Scientific Drivers for SSB/DSB Receiver Operation

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Abstract

The ASAC recommended in the report of its February meeting that "a careful assessment of the cost/performance tradeoff for SSB vs DSB operation of the receivers and their consequences for the IF subsystem and correlator should be undertaken in the next few months." Using assumptions in ALMA Memo no. 304, we show that for any reasonable mix of continuum and interferometer observations with ALMA at a number of receiver bands, SSB operation provides the most cost-effective means of achieving sensitivity.

1 Introduction

The ASAC recommended in the report of its February meeting that "a careful assessment of the cost/performance tradeoff for SSB vs DSB operation of the receivers and their consequences for the IF subsystem and correlator should be undertaken in the next few months."

In ALMA Memo No. 304, Thompson and D'Addario show that the sensitivity ratio S_{ssb}/S_{dsb} with perfect image rejection is the same in total power and interferometer mode for a spectral line source, but a factor of root two greater for a continuum source observed in interferometer mode than in total power mode. This plethora of factors complicates comparison of observational tradeoffs for ALMA.

In general, Thompson and D'Addario found that SSB provides better sensitivity for spectral line observations, particularly at higher frequencies, and that DSB operation provides better sensitivity for continuum observations. They evaluate sensitivity ratios in their Table 4.

Table 1: ALMA Memo No. 304, Table 4 Values of (SSB Sensitivity/DSB Sensitivity

Mode	225 GHz	650 GHz	950 GHz
Total Power			
Continuum	0.56 – 0.61	0.61 – 0.78	0.61 – 0.78
Line ρ=0	1.12 – 1.22	1.22 – 1.56	1.21 – 1.56
Line ρ=0.1	1.02 – 1.11	1.11 – 1.42	1.10 – 1.42
Interferometer			
Continuum ρ=0	0.79 – 0.86	0.86 – 1.10	0.86 – 1.10
Continuum ρ=0.1	0.72 – 0.79	0.79 – 1.01	0.78 – 1.01
Line ρ=0	1.12 – 1.22	1.22 – 1.56	1.21 – 1.56
Line ρ=0.1	1.02 – 1.11	1.11 – 1.42	1.10 – 1.42

Notes: When observing spectral lines in both sidebands (2SB), the results are the same as for continuum. Interferometric observations with one sideband suppressed via a frequency offset correspond to the spectral line case, even for a continuum source.

2 Advantages of DSB or SSB Operation

At present, the preferred mode of operation of ALMA is 2SB, a single sideband mode whereby both sidebands are recovered. What would be the observational consequences of DSB as a preferred mode over SSB? Clearly, if all ALMA observations were continuum, DSB should be the preferred mode. Much calibration–pointing, focus, and similar tasks–will certainly be done in continuum mode and could benefit from better performance.

Here, we examine the tradeoffs in sensitivity from the point of view of the question "what percentage of proposals must be continuum proposals to compensate for the decreased SSB sensitivity of the baseline ALMA, were it built to a DSB spec. Secondly, what is the cost increment of building ALMA to SSB rather than DSB specifications. Then, is it worth it to change the specification? Thompson and D'Addario defined

$$\alpha = \frac{systemtemperatureofdouble - sidebandsystem}{systemtemperatureofsingle - sidebandsystem} \tag{1}$$

and note that sensitivity is proportional to the inverse of noise, from the radiometer equation, so that

$$\alpha = \frac{single - sidebandsensitivity}{double - sidebandsensitivity} \tag{2}$$

and that to achieve a given sensitivity, integration time τ scales as

$$\frac{\tau_{DSB}}{\tau_{SSB}} \propto \frac{single - sidebandsensitivity^2}{double - sidebandsensitivity} \tag{3}$$

Note that at present, ALMA processes 16 GHz of bandwidth; the backend may have presented to it more than that and flexibly choose what is to be processed. As an example, a 2SB design for Band 6 may present 8 GHz in both polarizations in both sidebands to the system, or 32 GHz, from which any of a variety of combinations totalling 16 GHz may be processed. On the other hand, a DSB system perhaps a design for Band 7 with a 4 GHz bandwidth may present only 16GHz to the system, dual polarizations within bandwidths of only 4 GHz in each sideband. At any given observation, the system has access to e.g. spectral lines on the sky within only two 4 GHz windows as opposed to the access of the system to two 8 GHz windows with a 2SB system. This flexibility might be accounted in various ways, but in an accounting considering sensitivity only it is not included. On the other hand, a more complex 2SB system may not achieve sensitivity over an 8 GHz bandwidth to match that of the 4GHz DSB system. Both receivers must meet ALMA specifications, however, and we assume equal performance here allowing the superior flexibility of the 2SB design to offset any slight disadvantage in sensitivity. Since the LO system is designed to accommodate 8 GHz bandwidths, however, 4 GHz bandwidth systems may be limited in tuning range, unable to reach frequencies at the edges of the bands. Furthermore, since the baseline correlator processes two bits in its widest band modes, some penalty might be assessed against 'continuum' observations when compared to line observations at narrower bandwidths, where four bit correlation can be chosen. These factors, though difficult to assess numerically, lessen the effectiveness of double sideband continuum observing, and it is continuum observing which is most favored by double sideband operation.

Continuum observing will be performed by ALMA both for scientific purposes and for calibration purposes. Some of the latter will not employ the correlator–for example pointing and focus observations will probably involve square law detectors in the system rather than processing through the correlator. Since it is difficult to assess the demand for continuum observations on ALMA, we can estimate what fraction of time devoted to continuum observations will result in equal sensitivity for an SSB and a DSB ALMA.

Suppose ALMA is to satisfy N observing proposals. In fact, at a frequency ν we let f represent the fraction of time which ALMA spends doing continuum experiments, so that 1-f is the fraction of time spent doing line experiments. Furthermore, assume purely interferometric observations for now.

We can evaluate what value of f results in equal performance for the SSB and DSB ALMA using the numbers in ALMA Memo No. 304. For the DSB ALMA, the fN continuum programs will be accomplished faster relative to a SSB ALMA by an amount $\frac{S_{dsb}}{S_{ssb}}^2 = A_C^2$ where A_C is drawn from the continuum entry in the memo table reproduced in Table 1. Likewise, for line programs $\frac{S_{dsb}}{S_{ssb}}^2 = A_L^2$. The two arrays are equal when

$$f = \frac{A_C^2 - \frac{A_C^2}{A_L^2}}{1 - \frac{A_C^2}{A_L^2}}. \tag{4}$$

Results are given in Table 2 which shows, for example, that if ALMA spends more than 53% of the time satisfying continuum proposals, ALMA observing would be better satisfied by employing DSB receivers. For reference, the VLBA experience shows that fN $\sim$ 0.67 for instance. For most arrays, and for ALMA in particular, we expect f to be much less than 0.53, for the weather conditions cited in the memo, and for Band 6. In the high submillimeter bands 9 and 10, f=0.96; there is a strong preference for these receivers to operate in SSB mode as noted in Thompson and D'Addario.

Perfect image sideband rejection may be difficult to achieve. For a power gain ratio between sidebands defined as in Memo No. 304 ρ=0.1 these numbers drop to .24 and .76 for bands 6 and 9/10, respectively.

For total power observations, the fractions are 0.36 and 0.62 for the 1.3mm and deep submillimeter bands, respectively. For the case of ρ=0.1 they are 0.17 and 0.52. Thus, as the mix of total power observations increases, the advantage of SSB receivers drops but as long as continuum observations occupy less than 17% of the total (225 GHz; 52% submillimeter) the SSB receivers enjoy an advantage.

We conclude that for any ALMA operation in which continuum observations comprise more than 95% of observing time, DSB operation might be preferred. However, if line observations dominate, SSB operation is preferred except possibly for the case of ρ=0.1 and observations at millimeter wavelengths. SSB operation is still preferred for these observations unless the continuum fraction is greater than about one quarter of the mix.

We conclude that from a viewpoint of gaining the best sensitivity for ALMA, SSB operation is to be preferred. However, if the expense of obtain-

Table 2: Breakeven Fractions for ALMA DSB Observations

	225 GHz		**650 GHz**	
Case	Cont	F=0.25	Cont	F=0.25
$\rho = 0.$	0.53	0.47	0.95	0.85
$\rho = 0.1$	0.24	0.21	0.76	0.68

ing this were prohibitive, one might still prefer to operate ALMA in DSB mode. We next examine the costs of achieving SSB performance on ALMA.

3 Cost Effectiveness of DSB or SSB Operation

ALMA has new numbers for receiver costs, though they have not been blessed by the Front End Division Heads. I estimate the cost of a DSB receiver by using the costing for Band 7 used there. I estimate the cost of a 2SB receiver by using the costing for Band 6. I have estimates of the cost differential for the LO and backend also, which is nil in comparison. This gives the cost advantage per band of 2SB vs DSB in about as accurate a way as I can imagine. ($2M cheaper for DSB, with a hefty error bar on this). For recasting the whole of ALMA as a DSB system, estimates suggest a savings of $20-$25M might be achieved.

Thus, we have dollars for each case and sensitivity estimates for each case. We can compare for instance the cost of gaining the sensitivity we would need to match DSB line observations to SSB line observations in terms of, for instance, added collecting area. If the mix of continuum observations is, say 5% at 225 GHz then for an observation set which includes any fraction of total power observations, an SSB ALMA finishes a given project in 33% less time than a DSB ALMA for an increase in cost of $2M. To attain the same sensitivity increase with collecting area would cost roughly $65M at 225 GHz and roughly $163M at 650 GHz. If the mix of continuum observations were say 25% these numbers become $21M and $108M, respectively.

I conclude that we are better off gaining ALMA sensitivity through deploying SSB receivers. Building them is another question of course and the penalty of deploying DSB receivers during early operations is not so large that design of DSB receivers in bands where SSB technology is immature should proceed.