PROCEEDINGS OF SCIENCE

An ALMA beamformer for ultra-high resolution VLBI and phased array science

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By phasing all ALMA dishes together into a single effective aperture, ALMA can operate as both an exceptionally sensitive mm/sub-mm VLBI element and a beamformed array suitable for high frequency pulsar work. A detailed design for implementing a system to phase up the array has been completed and funding to build and integrate this capability into ALMA has been secured. Here we describe the basic elements of the system, outline the specifications, and review expected sensitivities. With this system in place, ALMA will become a key element in Global mm/sub-mm VLBI arrays that target a broad range of high sensitivity and high angular resolution science.

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1. Introduction

VLBI observations at the highest frequencies of 86 GHz and above have the potential to probe deeper into the cores of active galactic nuclei (e.g. [1] and [2] this conference) where observations of nearby objects, in particular M87 and Sgr A*, could allow investigating the extreme physical conditions down to the central massive black holes in those objects.

Unfortunately the sensitivity of VLBI arrays decreases at about 100 GHz with increasing frequency due to smaller and fewer telescopes capable of observing at mm-wavelength, and due to less sensitive receivers. A benefit of the high frequencies is that much more bandwidth is available in the observable bands. With the emergence of ever faster digital backends and recorders, wider receivers and IF bandwidths, the sensitivity of mm-VLBI observations can be increased above what was possible in the previous decade.

For more than 30 years, to increase VLBI sensitivity at cm-wavelengths, the signals of the antennas of local arrays (Westerbork array, VLA) have been added up coherently to deliver a single output to be used like other VLBI antennas, thus increasing the effective area and therefore the sensitivity of a VLBI array. The best example is the phased VLA which with its 27 antennas has been the most sensitive fully steerable VLBI element at cm-wavelengths with an effective collecting area equivalent to about a 125 m-telescope — significantly more than can reasonably be realized with a single steerable telescope.

At 86 GHz the Plateau de Bure interferometer has been phased successfully for years in GMVA (Global mm-VLBI Array, e.g. [3]) observations. Tests with the phased Plateau de Bure interferometer at 230 GHz showed that the array can be phased with sufficient efficiency and stability for VLBI. Both the CARMA and SMA [4] arrays have also recently been phased for VLBI observations at 1.3mm wavelength (e.g. [2]).

With the experience gained with phased arrays in VLBI it is obvious that we can increase the sensitivity of VLBI observing at 43 GHz and above by about a factor of three by phasing the ALMA array and including it in mm-VLBI arrays. The emergence of a phased ALMA will enable VLBI arrays capable of the highest angular resolution to achieve sensitive observations, not only of AGN, but also of micro quasars, astronomical masers, and high-z absorption systems [5].

2. Project description

2.1 Budget and institutions involved

The ALMA Phasing Project (APP) will be realised by an international consortium consisting of MIT Haystack, NRAO, MPIfR, NAOJ, ASIAA, and U. Conception. The project duration is planned to be 4 years, with a total workload of more than 25 work years and a total budget of more than 4 M$. Expected completion of the phasing system is in 2015. The funding for the project comes from a combination of pooled resources from international funding agencies.

2.2 Basic theory of phasing an array

For an N-element interferometer a phase $\phi_{\mathrm{obs}}(t)$ can be measured as a function of time t on the baselines between any two antennas i and j. The observed baseline phases are the sum of the structure phase of the observed source ϕ_{mod}, the instrumental phase ϕ_{ins}, the atmospheric phase ϕ_{atm} and a thermal noise term ϕ_n.

$$\phi_{\text{obs}}(t) = \phi_{\text{mod}}(t) + \phi_{\text{ins}}(t) + \phi_{\text{atm}}(t) + \phi_n(t)$$

The structure phases which have to be known with sufficient accuracy from a model, and the instrumental and atmospheric phases have to be removed from the observed baseline phases so that they can be added coherently.

Instrumental and atmospheric phases can be factorized by antenna so that after subtraction of the source model phases we can determine the N unknown sums of atmospheric + instrumental (or "antenna") phases. This is identical to the standard self-cal problem in VLBI and other interferometers with unknown "antenna phases". The problem is overdetermined for arrays of more than two antennas and we have to solve for N-1 antenna phases ψ_c as we are dealing with (antenna) phase differences. The calculated antenna phases $\psi_c(t) = L \cdot (\phi_{\text{obs}}(t) - \phi_{\text{mod}}(t))$ (where L is some linear transformation) are then used to correct the observed baseline phases. Usually one antenna is designated as the reference antenna r and for a standard least squares solution we get

$$\psi_{c_i} = \frac{1}{W}\left[\sum_{j,j\neq i} w_j \phi_{ij} - \sum_{j,j\neq r} w_j \phi_{rj}\right]$$

where w_j are antenna weights which could reflect the sensitivity of each antenna. W is the sum of the weights. It should be mentioned that the antenna-based noise $\psi_n(t)$ is actually reduced by a factor $\sqrt{N}$ from the baseline-based noise $\phi_n(t)$.

It is usually a good assumption even at mm and sub-mm wavelengths that the antenna phases vary slowly and that the data can be averaged for several seconds before decorrelation becomes an issue. For instance at Plateau de Bure solutions are calculated from 120 s of data. An optimal averaging time for calculating antenna phase corrections for ALMA will depend on the atmospheric conditions and the maximum baseline lengths in the array. The suggested method for ALMA is to calculate the corrections for time intervals $t_s \sim 10$ s and to extrapolate from each solution using Water Vapour Radiometer (WVR) data in order to follow atmospheric changes at the level of $t_f \sim 1$ s. First simulations with test data and WVR data indicates that our proposed approach will work at least under typical atmospheric conditions.

In the simplest case the program source is strong and compact enough (on ALMA scales) to serve also as phasing calibrator so that ALMA can be phased continuously. For weak sources and/or sources which are too extended a phasing calibrator has to be observed before each VLBI scan during which only the WVR data can be used to prevent too much decorrelation of ALMA.

2.3 Block diagram of the ALMA phasing system

ALMA was de-scoped in the development phase, but hooks for phasing were built into the correlator to make it relatively easy to implement VLBI at a later date. The parts that have to be added are: a) a hydrogen maser, b) a phasing system and software, c) VLBI formatting, data transport and recording.

In Figure 1 the block diagram of the ALMA phasing components and their location in the ALMA environment are shown. Existing and planned components are indicated by red and blue colour respectively, while green is used to group functional blocks together.

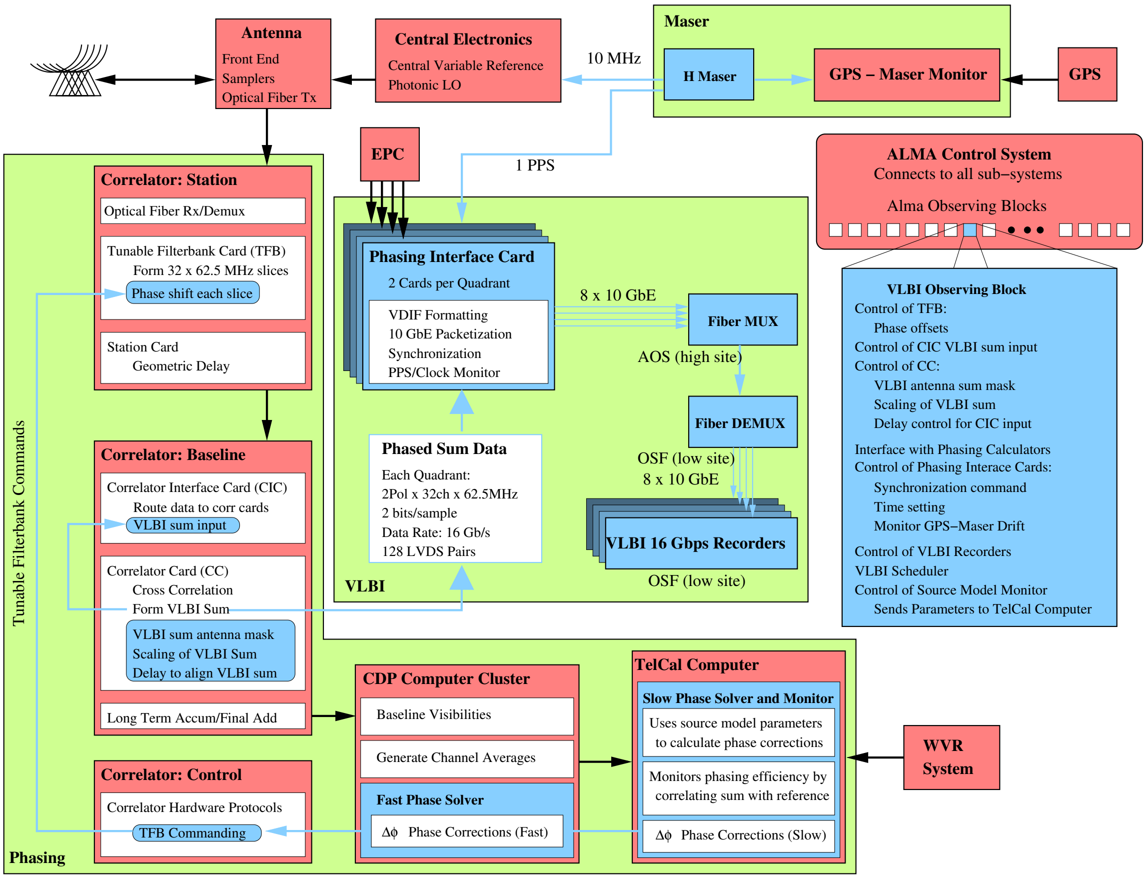

Figure 1: ALMA phasing block diagram. The red boxes exist, the blue boxes have to be added for phasing ALMA, and the green colour groups boxes into larger units

The H-maser will be used as a time and frequency standard for all of ALMA. It will replace the existing Rubidium standard. All the mixers in the frontends, the samplers and the VLBI formatting unit will be driven by 5 MHz and the 1 PPS signals provided by the maser.

The data from all the antennas enter the station part of the correlator where, amongst other things, the geometric delay compensation for the array is applied. The tunable filterbank can be used to apply phase shifts to the incoming telescope data as calculated by the phasing system.

In the baseline section of the correlator, in addition to forming the cross-correlations, the antenna data will be added and scaled to form the summed output for VLBI which will be forwarded to the VLBI formatting unit. In addition it will be correlated as “another antenna” against all other ALMA antennas for monitoring purposes. Antennas not to be included in the sum can be masked out.

Following the data flow of the *correlated* data, it will pass through the Correlator Data Processor where channel averages are formed. Averaged baseline data is passed on to the TelCal system. It applies various calibrations to the data. The TelCal system will be augmented with phasing software: the model phases will be subtracted from the baseline data and phase solutions will be calculated. Solutions and WVR data will be sent back via the Correlator Data Processor where the WVR measurements will be used to calculate “fast” corrections to the solutions. The estimated

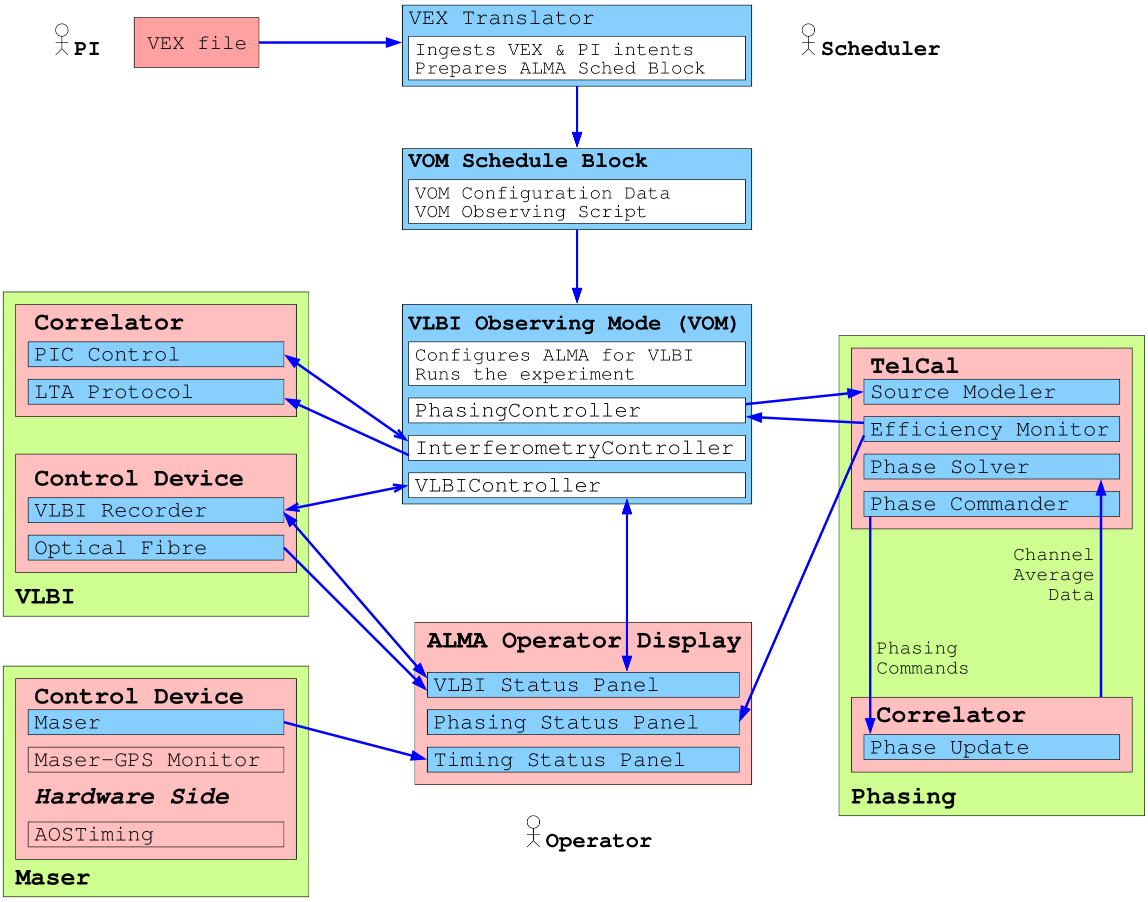

Figure 2: Modifications needed for ALMA software. The red boxes exist, the blue boxes have to be added for phasing ALMA, and the green colour groups boxes into larger units.

atmospheric plus instrumental phases will be sent back to the tunable filterbanks in the station part of the correlator to be applied to the antenna data streams.

In the VLBI formatting unit all processes are tightly synchronised to the 1 PPS of the H-maser. There, data are resampled to 2-bits per sample and are converted to a VDIF formatted data stream. The up to 64 Gbps of data are sent via fibres to the low site for recording on Mark 6 systems which are under development at MIT Haystack Observatory [6]. Four such systems will be able to record 16 Gbps of data each onto 32 disks. During a typical 10-hour observation up to 288 TB will be recorded at ALMA. A 5-station array will write about 1.5 PB at this data rate in 10 hours.

The whole process will be driven by the ALMA control system which will have to be expanded by a “VLBI observing block” (see Figure 1). This can also be viewed in Figure 2 where the project is depicted from the software point of view. In the centre stands the VLBI Observing Mode which receives as input a translated version of the VLBI VEX schedule. From here all components of ALMA and the phasing system are controlled and monitored. A model of the phasing calibrator will either be provided via the VEX file (the VEX standard offers an option to define source models) or extracted from a yet to be implemented calibrator data-base at ALMA.

3. Issues

The ALMA observing band is split into sub-bands of 62.5 MHz width. In contrast, VLBI has traditionally used sub-bands based on powers of two like 8, 16, 32, 64 ... MHz. To match the 62.5 MHz sub-bands of ALMA to the 64 MHz at other telescopes, the "zoomband" feature of the DiFX correlator [7] can be used, which allows correlations of a fraction of a sub-band against that of another station. As ALMA can tune its sub-bands flexibly the 62.5 MHz bands can be centred in the 64 MHz bands. As an alternative the sampling clock of the DBBC backends, which are used at the European stations, can be switched to match that of the ALMA samplers.

ALMA has linearly polarized receivers, while nearly all other VLBI antennas use circular polarisation to ease VLBI data processing and analysis. The VLBI DiFX correlator will be modified to convert ALMA linear polarisation to circular polarisation.

4. Project status

The project started in Q3 of 2011, although a lot of planning work had been done already before. A preliminary design review will take place beginning of November 2012. Special rules set by ALMA about how to develop, document, test and implement hardware and software at the site have to be followed. A first observation with a partial implementation is planned for Q4 of 2013. First science observations at 1 mm wavelength are planned for the commissioning phase.

Acknowledgments

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