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First Astronomical Fringe of a Test Correlator for the ALMA: Simultaneous Achievement of Wideband and High Resolution

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Abstract

The first astronomical fringe of a test correlator for the Atacama Large Millimeter/Submillimeter Array (ALMA) is obtained. The newly-developed test correlator system consists of two 4096-Msps Analog-to-Digital Converters (ADCs) and an FX-type correlator that can divide a 2-GHz correlation signal from one baseline into 131072 frequency channels. A fringe spectrum that contains 20 line features as well as continuum emission at $\sim$86.2 GHz was obtained by an interferometric observation of the Orion-KL regions using this test system connected to the Nobeyama Millimeter Array (NMA), demonstrating that the realization of high frequency resolution over a wide bandwidth is technically feasible. The installation of such a correlator system in the ALMA will greatly enhance its capability of multi-line imaging.

Key words: instrumentation:interferometers–techniques:spectroscopic–radio lines:general

1. Introduction

The Atacama Large Millimeter/Submillimeter Array (ALMA), a joint project of Europe, North America, and Japan, as a prospective partner, will consist of 64 antennas of 12-m diameter and a receiving system with 8 IF-bands, each of which has 2-GHz bandwidth in the single sideband (SSB) mode. Its large collecting area and instantaneous frequency coverage will enable us to carry out sensitive and efficient observations at millimeter and submillimeter wavelengths. At these wavelengths there are many line emissions arising from molecular/atomic/ionic species as well as dust continuum emission; these are important probes to study the physical and chemical properties and kinematics of the interstellar medium.

The simultaneous detection of continuum emission with a wide bandwidth and line emission with a high velocity-resolution using ALMA will open a door to new types of science (Momose et al. 2002). The current scientific requirement for the maximum frequency resolution of ALMA is $\sim$ 5 kHz to achieve sufficient velocity resolution, even when a line in the 40-GHz band is observed. Although it is not required to achieve 5-kHz resolution over the full range of The 2-GHz IF-band, a cross correlator that can *simultaneously* realize high frequency-resolution ($\sim$ 5 kHz) and a wide frequency coverage (2 GHz) is an ideal instrument for ALMA. The development of such a correlator, however, is technically difficult because faster signal processing is required.

As the first step to realize a correlator that simultaneously fulfills the ALMA requirements, we developed a test correlator system. It consists of (i) 2-bit analog-to-digital converters (ADCs) working at a 4-GHz sampling rate (Okiura et al. 2002) and (ii) an FX-type digital correlator that can divide a 2-GHz correlation signal from one baseline into 131072 frequency components (Iguchi et al. 2002). This paper presents the first astronomical fringe of this test correlator system connected to the Nobeyama Millimeter Array (NMA). An outline of this paper is as follows: capabilities and designs of digital spectral correlators, including our test correlator, are briefly described in section 2; the first fringe of the test correlator system is presented in section 3, and future prospects are discussed in section 4.

2. Capabilities and Designs of Digital Cross Correlators and the Test Correlator

For a cross correlator in radio interferometry, digital implementation has advantage over analog circuits in time-delay compensation and correlation calculations. Figure 1 shows the specifications of digital correlators being operated in connected radio interferometers. Their capability, which depends on the gate numbers in one LSI chip, can approximately be expressed by

$$\mathrm{N n_{lag} f_s \propto n_{ch}(n_{ch}\Delta f)}, \qquad (1)$$

where N is the number of LSIs implemented in a correlator, $n_{\rm lag}$ the number of correlation lags

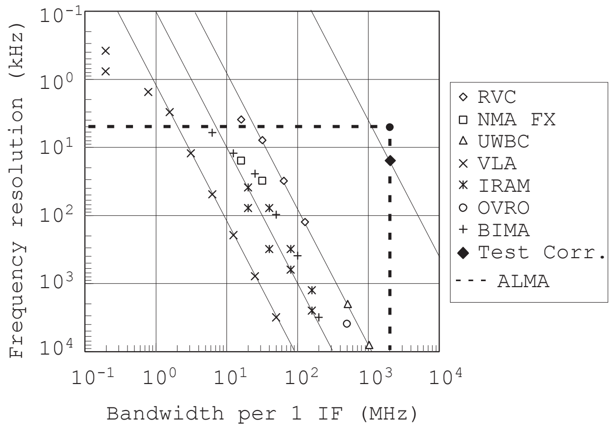

Fig. 1. Specifications of the frequency-resolution and bandwidth for several correlators. RVC is reported by Iguchi et al. (2000), NMA-FX by Shibata (1996), UWBC by Okumura et al. (2000), and the test correlator by Iguchi et al. (2002). Correlators of the VLA, IRAM, OVRO, and BIMA are also shown based on their Web pages or status reports. The scientific requirements for the ALMA are shown by the dashed lines.

comprised in one chip at a sampling frequency of f_s, $n_{\rm ch}$ the number of frequency channels, and Δf the frequency resolution. As shown in figure 1, the capabilities of a correlator that has different observing modes are on the slope where the value shown in equation (1) is constant.

The capability of the test correlator is also plotted in figure 1, showing that it is technically challenging. Table 1 compares the specifications between the test correlator and the FX correlator being operated in the NMA. The test correlator can achieve a higher frequency-resolution than the NMA FX over a much wider bandwidth, though the resolution is slightly lower than the ALMA requirement. There are two basic designs for a digital correlator: the XF-type in which the cross-correllation is calculated before Fourier transformation, and the FX-type in which Fourier transformation is performed before cross multiplication (Thompson et al. 2001). In this test correlator, the FX-architecture is adopted. More detailed information on the architecture and functions of the test correlator can be found in Iguchi et al. (2002) and a subsequent paper (S.K.Okumura et al. in preparation).

3. First Fringe Detection of the Test Correlator

3.1. Observations with the NMA

Interferometric observations to obtain the first astronomical fringe of the test correlator system were carried out during 2002 March 13 – 14. The field center was set to be the position of the SiO maser in the Orion KL regions. The center frequency was 86.152452 GHz, adjacent to the maser frequency. Figure 2 shows a block diagram of the observational setup. IF signals of 2-GHz bandwidth from the two antennas, B and F, 34 m apart from each other, were put into the ADCs of the test system. Each receiver was operated in the double sideband (DSB) mode.

Table 1. Comparison of NMA-FX and Test Correlators

	NMA FX	Test Corr.
Bandwidth (MHz)	32	2048
Spectral channels	1024	131072
Frequency resolution (kHz)	31.25	15.625

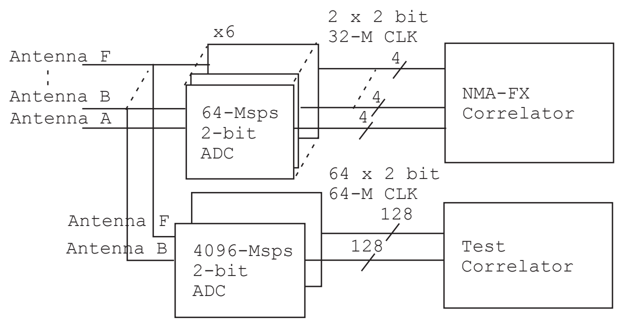

Fig. 2. Block diagram of the observational setup.

A phase-switching technique, consisting of 90°- and 180°- modulations at the local oscillators and synchronized demodulations at the correlator stage, was employed to suppress the image-band signal and DC-bias. IF signals from all of the antennas were also supplied to the NMA FX correlator, enabling us to simultaneously obtain data from both the correlators.

In the following, only the time-averaged fringe spectrum is presented. When the time-averaged spectrum is calculated, phase errors due to the atmospheric fluctuation and baseline error were corrected by assuming that the phase of the SiO maser sampled every 10.2 seconds should be zero. The passband characteristics, obtained by a 60-min observation of the quasar 3C 279 with the same setup as shown in figure 2, was calibrated after a time average.

3.2. Results

Overall 2048-MHz and 131072-channel fringe spectra of the Orion-KL regions, obtained by 70-min integration are shown in figure 3. It is the first time to obtain such a wide-band astronomical fringe from a *single* correlation product of digitized signals; 20 line features can be found by a careful inspection of the spectrum, as listed in table 2. All of the features can be identified as some known transition of a gas species, implying that the test correlator system correctly divided into different frequency components. The phase of the spectrum made by bunching each set of 128 adjacent channels (figure 4) is well-ordered along the frequency axis, indicating that the continuum emission from the Orion-KL regions is also detected with a 2-GHz bandwidth. These results clearly demonstrate the simultaneous capability of a wide frequency coverage and high frequency-resolution of the test correlator system.

Figure 3 also presents close-up views of some line features, showing differences not only

Table 2. Identification of the line features in figure 3.

Lines*	Freq.* (GHz)	Amp.†
OCS(7–6)	85.139108	2.2
CH_3CCH [5(1)–4(1)]	85.4556665	1.1
CH_3CCH [5(0)–4(0)]	85.4573002	1.2
CH_3OH [6(-2)–7(-1)E]	85.56797	1.8
$^{29}SiO(2–1;v=0)$	85.759132	1.3
$HCOOCH_3$[7(6,2)–6(6,1) A+E]	85.926858	1.1
$HCOOCH_3$[7(5,2)–6(5,1) E]	86.02108	0.67
$HCOOCH_3$[7(5,3)–6(5,2) A]	86.02943	0.78
$HC^{15}N$(1–0)	86.054961	1.8
SO[2(2)–1(1)]	86.09355	3.1
$HCOOCH_3$[7(4,4)–6(4,3) A]	86.21005	1.0
$HCOOCH_3$[7(4,3)–6(4,2) E]	86.22361	1.1
SiO(2–1;v=1)	86.243442	100
$HCOOCH_3$[7(3,5)–6(3,4) A]	86.26579	0.89
$H^{13}CN$[1-0;F=1–1]	86.340	2.7
CH_3OH[7(2)–6(3) A−]	86.61576	2.7
SO_2[8(3,5)–9(2,8)]	86.639108	2.0
CH_3CH_2CN[10(1,10)–9(1,9)]	86.819851	2.4
SiO(2-1;v=0)	86.846998	4.4
CH_3OH[7(2)–6(3) A+]	86.90306	2.2

* from "NIST Recommended Rest Frequencies for Observed Interstellar Molecular Microwave Transitions" by F. J. Lovas (http://physics.nist.gov/cgi-bin/micro/table5/start.pl).

† Peak value, normalized so that the SiO maser is 100.

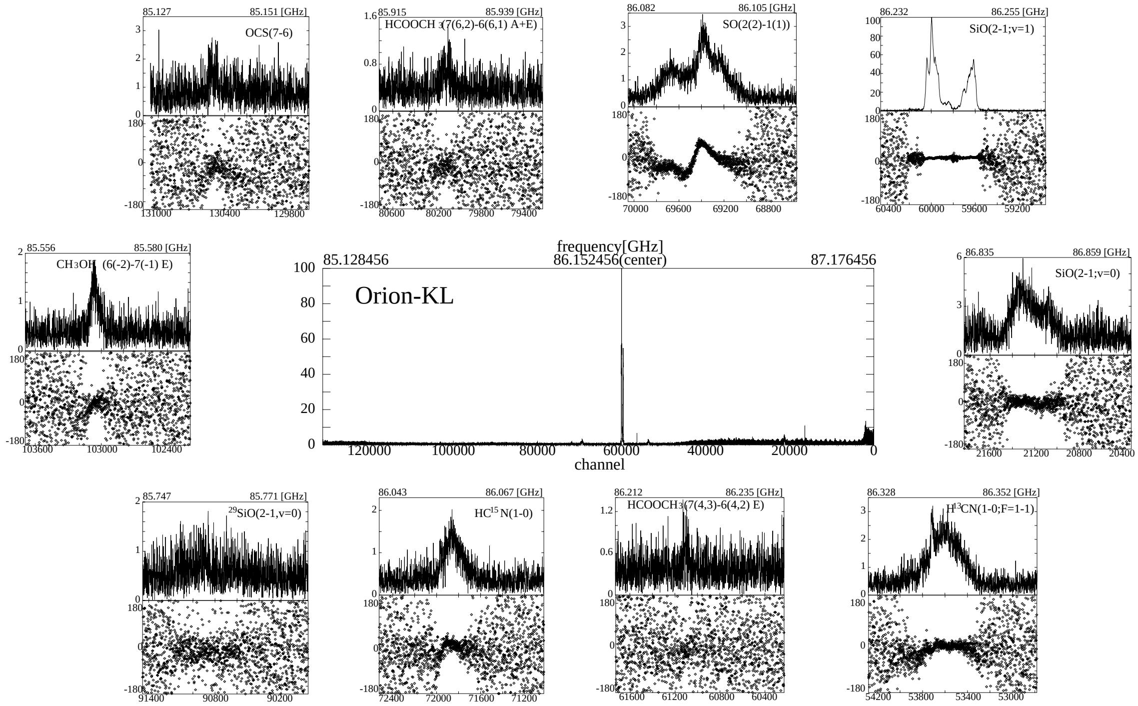

Fig. 3. Fringe amplitude of the Orion-KL regions with the test correlator system (*center*) and close-up views of some line features (*surrounding*). The amplitude is normalized so that the peak of the SiO maser is 100. The prominent amplitude fluctuation in channels $0-40000$ is due to the lower sensitivity of the video band (0 – 500 MHz) in the NMA IF-system. The abscissa of each close-up view covers the regions of ± 40.7 km s^{-1} (or ± 750 channels) around its center $v_{\rm LSR} = 0$ km s^{-1}, and the upper and lower panels show the amplitude and phase, respectively. Note that the band edge, 131072nd channel, can be seen in the close-up of the OCS line feature.

in intensity, but also in spatial distribution or velocity width among the line features. For example, the SO[2(2)–1(1)] emission, originating from the "expanding doughnut" with $\sim 20''$ in size (Plambeck et al. 1982), shows a remarkable variation of the phase along the frequency axis, corresponding to a systematic change in the spatial distribution with the line-of-sight velocity. On the other hand, the phases of both the maser and thermal lines of SiO, whose distributions are confined to near the field center (Wright et al. 1995), are almost flat. Molecules that are rich in the "hot core" (SiO, SO, HCN) show a wide velocity width, while those mainly distributed in the "compact ridge" ($HCOOCH_3$, CH_3OH, OSC) have a narrower velocity width (Minh et al. 1993; Wright et al. 1996).

Figure 5 compares the two SiO maser spectra simultaneously obtained with the test correlator system and the NMA-FX, showing perfect agreement over the line-emitting velocities, though the test correlator has twice higher frequency resolution. To evaluate the performance of the test correlator system, we estimated the signal-to-noise ratio (SNR) from the rms deviation of the phase in the frequency range of ± 7.8 MHz (corresponding to ± 50 channels of the test correlator) around the peak of the SiO maser (Thompson et al 2001). The SNR of the test

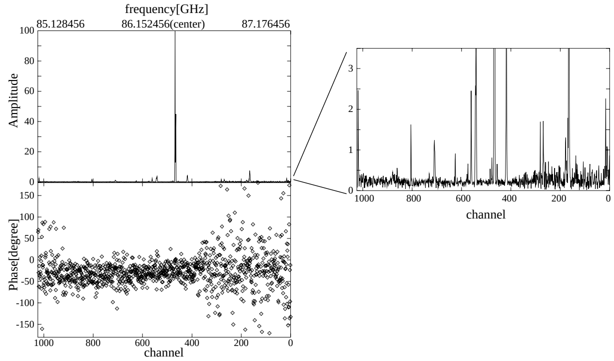

Fig. 4. Spectrum made by bunching each set of 128 frequency channels. The amplitude is normalized in the same manner as in figure 3

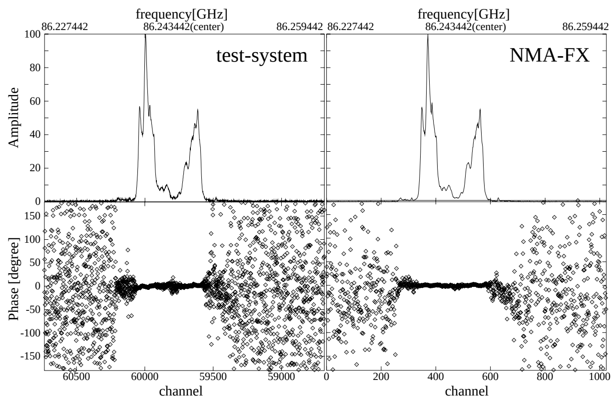

Fig. 5. Comparison of the SiO fringe spectra with a 32-MHz bandwidth between the test correlator and the NMA-FX correlator. The upper panels show the amplitude, while the lower panels show the phase. The amplitude is normalized in the same manner as in figure 3

correlator system was lower than that of the NMA-FX by about 38 %. This is mostly attributed to the incomplete setting of the ADCs; the threshold voltage in each ADC could not be tuned well when this experiment was carried out.

4. Future Prospects

We have successfully obtained the first astronomical fringe spectrum of the test correlator, demonstrating that the realization of high frequency-resolution over a wide bandwidth is technically feasible. Although the test correlator does not fulfill the ALMA specification, it will become possible to realize ~ 5 kHz resolution within the next few years by employing more advanced technology of digital implementation. Our observation using the test correlator has detected 20 features of line emission (table 2), even with a short integration time and a small collecting area. Since ALMA will have much higher sensitivity and better angular resolution, a correlator like our test system will add enhanced capability to conduct extensive multi-line imaging of many star-forming regions, not only in our Galaxy, but also in nearby galaxies.

Furthermore, such a correlator will be beneficial for various scientific programs with ALMA, e.g., systematic searches for narrow absorption features toward high-z quasars, or detailed studies of molecular tori associated with active galactic nuclei (Momose et al. 2002).

Although the test correlator can output 130-thousand frequency channels per correlation product, it is unrealistic to acquire such a large number of channels from each product in the ALMA case, because the data rate for the signal transmission or archiving system would become tremendously large. From a scientific point of view, it is also unnecessary to obtain all of the frequency components without smoothing: higher velocity-resolution should remain only in the ranges where a line feature is located, but the continuum components in the other ranges can be averaged and gathered into wider frequency channels after a passband calibration. Our obtained spectrum (figure 3), for example, contains 20 line features, each of which has a width of $\sim 10^3$ channels. Hence, the amount of data can be reduced by a factor of ~ 5 without any significant loss of information with heterogeneous channelization in the post signal processing.

The FX architecture, in which different frequency components in the signal from each antenna are divided before taking cross correlations, enables us to easily arrange such flexible channelization within one correlation product, and therefore seems suitable for an ALMA correlator. However, some architecture between the XF and FX (see Thompson et al. 2001) may also be promising. A further design study should be required to choose the optimum architecture for such a high-performance correlator system and to accommodate it into the IF- and data-transmission systems of ALMA.

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