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High-Performance FX Correlator System for enhanced ALMA

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ABSTRACT

We have proposed a FX correlator system for an enhanced ALMA. Maximum bandwidth per IF is 4096MHz and spectral resolving points per antenna per IF is 128 x 1024. The number of correlation is 3160 for 80 antennas per IF and the number of output frequency bins for each correlation is 16 x 1024. We will prepare 4 sets of this correlator for 4 IF bands. **This FX correlator system always realizes both high spectral-resolution (< 0.1km/s at 100GHz) and wideband (> 1000km/s at 850GHz) observations simultaneously for 4 IF bands up to 850GHz.** *Main changing point from the very large correlator system previously proposed is to apply **flexible frequency-channel smoothing** for the correlated data.* It reduces the output frequency data from 128 x 1024 to 16 x 1024 per IF and eliminates the fear that the large amount of the frequency channels might increase the costs of post-detection computing and archiving. *We estimate that the total cost of this FX correlator becomes half due to this change compared to the previously proposed one.*

1. REQUESTED PERFORMANCES FOR FUTURE CORRELATOR

In order to realize all the scientific goals with ALMA, -the correlator should not role out plausible experiments which would otherwise be allowed by the design[1].-, and ALMA future correlator should also support serendipitous discoveries.

1.1 REQUIREMENTS FROM MM AND SUB-MM SCIENCE

Much more molecular and ion line emission and absorption will be observed in the sub-millimeter wavelength than in the millimeter wavelength, and they are sometimes blended each other. Especially at star forming region like Orion, emission line forest is detected[2] shown in Figure 1. With the sensitivity of the enhanced ALMA, these line forests can be observed at more distant massive star forming regions. Thus ***the spectral resolution*** is one of the most important factors in order to analyze the target line emission correctly. We need the spectral resolution higher than 1MHz for the mapping observations of massive star forming regions like Orion. More than a few thousands of spectral channels are needed over the 4-GHz bandwidth for the success of not only line survey but also usual mapping observations in the sub-millimeter wavelength.

The proto-planetary disks are one of the most interesting objects to study using ALMA, and different kinds of physical conditions will be observed in one field of view of ALMA. In the outer edge of the disk at about 500 AU from the proto-star, excitation temperature is relatively low (about 10 K) and the Kepler velocity is 1 km/s. But in the inner edge of the disk at 0.1 AU from the star, excitation temperature and gas density become high and the Kepler velocity is about 100 km/s[3]. At the middle radius of about 10 AU from the star there might exist gap formation by a proto-planet. In order to investigate the molecular gas in the outer region and the gap formation, we need the velocity resolution of 0.1km/s. On the other hand, wide velocity coverage more than 100km/s is necessary for the gas in the inner edge of the disk. Further multi-line observations will be essential to study the physical and chemical evolution of such ploto-planetary systems, because different lines will be excited with such different kinds of physical and chemical conditions. We can also detect the continuum emission from the disk, and have to destingwish continuum and line emission precisely because we are able to obtain sensitive continuum data and emission line data simultaniously at one time. Thus **we should make wideband(>> 100km/s) and high-resolution(0.1km/s) observations simultaneously to go on the research for the physical and chemical evolution of the proto-planetary disks.**

Multi-line imaging study for nearby low-mass star forming regions become popular at millimeter wavelength, e.g., $C^{18}O(1\text{-}0)$, $H^{13}CO^{+}(1\text{-}0)$, and $^{13}CO(1\text{-}0)$. Sub-millimeter multi-line and continuum imaging study will be more powerful tool

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to investigate the formation and evolution of not only the proto-planetary system but also massive star-forming regions. For the molecular envelope of late-type stars, similar type of observations will be important and fruitful.

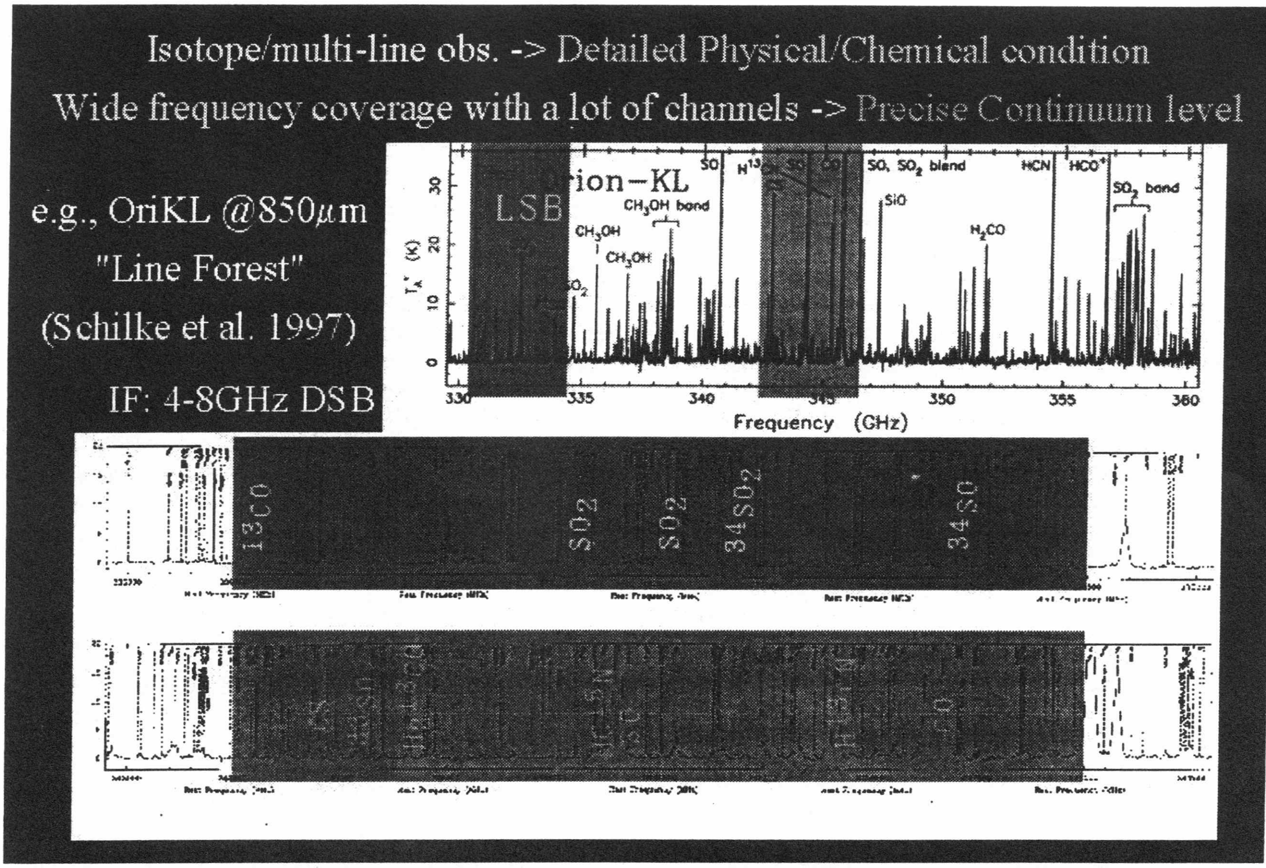

Figure 1. Orion KL wideband spectra at 850micron[2].

Extra-galactic millimeter and sub-millimeter observations require ***wide spectral window more than 1 % of the observational frequencies***, and wider continuous bandwidth more than 2GHz is necessary to observe the velocity field of distant objects at sub-millimeter wavelength up to 850GHz. In case of molecular line observations of radio-loud objects, subtraction of continuum from line emission is essential, and much more line-free channels will be needed for precise continuum subtraction[4] shown in Figure 2. Precise continuum subtraction depends on both the accuracy of passband calibration and the determination of continuum baseline level in a band. In order to obtain ten times better singal-to-noise ratio at continuum baseline (line-free regions) than that of the line channels, we need a hundred times more frequency channels, which corresponds to wide velocity coverage typically more than 1000 km/s (2.8 GHz at 850GHz).

We should support exciting serendipity like H_2O maser observations of NGC4258[5]. Using ALMA, we will be able to observe sub-pc regions of the nuclear molecular disks of nearby AGN at the distance less than 10Mpc. High excitation molecular and ion lines will be detected on the nuclear disks. Wide velocity coverage(> 1000 km/s) and relatively high-resolution(< 10 km/s) observations will be important up to 850GHz.

Much improvement of sensitivity with ALMA will allow us to detect weak emission, of course, and absorption line in distant galaxies[6]. Absorption line forest observations such as Dumped Ly alpha forest might be interesting to investigate the formation and evolution of galaxies. In this case we also need wider bandwidth(> 1000 km/s) including ambiguity in redshift z and high resolution(< 1 km/s) simultaniously.

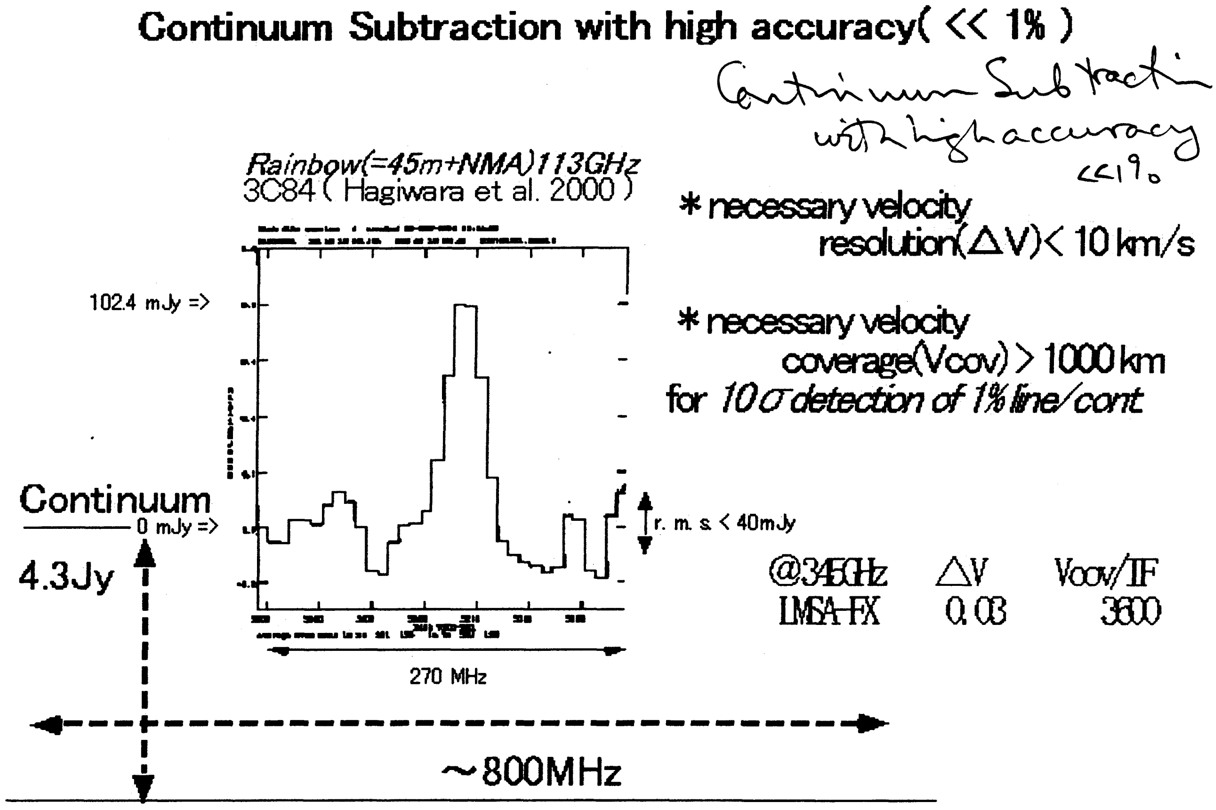

Figure 2. CO from the central region (< 1 kpc) of radio-loud galaxies[4]

1.2 REQUIREMENTS FROM ENHANCED ALMA SYSTEM

The enhanced ALMA means that ***ALMA will increase its sensitivity and obtain new capabilities at higher sub-millimeter wavelength due to the contribution of Japan***(see ALG report). It is now considered to consist of maximum about 80 antennas. ALMA SIS receivers will have their instantenious bandwidth of about 4GHz with better Trx. ALMA analog IF system will transmit both two sideband signals with both polarizations simultaneously from one receiver band. Thus the correlator system for the enhanced ALMA should process all the above analog data at one time to obtain ***better sensitivity*** and to ***save observing time***. If we proceed two polarization data at one time, we can always obtain two times better signal-to-noise ratio. In mm and sub-mm regions, several important molecular lines are existed in both upper and lower 4GHz bands (e.g., see Fig. 1), and for the higher sub-mm frequencies (> 600 GHz), good atmospheric condition (opacity < 1.0) will be occurred in the limited fraction of time(less than 40 % ; m\Matsushita et al.[7]). Thus simultaneous observations of both sidebands are effective to save observing time, especially for higher sub-mm observations.

Other than the sensitivity and saving observing time, more simple analog IF system will help us to reduce the analog parts and to ***save maintenance man-power and cost*** in case of the enhancement of the array.

2. HIGH-PERFORMANCE FX CORRELATOR SYSTEM FOR ENHANCED ALMA

2.1 COMPARISON OF FX AND XF ARCHITECTURE

First we will briefly review the comparison of the performance of FX and XF architecture. Originally Chikada et al.[8] described the cost-performance of FX and XF correlators. They calculated the total gate number of the FX-type correlator NG(FX) to that of the traditional XF correlator NG(XF) as a function of frequency channel number(n) and antenna number(Figure 8 in No.8 reference). They defined complexity of the operation Cg ; how many gates are needed to make one operation at unit clock frequency. Its unit is gate operation^{-1} MHz^{-1}. It is heavily depend on the technology. M is the total number of spectra obtained at one time, NO is the number of operation at unit time per one spectrum, and B is the bandwidth. Cg and NO are different between FX and XF.

NG = Cg x M x NO x B/n.

Cg in Nobeyama FX and XF type correlators(2-bit direct multiplier) were 400(F in FX type), 1100(X in FX type), and 30(XF type) in 1980s technologies. Here we again calculate Cg using the parameters of VSOP FX and UWBC[9]. Cg in 1990s' technologies are 570(F in FX type), 3900(X in FX type), and 21(XF type). Cg in X part of FX is larger than that in 1980s. However, rough trend about the ratio of NG(FX) to NG(XF) for n and M does not change between 1980s and 1990s. In case of 64 antennas with the same bandwidth, the ratios of NG(FX) and NF(XF) are calculated using both sets of Cg. They are shown in Figure 4. **In n > 1000,**

NG(FX)/NG(XF) < 0.1

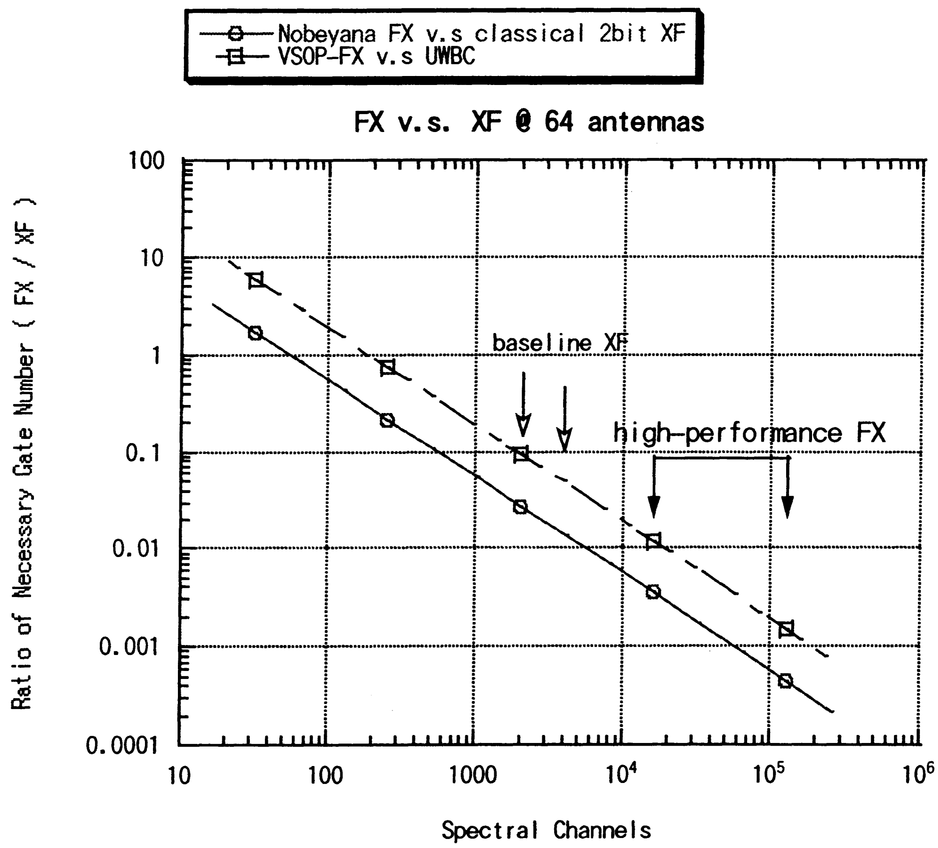

Figure 3. Ratio of necessary gate number of FX and XF

Other than the comparison of the necessary gate number, which corresponds to the cost-performance, several differences have been recognized between FX- and XF-type correlators. We made the score sheet of them in Table 1. Compared with XF correlator, FX loses its sensitivity due to the lack of FFT segment overlapping. Data overlapping in the time-domain is known to be an effective method to recover the sensitivity[8]. However, data averaging in the frequency-domain will make similar effect on the sensitivity of FX spectral data.

Table 1. Score Sheet of FX v.s XF

	FX	XF
Necessary gate number (shown in Fig. 3)	◎	△
Sensitivity	△	○
Bandwidth with high frequency resolution	◎	△
Application of multi-bit correlation	○	△
Initial developing cost	△(2 LSIs)	○(1 LSI)

2.2 SPECIFICATION OF HIGH-PERFORMANCE FX CORRELATOR

As the enhanced ALMA correlator system, **we propose high-performance FX correlator system** in order to satisfy the requirements described in section 1. The processing bandwidth per IF is 4096MHz assuming four IFs per antenna. The bandwidth does not depend on the IF numbers. Spectral resolving points at one F-part per IF is 128 x 1024 channels, and this number is also fixed for antenna and IF. We assume 2- or 3-bit sampling and correlation. *Main changing point from the very large correlator system previously proposed is **flexible frequency-channel smoothing**.* Just after the calculation of correlation, ***flexible frequency-channel smoothing*** is performed according to the request of observers. This function is *the main changing point from the very large correlator system previously proposed.* It reduces the output frequency data from 128 x 1024 to at most 16 x 1024 per IF. This method realizes the reduction of coat with maintaining the total bandwidth of 16GHz and the highest frequency resolution of 31.25 kHz simultaneously(Table 2). Total correlation number is 4 times 3160. This FX correlator system is characterized by the following performances : ultra-wideband(4096MHz), high frequency resolution by 256 x 1024 point FFT, and very large integration(3160 correlations / IF). This system should support the full polarization observations(RR, RL, LR, and LL correlations) and some kinds of single-dish mode observations.

We concluded that the "FX-type" correlator would be more suitable than the XF-type correlator for the above application : more than thousands of spectral channels and the correlations from a few tens of antennas (see Figure 3). The bandwidth per IF of 4096MHz corresponds to the instantenious bandwidth of ALMA SIS receivers with better Trx. We could always obtain both two sideband data with both polarizations simultaneously using 4 sets of the correlator system. It will contribute to obtain ***better sensitivity*** and to ***save observing time***. If we realize 3-bit sampling, we are able to increase the sensitivity from 88 % to 96 %. Other than the sensitivity and saving observing time, more simple analog IF system - the reduction of the number of IF from 8 to 4 - will reduce the analog parts and ***save mentenance man-power and cost***.

Table 2. Spectral resolving power of high-performance FX correlator system

	115GHz	345GHz	490GHz	850GHz
Velocity resolution (km/s)	0.08125	0.0272	0.0191	0.0110
Velocity coverage (km/s) / IF	10650	3550	2499	1441

High-performance FX correlator system consists of ultra-high speed A/D converters and a FX correlator. The sampling clock of the A/D converter is 8192 MHz with 2- or 3-bit sampling. The analog data from one IF of one antenna are sampled and de-multiplexed in the A/D converter, and 64 parallelized digital data are sent to the F-part of the FX correlator with 128MHz clock. In the F-part, delay compensation and 256 x 1024 - point FFT are performed for the 64 parallel data (Figure 5left). Functions of phase switching and fringe rotation are also supported in the F-part. In the X-part, the correlation of the 128 x 1024 - channel spectral data from different antennas is calculated and frequency-channel smoothing is performed. Then the number of frequency bin is reduced to 16 x 1024 or less and the smoothing spectral data are integrated (Figure 5right). We will summarize the specifications of high-performance FX correlator system in Table 3.

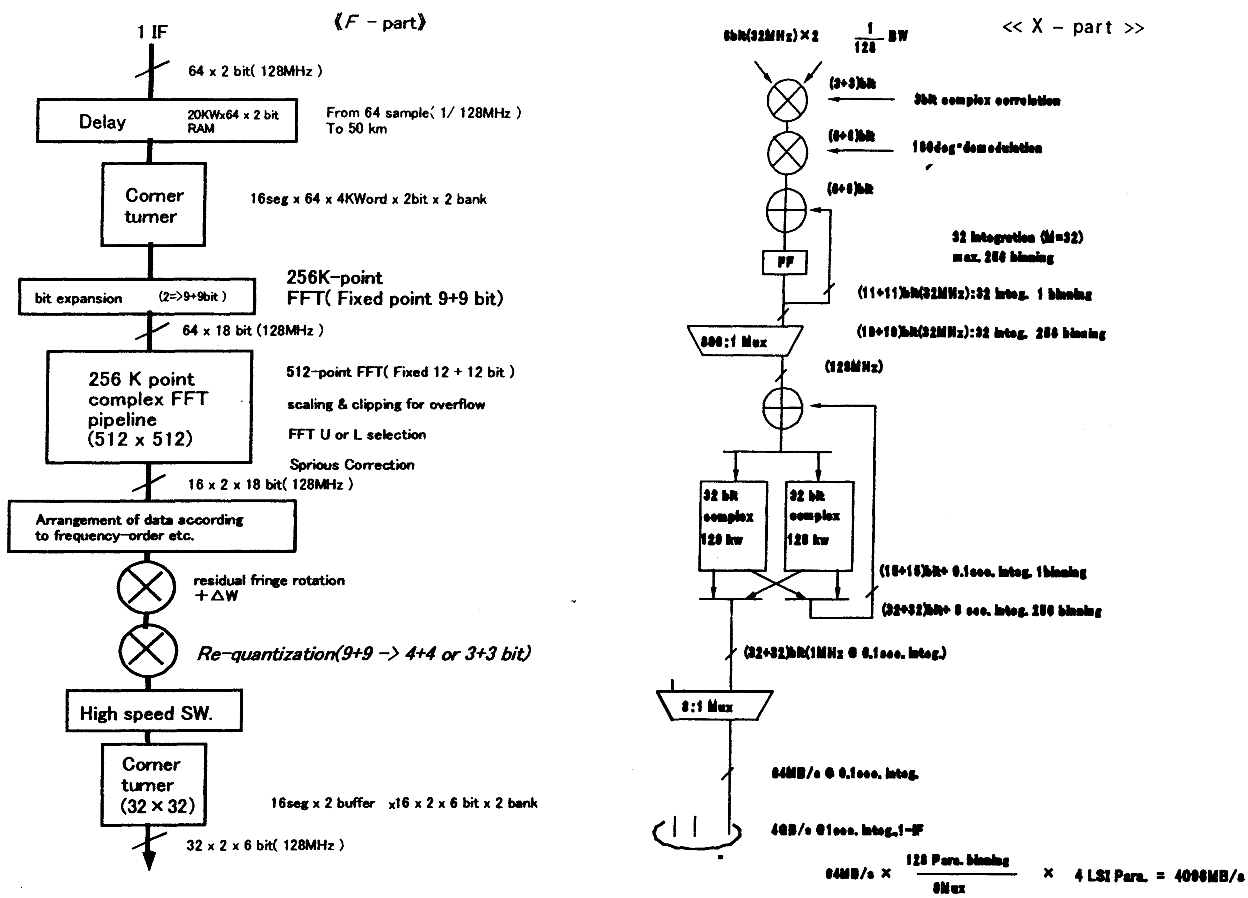

Figure 4. Block diagram of high-performance FX correlator. Left panel shows the F-part and the right panel shows the X-part.

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We install a new function, **re-quantization**, in the F-part of the FX correlator. After 256 x 1024-point FFT, the spectral data are normalized using auto-correlation data and we can decrease the bit number of the data sent to X-part. This function resolve the previous cabling problem of FX compared with XF, pointed out by Escoffier et al[10]. We have estimated the signal-to-noise ratio of the re-quantization of Gaussian noise with simulational study. It is about 0.96 with 3- or 4-bit re-quantization for a 512-channel spectrum with complex 18-bit expression.

Flexible frequency-channel smoothing is also newly applied for the spectral data just after the calculation of correlation in the X-part. Observers can determine the appropriate frequency-resolution for the corresponding frequency regions freely at the unit of highest frequency-resolution (see Table 2) over the full 4-GHz IF band. The example of the frequency-channel smoothing is shown in Figure 5. Such frequency binning has similar effect on the overlapping for recovering the sensitivity relative to XF correlator. The effect of binning on relative sensitivity is presented in Figure 6. We can obtain 5 % of relative loss of signal-to-noise ratio to XF correlator in the case of 8-channl binning, which is the average binning factor in the frequency-channel smoothing from 128K to 16K. The relative loss of 5 % corresponds to the increase of 0.6 %(=12% x 0.05) of 2-bit quantization noise.

Table 3. Specifications of high-performance FX correlator system for enhanced ALMA

<A/D>

Max. sampling speed	8192MHz
Sampling bit number	2-3bit
Block	S/H - 1:16 – 1:4 or S/H - 1:8 - 1:8
Output signal	2-3 bit 64 parallel
Output clock	128MHz

<FX>

Input signal	2-3 bit 64 parallel,
Clock	128MHz
Bandwidth per IF	4096MHz
number of FFT points	256 x 1024
Window function	YES
Re-quantization	YES
phase SW	YES
delta W correction	YES
Correlation bits	2 – 3 bits
Channel smooting	YES(16K, 8K, 4K, 2K, 1K*)
Min. integration time	16msec* faster for fewer channels (smoothing at X memory)
Number of antennas IF, and correlation	80*ant.3160corr.4IF
Max. data rate	4B x 2 x 16K / 0.1sec x 3160 = 404GB/sec/IF

*variable

Using this FX correlator system, **we can always map all the lines in the 4GHz DSB IF signals of both polarizations with enough velocity resolutions (< 0.1km/s at 100GHz) and obtain 4GHz-continuum data and line data with enough velocity coverage (> 1000 km/s at 850GHz) for each IF signal (Table 2).** *Realization of this correlator system will allow us to make breakthrough in both sub-millimeter line and continuum observations with enhanced ALMA.*

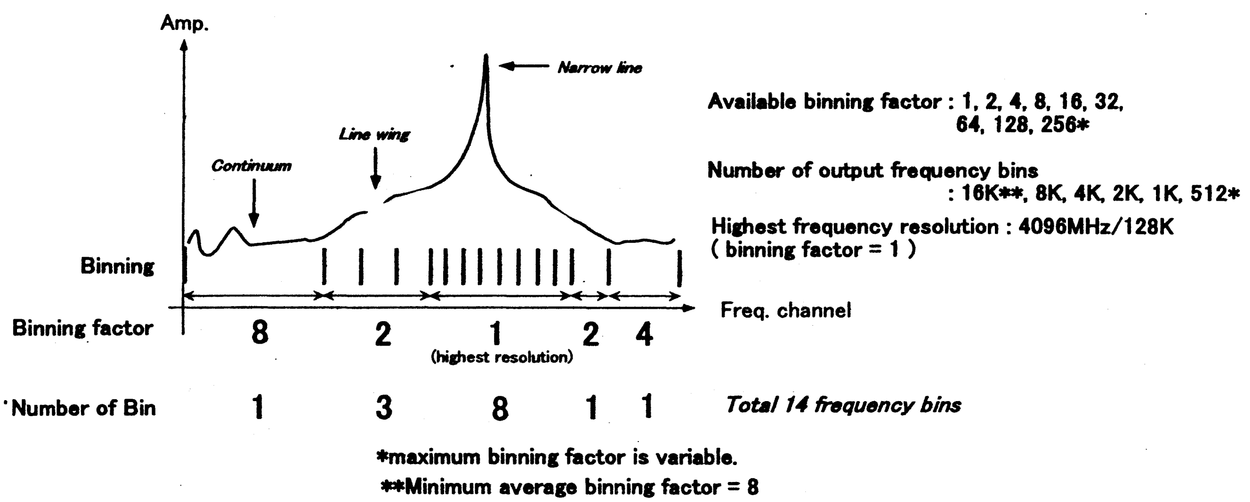

Figure 5. Example of the flexible frequency-region smoothing.

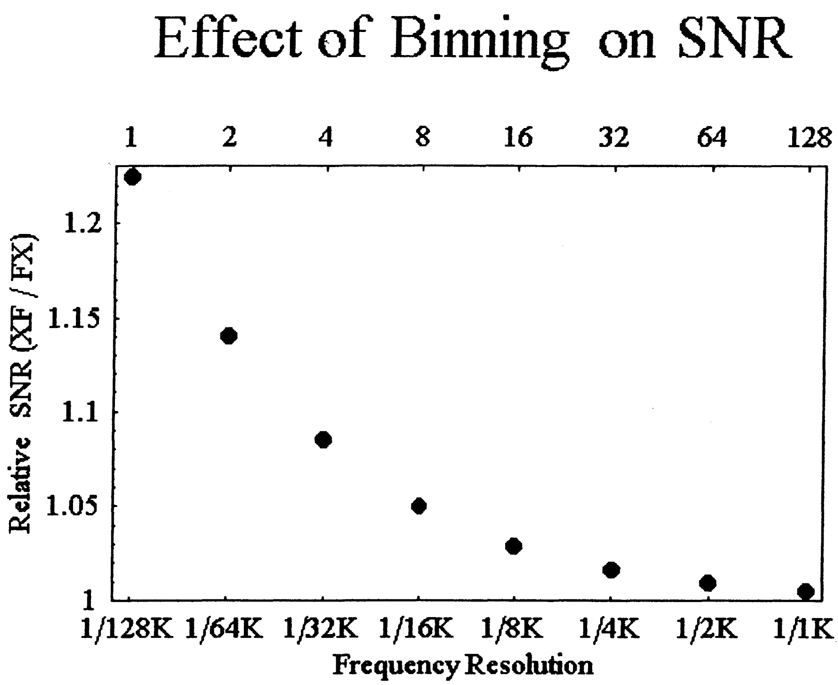

Figure 6. Effect of binning on relative FX signal-to-noise ratio to XF correlator

2.3 TECHNICAL KEY POINTS

The important technical issues to be resolved for the realization of the above correlator system : **1) ultra-high speed sampling (8192Mega sample/sec with 2 or 3bits), 2) a huge number of point FFT with enough computational accuracy, 3) power consumption of large LSI and pin limitation of boards between F- and X-part, and 4) large integration of circute for a few thousands of correlation.**

Now we have started the design and development of a minimum test system of the FX correlator to make experiments for the overcome of the technical issues 1) and 2) and to demonstrate the high-resolution and wideband correlator. This test system consists of two A/D converters and one FX spectro-correlator(1 baseline) with the bandwidth of 2048MHz. This correlator system has the "half" bandwidth of the final specifications, but the spectral resolving point is the same as the final one. Details of the test system and the progress of related experiments are described in Okumura et al.[11]

3. SIZE AND POWER ESTIMATE

Here we will roughly estimate the hardware size and power consumption. F-part consists of one delay-tracking board, two FFT boards, and two corner-turner boards including re-quantization and arragement of data-order. Five printed boards are necessary for F-part of one IF of one antenna. The total number of boards for F-part of 80 antennas per one IF is 400. In the X-part, 16 data-gathering boards, 16 correlation boards, and 2 multiplex boards are needed for the calculation of 3160 correlation and integration of 1/8 frequency-band data per one IF. Total printed boards of X-part per one IF is 272. We can reduce the amount of the circute of X-part to 1/4 applying the flexible frequency-channel smoothing(see section 2.2) and the method using a 'short-term' spectrum buffer previously reported in ASAC. Other than F- and X-parts, FX correlator has control part in order to interface the data and control network of ALMA system. It consists of 8 data-buffer boards, 4 CPU boards, and 8 "Gbit-ETHER" cards for the 1/8 frequency-band data per one IF. The total printed boards of controle part is

160. Thus the total printed boards for FX correlator per one IF is 832. We use relatively large back-plane to connect 20 – 30 printed boards. The number of back-plane for FX correlator per one IF is 20 for F-part, 8 for X-part, and 8 for control part. In this case, the size of the hardware of one IF is presented in Figure 7.

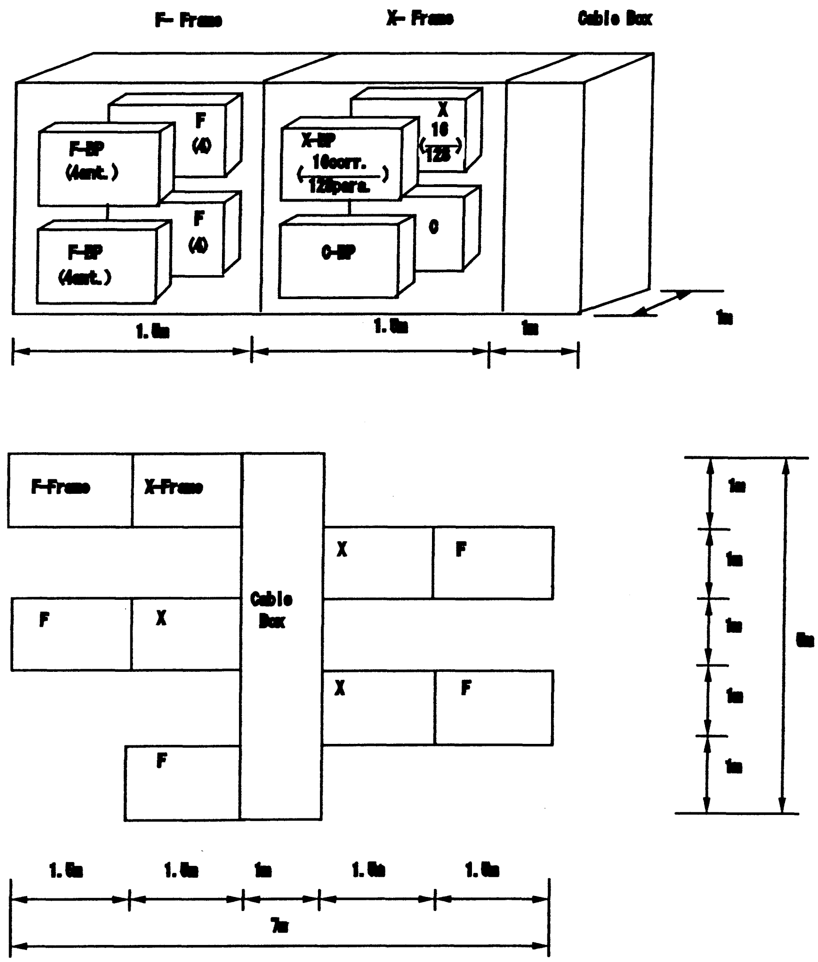

Figure 7. Hardware image of high-performance FX correlator (one IF)

Power consumption is also roughly estimated using the number of special-purpose LSIs. In the FX correlator for one IF, 640 FFT-LSI and 512 correlation-LSI are assumed with 0.18-micron gate-array. Typical power consumption of such gate-array installed M-gate circute is about 2 Watt. The total number of chips will be estimated about 4 times of the special-purpose LSIs in the case of FX. Thus the estimated total power consumption per one IF is 2Watt x 1152 x 4 ~ 10 kW.

4. PERSPECTIVES

We have successfully reduce the total amount of circute of the FX correlator becomes half compared to the very large FX correlator previously proposed due to the flexible frequency-channel smoothing(see section 2.2) and the method using a 'short-term' spectrum buffer previously reported in ASAC. So we have confirmed the estimated cost of the FX correlator previously announced at ASAC. However, for the observations of continuum and the line emission we know, the FX correlator still have much more scientific merits and nothing will be lost : we are able to proceed the wide-band (>1000km/s) and high-resolution(< 0.1 km/s) observations simultaneously. We will continue our efforts to make cost-reduction up to 40 % due to applications of new ideas for algorithm etc.

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