ALMA North America Cycle 4 Study Project Final Report: Diversifying the Scientific Applications of the ALMA Phasing System

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ABSTRACT

The Atacama Millimeter/submillimeter Array (ALMA) Phasing Project (APP) produced the hardware and software modifications necessary to bring Very Long Baseline Interferometry (VLBI) capabilities to ALMA. The resulting VLBI observing mode was introduced to the science community in ALMA Cycle 4 (2017), and two VLBI science campaigns have now been carried out successfully at ALMA. The current Cycle 4 ALMA North America (NA) Study was proposed to lay the groundwork for a variety of enhancements to the ALMA Phasing System (APS) that were not within the scope of the original APP project. These include: (1) devising an improved method for the handling of baseband delays; (2) development of procedures for use of the APS on fainter astronomical sources than is presently possible; (3) development of data acquisition and correlation techniques to allow the APS to be used for spectral line VLBI experiments. These tasks were intended as preparatory steps for a future full-scale implementation project (if approved). Formal approval of this implementation work has now been granted and is funded through an ALMA Cycle 5 NA Development project known as APP "Phase 2" (APP-2). As a result, efforts to implement capabilities designed and explored under the current Cycle 4 Study, as well as a previous Cycle 3 Study award, are now underway. This report provides a status summary of Cycle 4 activities and outlines follow-on work that is continuing as part of the ongoing Cycle 5 Development efforts.

1. Overview and Context

The ALMA Phasing Project (APP), led by S. Doeleman (MIT Haystack Observatory/Harvard Smithsonian Center for Astrophysics), was conceived to exploit the extraordinary sensitivity of ALMA for Very Long Baseline Interferometry (VLBI) science at millimeter

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(mm) and sub-mm wavelengths (Doeleman 2010; Matthews et al. 2018; hereafter M18). In addition to operating as a connected element interferometer, ALMA can function as the equivalent of a single very large aperture antenna if the data from its individual antennas are phase-corrected and coherently added. The APP provided the hardware and software necessary to perform these functions, enabled recording of the resulting data in a format suitable for VLBI, and put in place the infrastructure needed for ALMA to function as a VLBI station.

An optimally phased array provides a collecting area equivalent to the combined effective area of the individual antennas. Thus the addition of phased ALMA to existing mm VLBI networks, including the Global mm-VLBI Array (GMVA) and the Event Horizon Telescope (EHT) network, offers up to an order of magnitude boost in sensitivity. The geographical location of ALMA also provides a significant improvement in u-v coverage for many experiments, thereby enhancing the ability to reconstruct images of sources. In the case of the GMVA, the addition of ALMA to the array improves the north-south angular resolution by a factor of two.

As a culmination of the APP efforts, the first VLBI science campaign with ALMA was successfully carried out in April 2017, followed by a second in April 2018. The next VLBI campaign is planned in 2019 as part of Cycle 6. Objectives of the approved science programs during the first two VLBI cycles included high-resolution imaging of jets in active galactic nuclei (where the data are expected to illuminate jet formation and collimation processes) and explorations of the two closes supermassive black holes—the one at the center of the Milky Way (Sgr A*) and the one in M87 (e.g., Doeleman 2017). The latter observations, which achieve $\sim$30 μs angular resolution, enable probing these black holes for the first time on event-horizon scales. Consequently these data are expected to provide new insights into black hole accretion processes and stringent new tests of the predictions of General Relativity. Analysis of these new ALMA VLBI data sets by their respective proposing teams is currently underway.

Using phased ALMA as a "single-dish" rather than as part of a global VLBI network is also expected to enable new discoveries. For example, observations of pulsars at ALMA frequencies are poised to aid our understanding of pulsar emission processes (e.g., Torne et al. 2015; Mignani et al. 2017), and the Vela pulsar has already been detected during an ALMA Phasing System (APS) test observation using this mode (Cordes et al., 2017 and in prep.). There is hope that future searches near the Galactic Center may uncover new pulsars that can be used for relativistic tests at very high precision (Cordes et al. 2004, 2017; Eatough et al. 2015; Psaltis et al. 2016).

2. Motivation for the Cycle 4 Study

Although rich scientific returns are expected from these early mm VLBI observations with ALMA, the initial implementation of the APS offered to the general user community enables only the simplest use case, namely VLBI on continuum sources in Band 3 (3 mm) or Band 6 (1.3 mm) that are bright enough to permit phasing up the array on the science target (see M18). However, as described in a series of White Papers, the potential scientific applications of a phased ALMA are far more wide-ranging (Fish et al. 2013; Tilanus et al. 2014; Asada et al. 2017). To address these diverse science goals necessitates a variety of extensions and enhancements to the original APS.

The present ALMA NA Cycle 4 Study ("Diversifying the Scientific Applications of the ALMA Phasing System") was launched to continue laying the necessary groundwork for an APP "Phase 2" (APP-2), intended to bring additional capabilities to the APS beyond those that could be completed within the scope of the initial APP. These new capabilities are designed to broaden and diversify the scientific applications of the APS, allowing it to reach its full scientific potential. The period of performance was nominally 2016 October 1 to 2018 September 30.

Our Cycle 4 Study was a follow-on to our team's Cycle 3 ALMA NA Study "Extensions and Enhancements to the ALMA Phasing System", whose outcomes are summarized in Matthews, Crew, & Hecht (2018). Both the Cycle 3 and 4 Studies enabled a range of preparatory groundwork in anticipation of future full-scale APP-2 implementation efforts, pending the outcome of peer review and the approval of the ALMA Board of a subsequent Cycle 5 implentation proposal. This implementation effort was formally approved in late 2017 and is now funded through an ALMA NA Cycle 5 Development award. The APP-2 Development program is slated to extend through 2020 and is expected to lead to the introduction of new and enhanced ALMA VLBI capabilities during ALMA Cycles 7 and 8.

Because the work from our Cycle 4 Study naturally segues into the Cycle 5 Development program, the present report is designed to provide a "status summary" of ongoing tasks rather than a set of final results and conclusions. In the sections that follow, we summarize current results and ongoing work related to each of the three main topics covered under the Cycle 4 Study: (1) improvements in the handling of baseband delays; (2) enabling VLBI observations of weaker sources; (3) spectral line VLBI.

3. Topic 1: Improvement in the Handling of Baseband Delays

3.1. Background

During the initial phases of APP commissioning and science verification (CSV) it was recognized that while the phasing system appeared to be working nominally in Band 3, baseband 1 (BB_1), polarization X, the phasing efficiency was significantly diminished in polarization Y and in the other basebands (BB_2, BB_3, BB_4). Efficiency was seen to be further reduced in Band 6 (Matthews & Crew 2015a). This problem was ultimately traced to an aspect of the delay system that was not well documented or appreciated, even by ALMA experts. This circumstance in turn necessitated a change in the manner that the APS handles baseband delays (BBDs) in order to achieve acceptable phasing performance in all basebands, polarizations, and observing bands.

This "delay problem" is described in detail elsewhere (e.g., Matthews & Crew 2015b; M18). In brief, there is a fundamental limitation in the ability to optimize the delay corrections for recorded VLBI data that is inherent to the ALMA correlator design; namely, that all four basebands (and polarizations) share a common digitizing clock. Since the rotation of the phase of this clock is used for delay management, it is necessarily the case that only *one* polarization of *one* baseband can ever be optimally phased-up for the online recordings.

The delays corrections are handled differently for the archival science data model (ASDM) data associated with standard ALMA interferometric observations. In that case, the correction is made by the correlator data processor (CDP) processing nodes and is done as a phase-rotation operation on the correlation output visibility data. However, these corrections do not get applied to the data that are recorded for VLBI. More specifically, during normal ALMA operations, front-end delay corrections (which are stable and have typical values of ∼100-500 picoseconds) are referenced to baseband 1, polarization X in Band 3. Delay corrections for the other bands and baseband/polarization combinations are then performed in the CDP at the same time that a residual geometric delay correction ($<$15 ps) is applied. When the APS was operating, TelCal would use the data corrected by the CDP to compute a phasing solution to be applied to the tunable filter banks (TFBs). However, data *uncorrected* for the front-end delay were used to form the phased sum in the long-term accumulator (LTA) hardware. This is because the signals used for the phased sum are captured between the front end and the application of the CDP correction. This delay correction (fringe-stopping) is performed in software rather than hardware.

Because of time pressure to reach an operational capacity within the funded duration of the APP project, and in time to offer ALMA VLBI to the community in Cycle 4, the APP team devised and implemented a work-around for the underlying delay problem that involved turning off the BBD correction applied in the CDP computers so that the TelCal component of the APS could be instructed to calculate phases valid for adjustment in the TFB. Further details are described in M18 and Matthews, Crew, & Hecht (2018). While this produced a working system, the latter reference also contains a detailed discussion of some unfortunate drawbacks of the current delay system workaround. In brief, these drawbacks are: (1) phasing solutions are computed separately within several (typically eight) channel averages across each of the four basebands, effectively lowering the signal-to-noise ratio (SNR) of the phasing solutions; (2) small residual delays persist across each of the channel averages, resulting in small decorrelation losses; (3) the phasing efficiency calculations are corrupted by the lack of BBD corrections to the unphased "comparison" antennas that are present in the array during VLBI experiments; (4) the ALMA-only interferometric data obtained during a VLBI experiment require special handling (i.e., non-standard processing) to be used for science purposes.

3.2. A New Implementation of the Delay Fix

A new type of "delay fix" was devised under the current Cycle 4 Study and is presently being implemented as part of our Cycle 5 Development award. It will enable the Science Software Requirements (SSR) observing script to provide the delays to TelCal so that TelCal can do a full spectral window average. This will provide a higher SNR by a factor of $\sqrt{8}$) for the calculation of phases and in turn will allow direct phase up on weaker sources than is presently possible.

During ObsMode 7, the delay fix was identified as the highest priority task for the APP-2 team in preparation for Cycle 7, since all other future proposed APP-2 capabilities depend to some degree on its successful implementation for maximum operational efficiency. Work on the new delay fix is currently being tracked within three ICT tickets: ICT-11574, ICT-13106, and ICT-13107. Below we briefly comment on the objectives covered by each of these tickets.

3.3. TelCal Modifications (ICT-11574)

Work covered within ICT-11574 includes necessary modifications to TelCal and is being led by H. Rottmann (Max Planck Institut für Radioastronomie), in close consultation with the APP-2 team. These modifications will allow TelCal to receive several pieces of information from the SSR as "tuningParameters": (1) BBDs; (2) channel average frequencies; (3)

an indication of whether a delay present; (4) an indication of whether to use the new delay fix method or not. Item (4) is crucial, since as part of the TelCal modifications, the existing solution methods will be retained for testing and regression purposes.

With these inputs, TelCal will then be able to verify whether: (1) the expected delay is present; (2) no delay is present; or (3) otherwise. In case (1), the delay can be removed and the channel average phases averaged to provide a better phase estimate for the full band. In case (2), the data can simply be averaged. If everything is working properly, case (3) is not needed and so may be left for later implementation (deferring to the existing algorithm). After solving for the phases (of the entire band), TelCal can then restore the delay to provide good phases for every TFB or every channel average. The final outcome will be that TelCal should use the BBD information to shift all antenna phases such that they correspond to what the CDP would have produced.

3.4. SSR Modifications (ICT-13106)

ICT-13106 involves necessary changes to the SSR and is being led by G. Crew. With the updated delay fix, the SSR will need to provide several crucial pieces of information to TelCal, including: (1) the BBDs; (2) the channel average frequencies; (3) an indication of the first scan state (kept or not); and (4) expert parameter controls for testing.

During a VLBI observation, the modified SSR will query the telescope monitor and control database (TMCDB) for the BBDs and provide these to TelCal via tuningParameters. As noted above, it will also provide to TelCal in the same manner the channel average frequencies (from the spectral specification); the expected delay state for the first subscan of a sequence (e.g. "previous phases retained" or "reset the phases"); and an indication of whether to use the new delay fix method or not. VEX2VOM[1] and test scripts will need to be modified to support testing and operation for these various cases.

At start up, the SSR script will query the TMCDB and calculate the delays such as would have been applied by the CORR Spectral Processor task and pass this information to TelCal prior to observing any scans in VLBI mode. For testing and regression purposes, an ability to switch back and forth between the old delay fix method and the new method will be preserved.

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[1]VEX2VOM is a software tool designed by the APP to enable ALMA's VLBI observing mode (VOM) by marrying a VLBI schedule (in the form of a standard VLBI EXperiment or "VEX" file) with the ALMA-specific project specifications (see M18).

3.5. Possible Correlator (CORR) Modifications (ICT-13107)

As noted above, the new delay fix will improve the SNR of the phasing solutions, enabling direct phase-up on weaker sources. However, with this implementation, there will remain a small delay loss within each channel average (or TFB) that cannot be corrected. (Each channel average does a spectral average over the delay.) ICT-13107 addresses a possible solution to this issue. Specifically, the CDP spectral processing task can improve on this situation by making a phase-neutral BBF adjustment within each channel average prior to creating the averages. In the existing baseband/residual delay correction, the phase at the DC edge of the full band is preserved. In this case we want the delay correction with a phase adjustment so that the mean phase of each channel average is preserved. This possibility is being discussed with R. Amestica (National Radio Astronomy Observatory) and may be implemented in Cycle 7, if time allows. There are also changes being contemplated which may allow us to shorten the gap between subscans, which in turn may help to improve the PolConvert[2] process (the existing algorithm interpolates through the gap).

3.6. Summary and Future Prospects

The above mentioned software modifications are expected to be completed by mid-October 2018. Upon consultation with ALMA software leads, it was decided to implement the new delay fix as a patch to the current (Cycle 6) software. This will facilitate on-sky testing during the duration of Cycle 6, as it will allow APP-2 testing with the same software as being used for current Science observations. Initial on-sky testing of the delay fix (incorporating the above mentioned changes) is planned in October 2018.

A future planned modification to allow greater flexibility for spectral line VLBI (Section 5) will be to enable the SSR to instruct TelCal to ignore certain channels and assign phases to them based on adjacent channels. This will be done through an extension of the protocol of the TelCal 'tuningParameters' keyword.

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[2]PolConvert is software written by the APP Team to convert ALMA's linearly polarized data products to a circular basis during post-correlation, as is currently standard for astronomical VLBI. See Martí-Vidal (2016a, b) and M18 for details.

4. Topic 2: Enabling Phase-Up on Weaker Sources (Passive Phase-Up)

4.1. Background

As described in the previous section, the modified delay fix that is currently being implemented is expected to result in a boost in sensitivity of the APS by $\sim \sqrt{8}$. However, for sources that are still too weak for active phase-up, an alternative approach termed "passive phase-up" can instead be used. In this approach, the ALMA array is periodically phased up on a bright calibrator close in angular distance to the science target of interest (i.e., within a few degrees or less) and the computed phasing solution are then applied to the science target. During observations of the latter, the phasing system is turned off. The required cadence of the calibrator observations will depend on observing frequency and atmospheric conditions at ALMA.

4.2. Results

To date, several passive phasing tests have been performed at ALMA and shown to produced good-quality phasing results. An example is shown in Figure 1. These data were obtained during an APP CSV session in 2016 in Band 3. For this test a relatively weak polarized source, 3C138, (0.47 Jy, 7% polarized) was chosen to allow testing of the full system. A nearby bright calibrator, 0510+180 (2.3 Jy and $\sim 3^{\circ}$ away) was used to determine phases a few seconds prior to switching to the weaker source. The results are shown in Figure 1 (along with a previous scan on 0501−019). As can be seen from the actively phased targets 0510+180 and 0501−019, there was substantial scatter in the phases owing to the relatively poor weather (several mm of precipitable water vapor). Nevertheless, passive phase-up of 3C138 is clearly effective, as can be seen from the relatively small RMS scatter in the phases (indicating good coherence throughout the scan).

The passive phasing mode was also deployed during the successful observation and detection of the Vela pulsar (see Cordes et al. 2017 and in prep.). However, global VLBI fringes have not yet been obtained on a passively phased target despite multiple attempts. Current evidence suggests that this results from insufficient flux density of the "weak" targets on long baselines. We plan to further test this hypothesis by: (1) performing passive phasing tests and some brighter sources; (2) attempting passive phasing tests on the very short baseline with the Atacama Pathfinder EXperiment (APEX) telescope.

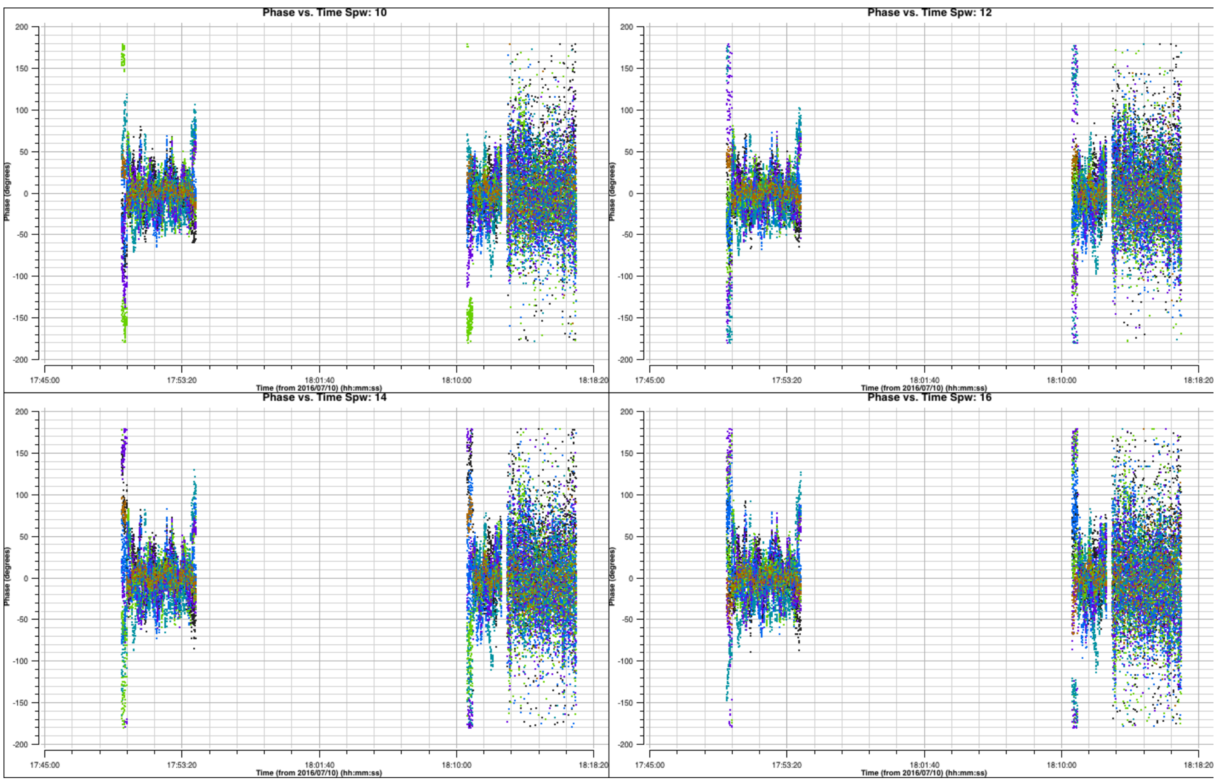

Fig. 1.— Results from a passive phasing test with the APS in Band 3, conducted in July 2016 under marginal weather conditions. Phase versus time for three scans (with gaps in time) is shown for each of the four correlator quadrants. The x-axis range spans approximately 23 minutes and the y-axis scale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

4.3. Summary and Future Prospects

Continuing work on the passive phasing mode is being tracked under SCIREQ-1440. Practical use of this capability by future ALMA VLBI users will require the following additional steps:

1. Introduction of a mechanism for observers to specify a suitable calibrator for phase-up (e.g., providing it in the proposal and the observing project).
2. Arrangements to convey to the VLBI schedulers that science targets are to be passively phased (e.g., requiring that this instruction be placed somewhere in the observing project).
3. Possible changes to the SSR to facilitate 1 and 2.

It is unlikely that the initial implementation of the passively phasing capability will provide the flexibility to allow observers to specify the observing cadence between source and calibrator. More likely, a fixed cadence will be imposed in Bands 3 and 6, along with constraints on the permissible flux density of the calibrators and the maximum permitted angular offset between calibrator and science target.

It is anticipated that the passive phasing mode will find its most common application as part of a future pulsar observing mode. This is a standalone observing mode in which phased ALMA is used as a sensitive "single dish". VLBI-mode data are recorded and used for the pulsar search, but observations at peer observatories are not needed. This mode has been successfully tested (Cordes et al. 2017) but is not yet formerly offered to the community. In contrast, the applications of passive phasing to traditional (global) VLBI are likely to be somewhat limited, since science targets too weak to allow direct phase-up of the array in many (if not most) cases will have insufficient correlated flux density on long baselines to produce a VLBI fringe. At longer wavelengths, such weak sources could be observed using the phase referencing technique (Alef 1988; Beasley & Conway 1995), but to date, phase referencing has had limited success at mm wavelengths because of short atmospheric coherence times and the added complication that many extragalactic sources become weaker and/or resolve out at higher frequencies (e.g., Porcas & Rioja 2002). This situation is expected to improve somewhat with the improved sensitivities enabled by the higher recording bandwidths that are now becoming available (Whitney et al. 2013). However, because of limited resources there are presently no plans by the APP-2 team to commission a "phase referenced" VLBI observing mode at ALMA.

5. Topic 3: Spectral Line VLBI

5.1. Background

As noted above, current APS capabilities are limited to a single continuum mode setup in Bands 3 and 6. However, a number of interesting science applications of the APS involve observations of spectral lines (see Fish et al. 2013; Tilanus et al. 2014). These include non-thermal (maser) lines observable in emission, as well as measurements of other weaker thermal lines in absorption (e.g., HCN or HCO+).

While the fundamental principles of using the APS for spectral line studies are the same as for continuum experiments, in practice, a number of modifications will be required in order to achieve the best possible performance and to produce a data set useful for spectral line science. These include:

Spectral window matching: In the case of spectral lines with extremely high brightness temperatures (i.e., masers), direct phase-up on the line emission should be possible. However, to maximize the SNR of the phasing solutions, the bandwidth of the spectral window used to compute the phasing corrections needs to be well-matched to the intrinsic linewidth, to avoid diminishing the band-averaged signal. The corrections computed from the line-containing channels should also be applied to adjacent continuum channels.

SSR modifications: Some modifications to the SSR will be needed to set up spectral line observations while still respecting ALMA baseline correlator bandwidth restrictions.

Modifications to the ALMA Observing Tool (OT): Offering a spectral line VLBI observing mode will require more flexibility within the OT, including the ability to place of lines of interest optimally within the observing band and the selection of portions of the band of interest for recording and correlation. An additional consideration is that the selected tunings need to be commensurate with the capabilities available at peer observatories, which are often considerably less flexible in their tuning options than ALMA.

Overcoming data rate bottlenecks: The ALMA correlator mode used for VOM operations provides 1920 spectral channels across each 1.875 GHz baseband, yielding a spectral resolution of ∼1.0 MHz (∼3.5 km s^{-1} at an observing frequency of 86 GHz, ∼1.3 km s^{-1} at 229 GHz). However, with four basebands being processed with full Stokes (as is required for all VLBI observations; see M18), the resulting data rates become rather high. Consequently, the ALMA single field interferometry (SFI) data are currently spectrally averaged by a factor of 8 during APS operations. Such coarse resolution is insufficient to allow meaningful analysis of spectral lines in the ALMA SFI data. Possible means to overcome this include use of alternate frequency division (FDM) correlator modes, designating a single correlator quadrant for special handling, and/or possibly limiting the number of phased antennas, N_A (i.e., exploring trade-offs in data volume, which scales with N_A, vs. sensitivity, which scales as $N_A^{0.5}$). Our investigations of this topic lead us to favor the option of reducing the spectral averaging on the baseband of interest, and further narrowing the bandwidth of that baseband channel through use of only a subset of the available TFBs.

Correlation: Under our previous Cycle 3 Study, our team developed and tested approaches to VLBI data correlation using so-called “zoom bands” (Deller et al. 2011) to account for the sampling differences between ALMA and other peer VLBI stations currently operating at 3 mm and 1 mm (see Matthews & Crew 2015c; M18). However, it will be necessary to modify this approach to enable correlation of spectral line data where the power is concentrated in select frequency channels and where final data product will require significantly higher spectral resolution. For example, fringe-fitting of the continuum data is currently done in the delay-fringe rate plane, but in the case of a spectral line where power is concentrated in the frequency domain, the delay function becomes broad and fringe-fitting may instead need to be performed in frequency-fringe rate space (Reid 1995). Further, our approach will need to be robust against the possibility of multiple peaks in the fringe rate due to atmospheric turbulence. Spectral line VLBI experts outside the core APP-2 team will be consulted on how to optimize approaches to these problems.

5.2. Future Prospects

The APP-2 team has begun exploring needed developments to enable spectral line VLBI capabilities at ALMA and discussing with relevant experts the best means of implementing this capability. Progress is being tracked under SCIREQ-1441. However, an optimized spectral line capability requires first implementing and testing the delay fix (see Section 3). It is therefore anticipated that spectral line VLBI will be introduced in Cycle 8 or later. This timeline will depend on ObsMode approval to pursue this capability, the availability of necessary CSV time on the array, and the availability of suitable peer sites for global spectral line VLBI testing and verification.

6. Study Deliverables

Our Cycle 4 Study anticipated several deliverables. The status of each is described below.

Hardware: None. No hardware was built, procured, or modified as part of this Study.

Software: This Study proposed to design and begin implementation of software modifications to the ALMA VOM as needed to overcome present system limitations and enable a wider range of scientific applications. These changes and their status are described in Sections 3 and 4.

Services: Five deliverables were proposed under this category.

(1) Recommendations for upgrades to the ALMA OT to support expanded VLBI observing capabilities. Through the ObsMode process and ICT ticket ICT-13127 the APP-2 has communicated with OT personnel regarding recommended OT updates. These include: (1) ability to schedule calibrations as needed for full polarization standard interferometry in Band 7; (2) a standard Band 7 local oscillator (LO) setup; (3) other minor fixes, such as making "Standard VLBI" a recognized mode.

(2) A memorandum that establishes flux density thresholds for operation of the APS. This memorandum remains pending, as it depends on the outcome of the on-sky testing of the delay fix software modifications to be carried out in October 2018.

(3) Tests of the APS using a "passive" phasing mode to enable VLBI on targets too weak for active phase-up. A summary of testing to date is provided in Section 3.

(4) A memorandum outlining guidelines for use of the APS in passive mode. This memorandum is pending, as it requires information from on-sky tests of the delay fix software to be carried out in October 2018.

(5) A report laying out procedures for operating the APS on spectral line targets. This task has been deferred until Cycle 8 or later (see Section 5).

A. Acronym Definitions

ALMA	Atacama Large Millimeter/submillimeter Array
APEX	Atacama Pathfinder EXperiment
APP	ALMA Phasing Project
APP-2	ALMA Phasing Project, Phase 2
APS	ALMA Phasing System
ASDM	Archival Science Data Model
BBD	Baseband Delay
CDP	Correlator Data Processor
CORR	(ALMA Baseline) Correlator
CSV	Commissioning and Science Verification
EHT	Event Horizon Telescope

FDM	Frequency Division Mode
GMVA	Global Millimeter VLBI Array
ICT	Integrated Computing Team
LO	Local Oscillator
MIT	Massachusetts Insitute of Technology
mm	millimeter
NA	North America
OT	Observing Tool
ps	Picoseconds
RMS	Root Mean Square
SFI	Single Field Interferometry
SNR	Signal-to-Noise Ratio
SSR	Science Software Requirements
TFB	Tunable Filter Bank
TMCDB	(ALMA) Telescope Monitor and Configuration DataBase
VEX	VLBI Experiment file
VOM	(ALMA) VLBI Observing Mode
VDIF	VLBI Data Interchange Format
VLBI	Very Long Baseline Interferometry

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