Final Report: Enabling New Science with the ALMA Phasing System - Phase 2 (APP2)

An ALMA North America Development Project

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Executive Summary: This document provides a summary of activities undertaken as part of the Cycle 5 ALMA North America Development Project "Enabling New Science with the ALMA Phasing System - Phase 2 (APP2)", whose period of performance extended from January 1, 2018 to August 31, 2024. APP2 provided a series of enhancements to ALMA's very long baseline interferometry (VLBI) and phased array capabilities, leading to the introduction of submillimeter (Band 7) phasing and VLBI capabilities, a passive phasing mode, a Phased Array (pulsar) observing mode, a prototype spectral line VLBI capability, an improved method of handling baseband delays, and a number of other minor system enhancements.

Contents

1 Background

The original ALMA Phasing Project (APP) was launched in 2012 with the goal of bringing phased array and VLBI capabilities to ALMA. That project, headed by principal investigator (PI) S. Doeleman (then at MIT Haystack Observatory), leveraged contributions from an international team to successfully develop, deploy, and commission the hardware and software necessary to enable ALMA and its original Baseline Correlator (BLC) to coherently phase up to 61 individual antennas and generate and record VLBI format data streams (see Matthews & Hecht 2017; Matthews et al. 2018a for details). The APP allowed ALMA become an anchor station of unprecedented sensitivity in global VLBI arrays operating at millimeter wavelengths beginning in ALMA Cycle 4, and enabled ground-breaking new science.

The original ALMA Phasing System (APS) that was developed under the APP was used in conjunction with the Event Horizon Telescope (EHT) at 230 GHz to achieve the first ever images of a supermassive black hole on event horizon scales (EHT Collaboration et al. 2019a), as well as the first scatter-corrected images of Sgr A* at 86 GHz (Issaoun et al. 2019). In the years since, ALMA's VLBI and phased array capabilities have been used for a growing list of cutting edge scientific investigations (e.g., Janssen et al. 2021; EHT Collaboration et al. 2021, 2022; Lu et al. 2023). However, many of these studies have taken advantage of expanded and enhanced capabilities that were introduced subsequent to the original APS, thanks to work funded through investments from the ALMA North America Development program.

Although the APP brought unique and valuable new scientific capabilities to ALMA, the resulting APS and VLBI observing mode (VOM) were limited in their flexibility owing a combination of software limitations, programmatic restrictions, and other factors. This in turn significantly restricted the breadth of ALMA's potential VLBI scientific applications. To address these limitations—and to significantly expand the scientific flexibility of the APS and VOM—two subsequent ALMA North America Development projects were conceived and approved. The first, the ALMA Phasing Project Phase 2 (APP2), the subject of this report, was launched in 2018 and extended from January 1, 2018 to August 31, 2024. The objectives and scope of APP2 are described in Sections 2, and 3, respectively, and the project outcomes are described in detail in the remainder of this report. The second project, the ALMA Phasing Project Phase 3 (APP3), had an overlapping performance period (January 17, 2022 – July 16, 2024). APP3 complemented APP2 by implementing several additional categories of VLBI developments including: (1) flexible tuning; (2) panchromatic VLBI (i.e., the ability to operate ALMA as a phased array in any available receiver band); (3) a fully flexible spectral line VLBI mode; (4) various other minor improvements and enhancements to the APS to improve its performance and versatility. APP3 and its outcomes were described in detail by Matthews & Crew (2024).

2 The Motivation for an APP "Phase 2"

When the original APS was first offered to the community in Cycle 4, ALMA VLBI users were presented with a strictly limited set of observing options: continuum mode observations with a fixed tuning set-up in either of two bands: Band 3 or Band 6. Furthermore, VLBI was restricted to sources bright enough to permit efficient and direct phase-up of the array using the target itself, even in less than band-optimal weather conditions (i.e., correlated flux density of $\geq$500 mJy on intra-ALMA baselines).

The features and specifications of the original APS were motivated primarily by those necessary to achieve the goal of imaging the nearby supermassive black holes M87* and Sgr A* on event horizon scales (e.g., Doeleman 2010). An extension of VLBI to Band 7 (i.e., to the submillimeter) was originally included as part of the APP, but was descoped owing to time and resource limitations, coupled with the lack of existing partner sites to support VLBI observing in that band. Various other VLBI observing options (e.g., those needed to enable flexible tuning or spectral line observing) were never within the scope of the APP.

As described in a series of articles and white papers dating back more than a decade, there has long been widespread community interest in exploiting the power of phased ALMA for a broad range of science applications beyond imaging black holes (e.g., Falcke et al. 2012; Fish et al. 2013; Tilanus et al. 2014). Indeed, the science case for a phased ALMA described in these various articles is diverse, ranging from the studies of molecular masers in the atmospheres of evolved stars and in the circumnuclear disks of megamaser galaxies, to studies of the high-frequency portion of pulsar spectral energy distributions, to measurements of molecular absorption lines in the environments of active galactic nuclei. However, owing to the limited flexibility of the original APS, many of these science areas could not be pursued.

The APP2 (and its sister project, the APP3) were conceived to address many of these deficiencies, thereby expanding the breadth of science possible using ALMA's phased array and VLBI capabilities. As described in the sections that follow, the APP2 succeeded in bringing to fruition a number of new capabilities and upgrades that have already proved critical for enabling the APS to reach its full scientific potential within the framework imposed by the design of the original ALMA BLC, ALMA's delay system, and various other pieces of ALMA hardware and software that are expected to remain in place until the ongoing Wideband Sensitivity Upgrade (WSU)[1] is completed early in the next decade (see also Section 8).

3 Project Scope and Deliverables

The original work breakdown structure (WBS) for APP2 called for development of six discrete software features (WBS 2.1 through 2.6; Section 4), as well as commissioning activities (WBS 3.0; Section 4), and miscellaneous ALMA support functions (WBS 4.0; Section 5), with an overarching project management structure (WBS 1.0; Section 6). Details on each of the WBS areas are given below. A fifth WBS element (5.0) called for coordination between APP2 and a National Radio Astronomy Observatory (NRAO)-led effort to develop a new ALMA correlator. However, owing to a subsequent restructuring of that effort by

[1] `https://science.nrao.edu/facilities/alma/science_sustainability/wideband-sensitivity-upgrade`

NRAO, WBS 5.0 was later descoped, as were a few of the other originally proposed APP2 WBS items (see Section 7 for details).

The originally approved APP2 period of performance was January 1, 2018 – September 30, 2020, but as described below, a funded extension, coupled with a no-cost extension, extended the project through August 31, 2024. These extensions became necessary owing to a series of circumstances beyond the control of the APP2 team, including technical and weather-related challenges, as well as the extended shutdown of ALMA during the COVID-19 pandemic.

Sections 4–6 of this document provide overviews of the various WBS items undertaken under the umbrella of APP2. For several of these topics, we also provide references to additional documents that contain more extensive discussions. Section 7 summarizes topics that were ultimately descoped and efforts undertaken (if any) on those areas prior to descoping. We briefly comment on future outlooks for ALMA VLBI in Section 8 and provide a short summary in Section 9. Acronyms used in this document are defined in Appendix A.

4 Software (WBS 2.0)

While the original APP included both hardware and software development efforts, APP2 did not include any hardware modifications to ALMA. Instead, all major new capabilities developed under this program relied exclusively on software developments. Specifically, the new software features originally proposed to be developed under APP2 focused on the following areas:

1. Improvement in the handling of baseband delays (the *"delay fix"*; WBS 2.1; Section 4.1)
2. A *source modeler* (WBS 2.2; Section 7.1.1)
3. Enabling *phasing in additional bands* (specifically Bands 1 and 7; WBS 2.3; see Sections 7.1.3 & 4.2, respectively)
4. A *passive phasing* mode to support VLBI observations of weak sources (WBS 2.4; Section 4.3)
5. A *prototype spectral line VLBI mode* (WBS 2.5; Section 4.4)
6. A *single-dish VLBI* capability (WBS 2.6; Section 7.1.2).

WBS items 2.2 (the source modeler) and 2.6 (single-dish VLBI) were subsequently descoped (see Section 7), and Band 1 phasing was deferred to APP3 (see Matthews & Crew 2024 and Section 7.1.3). We discuss development activities related to the remaining WBS 2.0 items below.

4.1 Improved Handling of Baseband Delays (the "Delay Fix"; WBS 2.1)

A full description of ALMA's "delay problem" for VLBI and the resulting "delay fix" effort are given in Crew & Matthews (2024) and references therein. Here we provide an abbreviated summary.

4.1.1 ALMA's Delay Problem for VLBI

During the initial on-sky testing and commissioning phases of the APP in early 2015, the project team discovered that the APS was operating with the expected efficiency only in the X polarization of the first correlator quadrant. Furthermore, the degradation of the performance was found to be more severe in Band 6 than in Band 3. After a systematic investigation, the source of the issue was identified as originating from the manner in which various delays are applied to the data used to form the phased sum (Matthews & Crew 2015b). Specifically, it was found that the documentation on the delay system made available to the APP team had been highly incomplete and that the delay management in the ALMA system is in fact handled in a manner different from what had been assumed throughout the design and review phases of the APS.

In brief, the source of this VLBI delay problem is as follows. The hardware used in the original ALMA design made it necessary to partition delays into multiple pieces for correction in various places. For normal ALMA operations, front-end delay corrections (which are stable and have typical values of ∼100-500 picoseconds) are referenced to the first baseband (BB_1), polarization X, of the Band 3 receiver. Delay corrections for the other receiver bands and baseband/polarization combinations are then performed in the correlator data processor (CDP) at the same time that a residual geometric delay correction (<15 ps) is applied for the various circuit elements of the front end. When the APS is operating, ALMA's TelCal computer uses the data corrected by the CDP to compute a phasing solution that is subsequently applied to the tunable filter banks (TFBs). However, data *uncorrected* for the front-end delay are used to form the phased sum in the long term accumulator (LTA) hardware. This occurs because the signals comprising the phased sum must be captured between the front end—where the phasing registers are available to apply phasing corrections—and the application of the CDP's corrections. This delay application methodology created a fundamental problem for the original APS design.

Following this discovery, to enable a functional phasing capability to be delivered within the project timeline of the APP, a workaround was devised by the APP team whereby the baseband delay (BBD) corrections were turned *off* in the CDP during APS operations. At the same time, the number of channel averages within each 1.875 GHz baseband (BB) was increased to 8, and the phasing software was modified to independently calculate a phasing solution for each of those channel averages (see Matthews et al. 2018a). This approach effectively solves for and removes the gross delay across each of the BBs. (Figure 1). This approach had the advantage that it could be implemented relatively quickly, avoiding a delay of at least a full observing Cycle in making the APS and VOM available to the community. This method of handling BBDs also enabled the APS to operate with a level of efficiency sufficient to meet its design requirements (Matthews & Crew 2015b, c; Crew

& Matthews 2015) and has been used for all VLBI observations since Cycle 4.

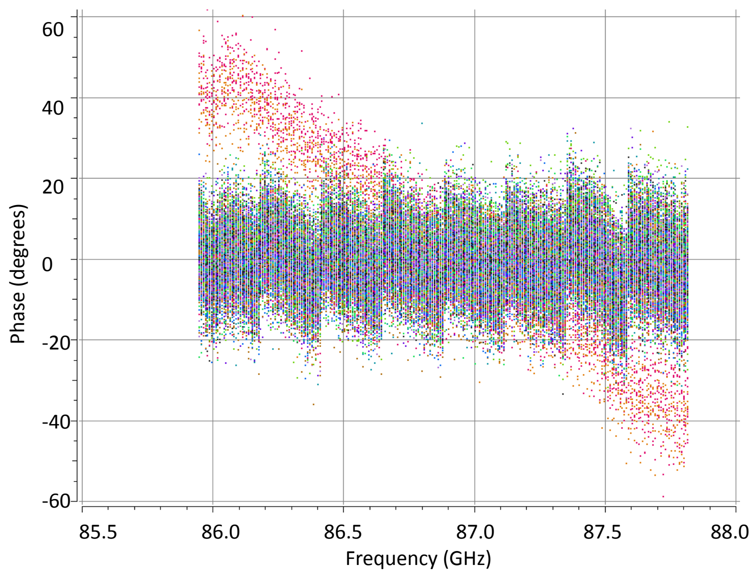

Figure 1: Visibility phase as a function of frequency for an APS test scan from April 2015. The red points show data from a baseline between an (unphased) comparison antenna and the phasing reference antenna that are *uncorrected* for delay, resulting in a phase slope across the 1.875 GHz band. The y-axis range is -60 to $+80$ deg. The other colored points represent data in each of 8 channel averages (each 234 MHz wide), to which APS phasing corrections have been independently computed and applied. Those corrections remove the delay slope across the full band, but leave a residual "sawtooth" pattern because of the application of the phasing corrections is on a per-channel average basis. This is a hallmark of the legacy delay handling method that has been in use for APS observations since Cycle 4 (see text for details).

While this "legacy" method of handling BBDs worked adequately and enabled delivery of science-quality data, it has certain disadvantages. First, there are decorrelation losses (albeit modest ones) associated with the residual delay errors across each set of channels used to form a single channel average, as illustrated in Figure 1; this results in a small, but avoidable loss in phasing efficiency. A second drawback is that the standard ALMA interferometry products that are archived in parallel with the VLBI data interchange format (VDIF) data stream during VOM operations require special (i.e. nonstandard) calibration and processing in order to use then for science (see Goddi et al. 2019). Third, this methodology complicates VLBI observations of spectral lines in cases where there are multiple lines of interest within the BB, or where the line of interest spans the boundary of a single channel average. Fourth, the online phasing efficiency calculations are corrupted by the lack of delay corrections to the unphased comparison antennas that are always part of the array during VLBI. Lastly, the need to sub-divide each BB into multiple (typically 8) channel averages decreases the effective bandwidth [and thus the signal-to-noise ratio (SNR)] for computation of the phasing corrections; in effect, for the case where 8 channel averages are used there is a loss of $\sim \sqrt{8}$ in sensitivity, thereby limiting the APS to brighter sources than the full sensitivity of ALMA would otherwise dictate. This latter consideration impacts so-called “passive” phasing applications as well, since it further limits the number of candidate calibration sources (“phasors”) available within a given angular separation from a science target (see Section 4.3).

In recognition of these issues, our team was awarded a pair of ALMA North American Studies (Matthews et al. 2018b, c) to devise an alternate strategy for the handling of BBDs during VLBI operations (i.e., a “delay fix”) that would circumvent several of the drawbacks of the current method. Among the options considered in those studies, the methodology that was ultimately deemed the most promising was designated for implementation and testing as part of the APP2 work package (WBS 2.1).

4.1.2 Adopted Approach

The basic framework adopted the delay fix is described in more detail in Matthews et al. (2018b, c) and Crew & Matthews (2024). In brief, the Software Science Requirements (SSR) script used for VLBI was modified to query the Telescope Monitor and Control Database (TMCDB) for the delay model information appropriate to the receiver band(s) to be used and then to pass along this information to TelCal, i.e., to the phasing engine. The SSR script was also updated to check if this was done in a previous execution in the same session. In theory this would have been sufficient, but for various reasons, the TMCDB delay model is in some cases of poor quality. Thus the observing script was additionally modified to conduct a delay calibration measurement in the band(s) to be used and directly measure the delays. Ultimately TelCal (which is fed the delay data) decides whether to use the empirically measured delays or fall back on the TMCDB delays. TelCal also provides comments on this for the SSR to push to its log. Work on implementation of the delay fix commenced in late 2018 and can be divided into two distinct development phases: ‘DF1’ (Section 4.1.3) and ‘DF2’ (Section 4.1.4), as described below.

4.1.3 A First Attempt at Implementing a Modified Delay Handling Method for VLBI (‘DF1’)

The original strategy for implementing the delay fix was to develop the necessary code changes and then carry out code testing and refinement during a dedicated mission at ALMA. During the mission, short sky tests were to be performed over the course of several days and analyzed in real time, and code modifications would be made in response to any issues. A mission dedicated to this effort was scheduled at ALMA in May 2019.

Prior to May 2019, essential changes to the SSR script were completed and modifications were made to the component of TelCal that performs APS phasing calculations. From the SSR side, the revised code was written to allow optional selection of the new delay fix. When that option was exercised, some additional steps were inserted into the logic; otherwise, the delay fix logic was not engaged. On the TelCal side, extensive changes to the APS machinery were required, resulting in a significant refactoring of the code. These included introducing the ability to retain data from the TMCDB for the life of the TelCal executable. Care was taken to properly partition the delay into coarse samples and to quantify the remaining delay relative to that partition. For added quality assurance, we also introduced a short calibration scan at the start of the project to provide an independent measurement of the delays and thereby a check on the retrieved TMCDB values. All of this basic functionality was tested in offline mode in October 2018.

Unfortunately the May 2019 mission was plagued by a range of issues, including a sequence of severe weather events, coupled with a catastrophic failure of the ALMA power plant. As a result, we were able to obtain only a handful of on-sky tests (totaling less than one hour) at the end of the mission, and what limited data we did obtain indicated that some of the delay fix code was not working correctly. Adding to the challenges of debugging these issues, protocol communication errors were occurring between SSR and TelCal, forcing time-consuming code fixes in order to allow any testing to proceed. (Those issues were later identified and resolved). The end result was that very little progress could be made on the delay fix during the May 2019 mission. Because the version of the code that emerged was not adequately debugged, the implemented changes (hereafter referred to as 'DF1') were not included in the subsequent Cycle 7 observing software release.

4.1.4 The Delay Fix – Take 2 ('DF2')

Work on the delay fix was expected to resume shortly after the aborted May 2019 mission. However, that plan was disrupted first by the transfer of our team's primary code developer to a new managerial role, followed shortly thereafter by start of the COVID-19 pandemic and a shutdown of ALMA operations. In response, a funded extension of APP2 was awarded that included provisions to restart the delay fix work, with one of us (GBC) taking over all aspects of the required coding and related development work.

Our revamped approach involved implementing a completely new delay fix engine (hereafter 'DF2') derived directly from the legacy delay handling methodology implemented by the APP team and in use since Cycle 4 ('DF0'). A "switch" was added to enable selection of the version of the code to be run. The new engine also offers an added option to average X and Y polarization phases, which in principle may be used to provide an additional $\sim \sqrt{2}$ improvement in SNR. As a historical note, development through DF1 (see Section 4.1.3) was done in the Subversion (SVN) repository, while the DF2 development was entirely within the Git repository.

For initial testing and debugging of DF2 we made extensive use of ALMA's offline test apparatus. This allowed building unit tests using Archival ALMA Science Data Model (ASDM) files to validate DF0 and DF1 (and later DF2) code changes. After resurrecting/creating several unit tests of DF0, comments and dead code were cleaned up from this version. Similar operations were then performed on DF1, to render the code more readable and comprehensible. The code makes use of various standard (but not well-documented) TelCal libraries, creating an additional challenge.

Once DF1 was cleaned up, it was cloned to DF2. From that point, DF0 and DF1 were essentially frozen (except for comments or white-space changes) and DF2 became the primary development version of the code. Full details of the remainder of the code development of DF2 are presented in Crew & Matthews (2024).

From this point, validation and testing of DF2 followed a rather different approach from DF1. After ALMA's return to operations in early 2021, following the height of the

COVID-19 pandemic, priority was given to scheduling PI science, leaving relatively little test and engineering time available. As a result, scheduling week-long commissioning and verification missions of the sort that we had conducted previously was no longer viable. Instead we adopted a more incremental approach to subsequent code development and testing to enable progress via short (often remote) on-sky tests that were coordinated with ALMA's two-month software release cycles. By ensuring that the necessary code was present in a given software release, it became possible to execute occasional on-sky tests when time and weather conditions permitted. This was especially efficient during periods when APP team members were present at ALMA to support VLBI Science campaigns, as in these cases the tests were able to double as verification tests for VLBI readiness.

4.1.5 Testing and Validation of the 'DF2' Delay Fix Code

Sample data from a variety of test observations using the DF2 code are provided in Section 5 of Crew & Matthews (2024). As detailed in that report, our testing shows that the delay fix appears to be working nominally for all bands tested to date (Bands 1, 3, 6, 7, and 9), and for both continuum and spectral line observing cases. One illustrative example for a spectral line target is reproduced in Figure 2.

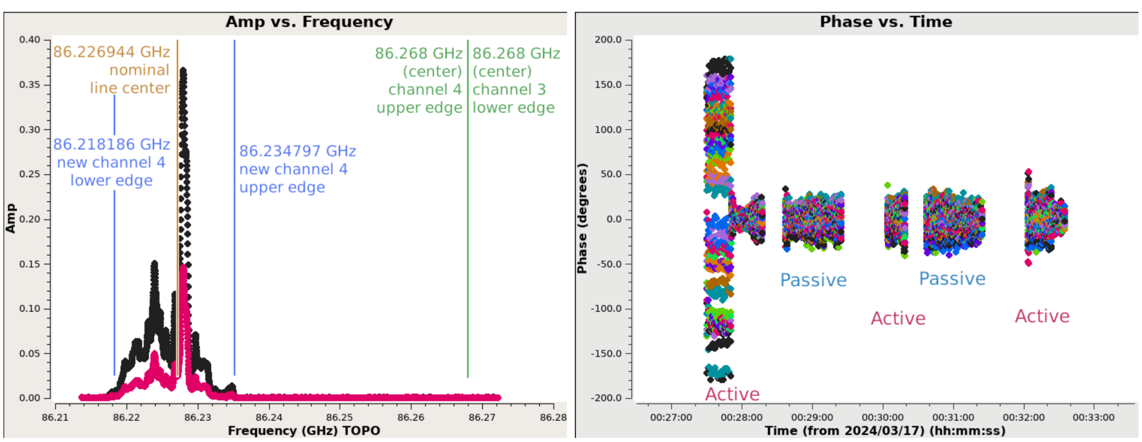

Figure 2: Results from an execution with the final DF2 code on the spectral line target VY CMa in Band 3 on March 17, 2024. Weather conditions were nominal, with precipitable water vapor (PWV) ∼3.5 mm and wind speed $v_{\rm wind}$ ∼3–4 m s^{-1}. *Left:* raw cross-correlation spectra for baseline between two sample baselines (black and red, respectively). These spectra are from BB_3, which was not used for VLBI, but was instead configured using a high spectral resolution set-up to capture the ALMA data with a channel spacing of ∼15 kHz. The panel is annotated to show the narrowing of channel 4 from its original 234 MHz width (spanned by 240 channels, each ∼976 kHz wide, starting at channel 960) to a width of 17 channels of ∼1 MHz width starting at channel 994. This is an LSB BB, so the channels are counted from the DC edge at 87205.5 MHz. The band center was at 86.268000 MHz. *Right:* visibility phase versus time on baselines between the phased antennas and the reference antenna. The pattern of scans alternates between active phasing (on the ^{28}SiO v=1, $J = 2 - 1$ line emission) and passive phasing. The large phase scatter at the beginning of the first scan is the result of the array being in an initially unphased state. Reproduced from Crew & Matthews (2024). Data source: `uid://A002/X114a61b/Xa89`.

Because of scheduling constraints and other practical issues, we were able to obtain only a handful of test observations that allow a direct, head-to-head comparison of the performance of APS with the delay fix versus with the legacy delay handling method. Results from one such back-to-back comparison case, obtained in Band 3, are shown in Figures 3 & 4). We see that in general, the behavior of the correlated amplitude and the phasing coherence are as good or better in the DF2 data. We were also able to examine a number of comparison cases using offline reprocessing with the DF0 engine following a successful DF2 sky observation. Figure 5 provides a statistical breakdown from one such case, showing phase differences on one scan (the phase-up scan) from a Band 6 observation.

Most of our initial testing of the delay fix was performed on relatively bright sources in order to help ensure that any significant problems could be readily identified. However, before recommending that the delay fix can routinely be used to lower the flux density threshold for actively phased VLBI targets at ALMA, it was also important to test the new delay handling method on weaker targets. For this reason, some additional on-sky testing was carried in October 2024 on moderately weak sources (<200 mJy). These tests also allowed on-sky validation of the polarization averaging option, which had previously been tested only in offline mode.

Results from one such a test carried out on October 14, 2024 in Band 7 are shown in Figure 6. This plot illustrates a successful application of the delay fix for its most demanding test to date: successful phasing in Band 7 with a 0.13 Jy phasor (J0219+0120), which is weaker than the current Band 7 limit by more than $\sqrt{8}$ (see also Section 4.1.6). This test observation used the delay fix, as well as the X and Y polarization averaging option described above. The "science target" (J0217+0144) was deliberately chosen to be brighter than the phasor (0.44 Jy) and relatively close in angular separation (0.5 deg). Weather conditions were quite good for Band 7 (PWV$\sim$0.68 mm and $v_{\rm wind}$ $\sim$1.75 m s^{-1}). The phasing efficiencies reported for the phasor observations were 93–97% in the four BBs. By contrast, the legacy delay handling algorithm was applied to the data offline and achieved lower efficiencies, in the range 82–92%. We anticipate that the efficiency contrast between the two delay handling methods is likely to be even greater in more adverse weather conditions. This would provide an important advantage given that the EHT often operates in less-than-ideal conditions due to the scheduling constraints. However, this remains to be tested empirically.

4.1.6 How Well Does the Delay Fix Work?

Our testing to date suggests that for observations that invoke the delay fix, the band-dependent flux density limits currently in place for VLBI phasing targets can now safely be lowered by $\sim \sqrt{8}$ (see Table 1), i.e., by factor expected based on the increase in available phasing bandwidth with the delay fix active. These suggested limits assume average observing conditions for the selected band.

At the time of this writing, it is still under discussion whether the flux density limits for active phasing targets will be formally lowered for VLBI observers starting in Cycle 12, either in accordance with the recommendations summarized in Table 1, or to some level in between the current limits and the newly proposed ones. As none of the VLBI projects selected for ALMA Cycle 11 require these weaker flux limits, there is still time to acquire

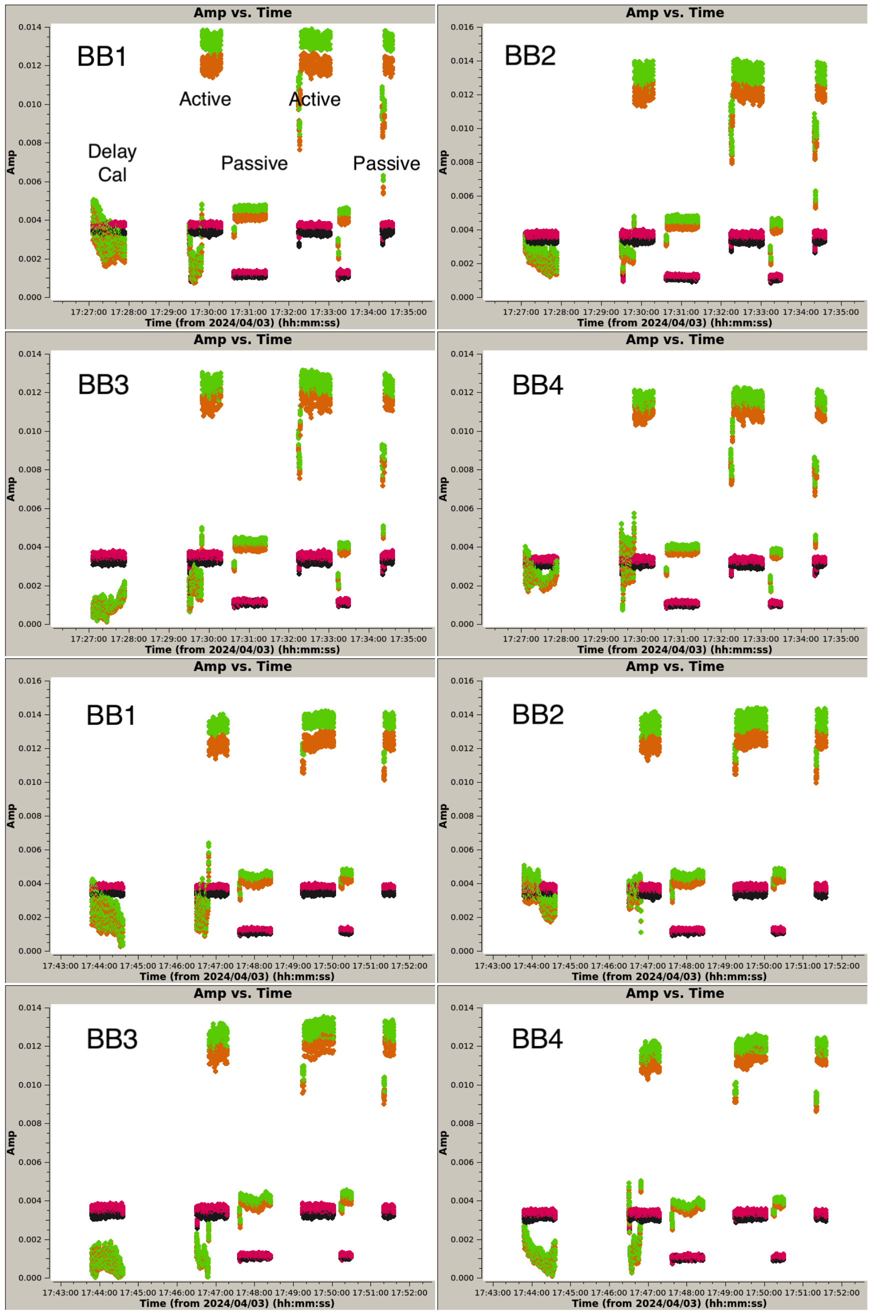

Figure 3: Correlated visibility amplitude (XX polarization) as a function of time for two consecutive Band 3 test observations on April 3, 2024. In each panel, baselines between the reference antenna and each of two comparison antennas are shown in black and red, respectively. Baselines between the phased sum "antenna" and the two comparison antennas are shown in green and orange, respectively. The first scan in the sequence is a "delay cal" measurement, followed by an alternating sequence of actively phased scans on J0403−3605 (10.6 Jy) and passively phased scans on J0428−3756 (3.3 Jy). The top four panels show results obtained using the new delay fix code (DF2); each panel corresponds to one BB, starting with BB_1 in the top left. The lower four panels show results for the same sequence of sources, obtained using the legacy BBD handling method (DF0). Data source: `uid://A002/X115643f/X4d60` and `uid://A002/X115643f/X4da7`.

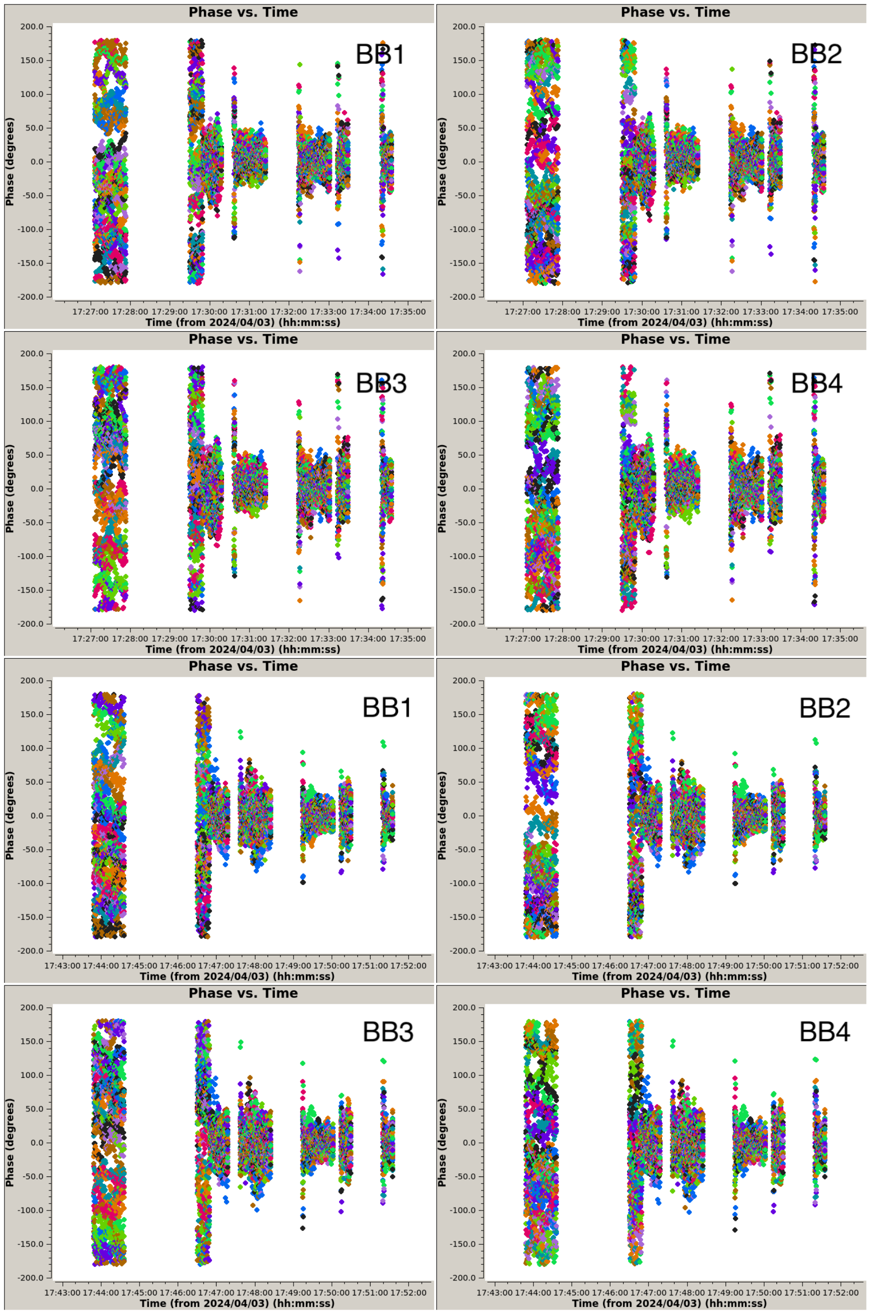

Figure 4: Visibility phase (in degrees) as a function of time for the test data sets shown in Figure 3. Data from baselines between the reference antenna and each of the antennas in the phased array are plotted in various colors.

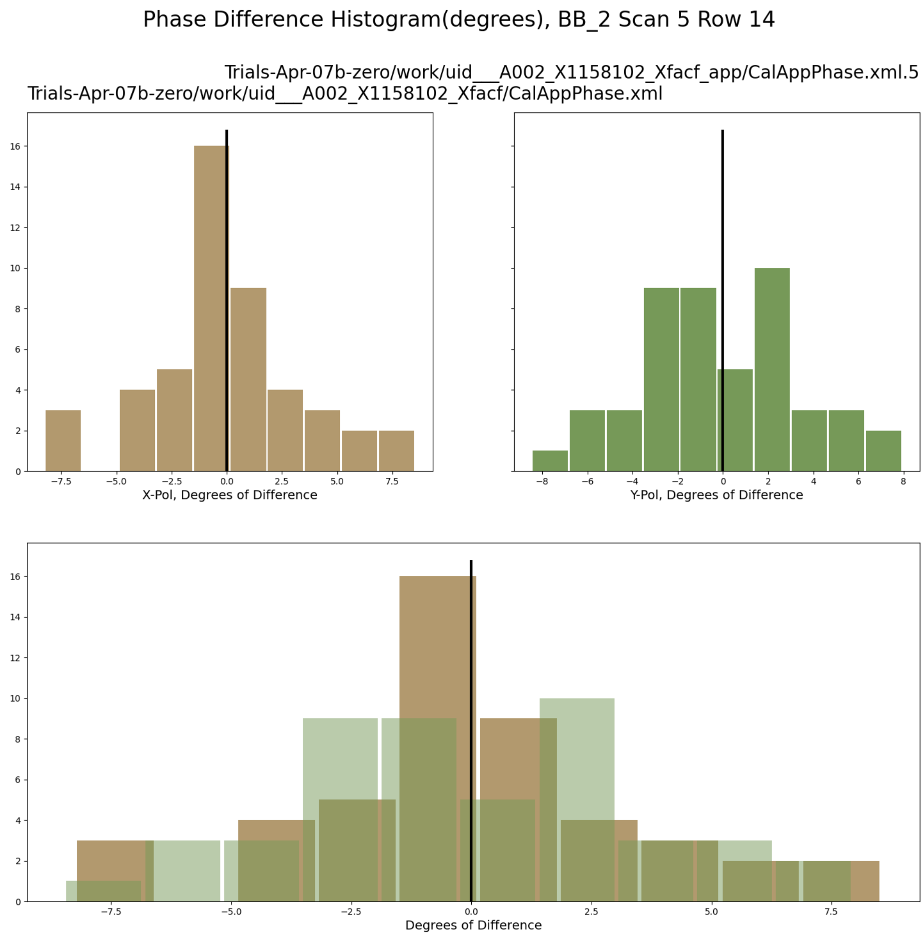

Figure 5: Performance evaluation of the new delay fix method of handling BBDs during VOM operations. Histograms are shown of the phase differences for all antennas for a single scan from BB_2 of during a Band 6 test observation on April 7, 2024. The plotted difference is between the actual DF2 phases (computed with the new delay fix algorithm active) and the phase adjustment that is produced offline on the same data using the legacy (DF0) delay handling setup. The top-left panel is for the X polarization (brown), the top-right panel is for the Y polarization (green). The two are overlaid in the bottom panel. The full spread of phase differences is small ($\pm$10 deg), implying that both methods are comparably effective on a bright target. Reproduced from Crew & Matthews (2024). Data source: `uid://A002/X1158102/Xfacf`.

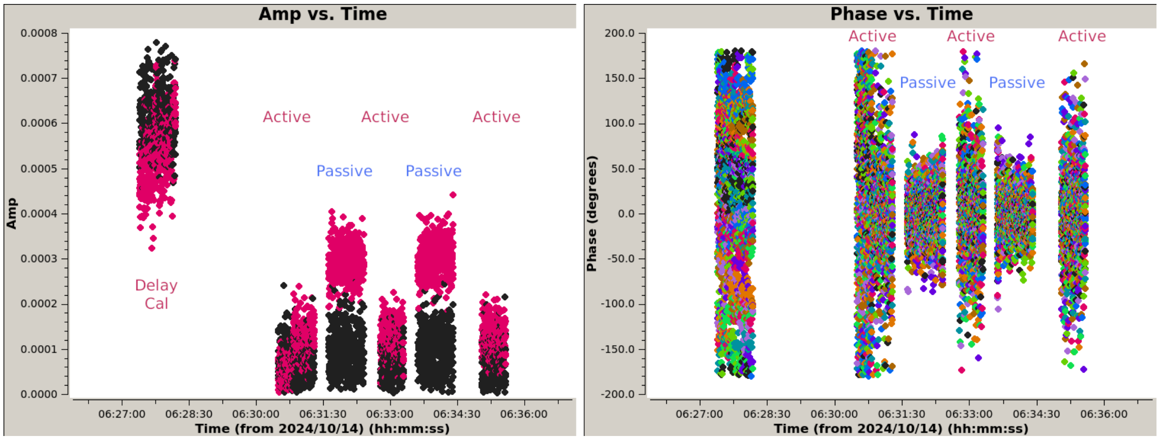

Figure 6: *Left:* Correlated visibility amplitude (XX and YY polarizations averaged) as a function of time for Band 7 test observations conducted on October 14, 2024. The results were obtained using the new delay fix code. Data are plotted for baselines between the phased sum and the reference antenna (red points) and the reference antenna and a comparison antenna (black points). The first scan in the sequence is a "delay cal" measurement, followed by an alternating sequence of actively phased scans on J0219+0120 (0.13 Jy) and passively phased scans on J0217+0144 (0.44 Jy). *Right:* Phase versus time for the same data set shown in the left panel. Data from baselines between the reference antenna and each of the antennas in the phased array are plotted in various colors. Data source: `uid://A002/X11eaef9/X11e08`.

Table 1: Suggested Flux Density Limits for Active Phasing

Band	**current (Jy)**	**revised (Jy)**	**revised, pol-averaged*** **(Jy)**
1	0.350	0.125	0.090
3	0.500	0.175	0.125
6	0.500	0.175	0.125
7	0.750	0.265	0.190

*with polarization averaging enabled.

additional test data prior to making a formal recommendation for any adopted adjustments to be imposed beginning in Cycle 12.

We note that with the new mode of handling the BBDs, the resulting bandpass may be less "flat" than with the legacy method, owing to the latter's use of multiple phase corrections per 2-GHz baseband. These bandpass effects have the potential to produce modest coherence losses when averaging is done over large portions of the band. However, as the ALMA receivers generally have relatively flat responses, this effect is expected to be small and should have minimal impact on the numbers presented in Table 1.

4.1.7 Should the Delay Fix Be the Default Delay Handling Method for VLBI?

At present we have insufficient experience to recommend that the new delay fix option always be used in place of the legacy method. However, thus far in using it for cases where the phasing target would have been below the recommended flux density threshold for the legacy delay handling method, we have seen consistently satisfactory performance.

One additional example is a set of recent phasing tests conducted in Band 9 (λ0.4 mm; ν ~640 GHz) in April 2024. These tests were done (in consultation with ALMA Management) in preparation for an external team to attempt a VLBI test at this frequency some time in late 2024. Despite the more challenging observing frequency compared with our previous highest frequency phasing frequency (Band 7)—both in terms of sky and receiver noise—array phase-up was achieved with a phasing efficiency of ~90% (see also Appendix D of Crew & Matthews 2024). Furthermore, although the number of Band 9 phasing tests has so far been small, we generally saw evidence of good phasing performance in Band 9 only when the delay fix was invoked, suggesting that the $\sim\sqrt{8}$ boost in SNR was advantageous. A caveat is that weather conditions affecting Band 9 performance may change rapidly and we had no direct back-to-back comparisons of the two methods in Band 9.

4.1.8 Delay Fix: Summary of Outcomes

As a result of APP2 development efforts, a working delay fix will be available for VLBI beginning in Cycle 11. This new method for handling BBDs can optionally be invoked instead of the legacy delay handling method (which remains in place). At present, the choice of which delay handling method to use for a given experiment will be left to the discretion of the Joint ALMA Observatory (JAO) staff supporting VLBI observations. We note that one case where the delay fix is expected to be particularly beneficial is that of passive phasing experiments where the available phasing calibration sources would otherwise be too weak for optimal performance with the legacy delay handling method. As more experience is gained with DF2 (e.g., through continued regression tests), these practices will likely evolve.

One important point that merits clarification and emphasis is that 'DF2' contains two branches: one for the delay fix and one that exercises a version of the legacy code. The setup commands for the phasing mode allows selection of which of the two delay handling methods is requested. An implication is that in principle, DF2 could be used exclusively for future observations, whether or not activating the delay fix is desired. An advantage of this is that in advance of Cycle 11, some modest improvements were incorporated in the legacy delay handling method present in the DF2 branch, including an improvement in speed (see Crew & Matthews 2024 for details), and these were not ported to D0 (which remained frozen).

4.2 VLBI in Additional Bands: Band 7 ("Submillimeter VLBI"; WBS 2.3)

4.2.1 Background

At the time the original APP was launched, there was already significant interest in expanding VLBI beyond Band 6 (ν ~230 GHz) and into the submillimeter (Falcke et al. 2001; Miyoshi & Kameno 2002; Krichbaum et al. 2008; Weintroub 2008; Fish et al. 2013). Operating at shorter wavelengths (specifically Band 7, or ν ~345 GHz) naturally increases the achievable angular resolution for a given baseline. It additionally samples a different portion of the spectral energy distribution of a given source and can expand the *uv* coverage compared with VLBI imaging observations in Band 6 alone. Furthermore, for observations toward the Galactic Center (particularly for Sgr A*), the measurements are expected to be impacted less severely by the effects of interstellar scattering, thus significantly enhancing the ability to reconstruct an image. For example, Johnson & Gwinn (2015) and Johnson (2016) showed that at 230 GHz, the fiducial blurring of Sgr A* expected from anisotropic scattering is equivalent to convolution with a Gaussian with FWHM$\sim$ 22μas along the major axis of the scattering disk. In contrast, at 345 GHz, the equivalent blurring kernel is only $\sim 10\mu$as.

As it turned out, during the period of performance of the APP only a handful of EHT sites had been equipped with 345 GHz receivers. This, coupled with time and resource limitations, resulted in submillimeter VLBI being descoped from the original APP. Instead, this capability was approved for development and commissioning under APP2.

4.2.2 Requirements and Approach

The core functionality of the APS is inherently frequency agnostic. However, there are practical and operational differences, both for phasing and for doing global VLBI experiments, in different ALMA bands due to frequency-dependent atmospheric effects, differences in receiver performance, and other factors. Crucially, the effects of tropospheric water vapor on the signal paths scale with increasing frequency, leading to greater coherence losses in Band 7 compared with Band 6. This impacts the quality of phasing on a local scale, but also makes doing global VLBI far more challenging (e.g., Pesce et al. 2024). Wind also has a more significant effect on phasing quality in Band 7 compared with Band 6 (see below) and the suitable observing windows for Band 7 VLBI with a global array are more restrictive.

In terms of software, the primary code changes required to support Band 7 VLBI were modifications to SSR scripts to support observations and schedule preparation in a new band, along with updates to the ALMA Observing Tool (OT) to accommodate an additional band and tuning set-up for VLBI. These updates were relatively straightforward. The bulk of the Band 7 VLBI effort therefore comprised on-sky testing and commissioning. In total $\sim$12 hours of on-sky test time was required to fully commission this capability (see below).

4.2.3 Commissioning: Standalone ALMA Testing

Phasing Tests Before embarking on global VLBI tests in Band 7 (Section 4.2.4) it was necessary to first demonstrate that ALMA's phasing machinery was operational in this band and that it was possible to routinely achieve acceptable levels of phasing efficiency under nominal Band 7 observing conditions. Furthermore, it was important to gain experience with operating the APS in Band 7 to assess how levels of PWV, wind speed, maximum (intra-ALMA) baseline length, and other variables tend to impact phasing performance.

To characterize phasing performance in Band 7 we analyzed a variety of short test observations obtained between 2015 and late 2021.[2] These test observations lasted anywhere

[2] A small number of Band 7 phasing tests were obtained with permission of ALMA Managements prior

from a few minutes up to ∼40 minutes and generally targeted bright ($\gtrsim$1 Jy) extragalactic radio sources known to be point-like on intra-ALMA baselines. Many of the tests were conducted during Engineering and Software time slots to minimize disruption to Science Observing. A more detailed analysis of these ALMA standalone data sets and a full characterization of APS performance in Band 7 were presented by Crew et al. (2023). Here we provide a summary.

Based on the results of our multi-year testing we found that under nominal Band 7 observing conditions at ALMA (PWV $\lesssim$2.0 mm; $v_{\rm wind}$ <10 m s^{-1}), ALMA is able to perform as a scientifically effective phased array and routinely achieve phasing efficiency $\eta_{\rm 345GHz} \gtrsim$0.5. An example of the performance of ALMA as a phased array in typical Band 7 observing conditions is shown in Figure 7. In this example, $\eta_{\rm 345GHz} \approx 0.9$. This performance is sufficient to allow ALMA to assume a crucial role as the most sensitive anchor station in global VLBI arrays operating at 345 GHz and provide roughly an order of magnitude boost in sensitivity, just as it did previously at 230 GHz (e.g., EHT Collaboration et al. 2019a).[3]

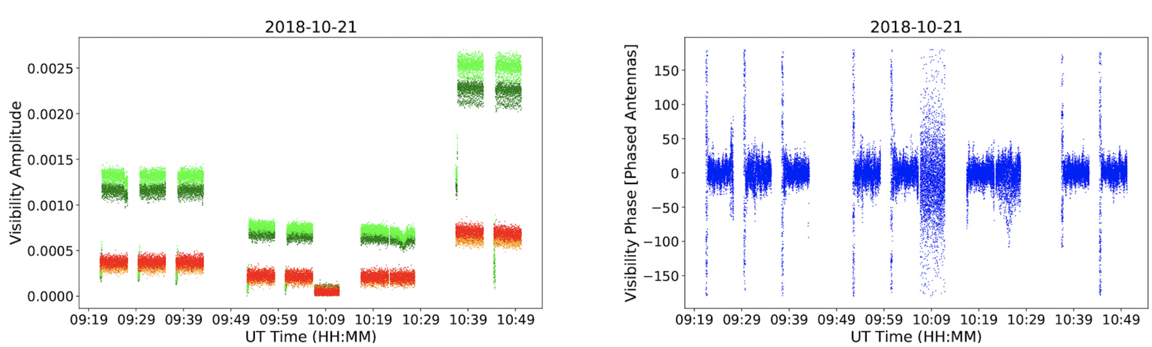

Figure 7: Illustration of the performance of the APS during a Band 7 (345 GHz) VOM observation as part of a VLBI test experiment on October 21, 2018. Weather conditions were nominal for Band 7 (see Section 4.2.4). *Left:* correlated amplitude as a function of time on two sets of baselines: (i) the phasing reference antenna with two unphased comparison antennas (red and orange points); (ii) the phased-sum antenna with the same comparison antennas (light and dark green points). *Right:* phase versus time on baselines between the reference antenna and the other phased ALMA antennas. In both columns, data from a single polarization (XX) in BB_3 are shown. Data in the other BBs and in polarization YY show comparable behaviors. Reproduced from Crew et al. (2023).

One important caution regarding Band 7 phasing operations that emerged from APP2 testing is that we found the phasing performance to diminish significantly during periods of high winds ($v_{\rm wind} \gtrsim$12 m s^{-1}), even when PWV was quite low. Indeed, under high-wind conditions, the effective collecting area of the phased array was seen to approach that of a single 12 m antenna. Thus phasing operations in Band 7 should generally be avoided

to the official start of APP2 in 2018.

[3]The quoted efficiency was achieved using the TelCal-based ("slow") phasing engine, and *without* use of the fast [water vapor radiometer (WVR)-based] phasing corrections (see Section 5.2). The fast corrections are expected to further boost Band 7 phasing quality in the vast majority of cases, particularly under less optimal weather conditions.

in such circumstances (e.g., Figure 8). We also concluded that to maximize data quality it is advantageous to limit the maximum baselines in the phased array to a few hundred meters or less when operating in Band 7. In other words, sensitivity lost by excluding a small number of long baseline antennas is nearly always outweighed by the overall higher phasing efficiency of the more compact array.

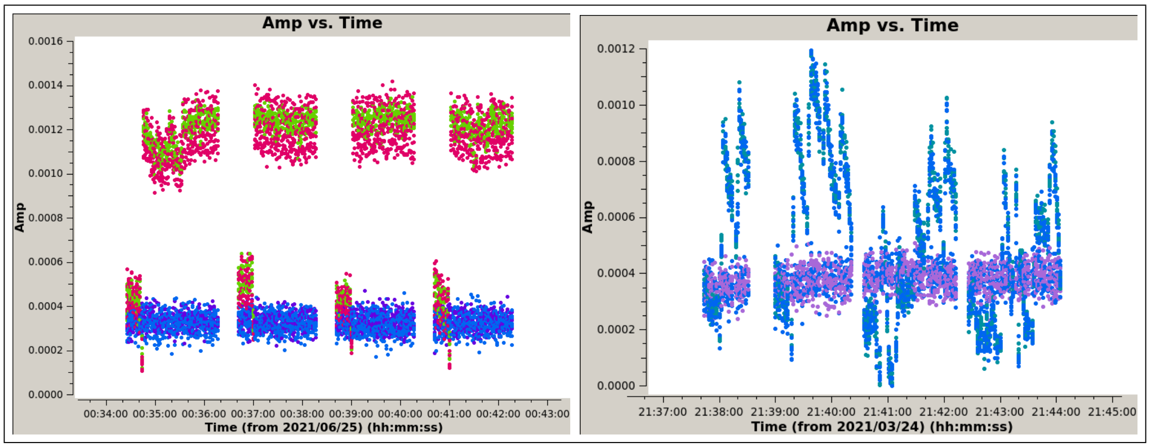

Figure 8: Illustration of the effects of wind speed on Band 7 phasing quality. Correlated amplitude versus time is shown on several baselines during two APS regression tests. *Left:* target J1337–1257 observed with 27 phased antennas on June 25, 2021; the PWV was ∼0.54 and the wind speed was $v_{\rm wind}$ ∼5 m s^{-1}. *Right:* J0522–264 observed on March 24, 2021 with 33 phased antennas, PWV∼2.2 mm, and $v_{\rm wind}$ ∼13 m s^{-1}. The horizontal clusters of purple points are from baselines between the phasing reference antenna and unphased comparison antennas. The blue points correspond to baselines between the sum antenna and the comparison antennas. In the left-hand panel there is some modest dispersion in amplitude of the phased signal, and the right-hand panel it is clear that the phasing quality is severely compromised. Data source: `uid://A002/Xed4381/X1ec` and `uid://A002/Xea6cf9/X1c1`.

QA2 As described in Crew et al. (2023), another component of validating the scientific readiness of ALMA as a phased array in Band 7 comprised undertaking a rough calibration of the interferometric visibilities and carrying out the equivalent of a Quality Assurance Level 2 (QA2). Since our Band 7 tests did not include the usual suite of calibrator measurements that are undertaken during normal science observations (see also Section 4.2.4), we completed a variety of quality checks using modified procedures based on those developed by Goddi et al. (2019). Part of this evaluation included successful Band 7 (ALMA-only) imaging of our various phasing targets (see Crew et al. 2023 for details).

4.2.4 Commissioning: First Global VLBI Tests in Band 7

Having successfully demonstrated ALMA's ability to perform effectively as a highly sensitive phased array in Band 7 (Section 4.2.3), the next critical step toward the formal approval of a Band 7 VLBI capability was the successful completion of a global VLBI fringe test in this band. Prior to the APP2, a few attempts at submillimeter VLBI had been made on single baselines, but VLBI fringes had never been achieved at wavelengths below ∼1.3 mm (Matthews & Crew 2015c; H. Rottmann, private communication). In addition to the challenges posed by weather conditions, other hurdles are that extragalactic sources tend to get weaker with higher frequency and that we have little a priori knowledge of their source structure on VLBI scales at 345 GHz.

Scheduling and Set-Up of the First Band 7 Global VLBI Test: October 2018 A first global VLBI test campaign at 345 GHz was arranged in collaboration with the EHT from October 17–21, 2018. In addition to ALMA, several EHT sites with working 345 GHz receivers were recruited to be part of the experiment: the Atacama Pathfinder EXperiment (APEX) telescope on the Chajnantor Plateau in Chile, the 30 m telescope of the Institut de Radioastronomie Millimétrique (IRAM) at Pico Veleta, Spain, a single (15 m) dish from IRAM's NOrthern Extended Millimeter Array (NOEMA) interferometer (situated on Plateau de Bure in France), the Submillimeter Array (SMA) on Mauna Kea, Hawaii (operated as a phased array of eight 6 m dishes), and the Greenland Telescope (GLT) in Thule, Greenland.

Because of the limited number of suitable target sources with mutual visibility from all sites, tests were conducted in 90-minute blocks using separate "Eastern" and "Western" arrays. The Eastern block included APEX, the GLT, the IRAM 30 m, and NOEMA, along with ALMA. For the Western block, ALMA was joined by APEX, the GLT, and the SMA.

At ALMA, all four BBs (2 GHz each) were recorded in dual polarizations to exercise the full 64 Gb s^{-1} VLBI recording capability. However, to minimize media requirements, other participating sites recorded only a single 2 GHz band with a center frequency of 347600000000.0 Hz (corresponding to ALMA BB_3). APEX recorded only a single polarization (RCP), while the remaining sites recorded dual circular polarizations (i.e., 16 Gb s^{-1} recording). While our primary goal was 345 GHz testing, the Eastern block included additional Band 6 (230 GHz) scans intended for verification and diagnostic purposes in the event that fringes were not obtained at 345 GHz.

The limited (90-minute) duration of the test sessions was intended to minimize impact on ALMA PI science, while still allowing enough time to ensure observations of at least three different target sources from each site. The decision on whether to trigger a VLBI observation on a given day was made during the preceding afternoon, during which representatives from all the participating sites convened for a telecon to discuss weather forecasts and technical readiness.

The October 2018 VLBI Observations On the first day of the October 2018 campaign (October 17 UTC), two schedules (one for the Eastern and Western arrays, respectively) were triggered. Unfortunately, ALMA was plagued by high winds which seriously degraded the performance of the phasing system (e.g., Figure 8). Weather conditions at the other Eastern sites also deteriorated following the trigger.

The weather in the East improved enough for a second VLBI trigger on the third day of the mission (October 19 UTC), despite the persistence of moderately high winds at ALMA ($v_{\rm wind}$ ∼10–15 m s^{-1}). An additional VLBI session with the SMA (as well as APEX and the GLT) was triggered on the fifth and final day of the October 2018 VLBI observing window. ALMA weather was extremely good during this observation (Band 8 conditions and estimated phasing efficiency of >90%; see Crew et al. 2023 and Figure 7).

Following VLBI science observations, typically complete sets of disk modules containing the VLBI data recordings are shipped from each participating observing site to the VLBI correlation centers at the Max Planck Institut für Radioastronomie (MPIfR) in Bonn, Germany and/or Haystack Observatory in Westford, MA. However, in the case of the October 2018 test, it was desirable to expediently evaluate the test results in anticipation of the capabilities review and ObsMode Go/No-go decision in late 2018.[4] Therefore each site identified a few of the most promising scans (comprising a few TB of data) and copied these to hard drives to hand-carry home. These scans were then e-transferred to Haystack for correlation and analysis immediately following the mission.

Correlation and Results from October 2018 Correlation of the October 2018 Band 7 experiment utilized the DiFX correlation software (Deller et al. 2011). Procedures were analogous to those followed for previous ALMA-EHT experiments in Band 6 (see Matthews et al. 2018a), with the minor exception that different frequencies are associated with the various VLBI data channels.

Data from Day 5 of the campaign were identified as likely to be among the highest quality (see above) and three scans from that day were the first to be correlated. All produced fringes on the 9448 km baseline between ALMA and Hawaii, marking the first-ever detections of a VLBI fringe at submillimeter wavelengths (λ0.8 mm) on an intercontinental baseline (see also Raymond et al. 2024). A sample fringe detection is shown in Figure 9.

Two correlated scans of data on the short ALMA-APEX baseline from Day 1 of the mission also resulted in Band 7 fringe detections, although the fringe amplitude was unexpectedly weak. An investigation showed that ALMA appeared to be operating nominally given the local observing conditions. This result was therefore thought to be related to a loss of stability in the local oscillator (LO) system at APEX (A. Roy, private communication).

Finally, on Day 3 of the mission (October 19 UTC), weather at ALMA was marginal, and weather at Pico Veleta was deemed marginal for submillimeter observing (opacity at 225 GHz was $\tau_{225} \sim$0.3, with PWV$\sim$4—5 mm). Despite this, successful Band 7 fringes were obtained between ALMA and the IRAM 30m telescope (Figure 10). To achieve this result, a fringe search was initially conducted using a neighboring scan at 230 GHz for the source BL Lac. The same correlation set-up then yielded a clear fringe detection (SNR$\sim$10) at 345 GHz for a consecutive scan on that target. The relative fringe SNRs in the two bands were consistent with expected estimates based on the relative system equivalent flux densities (SEFDs) for the two bands at the time of the observations ($\sim$18400 Jy at 345 GHz and $\sim$2320 Jy for 230 GHz; P. Torne, private communication).

Overall the results of the first global Band 7 VLBI test in October 2018 not only established that VLBI at these high frequencies is technically feasible, but also helped to underscore the crucial importance of phased ALMA's exquisite sensitivity for future

[4]ObsMode is an annual process aimed at preparing and evaluating capabilities for future ALMA Observing cycles (e.g., Takahashi et al. 2021).

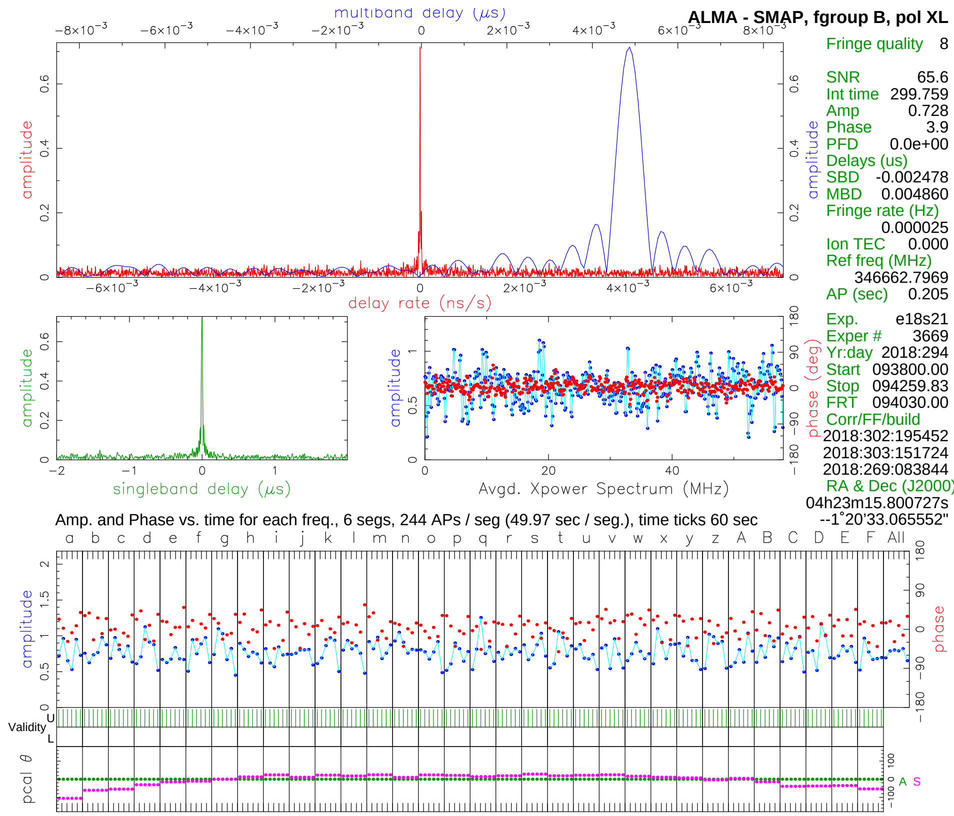

Figure 9: VLBI fringe detection at 346 GHz (Band 7) on the 9448 km baseline between ALMA and the SMA based on observations on October 21, 2018. The target was J0423-0120 (≈2 Jy at the time of the observation). The scan length was 300 s and the resulting fringe SNR was ∼66. Shown is a portion of the summary plot produced by the Haystack Observatory Postprocessing System (HOPS) "`fourfit`" program for one (mixed) polarization correlation product. *Top panel:* delay-rate fringe (red curve) and multiband delay (blue curve). *Middle left:* Single-band delay (i.e., correlation peak in lag space, averaged across all channels; green curve). *Middle right:* cross-power spectrum (Fourier transform of the single-band delay), averaged over the 32 channels; amplitudes are shown in blue, phases in red. The correlation amplitude is scaled by ∼10000 to avoid small numbers. *Bottom row:* Time histories of amplitude and phase for all channels. The green vertical bars indicate periods with valid data and the manual phase calibrations applied. In addition to the usual corrections (delay and rate adjustments, manual phases, etc.), in this example we have applied an "ad hoc" phase correction (≈50%) which used the atmospheric fluctuations seen on one polarization to correct the other.

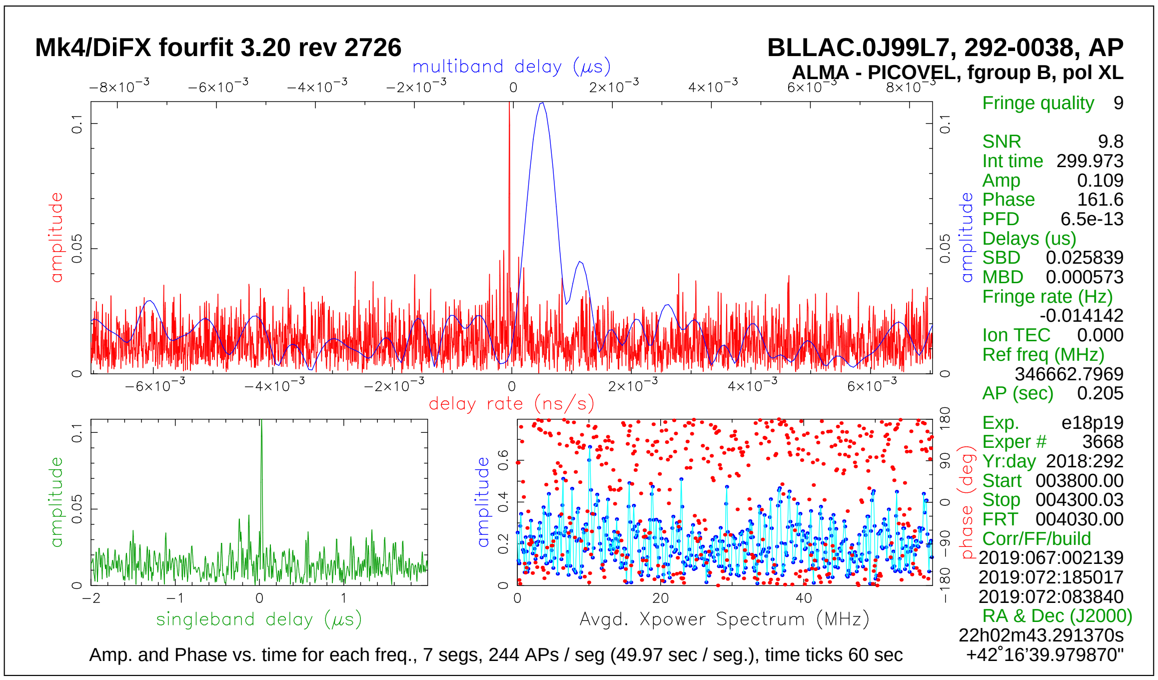

Figure 10: Band 7 (346 GHz) VLBI fringe detection of BL Lac on the 8024 km baseline between ALMA and the IRAM 30m telescope on Pico Veleta, Spain on October 19, 2018. Weather at both sites was relatively poor, resulting in a modest fringe SNR of ∼10. An ad hoc fringe-finding approach was used (see text). The format of this figure is similar to Figures 9. The data shown are mixed polarization (X for ALMA and L for IRAM).

submillimeter VLBI experiments. Indeed, during the October 2018 tests, no VLBI fringes were obtained on baselines that did not include phased ALMA.

An additional discussion of the global Band 7 VLBI tests from October 2018 was recently published by Raymond et al. (2024). That paper recounts the experiment from the perspective of the EHT Collaboration (EHTC) and contains additional technical details about the participating EHT sites, as well as discussion of the strategic importance of a 345 GHz VLBI capability for fulfilling the science goals of the EHT and the proposed Next Generation EHT (ngEHT). The APP2 team coordinated a public release of the data from the October 2018 experiment to coincide with the publication of the Raymond et al. paper. Those data are now available in the ALMA archive (see `https://almascience.eso.org/alma-data/eht-2018`).

4.2.5 Commissioning: A Second Global VLBI Test in April 2021

Although the October 2018 global VLBI experiment achieved a major milestone—the first ever VLBI fringes at submillimeter wavelengths ($\nu \sim$345 GHz)—the tracks executed during that campaign were of relatively short duration ($\lesssim$90 minutes) and therefore could not accommodate a full suite of calibrator measurements, as required to perform the full QA2 and `PolConvert`[5] processing that is normally undertaken for all ALMA VLBI science data. Consequently the formal recommendation in late 2018 was that the APP2 team should undertake a follow-up end-to-end Band 7 global VLBI commissioning test before this new capability was officially made available to the community.

The EHT currently provides the only array of peer observing sites for Band 7 VLBI, but they did not operate as an array during 2019. The following year (2020), ALMA was shut down as a result of the COVID-19 pandemic. Consequently, an opportunity to perform an additional global VLBI test in Band 7 did not arise until April 2021, during the annual ALMA-EHT science observing window. The planning and execution of this test, and the subsequent correlation and analysis of the resulting data, were described in detail by Matthews et al. (2021). Here we provide a short overview and a summary of the main outcomes.

The April 2021 Band 7 VLBI Observations The APP2's second global Band 7 VLBI commissioning test was conducted on April 19, 2021, at the end of the annual ALMA-EHT Cycle 7 campaign. Participating stations included ALMA operating as a phased array of up to 39 antennas and a global array of 8 EHT partner sites (see Table 2).

Because of COVID-19 restrictions, no APP2 personnel were present at ALMA. Instead, the APP2 team provided remote support and the test was executed by the Astronomer-on-Duty (AoD) in Santiago, M.-L. Gendren-Marsolais, in conjunction with an array operator at the Operations Support Facility (OSF).

Targets comprised several bright quasars that have been observed previously with VLBI at 230 GHz (Band 6), along with M87*, a primary science target of the EHT. The latter

[5]The `PolConvert` software allows conversion of ALMA's linearly polarized data products to a circular polarization basis for compatibility with most other millimeter VLBI stations; Martí-Vidal et al. (2016); Matthews et al. (2018a); Goddi et al. (2019). To achieve robust solutions it generally requires $\gtrsim$3 hour observing blocks to ensure sufficient parallactic angle coverage on the polarization calibrator.

Table 2: Participating Stations in the April 2021 Band 7 VLBI Test

Site	Location	Abbreviation	Codes
Atacama Large Millimeter/submillimeter Array	Chajnantor Plateau, Chile	ALMA	Aa A
Atacama Pathfinder EXperiment	Chajnantor Plateau, Chile	APEX	Ax X
Greenland Telescope	Thule, Greenland	GLT	Gl G
James Clerk Maxwell Telescope	Mauna Kea, Hawaii	JCMT	Mm J
NOrthern Extension Millimeter Array	Plateau de Bure, France	NOEMA	Nn N
IRAM 30m	Pico Veleta, Spain	PV	Pv P
Submillimeter Array	Mauna Kea, Hawaii	SMA	Sw S
Submillimeter Telescope	Mount Graham, Arizona	SMT	Mg Z

source was included in the test with special permission of JAO management and the ALMA Board. One motivation for this was that M87* is known to be relatively unpolarized at the resolution of intra-ALMA baselines, making it particularly well-suited for evaluating the performance of `PolConvert`.

The observing schedule spanned a total of 5 hours, split at ALMA into 5 scheduling blocks (SBs), plus an initial 30 minutes of ALMA-specific calibration observations. The weather at ALMA was excellent, with PWV$\sim$0.7–0.8 mm, root mean square (RMS) phase fluctuations $\sim$20–50 μm, and wind speeds $v_{\rm wind}$ $\sim$2–4 m s^{-1}. Metrics derived from the near-real-time Quality Assurance Level 0 (QA0) processing indicated that typical opacity values were $\tau_{225} \sim 0.05$. $T_{\rm sys}$ ranged from 95 to 276 K, and phasing efficiencies ranged from $\eta_{\rm 345GHz}$ $\sim$0.81 to 0.97. At the partnering EHT sites (Table 2), conditions were marginally acceptable for 345 GHz observing at the two Hawaiian sites, with opacity τ_{225} $\sim$0.08, but were less favorable at some of the other sites, with τ_{225} $\sim$0.18 at NOEMA and IRAM, τ_{225} $\sim$0.3 at the GLT, and τ_{225} $\sim$0.29–0.35 at the continental North American sites.

April 2021 Data Correlation and Post-Processing Correlation of the April 2021 Band 7 experiment was similar to that for the October 2018 test (see above). However, in addition, a new technique known as "output bands" (see Janssen et al. 2022), then under development, was adopted within DiFX to handle the special requirements of NOEMA, which operated as a phased array. The need for output bands arises owing to the fact that the 64 MHz channels used in VDIF for NOEMA are incompatible with the 62.5 MHz channels used at ALMA. The other challenge at the correlation stage was to accurately pin down ALMA's LO offset and thus prevent avoidable coherence losses (see Matthews et al. 2021; Matthews & Crew 2024; Section 5.3).

QA2 processing of the April 2021 test was performed using a slightly modified version of the same script that was used for QA2 processing of Band 6 observations from the 2021 VLBI Science campaign. The products generated during QA2 were then used for `PolConvert` processing of the post-correlation data. No significant modifications were required to adapt `PolConvert` to process the Band 7 data, and evaluation of the results suggested that the process worked nominally (see Matthews et al. 2021 and Figure 11, discussed below). In mid-2024, `PolConvert` was re-run for these observations using a different choice of flux and polarization calibrators. However, the results are comparable in quality to the original ones (C. Goddi, private communication).

As discussed above, one of the major challenges of VLBI in Band 7 is dealing with rapid atmospheric variations, which are different at each site, and lead to significant phase decorrelation. Part of our analysis therefore involved further exploration of best approaches for dealing with this. The "phase cal" systems, that are commonly used for VLBI at lower frequencies to calibrate the instrumental phases are generally not available at ALMA or other (sub)millimeter antennas, hence it is necessary to instead derive these instrumental phases on a per-channel basis using observations of a bright calibrator and then apply those phases to other scans in the track (a process known as "manual phase cal"). For calibration of the April 2021 test we also explored use of the so-called "ad hoc" phasing technique to further minimize the impact of atmospheric effects and found this approach to be quite effective thanks to ALMA's presence in the array. With ad hoc phasing, phase corrections derived on a pair of baselines to a sensitive "anchor" station (phased ALMA in this case) are subsequently applied to the baseline involving the two less sensitive stations in the triangle, resulting in improved SNR for VLBI fringes. This approach was also used successfully in Band 7 in 2018, and examples shown in Figures 9 and 10, discussed above.

April 2021 Results Following `PolConvert`, various data quality checks and array performance evaluations were carried out by the APP2 team (see Matthews et al. 2021 for a more extensive discussion). No attempt was made to produce images from the resulting data, as this was beyond the scope of the commissioning and science verification activities of the APP2 team and achieving adequate *uv* coverage on sources for imaging was not a priority in designing the experiment schedule.

The April 2021 test resulted in clear VLBI fringe detections for multiple target sources between ALMA and various EHT sites. Some examples of fringe detections for a scan on M87* are shown in Figure 11. This figure also demonstrates the successful application of `PolConvert` in Band 7. The expected correlated flux density of M87* at 345 GHz on ALMA-EHT baselines of $\sim$8-10 Gλ is $\sim$70–100 mJy, giving predicted fringe SNRs of $\sim$10 (see Figure 9 of Raymond et al. 2024). Prior to `PolConvert` the mixed polarization fringes are near the detection threshold. However, after application of `PolConvert` the fringe SNR values rose by $O\sqrt{2}$ into clear detectability on several baselines, with SNRs consistent with theoretical predictions. Detections were achieved on other baselines and scans as well (not shown here), including on baselines between ALMA and Pico Veleta, GLT, JCMT, SMA, and SMT. Note that the parallel hands are roughly comparable in amplitude (receiver gain corrections have not yet been applied) while the cross hands fringes (not shown) were below the detection threshold.

In contrast to the October 2018 experiment, where fringe detections were obtained exclusively on baselines to ALMA (see Section 4.2.4), there were also intra-EHT fringe detections during the April 2021 test. These detections benefited from application of the ad hoc phasing technique (see above). Further details of these (proprietary) EHT results will be described elsewhere.

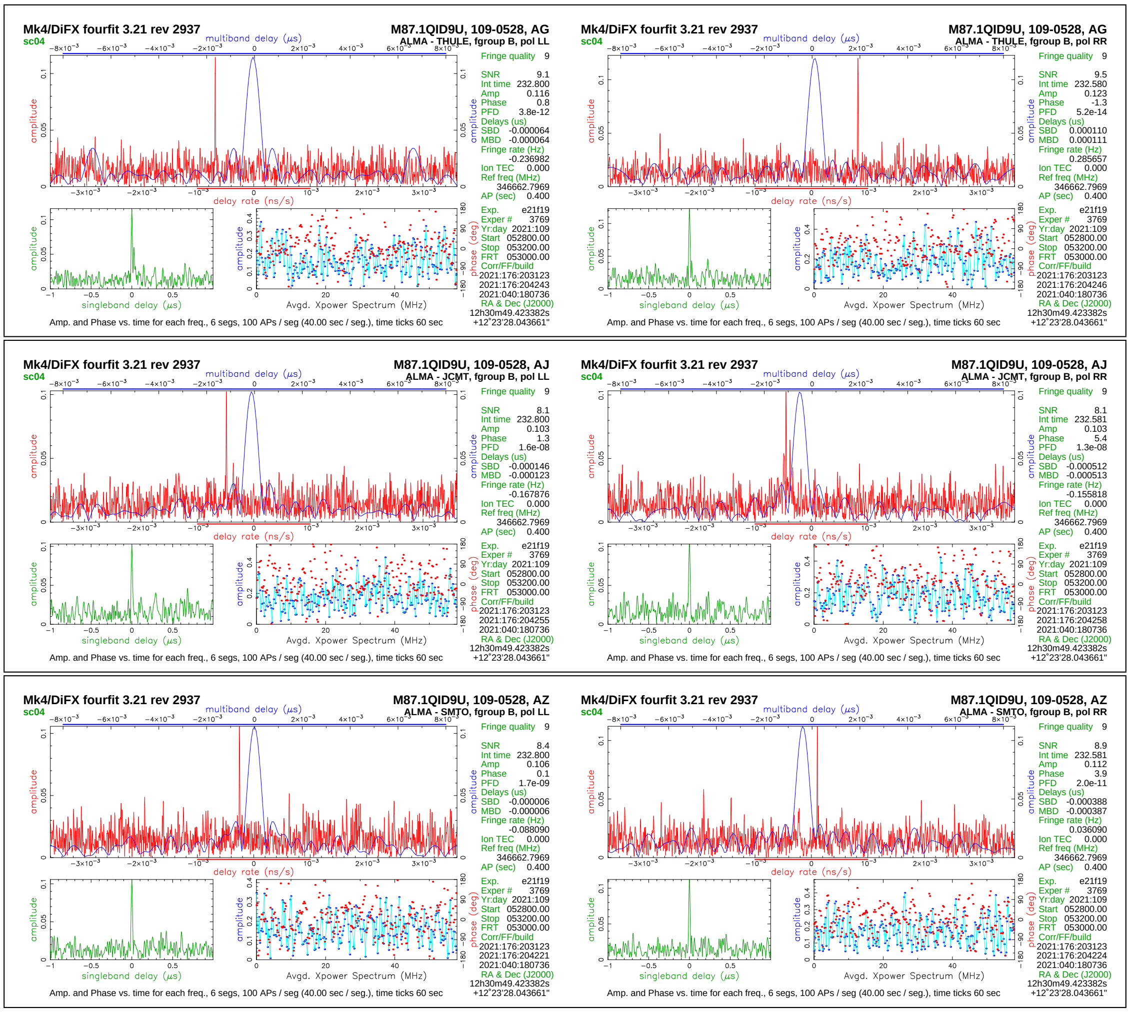

Figure 11: Sample Band 7 (345 GHz) VLBI fringe detections on M87*, obtained on April 19, 2021 between phased ALMA and three different EHT stations: GLT (top row), JCMT (middle row), and SMT (bottom row). The data are from a 232 second portion of a single scan and have been converted to a circular polarization basis using PolConvert; LL products are shown on the left and RR on the right. The panel formats are as in Figure 9. The EHT data are used courtesy of D. Marrone (SMT); Per Friberg (JCMT); Satoki Matsushita and Ming-Tang Chen (GLT).

Outcomes of April 2021 Test The results of the April 2021 Band 7 global VLBI test, in combination with the results from various standalone ALMA phasing tests in Band 7 (Crew et al. 2023) and the VLBI results obtained in October 2018 (Section 4.2.4) were collectively deemed to have demonstrated scientific readiness of this capability. A Band 7 VLBI observing capability was subsequently approved to be offered to the community starting in Cycle 9 (2023) and the first VLBI science observations in this band were executed in April 2023. Plans are underway for a future public release of the datasets from the April 2021 Band 7 experiment, as was done for the October 2018 Band 7 data (see above).

4.3 Passive Phasing (WBS 2.4)

4.3.1 Background and Motivation

During the first few Cycles in which ALMA VOM capabilities were offered (Cycle 4–7) there was a general requirement that phasing calculations be performed on the science target itself. That in turn implied that all accepted VLBI (continuum) targets—including both calibrators and science targets—needed to have adequate correlated flux density on intra-ALMA baselines to insure consistently good SNR for the phasing engine (which solves for phases using ∼234-MHz sub-bands; see Section 4.1.1). Since Cycle 4, programmatic recommendations have set those thresholds at ≥500 mJy for both Bands 3 and 6. In later Cycles, limits were added for Bands 1 and 7 of ≥350 mJy and ≥750 mJy, respectively.

The newly implemented delay fix (Section 4.1) now in principle offers an option to lower the source brightness requirement for active phasing targets by $\sim \sqrt{8}$ for any available VLBI band (see Table 1). However, to enable observations of even weaker sources, as well certain classes of spectral line targets, an alternative approach is the use of so-called "passive" phase-up, whereby the array is phased up at some fixed cadence (of order every few minutes or less) on a bright phasing calibrator ("phasor") close in angular distance to the science target (i.e., within a few degrees or less, depending on band). The computed phasing solutions from the calibrator are then applied for the duration of the subsequent science target scan while the phasing engine is paused until the next phasor scan, when the cycle repeats.

Provisions for passive phasing were built into the APS from its inception (Matthews et al. 2018a). However, owing to time constraints and other more urgent priorities during the initial launch of the APS, this mode received only partial testing during the APP period of performance and this capability was never formally evaluated for approval for VLBI science observing.

Preliminary testing under the original APP was sufficient to establish that the mechanics of passive phasing worked, and that under typical Band 3 and Band 6 observing conditions, phase coherence can be established and maintained for up to a few tens of seconds (or even a few minutes) on sources too weak to allow active phasing (e.g., Figure 12). One particularly powerful demonstration of the passive phasing mode was the successful detection of the Vela pulsar with phased ALMA in Band 3, where the correlated flux density of the source of interest is only ∼1 mJy (Cordes et al. 2017; Liu et al. 2019).[6] However, that Vela

[6]The Vela test was done as part of an ALMA North American Development Study led by J. Cordes (PI,

test observation used ALMA as a standalone array (what is now known as the "Phased Array" mode), not as part of a VLBI experiment. Indeed, at the conclusion of the APP there had not yet been a successful demonstration of a long-baseline VLBI fringe detection of a passively phased source. Furthermore, the initial Vela test was insufficient to allow a full end-to-end demonstration of the procedures for pulsar observing. For these reasons, additional commissioning of the passive mode, both for Phased Array (pulsar) observations (Section 4.3.3) and for VLBI applications (Section 4.3.2), was approved as part of the APP2 work package.

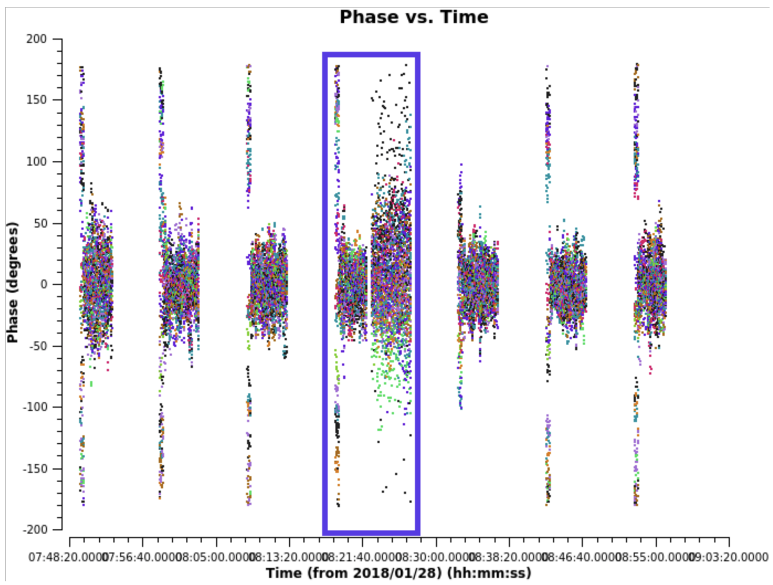

Figure 12: Results from a Band 6 test observation conducted on January 29, 2018, demonstrating successful *passive* phase-up of the array. Visibility phase versus time is shown for baselines from the various phased antennas (each indicated by a different color) to the phasing reference antenna. The data have been averaged over the 8 channel averages in each of the four BBs, and both polarizations are included. The total time interval plotted spans ∼72 minutes. The blue box indicates the interval of a passive phasing test that used the 2.2 Jy quasar J1337−129 as a phasor (observed for 3 minutes starting at 08:19:00 UTC) to phase-correct the 0.3 Jy quasar J1336−0829, 4.4° away. J1336−0829 was then observed for a 4.5-minute scan starting at 08:22:30 UTC, without any further phasing updates. Despite this, reasonable phase coherence is maintained, as evidenced by still-modest RMS scatter in the phases (∼ ±30 deg). Data source: `uid://A002/Xc9c531/X34bd`.

4.3.2 Commissioning of the Passive Phasing Mode for VLBI

In July 2016 the APP team incorporated a short passive phasing test as part of a Band 3 global VLBI test in conjunction with the Very Long Baseline Array (VLBA). However, no VLBI fringes were obtained on the passively phased target. A second attempt was carried

Cornell University; see Cordes et al. 2017). That project included a subaward to MIT Haystack (Co-PI, S. Doeleman) that supported direct involvement by one of us (GBC) and allowed close coordination with APP2 efforts.

out in Band 6 in late January 2018, shortly after the launch of the APP2 (as part of the 2018 EHT Dress Rehearsal[7]), but again, no fringes were obtained. The precise explanation for the absence of fringes in these two cases was never established, but examination of the phasing performance in the ALMA-only data suggested that the passive array phase-up was working nominally. The most likely explanation was therefore that the correlated flux densities of the passively phased targets were simply too low on long baselines to allow detections. Nonetheless, to fully exclude possible issues related to the functionality of the APS and/or the VOM when passive phasing was invoked, the APP2 team undertook additional testing of passive phasing during a commissioning and science verification mission in October 2018 (the same one during which the first Band 7 global VLBI observations were attempted (see Section 4.2).

During the October 2018 mission we inserted into our Band 7 VLBI schedule on Day 5 a sequence of four scans intended to allow further testing of passive phasing during a global VLBI experiment. In the first scan of the sequence, ALMA was actively phased up on the relatively bright source J0510+1800 (∼0.9 Jy at 345 GHz). In the subsequent scan, a weaker source J0521+1638; (∼0.18 Jy) was observed, ∼ 3 degrees away, and the previous phasing solutions were applied to it. Next, J0510+1800 was observed again with active phasing resumed; finally, J0510+1800 was observed once more, passively phased (Figure 13).

No VLBI fringes were detected on the weaker passively phased source J0521+1638. However, this is not particularly surprising; the ability to maintain phase coherence on a relatively weak source via passive phasing is no guarantee that VLBI fringes will be detectable on long baselines; the latter will be determined by the source structure on a given baseline (in this case, unknown), as well as the mean sensitivity of both participating stations. We did however achieve a fringe detection on the passively phased scan of J0510+1800 on the ALMA–SMA baseline (Figure 14), allowing us to confirm that the mechanics of the passive phasing mode are not adversely affecting the recorded VLBI data stream.

An additional test of passive phasing was also conducted in Band 6 in October 2018, at the end of the final "Eastern block" (see Section 4.2.4). During that test, ALMA, the GLT, NOEMA, and the IRAM 30 m all recorded in Band 6 (230 GHz) and performed an actively phased scan on BL Lac (∼2.7 Jy at 230 GHz), followed by a 5-minute passively phased scan on the same source. Strong fringes (SNR∼90) were detected on the latter scan and indeed, there was no discernible loss in SNR compared with the preceding, actively phased scans on the same source.

Lastly, we note that passive phasing was also tested successfully during global VLBI observations of spectral line targets as part of APP3. Sample results from such testing were presented by Matthews & Crew (2024).

4.3.3 An End-to-End Phased Array (Pulsar) Observing Test

As described in Section 4.3.1, the ability to use ALMA as a standalone phased array for pulsar science was first demonstrated through observations of the Vela pulsar in 2017 (Liu

[7]ALMA typically conducts a "Dress Rehearsal" in conjunction with a subset of EHT stations each year in late January as a readiness exercise in advance of the annual ALMA-EHT science campaign that occurs in March or April.

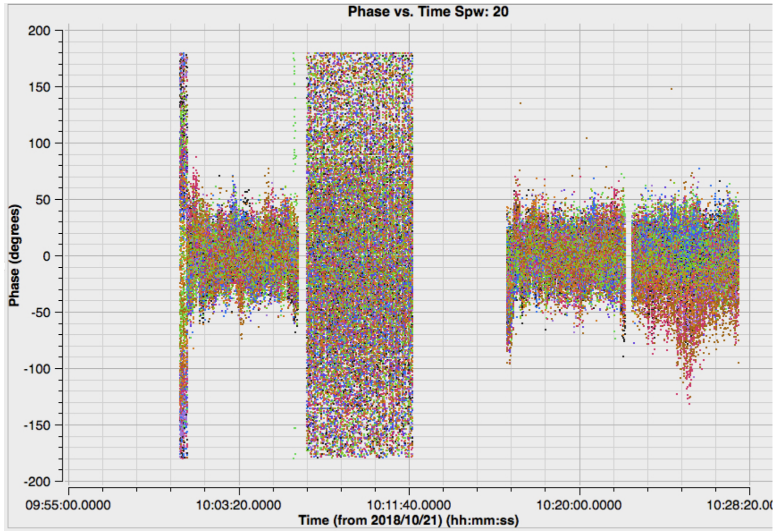

Figure 13: Results from a passive phasing test with the APS in Band 7 (345 GHz) on October 21, 2018. Phase versus time is plotted for baselines to the phasing reference antenna for four consecutive scans (separated by gaps in time) in one of the four BBs, polarization YY. Data from individual baselines are distinguished by color. The first scan used active phasing on the quasar J0510+1800 (∼0.9 Jy). The second scan on J0521+1638 (∼0.18 Jy and ∼ 3 deg away) was passively phased via application of the previous phasing solutions. The third and fourth scans are both on J0510+1800; the first of these is actively phased and the second is passively phased. Data source: `uid://A002/Xd395f6/Xd41f`.

et al. 2019). Subsequently this observing mode was assigned a new type of project code (".P") to distinguish it from VLBI projects (which are designated type ".V").

When conducting a .P observation, ALMA is operated as a phased array of 12 m antennas. Assuming 43 phased antennas, the collecting area is roughly equivalent to a parabolic dish of diameter ∼75 m, providing crucial sensitivity for the detection of the generally very weak signals emitted by pulsars in the millimeter band (e.g., Lorimer & Kramer 2005). The raw baseband data are recorded in VLBI format while simultaneously archiving the ALMA interferometric data products, the same as for VLBI projects. Thus from an observational standpoint at ALMA, it is nearly identical to observing for .V projects. However, because .P observations are not dependent on the participation of peer observing sites, their scheduling is not dependent on coordination with other telescopes. Furthermore, such observations can in principle be conducted outside of the designated VLBI campaign windows at ALMA, provided that suitable VLBI recording media are available and that the array is in a configuration where a large fraction of the baselines are $\lesssim$1 km (so as to maximize phasing efficiency; see Matthews et al. 2018a).

Because the first commissioning test of the .P mode did not include a full suite of calibrations (see Liu et al. 2019), it was deemed desirable to conduct a second commissioning observation on the same target (Vela), with the goals of: (1) exercising a new type of "QA2 lite" calibration and data reduction procedures on the ALMA interferometric data, and (2) generating fully calibrated and processed PSRFITS[8] files for the ALMA Archive from

[8]PSRFITS is a specialized version of the Flexible Image Transport System (FITS) format that

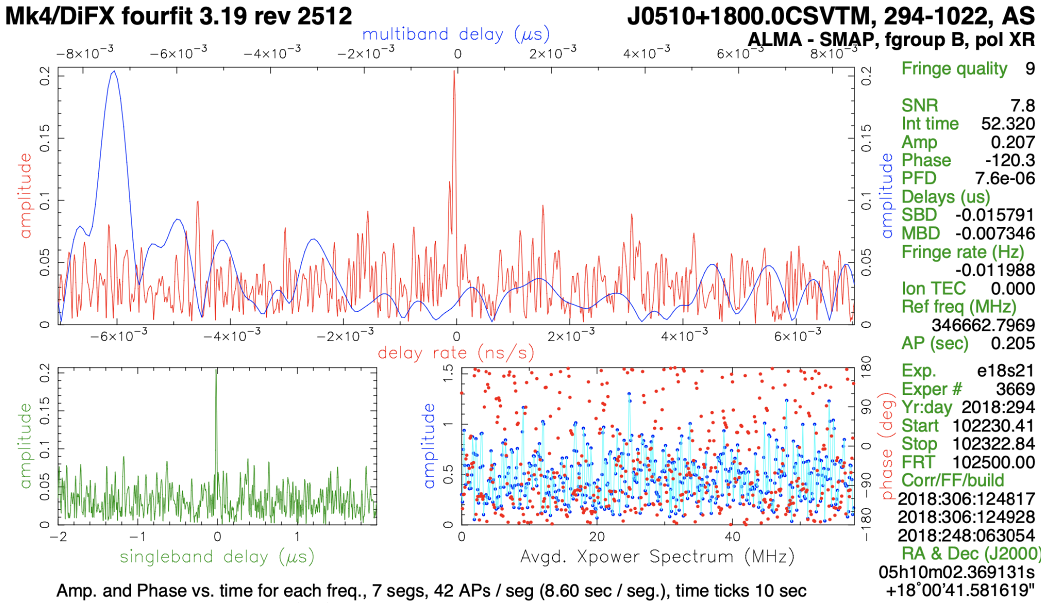

Figure 14: First demonstration of a VLBI fringe detection resulting from a passively phased source scan. J0510+1800 (∼1 Jy) was detected on the 9448 m baseline between ALMA and SMA. The format of the plot is the same as Figure 9. ALMA was phased up during the preceding scan on this source, but no active phasing was applied during the 52 s scan shown here. The observation was conducted at 346 GHz on 21 October 21, 2018. The data are in a mixed polarization basis (R-X).

the VLBI recordings using a special pulsar processing pipeline developed by the pulsar group in Bonn, Germany. Effectively, this second test observation was envisioned as a full end-to-end test of the Phased Array capability for pulsar science.

2021 Phased Array Observations A second commissioning test of the Phased Array mode was carried out in Band 3 on April 28-29, 2021 between 21:20–03:00 UTC, at the end of the nominal Global Millimeter VLBI Array (GMVA) observing window. There were 37 antennas in the phased array, plus five comparison antennas. The phased array radius was 600 m, with baselines ranging from from 14 m to 1260 m. The weather was excellent (PWV∼0.7–1.4 mm) and there were no known operational issues.

The array was passively phased using periodic observations of the neighboring phasing calibrators (phasors) J0828–3731 (∼0.52 Jy) and J0922–3959 (∼1.1 Jy). Each phasor observation spanned ∼70 s, followed by an observation of the science target Vela. For assessment purposes, we tested a range of different times on the primary source: 180, 240, 300, 360, 420, 480, 540, 600, 660, 720, 780 s. In addition to the phasors, other standard calibration sources were observed during the experiment, including J1037–2934 as a bandpass and flux calibrator and J1058+0133 as a polarization calibrator. In total, 48.7% of the observing time was spent on the primary target Vela.

is used for pulsar data; see `https://www.atnf.csiro.au/research/pulsar/psrfits_definition/PsrfitsDocumentation.html`.

For this test, the MPIfR pulsar group augmented the normal GMVA media to allow recording in 4 bands, centered at 86.268, 88.268, 98.268 and 100.268 GHz, respectively. (Normally for GMVA operations in Band 3, only BB_1 is recorded because of bandwidth limitations at some of the participating sites). At the time of the test, an issue was noticed with the tunings generated by ALMA's `LOSolutions` (a Java module used for tuning set-up) in that it produced tunings that were 3 MHz different from those requested. This issue was seen in other ALMA VLBI observations as well and the cause was identified after extensive investigations by the APP2/APP3 team (see Section 5.3). In any case, once this issue was recognized, it was not a fatal problem for this Phased Array test, as the offset is small compared with the total ALMA bandwidth, the test did not require a precise frequency tuning, as unlike VLBI experiments, correlation with data from other stations was not performed.

2021 Phased Array Post-Processing Following observations, the recorded VLBI data were shipped to MPIfR in Bonn for processing as described above. Meanwhile, the ALMA interferometric data from the experiment were reduced by by H. Messias (JAO) using a newly developed QA2 Lite version of the existing VLBI QA2 script that he had designed specifically for Phased Array projects (e.g., Figure 16.)

At the Bonn correlator the raw baseband data were read out and converted to PSRFITS using the `mpivdif2psrfitsALMA` routines that the MPIfR team had recently developed to speed up the pulsar data processing using the multi-threading capability of the Bonn correlator.[9] The outputted data products consisted of 32-bit floating point time samples in four Stokes with 8-μs time resolution and 32×62.5-MHz frequency channels across each 2 GHz BB. In general for Phased Array experiments, the choices for time resolution, frequency resolution, and number of outputted Stokes parameters can be specified by the PI, subject to certain constraints (see ALMA Technical Handbook for details).

Scans on the Vela pulsar were folded using a predetermined ephemeris with respect to the known pulsar period to examine the pulsar signal. The data processing ran smoothly and without any issues, providing confirmation that the updated pulsar processing software was robust and ready to support routine usage.

2021 Phased Array Data Analysis As it turned out, the pulsar signal was not detected in most of the scans from the 2021 Phased Array experiment. A signal was seen in a handful of scans, but it was time-variable and weak compared with the previous test in 2017 (Figure 15).

Upon investigation it was discovered that the phase center used for the 2021 test observation had adopted a J2000 position for the Vela pulsar that was *uncorrected* for the significant proper motion of this source ($\mu_{\alpha\cos\delta} = -49.68 \pm 0.06$, $\mu_\delta = 29.9 \pm 0.1\,\mathrm{mas\ yr^{-1}}$; Dodson et al. 2003). For ordinary ALMA observations, proper motion corrections are typically applied automatically by the online system. However, for VOM observations, the standard practice is to disable these corrections to ensure that telescope pointing coordinates at all participating sites exactly match the source coordinates specified in the VLBI schedule.

[9] `https://github.com/xuanyuanstar/MPIvdif2psrfits`

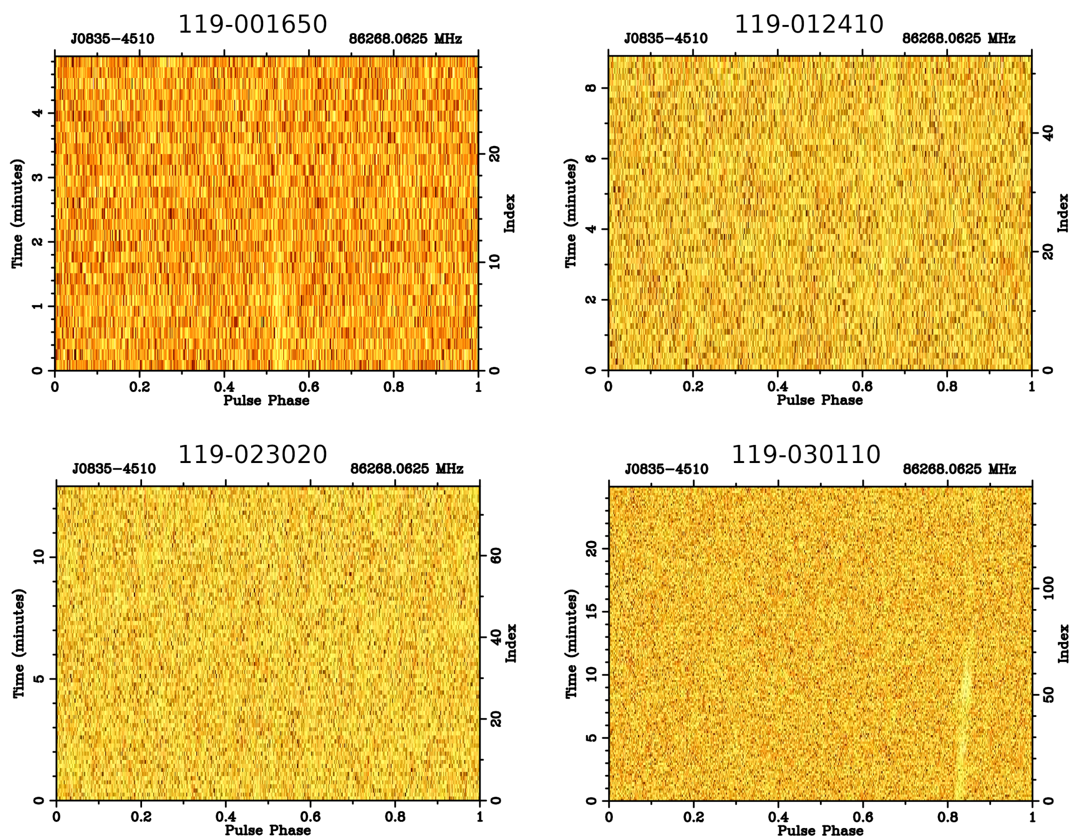

Figure 15: Signals from the Vela pulsar as a function of time for individual scans obtained in April 2021. Weak, time-varying signals are seen only in the thirteenth scan (119-001650), eighteenth scan (119-012410), and twenty-third scan (119-030110). This can be explained by a source position error during the test, which placed the pulsar outside of the phased array beam (see text for details). A sample no-detection (scan 119-023020) appears in the fourth panel. The data are from the spectral window corresponding to BB_1, centered at 86.268 GHz.

To clarify this point, we note that during phased array operations, the coherence matrix data for the full array are not recorded; thus all directional information is lost during the coherent summation of antenna signals that creates the sum signal recorded onto the Mark 6 VLBI recorders. In practice, this means that only signals at the phase center (i.e., within a field-of-view set by the size of the synthesized beam of the array) are recorded.[10]

Given that the maximum baseline of the 2021 test observation was 600 m, the ALMA synthesized beam had a FWHM of approximately 0.68 arcsec in Band 3. As neglecting the proper motion of Vela led to a position error of approximately 1.2 arcsec at the epoch of observation, this placed Vela outside of the phased array beam (though it was still within the ALMA primary beam). This was confirmed from the ALMA interferometric imaging data taken in parallel during the observation, which show the pulsar position to be consistent with the proper motion-corrected value at the epoch of observation (Figure 16). The apparent time variation that was seen seen in the pulsar signal can be attributed to the pulsar occasionally passing through a sidelobe, as these rotate over time with respect to the beam center during the track.

Outcomes of the 2021 Phased Array Test Despite the pointing error that compromised the quality of the data from the Phased Array mode test conducted in April 2021, the data nonetheless allowed successfully demonstrating the mechanics of executing a Phased-Array mode project and its subsequent post-processing. The test also enabled the development and successful demonstration of a QA2 Lite script for use by ALMA staff in processing the associated ALMA interferometric data from Phased Array experiments.

The impact of the uncorrected proper motion in this case also served to highlight the importance of making observers (both PIs and ALMA staff) generally aware of these sorts of special considerations when observing with ALMA as a phased array. To mitigate the risk of future compromised data for targets with significant proper motions, warnings and guidelines on this topic have been added to the ALMA Technical Handbook and Proposer's Guide.

The Phased Array mode was subsequently approved for Cycle 8 in 2021, in Band 3 only. Following APP3 work that made phasing capabilities available in other ALMA bands (Matthews & Crew 2024), the Phased Array mode was expanded to additional bands starting in Cycle 10. We note, however, that at the time of this writing, validation of OT functionality for the Phased Array mode has not been undertaken for all ALMA observing bands.

A Follow-Up Phased Array Test in 2022 Owing to the issues detailed above, a second 4 hr Phased Array test observation of Vela in Band 3 was scheduled and carried out, beginning on April 3, 2022 UTC. This time, Vela's coordinates were explicitly updated to correct for the proper motion. Twelve scans were obtained on Vela, with lengths ranging from 110 s to 350 s. Other details of the observational set-up were identical to the one carried out in April 2021 (see above). There were no known issues with the execution of

[10]The field-of-view of the standard ALMA interferometric data products obtained in parallel with the VLBI recordings is not affected.

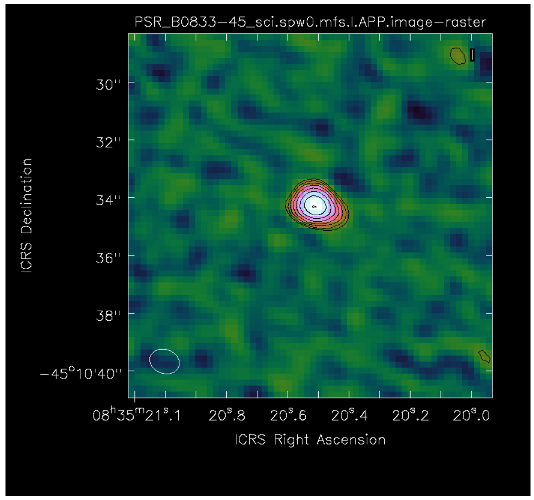

Figure 16: Stokes I image of the Vela pulsar (and surrounding nebula) at 86 GHz, derived from ALMA interferometric measurements obtained during the April 2021 Phased Array mode test. The image was produced via a "QA2 Lite" processing script, specially tailored to this observing mode (see text). The synthesized beam has a FWHM of 0.68 arcsec and is indicated in the upper right corner. The phase center of the observation was based on the J2000 coordinates of Vela uncorrected for proper motion, placing the pulsar just outside of the phased array beam.

the observation, although the weather conditions were marginal for Band 3 observing at ALMA.

This time, QA2 Lite processing of the resulting data showed the pulsar to lie approximately a fifth of a beamwidth from its expected position. However, we believe this offset to result primarily from weather-related phase errors rather than errors in the adopted position or proper motion corrections.

As with the previous Phased Array experiments, the VLBI recordings were again sent to Bonn for processing. Vela was clearly detected in all of the scans, with SNR values for the integrated pulse profiles obtained from each of the individual scans, $\mathrm{SNR_{int}}$, ranging from ∼10–214. All indications are that the APS was working nominally throughout the observation (K. Liu, private communication).

Figure 18 plots the derived peak SNR per pulse, $\mathrm{SNR_{ppp}}$, derived from

$$\mathrm{SNR_{ppp}} = \mathrm{SNR_{int}}/\sqrt{t_{\mathrm{obs}}/P_{\mathrm{p}}}$$

where t_{obs}=110...350 s, P_{p} is the pulsar period (89 ms in the case of Vela; Liu et al. 2021), and $\mathrm{SNR_{int}}$ is the SNR of the integrated pulse profile. Interestingly, the modulations in $\mathrm{SNR_{ppp}}$ appear to be real and may be related to intrinsic source variations (K. Liu, private communication). Follow-up investigations are ongoing.

4.3.4 Practical Usage of the Passive Phasing Mode for Phased and Array and VLBI Experiments

Following completion of the passive phasing tests described above (both for the VLBI and Phased Array cases), various practical and functional details were addressed in preparation

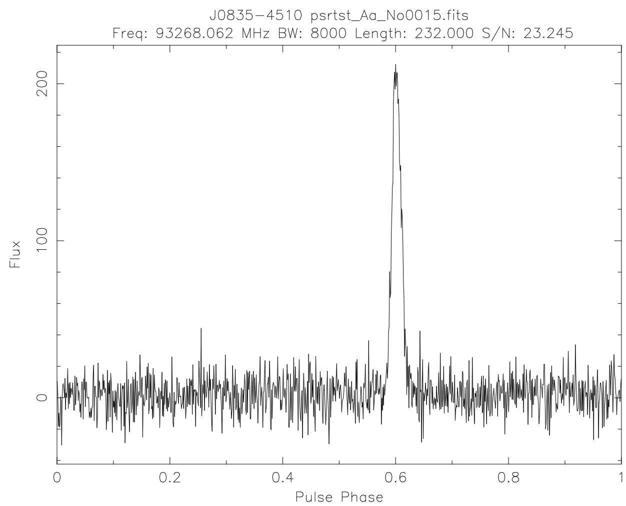

Figure 17: Sample integrated pulse profile detection of the Vela pulsar during a 232 s passively phased scan obtained on April 3 2022. The SNR of the integrated profile is $\mathrm{SNR_{int}} \sim 23$. Credit: K. Liu.

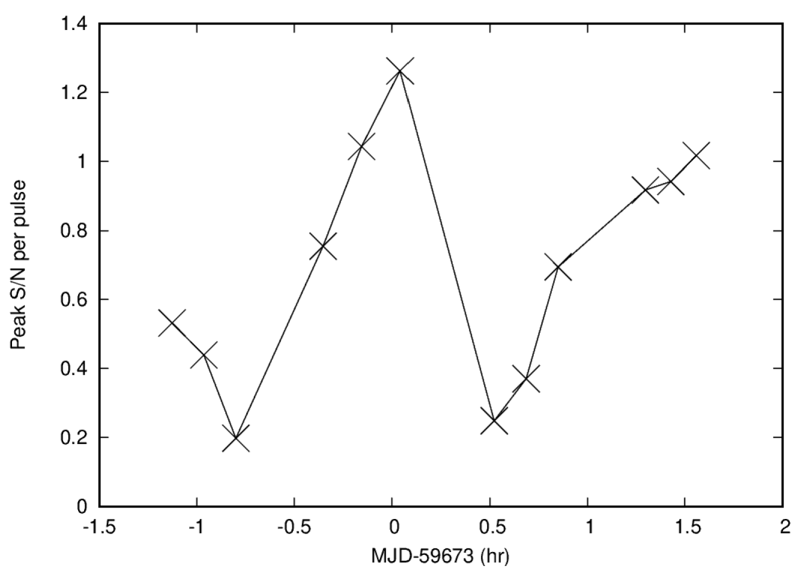

Figure 18: Peak SNR per pulse as a function of time for the Band 3 Phased Array test observation of the Vela pulsar, obtained on April 3, 2022. The crosses indicate the start times of individual (passively phased) scans, whose length ranged from 110 s to 350 s. The pulsar was securely detected in all 12 scans (see text for details). Credit: K. Liu.

for making this capability available to the user community. A description of the passive phasing mode was added to the ALMA Technical Handbook and to the ALMA Proposer's Guide, and guidelines were included which specify the maximum angular separation for the adopted phasor in each ALMA VLBI band. The latter were developed based on results from our own APP2 (and earlier APP) testing, as well as independent investigations of the impact of angular separation on the effectiveness of phase calibration at ALMA (e.g., Asaki et al. 2014; Maud et al. 2022).

Recommended cycle times for passive phasing were based on the knowledge that the APS TelCal phase solver typically takes ∼30-60 seconds to converge on a stable phasing solution for a bright calibrator.[11] Following application of these phase corrections to the passively phased target, our empirical findings led to the recommendation that typical integration times should range from ∼1-3 minutes, depending on the observing band, array size, and weather conditions. This balances decorrelation losses (that increase with longer scan durations) with efficiency and sensitivity losses caused by too frequent cycling. These estimates are in line with previous analyses of the coherence times at the ALMA site. For example, if we take as a goal achieving phasing efficiency of ≥90% (Matthews et al. 2018a), then based on Holdaway (1997), coherence times longer than 1 minute are achieved at the ALMA site approximately 50% of the time in Band 3 and ∼30% of the time for Band 6 under typical winter conditions (see his Figure 1). These intervals can be further extended by use of fast (WVR-based) phasing corrections (e.g., Asaki et al. 2014), but this was not directly explored under APP2 owing to an extended window during which the fast phasing mode was not operational (see Section 5.2).

Following successful commissioning of the passive phasing mode, the APP2 team worked with OT developers to implement the required updates to the OT to allow use of the passive phasing option. These updates included an ability to specify which targets should be passively phased, adding the functionality to search for a suitable phasor, and providing a provision to manually designate a preferred phasor.

Passive phasing was formally offered for the first time for standard VLBI observations in Cycle 8. With the introduction of the delay fix in Cycle 11 (Section 4.1), efficacy and applicability of this mode are likely to be further enhanced, since the minimum flux density threshold for phasor selection within the recommended search radius (both band-dependent quantities) will be lowered by $\sim \sqrt{8}$.

4.4 A Prototype Spectral Line Capability (WBS 2.5)

4.4.1 Background and Motivation

The ALMA receiver bands contain numerous astrophysically important spectral lines, and a number of scientific applications benefit from the study of these lines at extraordinarily high angular resolution (see Fish et al. 2013; Tilanus et al. 2013; Kim & Fish 2023). These lines include both non-thermal (maser) lines observable in emission from molecules such as SiO, H_2O, CH_3OH, and HCN (Boboltz 2005; Wootten 2007), as well as weaker

[11]This is now known to be a result of an issue in the BLC CCC software. However, it is unlikely to be fixed owing to competing priorities and ALMA's planned migration to the Advanced Technology ALMA Correlator (ATAC) within the next few years.

thermal lines detectable in absorption (e.g., HCN or HCO^+). Unlike continuum VLBI, where averaging over wide bandwidths (up to ∼8 GHz) can be used to boost sensitivity, spectral line VLBI is critically dependent on large collecting areas to achieve adequate SNRs within the individual narrow spectral channels (often having widths of a few tens of kHz or less). Phased ALMA, with its extraordinary sensitivity, is therefore poised to be a game-changer for spectral line VLBI studies.

The original ALMA VOM was designed and optimized for observations of continuum sources, and the APS capabilities that were offered in Cycles 4–7 comprised a single fixed frequency setup in Bands 3 and 6, respectively, intended for observations of continuum sources. However, under APP2 we took crucial steps toward implementing the software upgrades required to enable a full-fledged spectral line VLBI observing mode at ALMA and beginning the process of commissioning these capabilities. As described below, this resulted in a prototype spectral line VLBI observing mode that was offered in Cycle 8. This capability also served as the basis for a fully flexible spectral line VLBI mode that was subsequently developed and commissioned under APP3 and was offered starting in Cycle 9 (see Matthews & Crew 2024). Here we describe only the foundational work undertaken as part of APP2.

4.4.2 Required Updates to the APS and VOM and the Scope of APP2 Efforts

The fundamental principles of using the APS for spectral line studies are the same as for continuum experiments. Nonetheless, a number of software changes were required to enable the design and set-up of spectral line VLBI experiments, to ensure optimal performance on different types of spectral line targets, and to produce data sets suited to the unique needs of spectral line science. Additionally, some adjustments were required in how the data are handled during correlation, `PolConvert`, QA2, and other post-processing steps.

The primary areas to be addressed to support a spectral line VLBI mode at ALMA included the following:

- **Spectral window matching:** For emission lines with sufficiently high brightness temperatures (peak flux density $\gtrsim$15 Jy), direct phase-up of the array using the line emission (rather than the source continuum or a neighboring phasor) becomes possible. However, to avoid dilution of the signal and maximize the SNR of the phasing solutions, the bandwidth of the spectral window used to compute the phasing corrections should be well-matched to the intrinsic linewidth and centered on the sky frequency of the line peak. This task comprised the bulk of the enabling work for a spectral line VLBI mode.
- **The OT:** Prior to Cycle 9, the ALMA the OT offered only fixed frequency continuum observing set-ups for VLBI. Additional functionality was required to support spectral line experiments.
- **Spectral resolution of ALMA-only data:** The BLC mode used during VOM operations provides 1920 spectral channels across each 1.875 GHz BB, yielding a channel spacing of ∼1.0 MHz (∼3.5 km s^{-1} at an observing frequency of 86 GHz). However, to reduce data rates and volumes, VLBI continuum experiments are generally configured to spectrally average the ALMA interferometric data by a factor of 8.

Lifting this constraint boosts the scientific utility of the ALMA interferometry data products produced during spectral line VLBI observations, but verification through commissioning was needed to insure that no problems occurred with the resulting higher data rates.

- **Flexible configuration of non-VLBI BBs:** VOM operations at ALMA must be carried out using a specific frequency division mode (FDM) set-up of the ALMA BLC. However, in the case where the spectral line(s) of interest for VLBI are limited to a single BB, it is desirable to allow the observer to flexibly configure the remaining BBs using *any* FDM setup for the purpose of obtaining high spectral resolution, ALMA-only observations of any line of interest within the band. Although not recorded for VLBI, these additional observations are archived as part of the ASDM file. This required updates to the OT and QA2 scripts to allow such flexibility for .V projects.
- **Post-processing:** Some modifications to QA2, `PolConvert`, and subsequent fringe-finding and calibration procedures were needed to optimally process spectral line data.

Under APP2, and in preparation for Cycle 9, the APP2 team focused on commissioning a spectral line VLBI mode only in Band 3 owing to practical and logistical considerations. These included the less demanding weather requirements compared with Band 6, the flexibility of the VLBA and other 3 mm observing sites for scheduling commissioning observations throughout the year, and the ability to avoid the proprietary data use policies that apply to data obtained with EHT telescopes. To simplify the changes required in the OT and other subsystems, and to ensure tuning compatibility with partnering VLBI sites, no tuning flexibility was offered in Cycle 9 (it was later added and commissioned as part of APP3; see Matthews & Crew 2024).

These constraints effectively limited applications of the prototype spectral line mode to Galactic SiO maser sources, where the ^{28}SiO v=1, $J = 2 - 1$ transition at 86.243 GHz lay within the default Band 3 continuum tuning of BB_1. Under APP2 we focused exclusively on *actively* phased spectral line VLBI (i.e., where phase-up of the array is performed using emission from channels containing a bright maser line). The exploration of more flexible and advanced spectral line VLBI modes, including options for flexible tuning, observations in additional observing bands, use of passive phasing, and the possibility to observe absorption lines, all fell within the scope of APP3 (Matthews & Crew 2024).

All subsystem updates required to support an initial spectral line VLBI capability (see above) were completed and verified first through simulations, followed by on-sky testing. These included changes to TelCal, `PhasingController`, `VEX2VOM`[12], SSR codes, and the OT. Additionally, some adaptations were needed to existing fringe-finding and calibration procedures for ALMA VLBI data to experiments involving spectral line targets.

[12] `VEX2VOM` is specialized software that combines information about the VLBI observing schedule [as specified within a standard VLBI EXperiment (VEX) file] with the ALMA-specific project specifications contained in the OT-generated SB. The result is encoded in one or more SBs, which are executed by a Python script known as `StandardVLBI.py`, commonly referred to as an "SSR script" (see Matthews et al. 2018a).

4.4.3 Newly Implemented Features for Spectral Line Observing

Spectral Resolution of ALMA Interferometric Data During standard continuum VLBI observing, the ALMA interferometric data from each of the four 1.875 GHz BBs are averaged by a factor of 8 to decrease data rates and minimize data volumes. However, the resulting channel spacing (∼8 MHz) is often too coarse to permit detailed analysis of spectral lines present in the data. To circumvent this during spectral line VLBI experiments, this averaging is now eliminated in whichever BB(s) contain the primary line signal of interest for VLBI science (typically BB_1). This results in a channel spacing of ∼1 MHz (i.e., a spectral resolution of ∼6.8 $\mathrm{km\,s^{-1}}$ in Band 3 after Hanning smoothing). We stress that unlike the continuum case, during spectral line experiments VLBI recordings will typically be made for only one of ALMA's four BBs.

For any BBs recorded for VLBI, it is not possible to archive higher spectral resolution ALMA data in the corresponding BB because the Phasing Interface Cards (PICs) that serve as ALMA's VLBI backend are compatible only with a single ALMA correlator mode, namely the FDM configuration that offers a 1.875 GHz bandwidth per BB. Changing this would require at minimum a firmware upgrade to the PIC. After an assessment of the effort entailed in such an undertaking, it was decided not to included this within the framework of the APP2 or APP3 (see Matthews & Crew 2024). Nonetheless, that investigation resulted in the identification of the underlying cause of the lower amplitudes for the sum-comparison antenna correlations for the APS (see Matthews et al. 2018a and Crew et al. 2023).

We note that the aforementioned limitation does not affect the achievable spectral resolution of the VLBI data products; in principle that can be arbitrarily high and is set by the number of points used in the fast Fourier transform (FFT) during correlation. Nonetheless, observers may still wish to have available higher spectral resolution ALMA-only data to enable supporting science measurements. To allow this, starting in Cycle 9, up to three ALMA BBs may now be configured with other high spectral resolution FDM correlator configurations such as are normally available to ALMA spectral line observers during non-VOM operations. These extra BBs can be tuned to the same center frequency as BB_1, or retuned to capture other spectral lines, subject only to ALMA's usual tuning restrictions). Figure 19 shows an example of one of several different spectral setups that was tested during our spectral line VLBI commissioning in 2019. These tests confirmed that no data rate issues occur with the use of these high spectral resolution set-ups, regardless of the number of phased antennas (typically $\lesssim$43).

Phase-Up On a Line Source Modifications to the VOM were undertaken to enable efficient phase-up using the line signal from bright emission line sources. First, the number of allowable channel averages across the BB used for VLBI was increased from 8 (the default for continuum observing) to 32 (each 62.5 MHz wide), the maximum allowed by the current BLC. (Recall that it is the signals from these individual channel averages that are fed to TelCal for determination of the phasing solutions). However, for narrow lines, averaging the signal across a 62.5 MHz channel-average window might still result in significant dilution the line signal. Therefore we also added provisions to select only a subset of the spectral channels (plus a one-channel buffer on either side) within the channel average. Thus only the signal within the selected subset of spectral channels is sent to TelCal for calculations

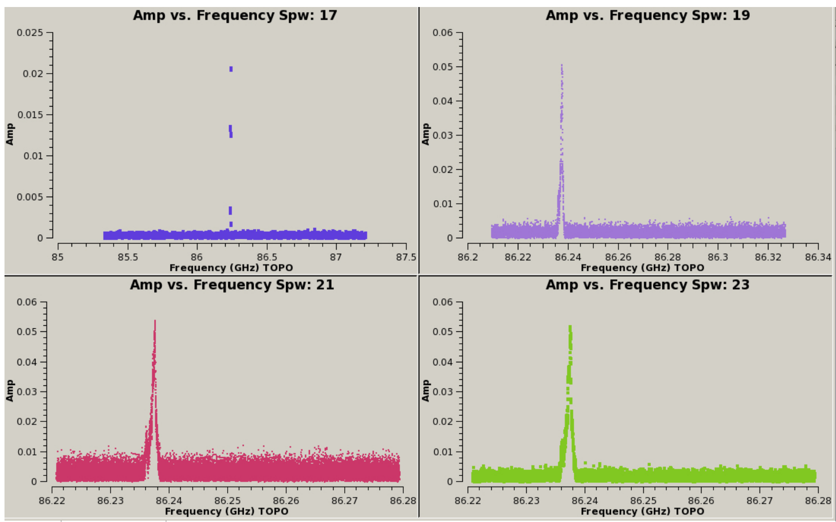

Figure 19: Sample cross-power spectra (polarization XX) for a single ALMA baseline during a 16 second scan on the evolved star IK Tau, as part of an ALMA spectral line commissioning test on September 30, 2019. All four ALMA BBs are shown. The strong line emission comes from the ^{28}SiO v=1, J=2-1 maser line. Each BB uses a different spectral setup. BB_1 (the only one for which VLBI recordings were obtained) used a 1.875 GHz bandwidth with 976 kHz spectral channels and full Stokes; BB_2 has dual linear polarizations, a 117 MHz bandwidth, and 30 kHz channels; BB_3 has a single polarization, 58.6 MHz bandwidth and 7.6 kHz channels; BB_4 has full Stokes with a bandwidth of 1.81 GHz and 30 kHz channels. Data source: `uid://A002/Xe19896/X372f`.

of the phasing solutions.

In principle, the phasing solutions determined from the selected set of channels could be propagated across the full band, such that each of the remaining channel averages is assigned a phasing correction $\phi_{\nu,n}$ according to $\phi_{\nu,n} = (\nu_n/\nu_0)\phi_0$, where ν_n is the center frequency of the n^{th} channel average, ν_0 is the center frequency of the channel average containing the line emission, and ϕ_0 is the phasing correction computed for the channel containing the line signal. However, because the delay fix (Section 4.1) was not yet available yet Cycle 8, and because the usable portion of the band remained relatively narrow (∼200 MHz) owing to the limited bandwidth of the peer VLBA stations, initially, only a single phasing correction was applied across the entire band, with no scaling by frequency. This frequency scaling capability has since been implemented in conjunction with the delay fix (Section 4.1) and will be present in the code for Cycle 11 and beyond. Offline testing have shown no issues, but as of the time of this writing, this option has not yet been well tested on-sky. In the case of Band 6, the correction is roughly a percent across each 2 GHz BB.

OT Changes Necessary updates to the OT were undertaken by the OT developers in consultation with the APP2 team and are described in ICT-15770. These included the following:

- Offering a "spectral line" option for VLBI projects.
- Adding a requirement to enter properties of the target spectral line (including line width, peak flux density, and systemic velocity), and the generation of warning messages if these parameters are out of range of what can be accommodated by the current observing mode.
- Requirement that the spectral window corresponding to BB_1 remain fixed to center frequency 86.268 GHz (to ensure tuning compatibility with other VLBI stations).[13]
- Allowance for BB_2, BB_3, and BB_4 to be flexibly tuned and configured if not recorded for VLBI.
- Requirement to enter a fixed observing date to be used for Doppler calculations. This allows computing the sky frequency of the spectral line of interest and will produce a validation error if the line is shifted out of band.

Regarding the second point above, the `VEX2VOM` implementation relies heavily on so-called "expert parameters". The information provided to the OT is encapsulated in one expert parameter that contains the instructions for channel adjustments. Since the properties of spectral lines do change with time, it is understood that that the ALMA staff will need to double-check the information in the epoch of observation to ensure the best results.

Post-Processing Tools and Procedures: QA2 The introduction of three non-phased, non-VLBI spectral windows into the spectral line VLBI observing mode set-up (see above and Figure 19) necessitated some updates to the original QA2 reduction script used for VLBI experiments. These included:

[13] This restriction was removed in Cycle 9.

- Modifying the criteria to select the science spectral windows (SPWs) based on a minimum number of channels, even if the data are not full polarization, to avoid loss of any high-resolution ALMA-only SPWs.
- Allowing different SPWs to have different numbers of channels.
- Adding extra logic to determine which SPWs are to be used for `PolConvert`.

C. Goddi implemented the necessary updates and supplied our team with tarballs containing the modified packages and deliverables necessary for `PolConvert` (see next paragraph).

Post-Processing Tools and Procedures: PolConvert As is the case for continuum VLBI experiments involving ALMA and the GMVA, the raw correlation products resulting from ALMA spectral line VLBI observations are in a mixed polarization basis: linearly polarized products for ALMA (X and Y) and circularly polarized products (R and L) for the other stations. Thus the `PolConvert` software package is used post-correlation to convert the ALMA data from a linear to a circular polarization basis (see Matthews et al. 2018a). Conceptually the `PolConvert` process is the same as for continuum data, but some software modifications were needed to accommodate spectral line data, including some setup work needed to make sure the correct SPW (the one used for VLBI) was ingested for the transformation. I. Martí-Vidal implemented the necessary updates and supplied our team with the modified scripts that were necessary.

Spectral Line Regression Test To facilitate further testing, and to insure that future ALMA software updates unrelated to VLBI did not "break" the new spectral mode, a spectral line VLBI regression test was developed for Band 3 (CSV-3600). The QA0 script used for VLBI was then modified to produce plots of the results from these regression tests. A complicating factor is that the locations of a given spectral line vary within the band owing Doppler shifts from the motion of the Earth around the Sun (and in the case of some maser lines, owing to variation in the line profile itself). Given the relatively coarse spectral resolution of the ALMA data in the SPW corresponding with the BB recorded for VLBI (see above), some of the effects (e.g., Earth rotation) can be safely ignored. The dominant correction results from the Earth's annual solar revolution, which produces a sinusoidal Doppler shift. It was thus easy to build a look-up table to propagate results for specific epochs on ^{28}SiO v=1, J=2−1 to an arbitrary observing date on a set of sources available over a day. As part of APP3, the look-up tables were eventually adjusted to appropriate frequencies of related transitions for use in other bands (Matthews & Crew 2024).

4.4.4 Testing and Commissioning of the Prototype Spectral Line Mode

A planned series of commissioning tests for the prototype spectral line VLBI mode was designed and executed by the APP2 team with the goals of achieving the following:

1. Validation of nominal standalone ALMA operations while using the spectral line VLBI mode.
2. Demonstration of array phase-up on spectral line sources.

3. Development of VLBI correlation approaches suitable for spectral line VLBI experiments involving ALMA.
4. Confirmation of VLBI fringes to ALMA on spectral line targets.
5. Validation of `PolConvert` on a spectral line VLBI experiment.
6. Quality assessment of the final spectral line VLBI data products.

Below we briefly summarize the on-sky testing conducted in support of these objectives.

Standalone ALMA Testing First steps in the commissioning of the spectral line VLBI mode at ALMA were conducted using ALMA as a standalone phased array in May, August, and September/October 2019. These comprised a variety of short on-sky tests intended to verify the changes to TelCal, `PhasingController`, `VEX2VOM`, and the SSR codes as required to accommodate the spectral line VLBI capabilities described above. These tests successfully demonstrated the following:

- Operation of the VOM with up to 32 channel averages in BB_1.
- Confirmation of the ability to turn off TelCal phasing corrections in any desired subset of the 32 channel averages within a BB (i.e., those that do not contain a line signal).
- Confirmation of the ability to form a channel average only a user-specified subset of its corresponding spectral channels.
- Demonstration of the ability to flexibly configure up to three BBs with high spectral resolution FDM correlator configurations (e.g., Figure 19) without disruption to the phasing machinery operating in the other BB.
- Demonstration of the ability to phase up ALMA using emission from a bright spectral line (e.g., Figure 20).
- Confirmation that use of spectral line set-ups does not result in any significant data rate issues.

First Global Spectral Line VLBI Test: Observations After successfully demonstrating the functionality of all APS and VOM changes in support of the prototype spectral line VLBI mode, the next step was to demonstrate this capability as part of a global VLBI test. For this purpose we submitted to NRAO a Director's Discretionary Time proposal to undertake a set of spectral line VLBI test observations in collaboration with the VLBA. That proposal was approved for scheduling in May 2019, but because of a power failure at ALMA, the observations were deferred to September 2019.

Originally we had proposed to carry out two independent four-hour VLBI sessions with the VLBA to guard against failures caused by technical and/or weather issues. However, because of a several-day period of high winds ($>$10 m s^{-1}) at ALMA during our campaign window, only one session could be fully executed (experiment BM494E on September 30, 2019). The executed VLBI observing schedule included as the primary "science" targets four Galactic SiO maser sources with well-known properties, along with several bright

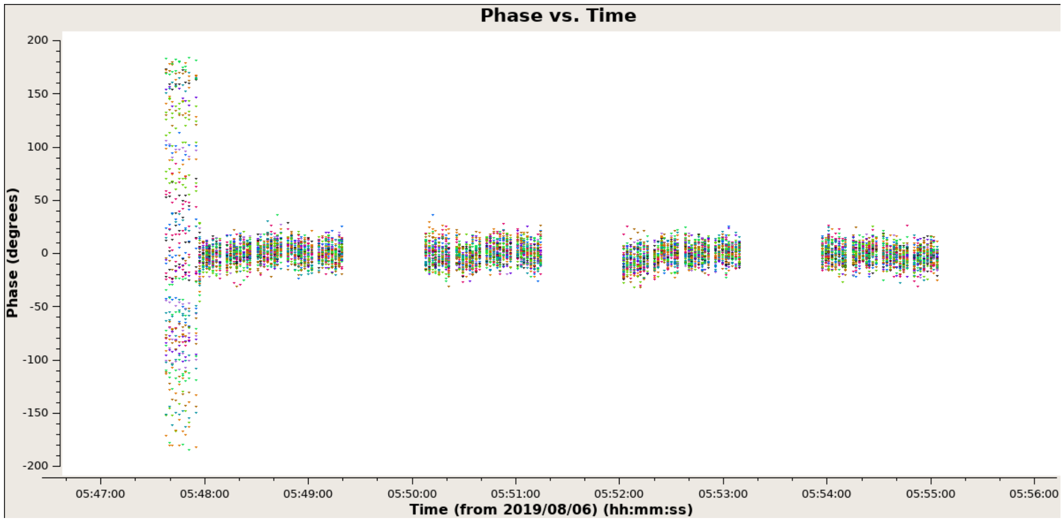

Figure 20: Example of phase-up of ALMA on a bright spectral line target. Phase versus time is shown for a Band 3 ($\nu \sim$86.2 GHz) observation of the evolved star WX Psc on August 6, 2019. The array was phased up using emission from the ^{28}SiO v=1, J=2−1 maser line, averaged over a window of ∼4 MHz. The x-axis spans approximately 7 minutes. Dispersion in the phases is quite small ($< \pm 20$ deg), despite the inclusion of baselines as long as 3 km in the phased array. The peak flux density of the SiO line at the time of the observation was ∼50–100 Jy. Data source: `uid://A002/Xdf9c1c/X873b`.

continuum sources for use as fringe finders, bandpass calibrators, and polarization angle calibrators.

All of the VLBA sites equipped with 3 mm receivers participated in the September 2019 test with ALMA (8 VLBA sites in total). ALMA used a phased array of 41 antennas and weather conditions there were excellent, with PWV<1 mm, winds speeds $v_{\rm wind}$ ∼2–4 m s^{-1}, and RMS path length fluctuations of ∼70μm.

First Global Spectral Line VLBI Test: Correlation The ALMA VLBI recordings from the September 2019 test were shipped to Haystack for correlation following the experiment. Meanwhile, NRAO staff performed an initial correlation of the VLBA-only baselines to identify the best-performing VLBA sites. Subsequently, a copy of the data from four of the best performing stations (Owens Valley, Pie Town, Fort Davis, and Kitt Peak) was sent to Haystack where a correlation of the ALMA+VLBA data was undertaken.

Because of ALMA's nonstandard sampling rate, a special correlation procedure involving appropriate "zoom bands" for all stations is required, even for continuum experiments (see Matthews et al. 2018a). LO offsets (−50 mHz on every channel) are also needed. The so-called `v2d` file used for the correlation must contain something like the following:

```
ANTENNA AA { datastreams=AaMod12,AaMod34 zoom=UseMe loOffsets = -0.05, ... }
DATASTREAM AaMod12 { filelist=mod-12-bm494e.flist }
DATASTREAM AaMod34 { filelist=mod-34-bm494e.flist }

# alma-vex-defs.py -rzoom -f 86252.650 -c 4 -w24.0
```

```
ZOOM UseMe {
      # 8 zoom bands in [85315.150000,87190.150000] 2 zm/ch mv 0 res 0
      # center 86252.650000, nInt x 0.000160000000000 s 0.000160000000000 s
      # 7680 ch/HOPS 20000 ch/ALMA 655360 ch/R2DBE Res 0.003125000000000 MHz
#     addZoomFreq = freq@86138.109375/bw@24.0/noparent@true  #< 86162.109375
      addZoomFreq = freq@86167.406250/bw@24.0/noparent@true  #< 86191.406250
#     addZoomFreq = freq@86196.703125/bw@24.0/noparent@true  #< 86220.703125
      addZoomFreq = freq@86226.000000/bw@24.0/noparent@true  #< 86250.000000
#     addZoomFreq = freq@86255.296875/bw@24.0/noparent@true  #< 86279.296875
      addZoomFreq = freq@86284.593750/bw@24.0/noparent@true  #< 86308.593750
#     addZoomFreq = freq@86313.890625/bw@24.0/noparent@true  #< 86337.890625
      addZoomFreq = freq@86343.187500/bw@24.0/noparent@true  #< 86367.187500
}
```

In this particular experiment, 4 zoom bands, each of width 24 MHz, were used for the continuum calibrators. All of the spectral lines lay within the second zoom band (DC edge at 86226.0 MHz). The `alma-vex-defs.py` script referenced above is part of the `m6support` package shared with the DiFX distribution. It generates as many zoom channels as will fit within the band, so in the above example several that were not needed are commented out. Using the `freqId` keyword, one also has the option to constrain the correlation to a single zoom channel of interest for all sources.

Because of the disparate sample rates at ALMA and the VLBA, some care in the choice of correlation parameters was required to accommodate the zoom band numerology constraints. The following set-up was used successfully to provide a 25 kHz frequency resolution:

```
SETUP tfive {
  tInt = 0.96
  subintNS = 32000000
  FFTSpecRes = 0.003125
  outputSpecRes = 0.0250
  xmacLength = 0
  strideLength = 0
  guardNS = 2000
}
```

Lastly, since ALMA has linear polarization feeds, a post-correlation conversion to a circular basis was undertaken using `PolConvert` (available in the DiFX distribution; see above).

First Global Spectral Line VLBI Test: Results The performance of phased ALMA was seen to be excellent throughout the BM494E experiment. Figure 21 shows a sample autocorrelation spectrum for one of our line targets, illustrating the exceptional SNR of the phased ALMA data products.

ALMA was successfully phased on several different line targets, in all cases with high phasing efficiency (up to ∼99%). Figures 22 and 23 show ALMA visibility phases and correlated amplitudes, respectively, as a function of time for scans on the spectral line targets.

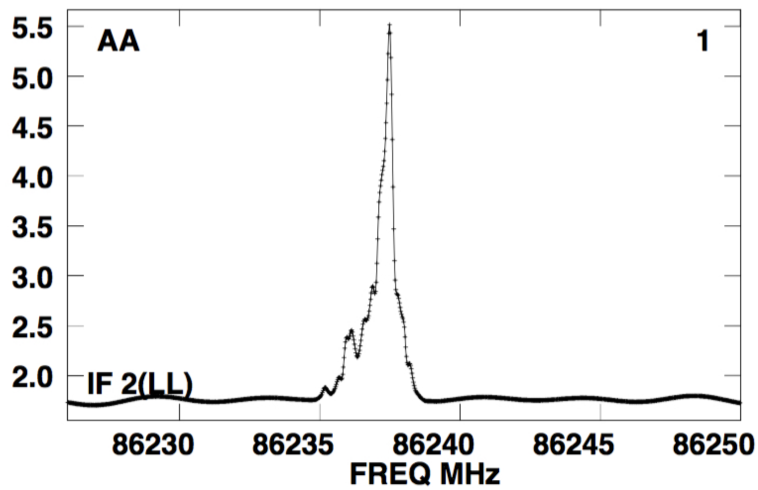

Figure 21: Uncalibrated ALMA VLBI autocorrelation spectrum of IK Tau (Stokes YY), based on a few seconds of data, showing the bright ^{28}SiO v=1, J=2−1 maser line. These data were obtained on September 30, 2019 as part of experiment BM494E (see text).

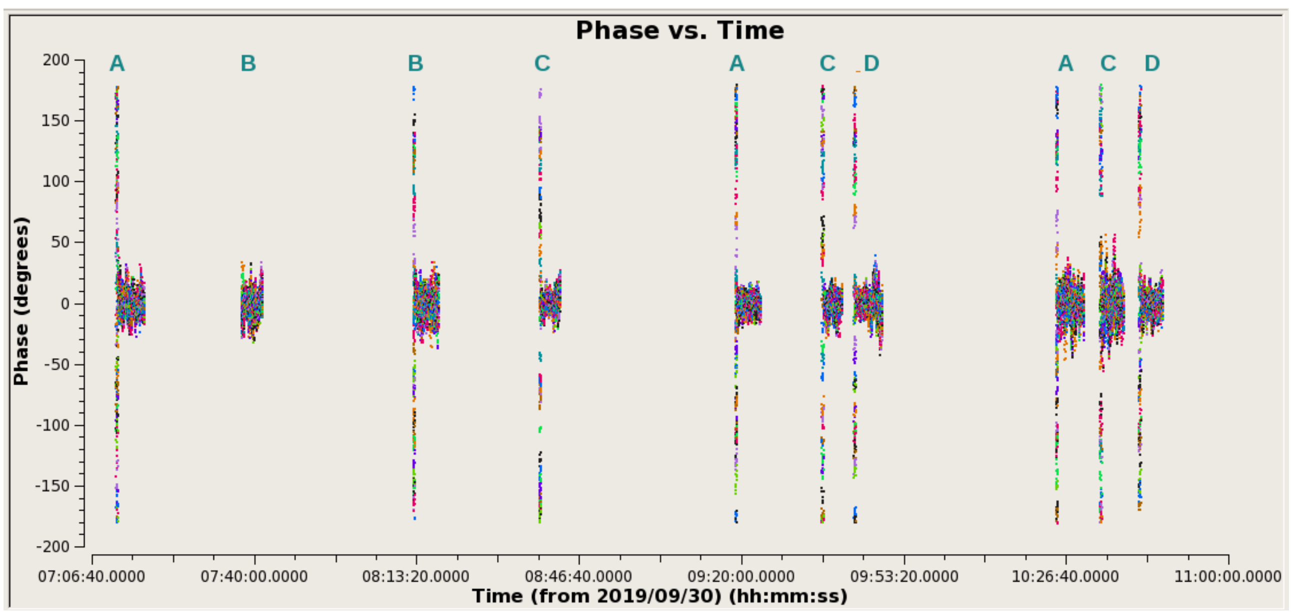

Figure 22: Plot of raw ALMA visibility phase as a function of time for the four actively phased SiO maser sources observed during the Band 3 global spectral line VLBI commissioning campaign on September 30, 2019 (experiment BM494E). The data shown are for baselines between the phasing reference antenna and the other 40 antennas in the phased array. For these four sources the array was phased up using data from a narrow spectral window centered around the ^{28}SiO v=1, J=2 − 1 maser emission. The four targets are distinguished by letter on the plot: IK Tau (A); WX Psc (B), Mira (C), and Orion Source I (D). Data source: `uid://A002/Xe19896/X372f`, `uid://A002/Xe19896/X3d29`, `uid://A002/Xe19896/X407a`, `uid://A002/Xe19896/X44b4`.

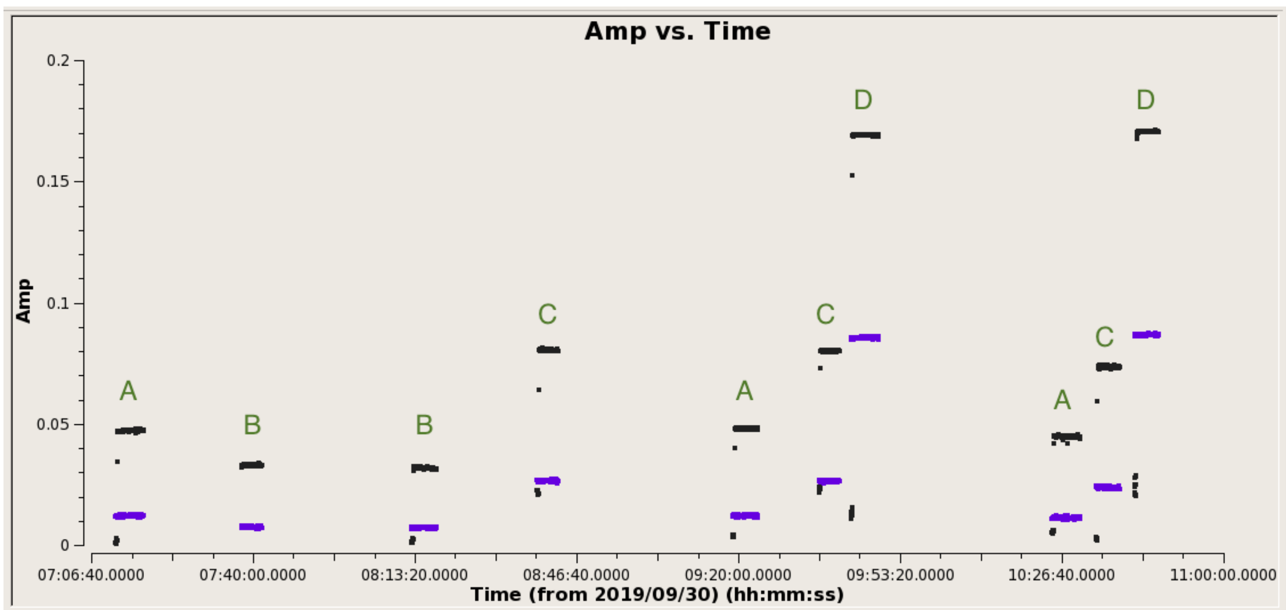

Figure 23: Raw correlated amplitude as a function of time for actively phased SiO maser sources observed during the Band 3 global spectral line VLBI commissioning campaign on September 30, 2019 (experiment BM494E). Data from the baseline between the phasing reference antenna and an unphased comparison antenna are shown in purple; data for the phased sum "antenna" correlated with the comparison antenna are shown as black. The array was phased up using data from a narrow spectral window centered around the ^{28}SiO v=1, J=2 − 1 maser emission from each source. The four targets are designated by letter: IK Tau (A); WX Psc (B), Mira (C), and Orion Source I (D). Data source: see Figure 22.

In the amplitude versus time plot, the correlated amplitudes are compared between the baseline involving the phasing reference antenna and an unphased comparison antenna (purple points) and a baseline involving the phased sum "antenna" and an unphased comparison antenna (black). For the points correlated to the sum signal, the correlated amplitude is, on the mean, expected to increase by $\sim \sqrt{N_A}$ compared with the points on the reference/comparison antenna baseline, where N_A is the number of antennas in the phased array. This expected behavior is seen for three of the sources, but for our brightest SiO line target, Orion Source I (labeled 'D'), the amplitude improvement in the baseline with the phased sum appears to be less than expected. We believe this is likely to be a manifestation of an issue previously noted for standard ALMA observations of bright targets. Owing to the way normalization of visibilities is performed in the ALMA BLC, effectively the amplitude scale of the visibilities gets reduced in proportion to the spectrally-resolved fractional contribution of the total power in the target field.[14] A consequence is that observers of very bright spectral line target should carefully check the amplitude scale of the resulting data and account for this effect in the error budget. Indeed, the normalization strategy adopted for the BLC was designed for sources that are weak compared to the system noise, but in the case of very bright spectral lines, this assumption is violated in a calculable way. To our knowledge, this problem is unique to ALMA and no one has yet reported the appropriate correction, although we plan to work on it in the future.

Turning to the VLBI data, fringes were detected between ALMA and the four correlated VLBA stations for all of the continuum sources in the VLBI schedule, as well as 3 of the 4 spectral line targets (the fourth line target was later found to have a coordinate error in the ALMA schedule). An example of a fringe detection on one of our spectral line targets, the evolved star WX Psc, is shown in Figure 24.

Prior to our test observations in September 2019, several of the VLBA sites had undergone software upgrades to their control computers. Unfortunately, this resulted in pointing problems at high frequencies, in some cases severe (see Blanchard 2021). This issue has since been mitigated, but it impacted the quality of the BM494E data by causing significant losses in correlated amplitude and fringe SNR. This precluded a rigorous, quantitative analysis of the VLBI results. We therefore do not include further details on the analysis of the BM494E data here. A more extensive analysis was instead carried out using data from a second spectral line VLBI test carried out in April 2021 (see next paragraph).

Second Global Spectral Line VLBI Test: Objectives Because of the impact of the VLBA pointing issues on the September 2019 spectral line VLBI test (see above), a second end-to-end global spectral line VLBI test was scheduled on April 26-27, 2021 at the end of the annual ALMA-GMVA observing window. The test was designated with project code C211D. Its duration (22:00–03:30 UTC) was sufficient to ensure adequate parallactic angle coverage on a polarization calibrator and allowed observations of several different line targets. Participating stations included phased ALMA (for the full duration), the Effelsberg (Ef) 100 m antenna in Germany (from 22:00-01:30 UTC), and a subset of the VLBA antennas (from 01:00-03:30 UTC).

Test C211D was conceived as an end-to-end demonstration of the spectral line VLBI

[14] `https://help.almascience.org/kb/articles/what-errors-could-originate-from-the-correlator-spectral-r`

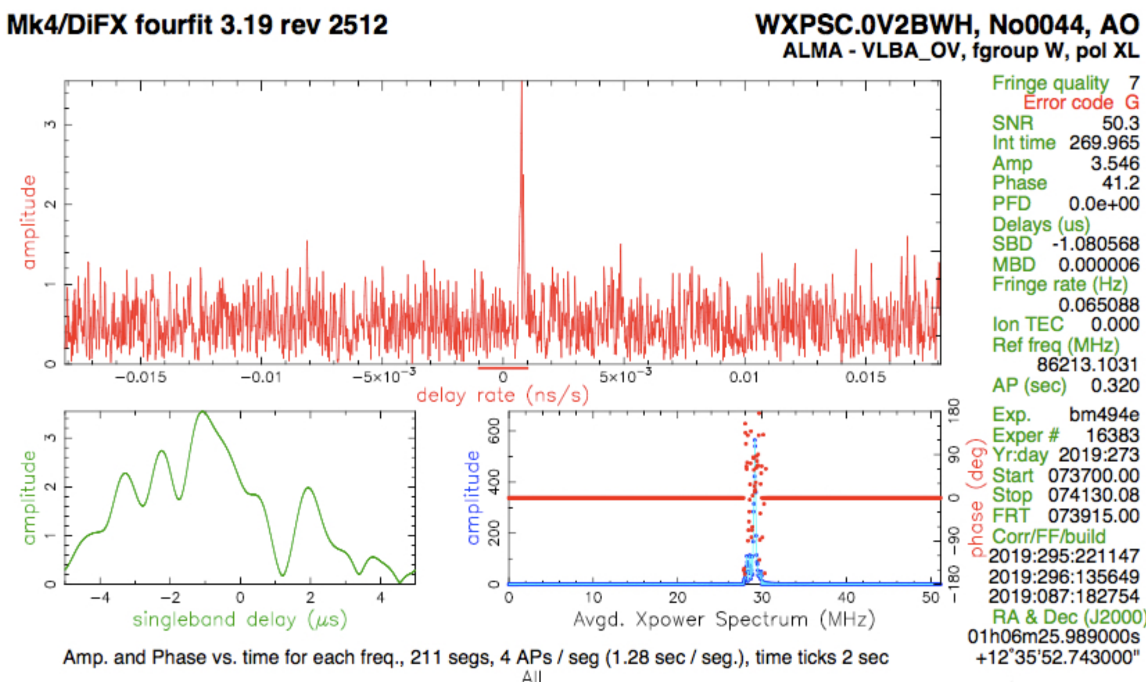

Figure 24: Spectral line VLBI fringe detection of the evolved star WX Psc on the 7895 km baseline between phased ALMA and the Owens Valley VLBA station on September 30, 2019. The detected emission is from the ^{28}SiO v=1, J=2-1 maser line at ν ∼86.2 GHz. The integration time was 270 seconds and the SNR is ∼50. The data are mixed polarization (XL). For an explanation of the individual panels, see Figure 9.

Table 3: Spectral Line Targets (2021)

Name	$V_{\rm LSR}$ (km s^{-1})	Sky Freq. (MHz)	S_p (Jy)
R Leo	-1.0	86233.46	$\sim$200 Jy
R LMi	0.2	86234.76	$\sim$200 Jy
VY CMa	22.3	86225.76	$\sim$1000 Jy
R Cnc	14.1	86227.40	$\sim$100 Jy

The tabulated sky frequencies correspond to the start of the obser-. vations on April 26, 2021. S_p is the estimated peak flux density of the ^{28}SiO v=1, $J = 2-1$ line at the time of the observations, taken from `https://www.oan.es/masersObservations/`

observing capability in Band 3, including schedule preparation, data acquisition, correlation, and post-processing. Specific goals included: (i) characterization of the performance of ALMA for spectral line VLBI observations at λ3 mm; (ii) demonstrate feasibility of detecting spectral line fringes on the long baselines between ALMA and Europe; (iii) further validation of the QA2 process for spectral line VLBI experiments; (iv) further validation of `PolConvert` for spectral line projects.

Second Global Spectral Line VLBI Test: Observations Targets for C211D included 4 Galactic SiO maser sources and several continuum calibrators. The continuum sources were intended for use as combined bandpass calibrators, fringe finders, and polarization calibrators. The SiO maser targets (Table 3) were selected based on having expected peak flux densities of $\gtrsim$100 Jy based on recent and historical monitoring data and as having good mutual visibility from all participating telescopes. The J2000 coordinates of the SiO maser sources used in the VLBI schedule were taken from SIMBAD and corrected for proper motion at the epoch of observation using the latest proper motion values from *Gaia* or *Hipparcos*.

Observing sequences consisted of 5–8 min scans on the various line targets interspersed with 3–5 min scans on a calibrator. Following standard practice for 86 GHz observing at the VLBA, during the schedule gaps after each significant antenna slew, the VLBA antennas were commanded to perform automated reference pointing corrections. Those were performed at 7 mm using the digital baseband converter (DBBC) backend and strong 43 GHz SiO line sources or bright 43 GHz continuum sources close to the target of interest. During these same schedule gaps, Effelsberg did pointing corrections using a series of four sets of cross scans in azimuth and elevation extending to $\sim$4–5 beamwidths, with corrections derived and applied based on the average of those scans.

As in the previous spectral line VLBI test (see above), BB_1 used the same fixed tuning as Band 3 continuum VLBI experiments and this was the only BB recorded for VLBI. For the GMVA stations the VLBI setup used the digital downconverter (DDC) mode with 128 MHz per intermediate frequency (IF) and 4 Gbps recording, resulting in total bandwidths of 512 MHz per polarization, centered at 86.268 GHz. Effelsberg and the VLBA sites recorded dual circular polarizations, while ALMA recorded dual linear polarizations.

Weather at ALMA was excellent (PWV<1 mm; wind speeds of a few km s^{-1}) and there were no known technical issues during the test. Twenty-seven antennas were included in the phased array. Weather at Effelsberg was also good (clear skies), and this site performed well with the exception of a few scans where source elevations were below 20°. Three additional European GMVA stations (Yebes, Metsahövi, Pico Veleta) had been scheduled to participate but were unable to join because of weather.

The VLBA pointing issues that had plagued our earlier spectral line test with ALMA (see above) were thought to have been mitigated at the time of the April 2021 test (Blanchard 2021). However, of the eight participating VLBA sites, only four produced useful data during the test: Brewster (Br), Owens Valley (Ov), Fort Davis (Fd), and Pie Town (Pt).

In total, six stations produced useful data during at least some portion of the C211D experiment: ALMA, Ef, Br, Ov, Fd, and Pt, providing baseline lengths ranging from 565 km (Fd–Pt) to 9638 km (ALMA–Ef). VLBI recording was done on the same disk modules used for other GMVA experiments, hence upon completion of the experiment, the modules were shipped to Bonn for correlation along with the other GMVA science experiments.

Second Global Spectral Line VLBI Test: Correlation Bonn is the default site for GMVA correlation and they kindly agreed to correlate the C211D test data. This effort was led by Y. Pidopryhora using version 2.6.2 of DiFX. As is standard for correlating VLBI experiments involving ALMA, zoom bands were used to handle the mismatched sampling rates between ALMA and the other stations (see above). To minimize data volumes, the correlated data include only a 32 MHz wide portion of the band, centered at 86.23 GHz. The selected band was wide enough to contain the ^{28}SiO v=1, $J = 2-1$ line of interest for all four maser targets. The spectral resolution of the correlated data depends on the choice of the number of FFT. For this experiment we opted for 31.25 kHz spectral channels and a time resolution of 1.024 seconds.

Second Global Spectral Line VLBI Test: Post-Processing Following correlation, `PolConvert` was executed to convert ALMA's linearly polarized data products to a circular basis. Examination of SNRs on ALMA baselines to our continuum calibrators before and after application of `PolConvert` showed the expected improvements in fringe amplitudes and SNRs in the corrected data.

Next, a FITS-IDI file containing the converted data was created and loaded into the Astronomical Imaging Processing System (AIPS) package for additional processing and analysis. In parallel, some additional data checks and analysis were also carried out using HOPS. However, HOPS is not currently optimized for analysis of spectral line experiments (see Hoak et al. 2022). We therefore focus our discussion on the results from our analysis in AIPS.

Second Global Spectral Line VLBI Test: Analysis Because relatively few spectral line VLBI experiments have been carried out to date at frequencies of $\gtrsim$86 GHz—and none of those involved ALMA—we provide some details of our subsequent calibration and data analysis steps for the CD211D experiment below, in the event that it may be of value to future users of this capability.

A complete set of calibration transfer tables (containing information on antenna gains, $T_{\rm sys}$, weather, and flagging) was constructed using information collected from the individual stations. For ALMA, the traditional VLBI 'ANTAB' (amplitude calibration) table is produced as a by-product of `PolConvert`. For Effelsberg, an appropriate ANTAB table was downloaded from `ftp://vlbeer.ira.inaf.it/vlb_arc/ftp/vlbi_arch/apr21`, while for the VLBA, the appropriate 'cal' and 'gains' files for experiment C211D (`c211dcal.vlba` and `vlba_gains.key`, respectively) were downloaded from `http://www.vlba.nrao.edu/astro/VOBS/astronomy/apr21/c211d/`, concatenated, and edited to meet formatting requirements and to remove antennas absent from the correlated data. Next the AIPS `VLOG` task was used to generate flag, $T_{\rm sys}$, and weather files for the VLBA stations. Finally, using this collection of files, an AIPS flag ('FG') table was generated using `UVFLG`, and master gains ('GC') and $T_{\rm sys}$ ('TY') tables containing entries for all participating sites were constructed using the `ANTAB` task. Additional bad VLBA antennas/polarizations noted in the operator's log were also flagged.

Before beginning additional calibration, a parallactic angle correction was applied to correct for the position angle rotation of the feeds of the non-ALMA antennas (AIPS `CLCOR`), and the recommended digital sampler bias was applied to the VLBA antennas to correct deviations of the voltage threshold levels from their optimum values (AIPS `ACCOR`). Outlying points were flagged using `SNEDT` before interpolating the solutions in time (`CLCAL`).

Antenna-based instrumental delays were determined via the "manual phase-cal" method, using AIPS task `FRING` and the continuum calibrator OJ287. As there was no single time interval where this source was observed on all baselines, separate scans and time intervals were selected for the ALMA–Ef baseline and the ALMA–VLBA baselines. Phased ALMA, being the most sensitive element in the array, was designated as the reference antenna. After testing a range of solution intervals, t_i, we found $t_i \sim$4 minutes to provide the highest SNR solutions. We note that this is significantly longer than the expected coherence timescales at 3 mm ($\sim$10–20 s). However, this behavior is consistent with the findings of Martí-Vidal et al. (2012) and can be understood as an indication that the instrumental delay is characterized by an average slope across the band that is stable on timescales much longer than the atmospheric phase fluctuations. We also found that spectrally averaging the data by a factor of 16 before running `FRING` increased the number of good solutions.

After application of the instrumental delay solution solutions to all observed targets, the amplitude portion of the bandpass was calibrated using the autocorrelation data for OJ287. Amplitude calibration (to convert from correlation coefficients to 'Jy' units) was then carried out using the so-called '$T_{\rm sys}$' method (using AIPS `APCAL`) for all sources, including the line sources. Opacity corrections were neglected.

Sample autocorrelation spectra for the spectral line target R Leo are shown in Figure 25, after application of amplitude and bandpass calibrations. The quality of the autocorrelation spectra from ALMA and Ef were excellent, but the quality of those for the VLBA stations was more varied.

At this stage, no fringe solutions could be found for the LCP polarization for the Fd and Pt VLBA antennas. Attempts to find solutions on other continuum calibrators and/or with different time ranges, solution intervals, etc., also failed, hence the LCP data for these two stations were flagged during further processing. This is consistent with the lack of SiO line detections in the autocorrelation spectra for these two antennas/polarization combinations. To ensure that the issues with the LCP products were not a result of either our correlation set-up or the `PolConvert` process, J. Blanchard (NRAO) kindly agreed to performed an independent correlation of the VLBA-only baselines for several of the continuum calibrator scans from our experiment at NRAO Socorro. His results confirmed that technical issues rather than correlation setup problems were the cause of the absence of fringes to certain VLBA sites during the test (J. Blanchard, private communication).

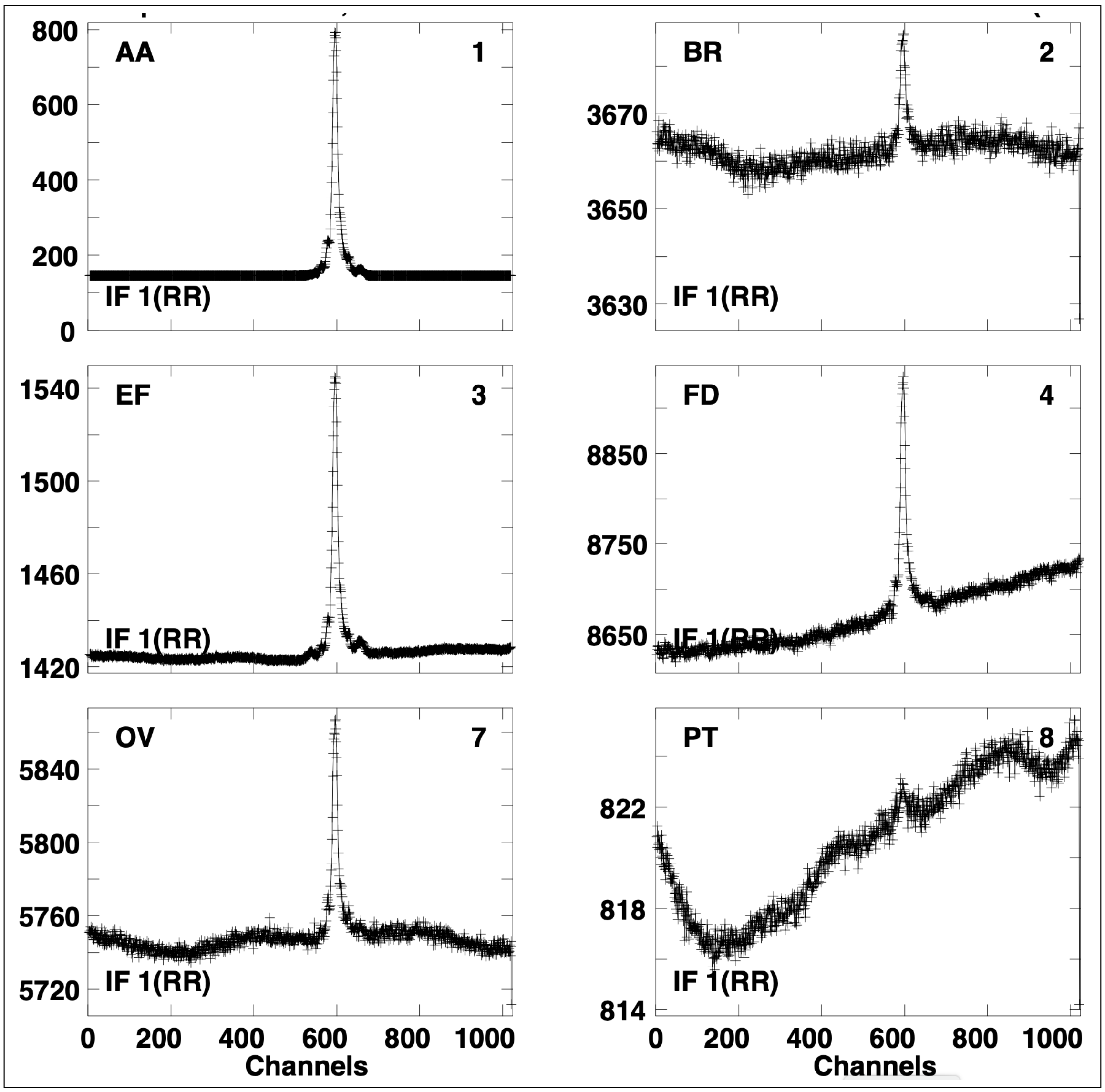

Figure 25: Sample autocorrelation spectra for the SiO maser source R Leo (RCP) from experiment C211D on April 26, 2021. The data from several scans are averaged. A bandpass correction derived from the autocorrelation spectrum of the continuum source OJ287 has been applied.

The next step in our processing used AIPS `FRING` to solve for the antenna-based residual delays and rates of the full set of scans on the continuum calibrators 1055+018, 4C39.25, and OJ287. We tested a range of solution intervals and found the optimal results with of $t_i \approx 1$ minute. The resulting solution tables were smoothed with a boxcar function, interpolated in time using linear phase connection to resolve phase and rate ambiguities, and then applied to all sources, including the line targets.

The AIPS task `CVEL` was used to correct the data for the spectral line sources for Doppler shifts that occurred during the course of the observations. These shifts cause the line emission to drift over time relative to a given spectral channel. Before running `CVEL`, `SETJY` was used to enter the source velocities for each target from Table 3 into the source ('SU') table, along with the reference pixel corresponding to the systemic velocity. A rest frequency of 86.243 GHz was assumed for the ^{28}SiO v=1, $J = 2 - 1$ line.

The final step of our calibration involved fringe fits to the four SiO line sources: R Leo, R LMi, R Cnc, and VY CMa, to determine residual delays and rates for these sources. For each target we examined the existing autocorrelation and cross-correlation spectra to identify a spectral channel containing strong and spatially compact line emission (the latter is evidenced by minimal variation of the line strength as a function of baseline length). That channel was then used for the fringe fitting with a solution interval of 30 s.

Second Global Spectral Line VLBI Test: Results Fringes to ALMA were detected on all four of our line targets during the April 2021 test. Line fringes were also detected between other baselines in the array, although the the range of baselines achieving detections varied depending on the particular source, scan, and polarization. This is not surprising given that that targets were observed at a range of elevations, the maser emission is expected to display a complex structure, and the fact that SiO maser emission may be polarized.

Our test in September 2019 had already confirmed that spectral line fringes can be readily detected on baselines between ALMA and North America—even when the performance of the partnering VLBA sites is suboptimal (see above). This is further underscored by the April 2021 tests. Figure 26 shows sample cross-correlation spectra from a single scan on R Leo for ALMA and two VLBA stations (Ov and Br). The line is detected with a peak amplitude of a few Jy on all three baseline pairs. The achieved SNR also appears to show good agreement with theoretical expectations. For ALMA, the nominal system temperature for the 12 m antennas in Band 3 is ∼70 K and the aperture efficiency is 0.71 (ALMA Technical Handbook). For a perfectly phased array of 27 antennas, the theoretical SEFD is thus ∼89 Jy. As per the VLBA Status Summary[15], typical SEFDs for the Ov and Br antennas are 5800 Jy and 3500 Jy, respectively. The theoretical noise, $\sigma_{\rm RMS}$ on each baseline (for a single polarization) can then be estimated as:

$$\sigma_{\rm RMS} = \frac{1}{\eta}\frac{\sqrt{({\rm SEFD})_1\,({\rm SEFD})_2}}{\sqrt{t\Delta\nu}} \qquad (1)$$

where η=0.88 for two-bit correlation, $\Delta\nu$=31.25 kHz is the width of a single spectral channel, and t is the integration time in seconds. For t=360 s, the expected 1σ RMS noise is

[15] `http://science.nrao.edu/facilities/vlba/docs/manuals/oss/referencemanual-all-pages`

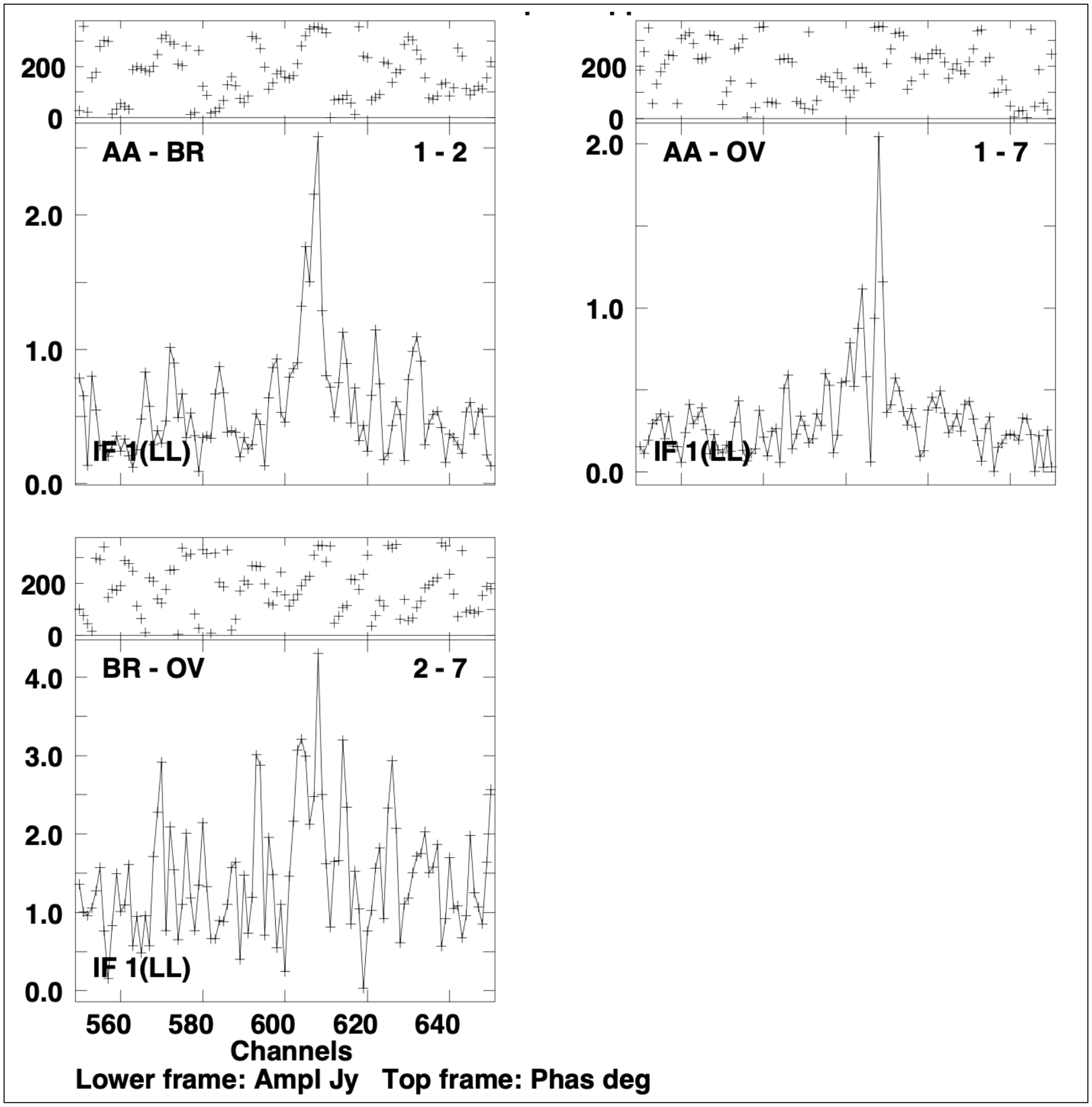

Figure 26: Sample cross-correlation spectra for the SiO maser target R Leo, observed on April 26, 2021 between ALMA and the Owens Valley and Brewster stations of the VLBA (polarization LL) as part of experiment C211D. The data are averaged over a single ∼6 minute scan.

thus $\sim$0.24 Jy (ALMA-Ov), $\sim$0.2 Jy (ALMA-Br), and $\sim$1.7 Jy (Ov-Br), comparable to the observed values.

The April 2021 test also confirmed that Galactic SiO maser sources are viable targets on the long baselines between ALMA and Europe. Figures 27 and 28 show sample fringe rate spectra and cross-correlation spectra, respectively, for two scans on R LMi. Figure 29 shows a sampling of fringe-rate spectra for several baselines for another target, VY CMa. We note that ALMA was not optimally phased during the VY CMa observations because of an error in the sky frequency used to designate the channel range for phasing. Despite this, fringes are still detected to ALMA (as well as on several of the other baselines).

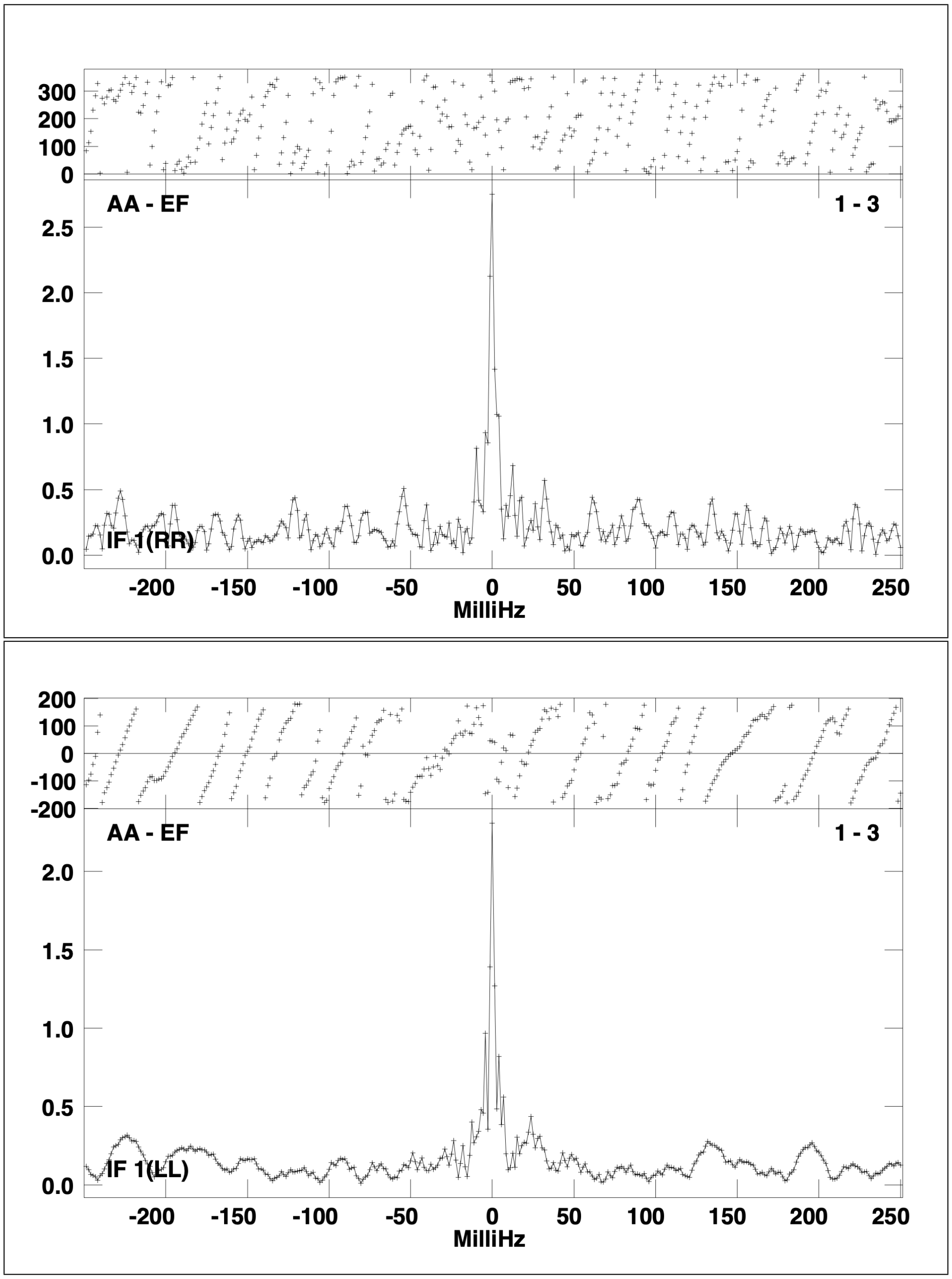

Figure 27: Fringe-rate spectra for the SiO maser target R LMi, observed on April 26, 2021 for the 9638 km baseline between phased ALMA and Effelsberg as part of experiment C211D. SNR is ∼10. Data for a single spectral channel containing strong maser emission are shown, with the RR polarization on top and the LL polarization in the lower panel. The data are averaged over a scan of duration ∼6 minutes after application of fringe solutions determined with a 30 s solution interval.

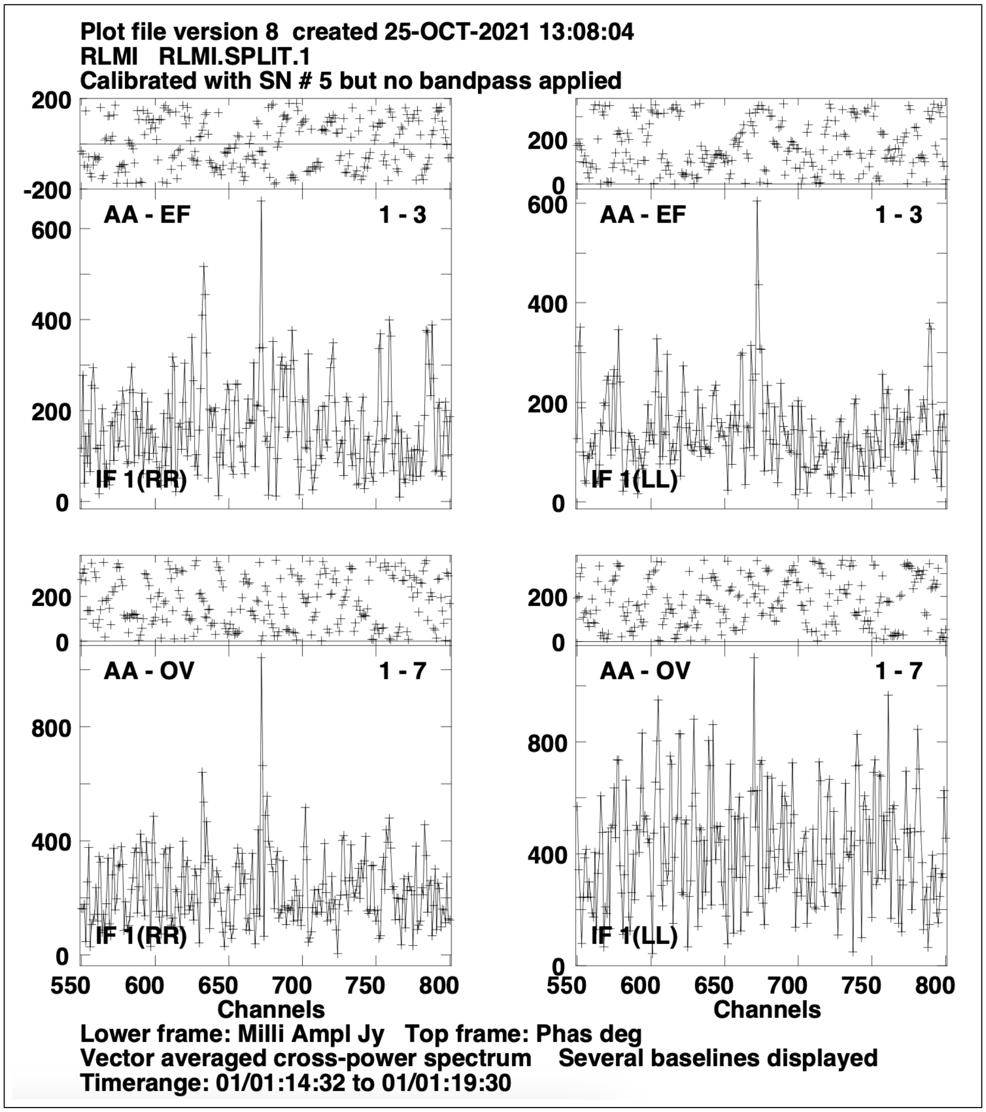

Figure 28: Sample cross-correlation spectra of R LMi for the 9638 km baseline between phased ALMA and Effelsberg (top) and the 7896 km baseline between ALMA and Owens Valley (bottom) on April 26, 2021 (experiment C211D). The data are averaged over a ∼5 minute scan. The RR polarization is shown on the left and LL on the right.

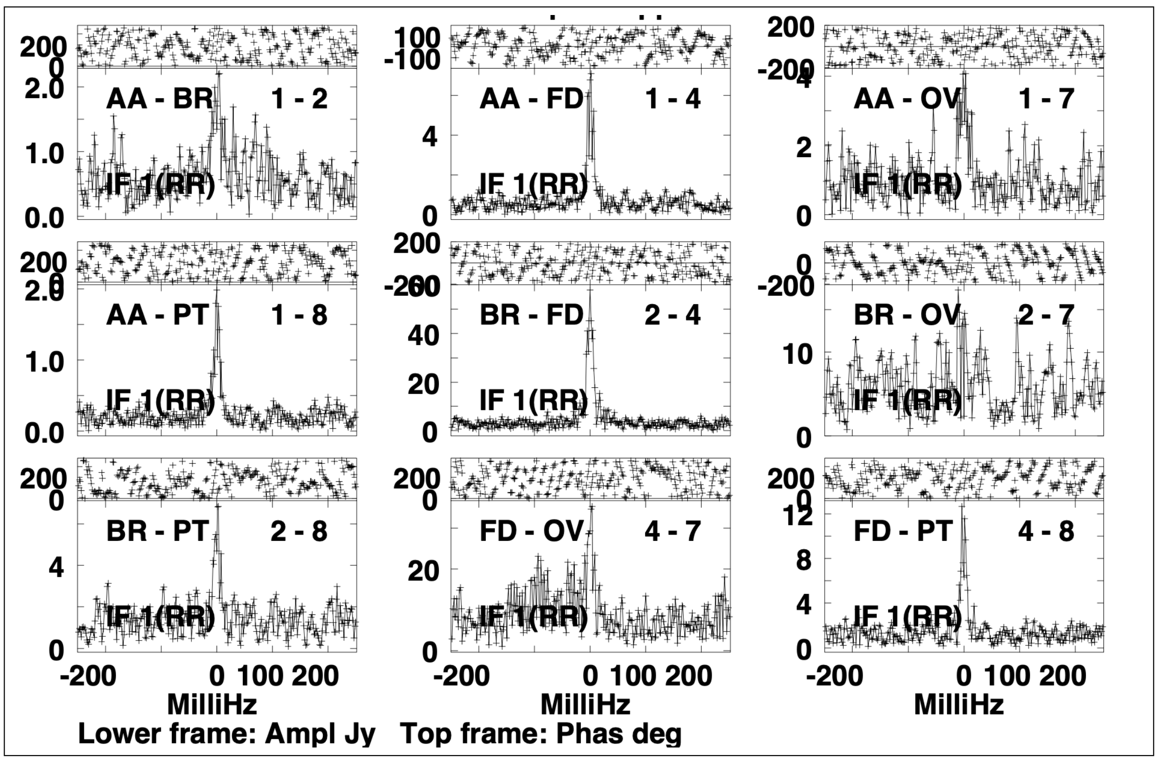

Figure 29: Sample fringe-rate spectra for the SiO maser source VY CMa (RR polarization) from April 26, 2021 (experiment C211D). The data from a single spectral channel containing strong maser emission are shown for several baselines. The maser emission from this star is detected on a range of baseline lengths, including both intra-VLBA baselines and intercontinental baselines (e.g., ALMA-Effelsberg).

4.4.5 Spectral Line VLBI Outcomes

As described above, testing undertaken under APP2 demonstrated that ALMA can be successfully phased on spectral line targets and is able to operate successfully in conjunction with the GMVA for spectral line experiments in Band 3. The results also give a preview of how dramatically the sensitivity boost provided by phased ALMA is expected to enhance our ability to undertake spectral line VLBI science at millimeter wavelengths.

Based on these results, the prototype spectral line observing mode developed under APP2 was approved and offered in ALMA Cycle 8. Starting in Cycle 9, this was superseded by a much more flexible spectral line VLBI observing mode (developed under APP3) offering flexible tuning, an extension to additional ALMA bands, and the option to phase the array using a choice of methods, depending on the properties of the science target (active phasing on the line, passive phasing, or phase-up on the target continuum emission). Ultimately the Cycle 8 version of the spectral line VLBI observing mode was not used for any approved science projects, but nonetheless its underlying development work served a crucial stepping stone for the fully flexible spectral line mode introduced in Cycle 9.

Based on the results of APP2 commissioning efforts, guidelines for the recommended peak line flux to allow the option of active phase-up on a line source are now included in the ALMA Technical Handbook. The recommendations are analogous to those currently in place for continuum sources, but scaled to account for the typically narrower bandwidth over which line emission is present. For example, Galactic maser sources typically have line widths of a few MHz, hence the effective bandwidth over which the signal used by the phase solver is integrated is $\sim$20–60 times narrower than the 234 MHz channel averages used in continuum mode observing. Consequently, it is recommended that actively phased SiO line targets in Band 3 should have peak flux densities of at least $\sim$2–3 Jy (compared with $\sim$0.5 Jy in the continuum case) to achieve optimum phasing efficiency (see the ALMA Technical Handbook, Cycle 9 or later for further details). These recommendations were supported empirically by our commissioning tests as described above, and by subsequent spectral line phasing regression tests. Weaker sources (and absorption line targets) may alternatively be observed using passive phasing.

One outstanding question related to spectral line VLBI observing concerns the issue of how the presence of an extremely high brightness temperature (masing) spectral line impacts the overall system temperature and thus the absolute array calibration. This was briefly discussed in Section 4.4.4 and is a topic that warrants further study.

5 Miscellaneous Support Tasks and Other Minor Features (WBS 4.0)

5.1 Python 3 Migration

ALMA computing has a policy to migrate software to current releases. This is important for security of externally-facing sites, but it is also useful to gain access to bug fixes and new developments. In the case of Python, which ALMA uses for certain activities, this created a need to respond to that community's proclivity to re-implement and deprecate working code found in various packages.

The initial version of Python used at ALMA was Python 2 (with version 2.0 released in 2000 and an end-of-life for version 2.7 in 2020[16]. A migration to Python 3 was then undertaken during the period of performance of APP2. Python 3 is sufficiently syntactically and semantically different from Python 2 such that a complete re-examination of all code was required to catch a variety of bugs resulting from code that executed without complaint, but produced incorrect results. This effort was not part of our formal APP2 work package and thus was somewhat of an "unfunded mandate". Nonetheless, we were able to incorporate it with the realm of "Miscellaneous Support Tasks and Other Minor Features" (WBS 4.0), a WBS category that had been intended to encompass unplanned efforts needed to deliver and maintain VLBI at ALMA.

At this juncture, the ALMA Observatory has shifted to Python 3.12 which is end-of-life in 2028, i.e. before the WSU will be completed. Therefore ALMA internal resources will be needed to maintain the current VLBI capability until its obsolescence.

5.2 Use of the Fast Phasing Mode

In addition to the "slow" phasing loop executed by TelCal on a 16 s cadence, the APS provides an optional "fast" phasing loop that is able to compute and apply in real-time phase corrections derived from the WVR units deployed on each of the individual 12 m antennas (see Matthews et al. 2018a). These fast corrections are currently computed and applied every 1.5 s and their use was commissioned as part of the original APP. However, prior to Cycle 8, the fast corrections were not used during VLBI science observations.

During the course of APP2, a pair of bugs was discovered that resulted in the fast mode no longer functioning. One problem resulted from WVR updates no longer being sent to the correlator control computer (CCC; ICT-18722) and the other was related to the CCC entering but not leaving the fast phasing mode at the desired time (ICT-19176). The causes were subsequently identified and fixed through work by the APP2 team.

Subsequent on-sky testing of the restored fast phasing mode consistently showed that the fast mode corrections are highly effective at reducing phase RMS under a range of observing conditions for Bands 3, 6, and 7. This reaffirms the conclusions of other studies of the effectiveness of WVR corrections for improving phase stability during standard (non-VLBI) ALMA observing (e.g., Maud et al. 2017; Matsushita et al. 2017). These findings lead to the adoption of the practice of using the fast corrections by default for all VOM operations in all offered bands. Examination for the QA0+ products from the Cycle 8 VLBI campaigns further indicated that it performed well.

One exception to the recommendation for universal use of the fast phasing mode is the case of the Phased Array mode, whose primary application is pulsar observing (see Section 4.3.3). Because such experiments require analysis of the data in the time domain, it is crucial to avoid as much as possible the introduction of unwanted periodic signals into the data. In April 2021 we obtained for the first time a test of the Phased Array mode with the fast phasing mode deployed. The resulting baseband data were shared with experts in pulsar timing and analysis in Bonn, Germany. The results of an analysis of the impact

[16] https://en.wikipedia.org/wiki/History_of_Python

of the fast mode on those data were inconclusive, hence out of abundance of caution it was determined that the safest approach is to continue avoiding the use of the fast phasing mode during pulsar observations.

5.3 LOSolutions

Another miscellaneous and unplanned APP2 (and APP3) activity involved resolving issues in the ALMA tuning system. There is a Java library (`LOSolutions`) that is used for all observing modes at ALMA for the conversion of a set of requested center frequencies for the four BBs into the precise tuning commands to the underlying hardware at all of the antennas. At the same time that use of ALMA by the EHT and GMVA provided unprecedented sensitivity for the analysis of VLBI fringes, it also enabled uncovering subtle features of the tuning system that had not previously been seen. This provoked follow-up investigations that ultimately led to the determination that the tunings requested at ALMA were not precisely those requested (to the extent that the hardware should provide them). This typically does not matter for ALMA, as small mis-tunings do not affect most ALMA science (the errors are at the sub-Hz level). However, for VLBI, this becomes an issue because of resulting sensitivity losses in the correlated VLBI data products.

Our investigation first turned up that the device that sets ALMA's LO1 was not being commanded with the full precision it supports. Later, changes to `LOSolutions` to address issues not related to VLBI introduced huge tuning errors (3 MHz in the case of the default set-up used for Band 3 VLBI). After considerable investigation with the help of ALMA and NRAO staff, we worked towards several fixes that finally addressed these issues. The system should now work correctly until WSU replaces it. Additional discussion of the `LOSolutions` issue may be found in Section 4.2.1 of Matthews & Crew (2024).

5.4 APP GUI Implementation and Improvements

The original APP team made regular use of ALMA's (test) graphical user interface (GUI) tool known as `CorrGUI`, along with other existing forms of graphical feedback, to aid in development and monitoring efforts. In addition, a prototype GUI dedicated to APS needs (`AppGUI`) was created to provide status updates on various aspects of VLBI/APS operations and to allow some additional online commanding capabilities. The original `AppGUI` thus provided a tool to monitor the actions of the APS and, if necessary, to intervene by issuing manual commands to adjust its operation. Under APP2, a variety of upgrades to `AppGUI` were introduced in response to newly developed features and to make its operation more robust.

5.4.1 General VLBI GUI Improvements

Under APP2, the prototype `AppGUI` received a major overhaul. The original plan had been to integrate the phasing reports from TelCal with the QuickLook system in use for all other telescope calibrations. However, the knowledge on how to do this was tied up in NRAO staff who were never truly available to complete the transition from the `AppGUI` prototype to the the QuickLook system. Since ALMA AoDs had had some training in the `AppGUI` we decided to continue with it as a special tool for VLBI. Indeed, some of its capabilities go beyond what QuickLook can do. Improvements undertaken include the following:

- A refactoring of the previous script to provide two different "main" loops: one for the original functionality and a second designed specifically for use by the ALMA array operator. The mode of operation is selected at start-up based on either the script name or a command-line. One loop will continue use of `AppGUI`, while the second is used in a new `maser_gui` tool for the operators (Section 5.4.2).
- Introduction of a "kill" button to remove unwanted pop-up windows or windows that for some reason become unresponsive (see Figure 30).
- Option to view pop-up plots illustrating performance of a given antenna in the phased array, including a quality metric for the phasing solutions and a history of the applied phasing corrections.
- Addition of a mechanism to allow easy cycling between the four VLBI BBs
- Ability to view VLBI recorder housekeeping information, along with scan check information.
- Improvements to the color scheme to be compliant with the Americans with Disabilities Act (ADA).

A screenshot of the main GUI panel is shown in Figure 30.

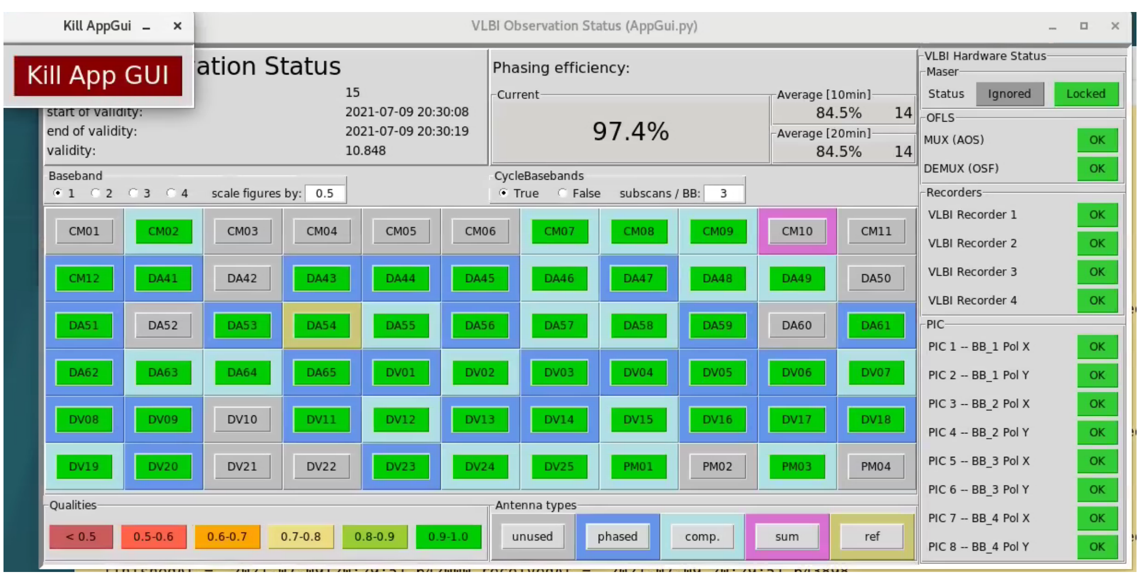

Figure 30: A sample of the main panel of the updated APP GUI (`AppGUI`) tool, which is used by the ALMA operator during VOM observations to monitor the phased array.

5.4.2 Maser GUI

As part of the original APP, a hydrogen (H) maser was installed at ALMA to serve as a frequency standard for VLBI (see Matthews et al. 2018a). It was also adopted as the standard for all regular (non-VLBI) ALMA operations, replacing ALMA's original rubidium clock.

ALMA's original H maser failed in April 2022, just prior to the annual ALMA-GMVA science campaign. In response, a new H maser was installed in 2023, with the original one (after repairs) left in place as a spare (see Crew & Matthews 2024; Matthews & Crew 2024). At the same time, it was noted that the primary indicator of maser health (its lock status) was not being continuously monitored. It was therefore decided to add to the VLBI GUI an option to display information on either of the two masers. When the GUI is run in "operator" mode (see Section 5.4.1) the ALMA operator now has available a window supplying information on maser lock status and other housekeeping information (Figure 31).

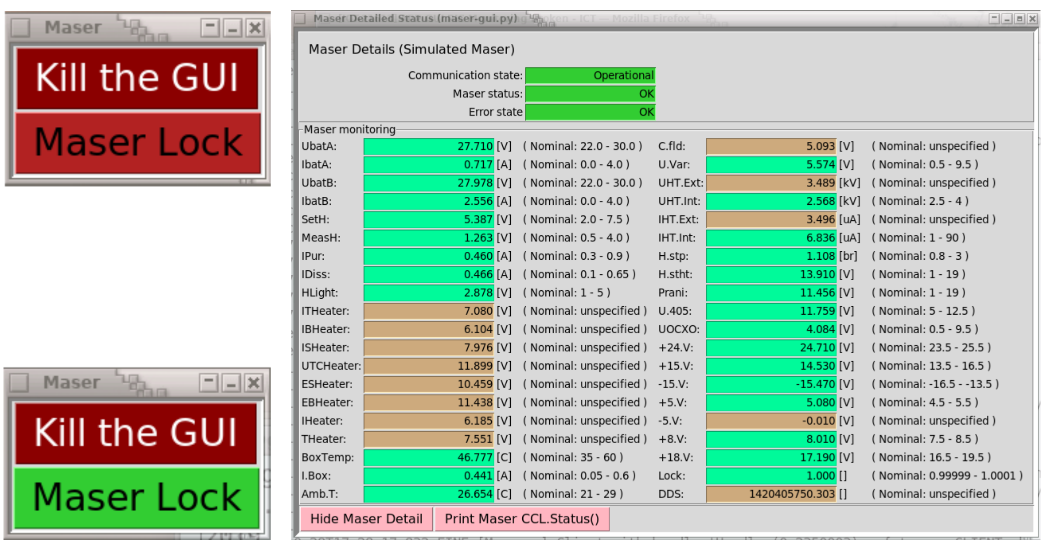

Figure 31: Screenshots of the updated `AppGUI`, run in "operator" mode. The GUI launches with the small two-button window. The lower button is green if the maser is locked (lower left image) and red if it is not locked (upper left image). Clicking on the "Maser Lock" button brings up a detailed report on the maser status, such as in the image at right.

5.5 Training Activities

Part of our activities under APP2 involved training of JAO staff and knowledge transfer in support of ALMA's desire to autonomously support VLBI observing, without assistance from external VLBI experts (see also Matthews & Crew 2024). To this end, a wealth of Confluence pages and other documents were produced during the project (see also Section 6.2). To aid with future navigation of this information, a "Roadmap Document" is in preparation that is intended to provide a guide to the entire VLBI observing system, with pointers to all relevant documentation.

In general, ALMA Development Projects conducted by teams external to ALMA/JAO require some training of ALMA staff to "take over" once the deliverables are met. In practice, this may be relatively straightforward for hardware deliverables, but more challenging for software developments, such as were carried out under APP2. The most significant reason for this is that software is continually changing; underlying operating systems and computer languages are upgraded every cycle to stay current, while at the same time, new software features are always being added to allow ALMA to do more with the same hardware.

In the infinite resource approximation, it may be feasible to document every detail of code that is implement and re-document it following every change. This would also required adequate staff to receive and review these documents and become trained on how to maintain the code. But in practice, human resources at ALMA are limited. Thus while the APP2 team remained active, some of these maintenance duties as related to VLBI were absorbed by the APP2 team. Meanwhile, since the APP2 was of finite duration, in parallel, the APP2 team strove to examine all parts of the current ALMA VLBI systems and identify individuals who would need to be trained on the required software maintenance for the next few years (until WSU is fully implemented). Note that the needed training covers not only the software, but all of the details of the special operations required by VLBI (recorder media handling, QA2, etc.). A plan was put in place for this, and at the time of this writing, it appears everything will be adequately covered.

6 Project Management (WBS 1.0)

6.1 Management Philosophy

All APP2 activities were conducted in accordance with established Systems Engineering policies, practices, and procedures. Michael Hecht (MIT Haystack) provided project management oversight, particularly during the early project phases, and contributed to the APP2 Project Plan (see Section 6.2).

The bulk of APP2 development efforts were coordinated and reviewed through the ALMA ObsMode process. Each ObsMode cycle, gating activities typically included delivery of a Test Plan to JAO, presentation of regular status updates to JAO staff through telecons and Zoom meetings, delivery of a document package prior to the annual Go/No-Go decisions, and a presentation during the annual ObsMode Go/No-Go decision telecon (see, e.g., Takahashi et al. 2021). However, ALMA did not formally convene an ObsMode process in 2023, and instead, APP2 activities were coordinated directly with the Director of Science Operations (DSO). Following the recommendation of the ALMA Board, APP2 activities were also independently reviewed annually by a panel of external experts, starting with a Technical Readiness Review in November 2018.

For all software development efforts, APP2 followed the standard ALMA software delivery process, which is organized around the implementation of specific and separable features. The evaluation criteria used for each new feature included successful offline testing, successful commissioning through on-sky tests, and a demonstration of stable operation through occasional regression testing.

6.2 Documentation

Documentation produced as part of the APP2 included the following:

- A Project Plan (including quality assurance, safety procedures, a risk register, and a project schedule)
- Monthly "4-Square" progress reports that summarized ongoing activities, updates to the Risk Register, and financial information.
- Software Design documentation
- Technical Manuals and Procedures (including annual updates to the VLBI- and Phased Array-related sections of the ALMA Technical Handbook and ALMA Proposer's Guide)
- Annual Test and Commissioning Plans
- Annual Acceptance Reports
- Science Requirements (SCIREQ) tickets
- Integrated Computing Team (ICT) tickets summarizing implementation, verification, and validation results
- A final Closeout report (this document)

A plan is underway to post projected-related documentation expected to be of general or historical interest (and that has not already been posted publicly) as part of the ALMA Technical Notes Series, which already includes several reports from commissioning activities conducted during the original APP.[17]. Documentation from APP3 is also expected to be hosted there. In addition, key documents will be posted to ALMA's Enterprise Document Management (EDM) system once a necessary update to this system is made by JAO staff.

7 Descoped Activities

As noted in Section 3, a few of the originally proposed WBS elements of APP2 were later descoped. In this section we describe those activities, the rationale for their exclusion from the APP2 work package, and outcomes from any activities undertaken in those areas.

7.1 WBS 2.0 Elements

Among the originally proposed software features to be developed under APP2 were a source modeler (WBS 2.2) and a single-dish VLBI capability (WBS 2.6). Both were descoped for reasons described below.

[17] https://almascience.nrao.edu/documents-and-tools/alma-technical-notes-a-subset-of-documents-from-tl

7.1.1 Source Models (WBS 2.2)

The source modeler concept would have introduced modifications to the TelCal-based phasing engine to enable use of a CLEAN component model (or a source model image) for the target during phasing calculations. In principle this could allow more robust phasing on targets that are not point-like on the scale of intra-ALMA baselines and/or that are not located at the field-of-view center.[18] One specific application that was envisaged was providing a new tool for pulsar searches near the Galactic Center.

Work was started on a source model-based phasing capability (ICT-2833), and the proposed approach was that a list of CLEAN components would be retrieved from the ALMA Archive at the time of a VOM observation. The required phasing adjustments would then be made in reference to this model within the TelCal APP phasing engine. However, it turned out that the Archive support team needed to do some development in order to support this. The APP team put the hooks in place (in the SSR) to access the data from the Archive, but the effort was stalled at this point during the original APP effort. The work package was carried over to APP2 in its incomplete state in the TelCal code. However, in the lead-up to Cycle 7, owing to competing priorities, this effort was again suspended pending the required Archive support. By the time the Archive resources were finally available to accept a source model, the TelCal team with the relevant expertise to assist with enabling the source model option was no longer available, increasing the complexity of this undertaking. Moreover, by this time, the one source (Sgr A*) which was thought to require this capability had been adequately observed twice (2017 and 2018) and preliminary analysis suggested that the results were of sufficient quality such that source model was no longer necessary for that target.

7.1.2 Single-dish VLBI (WBS 2.6)

A "single-dish" VLBI observing mode for ALMA was implicit in the design of the APS and VLBI subsystem since the original APP. Its intent was to enable ALMA to carry out VOM observations using just a single ALMA antenna rather than a phased array. This had the potential to allow ALMA to more flexibly schedule VLBI observations (including tests), since use of the full array would not be required. Thus VLBI could in principle be run in parallel with normal science observations through use of subarrays. In addition to helping to facilitate VLBI testing, this would have enabled VLBI operations outside the normal "campaign mode" (which is limited to a short window in March or April each year). This could allow ALMA to more readily participate in VLBI observations for targets-of-opportunity, or as part of experiments throughout the year that would benefit from the enhanced *uv* coverage of a station in the southern hemisphere.

In a formal sense, VOM operations with an "array" comprising just a single allocated antenna are not currently possible. This is because the VOM formally inherits code from `InterferometryController`, which in turn assumes the presence of at least one baseline (i.e., two antennas). Fortunately, there is operationally a straightforward workaround, since there is almost always another antenna that can be provided as a partnering comparison

[18] For the current APS the source model is always assumed to be a point source at the field-of-view center.

antenna, thereby satisfying `InterferometryController` and allowing a single-dish VLBI "sum". (The APS can only form a sum of an odd number of antennas, thus formation of a phased sum from the two antennas is not possible; see Matthews et al. 2018a).

Because the default mode of operation of the original APS was to assume phasing of as many antennas as possible, a first step to enabling a single-dish VLBI capability was to verify that no exceptions would result from invoking the VOM on a "phased array" comprising a single antenna (and if needed, modify the observing code to achieve this). Indeed, tests to verify this operation were performed as part of the January 2020 VLBI Dress Rehearsal campaign.

Sections 4 & 5 of the Cycle 7 Acceptance Report report detail the April 2020 observations and their analysis, respectively. The single-dish tests were conducted using features of the APS that allow different phased arrays to be assigned to the different BBs. When the four 2 GHz BBs are all tuned to the same center frequency, one can then make VLBI recordings of four different arrays and effectively perform "zero baseline" VLBI fringe tests between the different BBs. In this test, the full array of 39 antennas was assigned to BB_1 and antennas DA57, DV13 and DV18 were assigned to BB_2, BB_3, and BB_4, respectively. The resulting recordings were then analyzed in a standard manner using HOPS. An example fringe zero-baseline fringe detection resulting from that test is shown in Figure 32. This established the single-dish VLBI capability on a technical level.

Unfortunately, the onset of the COVID-19 pandemic a month or so later shut down the Observatory and inserted an extra year into Cycle 7. The Acceptance Report for VLBI was completed in April of 2020 (Crew 2020), one year before ALMA's return to operations allowed a "best effort" VLBI campaign in April of 2021 (prior to the true start of the Cycle 7 continuation) and this effort stalled.[19]

An additional result of this April 2020 single-dish VLBI test was that it allowed a resolution to some lingering issues regarding the efficiency loss due to the 8-bit to 2-bit truncation that normally occurs when the VLBI sum signal is formed. Normally, truncation of a continuous signal to 2-bits incurs a ∼12% loss (see Section 8.3.2 of Thompson, Moran, & Swenson 2017). However, in APS processing, the normal ALMA signal chain proceeds through an initial truncation to 3 bits, a regeneration of the signal and a truncation to 2 bits in the TFB, and finally a summation of N_A antennas to an 8-bit sum that is again truncated to 2 bits. Naively, we had originally presumed that the 8-bit to 2-bit reduction would do no worse than the standard 12% loss. However, we were finally able to measure the actual additional loss we found it to be only an additional ∼7%.

Having demonstrated the technical feasibility of single-dish VLBI with the current APS, programmatic and operational changes were required to allow its utilization. The operational change is that one good antenna must be held out from the normal "Science" array in the BLC for the period during which a single-dish VLBI project is to be observed. Likewise a comparison antenna is also needed—it may be a 7-m antenna not needed for the Atacama Compact Array (ACA) or a degraded 12-m antenna. Assuming that this observation is not part of one of the normally scheduled VLBI campaigns with the EHT or the GMVA,

[19] In April 2021 there were a sufficient number of antennas and sufficient supporting infrastructure to allow a successful remotely-supported VLBI campaign with fewer antennas than normal. The full recovery of the Observatory and its antennas was subsequently completed after the 2021 VLBI campaign.

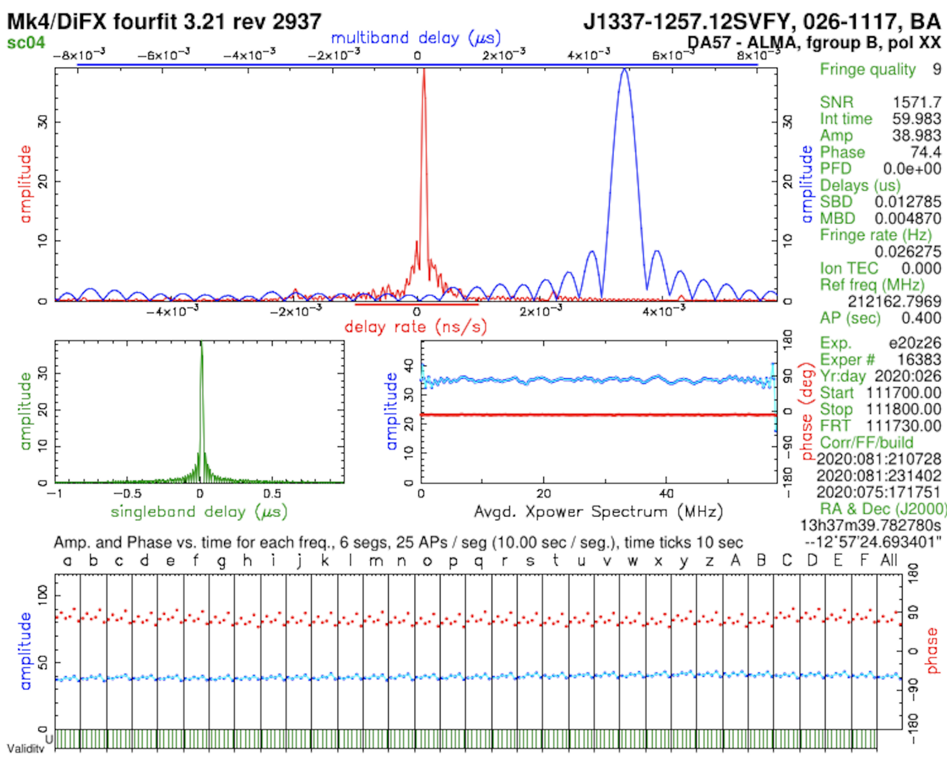

Figure 32: Zero-baseline fringe detection between an ALMA phased array of 39 antennas (designated ‘Aa’) and antenna DA57 (designated ‘A2’, and recorded as an “array” of one antenna) from a test performed in April 2021. The plot has a format analogous to Figure 9. Reproduced from Crew (2020).

arrangements for media would need to be made as well.

In terms of programmatic considerations, by the time the results of the April 2021 VOM observations had been evaluated, it was already too late in the year for consideration of a single-dish VLBI capability for Cycle 8. (The loss of a year of observing during the COVID-19 pandemic resulted in extra development time for Cycle 8, but only for features in process prior to the shutdown.) At the time there was discussion about considering inclusion of the single-dish VLBI in Cycle 9 or Cycle 10 if there was sufficient interest shown, not only at ALMA, but also from potential partnering sites such as the VLBA. Unfortunately two other independent developments conspired against this offering.

The first involved improvements to CCC handling of "homogeneous sequences" (see `ICT-7547`, created June, 2016). The low-level code for commanding BLC activities is rather complex and the implementation of subarrays made it worse.

The quanta of BLC observing are subscans, and every subscan requires some setup time (for which a reservation is made) prior to the execution of the subscan. Normal science observations then proceed with various higher-level collections of subscans appropriate for the particular Science observation. However, this machinery creates complications for the VLBI case because VLBI requires a setup followed by a replication of the same setup for the duration of the scan (i.e., VLBI uses a homogeneous sequence of identical subscans.) Once the various bits of time reserved for possible setup activities (which were actually also in the CONTROL component as well as the CCC) were identified and removed for the VLBI case, this allowed the recorded VLBI data to be completely matched by the parallel ALMA interferometric (ASDM) data in the archive. Prior to Cycle 8, there were $\sim$2-second gaps between subscans so that a $\sim$16-s subscan required $\sim$18 s to complete. In marginal weather this provided an extra 2 s for weather to decorrelate the signal in the recordings. Unfortunately, late in the acceptance of the Cycle 8 software other issues emerged (unrelated to VLBI) and it was suggested that homogeneous sequence handling be de-scoped to reach a stable software release. This would have been a serious problem for VLBI.

The compromise for Cycle 8 was to introduce a "lockout" of other subarrays during VLBI and allow homogeneous sequences for VLBI only. In the time available this was the only way to allow VLBI to benefit from the homogeneous sequence efficiencies without opening the potential for non-VOM observations to fail. It also served to make VLBI observations more robust in that it eliminated competition for the BLC input that is co-opted by the sum signal to be recorded for VLBI. We had instances of such competition during the Cycle 7 VLBI campaign which was the first time VLBI was not allowed exclusive use of the BLC (e.g., Figure 33). (This caused operator confusion at the time it occurred, but no apparent issue with the recorded data.) Unfortunately, the lockout in effect removes the subarray capability during VOM observing and thus eliminates the possibility of a single VLBI dish operating in parallel with normal, non-VLBI science observing.

The single-dish VLBI option thus became moot until resources could be allocated to eliminating the underlying cause of the need for the lockout. However, by early 2020, a second complicating factor emerged, namely that ALMA was already contemplating successors to the BLC as part of the ALMA 2030 vision (Carpenter et al. 2018) and what is now known as the WSU project. As a result, the human resources need to solve

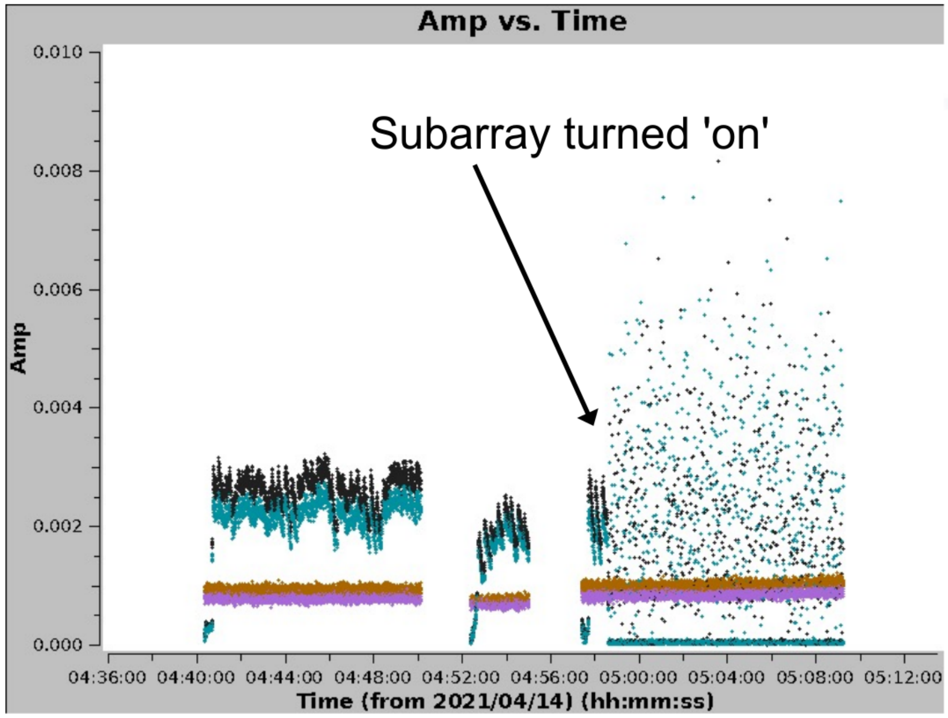

Figure 33: A plot of correlated amplitude versus time for a sequence of scans obtained in April 2021 in Band 3.

the current CCC issue had competing priorities and the effort to move forward with a single-dish VLBI capability with the current BLC was curtailed.

As part of the APP3 we proposed to investigate alternative options to single-dish VLBI involving sub-arrays that may have eliminated any required fixes to the CCC. However, efforts tied to subarraying were ultimately descoped from APP3 owing to resource limitations (see Matthews & Crew 2024). Nonetheless, the combination of the aforementioned efforts helped to increase appreciation of the value of ALMA as a single-dish VLBI site and such a capability is now likely to be a requirement for VLBI in the WSU era.

7.1.3 VLBI in Band 1 (WBS 2.3)

One other item under WBS 2.0 was also partially descoped, namely the enabling and commissioning of VLBI and phased array operations in Band 1. The reason was a delay in the schedule for the delivery and installation of Band 1 receivers to ALMA. Commissioning VLBI in Band 1 was instead carried out under APP3 as part of its broader effort to make VLBI operations feasible in any available ALMA band (see Matthews & Crew 2024).

7.2 WBS 4.8 (Polarization Beacon)

An artificial calibration source (or "beacon") was already in ALMA's plans during the original APP. This source was intended to deliver a linearly polarized signal of high purity, with negligible circular polarization. Additionally, measurements of the beacon could in principle be made much more quickly than a sky observation on a polarized source which typically requires 3 or more hours. From a VLBI perspective, there had been considerable interest in testing the efficacy of such a beacon beacon for aiding the `PolConvert` process. but unfortunately it was not delivered within the period of performance and thus was descoped. At the time of the original APP2 proposal it was thought that the beacon would finally be deployed at ALMA and become operational in Band 3 during 2017 and Band 6 by 2018. This was proposed as WBS 4.8 for APP2.

The APP2 team monitored the status of the beacon throughout the project performance period, but unfortunately, it never became available for routine use during this time frame. We did sort out a protocol for determining the parallactic angle swing of polarization targets so that observations shorter than 4 hours could be attempted, but in practice this strategy was never attempted for VLBI observations.

Recently ALMA staff conducted an engineering test with the beacon in Band 3, with further tests anticipated later in 2024 (S. Kameno, private communication). However, these activities did not included any testing specific to VLBI. It also has yet to be fully explored whether the beacon will be useful for polarization calibration in Bands 6 & 7 owing to its comparably weak power in these bands. As it is expected that the beacon will have important use for the WSU (S. Kameno, private communication) this is something that may warrant further exploration for VLBI in the future.

7.3 WBS 5.0 (Coordination with ALMA Correlator Upgrade)

As noted in Section 3, a WBS element 5.0 was introduced into the APP2 work package to enable coordination between the APP2 and an NRAO-led effort to develop a new ALMA correlator. However, subsequent to the formal start date of APP2, the plans for the new ALMA correlator were deferred and restructured (see Baudry et al. 2021), rendering formal coordination with the APP2 unnecessary. The ALMA correlator upgrade is now part of the broader WSU effort[20] (see also Section 8).

8 Looking Ahead

The enhanced and expanded VLBI capabilities that have been delivered thanks to APP2 (and the complementary APP3; see Matthews & Crew 2024) are expected to help ensure VLBI's continued relevance and importance at ALMA for the remainder of this decade and beyond. With the completion of APP2 and APP3, essentially all viable improvements to the current APS and VOM that can be accommodated within the framework of the original ALMA BLC and other current ALMA hardware and software systems have now been implemented (see e.g., Matthews et al. 2018a; Crew et al. 2023; Matthews & Crew 2024; Crew & Matthews 2024), or else have been explicitly descoped by JAO as a result of resource limitations and/or concerns about impacts on ALMA's non-VLBI software and observing modes.

[20] `https://science.nrao.edu/facilities/alma/science_sustainability/wideband-sensitivity-upgrade`

At the time of this writing, major new developments are underway at ALMA under the umbrella of the WSU, with the goal of fulfilling the vision outlined in the ALMA 2030 Development Roadmap (Carpenter et al. 2018). These activities will include deployment of a next-generation ALMA correlator (the Advanced Technology ALMA Correlator, ATAC; e.g. Harrison et al. 2024) whose design requirements include VLBI capabilities that match or exceed ALMA's current ones (Baudry et al. 2021). We note that based on our present knowledge, the implementation of VLBI with ATAC is expected to draw heavily on the existing APS infrastructure. Thus many or most of the new capabilities developed under APP2 are likely to survive in some form in the eventual implementation. Meanwhile, VLBI science with the newly commissioned APP2 capabilities on the existing BLC are expected to enable pathfinder VLBI science in advance of the full roll-out of the WSU.

We note that ALMA is currently using Red Hat Enterprise Linux release 8 (RHEL8), which is not expected to go to "end of life" before the WSU is completed. To ensure the viability of the VOM in the interim, it is strongly preferred that ALMA remain on RHEL8 until the WSU arrives. Holding Python at version 3.12 would also be sensible. Otherwise, greater effort may be needed to maintain ALMA's VLBI capability and to keep VLBI viable.

9 Summary

The APP2 has delivered a series of updates and enhancements to the original APS, resulting several new VLBI capabilities at ALMA. These include a passive phasing mode (Section 4.3), a standalone Phased Array model suitable for pulsar observations (Section 4.3.3), a prototype spectral line VLBI capability (Section 4.4), the demonstration and introduction of submillimeter (Band 7) phasing and VLBI capabilities (Section 4.2), a new method of handling baseband delays (Section 4.1), and various other minor system enhancements, including an improved VLBI GUI (Section 5.4). Other effort on the project included documentation, training of staff, and the migration of VLBI software to Python 3 (Section s5.1 & 5). Together with efforts carried out by a parallel ALMA Development award (APP3; see Matthews & Crew 2024), these newly launched capabilities will allow ALMA to expand the scope of groundbreaking VLBI science achievable at millimeter and submillimeter wavelengths and continue its role as the world's most sensitive station for VLBI in these bands.

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A List of Acronyms and Definitions

ACA ALMA Compact Array
ADA Americans with Disabilities Act
AIPS Astronomical Image Processing System
ALMA Atacama Large Millimeter/submillimeter Array
ANTAB Ancillary telescope calibration table introduced by AIPS
AoD Astronomer on Duty
APEX Atacama Pathfinder EXperiment
APP ALMA Phasing Project
APP2 ALMA Phasing Project, Phase 2
APP3 ALMA Phasing Project, Phase 3
APS ALMA Phasing System
Archive The software that connects to the ALMA Archive
ASDM Archival Science Data Model
ATAC Advanced Technology ALMA Correlator
BB Baseband
BBD Baseband Delay
BLC (ALMA) Baseline Correlator
Br Station code for Brewster
CCC Correlator Control Computer
CDP Correlator Data Processor
CONTRL The tree of software that controls ALMA observations
CSV Commissioning and Science Verification
DBBC Digital Baseband Converter
DDC Digital Down Converter
DF Delay Fix
DiFX Distributed FX *(VLBI Software Correlator)*
DSO Director of Science Operations
Ef Station code for Effelsberg
EDM Enterprise Document Management
EHT Event Horizon Telescope
EHTC Event Horizon Telescope Collaboration
Fd Station code for Fort Davis
FDM Frequency Division Mode
FFT Fast Fourier Transform—the algorithm used for digital Fourier transforms
FITS Flexible Image Transport System
FITS-IDI FITS Interferometry Data Interchange
FWHM Full Width Half Maximum
Gb Gigabyte

Gbps Gigabits per second
GLT Greenland Telescope
GMVA Global Millimeter Array
GPS Global Positioning System
GUI Graphical User Interface
HOPS Haystack Observatory Postprocessing System
ICT Integrated Computing Team
IF Intermediate Frequency
IRAM Institute de Radioastronomie Millimétrique
JAO Joint ALMA Observatory
JCMT James Clerk Maxwell Telescope (on Mauna Kea, HI station Mm)
KP Station code for 25 m VLBA antenna at Kitt Peak, Arizona
KT Station code for the 12 m EHT antenna at Kitt Peak, Arizona
LCP Lefthand Circular Polarization
LO Local Oscillator
LO1 The LO that creates the fundamental tuning for upper and lower sidebands
LOSolutions The (Java) software used by OT and CONTROL to tune LOs
LSB Lower side band
LSR Local Standard of Rest
LTA Long Term Accumulator
MIT Massachusetts Institute of Technology
MPIfR Max Planck Institute für Radioastronomie
ngEHT Next Generation Event Horizon Telescope
NOEMA Northern Extended Millimeter Array
NRAO National Radio Astronomy Observatory
ObsMode The process whereby Observation Modes are introduced or revised
OSF Operations Support Facility
OT Observing Tool
Ov Station code for Owens Valley
PI Principal Investigator
PIC Phasing Interface Card
PSRFITS Pulsar FITS format
Pt Station code for Pie Town
PV The IRAM 30-m telescope on Pico Veleta, near Granda, Spain
PWV Precipitable water vapor
Python The scripting language used at ALMA
QA0 Quality Assurance (at time of observations)
QA0+ Quality Assurance (at time of observations, enhanced version)
QA2 Quality Assurance Level 2 (performed prior to data delivery)
RCP Righthand Circular Polarization
RHEL8 Red Hat Enterprise Linux release 8
RF Radio Frequency
RMS Root Mean Square
SB Scheduling Block

SCIREQ Science Requirements
SEFD System Equivalent Flux Density
SMA Submillimeter Array
SMT Submillimeter Telescope
SNR Signal-to-Noise Ratio
SPW Spectral Window
SSR Science Software Requirements
SVN Subversion
TB Terrabytes
Telcal Telescope Control Computer
TFB Tunable Filter Bank
TMCDB Telescope Monitor and Control DataBase
USB Upper side band
UTC Coordinated Universal Time
VEX VLBI EXperiment file
VDIF VLBI Data Interchange Format
VEX2VOM Tool that merges VLBI plans within a VEX file with ALMA SB executions
VLBA Very Long Baseline Array
VLBI Very Long Baseline Interferometry
VOM VLBI Observing Mode
WBS Work Breakdown Structure
WSU Wideband Sensitivity Upgrade
WVR Water Vapor Radiometer