ALMA Memo 393
DSB versus SSB and Bandwith/Sensitivity tradeoff

S.Guilloteau, IRAM/ESO

May 13, 2002

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, considering DSB vs SSB and Bandwidth vs Receiver noise tradeoffs. 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.

Analysis of the Bandwidth/Receiver noise trade-off indicate that reduction of a factor 2 in detection bandwidth can be compensated by improvement by $25 - 30$ % in Receiver noise.

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 2SB mixers), with 1 (DSB mixer) or 2 IF amplifiers (2SB mixers). In this memo, I evaluate the impact in terms of performance of the various choices.

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

Table 1: ALMA specifications for receiver noise temperature.

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 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.

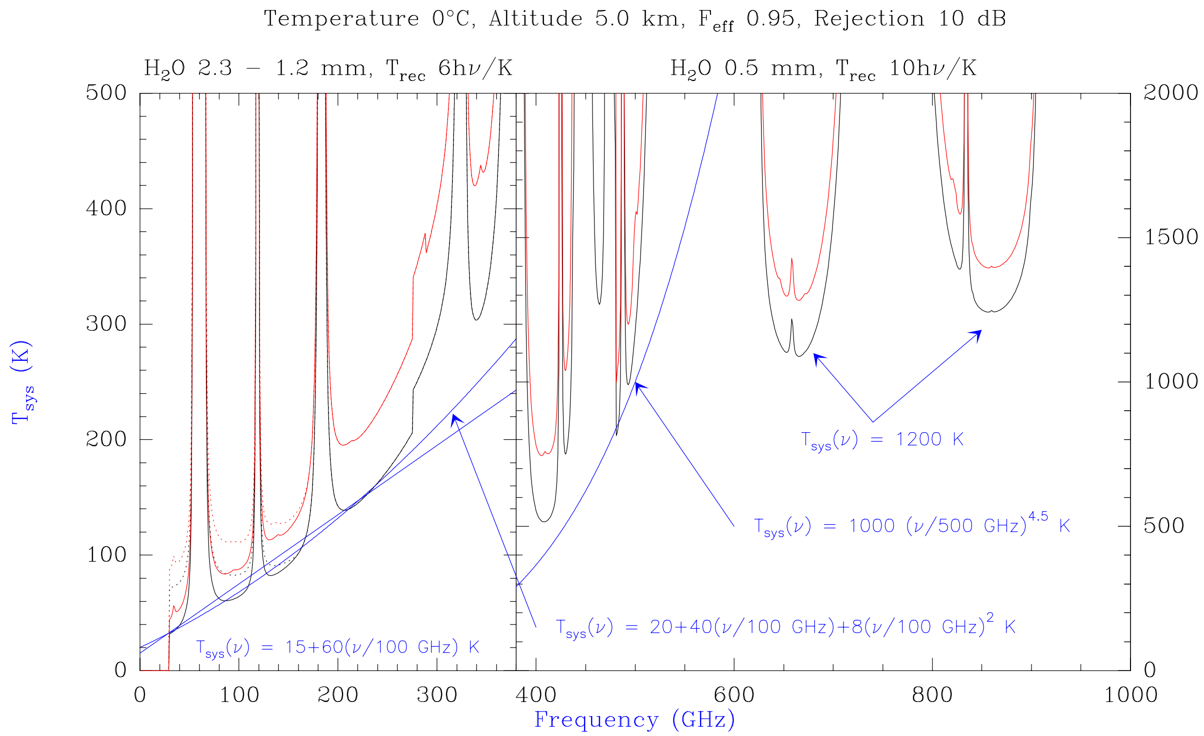

Figure 1: Expected SSB system temperature for ALMA. The black curves are for SSB tuned receivers, and the dashed curves are for DSB tuned receivers. The dotted curve assume Trec(DSB)=20 K below about 200 GHz as measured for the best receivers today, rather than the more optimistic $3h\nu/k$ value.

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.
- 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 Type of Observations

When comparing the relative merit of several receiver options (bandwidth, side-band separation), it is essential to evaluate which fraction of the time (or projects) is devoted to spectral line observations. As a 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: $X_{\mathrm{SSB}} = 35$ % 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.

Item 3 plays a special role, since it uses the fact that with a DSB tuning, one may observe simultaneously spectral lines which fall in opposite sidebands and have nearly equal intensities, or more precisely must be observed with similar noise level. I 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 in the mm bands are

- 348 GHz/LSB: 336 - 344 GHz
  C17O(3-2), $C^{34}S$(7-6), CH_3OH band, CS(7-6)
- 348 GHz/USB: 352 - 360 GHz
  HCO^+(4-3), SO_2 band
- 104 GHz/LSB: 92 - 100 GHz
  N_2H^+(1-0), $C^{34}S$(2-1), CS(2-1)

- 104 GHz/USB: 108 - 116 GHz
  $C^{18}O$(1-0), ^{13}CO(1-0), $C^{17}O$(1-0), ^{12}CO(1-0)
- 235 GHz/LSB: 223 - 231 GHz $C^{17}O$(2-1), H_2CO, ^{12}CO(2-1)
- 235 GHz/USB: 239 - 247 GHz $C^{34}S$(5-4), CS(5-4)

Near 100 GHz, a lower frequency tuning would allow to include $C^{18}O/^{13}CO$ 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 C_2H, C_3H_2, C_4H, HC_3N, C_3N). The sub-mm domain is also extremely rich in spectral lines.

4 Discussion

In Figure 2, the ratio β 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 β 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 β is lower than $\sqrt{2}$.

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 wavelengths, 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).

In Figure 2, the mean DSB/SSB sensitivity ratio β 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.

At mm wavelengths

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

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 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

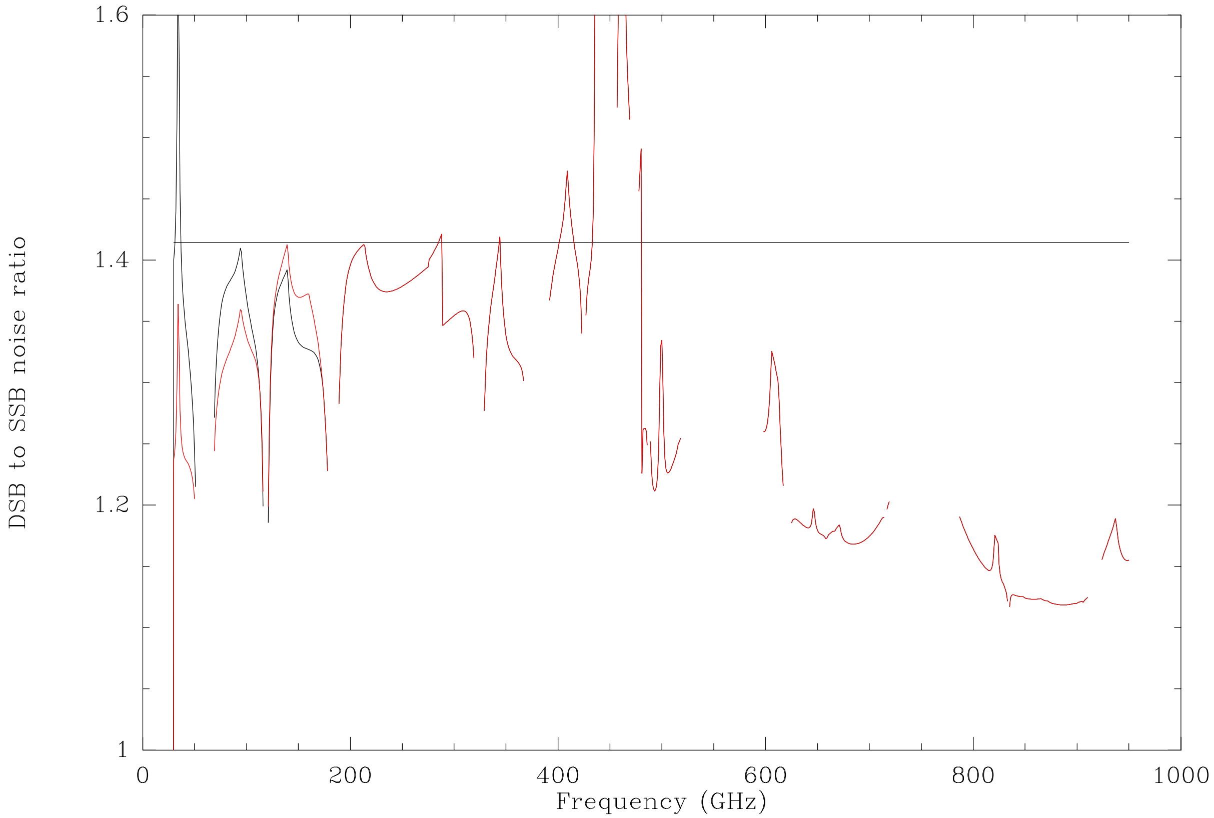

Figure 2: Ratio β of SSB system temperatures referred to outside the atmosphere for DSB receivers over that of SSB receivers

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

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

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

An alternate way is to compute the threshold of SSB observations above which SSB receivers offer advantages from

$$R = \frac{\beta}{\sqrt{2}} \times (1 - X_{\rm SSB}) + \beta \times X_{\rm SSB} = 1 \tag{3}$$

which gives

$$X_{\rm SSB} = \frac{1}{\sqrt{2}-1}\left(\frac{\sqrt{2}}{\beta} - 1\right) \tag{4}$$

Fig.3 gives this fraction as function of frequency. At submm wavelengths, SSB-like observations would need to cover more than 50 – 60 % of the observing time to give an advantage to SSB mixers under the present assumptions.

5 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, [Jewell & Mangum memo 300] concluded that SSB mixers are preferable. [Lamb memo 301] showed that under more realistic assumptions (i.e. unless the receiver noise is already quite low), the comparison may actually favor DSB operation. [Thompson & D'Addario memo 304] introduce the factor α 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 β, the ratio of "narrow band (i.e. SSB) system temperatures", which is easier to derive even in the case of imperfect sideband separation. With

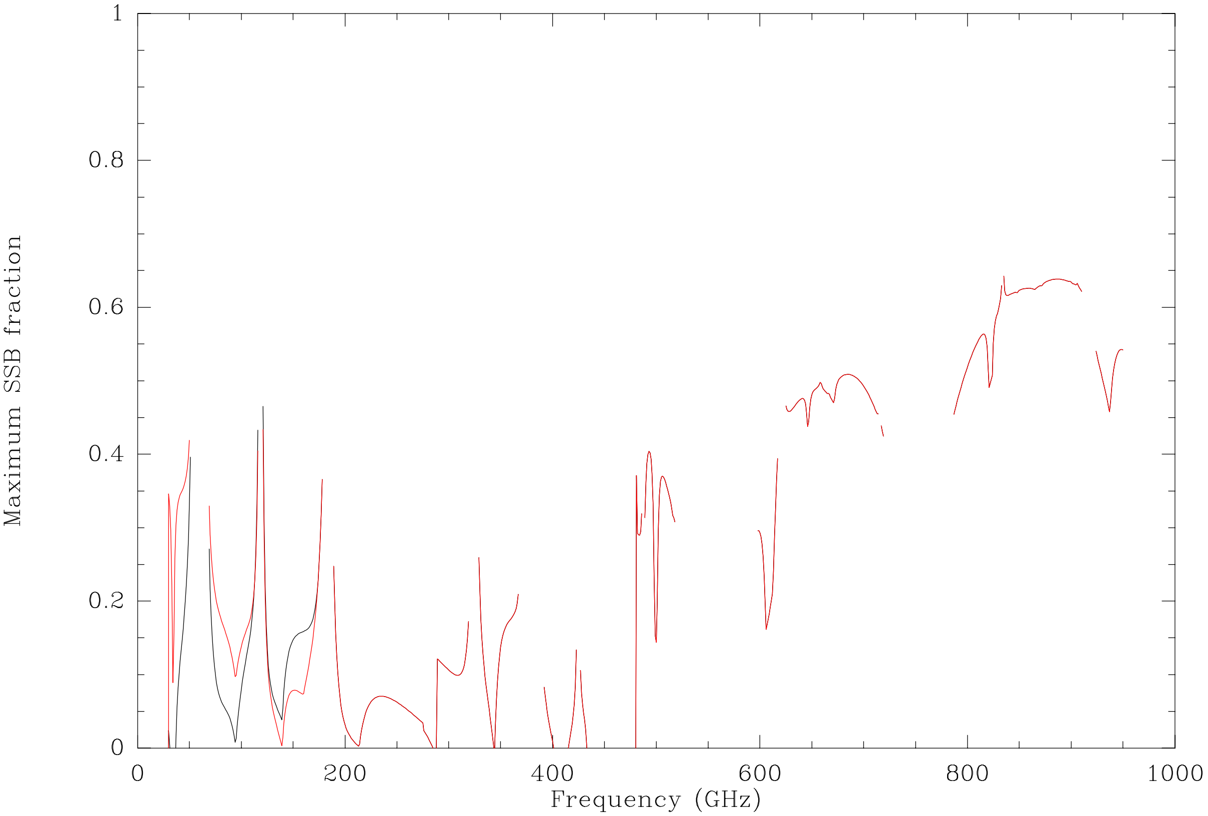

Figure 3: Minimum fraction of SSB-like observing time above which SSB receivers give a sensitivity advantage compared to DSB mixers

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 β for spectral lines (by definition), it is $\beta/\sqrt{2}$ for continuum. Noting that $\beta = 2\alpha$ given their respective definition, this is in agreement with [Thompson & D'Addario 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 [Thompson & D'Addario 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.

6 Bandwidth / Receiver Temperature trade-off

Large bandwidth is obviously preferable to small bandwidth for continuum-like measurements. On the other hand, if all observations were purely of a single spectral line, large bandwidths are of no use. In that case it would be preferable to build a lower bandwidth, lower noise receiver.

Hence, as for SSB versus DSB, there is a clear balance between noise temperature and receiver bandwidth. Let $X(B)$ be the fraction **in time** of SSB observations for a given bandwidth B, and $Y(B) = 1 - X(B)$ the corresponding fraction of DSB observations. Let assume we now divide the bandwidth by 2, and want to compute the fraction $X(B/2)$ of SSB observations to perform **the same observations with the same sensitivity**. To do so, the observing time in DSB should be doubled, while the time in SSB does not change. Hence

$$Y(B/2)/X(B/2) = 2Y(B)/X(B) \tag{5}$$

which gives after eliminating the $Y(i) = 1 - X(i)$

$$X(B/2) = X(B)/(2 - X(B)) \tag{6}$$

Now, we want also to reach the same sensitivity, i.e. for the SSB observations

$$T_{\mathrm{sys}}(B/2)/\sqrt{X(B/2)} = T_{\mathrm{sys}}(B)/\sqrt{X(B)} \tag{7}$$

which allows us to derive the required system temperature

$$T_{\mathrm{sys}}(B/2) = T_{\mathrm{sys}}(B)\sqrt{\frac{1}{2 - X(B)}} \tag{8}$$

which, as expected, goes between $1/\sqrt{2}$ and 1 when $0 \leq X(B) \leq 1$.

While deriving the relation between the system temperatures is trivial, we are only interested in deriving the relation between the **receiver** temperatures. To do this, the typical atmospheric opacities have to be included. Using the simplified equation

$$T_{\rm sys} = e^{\tau}(T_{\rm rec} + \eta(1-e^{\tau})T_{\rm atm} + (1-\eta)T_{\rm amb})/\eta \tag{9}$$

and the ratio of system temperatures from Eq.8 yields,

$$T_{\rm rec}(B/2) = T_{\rm rec}(B)\sqrt{\frac{1}{2-X(B)}} - (\eta(1-e^{\tau})T_{\rm atm} + (1-\eta)T_{\rm amb})\left(1-\sqrt{\frac{1}{2-X(B)}}\right) \tag{10}$$

Figure 4 shows the derived ratio of system temperatures, assuming $T_{\rm rec}(DSB) = 5h\nu/k$ for bandwith B. Since the fraction $X(B)$ is not known, curves are plotted for 5 values of $X(B)$. As expected, the Receiver temperature ratio must always be lower than the System temperature ratio, because of the contribution of the atmosphere.

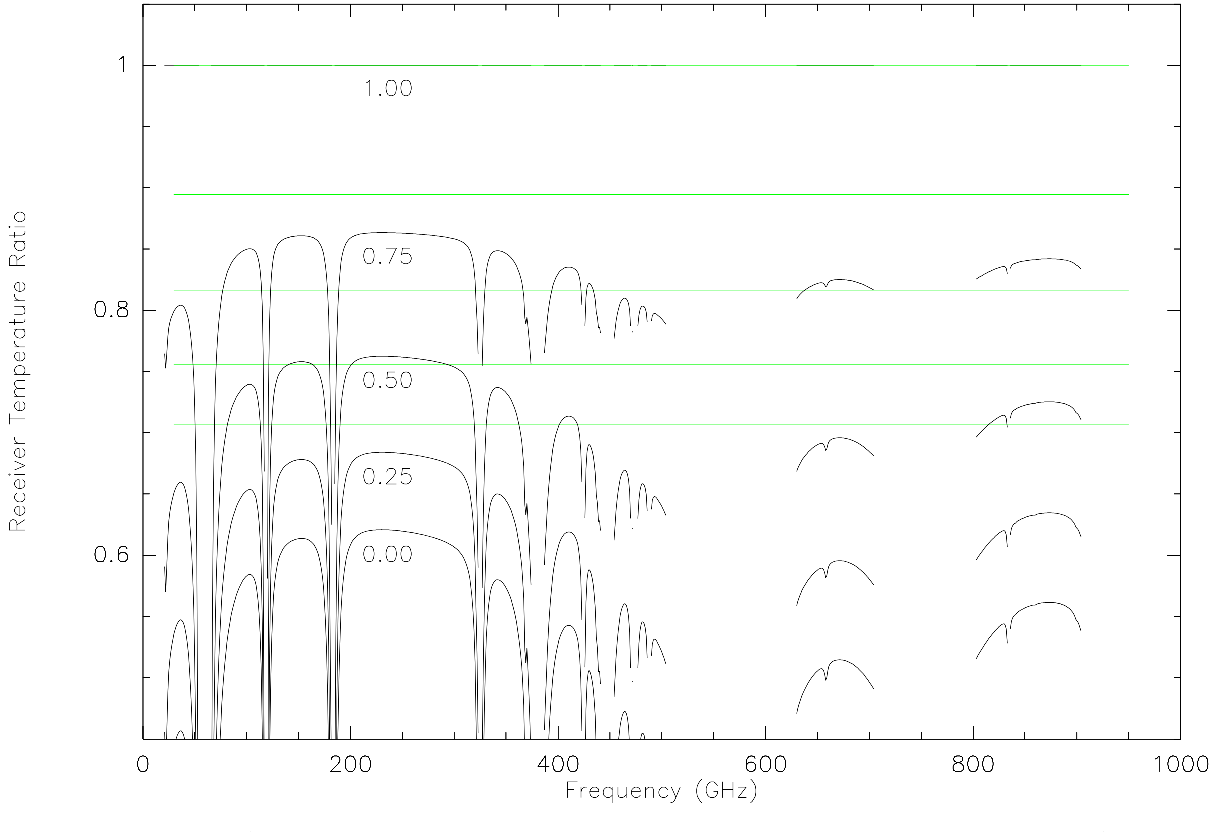

Figure 4: Ratio of Receiver temperature when the bandwidth is divided by 2, as function of frequency, for 5 initial fractions of SSB observations. The green lines shows the desired ratio of System temperatures.

Because of this fixed contribution by the atmosphere, the Receiver temperature ratio is obviously a function of the initial Receiver temperature. Fig.5 indicates how the ratio varies in this respect. It can be seen that, except for extremely good receivers, the effect is small.

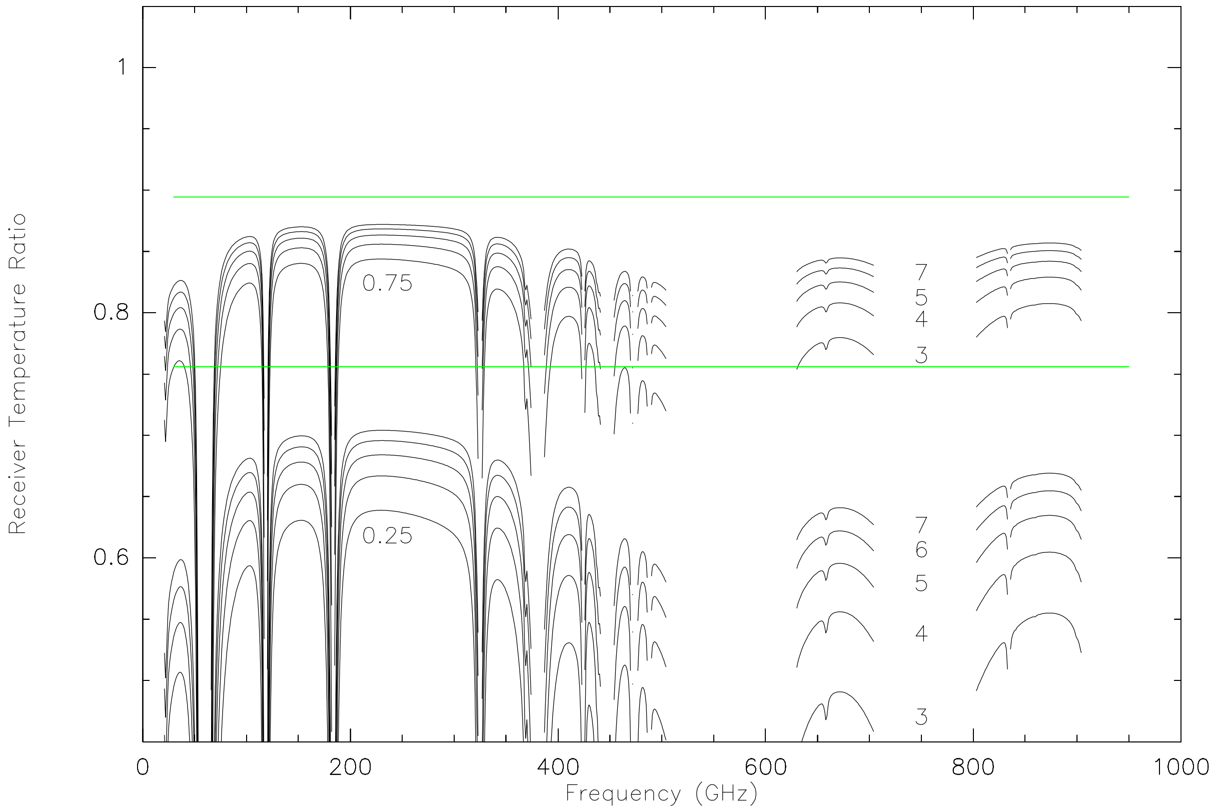

Figure 5: Ratio of Receiver temperature when the bandwidth is divided by 2, as function of frequency, for several initial receiver temperatures and two initial fractions of SSB observations

Using Fig.4-5 allows us to derive the improvement in receiver temperature required to compensate for narrower bandwidth. The fraction of SSB versus DSB observations is a serious unknown, but the arguments presented before (see Section 3) indicates values around 0.5. Using the ALMA baseline specifications for receiver performance (3 to 5 $h\nu/k$ DSB noise, see Table 1), improving the receiver temperature by about 25–30 % can compensate division of the bandwidth by 2; see Fig.6. An exception is Band 1, because of the low noise and larger (comparative) contribution of the atmosphere, and, to a lesser extent, Band 9 where the required improvement is rather 40–30 %. In practice, with good receiver design, the difference in noise temperature is not expected to exceed 10-20 %, making the wide band choice the most attractive.

7 Other considerations

7.1 Implication on correlator

DSB receivers (of bandwidth 2 × 8 GHz) can be competitive with SSB receivers (of bandwidth 8 GHz or 2×4 GHz as in a 4-8 GHz IF 2SB option), 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

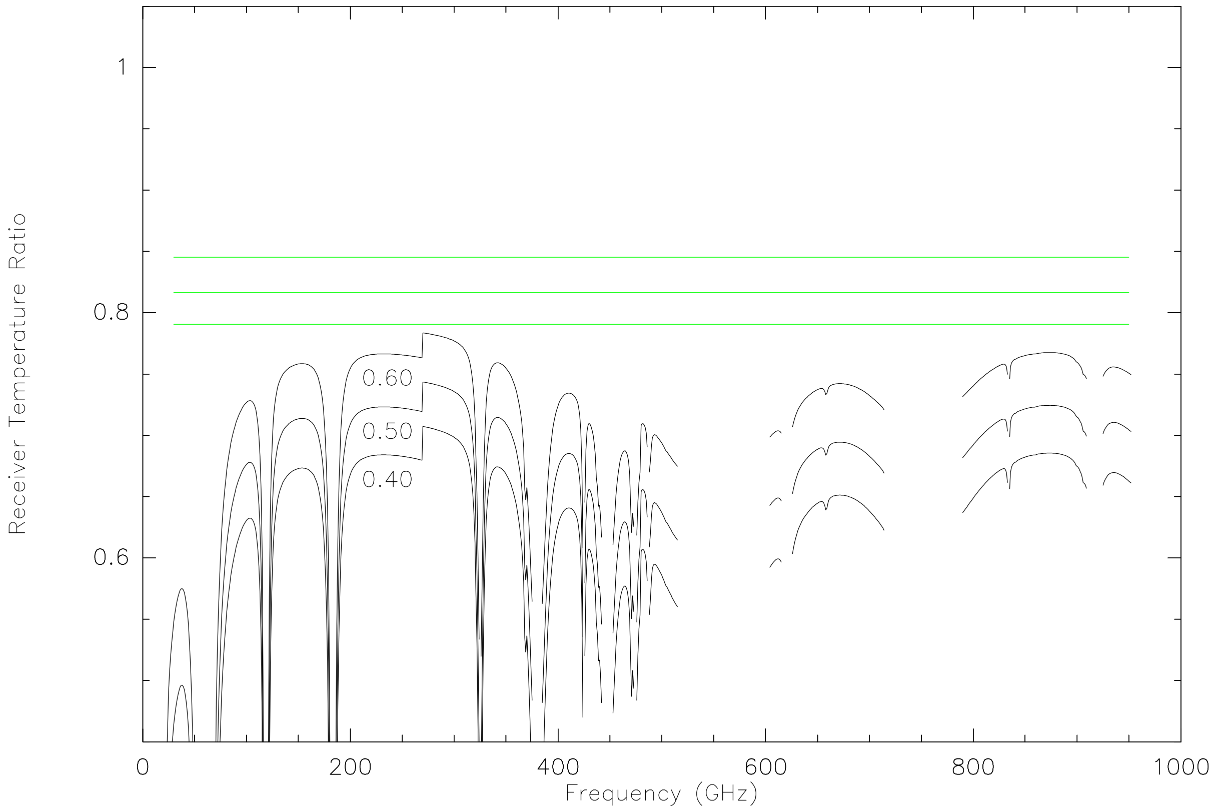

Figure 6: Ratio of Receiver temperature when the bandwidth is divided by 2, as function of frequency, for the typical ALMA conditions. Each curve is labeled by the value of the original fraction of SSB measurements.

to 35-40 % (at low frequencies). The proper use of 2SB receivers requires different basebands of the correlator to suppress different sidebands of the receivers.

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.

7.2 Receiver Saturation and Maintainability

An important aspect for receiver is the saturation level. Saturation ([Kerr memo 401]) is dependent on receiver bandwidth, and in this respect 2SB 4-8 GHz IF receivers could be less sensitive to saturation than DSB 4-12 GHz IF mixers.

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.

7.3 Upgrade Path

It is conceivable that during the construction of ALMA, some antennas be equipped with DSB mixers while others are equipped with 2SB (or SSB) mixers in the same band. To allow full hybrid use of DSB and 2SB mixers, it should be possible **to feed output of a DSB receiver simultaneously to the same input basebands of the correlator than the two IF outputs of the 2SB receivers**. This can be easily accomodated by specifying that DSB receivers must provide a double output. On the other hand, hybrid use of DSB and SSB (4-12 GHz IF) mixers is simple, but always result in a loss of half the bandwidth of the DSB mixers. This consideration favors a development path which starts with DSB, 4-8 GHz mixers, to move ultimately to 2SB, 4-8 GHz mixers.

7.4 Cost

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; this could be better quantified by the Receiver & System IPTs.

8 Conclusion and Recommendations

Based on the above discussions, I suggest to change the specifications of the ALMA receivers to incorporate the following:

1. Receivers for band 9 and 10 should be DSB, 4-12 GHz IF mixers.
2. Receivers for band 3 to 7 should be 2SB, 4-8 GHz IF mixers. This offers the best compromise in performance and saturation level.
3. An upgrade path starting from DSB mixers with 4-8 GHz IF, and finishing with 2SB 4-8 GHz IF mixers is the only one providing full performance of all receivers at all time.
4. The correlator must allow sideband separation (by Walsh functions) to be able to use DSB receivers.
5. DSB receivers which will be upgraded to 2SB must provide a double output.
6. There is significant sensitivity gain in Band 3 between receivers with $T_{\rm rec} = 50$ K SSB, and receivers with $T_{\rm rec} = 6h\nu/k + 4$ K. The later should be kept at least as a very serious goal for ALMA.

References

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