Report on the feasibility study of the enhanced correlator for 3-way ALMA to ASAC

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ABSTRACT

Here we summarize the feasibility study of the enhanced correlator proposed by Japan for 3-way ALMA. First we briefly review the scientific significance of the enhanced correlator, which does NOT depend on the correlator architecture. Then we describe the proposal of a high-performance FX correlator system for the enhanced correlator of 3-way ALMA. **This FX correlator system always realizes both super-high spectral-resolution (< 0.1km/s at 40GHz) and wideband (> 700km/s at 850GHz) observations simultaneously up to 850GHz for each 2GHz baseband of the ALMA IF system.** This FX system consists of 1024 x 1024 – point FFT parts, 4-bit cross-correlation parts, and control parts. **Re-quantization *and* flexible frequency-channel smoothing *is newly installed*.** **Re-quantization** reduces the lines of connection between F and X parts compared with the previous FX system. **Flexible frequency-channel smoothing** makes the output frequency channels from 524288(=512 x 1024) to 8192 per baseband and eliminates the fear that the large amount of frequency channels might increase the costs of post-detection computing and archiving. Realization of this correlator system will allow us to make breakthrough in both sub-millimeter line and continuum observations with 3-way ALMA. We present the specifications, estimated hardware size and power consumption, and preliminary plan for the implementation.

1. DESIRABLE FEATURES OF THE SECOND-GENERATION CORRELATOR FROM SCIENTIFIC REQUIREMENTS

The performance of correlators can be basically specified by the following two aspects: (i) the total bandwidth of the input signal, and (ii) the spectroscopic capabilities. When one observes an emission line to study the velocity structure in some astronomical objects, it is usually sufficient to resolve the line into ~100 frequency bins along the velocity axis. The ALMA Baseline Correlator will achieve $R_{1b} >= 10^3$ where R_{1b} = (velocity coverage across one baseband)/(velocity resolution) for any velocity resolution(Figure 1). The Baseline Correlator will fulfill most of the scientific requirements for line observations in the beginning phase of the array operation. It is expected, however, that demands for more comprehensive / more challenging observations unable to be made with the Baseline Correlator will be growing as the performance of the ALMA is being improved (e.g., by the progress of sub-millimeter receiver technology). A possible example of such observations is an imaging line survey of star-forming regions. In order to conduct this kind of observations efficiently, uniform velocity resolution as high as ~ 1km/s across all the basebands is required, but the Baseline Correlator cannot provide such features. Another example is a sensitive spectroscopic search for a gap cleared by a proto-planet in a circumstellar disk around young stellar objects. Although the full-width of the rotation velocity in a disk is as large as ~100 km/s, the velocity width of "absent emission" due to the gap can be as small as ~0.1 km/s because the gap width may be fairly small compared to the disk radius. In addition, it is necessary to obtain line-free channels with a sufficient bandwidth within the same baseband in order to make precise subtraction of the contribution of the continuum emission from visibility data. Therefore R_{1b} of $>\sim 10^4$, which cannot be available with the Baseline Correlator, is necessary to conduct the gap search toward YSO disks. A second-generation correlator for the enhanced ALMA should provide "enhanced" spectroscopic capabilities that enable us to make such comprehensive / challenging observations as described above. It should also be noted that higher spectral resolutions provided by the enhanced correlator will allow us: (i) to make ordinary line observations without any loss of continuum sensitivity, and (ii) to separate the contribution of line emissions from that of continuum emission precisely even in a "sub-millimeter line forest" toward massive star-forming regions. The Japanese correlator group is studying the FX-type architecture design for the enhanced correlator to make such comprehensive / challenging observations available.

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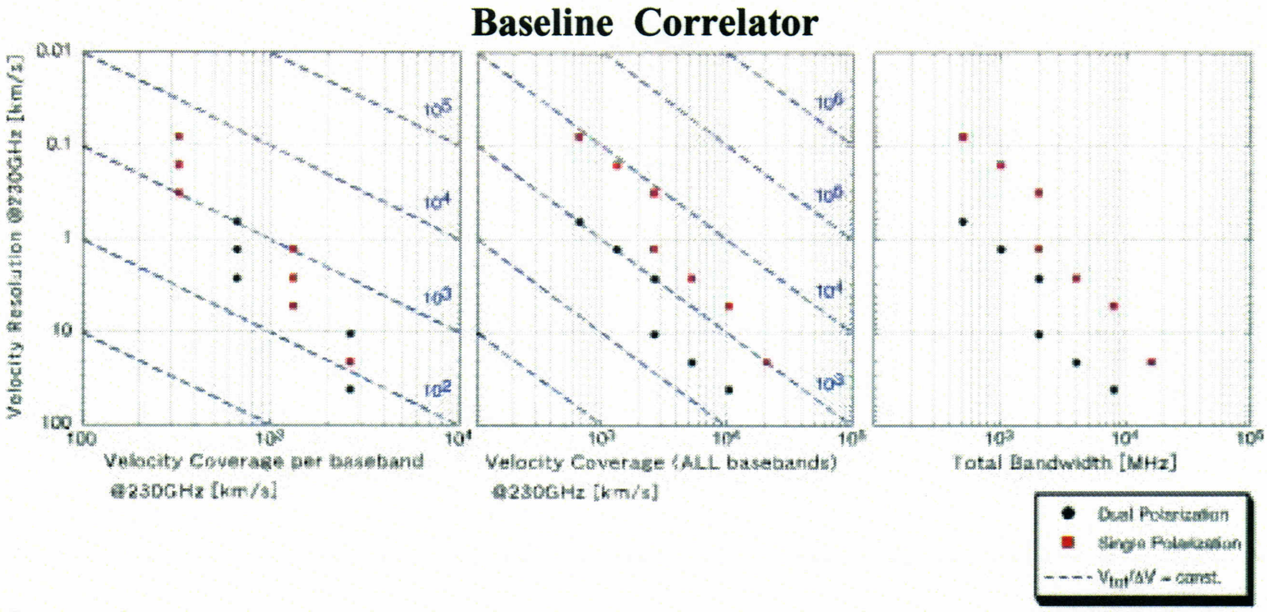

Figure 1. Performance parameters for typical operating modes of ALMA Baseline Correlator ;(a) velocity coverage per one baseband versus velocity resolution, (b) velocity coverage across all the baseband versus velocity resolution, and (c) frequency bandwidth across all the basebands versus velocity resolution. Note that Figures 1(b) and 1(c) are shown for the cases when a same operating mode is applied for all the basebands.

2. ENHANCED CORREALTOR SYSTEM PROPOSED BY JAPAN

We propose a high-performance FX correlator system : the processing bandwidth per one baseband is **2048MHz** assuming eight basebands per antenna. *The bandwidth does not depend on the number of basebands.* Spectral resolving points at one baseband is **524288**(=512 x 1024**)**, and *this number is also fixed for antennas and basebands*. Thus the highest spectral resolution is ***4 kHz***. We assume 3-bit sampling as the input of the correlator system. We make 1024 x 1024 -point FFT with 9 or more bits, ***re-quantization*** and **4-bit correlation**. Just after the calculation of correlation, ***flexible frequency-channel smoothing*** is performed according to the request of observers(Figure 2). It reduces the output frequency bins from 524288 to at most **8192** per baseband. This method realizes the reduction of cost with maintaining the total bandwidth of

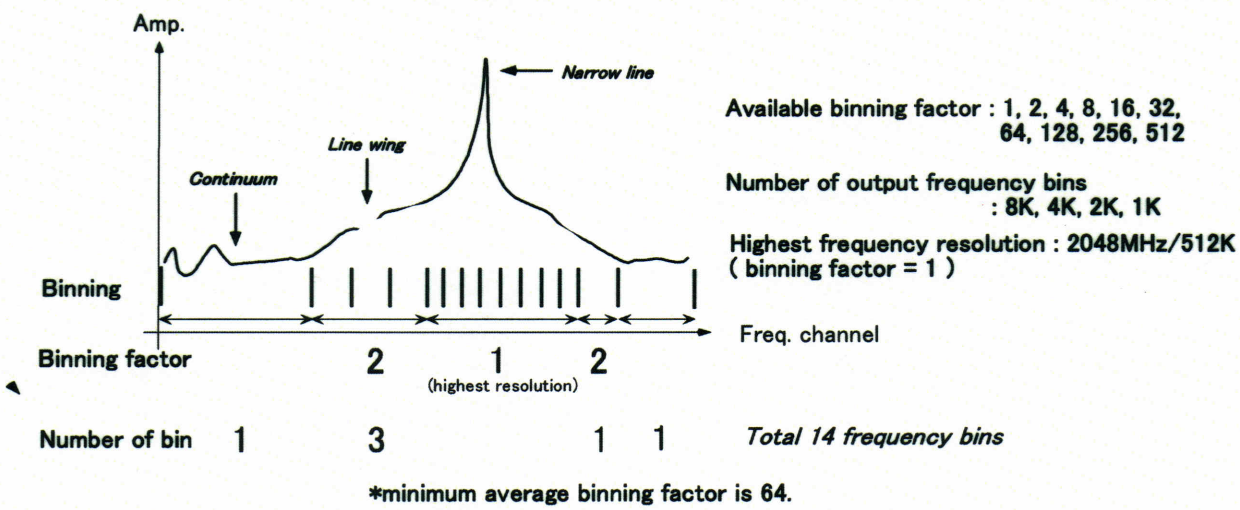

Figure 2. Example of the flexible frequency-region smoothing. K means 1024.

16GHz and the highest frequency resolution of 4 kHz simultaneously. Such frequency binning has a similar effect to the data overlapping for recovering the sensitivity relative to XF correlator. We can obtain 1 % of relative loss of signal-to-noise ratio to XF correlator in the case of 64-channel binning, which is uniformly averaged binning factor in the frequency-channel smoothing from 524288 to 8192. Typical (maximum) data rate is estimated to be 4Byte x complex x 8 x 1024channel x 2016correlations / 0.1(0.016)sec = 1.3(8.3) GB/sec/baseband. It is possible that the total maximum number of correlations is 3160 for each baseband of 80 antennas. This FX correlator system is characterized by the following performances : ***wideband(2048 MHz), super-high frequency resolution by 1024 x 1024 point FFT, and very large integration(max. 3160 correlations / baseband).*** This system should support the full polarization observations(RR, RL, LR, and LL correlations) and some kinds of single-dish mode observations. We will summarize specifications of the high-performance FX correlator system in Table 1.

Using this FX correlator system, **we can always map all the lines in the 2GHz-bandwidth 8 basebands with super-high velocity resolutions (< 0.1km/s at 40GHz), and obtain 16GHz-continuum data and line data with enough velocity coverage (> 700 km/s at 850GHz)**. We represent the observing mode of the FX correlator in Figure 3 and Table 2 compared to the Baseline Correlator.

Table 1. Specifications of the high-performance FX correlator system for enhanced ALMA

Item	**Specification**
Number of antennas	64 (max. 80)
Number of baseband inputs per antenna	8
Sampling rate per baseband input	4GHz
Digitizing format	3 bit, 8 level
Correlation format	4 bit, 16 level
Number of FFT points	1024 x 1024
Maximum baseline delay range	50 km
Re-quantization	9bit => 4bit
Output cross-correlation frequency bins per baseband per baseline	8192, 4096, 2048, 1024, 512*
Autocrrelation per antenna	Same as above
Product pairs possible for polarization	RR, LL, RL, LR (for orthogonal R and L; *total processing bandwidth of the signal is reduced from 16 to 8 GHz in this case.*)
Number of sub-array	No limitation (In the case of more than 4 sub-arraying, the same frequency-smoothing parameters have to be recommended.)
Data dump times	16msec, 1msec*(In this case, number of output bins is limited to 512.)

Table 2. Modes of the high-performance FX correlator

# of Digitizers	**Bandwidth/ Digitizer**	**Cross-pol Products**	**Freq. bins/ Product**	**At 230 GHz, in velocity space: Range**	**Resolution km/s**
8	2 GHz	Yes	8192	9391	0.325(0.005)*
8	2 GHz	No	8192	18783	0.325(0.005)*

*This is the case of the highest frequency resolution. See Figure 2 and section 2 about ***flexible frequency -region smoothing***.

3. FEASIBILITY STUDY OF THE PROPOSED FX CORRELATOR SYSTEM

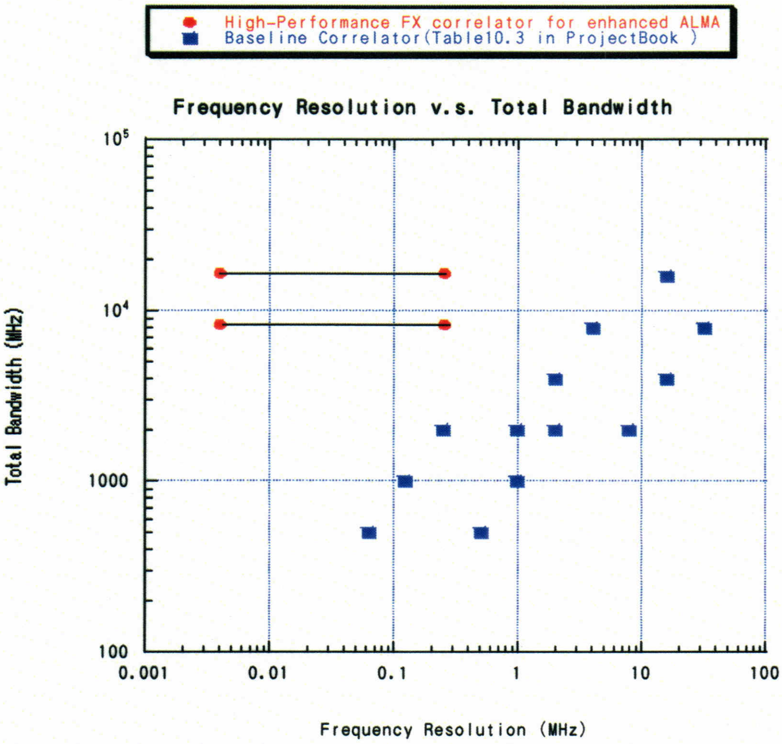

Figure 3. Total bandwidth versus frequency resolution for typical operating mode of ALMA Baseline Correlator(Table 10.3 in Project Book) and the high-preformance FX correlator system(Table 2). X-axis is the frequency resolution, and y-axis is the total bandwidth across all the basebands of ALMA. Left circle of FX correlator shows the highest frequency resolution obtained with the frequency resolving points of 524288(=512 x 1024) over 2-GHz bandwidth and the right one is the average frequency resolution with the output of 8 x 1024 frequency bins over the 2-GHz bandwidth.

3.1 TECHNICAL KEY POINTS AND PHASE 1 ACTIVITIES

The important technical issues to be resolved for the realization of the high-performance correlator system are as follows :

a) **High-speed sampling (>= 4096Mega sample/sec with 3bits),**
b) **A huge number of point FFT with enough computational accuracy (e.g., >100 k point of FFT),**
c) **Pin limitation of boards between F- and X-parts,**
d) **Power consumption of large LSI and large integration of circuit for a few thousands of correlation.**

Now we are making the development of a minimum test system of the FX correlator to make experiments for the overcome of the technical issue a), b) and c), and to demonstrate the high-resolution and wideband FX correlator. This test system consists of *two 4Gsps 2-bit A/D converters* and *one FX spectro-correlator(1 baseline)* with the bandwidth of 2048MHz. It will be completed at the end of September 2001. We will start the performance test with the combination of the test A/D converters and test FX correlator next autumn.

3.2 ESTIMATED PHYSICAL SIZE AND POWER CONSUMPTION

Here we will roughly estimate the hardware and power consumption of the high-performance FX correlator for enhanced ALMA of 64-antennas array with the reference of those of the test FX correlator. Preliminary requirements of printed circuit board and power consumption for the FX correlator system are shown in Table 3. The total number of boards per one baseband is 3192/8=399. Eight special-purpose LSIs to calculate FFT are installed on one FFT board. Four special-purpose LSIs to calculate correlations are also installed on one correlation board. As for the technical issue d) in section 3.1, power consumption rate of LSI are getting better due to the recent progress of technology. Now it is less than 0.02 μ

W/gate/MHz at the end of 2000 (0.18 μ m process, low-power mode). So we are able to put 1 - 2 Mega-gate circutes into one LSI at 128MHz clock cycle with usual air-cooling operation. Main contributions to the power consumption are two kinds of special-purpose LSIs(FFT and correlation) and large-scale memories. The FX correlator for one baseband, 512 FFT-LSI and 256 correlation-LSIs are necenssary with 0.18-micron process gate-array. Typical power consumption of such gate-array installed Mega-gate circutes is about 2 Watt. Considering these conditions, the estimated power consumption per one baseband is about 122199/8=15.3 kW. The corresponding physical size of the hardware is about 4m x 4.5m x 1.8m for one baseband.

Table 3. Preliminary printed circuit board requirements for the enhanced FX correlator

Item	# required	Size	Power
Delay board	256	381 mm x 237 mm	
FFT board	512	381 mm x 237 mm	
Corner-turner board	1024	381 mm x 237 mm	
		(F-part total)	76,992
Data-gathering board	320	381 mm x 237 mm	
Correlator card	512	381 mm x 237 mm	
Multiplex board	64	381 mm x 237 mm	
		(X-part total)	35,911
Control card	192	381 mm x 237 mm	
Data-buffer boards	192	381 mm x 237 mm	
'CPU+10Git-ETHER' board	120	381 mm x 237 mm	
		(Control part total)	9,296
TOTALS	3192		122, 199 w

3.3 PRELIMINARY SCHEDULE

Now we have estimated the implementation plan of the high-performance FX correlator system for the enhanced ALMA. We need 2 years to make detailed design of LSIs and printed circure boards from the start of financial year 2002. After that we make the prototype system and carry out the performance test during a half year, then manufacture the site correlators. Preliminary plans are presented in Table 4.

Table 4. Principal milestones for the implementation of ALMA enhanced correlator

Preliminary Design Review	2001-01/02(now)
Critical Design Review(?)	2001-12
Deliver test A/D and FX correlator system(one baseline) to NOBEYAMA	2001-09-30
Start detailed design of LSIs and printed board	2002-spring
Deliver first 1/4 to Chajnantor site	2006-summer
Deliver last 1/4 to Chajnantor site	2009-summer

4. SUMMARY

We propose the high-performance FX correlator system as an enhanced correlator of 3-way ALMA. ***This FX correlator system always realizes both super-high spectral-resolution (< 0.1km/s at 40GHz) and wideband (> 700km/s at 850GHz) observations simultaneously up to 850GHz for each 2GHz baseband of the ALMA IF system.*** We estimated reasonable hardware size and power consumption(less than 20 kW per one baseband) based on the detailed specifications. Realization *of this correlator system will allow us to make breakthrough in both sub-millimeter line and continuum observations with the enhanced ALMA.*