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For the upgraded ALMA Observatory

- TECHNOLOGY DEVELOPMENT -

iALMA optical efficiency requirements

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1 Change Record

Version	Date	Affected sections	Reason
1	3/2/2016	All	

2 Applicable and reference Documents

3 Acronyms

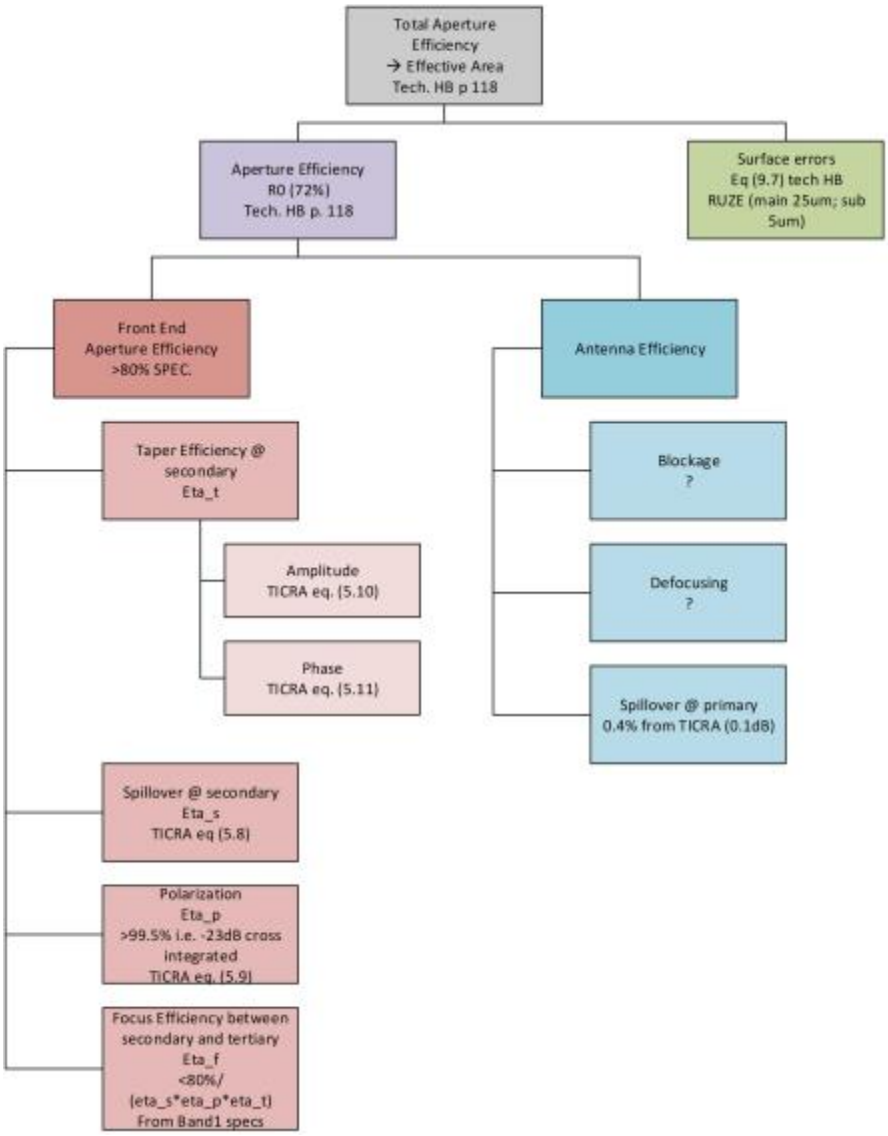
4 Table of content

5 Introduction and Scope

Scope of this document is to revise ALMA 2-3 band system optical efficiencies and requirements, highlight the cartridge dependent contribution and calculate the efficiency for the proposed configurations.

6 ALMA optical efficiency

The efficiency of ALMA as a system can be decomposed as the product of the efficiencies due to the different sources of degradation in the transmission of the signal. In fig a schematic view of the ALMA efficiencies.



This way the Total Aperture Efficiency η_{TOT} could be written:

$\eta_{TOT} = \eta_{ap}\ \eta_s$,

where η_{ap} represent the Aperture Efficiency and η_s is a term due to the surface accuracy of the primary mirror defined by the Ruze formula:

$$\eta_s = e^{\left(\frac{4\pi\sigma}{\lambda}\right)^2}$$

with σ representing the rms surface accuracy of the antenna; currently the specification of 25μm and 20μm for the 12m and 7m antennas are respectively used. The term η_{ap} is again the combination of the efficiencies due to two subsystem: η^{FE} the efficiency of the frontend subsystem and η^{M} the efficiency of the primary and secondary mirrors subsystem

$\eta_{ap} = \eta^{FE}\ \eta^{M}$.

In the following subsections we will describe η^{FE} (sec. 6.1) and η^{M} (sec 6.2)

6.1 Front End Aperture subsystem efficiency

The FE in several ways could degrade the transmission of the signal. η^{FE} is composed by the Taper Efficiency that is the degradation in the amplitude and phase of the signal, the spillover efficiency that represent the fraction of the signal that is present in the secondary mirror that is not picked up by the front-end, the polarization efficiency or rather the fraction of polarization loss and finally the focus efficiency between secondary and fore-optics.

$$\eta^{FE} = \eta^{FE}_{taper}\eta^{FE}_{spillover}\eta^{FE}_{pol}\eta^{FE}_{focus}$$

Where

$$\eta^{FE}_{taper} = \eta^{FE}_{amp}\eta^{FE}_{phase}$$

As well any sub-optimality in the optics (design and/or manufacturing) degrade the transmission of the signal.

6.2 Primary and secondary mirror subsystem efficiency

In this case the efficiency is cartridge design independent and it could be written:

$$\eta^{M} = \eta^{M}_{block}\eta^{M}_{spillover}\eta^{M}_{defocus}$$

Where:

- η^{M}_{block} is called *blockage* and represents the transmission loss due to the primary mirror obscuration caused by the secondary mirror and buffers;

- $\eta^{M}_{spillover}$ represents the fraction of the signal that is present in the primary mirror that is not picked up by the secondary mirror;
- $\eta^{M}_{defocus}$ is called *defocusing* and represents the misalignment between the primary and the secondary mirror that causes indeed a suboptimal position of the focus.

7 Efficiency requirements

Summing up all those terms we have:

$$\eta_{TOT} = \eta^{FE}_{amp}\eta^{FE}_{phase}\eta^{FE}_{spillover}\eta^{FE}_{pol}\eta^{FE}_{focus} \cdot \eta^{M} \cdot e^{\left(\frac{4\pi\sigma}{\lambda}\right)^2}$$

The η^{M}term is cartridge design independent and it is estimated to be $\eta^{M} = 0.9$; the overall requirement on the aperture efficiency $\eta_{ap} = \eta^{FE}\eta^{M}$, depends on the operating frequency and for the band 3 $\eta_{ap} = \eta^{FE}\eta^{M} = 0.71$ as stated in ALMA Cycle-2 Technical Handbook. Conservatively if with the 2-3 band we want to meet the band 3 requirement we should require that η^{FE} (cartridge dependent), should be η^{FE}≥0.8.

8 Sensitivity calculation

When dealing with the 12μm and 7μm Arrays, the point source sensitivity, σ_S is given by the standard equation:

$$\sigma_S = \frac{2kT_{Sys}}{\eta_q\eta_C A_{geo}\eta_{TOT}\sqrt{N(N-1)n_p\Delta\nu t_{int}}}$$

where:

- T_{sys} - system temperature. The system Temperature is built up from a number of elements that contributes to the noise as the receiver temperature, the sky temperature and the ambient temperature. The calculation of the system temperature along with the related parameters is described in sec: 9;
- η_q - quantization efficiency. A fundamental limit on the achievable sensitivity is set by the initial 3-bit digitation of the baseband signals. This is a fixed parameter equal to 0.96;

- η_C - correlator efficiency. This depends on the correlator itself and the correlator mode. For the aim of this document the correlator efficiency is set to 0.88;
- A_{geo} - this term is the physical area of the dish i.e. 113.1m^2 and 38.5m^2 for the 12 and 7 m antennas respectively;
- η_{TOT} - the optical coupling efficiency between the front-end and the secondary mirror. The physical meaning of this term and its calculation is already described in sec **Error! Reference source not found.**
- N - number of antennas. This defaults 34 for the 12-m and 9 for the 7-m Array;
- n_p -number of polarization. n_p = 1 for single polarization and n_p = 2 for dual or full polarization observation. Our default is np = 2;
- $\Delta\nu$- resolution element width. This should be equal to the full band (7.5 GHz) for continuum observation. (TBD)
- t_{int} - integration time

The associated surface brightness sensitivity (K) is related to the point-source sensitivity (Jy) by:

$$\sigma_T = \frac{\sigma_S \lambda^2}{2k\Omega}$$

Where Ω is the beam solid angle

9 T_{sys} calculation

The system temperature (T_{sys}) is built up from a number of elements that contribute noise as:

$$T_{sys} = \frac{(1+g)}{\eta_{eff} e^{-\tau_0 \sec(z)}} (T_{rx} + \eta_{eff} T_{sky} + (1-\eta_{eff}) T_{amb})$$

Where:

- T_{rx} -receiver temperature
- T_{sky}-sky temperature
- T_{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 this bands there is no contribution to the system temperature as the image sideband is either filtered out (SSB) or separated in the receiver (2SB).
- η_{eff}-the coupling factor or forward efficiency is $\eta_{eff} = \eta^M e^{(4\pi\sigma/\lambda)^2}$ this is equal to the fraction of the antenna power pattern that is

contained within the main beam. This term that is cartridge independent is 0.95.I guess this is equivalent to $\eta^{M}_{spillover}$ in the notation of this note Not crystal clear given the available documentation.

$e^{-\tau_0 \sec(z)}$-the fractional transmission of the atmosphere, where τ_0 is equal to the zenith atmospheric opacity and *sec(z)* is the air-mass at the transit. The angular distance between the zenith and the transit provide the minimum air-mass; this variable depends by the site position and the declination of the observed source.

T_{sky} and T_{amb} are corrected for the fact that required noise temperature (T_n) is defined assuming P_ν = kT and thus a correction for the Planck law is required, i.e.

$$T_n = T\left(\frac{h\nu/kT}{e^{h\nu/kT}-1}\right)$$

The receiver temperatures are already expressed in terms of the Planck expression and thus do not require this correction. The terms η_{eff} and $e^{-\tau_0 \sec(z)}$ both attenuate the source signal and we thus divide through by them to obtain a measure of the system noise that is relative to the unattenuated source.

The temperature of the Cosmic Microwave Background is not explicitly included in Equation 10 as it is included in T_{sky}.

10 Directivity and aperture efficiency

The directivity of a reflector antenna is the ratio between the Power emitted/received in a given direction (θ,φ) and the Total power:

$$D(\theta,\varphi) = \frac{P(\theta,\varphi)}{\int P(\theta,\varphi)d\Omega/4\pi}$$

The definition of the ideal directivity is:

$$D_{ideal} = \frac{4\pi A}{\lambda^2}$$

Where A is the physical aperture.

In general the aperture efficiency of a reflector antenna (η)is linked to the ideal directivity this way:

$$D = \eta D_{ideal}$$

so η is a factor of degradation respect to the ideal case. First of all we have to define the system for which we want to calculate the efficiency. In our case we are interested to the optical coupling between the front end and the secondary mirror: $\eta_{fe|s}$

The general case takes care also of other possible sources of coupling. In this case is defined a gain G:

$$G = D\eta_{\Omega} = D_{ideal}\eta_{\Omega}\eta_{optic}$$

where η_{Ω} is the Ohmic efficiency and represents any loss due to conductivity.

11 Optical efficiency calculation

The efficiency of the equivalent paraboloid illuminated by a particular front-end is calculated as the ratio of certain integrals over the aperture. Since the subtended angle of the aperture seen from the feed is small, we shall replace the aperture integrals with integrals over the solid angle, defined through

$$\Omega = \int_{\Omega} d\omega = \int_0^{2\pi}\int_0^{\vartheta_m} sin\vartheta d\vartheta d\varphi = 2\pi(1 - cos\vartheta_m)$$

With ϑ_m =3.58°.Thus the aperture A, and the equivalent focal length, f0, are connected through the approximate formula: $A = f_0^2\Omega$. The effects of the efficiencies of transmission losses in filters and windows cannot be included exactly, but estimates can be calculated .

We shall calculate the following four integrals:

- I1: integral of total power over Ω
- I2: integral of co-polar power over Ω
- I3: integral of co-polar amplitude over Ω
- I4: absolute value of integral of co-polar field (complex) over Ω

where it is assumed that all fields are normalized such that the total power emitted by the feed is 4 π.

$$I_1 = \int_{\Omega} |E_{TOT}|^2 d\omega$$

$$I_2 = \int_{\Omega} |E_{co}|^2 d\omega$$

$$I_3 = \int_{\Omega} |E_{co}| \; d\omega$$

$$I_4 = \left|\int_{\Omega} E_{co} \; d\omega\right|$$

The four efficiencies introduced here are defined through:

$$\eta_{spillover} = \frac{I_1}{4\pi}$$

$$\eta_{polarization} = \frac{I_2}{I_1}$$

$$\eta_{amplitude} = \frac{I_3^2}{\Omega I_2}$$

$$\eta_{phase} = \frac{I_4^2}{I_3^2}$$

12 ALMA case

In this section we will describe the sensitivity calculation for

a rappresentative "ALMA case".

12.1 T_{sys} parameters

- center frequency=67GHz
- sideband gain ratio g=0; g 6= 0 only for band 9 and 10
- zenith atmospheric opacity τ_0 = 0.137 this correspond to the 7th PWV Octile (Precipitable Water Vapor) and the relative column density 5.186mm;
- the receiver temperature T_{rx} is the one assumed in the ASC (Alma Sensitivity Calculator) as a function of the ALMA band. In this case band 2 T_{rx} = 30K
- T_{sky} (sky temperature): we used the OT's estimate of T_{sky} that estimates both the atmospheric opacity and the sky temperature using the Atmospheric Transmission at Microwaves (ATM) code. Then a correction is applied following eq. The value of T_{sky} used (before the correction) is 32.337K
- T_{amb} 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 270K (median value as measured from many years of monitoring data at ALMA site). The value used in the calculation is corrected again following eq.
- η_{eff} This parameter is set for other bands to 0.95 and is cartridge design independent.

13 Scientific case

TBD