New Science with the ALMA Phasing System

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Abstract

The ALMA Phasing Project (APP) delivered the technology needed to bring ALMA into the Very Long Baseline Interferometry (VLBI) community. This has been demonstrated by the recent results from the GMVA and the EHT on the two supermassive black hole targets SgrA* and M87[1]. However, the system was designed to be extensible to other science applications[2] within the VLBI community as well as for ALMA-only observations. This second phase of development (APP2) is on track to deliver new capabilities in future Cycles. These include lowered flux limits for continuum observations, extensions to other bands, a spectral line VLBI mode, and the compatibility of VLBI mode with ALMA subarrays. The ALMA Phasing Project - Phase 2 is funded by an ALMA North America Development Award.

ALMA Phasing Project, Phase 2 (APP2) Objectives

- **Lower Flux Limits:** The implementation of the ALMA Phasing System (APS) in Cycles 4–7 requires a target bright enough for phasing solutions, *i.e.,* a flux density of at least 500 mJy. Two pathways to lower flux density are to be developed.
- **Extend VLBI to Other Bands:** The original effort developed a continuum capability in Band 3 for use with the GMVA and Band 6 for use with the EHT. Bands 1 and 7 were contemplated for commissioning, however only Band 7 appears plausible in the near term.
- **Introduce a Spectral Line Observing Mode:** The APS was designed to work with the full 2-GHz continuum band, but APP2 will introduce a spectral line VLBI capability.
- **Introduce a Pulsar Observing Mode:** An ALMA NA Development study[3] demonstrated that pulsars could be observed and recorded with the APS. The APP2 is working towards making the capability generally available.

Other minor operational improvements are being implemented or investigated (compatibility with subarrays), but will not be described here. New capabilities are anticipated for Cycle 8 or Cycle 9.

Lower Flux Limits

One pathway to enabling use of the APS on fainter sources is to phase up on a bright quasar close to the science target of interest. This has been tested successfully on several occasions. In good weather conditions, the phases may remain stable for several minutes, see Figure 1.

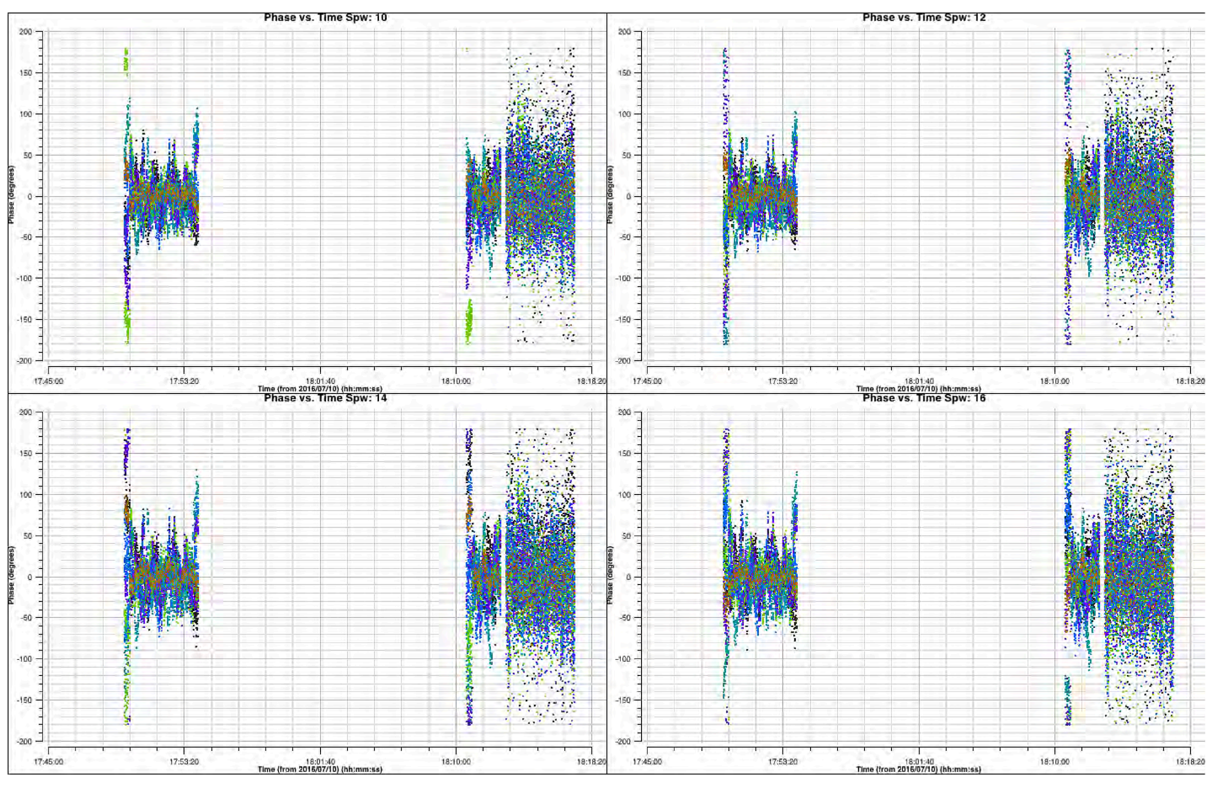

Figure 1: Results from a passive phasing test with the APS in Band 3, conducted in July 2016 under marginal weather conditions. Phase versus time for three scans (with gaps in time) is shown for each of the four correlator quadrants. The x-axis range spans approximately 23 minutes and the y-axis scale spans -200 to $+200$ degrees. The first scan is on the quasar 0501-019 ($\sim$2.3 Jy). The second (short) scan is on 0510+180 ($\sim$2.3 Jy), whose phases are retained for the final scan on 3C138 (0.47 Jy). All of the antennas from the phased array are plotted (designated by different colors). The relatively tight scatter in the phases of 3C138 about zero indicates that the phases are remaining coherent. A corresponding increase in the correlated amplitude compared with the unphased case (not shown) is also seen in the data.

The second pathway to lower flux density limits for the APS is to enable the phasing system to make use of the instrumental "baseband delays" during the calculation of the phasing corrections. This allows using the full 2-GHz band rather than the current set of 8 sub-bands (250 MHz each), resulting in a phasing limit of $\sim$200 mJy. This work is in progress and should be completed prior to Cycle 9.

Extend VLBI to Other Bands: Band 7

VLBI experiments were carried out between ALMA and several EHT stations (APEX, GLT, IRAM30m, NOEMA single dish and SMA) in mid-October 2018. Several bright quasars were chosen for the time allocation. Several fringes were obtained from the VLBI data captured, even though the weather conditions at all stations were sub-optimal. In particular, ALMA observations were made in the presence of strong winds (>10 m/s) which significantly lowers the array phasing efficiency (see Figure 2).

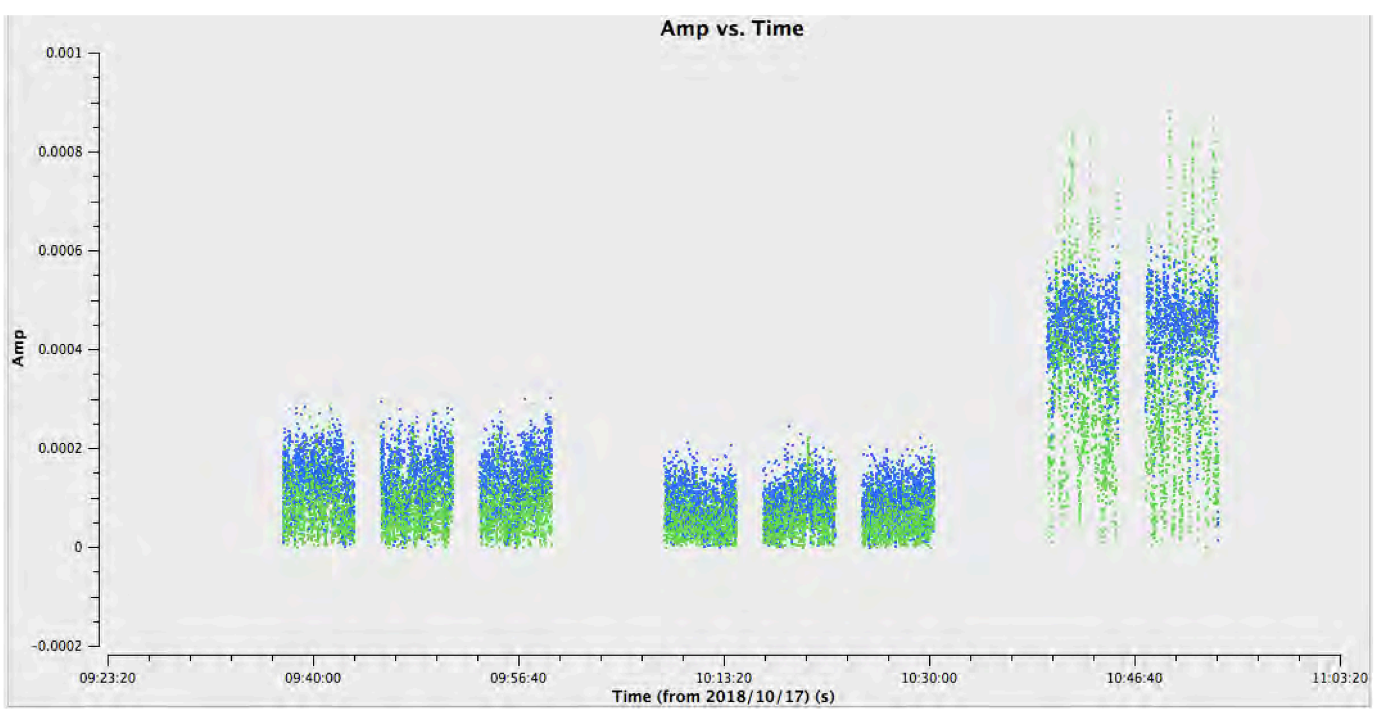

Figure 2: Illustration of the performance of the APS during a portion of the band 7 VLBI experiment on 2018 October 17. For each of the eight VLBI scans obtained during the session, correlated amplitude is plotted as a function of time on two baselines: (1) the phasing reference antenna with an unphased comparison antenna (green points); (2) the phased sum 'antenna' with the same comparison antenna (blue points). Data from a single correlator quadrant (baseband 3) and a single polarization (XX) are shown. The first three scans are of the source J0423–0120, the second three on J0510+1800, and the last two are on J0522–3627. The modest differences in correlated amplitude on these two baselines indicates that overall phasing efficiency was low. This is well explained by the high winds at ALMA (>10 m/s).

Spectral Line VLBI Observing Mode

This observing mode is a hybrid between the normal continuum VLBI observations and normal ALMA spectral line observations. One baseband (BB_1) is phased (either passively, or else using emission from a bright maser line from the target itself) and recorded as is done for standard Band 3 continuum VLBI experiments, and the other three basebands may be set to higher spectral resolution correlation modes to enable ALMA spectro-imaging of the target with higher spectral resolution. Results from an ALMA-only test observation are shown in Fig. 3 along with an ALMA-VLBA test from last month.

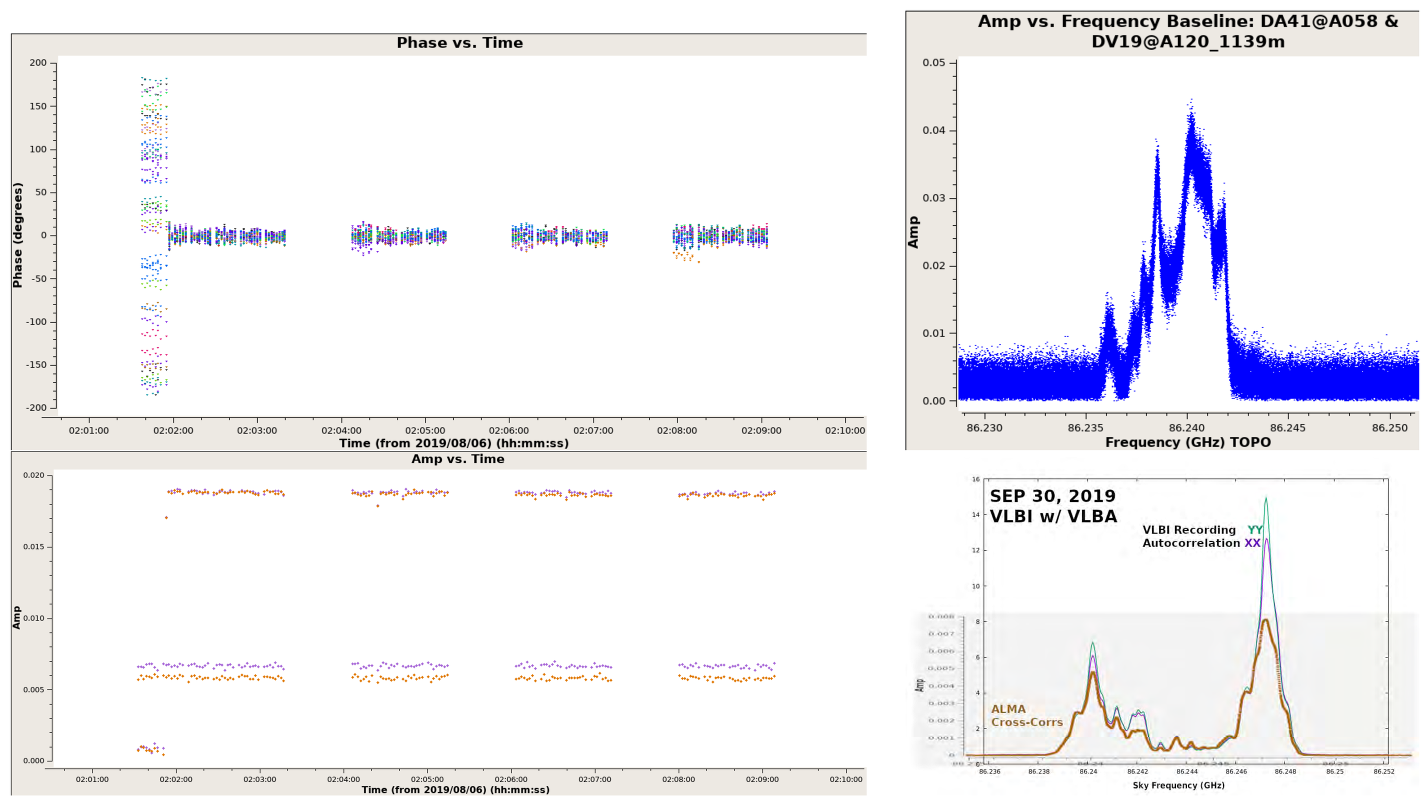

Figure 3: Recent observing results from August observations of the evolved star VX Sgr: the two left panels show the performance of the APS phasing-up on the SiO $\nu = 1, J = 2 - 1$ maser line shown in the upper right panel at higher spectral resolution. The top left panel shows the visibility phases with time for the antennas of the phased array. The lower left panel shows the visibility amplitudes on the reference antenna (stable at 0.006 in the figure) and the sum antenna (which jumps from 0.001 to 0.020). The colors in this figure reflect the two polarizations (XX and YY) which are independently phased. The figure in the right is from a September 30, 2019 observation of Orion Source I made for VLBI with the VLBA. The VLBA data are not yet available, but the figure provides a first comparison of the average of the ALMA XX cross-correlations on all antennas with the XX and YY autocorrelations of the recorded phased sum. Note the extreme difference in the amplitude scales.

Pulsar Observing Mode

An ALMA NA Study award [3] explored whether the passive phasing mode could be used to make observations of known pulsars. A test observation was made in 2017 and two processing pipelines were developed (at MPIfR and the CfA) to convert the raw VLBI recordings into the community-standard PSRFITS format. The full analysis is reported in [4] and all data are available at [5]. Fig. 2 from that work is shared here as Fig. 4.

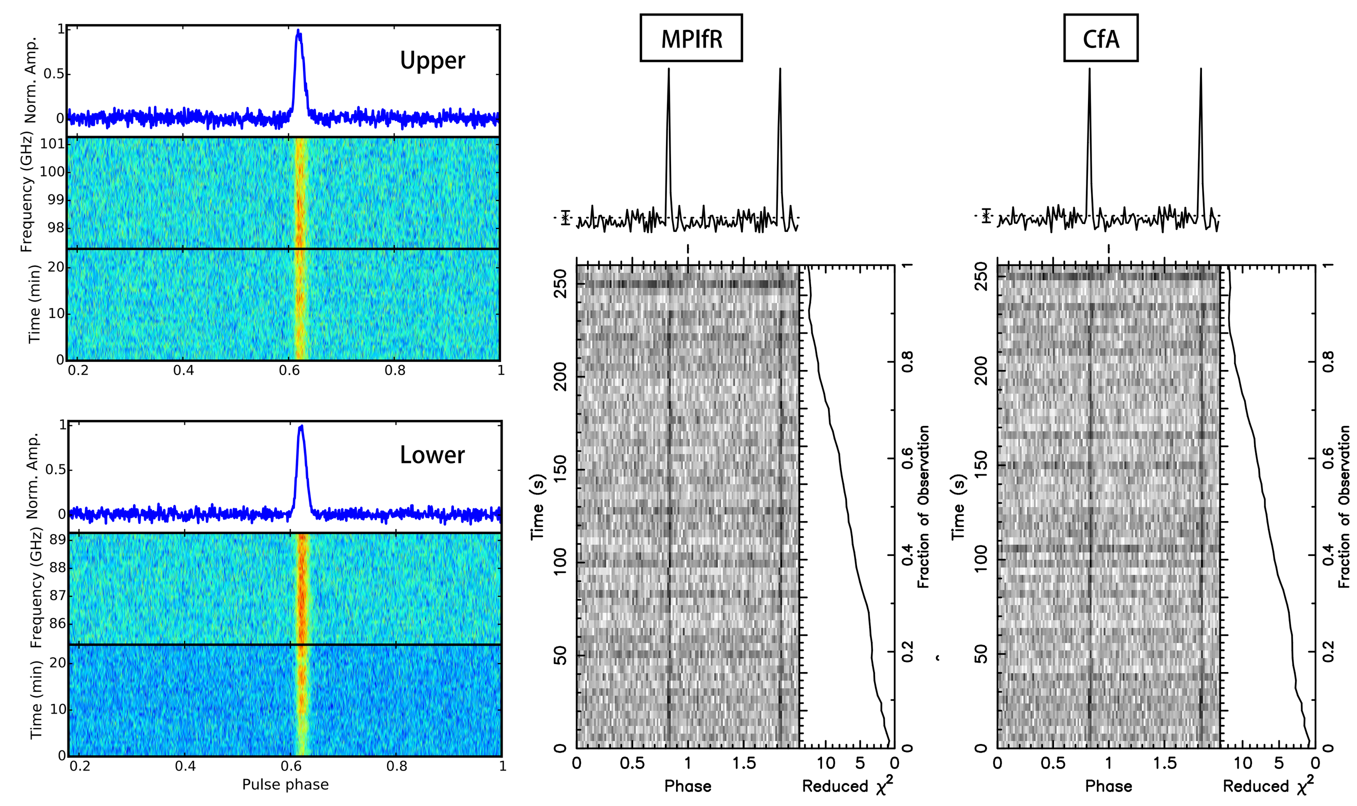

Figure 4: This figure shows an analysis of Vela pulsar observations from Jan 2017. Left panel: Pulse profiles detected in the lower (bottom, 85.268-89.268 GHz) and upper sideband (top, 96.268-101.268 GHz) of ALMA Band-3, using the MPIfR pipeline. Middle and right panel: Comparison of pulse profile achieved from the MPIfR and CfA pipelines. The MPIfR pipeline makes power detections of all four Stokes parameters in the frequency domain, while the CfA pipeline derives total intensity power directly from the state counts. The detection from these two pipelines shows highly consistent measures of detection significance in total intensity and the shape of the pulse profile of the Vela pulsar. Adapted from [4].

Current Status & the Path Forward

- **Lower Flux Density Limits:** Under consideration for Cycle 8.
- **Extend VLBI to Other Bands:** Band 7 is expected to be available Cycle 9 or later.
- **Introduce a Spectral Line Observing Mode:** Commissioning observations were taken last month, and are presently being analyzed. Under consideration for Cycle 8.
- **Introduce a Pulsar Observing Mode:** Under consideration for Cycle 8.

References

[1] Event Horizon Telescope Collaboration. "First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole". In: *ApJL* 875 (2019). DOI: 10.3847/2041-8213/ab0ec7.

[2] V. Fish et al. "High-Angular-Resolution and High-Sensitivity Science Enabled by a Beamformed ALMA". In: *astro-ph* (2013). eprint: arXiv:1309.3519.

[3] URL: https://science.nrao.edu/facilities/alma/alma-develop-old-022217/ADP_GC_Pulsars_Magnetars_Cordes_etal_20170ct14.pdf.

[4] K. Liu et al. "Detection of pulses from the Vela pulsar at millimeter wavelengths with phased ALMA". In: *ApJL* (2019). Accepted.

[5] URL: https://almascience.nrao.edu/alma-data/enhanced-data-products/vela-pulsar-j0835-4510.

Acknowledgements

Phase 2 of the ALMA Phasing project is supported by the ALMA NA Development Fund. We are also grateful for the support of our VLBI friends at ALMA, GMVA, EHTC and the VLBA.