Enhanced Science with the 2nd-Generation Correlator for the Atacama Large Millimeter / Submillimeter Array (ALMA)

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ABSTRACT

This paper presents scientific benefit brought by the 2nd-Generation Correlator for the Atacama Large Millimeter / Submillimeter Array (ALMA). The 2nd-Generation Correlator can simultaneously achieve both high frequency-resolution and wide frequency-coverage, opening a door to new types of science with the ALMA. In this paper three examples of such science are discussed in detailed.

1. INTRODUCTION

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 12m diameter and a receiving system with 8 IF-bands, each of which has 2 GHz bandwidth in 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 a lot of line emissions arising from molecular/atomic/ionic species as well as dust continuum emission, and these are important probes to study physical or chemical property and kinematics of the interstellar medium. Therefore, cross correlator that can simultaneously realize high frequency-resolution and wide frequency-coverage is a desirable instrument for the ALMA, and design and development activities to realize such a correlator (so called "2nd-Generation Correlator", or "2G Correlator") have been endorsed by the ALMA Science Advisory Committee (ASAC Report, October 2001).

This paper presents scientific benefit brought by the 2G Correlator. Specifications of the 2G Correlator currently studied are briefly described in § 2, and three examples of science that will greatly be progressed with the 2G Correlator are discussed in § 3.

2. SPECIFICATIONS OF THE 2G CORRELATOR

The 2G Correlator is aimed to provide three major improvements in comparison with the Baseline (or 1st-Generation) Correlator: (i) more than ten times higher spectral resolution, or larger number of spectral channels (> 8k per baseline) at the maximum bandwidth, (ii) 8.3 % higher sensitivity for continuum emission with fully 3-bit signal processing without sacrifice of the bandwidth, and (iii) flexible and efficient setting for both the continuum and line emissions by heterogeneous channelization in individual products, or IF bands. Fig. 1 shows the comparisons of the specifications between the Baseline Correlator and the FX-type 2G Correlator that is being studied by the Japanese Group (for more detailed, see [1] and [2]). It should be noted that European group is also studying a Hybrid XF-type Correlator which has similar specifications to the FX-type correlator. As show in Fig. 1, the 2G Correlator can *simultaneously* achieve high frequency-resolution *and* wide frequency-coverage, although the Baseline Correlator with XF-type architecture can achieve comparable performance to the 2G Correlator along each axis. This advantage of the 2G Correlator is mainly due to the difference in architecture; the 2G Correlator will have an architecture in which different frequency components in the signal from each antenna are divided before taking cross correlations, enabling us to arrange flexible channelization within one correlation product.

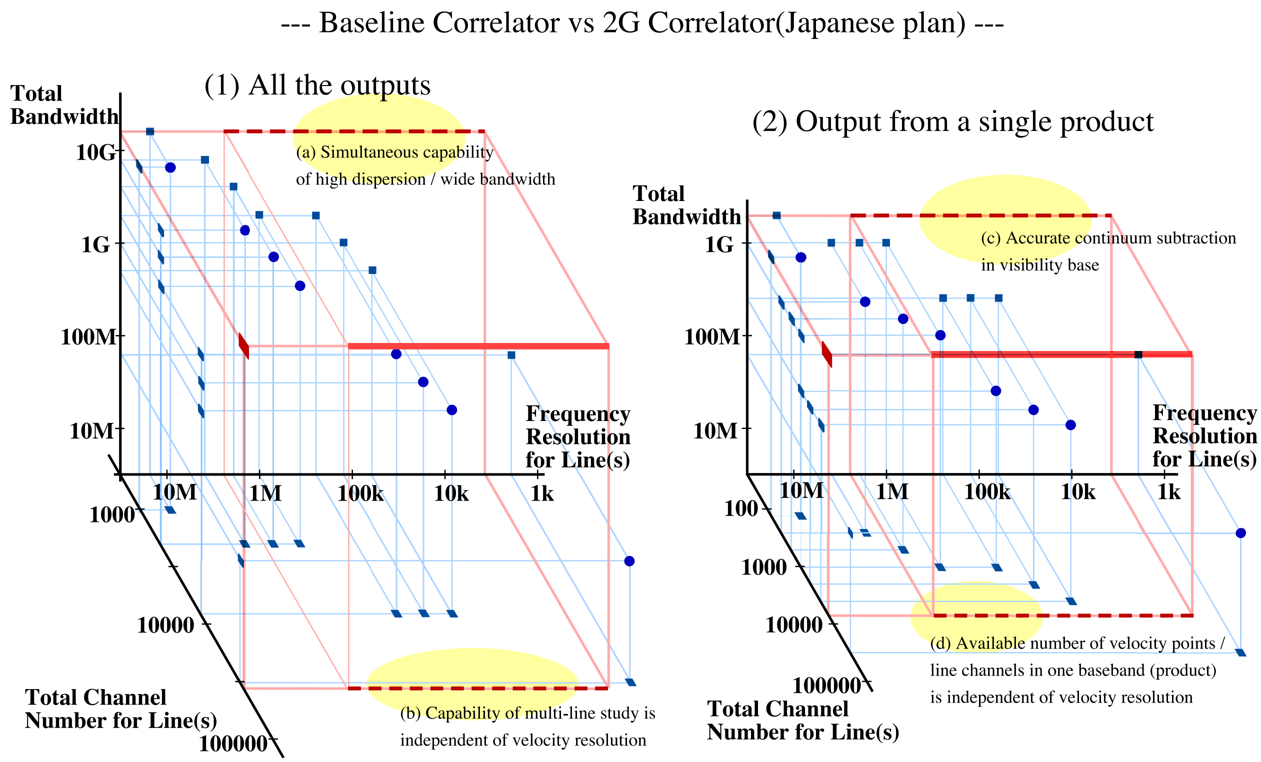

Figure 1: Comparisons of the specifications between the Baseline Correlator and the 2G Correlator planned by the Japanese working group. Specs are shown in the "space" composed by (i) total channels for line(s), (ii) frequency resolution for line(s), and (iii) total bandwidth. Blue dots in the space represent typical observing modes of the Baseline Correlator, and their projections onto each plane are shown by blue squares. Red thick lines represent the specifications of the 2G Correlator, and their projections onto each plane are shown by dashed lines. The left shows the cases for all the outputs (i.e., 8 IFs) and the right shows for a single product (1 IF). Yellow shade in each plane indicates the parameter spaces only attainable with the 2G Correlator.

The 2G Correlator will not only save the observing time in spectroscopic programs but also open a door to new types of sciences. In particular, it is quite beneficial to comprehensive but time consuming observations of highly ranked scientific targets, as described below.

3. SCIENCE WITH THE 2ND-GENERATION CORRELATOR

3.1. Multi-Line Study of Star-Forming Regions and Protoplanetary Disks

The first example of science that will greatly be enhanced by the 2G Correlator is multi-line study of galactic and extra-galactic star forming regions. Multi-line imaging will become a standard observing mode of the ALMA because its high sensitivity will make simultaneous imaging of many lines quite feasible. In star-forming regions or protoplanetary disks around young stars, it is expected that there are significant variations of temperature, gas density, kinematics and UV-field strength. In fact, interferometric spectral line survey of the core of the Orion molecular cloud at $\lambda = 1.3$ mm revealed significant differences in spatial distributions among the observed lines [3]: molecules that deeply relate to the grain mantle constituents are found in the vicinity of young stars while more fragile or complex molecules are seen further from the stars, suggesting strong excitation/chemical gradients exist near the massive young stars.

Combination of high angular resolution, high sensitivity and wide frequency coverage by the ALMA with the 2G Correlator can allow us to efficiently make similar observations toward many star forming regions, including those in nearby galaxies. Direct estimate of excitation temperature and column density of each gas species can be made by comparisons of line intensities among its various transitions. Such study will thoroughly reveal differences in spatial distributions and velocity fields among the observed molecular/atomic/ionic species on even tiny scales, and the connection between the properties of the interstellar medium and its external conditions will be understood.

In massive-star forming regions rich line features will be observed especially at submillimeter wavelengths (see Fig. 2), therefore accurate decomposition into line features and the continuum level of dust radiation should be required. This can also be achieved with the 2G correlator that can simultaneously realize high frequency-resolution and wide frequency-coverage.

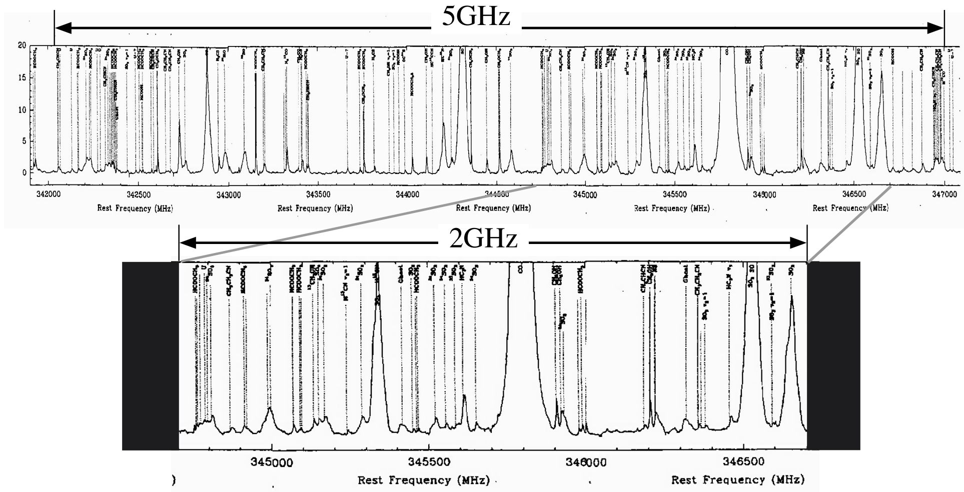

Figure 2: Part of the spectrum at $\lambda \sim 850\mu$m from the Orion KL regions with the Caltech Submillimeter Telescope [4]. More than a thousand lines are detected in the frequency rage of $325-360$ GHz by the observations whose sensitivity is $0.1 - 0.5$ K. The 2G correlator will efficiently reveal the line-by-line differences in column density distributions or excitation temperature with fine velocity resolution toward a lot of star-forming regions.

3.2. Observations of Molecular Gas toward AGNs

Observations of molecular tori associated with active galactic nuclei (AGNs) are also promising. It has been revealed by single-dish observations ([5], [6]) that the CO ($J = 1-0$) line from the central regions of NGC 5128 (Cen A), which is the nearest AGN, has velocity width of more than 500 km/s but also possesses narrow (< 0.5 km/s) absorption features (Fig. 3). Emissions with broad velocity width probably originate from circum-nuclear gas. Analysis of the CO isotropic emissions showed that the gas near the nucleus is fairly warm and dense, with the beam-averaged kinetic temperature of ~ 15 K and the density of $10^{3-4.5}$ cm^{-3} in $N(\mathrm{H}_2)$ [5]. On the other hand, absorption features with narrow velocity width are due to absorption of the non-thermal continuum from the very compact nucleus by cool ($4 - 10$ K) molecular clouds in the outer ($r \sim 1$ kpc) regions [6].

Molecular lines from many AGNs must have similar features in their profiles, therefore the 2G Correlator that can simultaneously realize wide frequency-coverage and high frequency-resolution will be a valuable instrument to study these objects (see Fig. 3 (c)). Detailed information on the physical condition and kinematics of circum-nuclear gas can be extracted from the broad-band emission features of molecules, giving us deeper insight into gas fueling process to the nuclei and star-formation activities at the center of their host galaxies. Observations of absorption features against AGNs, on the other hand, correspond to "pencil beam" measurements of the outer molecular clouds, providing us the characteristics of these clouds in active galaxies. Since the AGNs and surrounding "dusty" tori are strong continuum emitters at millimeter and submillimeter wavelengths, precise determination of the continuum level will be important: the 2G Correlator can do it well, as described in § 3.1.

3.3. Absorption Features toward High-z Quasars

The last example is systematic survey of high-z absorption lines toward quasars. Wiklind & Combes have extensively searched and studied the absorbing molecular clouds towards several radio sources at a high redshift

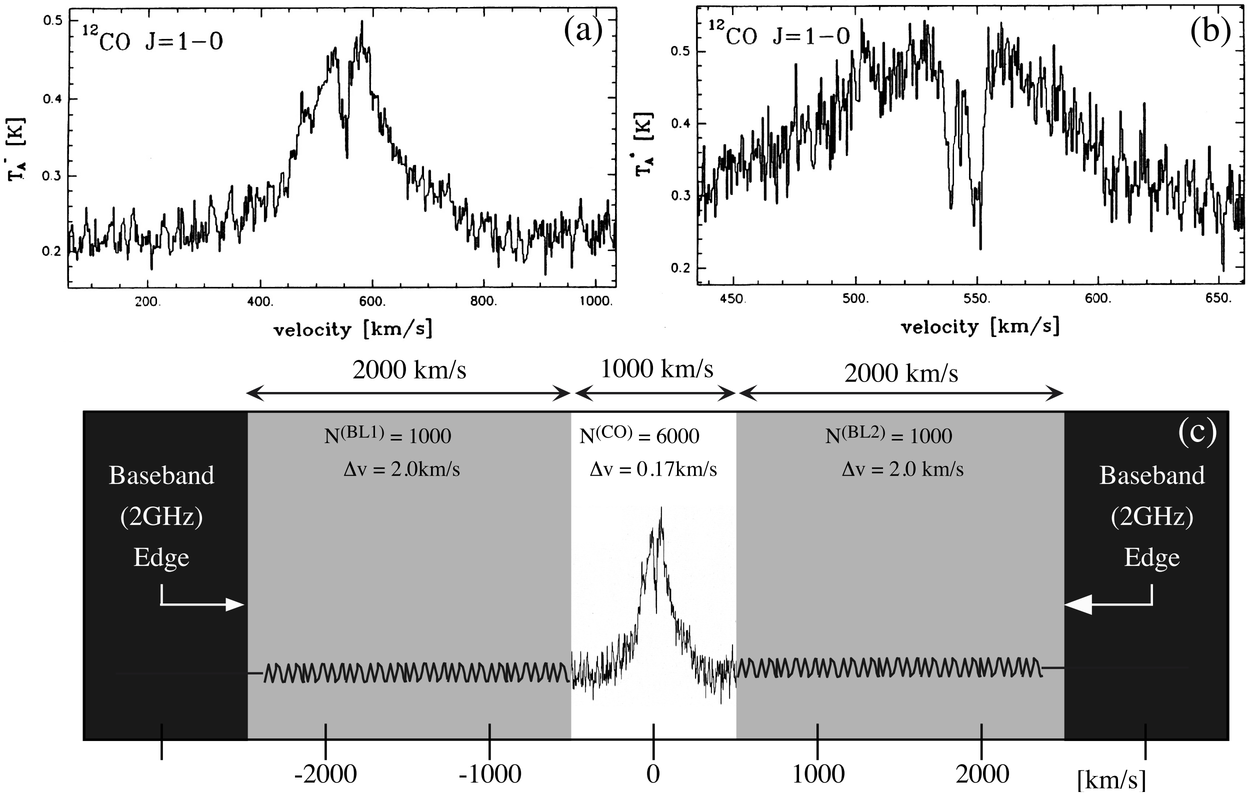

Figure 3: (a) CO($J = 1-0$) profile of Cen A obtained with SEST (from [5]). The velocity resolution is 1.8 km/s. (b) Same as (a) but 0.45 km/s resolution. (c) Possible configuration of the 2G Correlator. Line features can be observed with fairly high velocity-resolution while continuum level can be estimated from line-free regions.

(e.g., [7], [8]), and more than 30 transitions from 18 different species have been detected. Each system of absorption features is usually detected in several transitions of different species, allowing us to directly derive physical parameters (column density, excitation temperature etc.) of the gas components responsible for the features. Although the nature of their origin is still unclear, it may correspond to a “missing link” between Lyman-alpha clouds and proto-galaxies.

The redshift of these features cannot be predicted and, in addition, their velocity width is sometimes as narrow as a few km/s, suggesting the size scale of an absorbing molecular component can be the order of 1 pc. Hence, non-biased survey along the frequency axis with fairly high velocity-resolution is quite essential. The 2G Correlator will enable us to carry out this kind of observations with great efficiency, revealing detailed characteristics of the interstellar medium or the temperature of the cosmic microwave background (CMB) as a function of the redshift. These will be key information to understand the history of star-formation activity and to establish the theory of galaxy formation.

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