator will not perform any calculations when Kelvins have been specified unless a non-zero value for angular resolution has been entered. The calculator will also issue a warning if the angular resolution falls outside of the range corresponding to 125-m and 16-km baselines.

The calculator reports the values of τ, $T_{\rm sky}$ and $T_{\rm sys}$ that correspond to the entered frequency and PWV. A screenshot of the ALMA OT interface to the Sensitivity Calculator is shown in Fig. 1.

3 Calculating $T_{\rm sys}$

The system temperature is built up from a number of elements that contribute noise as

$$T_{\rm sys} = \frac{1+g}{\eta_{\rm eff} e^{-\tau AM}} \left[T_{\rm rx} + \eta_{\rm eff} T_{\rm sky} + (1-\eta_{\rm eff}) T_{\rm amb}\right]. \tag{1}$$

The various terms are

[1] http://www.almascience.org/

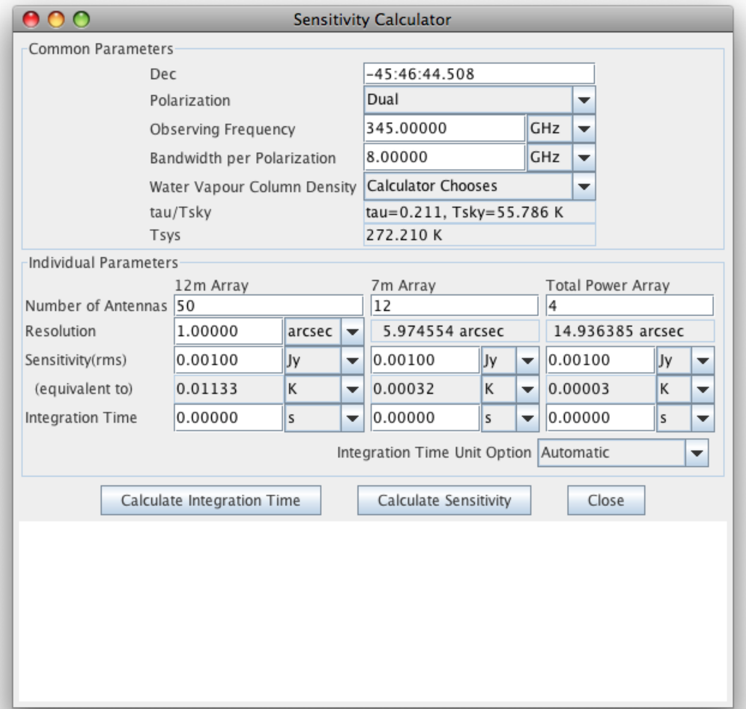

Figure 1: Screenshot of the ALMA Sensitivity Calculator as implemented in the ALMA Observing Tool. The white area at the bottom is for displaying error messages i.e. parameters out of bounds.

- $T_{\rm rx}$ – receiver temperature
- $T_{\rm sky}$ – sky temperature
- $T_{\rm amb}$ – ambient temperature (ground spillover)
- g – sideband gain ratio. For bands 1 and 2 (Single Sideband; SSB) and 3-8 (Sideband Separating; 2SB), $g = 0$. For these bands there is no contribution to the system temperature as the image sideband is either filtered out (SSB) or separated in the receiver (2SB). Bands 9 and 10 are Double Sideband (DSB) receivers and the correlated signal includes noise from both sidebands; therefore $g = 1$
- $\eta_{\rm eff}$ – the coupling factor, or forward efficiency. This is equal to the fraction of the antenna power pattern that is contained within the main beam and is currently fixed at 0.95
- $e^{-\tau AM}$ – the fractional transmission of the atmosphere, where τ is equal to the zenith atmospheric opacity and AM is the airmass at transit.

$T_{\rm sky}$ and $T_{\rm amb}$ are corrected for the fact that the required noise temperatures ($T^{\rm n}$) are defined assuming $P_\nu = kT$ and thus a correction for the Planck law is required. $T_{\rm sky}$ and $T_{\rm amb}$ are converted to their Planck equivalents as

$$T^{\rm n} = T \times \left(\frac{h\nu/kT}{e^{h\nu/kT} - 1} \right) \tag{2}$$

The receiver temperatures are already expressed in terms of the Planck expression and thus do not require this correction.

The terms $\eta_{\rm eff}$ and $e^{-\tau AM}$ both attentuate the source signal and we thus divide through by them in order to get a measure of the system noise that is relative to the unattenuated source.

$T_{\rm cmb}$ is not explicitly included in Equation 1 as it is already included in $T_{\rm sky}$.

Table 1: Receiver temperatures assumed in the ASC. For most of the bands we are currently assuming the ALMA specifications. In the case of bands 3, 6, 7 and 9, however, we are using “typical temperatures measured in the laboratory”; these are in many cases significantly better than the specifications. The octiles assumed for each band in the sensitivity equation are also shown.

ALMA Band	$T_{\rm rx}$ (K)	PWV Octile	Source
1	17	6	Specification
2	30	6	Specification
3	45	6	Laboratory
4	51	6	Specification
5	65	5	Specification
6	55	5	Laboratory
7	75	4	Laboratory
8	196	4	Specification
9	110	2	Laboratory
10	230	2	Specification

3.1 Receiver temperatures

For most of the ALMA bands, the calculator currently only uses the specifications for the receiver temperatures and not the actual measured values. However, for the Early Science bands (3, 6, 7 and 9), typical values measured in the laboratory are used as these are usually significantly better than the specifications. The values used in the ASC are given in Table 1. Note that single sideband noise temperatures are reported for bands 1-8 and double sideband temperatures for bands 9 and 10.

At the moment, no attempt is made to incorporate the frequency dependence of $T_{\rm rx}$ i.e. only a single value is used per band. The measured values are somewhat conservative and so are in between what we might expect at the centre and edges of the bands. Similarly, we only use one value for the specification, the one that applies “over 80% of the RF band”. Ultimately, it is the intention to use the actual measured values for all receivers and to incorporate the frequency response across the band.

Note that the calculator doesn’t concern itself with the so-called “zero-point fluctuations” as the requisite half photon of noise ($h\nu/2k$) is believed to have already been included in the noise measurements provided by the various receiver groups (A. Kerr, private communication).

3.2 Sky temperature

The emission from the atmosphere is often approximated as

$$T_{\rm sky} = T_{\rm atm}(1 - e^{-\tau AM}) \qquad (3)$$

where $T_{\rm atm}$ is the mean physical temperature of the atmosphere. However, a true estimate of the atmospheric emission is given by integrating the temperature profile using the Atmospheric Transmission at Microwaves (ATM) code (Pardo et al., 2001). This provides values of the opacity corresponding to the measured octiles of precipitable water vapour, in 100-MHz steps. The specific output used by the Calculator is an “equivalent black body temperature” ($T_{{\rm EBB},\nu}$) calculated by inverting the output radiance using the Planck function.

3.3 Ambient temperature

This is essentially spillover from the sidelobes of the antenna beam corresponding to emission from the ground and the telescope itself. This is held constant at 270 K.

4 The sensitivity calculation

Once $T_{\rm sys}$ has been determined it is possible to calculate the point-source sensitivity given a requested amount of observing time or vice versa.

4.1 12-m and 7-m arrays

When dealing with the interferometric arrays within ALMA, the equation used is

$$\sigma_{\rm S} = \frac{\rho\, T_{\rm sys}}{\eta_{\rm c}\sqrt{N(N-1)\, n_{\rm p}\, \Delta\nu\, t_{\rm int}}} \tag{4}$$

which has essentially been reproduced from the document "An Introduction to the IRAM Plateau de Bure Interferometer"[2]. The various symbols are

- ρ – antenna efficiency. This is equal to $2k/\eta_{\rm a}A$ where $\eta_{\rm a}$ is the aperture efficiency and A the area of the antenna. The aperture efficiency is in turn implemented, using the Ruze formula, as $0.8 \exp\left(-16\,\pi^2\sigma^2/\lambda^2\right)$ where σ is the rms surface accuracy of the antenna (the specification of 25 μm is currently used here)
- $\eta_{\rm c}$ – correlator efficiency. This is currently fixed at 0.88
- N – number of antennas
- $n_{\rm p}$ – number of polarizations. $n_{\rm p} = 1$ for single polarization and $n_{\rm p} = 2$ for dual and full polarization observations
- $\Delta\nu$ – resolution element width. $n_{\rm p}\,\Delta\nu$ is often referred to as the effective bandwidth. Note that for continuum observations, this should be equal to 7.5 GHz (= 4×1.875 GHz); the maximum usable bandwidth of a spectral window is limited to 1.875 GHz by the anti-aliasing filter through which the baseband signal passes
- $t_{\rm int}$ – integration time.

The associated surface brightness sensitivity is related to the point-source sensitivity by

$$\sigma_{\rm T} = \frac{\sigma_{\rm S}\lambda^2}{2k\ \Omega} \tag{5}$$

where Ω is the beam solid angle. This is related to the user-inputted spatial resolution, θ, by

$$\Omega = \frac{\pi\theta^2}{4\ln 2}. \tag{6}$$

4.2 Total power array

In the case of the single dishes, a different equation is used

$$\sigma_{\rm TP} = \frac{\rho\, T_{\rm sys}}{\sqrt{n_{\rm p}\, \Delta\nu\, t_{\rm int}}} \tag{7}$$

although the variables have the same meaning as in Equation 4.

The calculator currently multiplies the above by an additional $\sqrt{2}$ which is correct for switching observations (nutator), but not when On The Fly is being used when the factor will be much closer to unity. An additional factor of $\sqrt{1/N}$ takes into account the number of total power antennas.

[2] http://iram.fr/IRAMFR/GILDAS/doc/pdf/pdbi-intro.pdf

5 References

Pardo J., Cernicharo J., Serabyn E., 2001, ITAP., 49, 1683

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere (ESO), in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan. ALMA construction and operations are led on behalf of Europe by ESO, on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI) and on behalf of East Asia by the National Astronomical Observatory of Japan (NAOJ). The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA.