Very Large FX Correlator System for enhanced ALMA

Sachiko K. Okumura*[a], Yoshihiro Chikada[b], and Munetake Momose[c]

[a]Nobeyama Radio Observatory, National Astronomical Observatory, Nobeyama, Minamimaki,
Minamisaku, Nagano, 384-1305, Japan
[b]National Astronomical Observatory, Osawa, Mitaka, Tokyo, 181-8588, Japan
[c]Institute of Astrophysics and planetary science, Ibaraki University, Mito, Ibaraki, 310-8512, Japan

ABSTRACT

We are proposing a very large FX correlator system as an enhanced ALMA correlator. Maximum bandwidth per IF is 4096MHz. Spectral channels per baseline per IF is 128 x 1024 channels. The possible number of correlation is a few thousands per IF. This correlator system realizes both high spectral resolution (< 0.1km/s at 100GHz) and wideband (> 1000km/s at 850GHz) observations up to 850GHz. We have started the design and development of a minimum test system of the very large FX correlator in order to overcome several technical issues. This test system consists of two 2-bit A/D converters and one FX spectro-correlator. This correlator system has the bandwidth of 2048MHz, "half" bandwidth of the final specifications, but the spectral resolving point is the same as the final one. For the A/D converter, we are now measuring the sampling performance of high-speed sample-hold circute working up to 10GHz. For the FX correlator, we have finished the coefficient error estimation for the finite word length of FFT. More than 9-bit FFT calculation will make the coefficient error less than 3 %. We also apply a new function, re-quantization. It reduces the number of connection between F and X parts with almost keeping the sensitivity.

Keywords: Interferometry, spectroscopy, correlator, digital signal processing, sub-mm astronomy

1. INTRODUCTION

Atacama Large Millimeter Array (ALMA) is a new giant millimeter and sub-millimeter interferometer made with international collaboration of US and Europe (see http://www.mma.nrao.edu/). It consists of more than 50 antennas with 12-m diameter and has 10 receiver bands from 80 to 850 GHz. ALMA will image the universe with unprecedented sensitivity and sharpness at millimeter and sub-millimeter wavelength. Using ALMA, radio astronomers are going to observe various astronomical objects at a new window, sub-millimeter wavelength, as they do at millimeter wavelength now. In the sub-millimeter wavelength, we will observe " hot " interstellar matter around the active regions like proto-stars, late-type stars, starburst galaxies, and AGN. More and more sub-millimeter emission lines are excited in their molecular gas which have more than a few tens of degree K in excitation temperature, and larger flux of radiation is emitted from the dust heated by these active objects.

Now we are discussing the joint project of ALMA with Large Millimeter and Sub-millimeter Array(LMSA) originally planed in Japan. The joint project is called “enhanced ALMA”, which means that ALMA will increase its sensitivity and add new capabilities at higher sub-millimeter wavelength due to the contribution of Japan. Enhanced ALMA system will have nearly a hundred antennas, and we will be able to make the most sensitive sub-millimeter observations all over the world using the enhanced ALMA. This system allows us to make breakthrough in sub-millimeter astronomy.
In this paper we describe the requirements and specifications of the large spectro-correlator system for the enhanced ALMA, and present the contents of the design and development of a test system for the large correlator.

2. VERY LARGE FX CORRELATOR FOR ENHANCED ALMA

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

2.1 REQUIREMENTS FROM ENHANCED ALMA SYSTEM

Enhanced ALMA system is now considered to consist of maximum 96 antennas having four IF channels. We can always obtain both sideband signals with both polarization signals from one receiver band. Each IF signal has 4 GHz bandwidth because SIS receivers have its instantenious bandwidth of 4GHz. Thus the correlator system for the enhanced ALMA has to process the 4 sets of 4560 correlation data from 96 antennas, and the maximum bandwidth to calculate the correlation spectra for one IF signal is 4 GHz. Totally 16-GHz bandwidth correlation data should be calculated in the correlator system. This system should support the full polarization observations(RR, RL, LR, and LL correlations) and some kinds of single-dish mode observations.

2.2 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 with sub-millimeter observations[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 high excitation regions like Orion. More than a few tens of thousand spectral channels are needed over the 4-GHz bandwidth of IF 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 condition 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 invedtigate the molecular gas in the outer region of the disk 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 to study the gas in the inner edge of the disk. 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 a lot of emission line data simultaniously at one time. Thus we should make wideband(>> 100km/s) and high-resolution(0.1km/s) observations simultaneously to analyze all these physical conditions of the proto-planetary disks precisely. Multi-line imaging study for nearby low-mass star forming regions becomes popular at millimeter wavelength, e.g., $C^{18}O$(1-0), $H^{13}CO^+$(1-0), and ^{13}CO(1-0). Sub-millimeter multi-line imaging study will be more powerful tool to investigate the formation and evolution of the proto-planetary disks and proto-stars. 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, which correspond to wide velocity coverage more than 1000 km/s (2.8 GHz at 850GHz) will be needed for precise continuum subtraction[4] shown in Figure 2. We should support exciting serendipity like H_2O maser observations of NGC4258[5] shown in Figure 3. 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 forest in distant galaxies[6]. Such observations like Dumped Ly alpha forest might be interesting to investigate the 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].

Figure 3.CO from the central region (< 1 kpc) of radio-loud galaxies[5].

Therefore the enhanced ALMA correlator system should realizes both high spectral resolution (< 0.1 km/s at 100GHz) and wideband (> 1000 km/s at 850GHz) observations simultaneously up to 850GHz. This requirement is very much important for the success of the above sub-mm observations, especially at higher frequencies.

Table 1. Spectral resolving power of very large FX correlator system

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

2.3 SPECIFICATION OF VERY LARGE FX CORRELATOR

As the enhanced ALMA correlator system, we are proposing a following very large FX correlator system in order to satisfy the above requirements. Maximum bandwidth per IF is 4096MHz assuming four IF channels per antenna. The bandwidth does not depend on the IF numbers and spectral channels. Spectral channels per baseline per IF is 128 x 1024 channels, and the channel number is also fixed for baselines and IF. We assume 2- or 3-bit sampling. Total correlation number is 4 times 4560. 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 (Figure 8 in Reference No.7). This FX correlator system is characterized by the following performanes : ultra-wideband(4096MHz / IF), high frequency resolution by 128 x 1024 point FFT, and very large integration(4560 correlations / IF).

Table 2. Comparison of the test FX system and the very large FX correlator for enhanced ALMA

	test FX system	very large FX for enhanced ALMA
<A/D>		
Max. sampling speed	4096MHz	8192MHz
Sampling bit number	2bit	2-3bit
Block	S/H - 1:16 - 1:4 or	S/H - 1:16 – 1:4 or

		S/H - 1:8 - 1:8
Output signal	2 bit 64 parallel	2-3 bit 64 parallel
Output clock	64MHz	128MHz
<FX>		
Input signal	2 bit 64 parallel	2-3 bit 64 parallel,
Clock	64MHz	128MHz
Max. bandwidth	2048MHz	4096MHz
Overlapping	NO	YES?
Max. num. of FFT	256 x 1024	256 x 1024
Window function	NO	YES
Re-quantization	YES	YES
BW partitioning	NO	YES(2048, 1024? MHz)
Channel bunching	NO	YES(64K, 32K)
90/180 phase SW	YES	YES
delta W correction	YES	YES
Data compression	YES(at control WS)	YES(in the correlator? or control WS)
Min. integration time	0.64-3.2sec	< 0.1sec
Number of elements, IF, and correlation	2ant.1corr.1IF	max. 96ant.4560corr.4IF
Max. data rate(B/sec)	4B x 2 x 128K / 1sec about 1MB/sec	4B x 2 x 128K x 4560 x 4 / 0.1sec about 187GB/sec

Very large 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. In the X-part, the correlation of two sets of the 128 x 1024 - channel spectral data from different antennas is calculated and the correlated spectral data are integrated. Functions of phase switching and fringe rotation are supported in the FX correlator. The bunching of the spectral channels and the partitioning of the bandwidth are optional functions.

Using this FX correlator system, we can always map all the lines in the 4GHz DSB IF signals with enough velocity resolutions (< 0.1km/s at 100GHz ; see Table 1). Also we can obtain 4GHz-continuum data and line data with enough velocity coverage (> 1000 km/s at 850GHz ; see Table 1) for each IF signal. Realization of this correlator system will allow us to make breakthrough in both sub-millimeter line and continuum observations with enhanced ALMA.

3. DEVELOPMENT OF THE TEST SYSTEM FOR VERY LARGE FX CORRELATOR

3.1 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 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. Table 2 shows the comparison of the specifications of the test and final FX correlator systems.

3.2 TEST A/D CONVERTER

We have started the design and development of the 4096Msps 2bit test A/D converter. Analog signal is sampled with 4096MHz clock, and the 2-bit digital signal is de-multiplexed with 1:16 and 1:4. The output is 2-bit 64 parallel ECL data with 64 MHz clock. Goals of the development of this test A/D converter are to establish 8Gsps sampling technology, to confirm the sampling performance for radio astronomy (see section 3.1 technical key points 1)), and to measure the total 2GHz-BW spectral performance with the combination of the test FX correlator.

Figure 4. Block diagram of a high-speed sampling board of the test A/D converter

We designed the sampling and first DMUX part of the test A/D. Its block diagram is shown in Figure 4. We have made the evaluational board in order to measure the fundamental sampling performance of the high-speed sample-hold circute : sampling jitter, DC offset, and the width of the indicision region. On the board, one sample-hold LSI and one 1:16 DMUX LSI are implemented. We are able to make 1-bit sampling experiments of analog signal up to 8GHz. We have just confirmed that input noise data are correctly sampled with 8192 MHz clock. After the confirmation of the sampling performance, 2bit A/D converters will be manufactured using the above LSIs.

3.3 TEST FX CORRELATOR

We are developing the test FX correlator in order to overcome the above technical key points 2) and part of 3) in section 3.1. Using this test correlator, we confirm the computational accuracy for the 256 x 1024-points FFT and apply re-quantization to the spectral data. Re-quantization is the new idea to reduce the number of connection between F-part and X-part of the FX-type correlator. The test FX correlator consists of two F-parts and one X-part. It calculates one cross-correlation spectrum or one auto-correlation spectrum of 128 x 1024 frequency channels

.

We have estimated the coefficient error of twiddle factor for the finite word length of 256 x 1024 point FFT. We considered that real coefficients (a_{jk}) are expressed by the multiplex of true coefficients (A_{jk}) and error function (E_{jk}), $a_{ik} = A_{ik}E_{ik}$. Suffix j and k mean the series of Fourier transform, and in the case of j = 1,…,N and k = 1,…,M, a_{jk} is the coefficients of N x M FFT. E_{jk} behaves similar to the widow function of FFT, and Ejk is convolved to the time series of data. Thus the Fourier transform of the error function E_{jk}, which we call coefficient error profile, is multiplied to the instrumental profile of the spectral signal. Here we assume that the effect of coefficient error at each FFT stage is propagated to the latter stages as the superposition of all the coefficient error profiles.

Figure 5. Block diagram of the test FX correlator. Left panel shows the F-part and the right panel shows the X-part.

256 x 1024-point FFT in the test FX correlator is divided to two sets of 512-point FFT and the multiplication of 512x512 twiddle factor. We use Radix-2 architecture for the 512-point FFT. We have calculated the coefficient error profiles of the following cases : 1) N=2 and M=1,2,4,8,16,32,64,128,256, 2) N=M=512. Here we decided to use the fixed-point expression to simplify the FFT circute integrated into the LSI. Real twiddle factors are expressed with fixed-point rounded to the nearest whole number. In the case of 9-bit expression including a sign bit, the main lobe of the superposition of all the coefficient error profiles is about 0.96 and the first side lobe is about 0.0046. These are multiplied to the instrumental profile of the spectrum, and that causes the decrease of the gain and the addition of noise for a correlation power spectrum. The decrease of the gain of each channel is about 8 %, and the additive noise due to all the side lobes of the superposition of the error profiles is estimated to be about 3 %. Therefore more than 9-bit fixed point FFT calculation will make the noise due to the coefficient error less than 3 %.

We also install a new function, re-quantization, for the test 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. 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.

Block diagram of the F- and X-part of the test correlator is shown in Figure 5. Input of the test FX correlator is 2bit 64 parallel ECL data at 64 MHz clock. The data are first put into the delay compensation buffer. We are able to control it for both the usual delay tracking and the wave-front clock. After delay compensation, 256 x 1024-point FFT is performed with fixed point 18bit complex expression(real part 9bit and imaginary part 9bit including sign bits). 256 x 1024-point FFT is divided to two sets of 512-point FFT and the multiplication of 512x512 twiddle factor. The 64 parallel data are set to 32 sets of input data for the Radix-2 512-point FFT, and the 256 x 1024-point FFT is performed with parallel processing. After the FFT, 90-degree phase demodulation, delta W correction and re-quantization are performed for the 16 sets of the spectral data. The bit number is reduced from 18bit to 6 or 8 bit with re-quantization. Then the data are sent to the X-part and the complex correlation is calculated with 6 or 8 bit. To confirm the performance of re-quantization, we can select the re-quantized and correlated number of bits, 6 or 8 bits. After the correlation, 180-degree phase demodulation is performed, and the data are integrated to 0.64 – 3.2 sec. In the test correlator, only one LSI, 512-point FFT LSI, is designed and developed using 0.35 micron process gate array having a capacity of 1 Mega gates. Now the LSI design is almost finished and we use about 500 k gate for the 512-point FFT.

4. PERSPECTIVES

Now we started the design and development of very large FX correlator system for enhanced ALMA. Some of the technical key points will be overcome through our experiments using the test A/D converters and test FX correlator. Remaining technical points are the limit of power consumption of large LSIs and the large integration of circuit. They are heavily dependent on the digital technology available to us. Other than these technical points, mass production of hundreds of high-speed A/D converters and the huge data transfer to the achieve system have to be discussed in more detail in the future.

5. ACKNOWEDGEMENTS

We are grateful to Seiichi Sakamoto, Masato Tsuboi, Tetsuo Hasegawa, and Yasuo Fukui for fruitful discussions about the scientific requirements to the FX correlaror. A part of this work is financially supported by the grant of Toray Science Foundation.

6. REFERENCES

1. M. P. Rupen, D. S. Shepherd, and M. C. H. Wright, "Astronomical Requirements for the Millimeter Array Correlator", ALMA library (http://www.mma.nrao.edu/library/index.html), 1998
2. P. Schilke, T. D. Groesbeck, G. A. Blake, and T. G. Phillips, "A Line Survey of Orion KL from 325 to 360 GHz", *Astrophys. J. Supple.* 108, p301, 1997
3. C. Hayashi, K. Nakazawa, and Y. Nakagawa, "Formation of the solar system", *Protostars and planets II*, pp1100-1153, University of Arizona Press, Tucson, AZ, 1985 et al. 1985
4. Y. Hagiwara et al. 2000 in preparation.

5. M. Miyoshi, J. Moran, J. Herrnstein, L. Greenhill, N.Nakai, P.Diamond, and M. Inoue, “Evidence for a Black Hole from High Rotation Velocities in a Sub-pc Region of NGC4258”, *Nature*, **373**, pp.127-129, 1995.
6. T. Wiklind and F. Combes, “CO, HCO+ and HCN absorption in the gravitational lens candidate B02218+357 at z = 0.685”, *Astron. & Astrophys*, **299**, p382, 1995
7. Y. Chikada, M. Ishiguro, H.Hirabayashi, M. Morimoto, K. I. Morita, K. Miyazawa, K. Nagane, K. Murata, A. Tojo, S. Inoue, T. Kanzawa, and H. Iwashita, “A Digital FFT Spectro-Correlator for Radio Astronomy”, *Proceedings of an International Symposium Indirect Imaging Measurement and Processings*, p387, Cambridge University Press, Cambridge, England, New York, NY, 1983

---

[*] Correspondance: Email: sokumura@nro.nao.ac.jp