Future ALMA Receiver Needs
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Bilateral project receiver bands include Bands 3, 6, 7 and 9. At this writing the Front End Group has produced Draft Specifications dated 2003-May28 version 2.5 which I will assume presents the best knowledge now on the performance of these receivers. The definition of these bands is in Table 1, followed by excerpts defining the gross performance of the receiver cartridges in these Bands.

Table 1. **RF input and output ports**

Band	Start frequency	Stop frequency	Remarks	
1	31.3 GHz	45 GHz		FEND-21310-ZZZ
2	67 GHz	90 GHz		FEND-22310-ZZZ
3	86 GHz	116 GHz	operation to 84 GHz	FEND-23310-ZZZ
4	125 GHz	163 GHz		FEND-24310-ZZZ
5	163 GHz	211 GHz		FEND-25310-ZZZ
6	211 GHz	275 GHz		FEND-26310-ZZZ
7	275 GHz	370 GHz	operation to 372 GHz	FEND-27310-ZZZ
8	385 GHz	500 GHz		FEND-28310-ZZZ
9	602 GHz	720 GHz		FEND-29310-ZZZ
10	787 GHz	950 GHz		FEND-20310-ZZZ

Full specifications and requirements do not apply for operation outside nominal frequency limits.

The specification for receiver output port bandwidth and center frequency is:
Each signal channel shall provide 8 GHz total IF bandwidth per polarisation using one of the following alternatives depending on the mixing scheme selected:

1.1. 8 GHz bandwidth single-sideband (SSB), upper <u>or</u> lower sideband centred at 8.0 GHz
1.2. 8 GHz bandwidth double-sideband (DSB), centred at 8.0 GHz
1.3. 4 GHz bandwidth dual-sideband, (2SB) upper <u>and</u> lower sideband, centred at 6.0 GHz

Front End Noise Performance

This section applies only to the operational mode.

The following table shows the required noise temperature performance of the ALMA Front End. The noise performance is referred to its effective RF input port including all contributions from warm optics, dewar windows, and IR filters. It must take into account all noise contributions up to the Front End assembly IF output ports.

Depending on the selected mixer scheme the cartridge noise temperature shall not exceed the values of either T_{SSB} for SSB and 2SB response or $T_{DSB} = 0.5.T_{SSB}$ for DSB responses as follows:

Table 2: Specifications for maximum receiver noise temperatures

Band	SSB		DSB		
	T(SSB) over 80% of the RF band	T(SSB) at any RF frequency	T(DSB) over 80% of the RF band	T(DSB) at any RF frequency	

1	15 K	23 K	8 K	12 K	FEND-21910-ZZZ
2	28 K	43 K	14 K	22 K	FEND-22910-ZZZ
3	34 K	54 K	17 K	27 K	FEND-23910-ZZZ
4	47 K	76 K	24 K	38 K	FEND-24910-ZZZ
5	60 K	98 K	30 K	49 K	FEND-25910-ZZZ
6	77 K	126 K	39 K	63 K	FEND-26910-ZZZ
7	133 K	198 K	67 K	99 K	FEND-27910-ZZZ
8	181 K	270 K	91 K	135 K	FEND-28910-ZZZ
9	335 K	500 K	168 K	250 K	FEND-29910-ZZZ
10	438 K	655 K	219 K	328 K	FEND-20910-ZZZ

Remarks:

1. The frequency ranges of the bands in the table above are specified in section 3.3.1 of this document.
2. The noise temperatures shall be achieved for the full IF band, as defined in section 3.3.3
3. The noise temperature shall be calculated from measurements according to the Rayleigh-Jeans law.
4. The noise temperatures in this table are based on the approved "Specifications for the ALMA Front End Assembly", version 1.0, and the following.
5. Following an ASAC recommendation the values in the Table were calculated with the following formula:

$$T(SSB)= A * (h*freq/k) + 4 K$$

where h and k are the usual physical constants, and freq was taken as the centre frequency of a particular band. The frequency dependent quantity A has the following specification and values (over 80% of the RF band / at any freq):

Bands 1-6 (below 275 GHz)	Spec: A = 6 / 10
Bands 7-8 (275-500 GHz)	Spec: A = 8 / 12
Band 9 (602-720 GHz)	Spec: A = 10 / 15
Band 10 (787-950 GHz)	Spec: A = 10 / 15

Actual performance on the telescope will include contributions from the telescope (such as spillover) and from the atmosphere. We assume the forward efficiency for the antennas falls down from 0.95 at low frequencies to 0.90 at 900 GHz (as v^2). This assumption follows the observed behaviour of existing antennas, and should be verified by measurements on the prototype antennas.

The telescope specifications were established so as to minimize contributions from spillover, given the excellent character of the atmosphere at the site. The optimum frequency for observations versus weather conditions is given in Table 3, taken from ALMA Memo No. 372.

Table 3: Optimum frequency for observations versus weather conditions and percentage of observing time

Cumulative Time (%)	pwv (mm)	Freq (GHz)	% total time
99	5.0	31.3-90	25
75	2.3	230	25
50	1.2	350	25
25	0.7	410	15
10	0.3	690-950	10

Given these parameters we can consider what improvements might be made to system performance were new receiver bands to be constructed with superior performance. ALMA Memo No. 393 considered which of the three output port possibilities should be employed by each ALMA Band and recommended that receivers below 500 Ghz should provide 2SB performance. It recommended an upgrade path from the initial complement of receivers, which may be DSB, to an ideal complement, which would provide 2SB performance. Although this memo recommended use of a 4-8 Ghz IF, this particular recommendation was not strongly supported by arguments in the text, in my opinion[1]. It also recommended that improvement in the performance of Band 3 provided the best return, as this band will be used for supplying reference atmospheric phase corrections for program sources.

The ASAC recommended a priority order for ALMA Band construction. Band 1 was among the highest priority bands, but is not currently included, even in the Japanese enhancements. This band, with its unique science capabilities, must rank first among future receiver priorities. The remaining bands which are not included in the construction plan or among projected enhancements are Bands 2 and 5. The ASAC has recommended that Band 2 get priority between these two; the ESAC has voiced a similar opinion.

Band	Current Spec (K)	Improved Spec (K)	% Improvement	Equivalent Area Cost
3	54	42	17	$76M
4	75	61	19	$85M
6	130	104	20	$90M
7	240	201	16	$72M
8	316	261	17	$76M
9	587	496	16	$72M
10	730	610	16	$72M

As soon as all frequencies are covered by the ALMA Bands, an obvious option for further development is to replace bands with receivers of increased sensitivity. Clearly, a small increase in sensitivity may not be worth the expense; additionally the atmospheric contribution may render an increase ineffectual. We have calculated, then, how much of an increase in receiver sensitivity, given atmospheric conditions in Table 3, each two quanta of improvement at the frequency of interest, should provide. This could be evaluated by comparison to how many fully equipped ALMA antennas (at $7M each) would be needed to

[1]In the text, it was argued that larger bandwidths suffered from increased effects of mixer saturation. In fact, it is the *input* mixer bandwidth which affects saturation, not the output bandwidth; saturation is not a factor in the choice of output bandwidth.

provide equivalent sensitivity. This valuation may then be contrasted to the projected cost of making the improved receivers (estimated at $20M per band) to provide a measure of cost effectiveness.

Consideration of the frequency of use of a band--its duty cycle--should also be made; putative atmospheric parameters are given in Table 3 but demand factors are for present unknown (the Design Reference Science Plan may be useful for demand estimation). Clearly receiver improvement provide benefits more often at lower frequency.

It should be noted that Band 3 will not only be employed when between 2.3 and 5 mm of water is present; it is a fundamental calibration receiver. Improvement for median conditions (1.2mm pwv) would provide a 20%efficiency increase. Since this band is in constant use a factor accounting for the use frequency of a band would rank improvements to this band highest.

Clearly, submillimeter observing time is the scarcest ALMA commodity, with only ten per cent of the time available. Improvements in sensitivity, which can increase the submillimeter throughput, will clearly provide additional value to receiver improvements in that band. Furthermore, the final column in the table assumes that each antenna adds equal sensitivity. In fact, the antenna efficiency at the shortest submillimeter wavelengths is only about 30%, so several antennas would have to be added to increase sensitivity at those wavelengths compared to an equal fractional increase at lower frequency.

I conclude that if an average receiver band on ALMA were to cost $20M, the efficiency obtained by building a new suite of receivers with performance improved by $2h\nu/k$ would be worthwhile. Note also that there is more room for improvement in the higher frequency bands--the value of a two quantum improvement in those bands could arguably be two orders of magnitude more than a similar improvement at, for instance, band 4.

Summary

After completion of the full complement ALMA receivers, ALMA receiver upgrades will benefit array sensitivity. As Band 3 is expected to be used for calibration, upgrades to this band will benefit all programs. Highest demand is anticipated for the submillimeter bands; upgrades to these bands will provide ALMA users with more sensitive access to its most limited resource–good high frequency observing conditions.