# DSB versus SSB

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**Abstract**

The ALMA performances will depend on the receiver design and performances. Conflicting requirements on cost, reproducibility, maintainability, bandwidth and noise temperature affect the receiver design, and the capabilities of ALMA. This memo reviews the possible tradeoff between receiver complexity and ALMA performances. Realistic scientific applications are considered.

This memo reproduces the numerical results obtained in memo 304 using a different approach. However, the conclusion differ because I also account for a scheduling strategy in which high frequency observations are made only when the weather allows. Combined with a reasonable assumption on the distribution of continuum (or dual-line) observations vs single spectral line cases, this assumption favors DSB mixers at high frequencies. DSB receivers may provide a $\simeq 10\%$ advantage above 500 GHz, while SSB receivers would provide a $\simeq 10\%$ advantage below that frequency.

## 1 Introduction

In view of the large numbers of items to be produced for ALMA, simplifying the design and minimizing the cost to performance ratio is a very important process. This especially applies to receivers, which have a critical impact on the final performance, and highly varying degree of complexity depending on the chosen design. For example, per polarisation, a frequency channel may require 1 (single-ended, DSB mixer) to 4 mixers (balanced, side band separating mixers, hereafter SBS mixers), with 1 (DSB mixer) or 2 IF amplifiers (SBS mixers). In this memo, we evaluate the impact in terms of performance of the various choices.

## 2 Numerical Values

When comparing SSB to DSB operations, it is important to know the input parameters in terms of expected **receiver** performance. Unfortunately, the ALMA project still has a few inconsistencies at this level, some of which may be attributed to confusion between **mixer** and **receiver** performances.

The Receiver Specification version 1.0 indicate the numbers quoted in Table 1

These numbers are intended to be **receiver** temperatures, as measured at the vacuum window of the dewar. Note that the formula used to derive the expected SSB noise

| Band | Frequency | T(DSB) | | T(SSB) | |
|---|---|---|---|---|---|
| 2 | 86-116 | 3 h$\nu$/k | 15 K | 6 h$\nu$/k+4 | 34 K |
| 3 | 125-163 | 3 h$\nu$/k | 20 K | 6 h$\nu$/k+4 | 44 K |
| 4 | 163-211 | 3 h$\nu$/k | 27 K | 6 h$\nu$/k+4 | 58 K |
| 5 | 211-275 | 3 h$\nu$/k | 34 K | 6 h$\nu$/k+4 | 73 K |
| 6 | 275-370 | 4 h$\nu$/k | 61 K | 8 h$\nu$/k+4 | 126 K |
| 7 | 385-500 | 4 h$\nu$/k | 84 K | 8 h$\nu$/k+4 | 172 K |
| 8 | 602-720 | 5 h$\nu$/k | 155 K | 10 h$\nu$/k+4 | 315 K |
| 9 | 787-950 | 5 h$\nu$/k | 205 K | 10 h$\nu$/k+4 | 415 K |

Table 1: ALMA specifications for receiver noise temperature.

temperature from the DSB noise temperature of a single receiver actually assumes the temperatures are **mixer** temperatures. Since, in practice, other components (e.g. the horn/lens at the mixer input) contribute to the DSB noise, the assumed formula to derive SSB noise temperatures is pessimistic.

Another approach to estimate the ALMA receiver performance is to use the achieved performances on current instruments. From Figure 5.8 of the ALMA project book, one may see that, while the 3-4 $h\nu/k$ noise level has been reached for receivers above 200 GHz, below this frequency the best noise temperatures are of order 20 K DSB, nearly independent of the frequency. This value is confirmed with current receivers operating e.g. at the IRAM Plateau de Bure interferometer, which have 25 to 35 K DSB noise temperatures at 3 mm and 1.3 mm. It suggests the noise contribution from other elements than the mixer become dominant at these lower frequencies. A detailed noise breakdown would be worthwhile for further understanding.

Given these uncertainties, two input models have been computed to compare the DSB vs SSB ALMA operations. The models only differ below 200 GHz. The "standard" one follows Table 1, the other assumes T(DSB) = max(20,T(standard)) and T(SSB) = 2 T(DSB).

Figure 1 represents the expected single sideband system temperature obtained with the two models, for DSB and SSB receivers. They were computed using the following assumptions

- High frequency observations are assumed to be performed under the best observing conditions. As a result, low frequency observations are only carried out with higher water vapor content. Below 300 GHz, the precipitable water vapor content was assumed to be 2.3 mm, corresponding to the 75 % percentiles at Chajnantor. Between 300 and 500 GHz, I assumed 1.2 mm of water vapor, corresponding to the 50 % percentile. Above 500 GHz, I assumed 0.5 mm, corresponding to the 25 % percentile.
- The forward efficiency is assumed to drop from 0.95 at low frequencies down to 0.90 at 900 GHz, with a parabolic dependency on frequency
- The standard ATM model from Cernicharo (1985) was used.
- A 10 dB sideband rejection is assumed for SSB tuning, consistent with the ALMA specification.

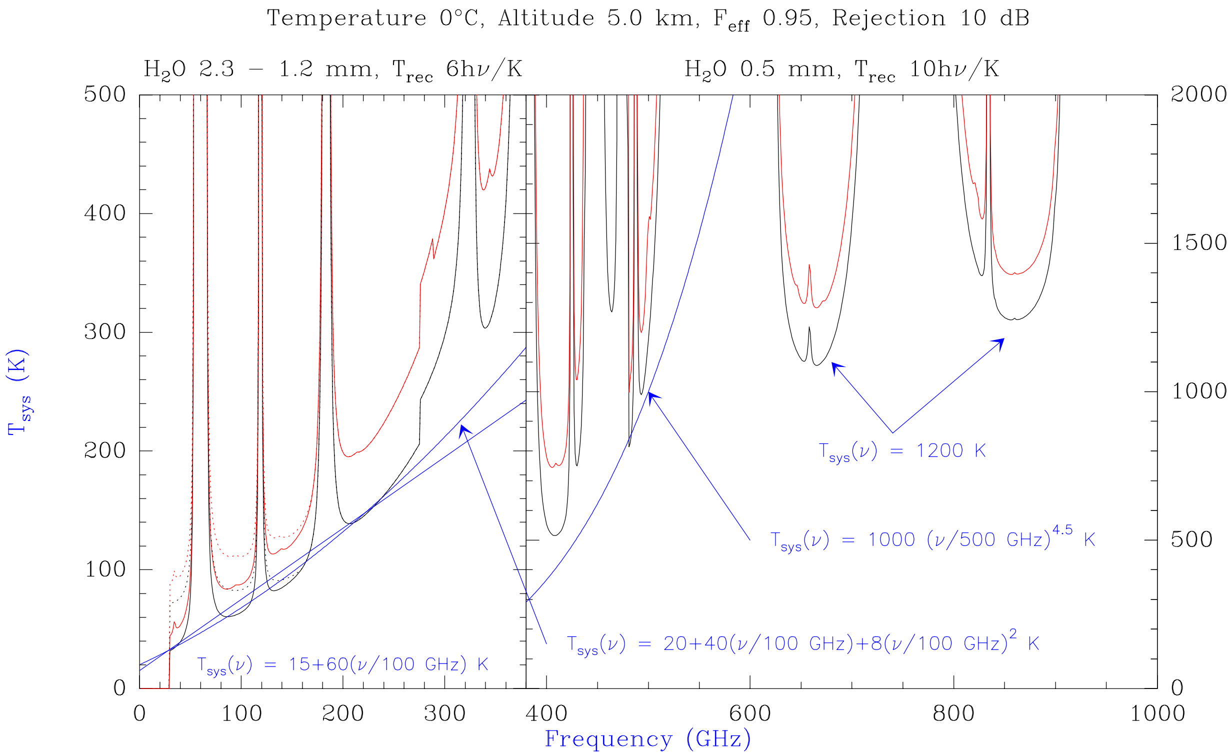


Figure 1: Expected SSB system temperature for ALMA. The black curves are for SSB tuned receivers, and the dashed curves are for DSB tuned receivers. The dotted curve assume Trec(DSB)=20 K below about 200 GHz as measured for the best receivers today, rather than the more optimistic $3h\nu/k$ value.

- Whenever possible, contributions from opposite sideband are taken into account by using the most favorable tuning (i.e. chosing the LO frequency such that the image bands as the minimum sky opacity). At band edges, the tuning choice which minimizes the required LO tuning range is selected, even if it results in higher noise.
- The Signal and Image frequencies are assumed to be separated by 12 GHz, as appropriate for a 4-8 GHz IF output. The modifications if we use a 16 GHz separation, as appropriate for a 4-12 GHz IF output, are relatively minor. Moreover, in practice, the exact frequency setup (including the spectral lines to be observed) is required to derive the noise temperature at a given frequency.

The various assumptions have visible effects on the computed system temperatures. For example, the discontinuity at 275 GHz is due to a combination of higher assumed Trec in band 7 together with less favorable tuning condition than in band 6. Near 287 GHz, the slight discontinuity for the DSB case appears because the tuning possibilities allows to select a better sideband combination.

The “pessimistic” model is shown in dotted curves, while the plain curves reflect the expected system temperatures with the ALMA specifications. Note that the “pessimistic” DSB model give system temperatures twice larger than the ALMA specifications for SSB receivers...

# 3 Discussion

In Figure 2, the ratio $\beta$ of SSB system temperatures from DSB and SSB receivers are plotted as a function of frequency. The two curves correspond to the ALMA specifications and the worst case assumptions. When the ratio $\beta$ is higher than 1, single spectral lines observations are better performed with SSB receivers. However, because a DSB system can recover twice the bandwidth of a SSB system, continuum observations are better performed with DSB receiver when the ratio $\beta$ is lower than $\sqrt{2}$.

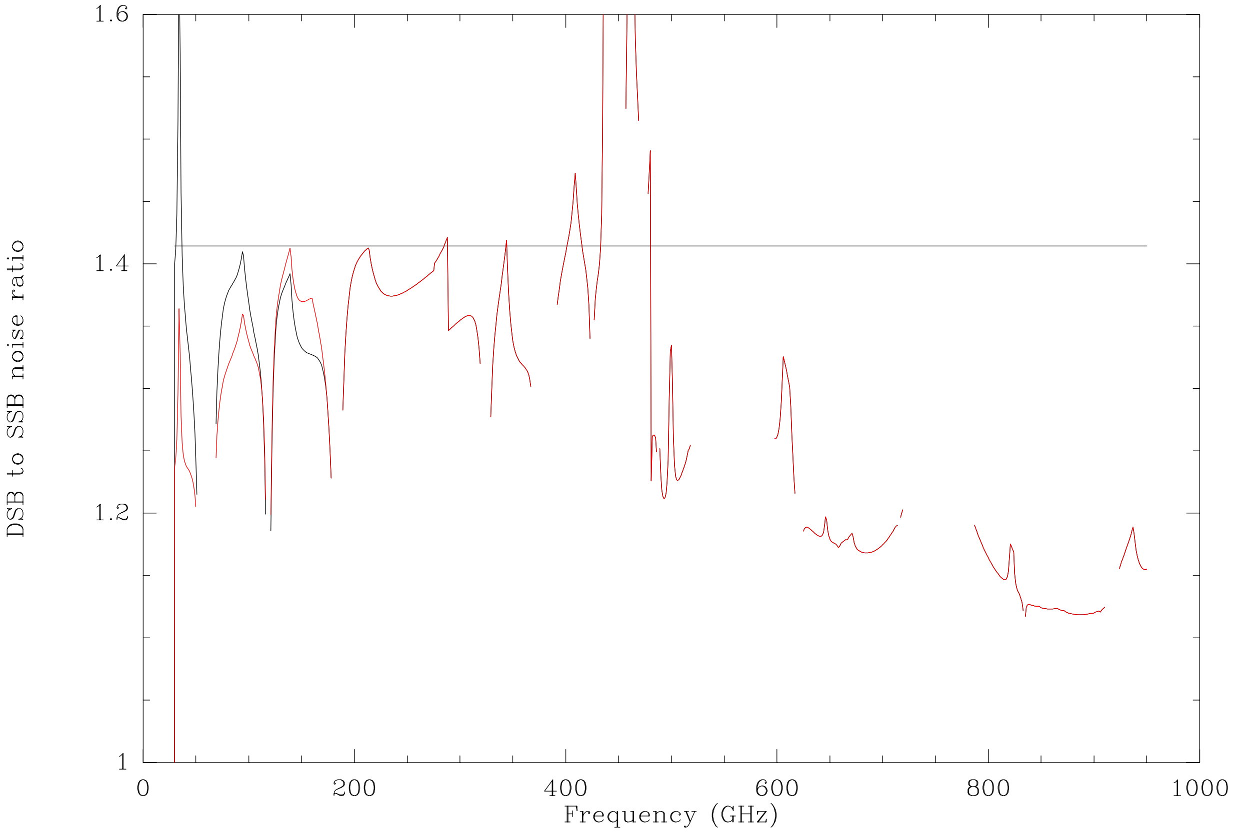


Figure 2: Ratio $\beta$ of SSB system temperatures referred to outside the atmosphere for DSB receivers over that of SSB receivers

As already pointed out, at very high frequencies, the gain offered by SSB receivers is only 10-20 % for spectral lines, but the DSB receivers are more effective for continuum observations. At mm wavelength, SSB receivers are almost 35 to 40 % more sensitive than DSB receivers for spectral lines observations, making them also almost as sensitive than DSB receivers for continuum observations. The assumptions made upon the specific performances of the receivers as function of frequency have only a small impact in this comparison (but a large one on the effective system temperature).

When comparing the relative merit of the two options, it is thus essential to evaluate which fraction of the time is devoted to spectral line observations. As an first order estimate, let us use the following numbers:

1. Pointing, Focus, Phase and Flux calibration: 15 % of time

2. Continuum measurements or complete frequency surveys: 30 % of time (high redshift objects, line searches)

3. Multi-transition studies with lines separated by 8 to 24 GHz (i.e. requiring opposite sidebands of the receivers): 20 % of time (e.g. proto-planetary disks, circumstellar envelopes)

4. Single spectral line: $X_{\rm SSB} = 35$ % of time (High resolution images of galaxies, or other objects for which one spectral line dominates the time estimate)

Some details are given below. Items 1-3 are all equivalent to continuum observations. Only item 4 is a pure spectral line observation, for which the SSB system temperature is the appropriate number.

In Figure 2, the mean DSB/SSB sensitivity ratio $\beta$ is about 1.35 for frequencies lower than 400 GHz, and $\beta \simeq 1.15$ for frequencies above 600 GHz (which represent about 25 % of the available observing time).

We may compare the effectiveness of the two receiver design by deriving the mean sensitivity ratio separately for these two bands.

$$R(< 400) = \frac{1.35}{\sqrt{2}} \times (1 - X_{\rm SSB}) + 1.35 \times X_{\rm SSB} = 1.08 \qquad (1)$$

i.e. the DSB tuning is less efficient by about 8 % than the SSB tuning if the project statistics follows the assumption. It is essential to realize that the factor $1/\sqrt{2}$ used in Eq.1 is only valid **if the correlator is able to process simultaneously the two opposite sidebands for a DSB receivers**. This implies a phase switching demodulation technique, with a minimum integration time of order 1sec for a complete cycle. A frequency offset technique to reject one unwanted sideband would not allow this gain. Eq.1 is of course only an approximation, since with different efficiencies for single lines than for continuum, the time spent on each type of project will differ with both types of receivers. However, the effect remains small. Note that if the fraction of pure SSB projects drops to 15 %, the two tuning approaches are equally efficient.

At the higher frequencies, the sensitivity ratio is

$$R(> 400) = \frac{1.15}{\sqrt{2}} \times (1 - X_{\rm SSB}) + 1.15 \times X_{\rm SSB} = 0.92 \qquad (2)$$

i.e. DSB receivers are more efficient by about 8 %, again under the assumption that the two sidebands are processed.

In the above assumptions, we use the fact that with a DSB tuning, one may observe simultaneously spectral lines which fall in opposite sidebands and have nearly equal intensities (or rather must be observed with similar noise level). We attribute about 20 % of the observing time to such projects. One may of course doubt that so many projects will make use of such coincidence. However, a very simple inspection of a spectral line catalog shows this may not be unrealistic. Example of possibilities are

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348GHz/LSB:   336 - 344 GHz
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             C17O(3-2), C34S(7-6), CH3OH band, CS(7-6)
348GHz/USB:  352 - 360 GHz
             HCO+(4-3), SO2 band

104GHz/LSB:   92 - 100 GHz
             N2H+(1-0), C34S(2-1), CS(2-1)
104GHz/USB:   108 - 116 GHz
             C18O(1-0), 13CO(1-0), C17O(1-0), 12CO(1-0)

235GHz/LSB:   223 - 231 GHz
             C17O(2-1), H2CO, 12CO(2-1)
235GHz/USB:   239 - 247 GHz
             C34S(5-4), CS(5-4)
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Near 100 GHz, a lower frequency tuning would allow to include C18O/13CO and HCO+, HCN for example. Although some lines are much stronger than others, the weak ones require similar sensitivity levels. Similar cases can be found at other frequencies. Specific examples can also be found for carbon stars (e.g. combinations of C2H, C3H2, C4H, HC3N, C3N).

# 4 Comparison with previous work

There are a number of presentations on the SSB vs DSB case in the ALMA memo series, which may lead to confusion in the comparison. In particular, earlier memo 170 by Jewell & Mangum concluded that SSB mixers are preferable. In memo 301, J.Lamb showed that under more realistic assumptions (i.e. unless the receiver noise is already quite low), the comparison may actually favor DSB operation. In memo 304, Thompson & D'Addario introduced the factor $\alpha$ as the ratio of "broadband (i.e. DSB) system temperatures", and showed that with this definition, the sensitivity ratio of DSB vs SSB systems is different for an interferometer than for a total power system.

I use here a different ratio $\beta$, the ratio of "narrow band (i.e. SSB) system temperatures", which is easier to derive even in the case of imperfect sideband separation. With this approach, it is straightforward to derive the sensitivity for continuum observations as the summation over the whole continuum bandwidth, since the signal from any frequency is uncorrelated with that from any other frequency. For a DSB system, if the correlator allows sideband separation, this bandwidth is twice that available in a SSB system. We thus easily derive that since the ratio of sensitivities DSB/SSB is $\beta$ for spectral lines (by definition), it is $\beta/sqrt2$ for continuum. Noting that $\beta = 2\alpha$ given their respective definition, this agrees with memo 304. Sideband separation mixers could obviously provide a clear advantage if the IF and correlator system allows to process the full bandwidths from the two sidebands.

This note differs slightly from memo 304 in its conclusion, by giving an advantage to DSB receivers at the highest frequencies. This is a combination of two effects: slightly higher assumed receiver noise ($5h\nu/k$ vs $4h\nu/k$) but mostly lower atmospheric opacity, since I assumed high frequency work will only be done under the 25 % best conditions.

This assumption is equivalent to consider only the lowest values given in Table 4 of memo 304 for frequencies 650 and 950 GHz, but the highest for 225 GHz.

## 4.1 Other considerations

DSB receivers can be competitive with SSB receivers, but only if the correlator allow the sideband separation and simultaneous treatment. If the correlator only allows sideband rejection, SSB receivers offer a net gain of 10-15 % (at high frequencies) up to 35-40 % (at low frequencies).

A 10 % effect or so is always difficult to argue about on purely scientific grounds. However, converted to project cost, this can be debated as a 75 M$ question. Cost savings due to the reduction in the number of SIS junctions, mixers, IF amplifiers, IF outputs will not amount to such a total, but may be up to 25 M$. This could be better quantified by the Receiver & System IPTs.

Long term considerations in the maintainability of the more complex SSB mixers compared to simpler DSB receivers are more difficult to assess. The reliability aspects may become a major issue. Based on the IRAM experience, the weakest point in current receivers is the cold IF amplifier, followed by multipliers for the LO generation, suggesting that there is a cost benefit in reducing the number of IF channels.

It is important to stress that to benefit from the line coincidences in the DSB mode, a sufficient number of channels must be available in the correlator. The baseline design is only marginally adequate in this respect.