The Next Generation ALMA Correlator USNC-URSI National Radio Science Meeting

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***Abstract*—A Cycle 3 ALMA Development Study entitled *Digital Correlator and Phased Array Architectures for Upgrading ALMA* was completed in 2017. SAO led a consortium staffed with an international group of domain experts. The team developed science-driven architectures that greatly enhance bandwidth and continuum sensitivity; and are flexible, to facilitate modes providing extremely fine spectral resolution and native phased array VLBI recording, among others. Increased reliability, as well as reduced size, power consumption and life-cycle costs, are important natural benefits of these architectures which use state-of-the-art computing platforms and interconnect. A variety of technologies and algorithms were studied balancing costs and timelines against benefits. A detailed and practical system design is documented and justified in a comprehensive report to be submitted as an ALMA memo. This summary paper gives an outline of the proposed next generation ALMA digital system.**

I. Introduction

Recent developments at the Submillimeter Array (SMA) [1] demonstrate the feasibility and potential of ultra-wide band digital processing with fine uniform spectral resolution and VLBI capability. Figure 1 shows what the upgraded SMA can do. The extrapolation to ALMA is an exciting prospect indeed.

A system-wide specification of the next generation ALMA system (see table I) was developed for the Cycle 3 Study. Published findings from the ALMA Science Advisory Committee (ASAC) [2], as well as consultations with scientists and other experts across the International ALMA community, guided the requirements. While the requirements of next generation ALMA are outside the Study's purview, they were absolutely necessary at the outset to focus the work. The intent is to stimulate community-wide conversation leading to consensus.

We view the Study as Phase I of three phases of development. A Phase II bench prototype has been proposed, the implementation of which would retire substantially all development technical risk, and serve to pin down the timeline and costs of Phase III installation, verification, and commissioning.

II. Enabling new frontiers in ALMA science

Unsurpassed instantaneous bandwidth for spectral line surveys will provide truly unbiased connections between chemistry and the planet formation process in protoplanetary disks. An order of magnitude increase in coverage of spectrally surveyed star forming regions and extragalactic sources will provide entirely new approaches to chemical evolution across a range of exciting sources. Proportional increase in the cosmic volumes accessible via intensity mapping allows complete inventories of galactic gas at high-redshifts and new views of the physics of galactic evolution across cosmic time. Simultaneous line detection facilitates rapid high-z redshift surveys, demystifying the accumulation of galactic stellar mass.

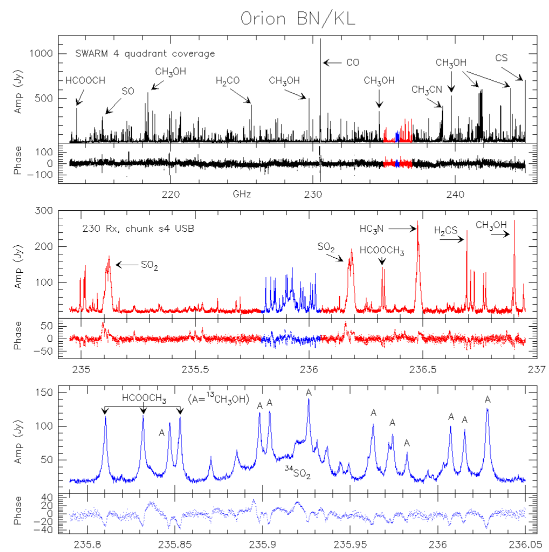

Fig. 1. The spectrum of Orion BN/KL covering an instantaneous 32 GHz on the sky with 140 kHz resolution across the full bandwidth. The data were taken on 26 January 2017 UTC with the SMA Wideband Astronomical ROACH2 Machine (SWARM), a FPGA based FX packetized back end. From the top the three panels show: the full 32 GHz, a single 2.0 GHz 'chunk' from one of 16 IF-ADC channels; and a detail of just over 200 MHz span, revealing the fine structure available in *all the data*—the 200 MHz blue fragment could be placed anywhere to reveal similar detail.

In the time domain, new evolutionary studies of transients in the millimeter and submillimeter are enabled, providing insight into mechanisms for variability in γ-ray bursts, which peak in the ALMA bands. Cometary studies rely on rapid cadence observations to disentangle coma versus jet emission: the key to solving the puzzle of their origin. VLBI features [3] allow ALMA to form multiple beams, becoming the anchor station of the Event Horizon Telescope (EHT). With earth-size apertures, and EHT evolving to band 7, our direct views of black hole event horizons sharpen, addressing the most fundamental questions in astronomy, physics and mathematics.

III. Assumed ALMA-wide requirements

The Development Study was broken down into eight work packages, each researched in depth by a focused team. An abbreviated listing included specifications, platform and architecture for F-engine, corner-turn, and X-engine, VLBI phased array mode [3], and staging for installation. Table I gives a highly abbreviated summary of the key *assumptive specifications* developed in the first work package, and used by the others.

TABLE I
Abbreviated assumed specifications for study.

Parameter	Specification	Remarks
# antennas	72	configuration
Max. baseline length	300 km	Sets max delay
Instantaneous BW	64 GHz	16 GHz/SB/Pol
Baseband (BBC) BW	8 GHz	single ADC block
Finest spectral resolution	0.01 km/s:1 kHz	band 1, cold cores
Effective bits	4	99% digital efficiency
Spec. dynamic range	10,000:1	weak lines near strong
Spec. dynamic range	1,000:1	lines on continuum
readout interval	16 ms	for x-correlations
reconfiguration time	1.5 seconds	agile mode change
VLBI mode	phased sum out	two subarrays

IV. An outline next generation system design

The proposed digital system is an optimized supercomputer that receives antenna data over a packetized network interface, and delivers full Stokes cross-correlation fringe visibilities, auto-correlations, and coherently phased antenna sums at its output. An 8 GHz *BaseBand Converter* (BBC) band in two polarizations readily scales by replication to the 64 GHz instantaneous sky coverage our Study requirements target. An ultra-fine spectral resolution setting of 1 kHz is available, useful to resolve lines in cold starless cores using ALMA Band 1. This astonishing resolution aggressively drives the output data rate, so modes to throttle the output are provided.

Historically in radio interferometry, *XF* correlators—cross-correlation first, with Fourier transform in software on the integrated lags—have been favored because expensive wide multipliers are not needed since the bit-width in the X-stage remains at the width of the sampled data. The advent of wide multipliers in digital signal processing hardware such as field programmable gate arrays (FPGAs) has effectively reduced the penalty for bit growth in the butterflies of the Fast Fourier Transform (FFT). The well known economy of the Cooley-Tukey algorithm, and correlation collapsing to bin-wise cross-multiplication in the Fourier domain, yields computational savings. So the number of instantiated multipliers for a given array size and spectral resolution is substantially reduced. Thus FX architecture allows for great economy in systems with fine spectral resolution and large numbers of antennas. *Packetized* FX correlators are now widely employed in radio astronomy [4], and are a clear choice for next generation ALMA.

ALMA presently samples 3-bit data; while 2-, 3- and 4-bit arithmetic are available, the high resolution modes are limited to 2-bit and 88%. Wide multipliers facilitate processing of wider bit-widths, thereby improving the digital efficiency of the correlator from 88%, for a two bit machine, to 99% for 4-bits. An 11% increment equates to 22% less integration time for a given SNR, yielding an effective 80 extra nights per year.

Communication between F-processing nodes, which operate on full-bandwidth data from a subset of antennas, and X-processing nodes, which operate on a fraction of the bandwidth from all antennas, requires at least three duplex ports per antenna on a 100 Gbps Ethernet switch. Since different ALMA BBCs handling independent band fractions may be handled by entirely separate and independent systems, the implementation quantum is a system for 72 antennas, capable of dealing with 8 GHz BBC bandwidth, two polarizations, one sideband, and 4-bit samples, or 16 GHz in total. This amounts to 256 Gb/s per dual-polarization antenna. Quadrupling this system covers the full 64 GHz bandwidth of the upgraded ALMA. A *dual band* mode can be supported by further parallelization.

V. Conclusion and future work

Increasing ALMA's bandwidth is the least expensive approach to improving its sensitivity. Reduction of power, magnified by concomitant lower cooling requirements reduces life-cycle costs and improves robustness against power disruptions. *Using current and conservatively projected technologies one can build a system that enables all ALMA Development priorities, with improvements in reliability, power and size.*

The next-generation correlator and phased array is the central component of a system-wide enhancement of ALMA. This includes wideband receivers, analog-to-digital converters [5], Digital Transmission System (DTS) and a data pipeline with commensurate capacity and speed. The context is an overall system-engineering plan for ALMA Development. Consensus on system-wide next generation ALMA requirements is a prerequisite. The next step is to comprehensively validate a bench prototype of this radically new correlator and phased array for ALMA, substantially retiring technical risk of full deployment.

Acknowledgement

A North America Cycle 3 ALMA Development Study funded many of these developments.

References

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