Atacama
Large
Millimeter
Array

Summary of the Third ALMA Phasing Project (APP) Commissioning and Science Verification Mission: 2015 July 28 - August 3

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Memorandum

To: The ALMA Community

From: Lynn D. Matthews and Geoffrey B. Crew, MIT Haystack Observatory

Date: September 14, 2015

Subject: Summary of the third ALMA Phasing Project (APP) Commissioning and Science Verification mission: 2015 July 28 - August 3

1 Background and Objectives

The third Commissioning and Science Verification (CSV) mission for the ALMA Phasing Project (APP) was carried out during the ALMA Extension and Optimization of Capabilities (EOC) Week from 2015 July 28 - August 3. Summaries of the first two APP CSV campaigns (hereafter the January and March campaigns, respectively) can be found in ALMA Technical Notes 16 and 17.[1].

The primary objective for the third APP CSV campaign was to perform intercontinental Very Long Baseline Interferometry (VLBI) fringe tests between phased ALMA and remote stations in Band 3, Band 6, and (conditions permitting) Band 7. Secondary objectives included preparations for making the APS available to the community for ALMA Cycle 4 and training ALMA staff in the operation of the ALMA Phasing System (APS).

At the time that planning for the July-August campaign began in early June, the APP team had already successfully obtained VLBI fringes between ALMA and the Atacama Pathfinder Experiment (APEX) telescope in Band 6 (see ALMA Technical Note 16). However, ALMA was effectively operating as a single antenna during those tests (i.e., the array was unphased). Furthermore, as described in the APP's formal CSV plan, obtaining fringes on this short (∼2 km) ALMA-APEX baseline is considered to be only a first step in commissioning a capability intended for regular use on baselines of up to several thousand kilometers. For example, it important to establish that VLBI fringes can be obtained routinely in both Bands 3 and 6 and that it is possible to operate successfully in conjunction with partner sites employing heterogeneous VLBI backends. In addition, only VLBI tests with three or more partner sites allow phase and amplitude closure tests, which offer important checks on system performance. Furthermore, APEX recorded only a single circular polarization, whereas dual polarization VLBI data sets are required to fully test the PolConvert software (Martí-Vidal et al. 2014)[2] developed by the APP team to handle the "mixed" polarization signals obtained on baselines between ALMA (which records dual

[1] https://almascience.nrao.edu/documents-and-tools/alma-technical-notes/
[2] http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=230

linear polarizations) and other VLBI sites (which typically record single or dual circular polarizations).

During the March campaign, several minutes of Band 6 VLBI data on a calibrator source had previously been recorded on baselines between phased ALMA and three other remote sites. The other sites were recording as part of an Event Horizon Telescope (EHT) experiment. (ALMA was not formally part of the EHT campaign, and the ALMA CSV data were not shared with the EHT project). However, despite a successful fringe detection on the baseline been ALMA and the IRAM 30-m antenna in Spain, the March observations were too limited in scope to fully satisfy APP commissioning needs (see ALMA Technical Note 17 for details).

2 Personnel

APP personnel on site during the 2015 July-August CSV campaign included Geoffrey Crew and Lynn Matthews (MIT Haystack Observatory) and Alejandro Saez (JAO). The ALMA Science lead during the week was Gianni Marconi. The APP team was also assisted during the mission by Akihito Hirota, who was on site to support ALMA EOC activities. Hirota had been previously designated as an APP contact for aiding in the implementation of VLBI scheduling blocks (SBs).

APP team members Jay Blanchard (University of Concepción) and Alan Roy (Max Planck Institut für Radioastronomie; MPIfR) supported coordinated operations at APEX (see below). The APP also received observing support at other remote sites from colleagues at the National Radio Astronomy Observatory (NRAO), the Smithsonian Astrophysical Observatory (SAO), Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), and MPIfR. Finally, Vincent Fish (MIT Haystack) provided support remotely in the preparation of VLBI observing schedules.

3 Resources and Set-Ups Employed

3.1 Software Release

The APP used software release 2014-6-B during the July-August mission, the same release that was used for most ALMA EOC activities during the week. In contrast to the two previous APP CSV campaigns, this avoided the necessity of switching software versions when executing APP tests, helping to increase efficiency and scheduling flexibility.

3.2 Antennas

The configuration of ALMA antennas during the July-August mission contained maximum baselines of up to $\sim$1.6 km. Arrays comprising up to 42 antennas were used by the APP for testing. However, for reasons described below, the bulk of the APP data during the July-August mission were taken with an array of 8 or fewer antennas.

3.3 Remote VLBI Stations

Partner sites for the series of VLBI experiments to be conducted during the mission were arranged several weeks in advance. To enable Band 3 (3 mm) VLBI testing, the APP submitted a Director's Discretionary Time proposal to the Very Long Baseline Array (VLBA) and was awarded 4 hours of coordinated VLBA observing time. A comparable time allocation for Band 3 work at Effelsberg was also awarded through the MPIfR.

Because weather conditions across continental North America and Europe are generally unfavorable for observing at $\lesssim$1 mm-wavelengths during the northern hemisphere summer, stations in Hawaii were deemed the most promising partner sites for long baseline tests in Bands 6 and 7. Consequently, the APP negotiated two four-hour sessions with both the Submillimeter Array (SMA) and the James Clerk Maxwell Telescope (JCMT), respectively,[3] through Director's Discretionary Time. Finally, 10 hours were allocated on APEX through the combined contributions of MPIfR and the University of Concepción.

3.4 Time Allocation

In total, approximately 25 hours of ALMA time (inclusive of down time) were devoted to APP CSV activities and APP-related testing during the July-August EOC week. These included a total of approximately 15 hours used for a series of four coordinated VLBI campaigns (see §4). Approximately 10% of these activities were conducted during engineering time, and the remainder were during EOC time.

3.5 Observing Targets

Observing targets selected for the mission comprised bright quasars selected from the ALMA Source Catalogue and the SMA Calibrator List, along with two well-known Galactic SiO maser stars. Positions for the two maser sources were taken from the SIMBAD database and corrected for the stellar proper motion using the corrected *Hipparcos* proper motions given in SIMBAD.

3.6 Data Collected

Approximately 28 GB of standard ALMA interferometry (ASDM) data were collected in Bands 3, 6, and 7, and $\sim$27 TB (per quadrant) of VLBI-mode data were recorded simultaneously.

4 Summary of Activities and Results

4.1 Initial Testing and Preparations

A few days prior to the campaign, a remote check-out of the Mark 6 VLBI recorders at the Operations Support Facility (OSF) led to the discovery that regression tests performed on

[3] The JCMT does not currently operate in Band 7.

July 8 had produced no recorded VLBI data. The cause was found to be an outdated VLBI Data Interchange Format (VDIF) epoch used by the cplane/dplane code. (The underlying issue has been repaired in a new version of cplane/dplane to be released and installed at ALMA later this year. In the meantime, the problem can be solved operationally with a restart of cplane each semester.)

VLBI schedules and VEX files for ALMA and all other participating sites were prepared prior to the start of the mission (with the exception of those used for the Band 7 observing; see §4.8). As of the July-August mission, VLBI observing at ALMA is still executed in a "manual" mode, with the VEX file used only as a guide to scheduling. Efforts by the APP are underway to produce a VEX2VOM software tool that will translate standard VLBI VEX files into SBs that can be executed in a manner analogous to standard ALMA SBs, as will be demonstrated later this year.

A one-day travel delay incurred by Crew and Matthews resulted in the cancellation of planned software testing and Cycle 4 preparatory work using the SCO2 simulator in Santiago prior to the start of the mission.

4.2 Baseline Correlator Issues

Following the arrival of Crew and Matthews at the OSF, a one-hour session was scheduled for the morning of July 29 (06:30-07:30 CLT) to allow regression tests of the phasing system, verification of the planned frequency set-ups, and other useful checks prior to the first VLBI session. Unfortunately, ongoing problems with the baseline (BL) correlator forced cancellation of these tests.

Later that afternoon, the ALMA engineering team implemented a fix to the correlator in the form of an increase in the timeout related to the TMCDB access of the CAI map. Subsequent regression tests by the engineering group showed that this resolved the fundamental problem. However, the origin of the problem was still unidentified, and this change increased the amount of time required to set up all observing modes.

Correlator-related problems persisted during the remainder of the EOC week. For example, longer-than expected delays occurred when standard commands were issued (e.g., pointing or focusing sequences or the execution of normal scans), resulting in significantly increased setup times and overheads. For the APP, this meant that a number of planned VLBI scans had to be skipped to allow adequate time to complete routine pointing and system temperature ($T_{\rm sys}$) measurements during the session. Correlator restarts were required several times during both APP and EOC activities, and in several instances, a "cleanup" command was required at the start of an APP session before execution blocks would run successfully.

4.3 Session 1: Band 6 VLBI Fringe Tests with APEX, SMA, and JCMT

The first coordinated VLBI session of the July-August mission was carried out on July 30 from 07:00-11:00 UT. In addition to ALMA, participating sites included the SMA, JCMT, and APEX. All observations were conducted in Band 6 (1.3 mm). The targets comprised four bright quasars chosen to have good mutual visibility from Chile and Hawaii: 0006-063, 1924-292, 2232+117, and 3C454.3. These targets had expected flux densities at 1.3 mm between $\sim$2–12 Jy.

Because none of the peer stations were capable of matching the data rate of ALMA, during VLBI testing it would have been sufficient to record the output of only a single ALMA correlator quadrant (1.875 GHz bandwidth, with dual linear polarizations). However, data from all four quadrants, identically tuned to a central sky frequency of 227.122 GHz, were recorded to afford redundancy and more complete testing of the APS hardware and performance.

The APP team was granted access to the ALMA array 30 minutes prior to the start of the session to perform standard set-up and start-up procedures. An array of 42 12-m antennas was defined, 39 of which were assigned to the phased array, and 3 of which were designated as unphased comparison antennas.

Because of the extra overheads that resulted from the correlator issues described above (§4.2), VLBI recording on the source 1924-292 did not begin at ALMA until 07:16 UT. At that time, the weather was clear and the precipitable water vapor (PWV) at the Array Operations Center (AOC) was $\sim$1 mm. Only the slow phasing loop was used for most of observations executed during this session (i.e., no water vapor radiometer (WVR) corrections were implemented via the fast phasing loop), but during one 5-minute execution block, both the fast and the slow loop were tested.

Soon after the start of the session, it became clear from inspection of spectra on the CorrGUI that a significant fraction of the ALMA data were being severely compromised. In particular, as each 5-minute execution block progressed, the phases in many of the cross-correlation spectra began to exhibit abrupt and time-varying phase jumps at the boundaries of the 32 individual tunable filter bank (TFB) channels that span each baseband. The jumps were often, but not always, of magnitude $\pi/2$. These patterns were seen to change between subscans, sometimes partially "recovering" (as a result of the phasing corrections being applied by the APS) before becoming corrupted again (Figure 1).

The team was alerted that some firmware changes had been implemented since the previous APP phasing tests several weeks earlier, so an attempt was made to revert back to an older version of the firmware. However, this had no effect on the observed behavior.

4.4 Diagnosing the Cause of Data Corruption During the First VLBI Session

Immediately following the conclusion of the first VLBI session, logs and CAN commands generated during the session were examined, and several test observations were performed with the goal of isolating the cause of the data corruption that affected the preceding session. Through these investigations, it was recognized that the problem appeared to be linked somehow to the station cards. Among the groups of four antennas that share a single station card, the cross-correlation spectra were seen to behave consistently normally. Furthermore, examination of the data in CASA showed that it was possible to divide the station cards into four groups such that baselines between antennas within each group were well-behaved, while baselines between antennas in different groups exhibited the type of behavior shown in Figure 1. This suggested that the different station cards were not getting their delay updates synchronously. However, the root cause was not clear.

It was recognized that the above problem could potentially be related to issues raised one month earlier in the ICT JIRA ticket ICT-5401. As discussed in that ticket, the phases applied to the TFBs as a result of the APS calculations should remain in effect until updated by the PhasingController. However, test data obtained by the APP team following the March mission (2010 April through 2015 June) often displayed phase and amplitude glitches at the start of scans.[4] Discussion of this new station card-related behavior was subsequently added to the ICT-5401 ticket, as it was hythothesized that the two effects might be linked.

4.5 System Temperature Measurements

Measurements of $T_{\rm sys}$ during Session 1 and the remainder of the APP campaign were performed by running periodic DelayCal measurements (in FDM mode). This approach was adopted after it was discovered that sensible values of $T_{\rm sys}$ were not being produced by TelCal whenever a CALIBRATE_ATMOSPHERE command was executed as part of an APS observation. It was later determined that the cause of this is that the first integration of a calibration subscan is automatically flagged by the on-line system to safeguard against possible movement of the calibration device at the start of each subscan. However, since each subscan of a standard APS observation presently contains only a single integration, all of the calbration data ended up flagged. A workaround will require increasing to 4 integrations per subscan for future APS operations.

4.6 Session 2: Additional Band 6 VLBI Fringe Tests with APEX, SMA, and JCMT

A second VLBI session involving ALMA, the SMA, and APEX was scheduled for July 31 from 07:00-11:00 UT. The original plan was to carry out this test in Band 7 (0.87 mm), weather permitting. However, owing to concerns about the data quality from the first VLBI session, coupled with predictions of marginal weather conditions in Hawaii, a decision was made to observe once again in Band 6. As a result of this change, the JCMT (which does not have a Band 7 receiver) was also able to join the session. Targets and frequency setups were the same as for Session 1.

As a way of mitigating the problems encountered during the first VLBI session, ALMA was initially operated with an array of only four antennas, all sharing a single station card. Because of larger than expected start-up overheads, VLBI recording at ALMA during the second session did not begin until 07:40 UT.

After monitoring the behavior of the 4-antenna array for a short time, four more comparison antennas (all sharing a second station card) were added to the phased array, for a grand total of 8 antennas, 7 used as part of the phased array. These two sets of four antennas had been seen to be part of a synchronized group during the previous session.

[4] Additional illustrations are available at https://ictwiki.alma.cl/twiki/bin/view/Control/AppNonMissionCommissioning03.

With these concessions, the type of data corruption seen during Session 1 was largely eliminated, although the session was plagued by other problems. A correlator crash necessitated a full system restart, and two attempts were required to restart the correlator software. In several scans it was observed that both the autocorrelation and cross-correlation data were identically zero, analogous to a problem seen during the March campaign (see Figure 3 of ALMA Technical Note 17). Finally, occasional scans were corrupted by what had previously been termed a "porcupine" pattern in the cross-power spectra—so-called because of the appearance of amplitude surges at the boundary of each TFB. This problem was reported by the APP during both the January and March missions and is documented in ICT-4815 (see also Figure 5 of ALMA Technical Note 17). Despite the various issues, valid VLBI data were recorded during Session 2, and scans were obtained when all four participating stations were believed to be operating successfully.

A special DelayCal test run in frequency division (FDM) mode was executed later in the day in an attempt to diagnose the cause of the porcupine pattern, but it failed to reproduce the problem. However, that same DelayCal observation (uid://A002/Xa72573/X6c2), which was performed with an array of 21 antennas, *did* exhibit time-varying patterns of phase jumps on TFB boundaries, analogous to those seen during VLBI Session 1. This firmly established that these events are not unique to the VLBI mode observing and were not being caused by APP software, hardware, or firmware.

4.7 Session 3: Band 3 VLBI Fringe Tests with the VLBA and Effelsberg

The Band 3 (3 mm) VLBI session with the VLBA was slated to be triggered on one of three nights during the EOC week, depending on weather forecasts for the North American stations. Ultimately, the session was scheduled on August 1 between 06:00-10:00 UT. This UT range was selected as providing the most favorable odds of stable weather conditions at all of the various stations.

The targets consisted of the bright quasars 3C454.3 and 1924-242 and the SiO maser sources VX Sgr and *o* Ceti. Both 1924-242 and VX Sgr remained at rather low elevation for most of the VLBA stations; however, this was considered an important feasibility test for future VLBI observations of the Galactic Center and other southern sources using ALMA in combination with Northern Hemisphere sites. Effelsberg also participated in this session; however, only one of the four targets (3C454.3) was mutually visible from Northern Europe during the observing window.

Weather conditions at ALMA were extremely stable and dry (suitable for Band 10 observing, with PWV$\sim$0.4 mm), although conditions were less optimal at some of the VLBA sites. Nonetheless, useful data were obtained at six of the eight VLBA stations that were equipped with 3-mm receivers. (Kitt Peak did not observe because of issues with electronics, and the Pie Town data were compromised by pointing problems).

ALMA operated with an array of 8 antennas (7 phased) for the bulk of the session. Because of an operator error, an array was initially created with 12 antennas instead of 8. This array was tested during the initial scan, but was quickly seen to exhibit the types of phase instability issues first seen during Session 1, hence it was necessary to create a new array with only 8 antennas.

The band centers of all four ALMA quadrants were set to ν_0=86.268 GHz during the entire session. Both the VLBA stations and Effelsberg recorded smaller maximum bandwidths than ALMA (512 MHz), but as during the first two sessions, all four ALMA quadrants were recorded for redundancy and testing purposes. In the case of the VLBA, the digital down-converter (DDC) personality of the ROACH digital backend (RDBE) was selected, and two 128 MHz channels (dual polarization) were tuned to be contiguously centered on ν_0. This set-up simplifies the problem of correlation of the ALMA-VLBA baselines despite their differing sampling rates (see §4.10). Furthermore, these tuning choices place the SiO $v = 1$, J=2-1 maser line away from band edges and TFB boundaries for most Galactic sources.

No other major problems occurred during the remainder of this session, and the APS appeared to be operating normally.

Examination of data obtained for the two SiO line sources confirmed that the masers were bright at the epoch of the observations (several Jy or more) and permitted confirmation that the APS frequency specifications were being commanded correctly. Those data also demonstrated the feasibility of phasing up on a bright line source without any modifications to the standard "continuum" mode of operation of the phasing system (Figure 2).

4.8 Session 4: Band 7 VLBI Fringe Tests with APEX

Following the VLBI sessions described above, two more hours remained available at APEX for APP activities. Two one-hour sessions were therefore scheduled to perform additional VLBI testing with ALMA at 19:00-20:00 UT and 21:30-22:30 UT on August 1.

The separation between the two sessions was inserted to allow better parallactic angle coverage of the two selected targets—the polarization calibrators 3C279 and 1337-129. Good parallactic angle coverage is important for PolConvert testing (see §1), but was difficult to obtain in the other VLBI sessions owing to the large east-west separation between participating sites (which in turn is not conducive to tracking sources for extended time periods).

Because of the dry and stable conditions, it was decided to perform these tests in Band 7, a first step in demonstrating future phasing capability at higher frequencies than dictated by current APP requirements.[5] At the start of the tests, ALMA Engineering had a significant fraction of the ALMA antennas in use, hence the APP was limited to an array of 5 antennas (3 phased). The band centers of all four ALMA basebands were set identically to 341.050 GHz.

During the first of the two sessions, APEX experienced serious issues with phase stability of their Band 7 receiver as well as pointing problems. A clock offset also affected their first four scans. Thus it appears unlikely that this data will be useful for the intended parallactic angle coverage work on PolConvert.

One additional ALMA issue documented during the Band 7 VLBI tests were frequent instances of scans with "zero" autocorrelation data. Subsequent to the VLBI sessions, a

[5] Band 7 operation was part of the original APP plan, but later descoped. It is relevant as well to a pending ALMA Study Proposal proposal and to providing additional information for characterizing the performance of the phasing system.

series of additional DelayCal tests were run in FDM mode in an attempt to trigger and diagnose this problem, but it was not reproduced during those tests. Reproducing the bug in DelayCal is an important diagnostic to isolate potential issues between the mode and software used for VLBI/Phasing activities and normal ALMA observing modes. (For example, the LTA cards are programmed slightly differently in VLBI mode to correlate with the sum antenna signal via CAI 63. Equally, the setup for subscans is different in VLBI mode because of the phase adjustments. On the other hand, the correlator data processor (CDP) processing software is identical for non-sum antennas, so issues with the autocorrelation are likely to be due to common failure modes.)

4.9 Solving the Station Card Synchronization Problem

4.9.1 Initial Tests of a Sofware Patch

On August 1, further investigation of the problem via the (engineering) diagnostic port of the CAN bus concerning the lack of station card synchronization revealed that a rogue APPLY_CONFIGURATION command was being issued at the start of each scan, something that is unnecessary when nothing in the configuration is changing. However it had been thought harmless to apply, and there were other sub-array development reasons for doing so. Furthermore, it was found that no associated SYNCHRONIZE command was issued to the station cards, and the APPLY_TFB_PHASES command was not being applied following APPLY_CONFIGURATION. These problems are consistent with the types of data corruption experienced during Session 1.

On August 2, the ALMA software group provided a patch that was hoped would eliminate the ongoing problem with station card synchronization–basically to remove the potentially offending APPLY_CONFIGURATION command. Testing of this patch later that day produced phasing results that initially appeared promising, but upon closer inspection still appeared to show a significant degree of corruption. An analysis of the system logs showed many strange things happening that have not been fully explained to date.

4.9.2 Additional Testing During the August 25 EOC Week

On August 26, during the next EOC week following the July-August mission, additional testing was performed in which the unneeded "APPLY" commands identified during the testing on August 1 (see §4.9.1) were eliminated. This testing grew out of a similar problem found in sub-array testing (one sub-array in time division (TDM) mode with another in FDM mode). That problem was resolved by firmware changes related to configuration change processing and removal of the spurious APPLY_CONFIGURATION command which was in effect exercising the firmware bug. Subsequent tests with an array of 10 antennas on August 26, and 27 antennas on August 27, show that this fix appears to have entirely eliminated the station card synchronization issue that plagued the July-August mission (Figure 3). The problem of phase and amplitude "glitches" at the start of scans seen during various test observations several weeks prior to the July-August campaign also appears to be eliminated.

4.10 Correlation of VLBI Data

Following the July-August mission, disk modules from one of the four Mark 6 recorders were shipped to Haystack. (Data from the other 3 quadrants are redundant and are, at present held in the recorders as protection against potential data losses in shipment.) Selected APEX VLBI scans had also been copied onto these disks prior to shipping.

At the time of this writing, no attempts have been made to correlate data from either the Band 6 or 7 VLBI tests owing to time constraints. Part of the reason is that the SMA data must be resampled due to the current operational mode of the SWARM correlator, and that is likely to take a few weeks to work out. It is expected that this work will be carried out at Haystack later in 2015. Initial analysis efforts following the mission were focused instead on the Band 3 data, since the VLBA data modules needed to be copied by the APP team and returned to NRAO within a week of their reception at Haystack, at which point the disks would be recycled for new experiments.

Approximately two weeks after the July-August mission, the disk packs from each of the VLBA sites were first shipped to the NRAO in Socorro for correlation of the VLBA-only baselines. The NRAO is presently unable to play back data from the Mark 6 generation of recorders used at ALMA and hence could not process the ALMA baselines. However, this initial pass at correlation permitted identification of the subset of VLBA stations that obtained useful data. It also produced a standard FITS data set for examination within AIPS, and generated other plots and information that are produced by default for VLBA observers for use in the post-correlation analysis. The FITS data were used to provide quick checks on data quality and frequency specifications.

Following correlation of the VLBA baselines in Socorro, the disk packs from the six useful stations were shipped to Haystack for copying, followed by commencement of an e-transfer of a copy of the data to Bonn. It is anticipated that Bonn will perform the full correlation of the ALMA, VLBA, and Effelsberg Band 3 data. However, in advance of this, some correlation tests were performed at Haystack, primarily to verify data integrity and derive necessary clock settings.

Initially, short segments of data from a few selected VLBA baselines were correlated at Haystack using Haystack's copies of the data. These results were compared against the data products produced in Socorro. The results were found to be identical, providing a check on the integrity of the copied data (Figure 4).

Subsequently, attempts were made to obtain fringes on baselines between ALMA and the six usable VLBA stations for a 5-minute scan on the bright quasar 3C454.3. Zoom bands were employed with the DiFX software correlator to handle the differing sampling rates of ALMA compared with the VLBA stations. Fringes were readily detected on baselines between ALMA and all six of the functioning VLBA stations (Mauna Kea, Hawaii; Brewster, Washington; Owens Valley, California; Fort Davis, Texas; North Liberty, Iowa; see Figure 5). *This marks the first time that VLBI fringes have been detected using ALMA in Band 3.*

5 Ongoing and Future Work

As noted above, the Band 3 VLBI data are now being transferred to Bonn where a full correlation of all four target sources will be undertaken for all of the baselines between ALMA, Effelsberg, and six of the VLBA stations. Correlation of the Band 6 and 7 experiments will be carried out at Haystack. Following correlation, several types of analyses will be carried out with these data sets, including examination of phasing efficiency, closure phases and amplitudes, and imaging. These data will also be used to develop a set of guidelines and prescriptions for post-correlation calibration and processing of VLBI data involving phased ALMA.

Tests of the PolConvert software using a small portion of the data from the Band 3 observations is ongoing. Results from this analysis will be presented in a separate memorandum. Finally, the APP team is awaiting an opportunity some time later in 2015 to perform additional testing of the phasing system with a full complement of antennas (>50) to insure that performance requirements are met following the recent updates that eliminated ongoing problems with phase corruption caused by unsynchronized station cards (see §4.4 and §4.9).

Given the issues with correlator during this campaign (which limited us to a very small phased array), we anticipate that at least one more session in each of Bands 3 and 6 will be required to complete an analysis suitable for the full verification of phased ALMA VLBI data.

6 Summary

A series of VLBI campaigns was carried out during the third APP CSV mission in 2015 July-August. These tests permitted intercontinental fringe tests between phased ALMA and several independent stations in Bands 3 and 6. Band 7 VLBI fringe tests were also performed on the short baseline between phased ALMA and the APEX antenna. Successful Band 3 fringes have been detected between phased ALMA and six antennas of the VLBA. Correlation of the remaining data is ongoing.

The mission was impacted by ongoing problems with the BL correlator, which led to a $\sim$25% loss in observing efficiency. In addition, a portion phased ALMA data, as well as other unphased FDM mode data taken during the mission were severely compromised by time-varying phase jumps at the boundaries of the individual TFB channels. These errors were unrelated to the APS itself, and their cause was identified during the mission as arising from a lack of synchronization between the signals from different station cards that occurred only during FDM mode observations. To mitigate the impact of this problem on APS observing, it was necessary to limit APS observations to array sizes of no more than 8 antennas for most of the mission.

Following the July-August mission, the origin of the station card synchronization problem was fully diagnosed and solved. Subsequent phasing tests have shown that the entire APS now appears to be functioning as expected for arrays of up to at least 27 antennas. Tests with larger arrays are pending.

Additional information on the July-August APP CSV mission is available on the mission wiki page: https://ictwiki.alma.cl/twiki/bin/view/AppMissionChileCommissioning04.

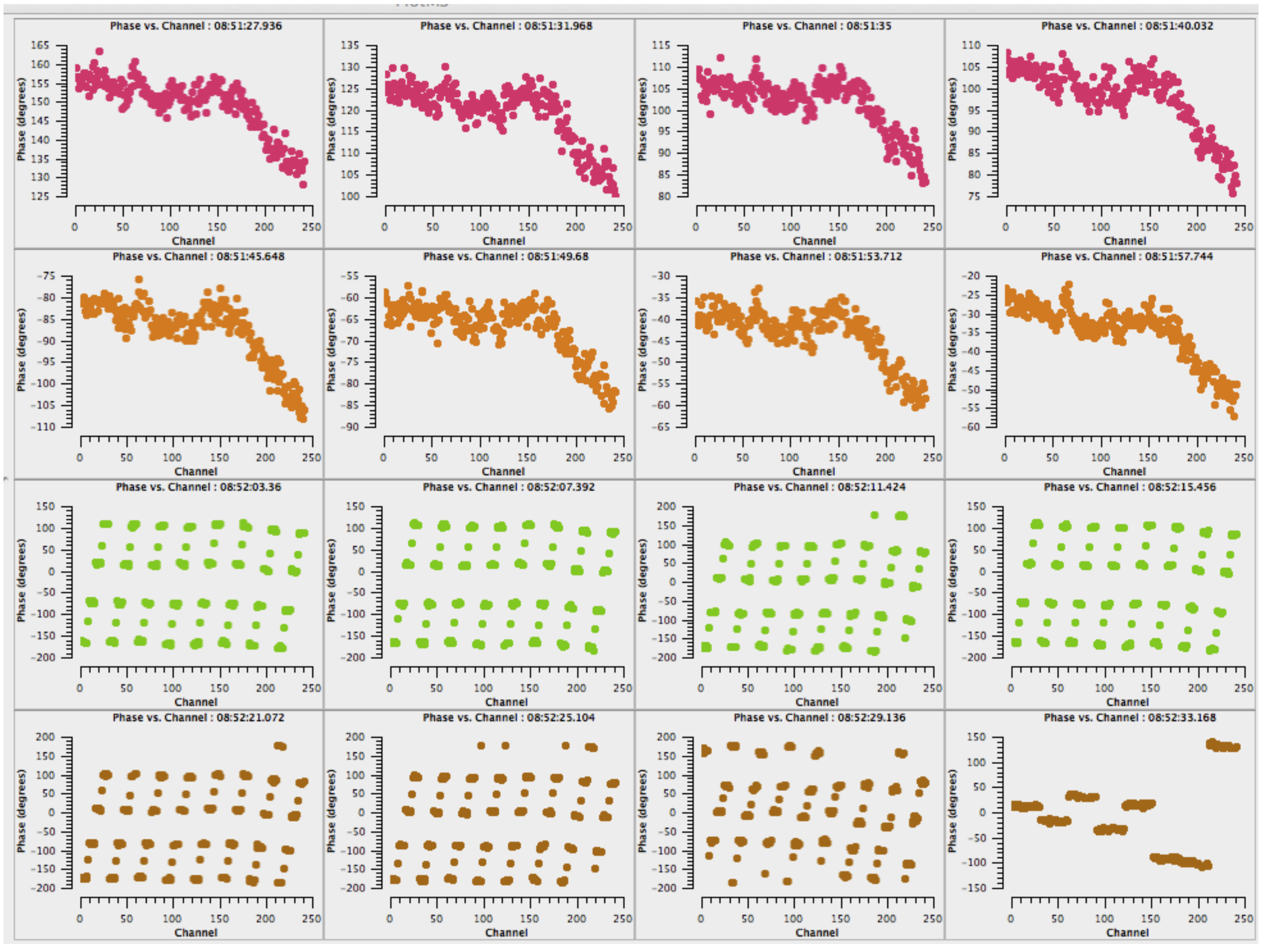

Figure 1: Examples of corrupted cross-power spectra obtained during Band 6 APS observations of the quasar J2253+1608 on 2015 July 30. Data are shown for a baseline between antennas DA44 and PM03 within a single baseband (baseband 1) and a single polarization (YY). Each row shows four consecutive subscans comprising a single 12-second scan. The first four scans of the 5-minute observation are plotted. During the third and fourth scans, the phases become severely corrupted and exhibit abrupt jumps at the boundaries of individual TFB channels. In the lower right panel, the phases appear to partially "recover" as a result of the phasing corrections that were computed and applied independently to each one-eighth of the band. However, the phases once again become fully corrupted in subsequent scans (not shown). Data source: uid://A002/Xa7118c/X317.

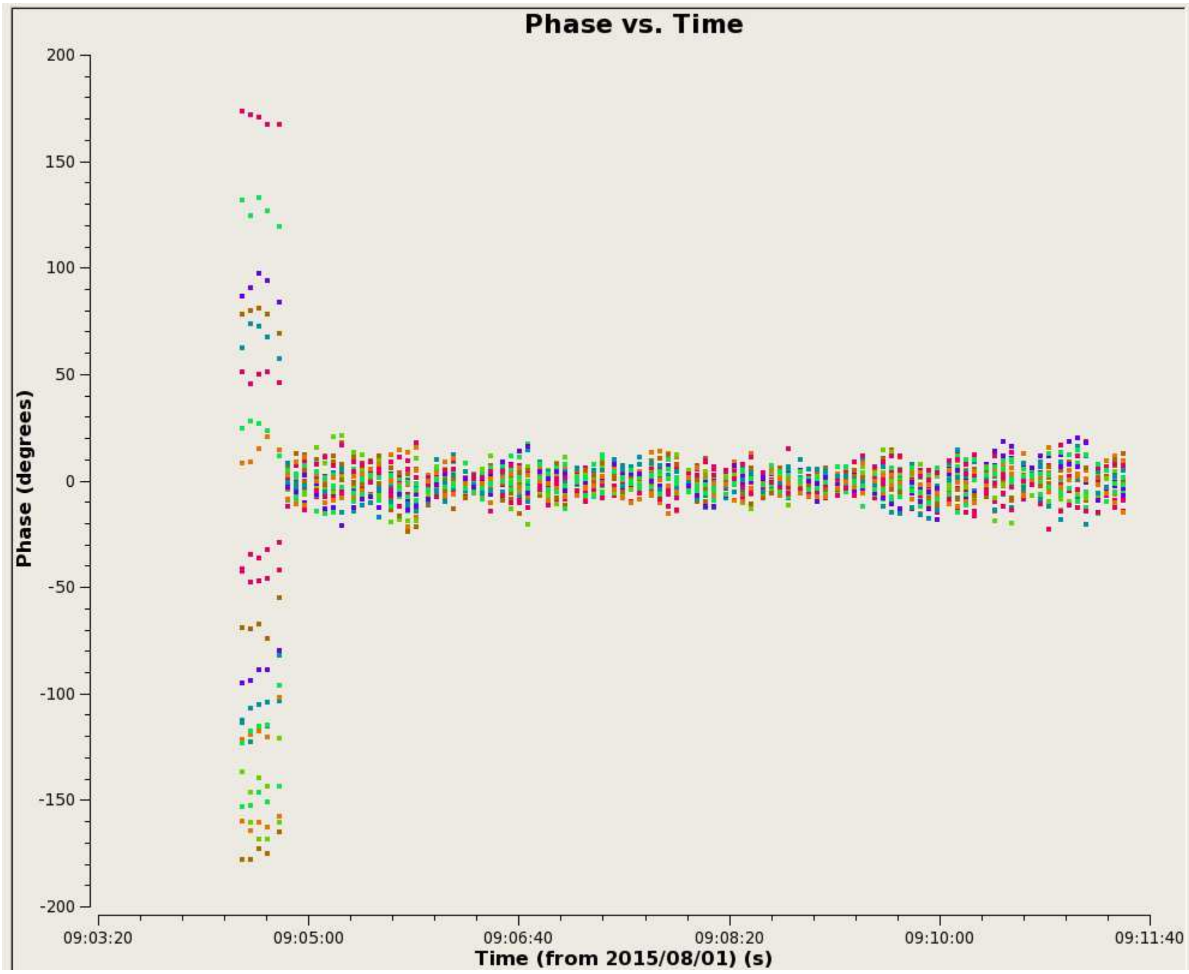

Figure 2: Phases as function of time during a ∼7-minute Band 3 observation of the SiO maser source *o* Ceti, obtained on 2015 August 1. Data for baselines between the seven phased ALMA antennas are plotted in different colors for the XX polarization in baseband 1. Eight channel averages were computed across the 1.875 GHz baseband, but only the data from the channel average containing the line emission (centered at 85.447199 GHz) are shown here. The tight convergence of the phases toward zero demonstrates that phase-up can be readily achieved on a strong line source even when the default APS "continuum" observing set-up is employed. Data source: uid://A002/Xa72fea/X297.

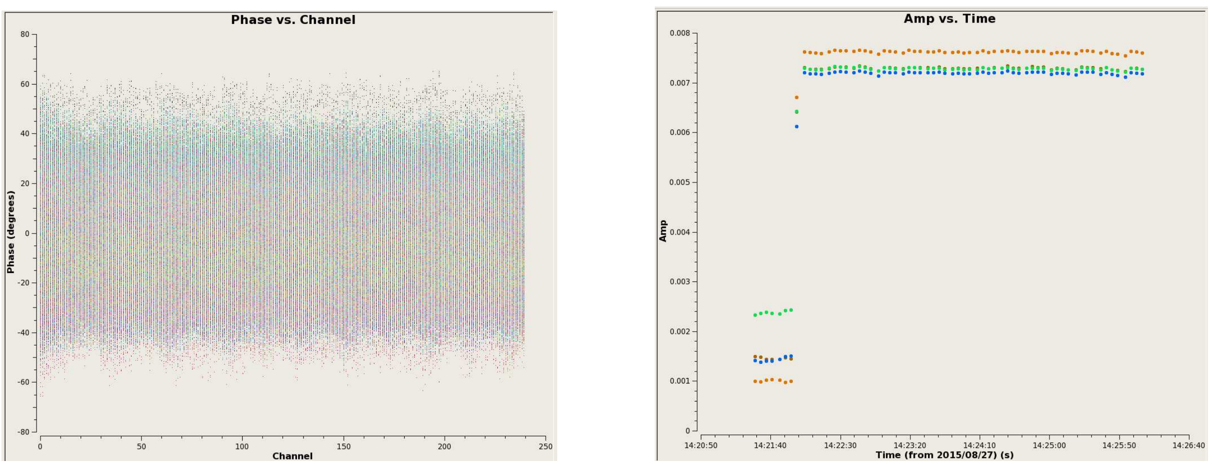

Figure 3: Band 3 observations with the APS obtained on 2015 August 27 using an array of 27 antennas (25 of which were phased). Approximately 4 minutes of data are shown. The *left panel* shows phase as a function of channel number for all of the baselines between antennas used in the phased sum. All four basebands and both the XX and YY correlations are plotted together. The synchronization errors between antennas on different stations cards have now been eliminated, along with the resulting phase jumps between TFB channels (cf. Figure 1). The *right panel* shows correlated amplitude as a function of time for a baseline between the phased sum "antenna" and the unphased comparison antenna DA52. Data for the four basebands (XX polarization) are indicated by different colors. The correlated amplitude shows the expected increase by approximately the square root of the number of phased antennas ($\sqrt{N_{\rm A}} = 5$) following phase-up. This plot also confirms the elimination of previously seen "glitches" (drops in amplitude) at the start of each 16-second scan. Data source: uid://A002/Xa8fb82/X41.

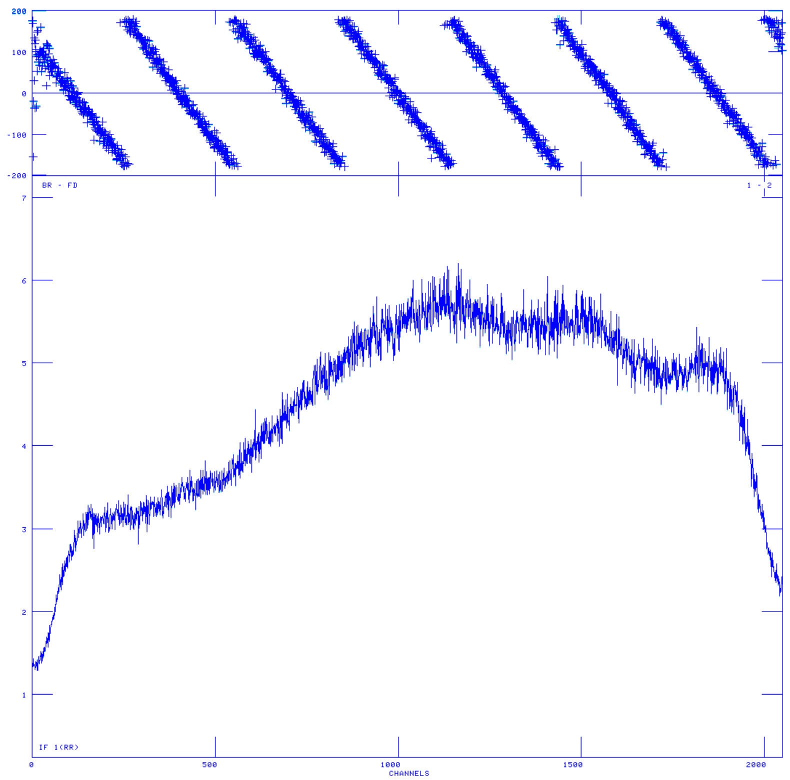

Figure 4: Sample cross-correlation spectrum for the source 3C454.3 on a baseline between the Brewster and Fort Davis VLBA stations. The top (bottom) panels show phase (amplitude) as a function of channel number over a 128 MHz band. The version of the data correlated by NRAO is shown in blue; a version correlated at Haystack (based on a copy of the raw data made at Haystack) is shown in turquoise. The two plots are virtually indistinguishable, rendering the turquoise points nearly invisible; this demonstrates the robustness of the copied data and the correlation procedures being employed at Haystack.

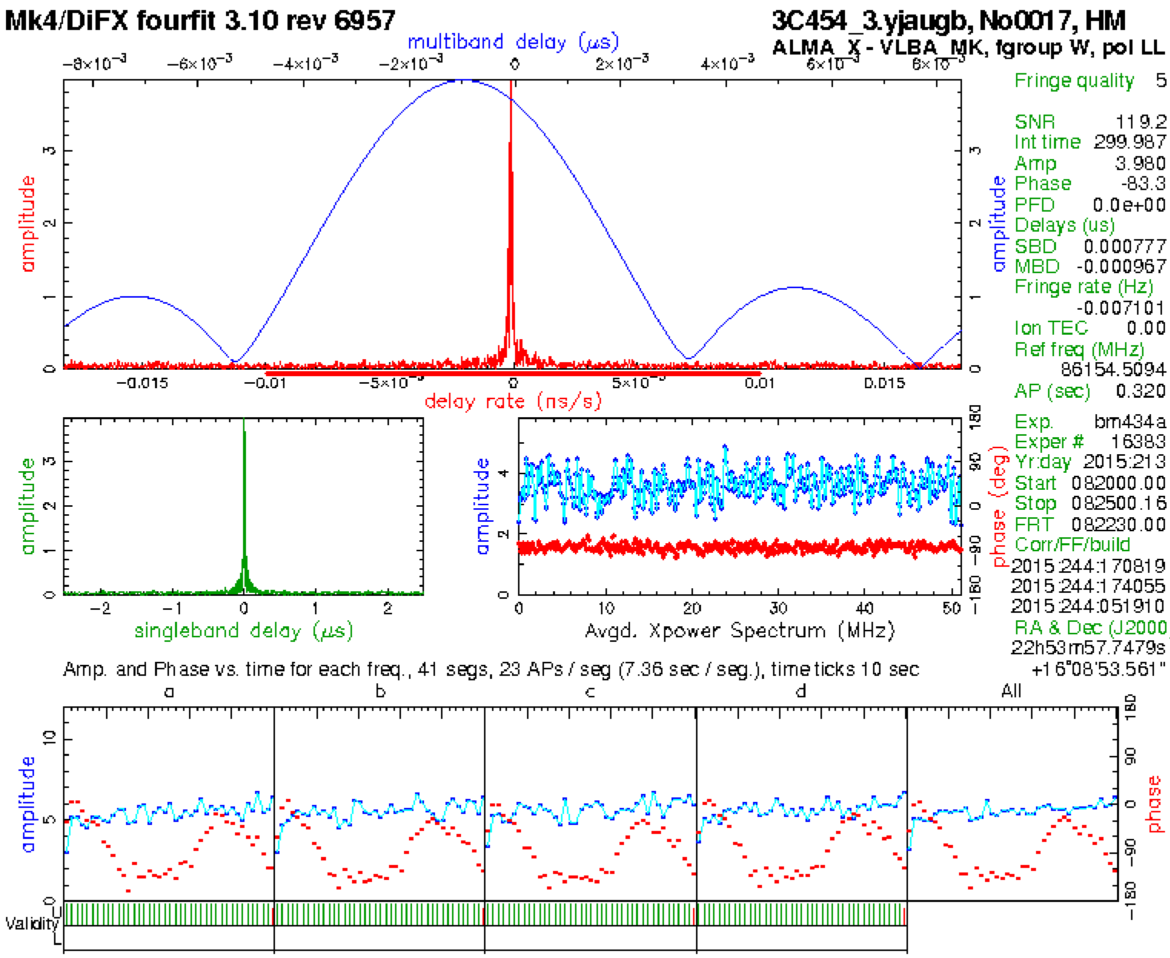

Figure 5: Band 3 (3 mm) VLBI fringe detection on 3C454.3 on a ∼6600 km baseline between phased ALMA and the VLBA antenna on Mauna Kea (MK), Hawaii. The data were obtained on 2015 August 1 at 08:20 UT with seven 12-m antennas in the phased ALMA array. The X polarization data from ALMA is correlated against the L polarization data from MK. Approximately 300 seconds of data are shown. The high signal-to-noise ratio (>100) is evident from the clear peaks in the delay rate (red curve, top panel), in the single-band delay (green curve, center-left panel) and in the multi-band delay (blue curve, top panel). The center-right panel shows amplitude (blue) and phase (red), averaged over all baseband channels at a resolution of 100 kHz. (The correlation was performed at 3.125 kHz resolution). The lower plot shows amplitude (blue) and phase (red) as a function of time for each of the thirty-two 51-MHz frequency channels. (The wings of the 62.5 MHz ALMA TFB channels were not included).