Atacama Large Millimeter Array

Summary of the Fourth ALMA Phasing Project (APP) Commissioning and Science Verification Mission: 2016 April 3-8

ALMA Technical Note: Number 19
Status: Final

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Memorandum

To: The ALMA Community

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Date: March 28, 2017

Subject: Summary of the Fourth ALMA Phasing Project (APP) Commissioning and Science Verification mission: 2016 April 3-8

1 Background and Objectives

The fourth Commissioning and Science Verification (CSV) mission for the ALMA Phasing Project (APP) was carried out during the dates of April 3-8, 2016. Descriptions of prior APP CSV campaigns can be found in ALMA Technical Notes[1] 16 through 18 and references cited therein.

The primary objectives of the fourth APP CSV campaign were twofold: (1) to execute Very Long Baseline Interferometry (VLBI) observing mode (VOM) observations using Schedule Blocks (SBs); (2) to carry out the first end-to-end testing of intercontinental VLBI sessions in both Bands 3 and 6. While intercontinental VLBI fringes with ALMA have already been obtained during previous CSV campaigns (Matthews & Crew 2016b, c), those sessions were not conducted in a manner identical to future VLBI science campaigns (i.e., they used manual execution of observing commands rather than SBs) and did not involve observations of a full suite of ALMA and VLBI calibrators. Secondary objectives of the fourth CSV mission included further development work on an ALMA Phasing System (APS) graphical user interface (GUI), additional testing of the fast phasing loop (under a wider variety of weather conditions), tests of the phasing system in Band 7 (in support of an ongoing North America ALMA Study award), and the training of ALMA staff in the operation of the VOM and the APS hardware and software.

At the time of the fourth CSV mission, proposal calls announcing the availability of the APS for VLBI observations in Cycle 4 had already been issued. Despite this, critical aspects of APS operations necessary for successful VLBI science campaigns had not yet been fully commissioned. These included:

- Operation of VLBI-mode observing using SBs generated with VEX2VOM.[2]

[1]https://almascience.nrao.edu/documents-and-tools/alma-technical-notes/

[2]VEX2VOM is an APP software tool that translates information from a standard VLBI Experiment (VEX) file (including information about VLBI sites, scan timing, and other ancillary information) into information needed to successfully execute the VLBI Observing Mode (VOM) at ALMA.

- Successful execution of a full >3-hour[3] VLBI session, including observations of all necessary ALMA and VLBI calibrators.
- Full (post-correlation) testing of the PolConvert software (Martí-Vidal et al. 2014, 2016a, b) to convert ALMA's linearly polarized correlation products into circular polarizations.
- End-to-end calibration and analysis of a VLBI data set that includes phased ALMA as a VLBI station.

2 Personnel

APP personnel on site during the April 2016 CSV campaign included Geoffrey Crew and Lynn Matthews (MIT Haystack Observatory), Helge Rottmann (Max Planck Institut für Radioastronomie = MPIfR), and Alejandro Saez (Joint ALMA Observatory = JAO). The ALMA Science lead during the week was Lars-Åke-Nyman (JAO). The APP team received additional on-site support during the mission from Violette Impellizzeri (JAO), who has been designated as ALMA's "Friend of VLBI", and Akihito Hirota (JAO), who had been previously designated as the APP's contact for assistance with the implementation of VLBI SBs.

The APP was also supported by colleagues stationed at other remote sites, including Effelsberg (operated by MPIfR), the Submillimeter Array (SMA; operated by the Smithsonian Astrophysical Observatory), the James Clerk Maxwell Telescope (JCMT; operated by the East Asian Observatory), the Heinrich Hertz Submillimeter Telescope (SMT, operated by the University of Arizona), and the Large Millimeter Telescope (LMT; operated by the University of Massachusetts, Amherst and the Instituto Nacional de Astrofisica Óptica y Electronónica). Lastly, Vincent Fish (MIT Haystack) was responsible for preparation of VLBI observing schedules.

3 Resources and Set-Ups Employed

The observations were prepared with the Cycle 4 Observing Tool (OT), which had just been released for the Call for Proposals, in the same manner as planned for Cycle 4 science projects. For the VLBI sessions, a "science" target was selected (i.e., a relatively bright quasar of flux density 1-2 Jy), along with a suite of VLBI and ALMA calibrators of the type needed to conduct a fully calibrated VLBI science experiment.

3.1 Software Release

The APP used software release R2015.8 during the mission. This release had only limited on-sky testing by ALMA staff prior to the time of the campaign and had not been tested

[3]The minimum duration of a VLBI session is set by the requirement to obtain adequate parallactic angle coverage on a polarization calibrator in order to enable robust conversion of the ALMA data from linear to circular polarization (Martí-Vidal et al. 2016a, b).

at all in the FDM correlator mode used for APS operations. Because ongoing ALMA Cycle 3 science observations required an earlier software release, all APP activities during the mission necessitated a software switch. This procedure results in $\sim$1 hour of downtime during which ALMA cannot observe.

3.2 Antennas

The ALMA antennas were in configuration C36-2/3 during the mission, providing baselines between 15 m and 460 m. Arrays of up to approximately 40 antennas (including both 12-m and 7-m antennas) were used by the APP for testing.

3.3 Remote VLBI Stations and Observing Dates

Partner sites for the series of VLBI experiments to be conducted during the mission were arranged in advance. For 1.3 mm (Band 6) VLBI testing, the APP coordinated with the Event Horizon Telescope Consortium (EHTC), which was conducting a science campaign during dates overlapping with the APP CSV mission. Stations participating in the 1.3-mm network included the LMT in Mexico, the SMA and JCMT in Hawaii, and the SMT in Arizona. However, only two of these sites were able to participate in VLBI during ALMA CSV time (see Section 5.6).

To enable 3 mm (Band 3) VLBI testing, the APP submitted a Director's Discretionary Time proposal to the National Radio Astronomy Observatory (NRAO) for time on the Very Long Baseline Array (VLBA). This proposal was awarded 4 hours of coordinated VLBA observing time (program BM452A). Unfortunately, because of poor weather at ALMA, this program could not be executed during the mission. A make-up observation was scheduled on 2016 July 10. Results from that campaign will be described in a future ALMA Technical Note. Despite the postponement of the VLBA session, a 4-hour Band 3 VLBI test session was executed between ALMA and Effelsberg on 2016 April 5. However, it did not result in the detection of VLBI fringes (see Section 6.1).

3.4 Time Allocation

In total, approximately 30 hours of ALMA time were devoted to APP CSV activities and APP-related testing during the April 2016 campaign. Approximately 30% of these activities were conducted during engineering time, and the remainder were during regular ALMA science time. However, a large fraction of the "science" time used by the APP was in fact during intervals when the weather was unsuitable for carrying out any of the ALMA science programs in the Cycle 3 observing queue.

3.5 Observing Targets

VLBI targets selected for the mission comprised well-known bright (>1 Jy) quasars and other compact sources from the ALMA Source Catalogue that are known to be unresolved on scales of the longest ALMA baselines. Standard ALMA calibrators (including phase, bandpass, flux, and polarization calibrators) were also observed as part of the global VLBI sessions.

3.6 Data Collected

Approximately 480 GB of standard ALMA interferometry (ASDM) data were collected in Bands 3 and 6, and ∼6 TB (per quadrant) of VLBI-mode data were recorded.

4 Background: Known Issues Leading Up to the Mission

As described in Matthews & Crew (2015c), a problem with the ALMA station cards impacted the quality of the phasing data obtained during the last major APP CSV campaign in July/August 2015. A solution to that issue was subsequently identified and implemented in late August 2015 (see http://ictjira.alma.cl/browse/ICT-5401). Following that fix, APS data acquired during test sessions executed by JAO staff in late August and early September were found to be of excellent quality, with high phasing efficiency (≥90%; Crew & Matthews 2015).

On November 11, 2015, some additional observations with the APS were carried out by JAO staff to test a software modification that enabled implementation of 16 or 32 spectral windows (spws) across a single baseband instead of the previously permitted maximum of eight.[4] Two observations of several minutes duration were obtained in Band 3 on the bright quasar 1924-292. There were 38 antennas in the array, 37 of which were phased. Baselines ranged from ∼250 m to ∼ 14.2 km.

Examination of the data sets obtained on November 11 displayed poor phasing quality despite what should have been satisfactory Band 3 observing conditions. Figure 1 shows phases as a function of time for all baselines between phased antennas for one of the data sets. Properly phased data should show all points clustering near zero phase. Instead, the phases are seen to scatter throughout the range ±180° for nearly the entire observation.

Figure 2 shows the behavior of phase versus time for several baselines plotted individually. Inspection shows that upon phase-up, the dispersion in the data points (caused by phase offsets between the individual spws in each baseband) drops markedly. However, instead of converging near zero, the corrected phases in all four basebands cluster near a seemingly random phase, after which the phases drift with time. This behavior is seen on all baselines despite the continuous application of phasing corrections.

We performed additional off-line tests in CASA, computing corrections to the phases using a single phase-only iteration of self-calibration. Solution intervals as coarse as 60 seconds dramatically improved the phases, suggesting that neither the weather nor the long baselines alone could fully account for the behavior in the raw data.

Our next opportunity to examine data acquired with the APS did not occur until March 2016, at which time data were taken by JAO staff for the purpose of testing VLBI SB

[4] See http://ictjira.alma.cl/browse/ICT-4656.

execution. Observations were again performed in Band 3. In this case, the array contained 45 antennas, 37 of which were phased. Baseline lengths ranged from 15 m to 460 m.

Poor phasing quality and drifting of phases with time were again seen in those data. Figure 3 shows phase as a function of baseline length for all pairs of phased antennas. Only for the few shortest baselines do the phases lie near the expected values near zero. For longer baselines, not only does the phase dispersion increase, but points appear to be preferentially absent from the region around zero phase. This behavior suggests that the phases are not merely random (as would occur, for example, if the phasing system were turned off, or the weather were extremely unstable), but instead that either invalid corrections are being applied, or else that the corrections are someone being systematically corrupted. However, no log messages that implied incorrect commanding or missed phasing applications were found. Since no part of the phasing software was modified following the successful phasing observations in September 2015, this suggests that the computed phasing corrections are being corrupted elsewhere in the signal chain.

Subsequent APS observations obtained during the same March 2016 session showed further deteriorating phasing behavior. Examination of the phase as a function of frequency for these data revealed phase wrapping and steep phase slopes, indicative of delay errors. Furthermore, these slopes changed as a function of time (Figure 4).

In an attempt to diagnose the source of the problem, further tests on the data was performed in "off-line" mode—i.e., by manually applying the phasing algorithm on the newly obtained ALMA data sets. In the event the phasing software had simply not been operational during the real-time observations, this off-line processing should have resulted in well-phased data. Instead, these tests showed that while the phasing software could sometimes find correct-looking solutions post facto, at other times, both the raw and off-line corrected data looked poor.

Several noteworthy changes occurred at ALMA between mid-September 2015 (when phased data were seen to be of excellent quality) and the next APS test on November 12, making it challenging to diagnose and isolate the source of the recurring phasing issues. First, ALMA began a switchover from 32-bit to 64-bit computing systems. Second, they switched python version from 2.6 to 2.7. Finally, the November 12 test was the first APS test performed with software R2015.8 instead of R2015.6. While in principle, regular regression testing of the APS by ALMA staff would have helped to pinpoint any ALMA updates that produced changes in the behavior of the phasing system, in practice, such regression tests were largely precluded during Cycle 3 because of the different software version requirements for APS operations compared with normal science operations. There were a number of debugging investigations launched, with no "smoking-gun" explanation for the problems. In particular, the Data Capture and Delay systems were checked over thoroughly. At the time of this memo, these behaviors remained unexplained. Importantly, they did not appear again subsequently, including APS data taken in July 2016 or January 2017.

5 Summary of Activities and Results During the April 2016 CSV Campaign

Upon arrival, it quickly became clear that it would not be possible to run the project SBs directly from the Archive in a dynamic/interactive array as was originally envisaged, and which had already been demonstrated in simulation during the previous December. The issue was related to the hand-over of the Archive software from Cycle 3 (for operations) to Cycle 4 (for new proposals); the SBs in question were not (yet) compatible with the Archive available in the Cycle 4 software candidate. Fortunately, the SSR testing harness included a script to execute an SB as found in a disk file (e.g., SchedBlock1.xml), so it was straightforward to run this script with a manual array.

5.1 April 3: Standalone ALMA Testing

Because of the issues we had seen leading up to the April mission (Section 4), we began on the morning of April 3 with a series of VLBI regression tests and DelayCal measurements at ALMA using the Cycle 3 software release (R2016.6) and both TDM and FDM correlator modes. During these tests, which included a phased array of 25 antennas, a fairly large dispersion in the phases was seen (Figure 5). However, this appeared to be consistent with the weather conditions [$\sim$3 mm of precipitable water vapor (PWV) and quite unstable], and we saw no clear evidence for the types of behaviors seen during tests between November 2015 and March 2016 (Section 4). This tentatively suggested that the earlier problem(s) were linked with software release R2015.8, although we did not obtain sufficient data with the Cycle 3 release to establish this with certainty.

Later in the afternoon of April 3, a switchover from the Cycle 3 software to R2015.8 was performed, and the APP Team carried out a series of tests over the course of several hours. These were standalone ALMA tests (i.e., no other VLBI sites were recorded). Tests included:

- An initial regression test in the Cycle 4 candidate.
- Variation of the total number of antennas in the array, as well as the number and types of of antennas designated for phase-up, to assess impact on phasing quality.
- The execution of calibrator scan measurements as part of a VLBI SB.

Phasing behavior appeared acceptable during the initial regression test scan. However, in subsequent observations, evidence was seen that DelayEvents (DGCK) were not being properly applied. (Subsequent detailed investigation of the DGCK logs turned up no obvious errors, and so the issue is either un-logged bugs, or weather, with the latter appearing most likely.)

In some of the subsequent observations, phase slopes as a function of frequency were present in data obtained on ALMA calibrators, indicating a problem with the application of delays. It was determined that the restoration of the baseband delay (BBD) was not being done prior to the final polarization calibrator scans in the ALMA calibrator ("calalma") sequence. A revision was subsequently made to the way ALMA-specific calibrations were handled in order that the BBDs would get properly reset. [The default BBD corrections are not applied during APS operations (i.e., are not applied during VOM scans; see Matthews & Crew 2015b), but are applied during the ALMA calibrator observations taken during a VLBI session with ALMA.]

Despite this fix, in subsequent scans taken with the VOM, we continued to see generally sub-optimal performance by the phasing system, even in scans where the array size and number of phased antennas were reduced. Signatures of delays issues were also seen during some of the VLBI scans (e.g., Figure 6). No obvious problems were seen in the corresponding CDP logs, suggesting that the issues were most likely weather-related.

5.2 April 4: More Standalone ALMA Tests

Additional standalone ALMA testing of the APS was undertaken on April 4. The APP team was granted an extended session during the afternoon (engineering time) and continuing into the evening because the weather was unsuitable for executing any of the queued Cycle 3 science projects. The types of APS tests performed were similar to those on the previous day, including additional tests of the observing script to insure that it would not skip key calibrator observations because of timing issues. A forecast for poor weather at ALMA led to the postponement of the scheduled 3-mm VLBI tests with the VLBA and Effelsberg until April 7 (but see Section 5.3).

5.3 April 5

Despite postponement of the 3-mm VLBI session with the VLBA, staff at Effelsberg agreed to record a VLBI session with ALMA during a 4-hour window from 07:00-11:00 UTC, providing a useful "dress rehearsal" of end-to-end VLBI operations.

Conditions at Effelsberg were poor, with high humidity and drizzle (PWV$\sim$18 mm). PWV at ALMA ranged from $\sim$5-6 mm during the session, but conditions were nonetheless quite stable. The ALMA array included 40 antennas (both 7-m and 12-m dishes), 33 of which were part of the phased array.

At ALMA, preparations for the VLBI session got underway approximately two hours before the scheduled start time of the VLBI recording. The R2015.8 software was already active, so no software change was needed. However, several issues were encountered upon start-up. First, for unknown reasons, the system failed to accept the first manually-defined antenna array. Subsequently, a correlator reset was required. The timing of the phasing interface cards (PICs) was found to be off by 48 ms initially, and both PICs associated with correlator quadrant 4 were unresponsive.

Once these issues were resolved and all systems were operational, standard focus and pointing operations were performed. However, because of the earlier issues, the first VLBI SB was launched slightly late (i.e., $<$15 minutes before the first VLBI scan). This caused the observation of the ALMA polarization calibrator to be skipped over. Steps were taken to prevent this from occurring in future executions, since the polarization calibrator measurements are critical for performing the linear-to-circular polarization conversion of ALMA data for all APS observations, even those where the science objectives do not involve polarization measurements (see Section 7).

Following this series of start-up issues, the April 5 session with Effelsberg allowed successful testing of the option to record only select correlator quadrants (in this case, quadrant 1) instead of all four quadrants. This recording option will be exercised during Cycle 4 science observations, since during Cycle 4, no other VLBI partner sites will match ALMA's total bandwidth. [We note, however, that even when only select quadrants are recorded in VLBI mode, data from all four quadrants are still present in the standard interferometry data (SFI) from the ALMA correlator and will be present in the ALMA ASDM file.]

Examination of ALMA SFI data from the first ALMA-Effelsberg VLBI scans in near-real time showed good phasing behavior, although it was discovered that the associated CalAppPhase.xml table was missing entries for various subscans. This was found to be related to the fact that some of the subscans during the session were never processed. A subsequent investigation revealed that this was caused by a combination of two factors: (1) creation of the metadata took too long for some of the scans[5]; (2) the WVR calibration scan prior to each VLBI scan encroaches on the first subscan. Minor adjustments to the SSR script quickly solved this latter problem, and the metadata bug has since been fixed.

In all, approximately one hour of good data was obtained during the early part of the VLBI session before a series of software problems disrupted the remainder of the session. One issue was that "exceptions" were being periodically reported to TelCal by the pointing software. It was recognized that this could be mitigated in the future by increasing the value of "MaxPointingSeparation" to avoid automatic pointing after every large slew (since default ALMA pointing is sufficient for VLBI observing, particularly in Band 3).

Following the VLBI session with Effelsberg, additional ALMA-only testing was performed during the afternoon, including installation of some software patches. Plans were also made for Band 6 VLBI tests during the morning of April 6, in concert with the EHT. However, later in the afternoon of April 5, weather conditions deteriorated at the ALMA high site. Precipitation was reported, and operations were shut down around 17:00 local time (20:00 UTC). Operations resumed $\sim$30 minutes later, but worsening conditions (freezing fog and sleet) led to the ALMA dishes being stowed for the night at around 23:00 UTC. The planned Band 6 VLBI session was consequently postponed until April 8.

5.4 April 6: Simulated Band 6 VLBI

Owing to the shutdown status of the array, a Band 6 VLBI schedule was exercised in simulation mode during the early morning hours of April 6. (In this mode, actual receiver noise is recorded, but the antennas do not point). Two of the four SBs that comprised the full schedule were successfully executed, after which the test was terminated. No aborts were encountered, but the ALMA polarization calibrator was not "observed". It was found that this was because the polarization calibrator that had been selected through a "query" was no longer observable. To avoid this issue in the future, the decision was made that the ALMA calibrators should be specified explicitly in the ALMA OT rather than being selected through queries at the time of observation.

[5] See http://ictjira.alma.cl/browse/ICT-7124.

5.5 April 7: Simulated Band 3 VLBI

The late afternoon/evening hours of April 6 exhibited a repeat of the weather pattern of the preceding day, namely increasing clouds and humidity, culminating in freezing fog conditions after sunset. This led to another shutdown of the Array during the early morning hours of April 7, forcing a cancellation of the scheduled 3-mm VLBI session with the VLBA.

During the shutdown, a portion of the 3-mm VLBI schedule was run in simulation mode (see Section 5.4). A time-out error occurred upon the initial start-up, but this was eliminated by reducing the array size from 59 to 40 antennas. The cause of this issue remains unresolved at the time of this writing, but it appears to occur only during the use of simulated mounts (see http://jira.alma.cl/browse/PRTSIR-9441).

5.6 April 8: Band 6 VLBI Session with the EHT

A four-hour Band 6 (1.3-mm) global VLBI session was carried out on the morning of April 8 (local time). Because of weather (rain) and equipment issues (problems with receiver stabilization), respectively, the SMT and JCMT were unable to participate, leaving the LMT and SMA as the two available partner sites.

The nominal schedule ran from 07:00-11:00 UTC, but the ALMA schedule was launched approximately 35 minutes prior to this to perform pointing checks and execute ALMA-specific calibrations, including observations of gain, bandpass, polarization calibrators in standard (non-VLBI) mode, as well as system temperature (T_{sys}) measurements. The first ALMA SB was launched on time and without any issues.

Weather at ALMA at the start of the session was nominal for Band 6 (PWV$\sim$2.2 mm and relatively stable). The ALMA array contained 39 antennas, 37 of which were part of the phased array. The SMA and the LMT sites both reported good weather and no major technical problems during the session. The SMA recorded 5 phased dishes in dual polarizations, along with two single dishes in opposite polarizations.

6 Correlation

Following the April 2016 mission, the modules containing $\sim$6 TB of recorded ALMA VLBI data were shipped to Haystack and arrived in late April. The subsequent correlation and analysis of these data is described in the sections that follow.

6.1 Band 3

The Band 3 scans involving ALMA and Effelsberg were copied off the disk modules and transferred electronically from Haystack to Bonn in late May 2016. W. Alef (MPIfR) subsequently reported that a zero baseline correlation between the two backends at Effelsberg produced fringes, confirming that the telescope was able to see the target sources despite the poor weather at that site. However, no fringes were found between Haystack and Effelsberg during multiple correlation attempts in late May and early June 2016.

It was subsequently discovered that the Band 3 frequency settings at ALMA did not match the intended values owing to improperly specified “weighting” values in the spectral specification. (Strictly speaking, this is an OT bug, but it has been resolved in VEX2VOM by updating the Band 3 weights.) The underlying problem is that the frequencies of the four bands may not be arbitrarily, independently assigned, and the configuration provided to the LO system did not specify which band *mattered*. The fix was to weight the band being recorded as 100% and downgrading the others to smaller values.

As of this writing, further fringe searches have not been attempted with the ALMA-Effelsberg data, as efforts instead were focused on the multi-baseline Band 3 VLBI data set obtained in 2016 July. Results from the July Band 3 tests will be described in a forthcoming ALMA Technical Note.

6.2 Band 6

6.2.1 Fringe Detection

The Band 6 global VLBI data obtained during April 2016 mission were correlated at Haystack using the DiFX software correlator (Deller et al. 2007). “Zoom bands” were used to compensate with the sampling difference between ALMA and the other EHT sites (Deller et al. 2011). Fringe-fitting was subsequently performed using fourfit, a component of the Haystack Observatory Postprocessing System (HOPS).[6] A full report on the correlation procedures used for the Band 6 data will be described in a forthcoming memorandum by one of us (GBC).

High signal-to-noise ratio fringes were obtained on multiple sources between phased ALMA, the LMT, and the SMA in both the “lo” and “hi” bands (e.g., Figure 7). These two bands are centered at 227.1 GHz and 229.1 GHz, respectively, each with a total bandwidth of 1.8 GHz. At the SMA site, fringes were obtained between ALMA and both the phased SMA array and an independent SMA reference antenna.

Following the initial fringe detection, B. Corey (MIT Haystack) computed an improved site position for ALMA of X =2225061.55210 m, $Y = -5440056.66740$ m, $Z = -2481685.66880$ m which was then used during a re-correlation of the data. There was no obvious improvement in the quality of the results, implying there may still be residual errors in positions for all of the sites of up to $\sim$1 meter.

7 Polarization Conversion

The April 2016 global VLBI experiment represented the first ALMA VLBI experiment during which a full suite of calibration measurements was obtained. This data set therefore enabled the most complete testing and evaluation to date of the PolConvert software developed by the APP team for the purpose of converting ALMA’s linear polarization products to circular polarization (Martí-Vidal et al. 2014, 2016a, b). PolConvert is run post-correlation, and for future ALMA VLBI science programs, this processing step will be

[6]http://www.haystack.mit.edu/tech/vlbi/hops.html

performed for each Principal Investigator (PI) by ALMA staff as part of the QA2 process prior to the delivery of the VLBI data to the PI.

Results of the PolConvert testing performed with the April 2016 data are described in detail in Martí-Vidal et al. (2016a) and will not be repeated here. In short, this crucial calibration procedure is now fully operational (e.g., Figure 8).

8 Band 6 VLBI Data Analysis

A preliminary analysis of the Band 6 VLBI data from the April 8 experiment was performed by one of us (VLF), primarily using tools available in HOPS. A summary of some initial findings is provided below. While some of these findings merit follow-up investigation with future data sets, no issues were identified that are expected to have a significant impact on the scientific usefulness of the data. Indeed, the overall data quality from the experiment is found to be consistent with design requirements of the APS and suitable to meet the science requirements of Cycle 4 VLBI observers.

Phase-Up: It was found consistently across all scans that the first 3 or 4 seconds of data on ALMA baselines have much lower correlation coefficients ("amplitudes") than the rest of the scan. This suggests that for optimal observing efficiency, the phasing loop should be started approximately 5 additional seconds earlier than it was during this experiment. This adjustment has now been implemented.

Dropouts: On many scans (e.g., Figures 9), the correlation coefficient on ALMA baselines is seen to dip significantly for short periods of time. During these "dropouts", the correlation coefficients become progressively lower over a period of 15–35 seconds before rather sharply recovering. As these drops occur simultaneously on the ALMA-LMT and ALMA-SMA baselines, it is clear that the effect originates at ALMA. This behavior indicates a deterioration of the phasing efficiency, the most likely explanation for which appears to be atmospheric effects (e.g., highly variable opacity).

Examining the phase as a function of time for baselines between phased ALMA antennas during the scans shown in Figures 9, it is seen that indeed, scatter in the phases is high at the times corresponding to the "dropouts" in VLBI data (Figure 10). Furthermore, it can be seen in that the quality of the phasing is a clear function of baseline length; phasing efficiency is consistently high for baselines shorter than 50 m (Figure 10, left), but shows much greater variation for baselines >150 m (Figure 10, right). This trend is further underscored in Figure 11, which plots phase as a function of u-v distance for the same scans.

Late Starts: During a handful of scans, ALMA got off to a late start. In the example shown in Figure 12, it appears that ALMA was completely off source for nearly the first minute, then was unphased for a while, and then phased up. Indeed, running fourfit on the ALMA-LMT baseline over the first 45 seconds fails to find a fringe, while running fourfit over the last 45 seconds finds the fringe with SNR >420. Both the ALMA-LMT and

ALMA-SMA baselines are affected, but not the LMT-SMA baseline (for which the SNR over the first 45 seconds is 11.7).

Delay/Rate Drifts: When fourfit is used to find a fringe, the algorithm looks for a single value of the residual multiband delay and a single value of the residual delay rate to fit the data. However, these values are seen to be changing on ALMA baselines. When fourfit is restricted to run individually on each of the 32 channels across the 1.8-GHz band, it locks in on different values of the delay rate (Figure 13). Alternatively, if fourfit is run on all channels but restricted to consecutive 10-second segments of the data, it locks in on different values of the multiband delay. In both cases, the trend is linear.

These two effects are manifestations of the same underlying issue. A *delay* is a change of phase with frequency: $\partial\phi/\partial\nu$, while a *delay rate* is a change of phase with time: $\partial\phi/\partial t$. The fact that there is a drift in the residual multiband delay with time indicates that $\partial/\partial t(\partial\phi/\partial\nu) \neq 0$. Likewise, the change in the residual delay rate with frequency indicates that $\partial/\partial\nu(\partial\phi/\partial t) \neq 0$.

We do not see evidence that these second-order partial derivatives are zero on non-ALMA baselines. However, the effect is subtle, requiring both very high SNR and very large spanned bandwidth to be noticeable.

Linear drifts of delay rate with channel are apparent on a number of high-SNR scans on ALMA baselines (Figure 14). The plotted scan is typical of these drifts, showing an increase of approximately 3×10^{-9} μs/s from one end of the ~ 1.8 GHz frequency band to the other. This produces a small but noticeable effect, which will produce a corresponding small loss of amplitude.

9 Progress on Secondary Objectives

Tests of a prototype python-based APS GUI designed by H. Rottmann were performed during the mission and demonstrated the promise and utility of such a tool. Such a GUI is envisioned to provide status on various aspect of VLBI and APS operations, as well as to offer some online commanding capabilities to adjust APS operations in real time (e.g., changes in the specification of which antennas to include in the phased array). Based on experience gained, updates and improvements to the GUI will be implemented and tested during future observing sessions, subject to the availability of funding for the APP team.

Poor weather conditions during the mission precluded planned testing of the phasing system in Band 7 and further testing of the fast phasing loop. Neither of these capabilities will be offered during ALMA Cycle 4, and this work will be rescheduled as opportunities allow.

10 Summary

A successful 4-hour Band 6 (1.3 mm) global VLBI session with phased ALMA was carried out in April 2016 as part of APP CSV. To the extent possible, all aspects of the observations were carried out in a manner identical to what will be used for conducting VLBI science observations with phased ALMA during ALMA Cycle 4. An exception is that an archiving bug precluded the automated launch of the VLBI SBs. (This problem has since been remedied). The session included observations of all calibration sources needed for end-to-end processing of both the VLBI data and the standard ALMA interferometry data.

The resulting Band 6 data set resulted in fringe detections for multiple bright continuum sources (>1 Jy) on all three baselines of the ALMA-SMT-LMT triangle. Following correlation of the VLBI data, the ALMA VLBI data were successfully converted from linear to circular polarization products using the PolConvert software developed by the APP team (Martí-Vidal et al. 2016a). A Band 3 (3 mm) global VLBI experiment scheduled for April 2016 was postponed until July 2016 because of poor weather at ALMA.

Additional information on the April 2016 APP CSV mission is available on the mission wiki page. [7]

11 References

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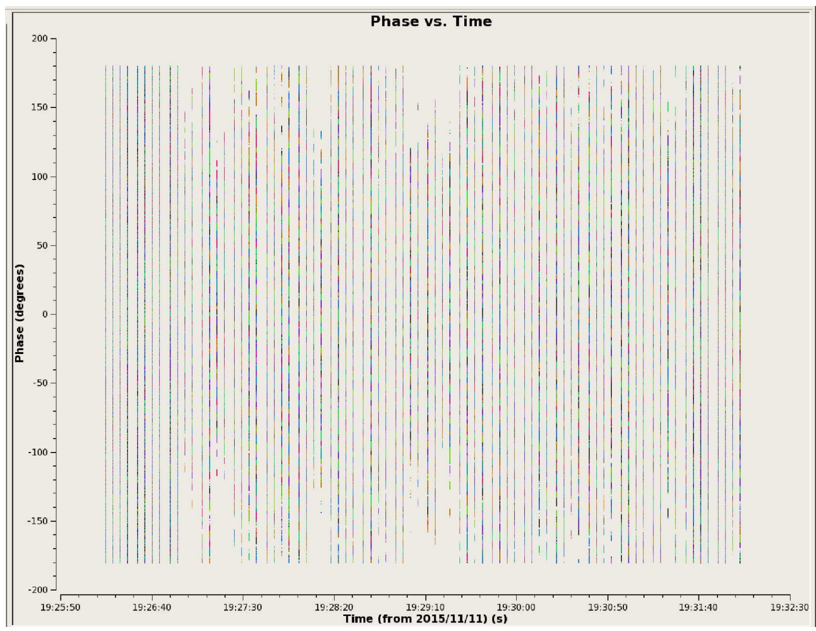

Figure 1: Band 3 observations with the APS obtained on November 11, 2015. The target was the bright quasar 1924-292. Phase as a function of time is plotted for data for baselines between all phased antennas (37 in total) from the first correlator quadrant, XX and YY polarizations. Approximately 360 seconds of data are shown. Data source: uid://A002/Xacba6b/X15.

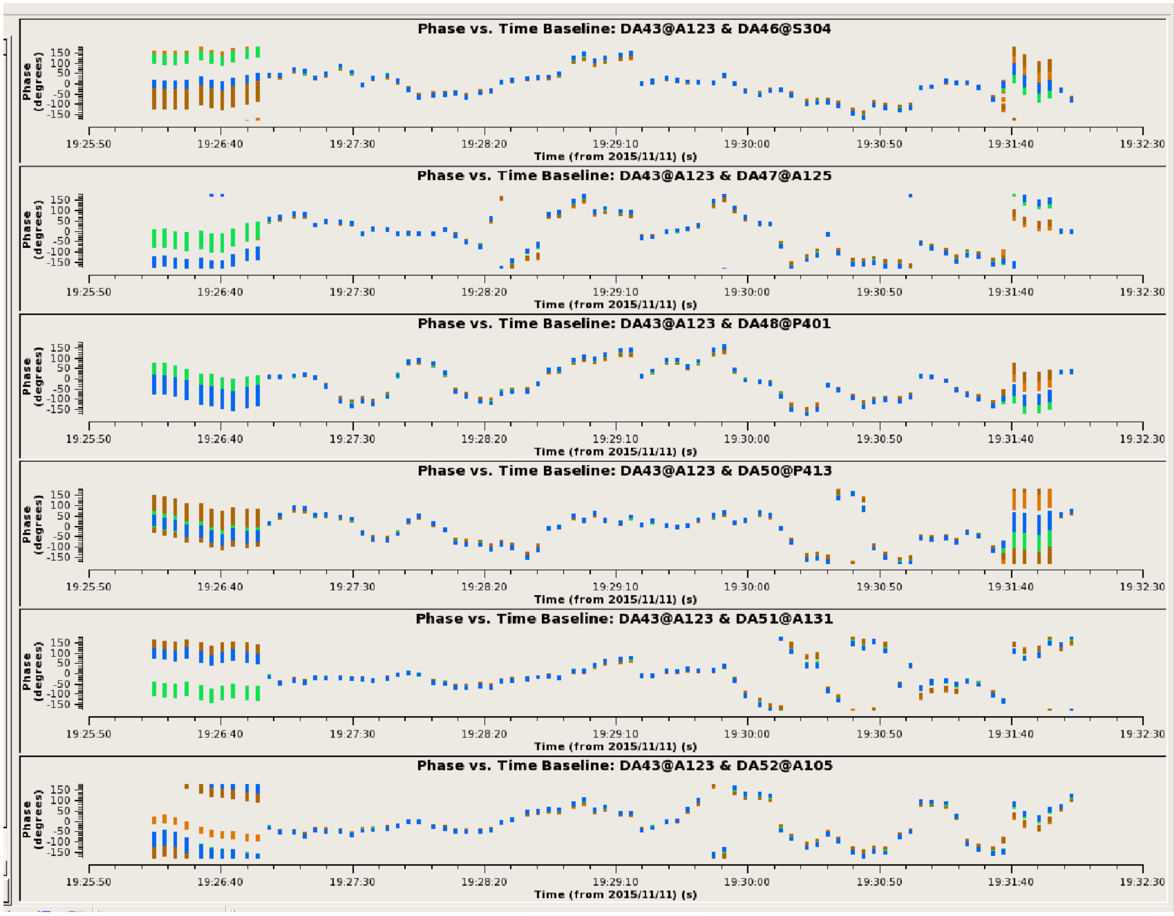

Figure 2: As in Figure 1, but showing several baselines plotted individually. Here, only XX data are shown, and the the four colors correspond to the four correlator quadrants. Once phase-up is achieved near 19:26:55 UT, the dispersion in the phases within in baseband decreases markedly, with values converging near zero phase, as expected. However, the phases subsequently drift, with the four quadrants varying in lock-step. A complete loss of coherence occurs near the end of the scan.

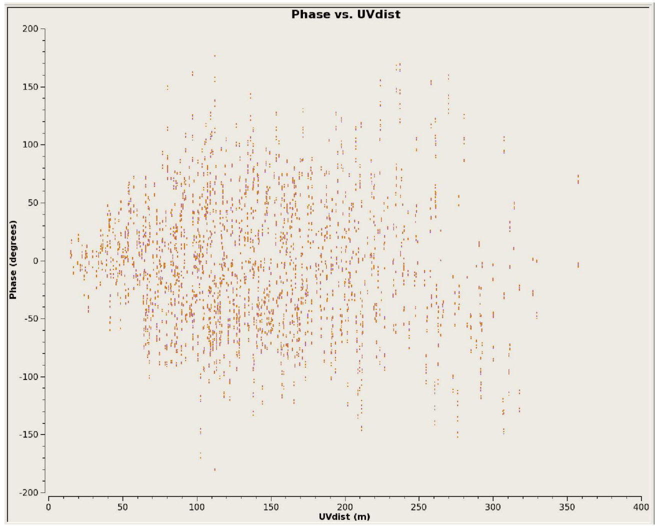

Figure 3: Band 3 data obtained with the APS on March 24, 2016. Phase is plotted as function of u-v distance for all baseline pairs of phased antennas. Note that only for the few shortest baselines do the phases lie near the expected values near zero. For longer baselines, not only does the dispersion increase, but points appear to be preferentially absent from zero phase. This behavior suggests that the phasing corrections are being corrupted. Data source: uid://A002/Xb0dfe8/X6a2.

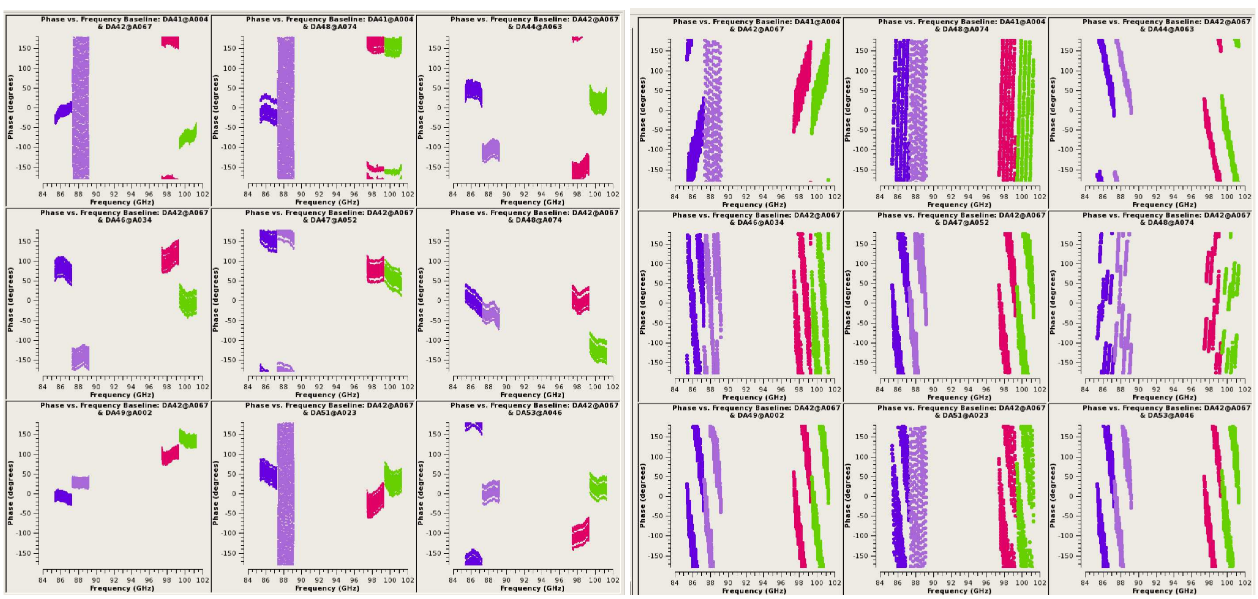

Figure 4: Band 3 data obtained with the APS on March 24, 2016. Phase is plotted as function of frequency for several baselines in Stokes XX. Different colors indicate the four correlator quadrants. During an early scan (scan 3, left panel), some of the data in spw 2 are clearly corrupted. However at later times (e.g., scan 26, right panel), severe delay errors are evident in all four quadrants as evidenced by the steep slopes in phase as a function of frequency. Data source: uid://A002/Xb0dfe8/Xeed.

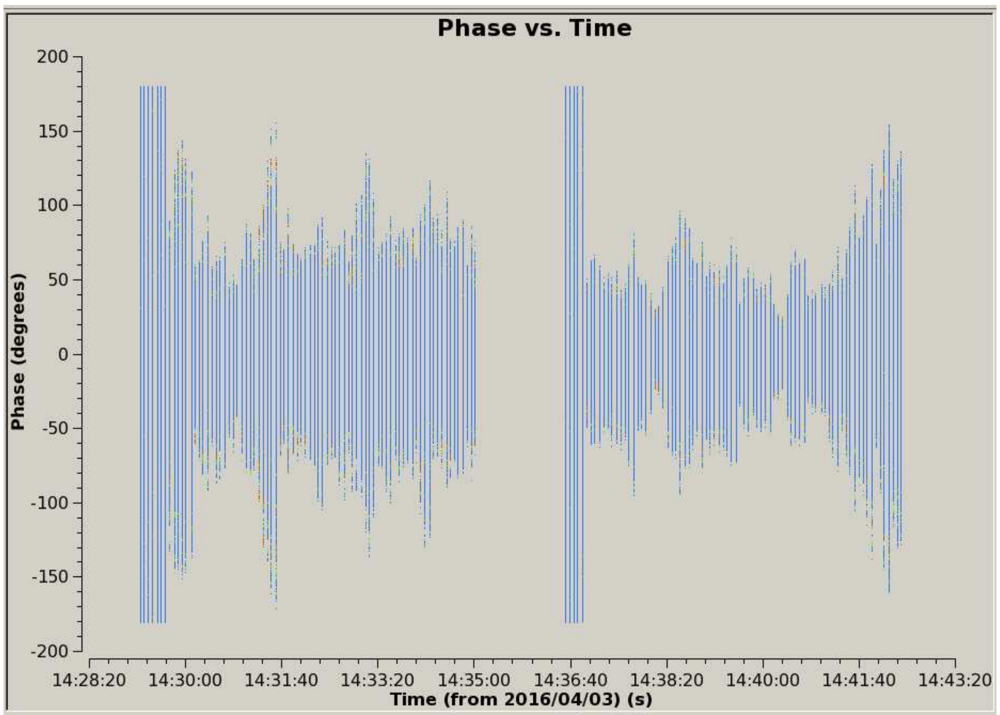

Figure 5: Band 3 regression test data obtained with the APS on April 3, 2016 using the Cycle 3 software release. Phase is plotted as function of time for all four correlator quadrants, XX polarization. While the scatter in the phases is high, it appears to be consistent with the unstable weather conditions. There is therefore no evidence for the types of phasing problems seen in test data from November 2015 and March 2016 (cf. Figures 1-4). Data source: uid://A002/Xb1586e/X4b2f.

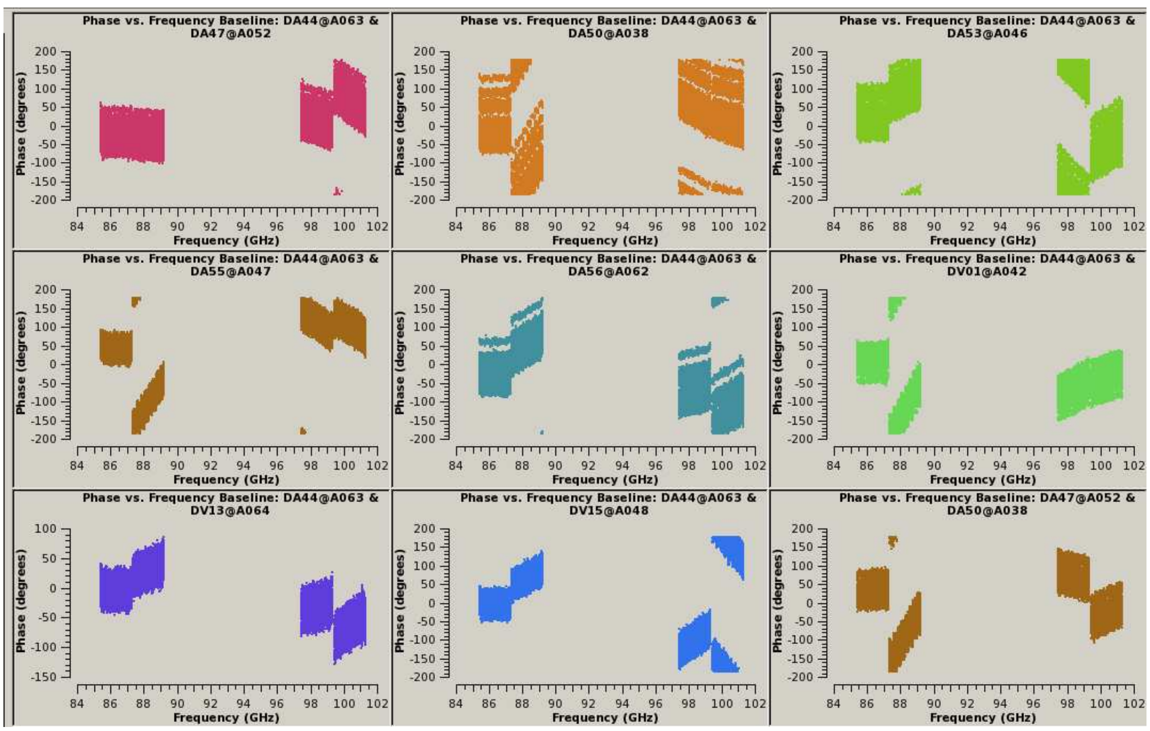

Figure 6: Band 3 test data obtained with the APS on April 3, 2016 using software release R2016.6. In each subpanel, phase is plotted as function of frequency for all four correlator quadrants, XX polarization, during a single scan on a baseline between phased antennas. Phased slopes are visible in several of the panels, indicating delay errors. Data source: uid://A002/Xb16072/X1cc.

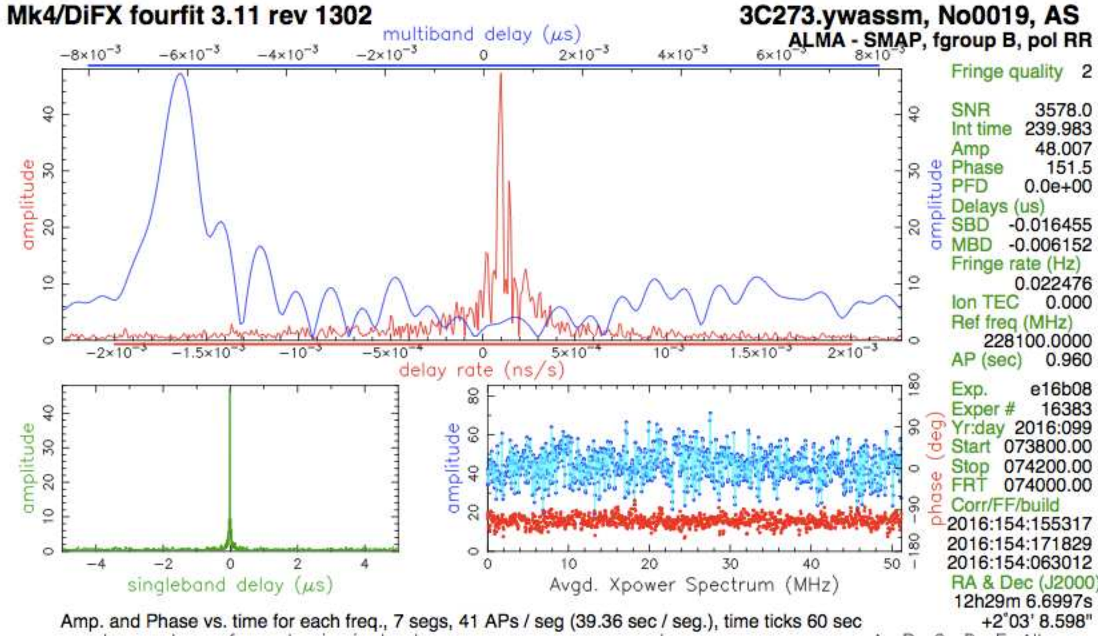

Figure 7: Band 6 (228.1 GHz) VLBI fringe on the quasar 3C273 obtained between phased ALMA and the phased SMA on April 8, 2016. The plot shows a correlation between ALMA's X polarization and the SMA's R polarization based on 4 minutes of data.

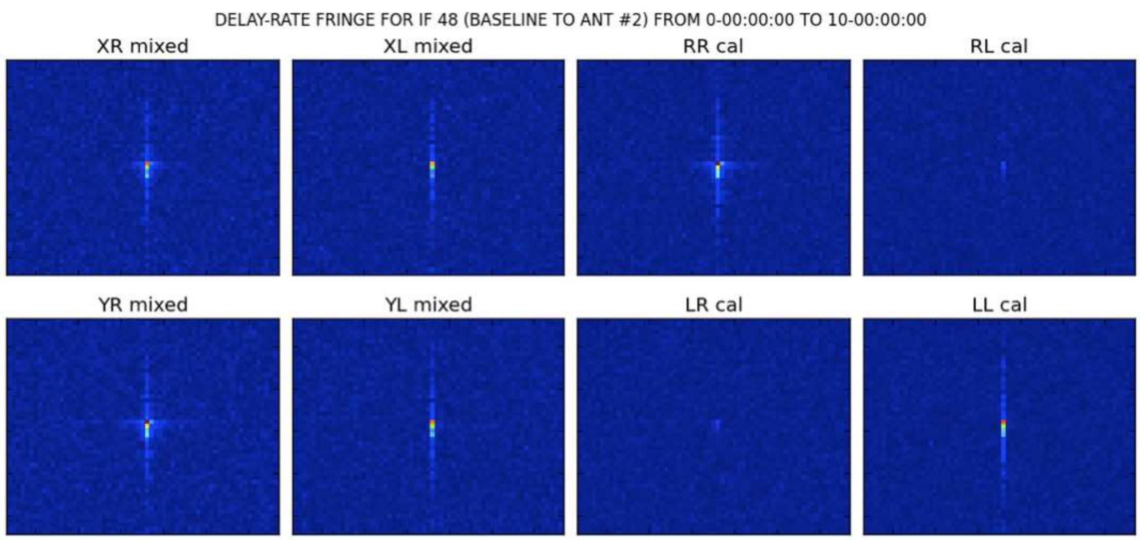

Figure 8: Delay rate fringe amplitudes for the source 3C279 on a baseline between ALMA and the LMT (Band 6). The data were obtained on April 8, 2016. The four left panels show the "mixed" linear and circular polarization products prior to the application of PolConvert. The four right panels show the data after PolConvert. The signal in the cross-hand products is negligible after the conversion, indicating robust operation of the conversion software. From Martí-Vidal et al. (2016a).

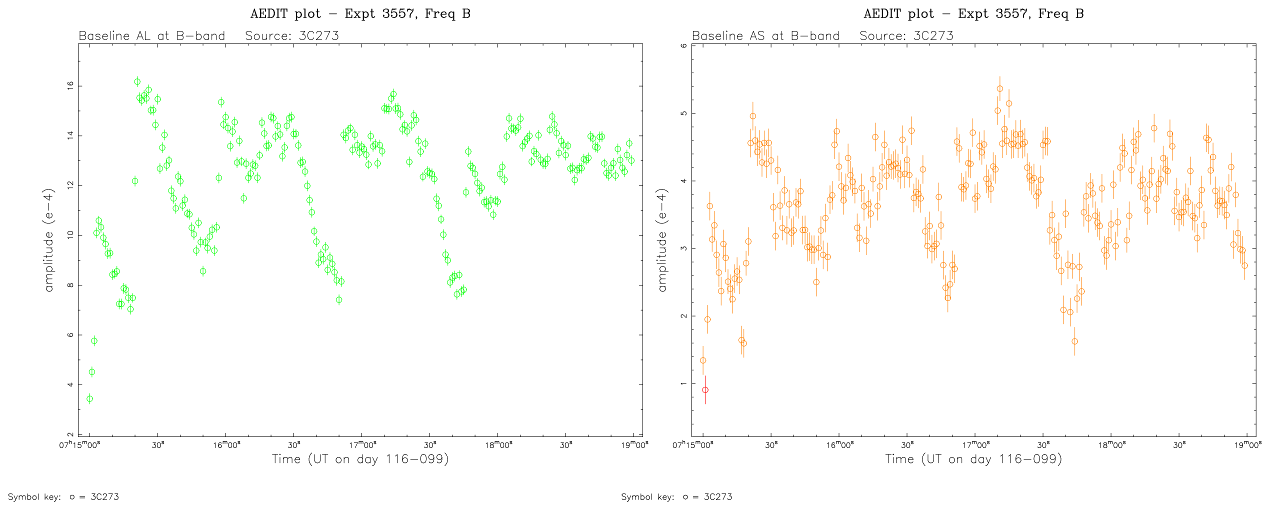

Figure 9: Amplitude vs. time during a Band 6 VLBI scan on 3C273 for the ALMA-LMT (left) and ALMA-SMA (right) baselines, RR polarization, obtained on April 8, 2016. The correlation coefficients are seen to decay frequently, reflecting a loss of phasing efficiency, but then recover to a nominal level. These dropouts occur at the same time on two different ALMA baselines, indicating that the issue originates at ALMA.

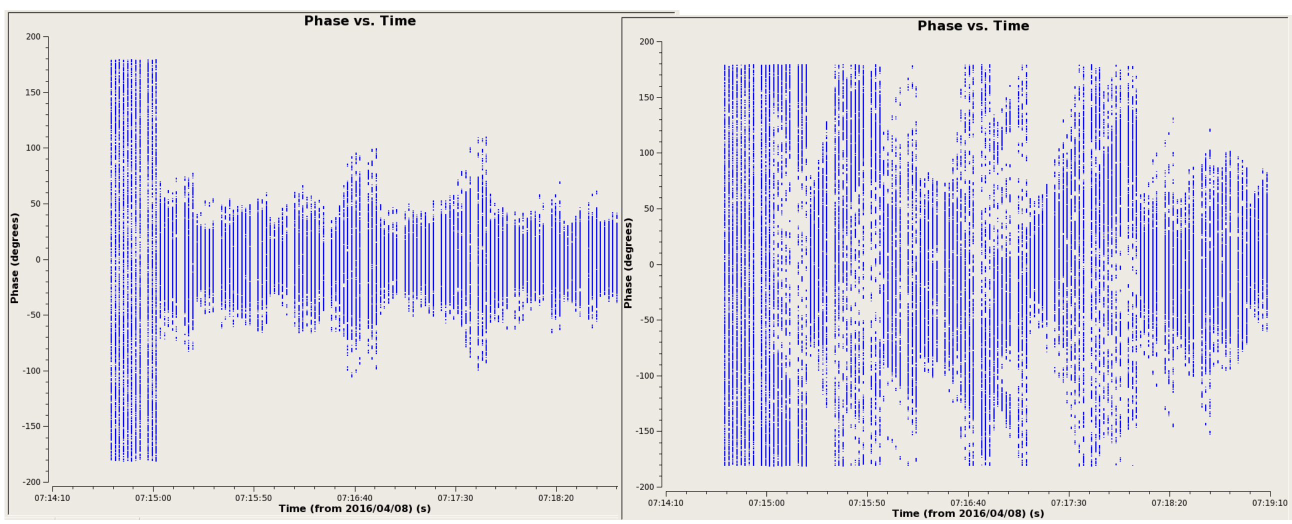

Figure 10: Phase as a function of time for ALMA Band 6 observations of the quasar 3C273, taken during the global VLBI CSV experiment on April 8, 2016. Baselines between the 37 phased antennas are shown for the XX polarization in a single correlator quadrant (corresponding to the VLBI "hi" band; see text). The left panel is restricted to baselines $\leq$50 m, while the right panel is restricted to baselines between 105-305 m. Scatter is the phases is consistently smaller on the shorter baselines. Periods of higher phase scatter in the longer baselines correspond in time to the correlation coefficient (amplitude) dropouts seen in the VLBI data (Figure 9). Data source: uid://A002/Xb187bd/X2d5.

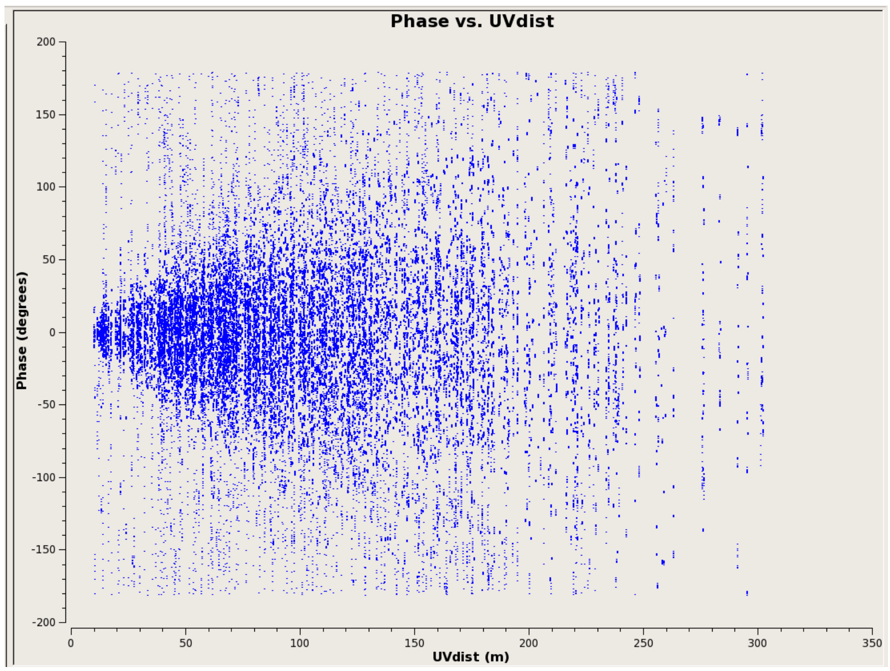

Figure 11: Phase as a function of u-v distance for the same Band 6 data as shown in Figure 10. Scatter in the phases increases systematically with increasing baseline length. Data source: uid://A002/Xb187bd/X2d5.

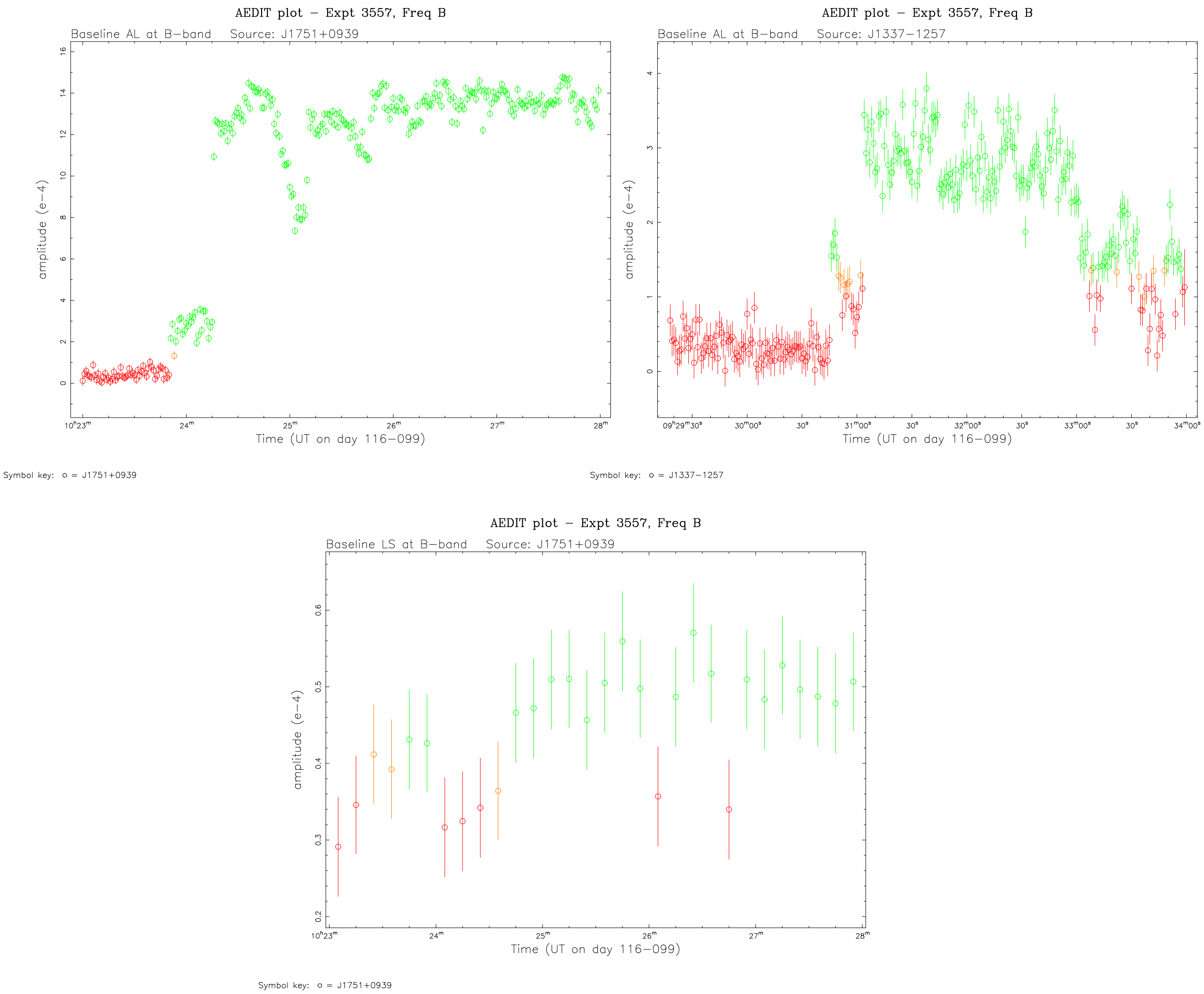

Figure 12: Additional results from the Band 6 VLBI data of April 8, 2017. Amplitude vs. time for one scan on the ALMA-LMT (top left), ALMA-SMA (top right), and LMT-SMA (bottom) baselines (RR polarization). ALMA has issues for approximately the first minute of the scan (red points). The LMT-SMA baseline produces acceptable quality data during part of this minute. LMT-SMA data are averaged to 10 seconds because of the much lower signal-to-noise ratio on this baseline.

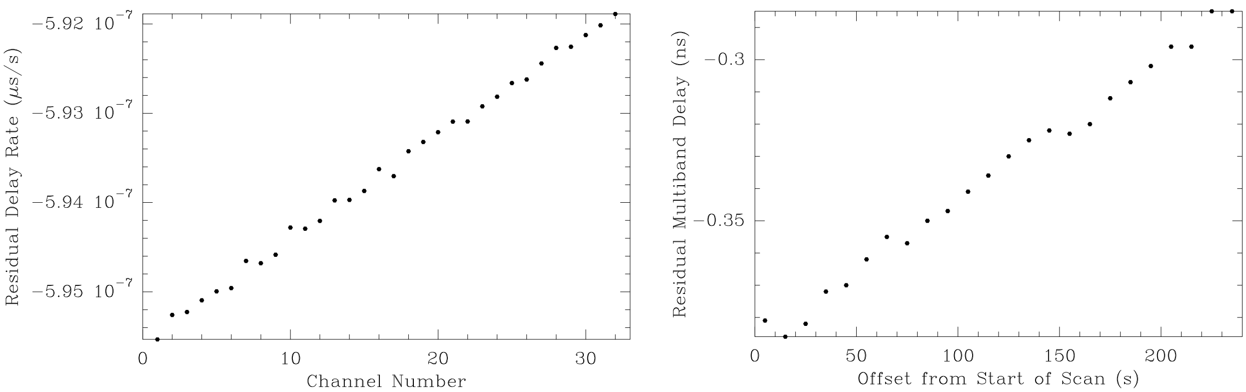

Figure 13: Additional results from the Band 6 VLBI data of April 8, 2017. *Left:* The residual delay rate as a function of frequency channel for the first scan on 3C279 on the ALMA-LMT baseline, LL polarization. There is a linear drift in the residual delay rate with frequency. *Right:* The residual multiband delay found by fringe-fitting different 10-second segments of the data. There is a linear drift of residual multiband delay with time.

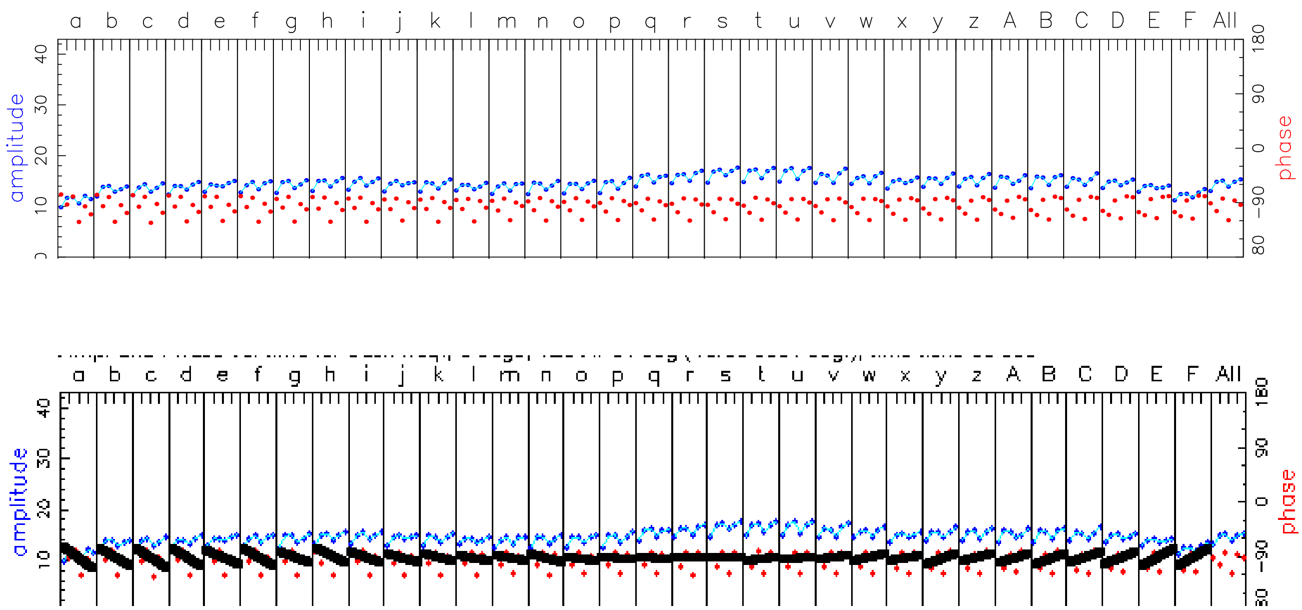

Figure 14: Additional results from the Band 6 VLBI data of April 8, 2017. *Top:* The red points show the phase vs. time on the ALMA-LMT baseline (LL polarization) on the first scan of the experiment for each of the 32 frequency channels (labeled by letter). *Bottom:* The same plot, but with a line drawn in connecting the first and last time points within each channel. The effect of different residual delay rates (i.e., time-varying phases) is evident in each channel.