# VLBI Potential of the ALMA Telescope in the Millimetre

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## Abstract

*VLBI is not currently supported in the present ALMA construction plan. However, several receiver bands of interest will be available to perform mm/submm VLBI observations with the high gain ALMA antennas (phased array or subarray). In the mm/submm domain where angular resolution is maximized, addition of the large ALMA collecting area would provide a definite sensitivity and mapping advantage. Details of compact components in bright AGN's and highly redshifted sources could be revealed with good sensitivity – even though the brightest sources could remain unresolved with the longest terrestrial baselines. In addition, there are several mm/submm cosmic masers of interest in evolved stars or galactic star-forming regions which could be mapped with baselines in the range 100 – 1000 km. Finally, on the basis of recent ideas discussed in the ALMA correlator team, we briefly comment on the ability of the ALMA correlator to support VLBI operation.*

## ALMA VLBI and ALMA bands

The current electronics construction plan for the Atacama Large Millimeter/submillimeter Array (ALMA) does not support VLBI observations. However, VLBI will be possible in the future with phased array outputs for up to 64 12-m antennas or with less antennas in one sub-array; there is a minimum of 4 sub-arrays available in the system. The ALMA Local Oscillator (LO) chain is designed in such a way that later substitution of the current master frequency standard by a hydrogen maser is possible. Other LO components are not meeting VLBI requirements and there are two different routes for future ALMA VLBI: either replace these components at a later stage, or add another sub-array to the existing ones to provide the upgraded path for VLBI.
The ALMA Compact Array (ACA), a major Japanese deliverable consisting of 16 antennas distributed within the inner part of the main array, could also perform VLBI as a stand-alone element (with 16 or less antennas).
The main array and the ACA are equipped with the same receivers. The ALMA priority bands cover from 84 to 950 GHz in 8 different bands. Two frequency ranges falling in the ALMA bands 3 and 6 are of clear interest for future mm VLBI: *(a)* the *85 – 95 GHz frequency range* where global mm VLBI observations have been performed; *(b)* the *210 – 230 GHz range* where more 'experimental' VLBI observations have also been accomplished. With expected SSB temperatures around 40 and 80 K high sensitivity is expected in ALMA bands 3 and 6. It is conceivable that in a near future submm VLBI will be attempted. ALMA bands 7 and 8 (up to 500 GHz) will provide high sensitivity (around 150 – 190 K system temperature). All ALMA bands provide two polarizations and the instantaneous bandwidth reaches 8 GHz in 2 Side Bands (and a total of 16 GHz in band 6).
In this poster we comment on:

- the potential interest of mm VLBI to explore extragalactic continuum sources and galactic line sources;
- the VLBI sensitivity/imaging enhancement resulting from the ALMA antennas observing with existing or future mm/submm arrays;
- the ALMA correlator potential for VLBI.

## Continuum and line radio sources

*Extragalactic radio sources* are not or are less self-absorbed in the millimetre than in the cm-wave domain ⇒ the source flux density, S, and the source size, $\theta$, are thus directly related:
$S \propto T_b\, (\theta/\lambda)^2$ where $T_b$ is the source brightness temperature.
At the $10^{12}$ K Compton limit even sources as bright as 1 to 0.5 Jy will have very small sizes ~ 8 – 12 and 3 – 4 microarcsec at 3 and 1 mm, respectively. Such sources will not be resolved even with the longest terrestrial baselines. However, many extragalactic sources are well below the Compton limit and mm VLBI imaging with antennas distributed across a few thousand km around the ALMA site will be of interest. With 5000 to 10000 km baselines, resolutions of 40 to 20 microarcsec are achieved at 1 mm and ultra fine structural details could be obtained for the most compact components in the brightest AGN's. In the direction of Sgr A* (above the ALMA site) spatial scales close to the expected accretion disk around the central black hole could be mapped.

*In our Galaxy*, only relatively short baselines ~ 100 – 1000 km are likely to bring new results in the direction of radio continuum stars or other compact objects – with the exception of Sgr A*. This is because for relatively nearby objects the ALMA broad band connected array will detect 10 microJy sources in 1 hour, and, with its longest baselines ~ 15 km, will provide 15 milliarcsec resolution at 1 mm. Good position accuracy (~ 2 mas) will also be achievable with the longest baselines of the ALMA connected array for a well calibrated atmosphere and for long observing sessions (astrometry).

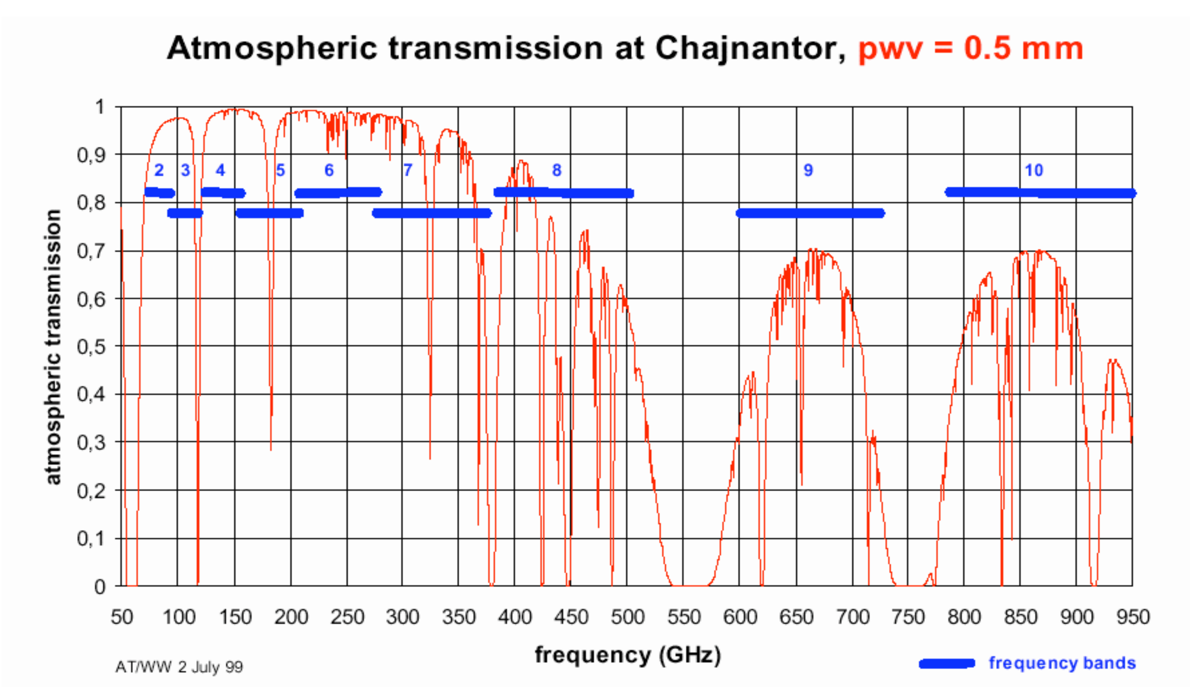
*Maser line sources* have been observed in many evolved stars and star-forming regions of our Galaxy. Their brightness temperature may exceed $10^{10}$ – $10^{12}$ K in highly compact areas associated with the coherent maser amplification process. There are several SiO, HCN, $HC_3OH$ and $H_2CO$ lines of interest in many sources but the most promising masing lines are those of water because: *(a)* it is a widespread species present in many stars and star-forming regions; *(b)* mm and sub-mm water line transitions have already been observed in several stars and compact HII regions (including Orion and Sgr B2). Several of these lines fall in the ALMA bands 7 and 8 covering the 275 to 500 GHz frequency range. The brightest water lines could be used to self-calibrate the connected ALMA array images and at the same time could deserve VLBI observations with moderately extended baselines (~ 100 – 1000 km).
(Note: Strong extragalactic maser line sources have been observed in OH and $H_2O$ at cm wavelengths only.)

## Sensitivity enhancement with ALMA and future new mm facilities

The successful 3-mm VLBI observations performed with the IRAM sensitive telescopes together with other European antennas and the VLBA, and the more 'experimental' detections at 1.3 mm of Sgr A* suggest that including some of the ALMA dishes or the full ALMA phased array would be beneficial to the VLBI science.

We estimate that at 3 mm the detection threshold for any single baseline including the most sensitive antenna in Europe – the IRAM 30-m dish – would be improved by about a factor of 3 if the phased sum of only 16 antennas of the ALMA array would replace the 30-m. Addition of the ALMA antennas would thus improve significantly the dynamic range of images obtained with the smaller antennas of any existing mm VLBI array. At wavelengths smaller than 3 mm including the ALMA antennas is even more advantageous because of the extremely good atmospheric transparency of the ALMA site (see transmission at Chajnantor for 0.5 mm precipitable water).

It is interesting to note that in the future, several mm/submm telescopes (very) close to the ALMA site could be equipped for VLBI. Baselines around 100 km would be ideal to investigate the physics of maser line sources or to obtain details in radio continuum stars and their immediate vicinity. These telescopes include, APEX, the Cornell-Caltech Atacama 25-m telescope and other projects in discussion.




## ALMA Correlator for the connected array

The ALMA digital correlator combines the processed outputs from up to 64 antennas (2016 antenna pairings) to form a single radio telescope using a digitized instantaneous bandwidth of 8 GHz (4 x 2 GHz basebands) per polarization. The main specifications of the ALMA correlator are given in Table 1. There are 8 digitizers located in each antenna of the array.

**Table 1.** ALMA correlator specifications.

| Item | Specification |
| --- | --- |
| Number of antennas | 64 |
| Number of baseband channel inputs per antenna | 8 |
| Input sample format | 3 bit, 8 level at 4 GSample/s per baseband channel |
| Correlation sample format | 2 bit, 4 level and 4 bit, 16 level; Nyquist and twice Nyquist |
| Maximum baseline delay range | 30 km |
| Hardware cross-correlators per baseline* | 32,768 leads + 32 768 lags |
| Hardware autocorrelations per antenna* | 32,768 |
| Typical performance in digital hybrid modes | 8192 spectral points provided for each pair of baseband inputs** |
| Product pairs possible for polarization | HH, VV, HV, VH (for orthogonal H and V) |

* 62.5 MHz correlators (125 MHz clock rate), divide by 32 to get number of equivalent 2 GHz correlators.
** Resulting in 8192, 4096 or 2048 spectral points across the baseband spectrum, depending on polarization mode.

The correlator system consists of 4 identical and independent quadrants. Each quadrant processes up to 4 GHz (1 polarization pair) for all 64 antennas. The input cards to the correlator are digital filter cards each one dividing each baseband into 32 sub-channels whose center frequencies are independently tunable. The correlator part of the system consists of 32 'planes' providing the auto- and cross-correlation functions for each polarization product. Each 'plane' processes a frequency sub-channel (Frequency Division Mode) or a 'time slice' packet of digitized data (Time Division Mode where the correlator is a pure XF machine).

## ALMA Correlator for VLBI (in discussion)

Each quadrant of the ALMA correlator provides summed antenna outputs for VLBI. Each correlator 'plane' poutputs 4 signals (8-bit precision) for two basebands in a quadrant. Each summation output (with LVDS drivers) corresponds to one antenna only or to the sum of 2 or more phased antennas in the array. The number of phased antennas is determined with a programmable 'include/exclude mask'.
Two operating modes are proposed for VLBI (see Figs. below). *Frequency Division Mode*: a cross-bar switch is used to make a valid summation of 8 subbands out of 64 available in 2 basebands => 500 MHz BW. *Modified Time Division Mode*: any BW from 0 to 1 GHz can be selected.

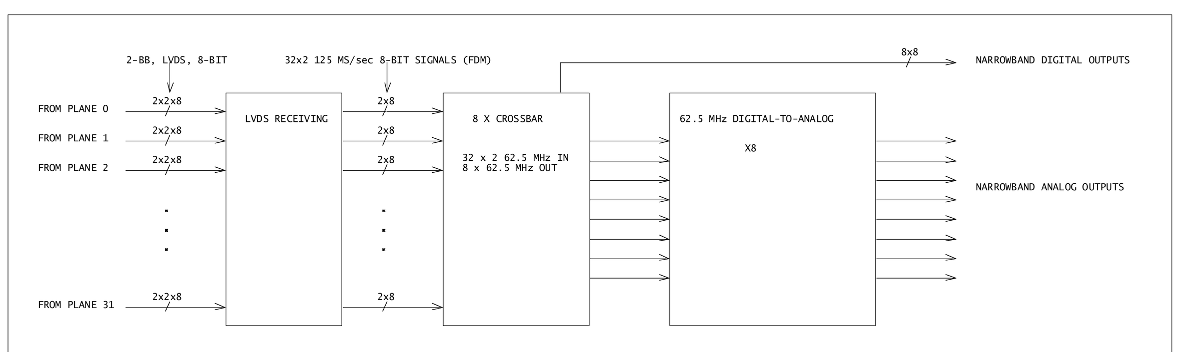


FIGURE 1 BLOCK DIAGRAM OF PHASED SUMMATION LOGIC (FREQUENCY DIVISION MODE)

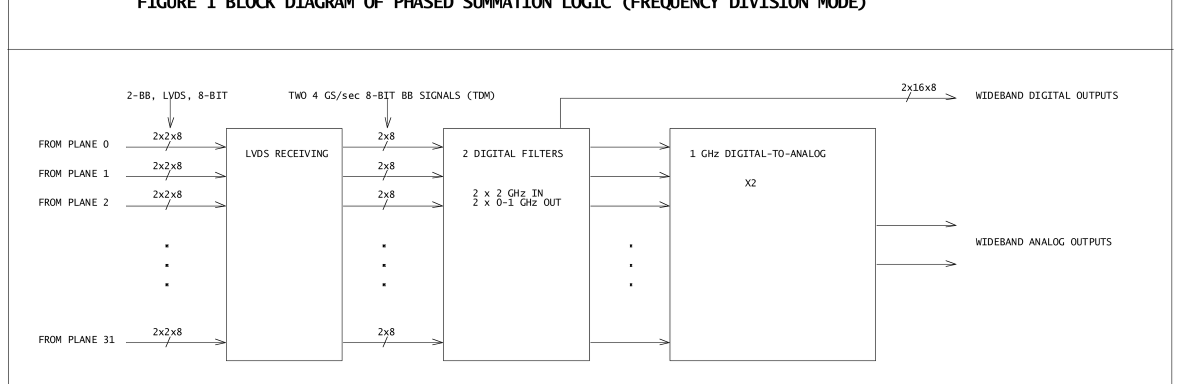


FIGURE 2 BLOCK DIAGRAM OF PHASED SUMMATION LOGIC (TIME DIVISION MODE)

*Additional equipment required to perform VLBI:*

- New card for LVDS input cables and to process them before connection to a VLBI terminal or to e-VLBI bandwidth up to 1 GHz.
- Adapt ALMA 125 MHz clock to standard VLBI rates => clock rate change logic required or use of analog outputs to drive terminal.