Final Report: Enabling New VLBI Science with the ALMA Phasing System - Phase 3 (APP3)

An ALMA North America Development Project

Authors: Lynn D. Matthews, Principal Investigator (Massachusetts Institute of Technology Haystack Observatory)

Geoffrey B. Crew, Software Lead (Massachusetts Institute of Technology Haystack Observatory)

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Executive Summary: This document provides a summary of activities undertaken as part of the ALMA North America Development Project "Enabling New VLBI Science with the ALMA Phasing System - Phase 3 (APP3)", whose period of performance extended from January 17, 2022 to July 16, 2024. The successful completion of this project has resulted in the introduction of flexible tuning for ALMA very long baseline interferometry (VLBI) operations, a fully flexible spectral line VLBI observing mode, and the enabling of panchromatic VLBI, allowing ALMA in principle to operate as a phased array in any available receiver band. The project also carried out a series of activities aimed at maintaining and optimizing existing VLBI infrastructure and provided training to staff at the Joint ALMA Observatory (JAO) to enable a transition to autonomous VLBI observing. A video feature and accompanying news article were produced near the conclusion of this project to make the results accessible to a broader audience.

Contents

1 Background

Starting in 2012 a series of ALMA North America Development projects led by the Massachusetts Institute of Technology (MIT) Haystack Observatory helped to enable the introduction of very long baseline interferometry (VLBI) capabilities at ALMA, the world's most sensitive millimeter/submillimeter observatory. These capabilities have subsequently allowed the extraordinary sensitivity of ALMA to be exploited for ultra-high angular resolution science.

Under the original ALMA Phasing Project (APP; principal investigator: S. Doeleman), a Haystack-led international team developed, deployed, and commissioned the hardware and software necessary to enable ALMA and its original Baseline (BL) Correlator to coherently phase up to 61 individual antennas and generate and record a VLBI format data stream (see Matthews & Hecht 2017; Matthews et al. 2018 for details). In conjunction with the Event Horizon Telescope (EHT), the original ALMA Phasing System (APS) was critical to achieving the first ground-breaking images of a supermassive black hole (M87*) on event horizon scales (EHT Collaboration et al. 2019a). Since then, ALMA's VLBI and phased array capabilities have played a part in a growing series of high-impact scientific studies (e.g., Janssen et al. 2021; EHT Collaboration et al. 2021, 2022; Lu et al. 2023).

The ALMA Phasing Project Phase 2 (APP2), with a period of performance extending from January 1, 2018 – August 31, 2024 (principal investigator: L. Matthews) subsequently worked to further enhance and expand ALMA's VLBI capabilities, leading to the introduction of sub-mm (Band 7) phasing and VLBI capabilities (Crew et al. 2023; Raymond et al. 2024), a passive phasing mode[1], a phased array (pulsar) observing mode (see Cordes et al. 2017; Liu et al. 2019), a proto-type spectral line VLBI capability, an improved method of handling baseband delays (Crew & Matthews 2024), and various other minor system enhancements. Further details on the outcomes of the APP2 will be summarized elsewhere (Matthews & Crew 2024, in preparation).

While APP and APP2 brought important new scientific capabilities to ALMA, they left some significant limitations to the flexibility of ALMA's VLBI observing mode (VOM), which in turn limited the breadth of its scientific applications. To address these, a third phase of the APP (APP3), the subject of this report, was conceived to supply additional categories of VLBI developments: (1) *flexible tuning*; (2) *panchromatic VLBI* (i.e., the ability to phase up ALMA in any available receiver band and undertake VLBI in any band where peer observing sites are available); (3) a fully flexible *spectral line VLBI* mode. As described below, APP3 also introduced various other minor improvements and enhancements to the APS to improve its performance and versatility. APP3 completed delivery of the bulk of the developments required to support each of the aforementioned major new capabilities in Cycle 10, with some minor tasks continuing into Cycle 11 and later.

This report summarizes the goals of APP3, the work undertaken as part of this project, and the new VLBI features that have been delivered under this program. Additional details about the development and commissioning of VLBI capabilities developed under APP3 are

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[1] Passive phasing enables VLBI observations of arbitrary weak targets by allowing the use of phasing solutions determined from a nearby calibrator to phase up the array rather than solutions computed from the science target itself.

also available in various memos and reports referenced herein.

2 The Motivation for an APP "Phase 3"

With the original APS offered to the community starting in Cycle 4, ALMA VLBI users were presented with minimal flexibility. Options available were limited to continuum mode observations in either of two bands: Band 3 or Band 6. Both bands were restricted to a single, fixed tuning set-up, and through Cycle 7, VLBI targets were limited to those bright enough to permit efficient and direct phase-up of the array (i.e., correlated flux density of $\geq$500 mJy on intra-ALMA baselines).

The features and specifications of the original APS were motivated primarily by the requirements necessary to achieve the goal of imaging the nearby supermassive black holes M87* and SgrA* on event horizon scales (e.g., Doeleman 2010). Furthermore, some desired features (in particular, the extension of VLBI to Band 7) had to be descoped owing to time and resource limitations, while other options (e.g., those needed to enable flexible spectral line observing) were not included in the scope of the original design.

As described in the white papers by Fish et al. (2013) and Tilanus et al. (2014), there has been wide and longstanding community interest in exploiting the power of phased ALMA for a broad range of science applications beyond imaging black holes. Indeed, the science case for a phased ALMA described in these white papers is incredibly broad and diverse, ranging from the studies of molecular masers in the atmospheres of evolved stars and the circumnuclear disks of megamaser galaxies, to studies of the high-frequency portion of pulsar spectral energy distributions, to measurements of molecular absorption lines in the environments of active galactic nuclei (AGN; see also Falcke et al. 2012; Colomer 2015). However, owing to the aforementioned limitations of the original APS, science cases such as these could not be pursued using ALMA.

As noted in Section 1, the APP2 was conceived to enhance and expand the capabilities of the original APS and VOM, and that program has successfully developed, implemented, and tested several new VLBI capabilities. A third and final phase of the APP, APP3, was then proposed to bring to fruition some additional upgrades that were critical for to allowing the APS to reach its full potential within the framework imposed by the design of the original ALMA BL Correlator, ALMA's delay system, and various other pieces of ALMA hardware and software that are expected to remain in place until the ongoing Wideband Sensitivity Upgrade (WSU)[2] is completed early in the next decade.

3 Project Scope and APP3 Deliverables

The work breakdown structure (WBS) for APP3 consisted of five elements. WBS 1.0 comprised Project Management (Section 8) and WBS 5.0 concerned Broader Impacts (Section 9). The other three WBS elements, comprising the bulk of APP3 efforts, included the following set of approved development, commissioning, and support activities:

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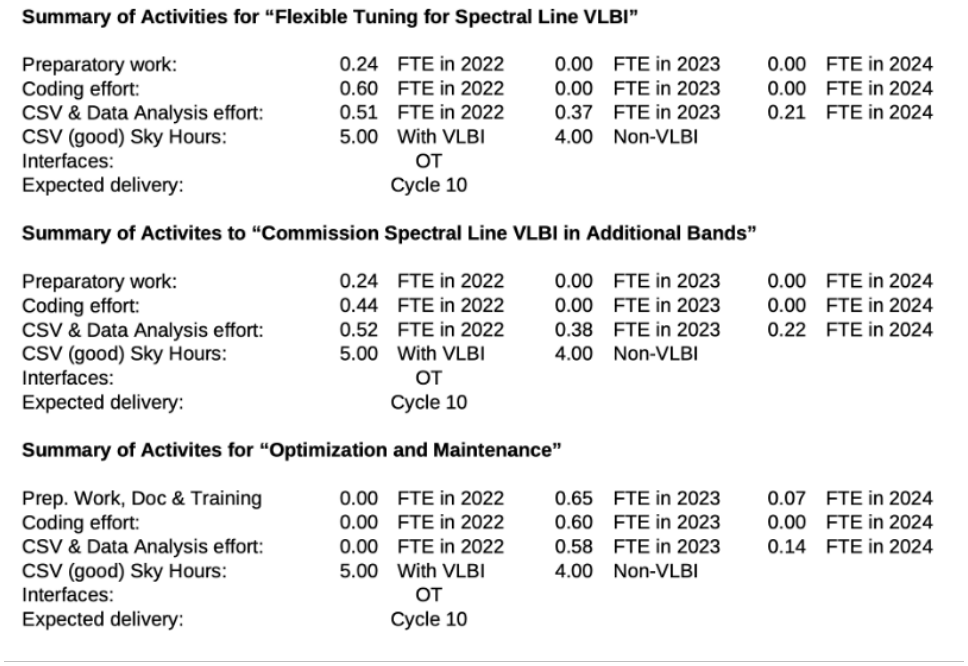
[2] `https://science.nrao.edu/facilities/alma/science_sustainability/wideband-sensitivity-upgrade`

1. Enabling flexible tuning for VLBI (WBS 2.0)
2. Spectral line VLBI with flexible tuning (WBS 2.0).
3. Enabling VLBI (spectral line or continuum) in any ALMA band (WBS 3.0).
4. Optimization and maintenance of existing VLBI capabilities (WBS 4.0).

For items relating to WBS 2.0 and 3.0 we describe in the sections that follow the motivations for these implementations, followed by a description of the development and commissioning work entailed in their deployment and testing at ALMA. The originally proposed timelines and personnel efforts for those activities are summarized in Figure 1. Section 7 summarizes the range of activities undertaken under the umbrella of WBS 4.0. We close with some brief remarks on the future of VLBI at ALMA (Section 10) and a summary of project activities (Section 11).



Summary of Activities for “Flexible Tuning for Spectral Line VLBI”

Preparatory work:	0.24	FTE in 2022	0.00	FTE in 2023	0.00	FTE in 2024
Coding effort:	0.60	FTE in 2022	0.00	FTE in 2023	0.00	FTE in 2024
CSV & Data Analysis effort:	0.51	FTE in 2022	0.37	FTE in 2023	0.21	FTE in 2024
CSV (good) Sky Hours:	5.00	With VLBI	4.00	Non-VLBI		
Interfaces:	OT					
Expected delivery:	Cycle 10					

Summary of Activites to “Commission Spectral Line VLBI in Additional Bands”

Preparatory work:	0.24	FTE in 2022	0.00	FTE in 2023	0.00	FTE in 2024
Coding effort:	0.44	FTE in 2022	0.00	FTE in 2023	0.00	FTE in 2024
CSV & Data Analysis effort:	0.52	FTE in 2022	0.38	FTE in 2023	0.22	FTE in 2024
CSV (good) Sky Hours:	5.00	With VLBI	4.00	Non-VLBI		
Interfaces:	OT					
Expected delivery:	Cycle 10					

Summary of Activites for “Optimization and Maintenance”

Prep. Work, Doc & Training	0.00	FTE in 2022	0.65	FTE in 2023	0.07	FTE in 2024
Coding effort:	0.00	FTE in 2022	0.60	FTE in 2023	0.00	FTE in 2024
CSV & Data Analysis effort:	0.00	FTE in 2022	0.58	FTE in 2023	0.14	FTE in 2024
CSV (good) Sky Hours:	5.00	With VLBI	4.00	Non-VLBI		
Interfaces:	OT					
Expected delivery:	Cycle 10					

Figure 1: **Project Timeline**—Project timeline for APP3, taken from the approved ALMA North America Development proposal.

4 Flexible Tuning for VLBI (WBS 2.0)

4.1 Motivation and Background

ALMA’s initial VLBI observing capability provided only a single, fixed tuning set-up in each of the offered bands (initially Bands 3 and 6, with Band 7 added in Cycle 9). Consistent with this restriction, the ALMA Observing Tool (OT) did not include any provisions to alter the tuning for VLBI experiments. However, a fully-flexible spectral line VLBI observing necessarily requires an ability to tune to specific lines of interest and adjust their placement within the observing band. Continuum observers also may benefit from the ability to adjust the default tuning, e.g., to expand the *uv* coverage, to avoid atmospheric absorption lines, or to match the tuning adopted by a partnering observatory (where IF bandwidth and local oscillator (LO) settings are in some cases considerably less flexible than ALMA's).

4.2 Software Requirements and Updates

4.2.1 Tuning at ALMA

While ALMA's tuning system is highly flexible, it is also complex and posed some unexpected challenges for VLBI operations. ALMA's front end tuning system consists of two analog LOs that define the 2.000 GHz basebands used for making observations. The details of its operation are contained within a Java module (`LOSolutions`) which receives as input a "spectral specification" according to the needs of the observer and generates as output the precise settings for all of the tunable parameters. `LOSolutions` is used by the OT to verify the spectral specification as part of "phase 2", during which the scheduling blocks (SBs) that control the observation are generated. The spectral specification is later passed to the `CONTROL` system which again uses `LOSolutions` to tune the LOs. A complication of all of this is that the detailed hardware specification is not actually captured anywhere with a precision appropriate to the needs of VLBI.

Owing to its underlying complexity, a variety of minor issues with the implementation of `LOSolutions` went unnoticed during ALMA commissioning, in large part because most ALMA-only observations are not affected by small tuning errors. However, in VLBI, minor tuning errors at one station translate into coherence losses on all baselines to that station. And since ALMA is in general the most sensitive station in VLBI arrays operating in the mm regime, these errors can become a limiting factor in VLBI data quality.

During the analysis of the first ALMA VLBI science observations from 2017, a "bowl" shape was seen in plots of phase errors as a function frequency, indicating a tuning issue at one of the VLBI stations (see an extended discussion in the Cycle 7 Acceptance report by Crew 2020). An example of this phenomenon is reproduced in Figure 2. Ultimately tuning errors were identified at ALMA and two other stations. Prior to the including of phased ALMA and wide-banded EHT stations in mm VLBI arrays, phase measurements were generally too noisy to see the effect. A so-called "LO offset" procedure was subsequently included in the VLBI correlation to make a first-order correction.

Discussions with ALMA system engineer Nick Whyborn led to ultimately tracing part of the error to a lack of precision in the software that commands the CVR which generates the "LO1" tuning frequency.[3] A fix for this issue was attempted in Cycle 6. However, additional issues (unrelated to VLBI) that had been identified with `LOSolutions` were fixed incorrectly at the same time, leading to tuning issues that seriously impacted VLBI, particularly in Band 3.

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[3] The CVR is a commercial unit that generates a frequency of at most 20 GHz; this is then multiplied by odd factors to reach the required "LO1" frequency, which creates the fundamental tunings of the upper and lower sidebands.

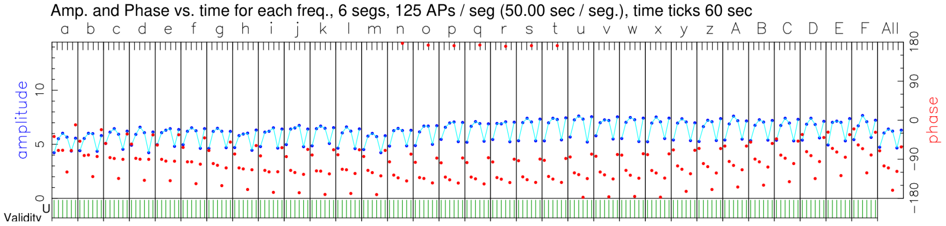

Figure 2: **Example of the "bowl"**—An example of the "bowl" that occurs on a VLBI baseline to ALMA as a consequence of tuning errors (see Figure 33 of Crew 2020 for more detail). The 32 panels (labeled 'a' through 'F') show phase (red) and amplitude (blue) with time for each sub-band/channel used in the VLBI fringe search. Although there is scatter in the phases, the phase is systematically lower in the middle channels and higher at the edge channels. This results from a relative tuning error at the participating stations.

Ultimately, a total four issues with `LOSolutions` were identified:

- *LO solutions software cannot always tune all basebands to the same specified frequency.* This typically only arises in special testing (e.g., as has been done for VLBI), since most science projects do not need all 4 basebands tuned identically. The workaround is to have at least two different center frequencies.

- *In some cases the maximum error in baseband frequencies increased since the application of prior fixes.* There are restrictions on what LO2 can do (8–14 GHz with oddly placed MHz-sized holes every 125 MHz). In particular, the Global Millimeter VLBI Array (GMVA) band needs to have a center at 86.268 GHz, but now winds up with 86.271 GHz.

- *LOsolutions is often producing LO2 frequencies 0.1 Hz (100 mHz) from optimal.* The EHT has sufficient sensitivity to make this error quite obvious on several baselines to ALMA.

- *LOSolutions disrespects user preferences.* The system allows the user to provide guidance for tuning the four basebands, expressed as a percentage, but that guidance was being ignored.

One option that was explored to address the various tuning issues was the adoption of so-called "hardware tunings" for VLBI. Significant time and effort was expended exploring the use of hardware tuning solutions, but those efforts encountered serious (and in the end, insurmountable) challenges. One issue is that hardware tunings had been designed for use only by expert users, with only a handful of individuals possessing the relevant expertise. Another key limitation is that any tunings deemed "mission critical" to VLBI would require explicit individual verification.

Several candidate hardware tunings were implemented and evaluated with (ALMA-only) VOM test observations. However issues with the OT and the ALMA Archive (specifically, Band 1 turned into "Band 3") precluded meaningful analysis. In the end, a decision was reached to abandon the concept of hardware tunings for VLBI. Instead, `LOSolutions`

Table 1: Stations Participating in TA037

Station	ID Code[1]	ID (HOPS)[2]	Location	Comment
ALMA	Aa	A	Chajnantur	86.067...GHz
ALMA	Aq	Q	Chajnantur	86.266...GHz
Brewster	Br	b	VLBA, Washington	128 MHz sub-bands
Fort Davis	Fd	f	VLBA, Texas	(same)
Kitt Peak	Kp	k	VLBA, Arizona	(same); 25 m VLBA dish
Los Alamos	La	l	VLBA, New Mexico	(same); recorder issues
Mauna Kea	Mk	m	VLBA, Hawaii	(same); late start
North Liberty	Nl	n	VLBA, Iowa	(same)
Owens Valley	Ov	o	VLBA, California	(same)
Pie Town	Pt	p	VLBA, New Mexico	(same)
Effelsberg	Ef	B	Germany	64 MHz sub-bands
Onsala	On	X	Sweden	(same)
Yebes	Ys	Y	Spain	poor weather
Haystack	Hh	H	Massachusetts	2.048 GHz baseband; crystal; single pol.

[1] Capitalization of the second letter of the station code is the convention of some software packages (e.g., AIPS).

[2] The HOPS package uses single letters for station designations.

was repaired in `ONLINE-2022SEP` and this updated version was used for VLBI projects starting in Cycle 10. This necessary fixed involved only one byte of code, but the bug took several months to find.

In addition to the fixes to `LOSolutions` described above, enabling flexible tuning for VLBI experiments at ALMA required software updates to several subsystems, including the OT, `VEX2VOM`, and the SSR code. For readers unfamiliar with ALMA VLBI, `VEX2VOM` is specialized software that combined information about the VLBI observing schedule [as specified within a standard VLBI EXperiment (VEX) file] with the ALMA-specific project specifications contained in the OT-generated SB. The result is encoded in one or more SBs, which are executed by a Python script known as `StandardVLBI.py`, commonly referred to as an "SSR script" (see Matthews et al. 2018 for more details).

The required changes to `VEX2VOM` and the SSR codes were undertaken by the APP3 team. They also worked in parallel with ALMA's OT developers to define and test required changes to the OT. These included:

- Populating the OT with 'standard' tunings in Bands 1, 3, 6, and 7 to be used as a default starting point for all set-ups
- Providing an option for the PI to modify the standard tuning, if desired.

4.3 Flexible Tuning Validation

To validate and commission flexible tuning for ALMA VLBI observing, we originally proposed a short test session to be included in the April 2022 GMVA session. This test session was to employ non-standard Band 3 tunings at ALMA as well as several GMVA sites. As of 2022, several of the the European stations of the GMVA had available several previously vetted LO1 tuning options that differed from the standard one used for ALMA-GMVA observations. Those included 85300 MHz (sky frequency range 85812–86324 MHz), 85800 MHz (86312–86824 MHz), and 86000 MHz (86512–87024 MHz). We opted for the lowest frequency tuning for the test and selected a set of continuum and SiO maser targets that would be observable during an available test slot. Unfortunately, ALMA's hydrogen (H) maser failed a day before the planned test (see also Section 7.5), leaving ALMA unable to participate in the April 2022 GMVA session.

Thanks to the efforts of ALMA's engineering staff, ALMA's H maser was resurrected later in April 2022 and by the end of April had stabilized and was operating normally. At that point, colleagues at the Very Long Baseline Array (VLBA) and three European observatories [Onsala (ON), Effelsberg (EF), and Yebes (YB)] generously agreed to support a special 3 mm VLBI test campaign with ALMA. This was scheduled on April 27, 2022 under VLBA project code `TA037`. The Haystack 37m dish in Westford, MA was also readied to join.

In preparation for `TA037`, a set of Galactic stellar objects containing suitably strong SiO masers was identified to serve as targets. Peak SiO flux densities of the ^{28}SiO v=1, J=2 − 1 line in the selected sources were estimated to be a several Jy or more based on extrapolations from recent SiO maser flux density measurements of the ^{28}SiO v=1, $J = 1-0$ line at $\lambda \sim$7 mm (rest frequency 43.12203 GHz) that were performed by the staff at Yebes Observatory.[4] A few bright continuum calibrators were also selected for our assigned local sidereal time (LST) window with help from the GMVA scheduler Thomas Krichbaum.

Source coordinates were updated to the current observing epoch to account for proper motions using the best available *Gaia* or *Hipparcos* values.[5] Based on the Yebes-derived local standard of rest (LSR) velocities, sky frequencies for the ^{28}SiO v=1, J=2−1 maser line (rest frequency 86.24337000 GHz) were computed for each line target at the time of the observations. Expected SiO linewidths for each source (used to determine the optimum phasing bandwidth; see below) were taken from the literature.

The programmed line positions were set via the `SpecLineList` expert parameter (EP; see Section 6.2 for further discussion) and contained the VEX source name, the band center frequency in GHz, the line width in MHz, and a comment field containing a project code.[6]

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[4] `https://www.oan.es/masersObservations/`

[5] While ALMA's online systems are capable of applying proper motion corrections, in VLBI it is conventional to enter corrected coordinates directly into the VEX file to ensure that they are identical at all stations.

[6] The "ta027" listed in the comment field reflects the originally assigned NRAO project code; it was later changed to TA037 to avoid a name duplication in the archive.

```
VXSGR:86.252303:3.0:ta027
IRC+10011:86.242794:3.0:ta027
OCETI:86.227704:2.0:ta027
RRAQL:86.246975:3.0:ta027
V468CYG:86.266737:2.0:ta027
```

This was then comma-delimited and presented as the `SpecLineList` expert parameter.

At the time our flexible tuning test was being planned, there was no clear timeline for implementation of a fix for the (known) bugs in `LOSolutions`. Thus the spectral specifications were initially set up using hardware tunings (see Section 4.3.1). As the primary goal of the test was to demonstrate successful VLBI fringes could be achieved with nonstandard tunings, we set up one baseband (BB_1) to match the peer sites using the lower LO1 (i.e., 86.068 GHz) and set up a second baseband (BB_2) using the normal 86.268 GHz center that has been adopted to date for Band 3 continuum VLBI experiments with ALMA. VLBI recordings were made for both of these basebands. The other two basebands (BB_3 and BB_4) were observed and archived as part of the ALMA archival science data model (ASDM) data set, but were not recorded for VLBI. For those, high spectral resolution setups were used to allow acquisition of complementary ALMA-only data sets for the line targets.[7]

4.3.1 A Flexible Tuning Test Execution in Band 3 (TA037)

Table 4.2.1 summarizes the stations that participated in the `TA037` test. The VLBA sites used a common setup with 4 128 MHz digital downconverter (DDC) sub-bands and dual (circular) polarization recording. The European sites covered the same bandwidth but with a 64 MHz polyphase filter bank (PFB) channel set, again recording both polarizations. The Haystack site was able to join for select scans with a single (linear) polarization. Haystack used the same ROACH2 DBE (R2DBE) backend favored by EHT VLBI sites. As Haystack was not equipped with an H maser, it instead used a high-quality crystal oscillator as a frequency standard, which added complexity to the correlation (see Section 4.3.2) and may impact achievable coherence timescales. However, as discussed below, the baseline to Haystack provided the advantage of full frequency coverage (in one polarization) of the entire ALMA band. At ALMA 43 antennas were included in the phased array. The precipitable water vapor (PWV) was ∼1 mm and the wind speeds were $\lesssim 10$ m s^{-1}.

Upon execution of `TA037` at its appointed time, it was quickly discovered that there was an error in the hardware tuning setup [units of GHz had been specified in the First LO-Offset Generator (FLOOG) instead of MHz]. This underscored the risks of complexities of using hardware tunings. A planned validation to check tunings for the GMVA prior to the experiment would have caught this earlier, but that test had to be skipped as a result of an H maser failure at ALMA (see also Section 7.5). In order to proceed with the `TA037`

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[7] The operation of the APS in any given baseband is only compatible with a single BL Correlation mode that yields a 1.875 GHz bandwidth per polarization and a maximum spectral resolution of ∼1 MHz, which is generally too coarse for scientifically meaningful analysis of maser lines. However, starting in Cycle 8, the option is available for basebands not recorded for VLBI to be flexibly configured by the project PI using any of ALMA's available frequency definition (FDM) correlator modes (see Section 6).

test, the project was quickly modified to use `LOSolutions` for the tunings and only a few minutes of the test were ultimately lost.

An important side effect of this change was that the tunings in the two basebands were not precisely offset by 200 MHz as had been originally planned. Instead, `LOSolutions` gave us BB_1 at 86.067999999898 GHz (off by 102 mHz) and a BB_2 tuning of 86.266240624998 GHz (off by 1.8 MHz). This caused additional complications in the correlation (see Section 4.3.2).

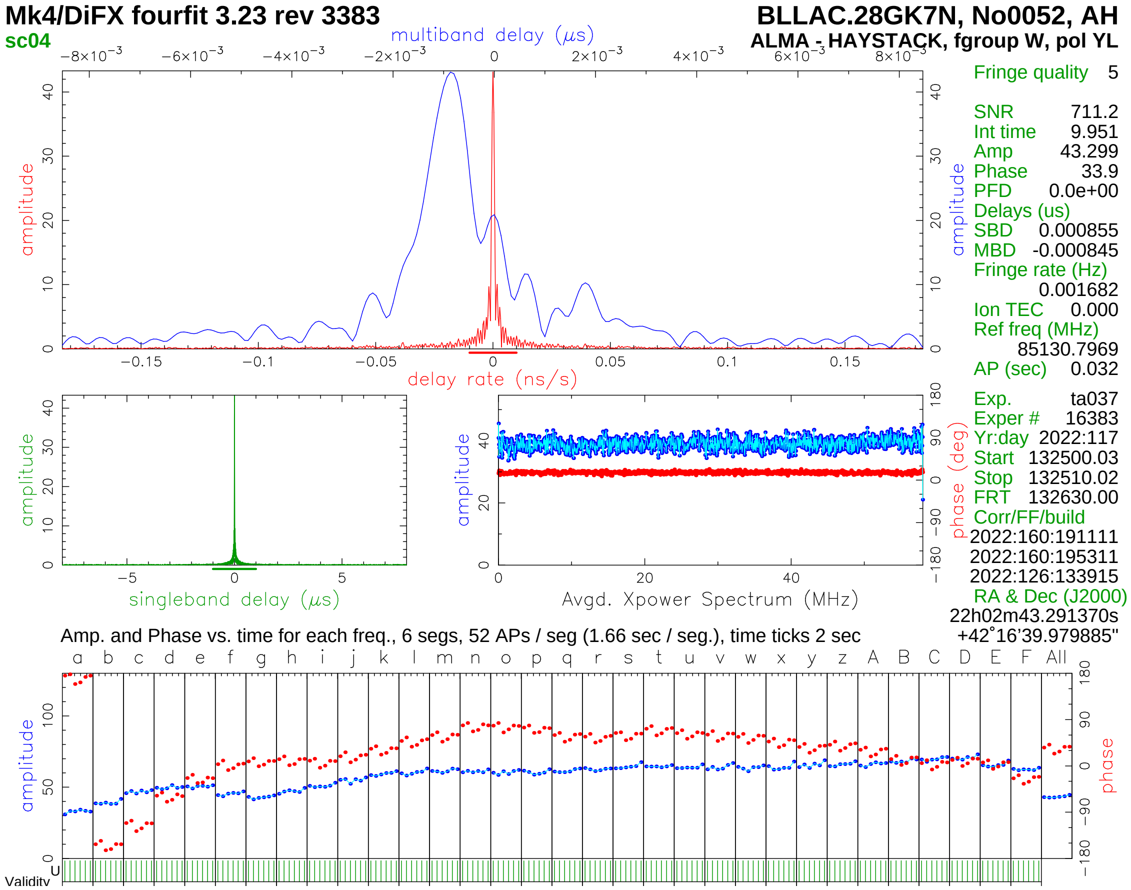
4.3.2 Correlation for the Flexible Tuning VLBI Test

General Remarks Staff at NRAO in Socorro performed a preliminary correlation of the VLBA-only portion of the `TA037` experiment and made the results available to us via a FITS file. Subsequently they shipped the VLBA recording media to Haystack for copying. In parallel, data from the European stations were e-transferred to Haystack, as were select ALMA scans. Once data for the full experiment were in place (approximately one month after the observations), a full VLBI correlation was carried out at Haystack. As a first step, several test correlations were made using portions of the two ALMA recordings (from BB_1 and BB_2, respectively) and the Haystack (single pol) recording. The two ALMA basebands use independent electronics and signal paths, hence this enabled meaningful independent tests, as well as a "quasi-zero baseline" correlation between the two bands (see below).

The inclusion of Haystack in the correlation introduced some additional complexities, which are described below. The other major challenge was that ALMA's 62.5 MHz (× 15/16) recorded bands make things quite complicated when used in conjunction with stations whose bandwidths are powers of two, including the VLBA (128 MHz bands) and the three European stations in the present experiment (64 MHz bands). Adding in a second ALMA band shifted by nearly (but not exactly) 200 MHz made things even more complex. In the end, we experimented with different "zoom band" arrangements in the software correlator package DiFX (Deller et al. 2011) that would allow using both ALMA bands with any of the other stations. Fortunately, a recently implemented feature in the DiFX correlation software known as "output bands" (see Janssen et al. 2022) made it possible to specify arbitrary channelization in the correlation. This technology does the correlations with a large number of oddly-sized zoom bands, and then stitches the results together with the desired channelization at the output stage. One drawback is that the code to analyze this case was still under development, so automatically calculating and applying manual phase and delay calibrations was not possible. For a quick-look fringe analysis, however, the situation was sufficiently tractable to enable a successful demonstration of tuning flexibility. A second drawback is that there are glitches at the underlying zoom band boundaries that also need to be flagged.

Several correlation schemes were explored: regularly spaced output bands of 14 MHz width, regular zoom bands of width 20, 32, 34, 46 and 58 MHz, and finally 20 MHz output bands. The latter was ultimately used for the post-correlation analysis in AIPS (Section 4.3.3). The 58 MHz channelization allowed for a fringe search to Haystack using the full 2-GHz bandwidth, as shown in Figure 3.

In addition to our analysis of the full recorded band, we also examined the quasi-zero baseline between the two independent ALMA basebands, "ALMA(A, BB_1)" and "alma(Q,



Mk4/DiFX fourfit 3.23 rev 3383

sc04

BLLAC.28GK7N, No0052, AH

ALMA - HAYSTACK, fgroup W, pol YL

Fringe quality 5

SNR 711.2
Int time 9.951
Amp 43.299
Phase 33.9
PFD 0.0e+00
Delays (us)
SBD 0.000855
MBD -0.000845
Fringe rate (Hz)
0.001682
Ion TEC 0.000
Ref freq (MHz)
85130.7969
AP (sec) 0.032

Exp. ta037
Exper # 16383
Yr:day 2022:117
Start 132500.03
Stop 132510.02
FRT 132630.00
Corr/FF/build
2022:160:191111
2022:160:195311
2022:126:133915
RA & Dec (J2000)
22h02m43.291370s
+42°16'39.979885"

Amp. and Phase vs. time for each freq., 6 segs, 52 APs / seg (1.66 sec / seg.), time ticks 2 sec

Figure 3: **ALMA-Haystack fringe results using a 86.068 GHz band center**—Fringe detection based on a full 2-GHz correlation between BB_1 at ALMA and a similarly tuned band at the Haystack 37 m antenna on the bright continuum source BL Lac. The Haystack receiver accounts for much of the phase and amplitude variation across the band. The fringe search was made using the Haystack Observatory Postprocessing System (HOPS) `fourfit` tool, which provides a one-page summary report of which only the top portion is shown. The red curve in the top panel is the delay-rate spectrum for the optimal fringe. The blue curve in the same channel is the multiband delay. The single-band delay is shown by the green curve in the small center panel, and its Fourier transform (the cross-power spectrum appears with amplitude in blue and phase in red) is in the other small panel. At the bottom are the amplitude and phase as a function of time for all 32 channels. The green bars along the bottom shows the validity of the recordings throughout. (Short red bars would appear if the recordings were compromised.)

BB_2)". Here it is worth noting that traditionally a "zero baseline" test refers to a case where there is a zero delay between recorded signals, and it is typically used to evaluate the performance the post-receiver recording system. In our present case, "ALMA" and "alma" refer to two separate signal chains derived from the ALMA Band 3 receiver, each of which includes a different set of phasing corrections applied to the antennas participating in the sum. The basebands are offset by (about) 200 MHz and a different set of switches and filters inserts various delay and phase modifications. What is non-standard in our case is that the signals in question are summed from the set of phased antennas and the delay system is using a common position for the two virtual "sum" antennas. Moreover, the delay implementation for BB_1 is more exact than the one for BB_2.

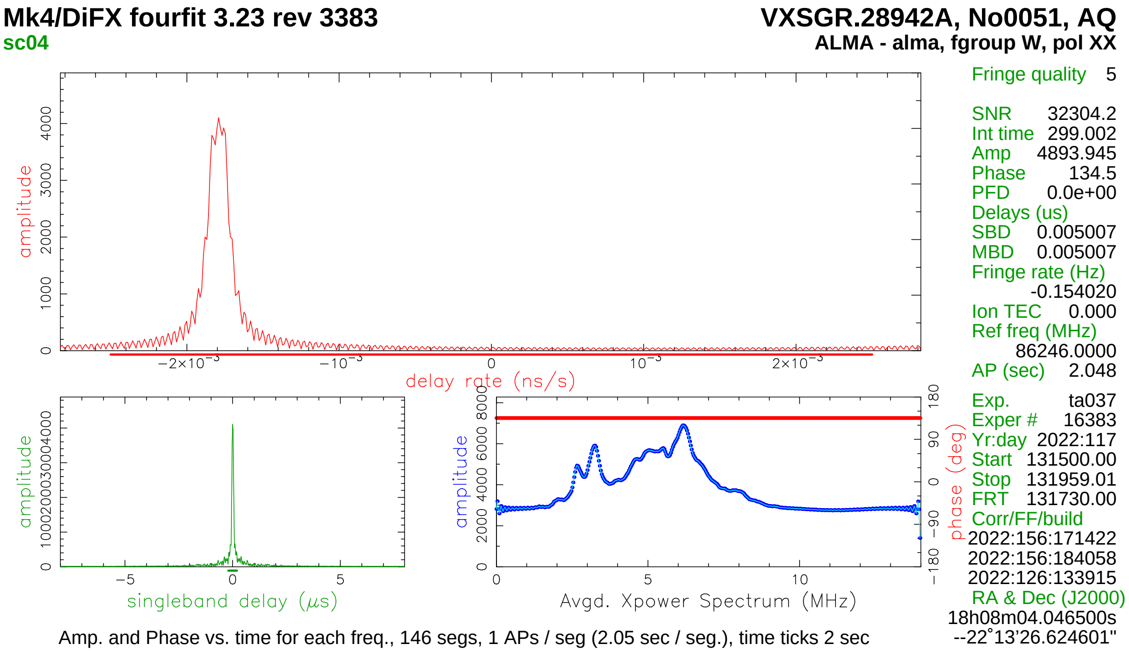


Figure 4: **ALMA-alma quasi-zero baseline fringe on VX Sgr**—Fringe detection generated using the HOPS `fourfit` tool for the ^{28}SiO v=1, J=2−1 maser line in VX Sgr (XX polarization) for the quasi-zero baseline between the two independent ALMA basebands (referred to as "ALMA" and "alma" or "A" and "Q"). The format of the plot is similar to Figure 3. The data were obtained at 13:15:00 UTC on April 27, 2022 as part of experiment `TA037`. Approximately 300 s of data were averaged. See Text for additional discussion.

For this quasi-zero baseline test the tuning and channel mismatches necessitated the use of zoom bands or output bands. For our preliminary examination we used a version of the data outputted with 14 MHz channels. As an example from that test, a fringe for the SiO maser target VX Sgr on the "ALMA-alma" baseline is shown in Figure 4. The cross-power spectrum of the fringe is essentially an autocorrelation and can thus be directly compared with the standard autocorrelations generated for the various ALMA antennas in the ASDM file (e.g., Figure 5).

The delay rate exhibited in Figure 4 is rather peculiar and is not fully understood as of this writing. One possible explanation is that it results from the fact that the geometric

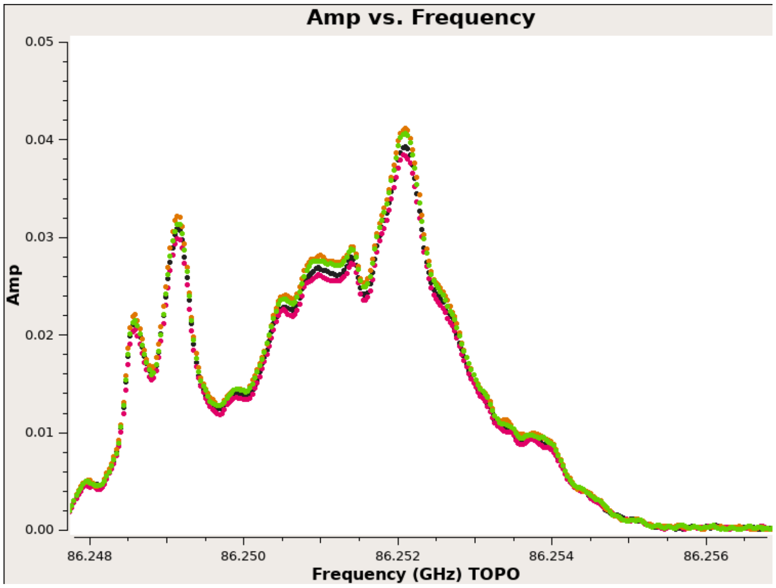


Figure 5: **ALMA-only visibilities on VX Sgr**—Raw (uncalibrated) full-scan average spectra of the ^{28}SiO v=1, J=2−1 line in VX Sgr (polarization XX) generated from the ALMA ASDM data for the same time interval and bandpass as shown in Figure 4. Data for several baselines are shown in different colors. Data source: uid://A002/Xf82791/X3c39.

delay model at ALMA is optimized for BB_1—i.e., the finest component of the delay is a small phase rotation that is computed and applied for BB_1, but only approximately correct for BB_2.

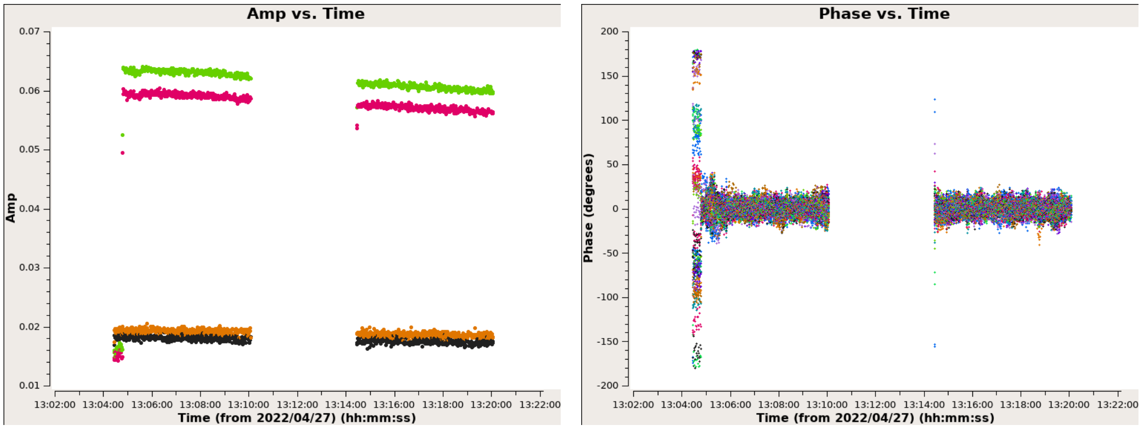


Figure 6: **APS performance on VX Sgr scans in Band 3**—Phasing results for the spectral line target VX Sgr, observed during a Band 3 VLBI test (`TA037`) on April 27, 2022. *Left:* Amplitude as a function of time on baselines from the phased sum antenna to comparison antennas DA47 and DV09 (XX pol only). *Right:* phase vs. time for baselines to the reference antenna (DV06) and each of the 43 antennas in the phased sum. At ALMA the PWV was ∼1 mm with wind speeds of 8–10 m s^{-1}, and the RMS phase fluctuations were $\sim \pm 20^\circ$. Data source: uid://A002/Xf82791/X3c3.

Table 2: TA037 Scans

Scan	Notes	Start	Source	Label[1]	Comments
No0019	+	2022y117d11h35m00s	RCAS	- (-)	not correlated
No0022	l E	2022y117d11h46m00s	V468CYG	f (m)	
No0025	l E	2022y117d11h56m00s	V468CYG	f (m)	
No0029	q E	2022y117d12h07m00s	BLLAC	- (-)	
No0034	l E	2022y117d12h18m00s	IRC+10011	e (k)	
No0037	q E	2022y117d12h29m00s	3C454.3	- (-)	
No0040	l E	2022y117d12h40m00s	IRC+10011	e (k)	
No0043	q x E	2022y117d12h51m00s	OCETI	d (j)	
No0048	l	2022y117d13h05m00s	VXSGR	e (l)	
No0051	l h	2022y117d13h15m00s	VXSGR	e (l)	
No0052	q h	2022y117d13h25m00s	BLLAC	- (-)	
No0056	l	2022y117d13h35m00s	RRAQL	e (l)	
No0059	l	2022y117d13h45m00s	RRAQL	e (l)	
No0062	l	2022y117d13h55m00s	RRAQL	e (l)	

[1] HOPS channel labels in the 14 (20) MHz correlation schemes (see Text).

`+` ALMA missed this scan due to the hardware tuning issue

`h` ALMA data was e-transferred to Haystack for a quick look

`l` a line source

`q` a quasar

`x` except for Nl, the VLBA missed this scan

`E` Ef and On available; Ys observed but in poor weather

Based on examination of the ALMA ASDM data for experiment `TA037`, the APS performance was nominal. As an illustration, Figure 6 shows the correlated amplitude and phase as function of time for the two VX Sgr scans (No0048 and No0051) on select ALMA-ALMA baselines. Both scans were actively phased using the ^{28}SiO v=1, J=$2-1$ line emission.

Special Considerations for Correlation on the ALMA-Haystack Baseline A challenge in correlating the data from the Haystack 37 m antenna as part of the `TA037` experiment was that the quartz crystal used as a frequency standard at Haystack was not monitored carefully prior to the experiment, and thus its drift was not well characterized. This made fringe searches particularly challenging, and significant effort was required to recover a clock model for the pair of scans that matched the available ALMA data. Nonetheless, this exercise served a good testbed to address correlating mis-tuned ALMA observations.

The correlation of baselines to ALMA generally requires a precise frequency specification and the use of zoom bands with a finer spectral resolution for the correlation than is desired in the output data set. This ensures that proper alignment can be achieved with the different bandpasses used at other stations. Typically a 15.625 kHz resolution is used. This then requires the frequencies to be multiples of that. However, with the ALMA tunings deployed in `TA037`, which were odd values chosen by `LOSolutions`, this was not possible. Since in general exact tunings are often not possible, there is an option in the DiFX correlation software that makes it possible to specify an "LO offset" for every recorded frequency. This option makes the small frequency adjustments so that the channels "line up". However, this option was introduced to handle small errors, and it has not been well explored for larger errors such as enountered for this experiment.

For the BB_1 data, the offset required was -0.102 Hz. For BB_2, the initial setup used a -9375.002 Hz offset with a declared center frequency of 86266.250000 MHz. However, this resulted in large coherence losses (tens of per cent). A later setup with a 86266.2421875 MHz center frequency and an offset of -1562.502 Hz produced much better results (although losses were still a few per cent).

4.3.3 Flexible Tuning VLBI Test (TA037) Analysis

Analysis using the HOPS `fourfit` package showed that there were generally good fringes for the continuum sources between ALMA and most of the other stations in the `TA037` experiment, including both the Effelsberg and Onsala European sites and bulk of the VLBA sites. However, as HOPS is not well-suited for fringe searches on spectral line targets, a subset of the `TA037` scans (including two scans of VX Sgr and three scans on bright continuum calibrators) was converted to FITS to allow importation into AIPS:

```
Scan Source Timerange RA(2000.0) Dec(2000.0)
1 BLLAC 12:07:01 - 12:09:57 22:02:43.2914 42:16:39.980
2 3C454.3 12:29:01 - 12:32:59 22:53:57.7479 16:08:53.561
3 VXSGR 13:05:01 - 13:09:58 18:08:04.0465 -22:13:26.625
4 VXSGR 13:15:01 - 13:19:58 18:08:04.0465 -22:13:26.625
5 BLLAC 13:25:01 - 13:27:57 22:02:43.2914 42:16:39.980
```

The decision to examine only a small subset of the data in AIPS was based on time constraints leading up to the Go/No-Go deadline for Cycle 10. The red supergiant VX Sgr is a well-known SiO maser source, while BL Lac and 3C454.3 are strong continuum calibrators with estimated 3 mm flux densities of 8.9 Jy and 5.3 Jy, respectively, based on the latest available Band 3 measurements in the ALMA Calibrator Catalogue.

Because the `TA037` data were correlated in multiple passes, the various pieces were read separately into AIPS and concatenated. The correlator passes used to produce the line scans included only a 20 MHz portion of the band centered at 86.248016 GHz. There were 512 spectral channels, yielding spectral resolution of 39.065 kHz ($\sim$0.13 $\mathrm{km\,s^{-1}}$). The continuum scans were processed with a wider bandwidth (160 MHz), spanned by 8 "IF channels", each of 20 MHz and with a spectral channel spacing identical to the line scans. However, only IF channel 5 (matching the band center and bandwidth of the line scans) was used for the present analysis. The integration time in all cases was 2.048 s.

No `PolConvert`[8] processing was done on the `TA037` data, hence the data read into AIPS remained inherently on mixed polarization basis, with ALMA's linearly polarization products relabeled "R" and "L". This relabeling was done using a Python utility developed by Jan Wagner (`polrelabelDiFX.py`) since FITS does not accommodate mixed pols. The resulting FITS data remain as intrinsically mixed polarization, but the purposes of these tests, this had no significant impact on our analysis.

Stations present in the data set included ALMA (with two independently tuned basebands, designated AA and AQ; see Section 4.3), Onsala (ON), Effelsberg (EF), and 8 VLBA stations (BR, FD, KP, LA, MK, OV, PT, NL; see Table 2 for the station code designations).[9] Yebes also participated in the experiment, but owing to poor weather, no useful data were recorded. The Haystack 37m antenna (see Section 4.3) did not participate in this subset of scans.

As a first step to creating a combined master data set in AIPS, it was necessary to reconcile the antenna, source, and frequency identifications of the different data chunks using AIPS task `MATCH` before combining them into a single master data set with `DBCON`. Following this latter step, the reference frequency was reset to the band center (using task `CENTR`) and u, v, w values were appropriately rescaled. Lastly, the data were re-indexed and a new 'CL' table was created using `INDXR`.

The VLBA generates for every experiment a set of files containing metadata needed to perform a complete calibration of its stations (e.g., online flagging information, gain curves, system temperatures). The corresponding files for `TA037` (ta037cal.vlba, ta037log.vlba, and vlba_gains.key) were downloaded from the VLBA web archive[10], and after some necessary reformatting, were processed using the task `VLOG` to produce a series of ascii tables that can be read by AIPS and appended to the data set in the form table extension files. These included an ANTAB table (traditionally used in VLBI For carrying out a priori amplitude calibration) and initial flagging information. The generated flags (which includes

---

[8] `PolConvert` (Martí-Vidal et al. 2016) is specialized software run at the VLBI correlation sites following the observations to convert ALMA's linearly polarized data products to a circular basis for compatibility with other VLBI stations that record circularly polarized data (see also Matthews et al. 2018).

[9] 'KP' refers here to the 25 m Kitt Peak VLBA antenna, not the Kitt Peak 12 m antenna used as part of the EHT (Section 6.3)

[10] `http://www.vlba.nrao.edu/astro/VOBS/astronomy/apr22/ta037/`

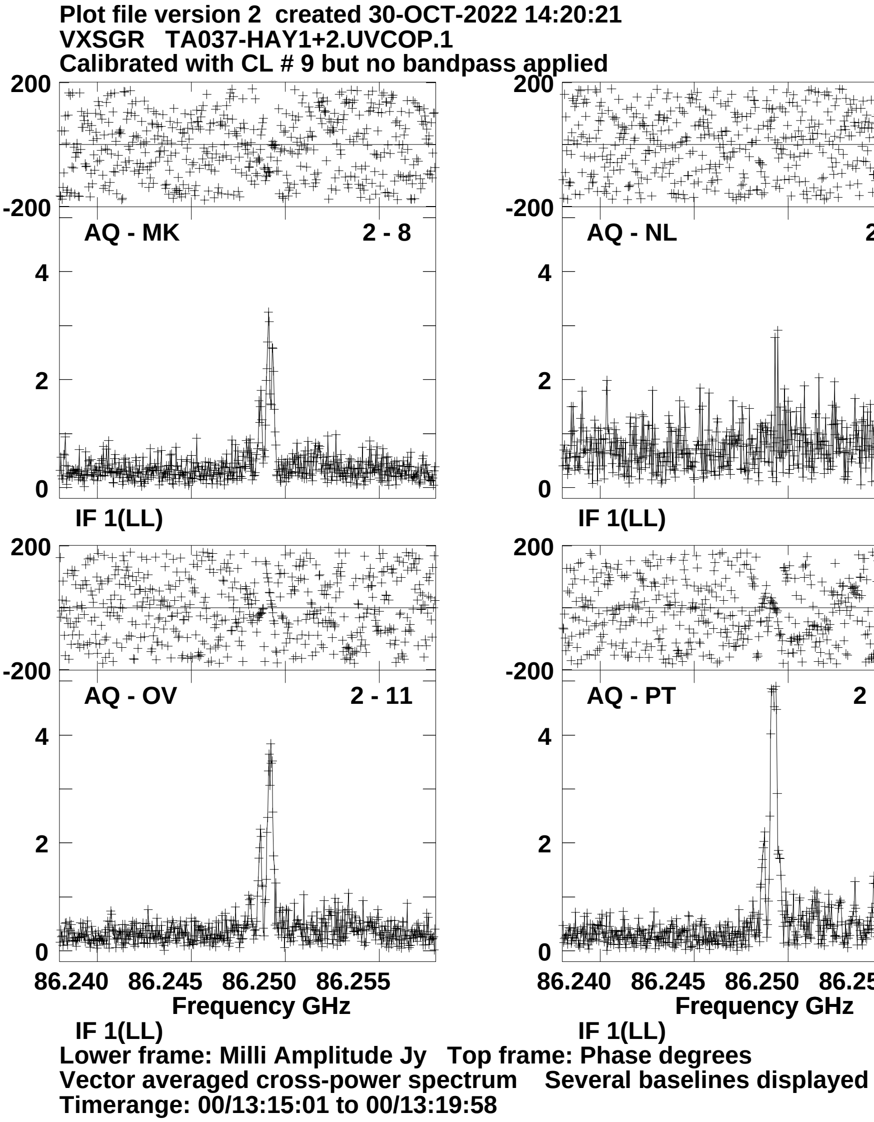


Figure 7: **Band 3 VX Sgr cross-power spectra (Stokes YL) on select ALMA-VLBA baselines**— Sample Band 3 cross-power spectra of the ^{28}SiO v=1, J=2−1 line in VX Sgr on baselines between ALMA BB_2 (code AQ) and several VLBA stations. Station codes are defined in Table 1. The mixed YL polarizations (labeled 'LL' here) are shown. The data have been calibrated for the instrumental delay using corrections derived from the continuum calibrator BL Lac and for the residual delay rate using solutions obtained from a single spectral channel of the line data (see Text for details). For each panel, phase as a function of frequency is shown along the top, and amplitude (in uncalibrated units) vs. frequency along the bottom. Approximately 5 minutes of data are vector averaged, starting at 13:15:01 UTC. The data were obtained on April 27, 2022 as part of experiment `TA037`.

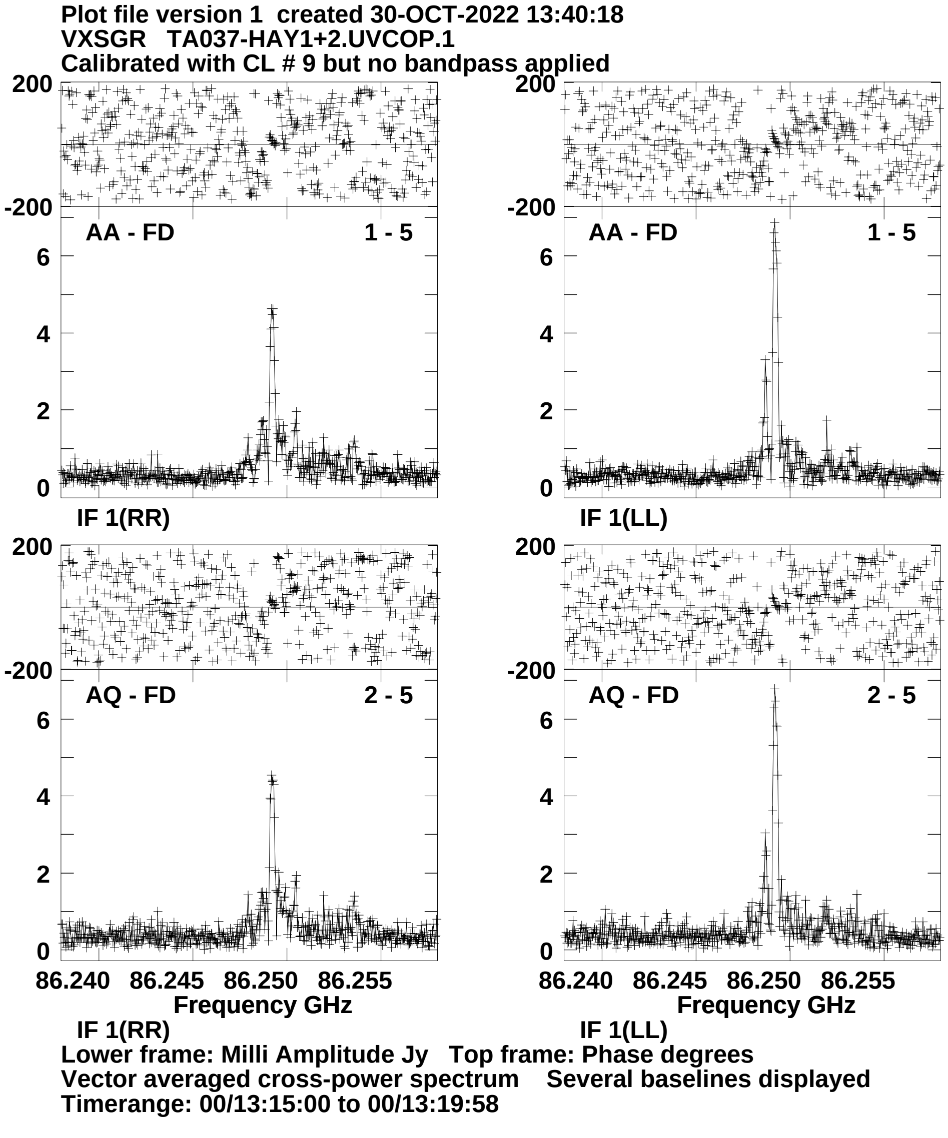


Figure 8: **Band 3 VX Sgr cross-power spectra on an ALMA-FD baseline**— As in Figure 7, but the top two panels show detections between ALMA BB_1 ('AA') and Fort Davis (FD) (XR and YL polarizations, labeled 'RR' and 'LL'), while the lower panels show the baseline between FD and the independently tuned ALMA BB_2 ('AQ'). Importantly, the two independent ALMA tunings are found to show fully consistent results.

information for the VLBA stations only) were imported using `UVFLG` to generate a flag ('FG') table on the master data set. Similarly, the ANTAB information was imported using the `ANTAB` task to produce a 'TY' table. Separate ANTAB tables were downloaded for the ON and EF stations via anonymous ftp[11] and concatenated with the VLBA information to create a single TY table for future use. However, because Quality Assurance Level 2 (QA2) had not yet been run on the ALMA data, ANTAB entries were not yet available for ALMA. Therefore no amplitude calibration was attempted during the analysis presented here. As a final pre-calibration step, the autocorrelation measurements were used to correct the data for digital sampler biases (task `ACCOR`).

As an initial step in the calibration, a "manual phase cal" was performed using a global fringe search with a 60 s portion of one of the BL Lac scans to solve for the instrumental delay (AIPS task `FRING`). AQ (ALMA baseband 2) was selected as the reference antenna. To circumvent issues caused by the extremely high signal-to-noise ratio (SNR) on the AA-AQ (inter-ALMA) baseline, the `FRING` parameter `WEIGHTIT` was set to 3.0 to impose unity data weighting for this preliminary analysis. After applying these solutions to all of the data, residual delays and rates were solved for on each of the continuum scans using 60 s solution intervals. For the continuum targets, clear fringe detections were detected on baselines to ALMA by all participating stations, including EF, ON, and each of the participating VLBA sites.

Because neither of the continuum calibrators was close in angular separation to the spectral line target VX Sgr, application of the residual delays and rates derived from the continuum calibrators to VX Sgr did not produce perceptible improvements in the coherence and SNR of the line emission. Instead, a residual fringe rate for VX Sgr was derived via a fringe fit to a single strong line channel (channel 290) with 60 s solution intervals (again using task `FRING`). Following this step, clear detections of the ^{28}SiO v=1, J=2−1 line were obtained on a wide range of baselines in both of the VX Sgr scans. Some examples are shown in Figure 7, including baselines between ALMA and, respectively, Mauna Kea, HI (MK; 9446 km), North Liberty, IA (NL; 7142 km), Owens Valley, CA (OV; 7896 km), and Pie Town, NM (PT; 7198 km). VX Sgr was not accessible to the stations in Europe during these scans.

Lastly, having two independently tuned ALMA basebands in our experiment allowed us to obtain important confirmation that ALMA's VOM functions nominally independent of the adopted tuning. As illustrated in Figure 8, results for the two independent ALMA basebands (both of which had passbands that captured the ^{28}SiO v=1, J=2−1 line, but with different tunings at the band center) are *fully consistent*, providing important validation of the use of flexible tuning for VLBI.

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[11] `ftp://vlbeer.ina.inaf.it/vlb_arc/ftp/vlbi_arch/apr22`

5 Panchromatic VLBI (WBS 2.0)

5.1 Motivation for Enabling VLBI "in Any Band"

As described above, VLBI at ALMA was initially restricted to two bands (Bands 3 and 6), each of which was limited to a single, fixed tuning option. Thanks to work done under APP2, sub-mm (Band 7) phasing and VLBI were tested and commissioned successfully (Crew et al. 2023; Raymond et al. 2024) and subsequently offered in Cycle 7.

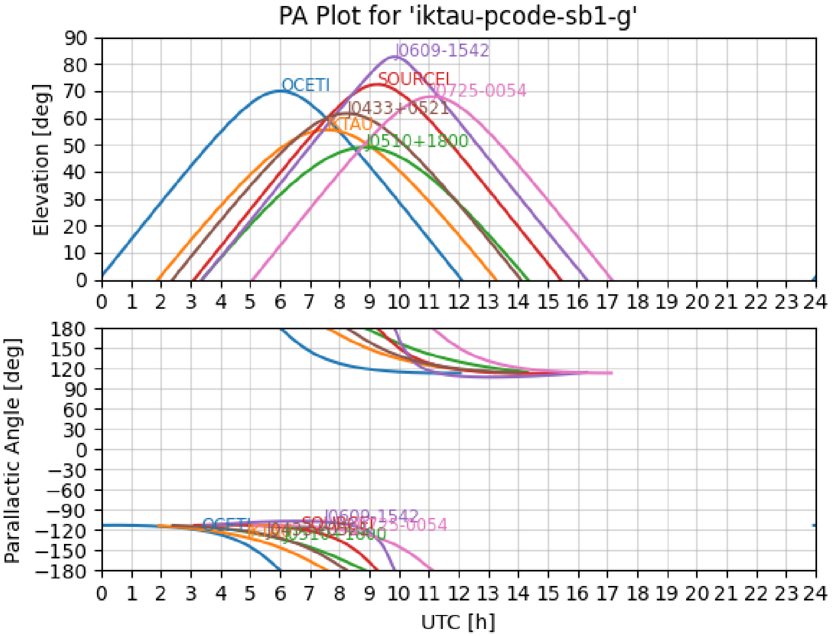


Figure 9: **TA037B planning**—Plots of elevation (top) and parallactic angle (bottom) as a function of time as seen from ALMA for sources observed as part of the `TA037B` Band 1 test on October 4, 2022. The VLBI schedule ran from 08:00–11:00 UTC.

More recently, ALMA has deployed another receiver band, Band 1 (operating at 35-50 GHz, or $\lambda \sim 7$ mm), which was offered for the first time for standard interferometry in Cycle 10. The Band 1 receivers have an 8 GHz IF and are the only upper sideband (USB) receivers currently used for VLBI. Band 1 is of particular interest for phased array and VLBI science since it contains astrophysically important spectral lines and overlaps with the passband of Q-band receivers on the VLBA. Several of the European GMVA sites also have receivers at this frequency. Additionally, Band 1 is considered an important band for future high-frequency pulsar studies. Pushing pulsar studies into the mm regime has long been recognized as crucial for better understanding pulsar physics and emission mechanisms (e.g., Torne 2018). However, owing to their steep spectra (e.g., Lorimer & Kramer 2005) pulsars are generally quite faint at mm wavelengths, making high sensitivity observations (such as can be provide by phased ALMA) critical for their detection (see Liu et al. 2019).

While Band 1 extends the lower frequency coverage of ALMA, there has been a growing

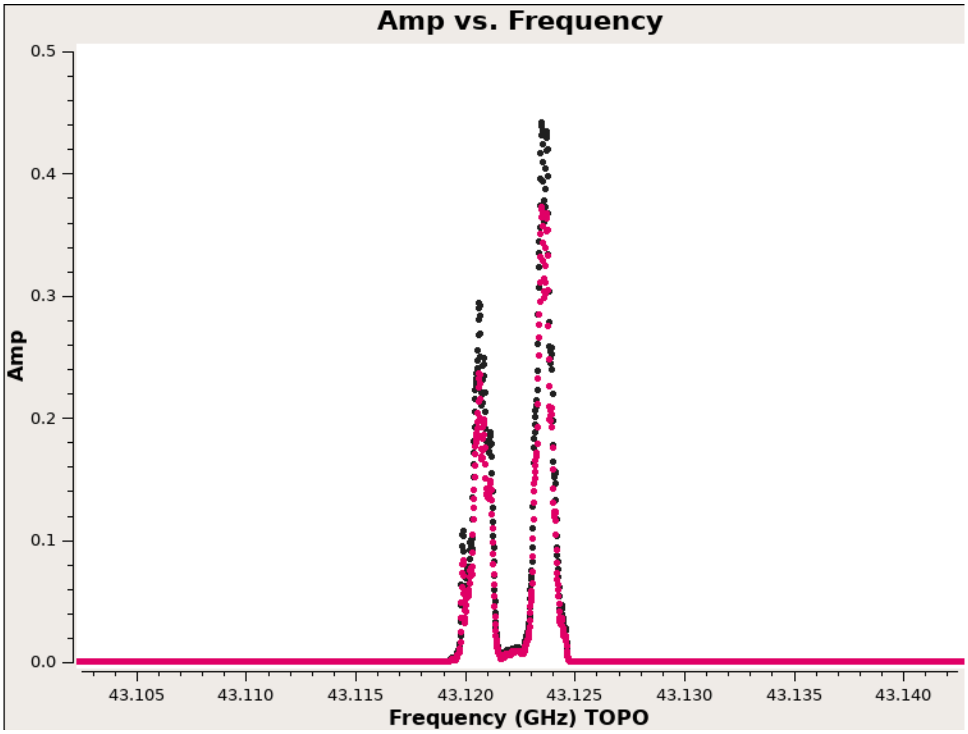


Figure 10: **High-resolution ALMA spectrum of the ^{28}SiO v=1, J=1-0 line in Orion Source I**—Full scan-averaged, uncalibrated ALMA spectrum of the ^{28}SiO v=1, J=1-0 line (XX polarization) from Orion Source I on two baselines, as observed during the Band 1 VLBI test experiment `TA037B` on October 4, 2022. These data were obtained using a high-resolution observing setup in one of the basebands not recorded for VLBI (BB_3). Channel spacing is ∼15 kHz. Data source: uid://A002/Xff294f/X531e.

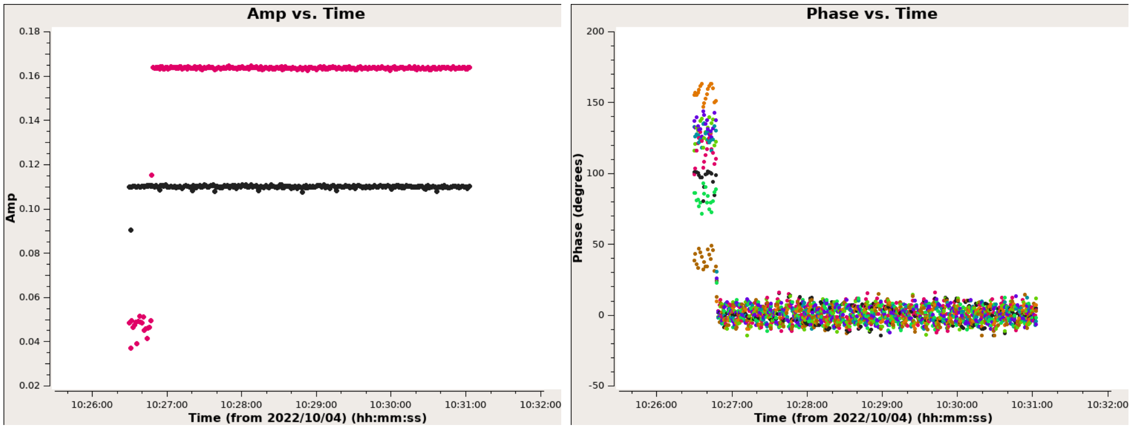


Figure 11: **APS performance on Source I scans during TA037B**—*Left:* Correlated amplitude vs. time on baselines from the phased sum antenna to the unphased comparison antenna PM04 (XX polarization only). *Right:* phase as a function of time for baselines to the reference antenna (DV13) for all 9 antennas in the phased sum. RMS phase fluctuations of $\sim \pm 10°$. The PWV at most antennas was about 0.75 mm with wind speeds ~6 m s^{-1}. It is improbable, but nevertheless possible for 9 random phases to all be > 0, which is why the scatter in phase plot during the first several seconds of the scan (i.e., prior to phase-up) is one-sided. Data source: uid://A002/Xff294f/X531e.

push to explore whether ground-based VLBI may be extended to still *higher* frequencies beyond Band 7 (e.g., Pesce et al. 2024; M.-T. Chen, priv. comm.). Lastly, while there are not currently peer VLBI networks operating in the equivalent of ALMA Bands 2, 4, and 5, such sites may come online in the future, providing a new window on science in the years before the WSU is fully realized. These bands are also of possible interest for pulsar studies (see, e.g., Torne 2018).

5.2 Software Requirements

Most parts of the original APS itself were designed to be band-agnostic. Therefore the primary challenge was to find and remove all band-specific restrictions imposed during VLBI observing (owing to the original restriction of VLBI to Bands 3 and 6) and then to make explicit tests of the various capabilities in all of the remaining bands. Among the required changes were modification of the SSR and SB scripts to allow APS/VOM operation in any ALMA band, updates to Quality Assurance Level 0 (QA0+) and QA2 scripts, and changes to the OT.

The primary OT changes needed for panchromatic VLBI included enabling selection of additional ALMA bands for VLBI, establishing recommended flux density limits for phasing targets in each band, provision of guidelines on the maximum angular separation for passive phasing calibrators (“phasors”) for each case, and defining a set of default VLBI frequency specifications for each ALMA band (which may, however, be tweaked by the user; see Section 4.2). The APP3 team worked with the OT programmers to define and subsequently vet these various modifications. The default tuning for Band 1 was also selected and added to the OT. Its definition was chosen for comparability with prospective peer observing sites and is summarized in the ALMA Technical Handbook.

As of this writing, default tunings have not yet been defined for Bands 2, 4, 5, 9, and 10 and these bands are not selectable within the OT since ALMA did not formally offer them for VLBI in Cycle 11. The APP3 team has filed a pending Cycle 12 ticket (SCIREQ-2855) to request that these be enabled in the OT and will follow this with an ICT ticket to capture the development of a set of default tunings appropriate for each band.

5.3 On-Sky Testing and Verification

On-sky verifications of "VLBI in any band" focused primarily on the newly available Band 1. A few recent standalone ALMA phasing tests in Band 9 were also carried out (see Section 5.3.5).

5.3.1 Band 1 Testing (TA037B)

To validate phasing operations in Band 1 we devised a plan that consisted of a short execution to verify tunings at the start of Cycle 9 followed by a 3 hour global VLBI session (08:00–11:00 UTC on October 4, 2022; project code `TA037B`) in collaboration with the VLBA. This test simultaneously supported the validation of fully flexible spectral line VLBI capabilities (see Section 6). At the time of our test, only a subset of the ALMA antennas has been equipped with Band 1 receivers, hence we operated with a small phased array of 9 12 m antennas. The adopted tuning (using the repaired `LOSOlutions`) was as follows:

```
BB Request       ((CVR freq)*factor -offset) + offset)*mult    LO2 freq            Result           Offset Sideband  Weight
b1  43.168000000 (( 5.033928571429*7 -0.125) + 0.0325)*1 +     11.023000000000-3 =  43.168000000003   +3.0 mHz USB   100.0 %
b2  43.122000000 (( 5.033928571429*7 -0.125) + 0.0325)*1 +     10.977000000000-3 =  43.122000000003   +3.0 mHz USB   100.0 %
b3  43.122000000 (( 5.033928571429*7 -0.125) + 0.0325)*1 +     10.977000000000-3 =  43.122000000003   +3.0 mHz USB   100.0 %
b4  43.122000000 (( 5.033928571429*7 -0.125) + 0.0325)*1 +     10.977000000000-3 =  43.122000000003   +3.0 mHz USB   100.0 %
```

This setup gave a VLBI central frequency of 43.168 GHz (for BB_1) and the band center for the three non-VLBI bands (which were used for parallel high spectral resolution ALMA-only observations) was 43.122 GHz.

The targets we selected were three spectral line sources known to have strong emission in the ^{28}SiO v=1, J=1 − 0 line, (rest frequency 43.122 GHz), along with a selection of bright continuum and polarization calibrators (see Figure 9). To enable a QA2 analysis of the kind typically performed by ALMA staff following observations (and before delivery of data products to PIs), we included extra ALMA polarization targets, since polarization in Band 1 had at the time not yet been well characterized.

Sky positions of the line targets were updated to correct for proper motions according to the best available information from *Gaia* Data Release 3 and Goddi et al. (2011). For the line targets, expected sky frequencies for the SiO line emission were computed for the time of observation using LSR velocities of each target from the literature. Bandwidths for the phasing windows used for each line source (see below) were also estimated from published line profiles.

The entire `TA037B` test project was constructed of 4 SBs, three for each of the possible pre-test execution dates (on October 1, 2 and 3, 2022), and a fourth for the actual global VLBI test. The pre-tests contained a short scan on each of the three spectral line targets and were intended as checks on tunings and target coordinates.

In addition to validating tunings, the pre-tests provided useful checks of the target positions. Since the ALMA observations must be done through a common VEX file shared with the other participating stations, it is necessary to make the corrections for proper motion to the epoch of observation directly in the VEX file, since none of the other sites have these corrections embedded in the software equivalent to the `MountController` software at ALMA. As for our other spectral line VLBI tests (Section 6.2, 6.3.1), "hints" were used in the preparation of all SBs, i.e.:

```
global:SpecLineList=OCETI:43.11502:0.7:linewidth 5km/s,
                    IKTAU:43.11854:1.4:linewidth 10km/s,
                    SOURCEI:43.12080:5.7:linewidth 40km/s
global:SpecLineBB1Only=1
```

(There are only two lines in the "hints" file, but the text is wrapped here for readability).

Our pre-test was executed on October 2, 2022. While it established that our positions and tunings were correct, it revealed that something was wrong with the results from the APS. Upon investigation we established that the channel-average code used to define the portion of the spectral band used to compute the phasing solutions for the line targets in the `VLBICalTarget` module was not compatible with USB receivers. The explanation for this is as follows: the phasing system works in channel average space and the ASDM specification is ambiguous on the semantics of channel averages. For most ALMA observations, the channel averages contained in the ASDM are averages across the entire spectral window. However, for the APS we subdivide the full 1.875 GHz band into 8 portions according to indices defined from the full 1920 point spectrum. In the BL Correlator implementation of the APS, the sense of the indices is that 0 refers to the "DC edge" and increasing indices move away from that. This results in different senses for USB versus lower sideband (LSB). We were able to implement a solution for this issue when the main experiment was run (see Section 5.3.2). A further complication of all of this is that the mapping of channel averages to sky frequencies (e.g., as seen in the ASDM data when viewed in CASA) was correct in only one sideband at the time of the `TA037B` test.

5.3.2 Execution

The full `TA037B` test was executed on October 4, 2022. The ultimate solution to the USB phasing issue described above was to modify the coding to handle both LSB and USB calculations. However, as there was insufficient time for this prior to our `TA037B` test, a temporary solution was to flip the requested line position around the center frequency for BB_1, i.e.,

```
global:SpecLineList=OCETI:43.22098:0.7:width 5km/s,
                    IKTAU:43.21746:1.4:width 10km/s,
```

```
SOURCEI:43.21350:6.0:width 40km/s
```

While this solved the phasing problem, it broke the existing QA0+ script (until a special option to cope with this was added). It took a few iterations to get the fixed version (version 8) properly running, but in the end, most of the scans were executed with proper phasing and sufficient ALMA calibrations to enable QA2. Sample results for one of the scans on Orion Source I are shown in Figures 10 and 11.

5.3.3 TA037B Correlation

During past APP commissioning tests that partnered with the VLBA, NRAO performed an initial correlation of the VLBA-only baselines for diagnostic purposes and then shipped the recorded VLBA disk packs to Haystack for copying. This enabled subsequent correlation of the full experiment (ALMA+VLBA) to be done at Haystack. In the case of `TA037B`, NRAO did their initial correlation, but was delayed in their ability to release the disk packs. Consequently only a limited subset of the `TA037B` scans were analyzed prior to the deadline for ObsMode 2022 review of new capabilities. Initially, two good-quality scans were identified for e-transferred to Haystack for correlation, one on Source I and one on the continuum calibrator OJ287, viz.:

```
   Scan      Source    Timerange           RA(2000.0) Dec(2000.0)
No0019   SOURCEI   10:27:01 - 10:30:59   05:35:14.5236 -05:22:30.671
No0022   OJ287     10:49:01 - 10:52:59   08:54:48.8749 +20:06:30.641
```

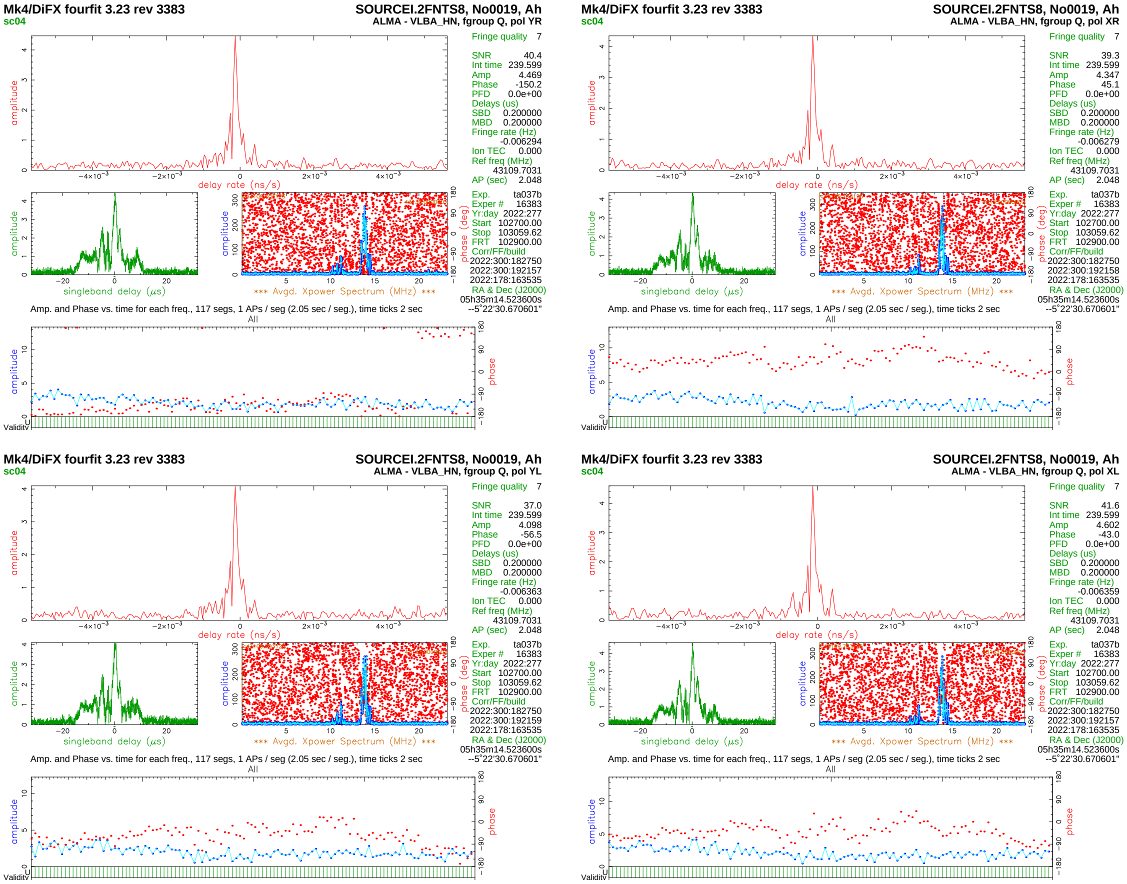
The selection of these two scans for our initial data assessments was based on the recommendation of VLBA staff following an examination of the VLBA-only correlation results. The conditions at ALMA at the time of those scans were outstanding, with PWV$\sim$0.75 mm and a wind speed of $\sim$6 m s^{-1}.

Three VLBA antennas were unable to participate in the `TA037B` experiment: Kitt Peak because of fires, and Pie Town and Brewster owing to technical issues. In addition, the source elevation at Mauna Kea was quite low during the above two scans. Therefore only data from Saint Croix (SC), Hancock (HN), Los Alamos (LA), and North Liberty (NL) were considered.

The correlation setup used at Haystack was similar to that used in `TA037` (Section 4.3), but with all frequencies shifted down to Band 1. (HOPS refers to frequencies by RF band letters, which in this case is 'Q-band' for 33 GHz to 50 GHz range.) Six of the ALMA frequency channels sit easily in four of the VLBA DDC bands, so the data could be correlated with DiFX using conventional zoom bands.

5.3.4 TA037B Analysis

A sample fringe detection of the Orion Source I ^{28}SiO v=1, $J = 1 - 0$ maser (obtained using the HOPS `fourfit` package) is shown in Figure 12. `PolConvert` has not been run on the data, so they remain in a mixed polarization basis. Figure 12 shows the fringes for all four (mixed) polarization products, with data restricted to a passband near the SiO line.



```
Mk4/DiFX fourfit 3.23 rev 3383                SOURCEI.2FNTS8, No0019, Ah
sc04                                ALMA - VLBA_HN, fgroup Q, pol YR
Fringe quality   7

SNR             40.4
Int time     239.599
Amp            4.469
Phase         -150.2
PFD         0.0e+00
Delays (us)
SBD       0.200000
MBD       0.200000
Fringe rate (Hz)
           -0.006294
Ion TEC        0.000
Ref freq (MHz)
          43109.7031
AP (sec)       2.048
Exp.          ta037b
Exper #        16383
Yr:day      2022:277
Start      102700.00
Stop       103059.62
FRT        102900.00
Corr/FF/build
   2022:300:182750
   2022:300:192157
   2022:178:163535
RA & Dec (J2000)
  05h35m14.523600s
   --5°22'30.670601"
Amp. and Phase vs. time for each freq., 117 segs, 1 APs / seg (2.05 sec / seg.), time ticks 2 sec
```

```
Mk4/DiFX fourfit 3.23 rev 3383                SOURCEI.2FNTS8, No0019, Ah
sc04                                ALMA - VLBA_HN, fgroup Q, pol XR
Fringe quality   7

SNR             39.3
Int time     239.599
Amp            4.347
Phase           45.1
PFD         0.0e+00
Delays (us)
SBD       0.200000
MBD       0.200000
Fringe rate (Hz)
           -0.006279
Ion TEC        0.000
Ref freq (MHz)
          43109.7031
AP (sec)       2.048
Exp.          ta037b
Exper #        16383
Yr:day      2022:277
Start      102700.00
Stop       103059.62
FRT        102900.00
Corr/FF/build
   2022:300:182750
   2022:300:192158
   2022:178:163535
RA & Dec (J2000)
  05h35m14.523600s
   --5°22'30.670601"
Amp. and Phase vs. time for each freq., 117 segs, 1 APs / seg (2.05 sec / seg.), time ticks 2 sec
```

```
Mk4/DiFX fourfit 3.23 rev 3383                SOURCEI.2FNTS8, No0019, Ah
sc04                                ALMA - VLBA_HN, fgroup Q, pol YL
Fringe quality   7

SNR             37.0
Int time     239.599
Amp            4.098
Phase          -56.5
PFD         0.0e+00
Delays (us)
SBD       0.200000
MBD       0.200000
Fringe rate (Hz)
           -0.006363
Ion TEC        0.000
Ref freq (MHz)
          43109.7031
AP (sec)       2.048
Exp.          ta037b
Exper #        16383
Yr:day      2022:277
Start      102700.00
Stop       103059.62
FRT        102900.00
Corr/FF/build
   2022:300:182750
   2022:300:192159
   2022:178:163535
RA & Dec (J2000)
  05h35m14.523600s
   --5°22'30.670601"
Amp. and Phase vs. time for each freq., 117 segs, 1 APs / seg (2.05 sec / seg.), time ticks 2 sec
```

```
Mk4/DiFX fourfit 3.23 rev 3383                SOURCEI.2FNTS8, No0019, Ah
sc04                                ALMA - VLBA_HN, fgroup Q, pol XL
Fringe quality   7

SNR             41.6
Int time     239.599
Amp            4.602
Phase          -43.0
PFD         0.0e+00
Delays (us)
SBD       0.200000
MBD       0.200000
Fringe rate (Hz)
           -0.006359
Ion TEC        0.000
Ref freq (MHz)
          43109.7031
AP (sec)       2.048
Exp.          ta037b
Exper #        16383
Yr:day      2022:277
Start      102700.00
Stop       103059.62
FRT        102900.00
Corr/FF/build
   2022:300:182750
   2022:300:192157
   2022:178:163535
RA & Dec (J2000)
  05h35m14.523600s
   --5°22'30.670601"
Amp. and Phase vs. time for each freq., 117 segs, 1 APs / seg (2.05 sec / seg.), time ticks 2 sec
```

Figure 12: **HOPS quick-look fringe on Orion Source I (Aa–Hn baseline)**—A collection of HOPS `fourfit` plots showing detection of the ^{28}SiO v=1, J=1-0 maser in Orion Source I in all four mixed polarization products (YR, XR, YL, XL) on the ALMA–Hancock (HN) baseline. The results were obtained as part of the Band 1 test `TA037B` on October 4, 2022.

To enable further post-correlation analysis of data from the `TA037B` experiment in AIPS, a FITS file was created from the subset of correlated data. As for `TA037` (Section 4.3.3), a Python script was first used to relabel the mixed polarization products as circular so that a FITS files could be created. The resulting data set had a total bandwidth 348 MHz, spanned by 6 IF channels, each 58 MHz wide with 3712 spectral channels, giving a spectral resolution of $\sim$0.1 km s^{-1}. As the ^{28}SiO v=1, J=1-0 emission from Orion Source I was confined to IF channel 3, only that IF channel was considered in the current analysis.

After copying out IF channel 3, the reference frequency was reset to the center of the new spectral band (using task `CENTR`) and u, v, w values were scaled to the new reference frequency. The resulting band center was 43.138707 GHz. Subsequently the autocorrelation measurements were used to correct the data for digital sampler biases (task `ACCOR`).

Because the QA2 products were not yet available for ALMA (including the system temperature information necessary to construct an ANTAB table) no amplitude calibration was attempted during our analysis. To calibrate the instrumental delays, a global fringe fit was performed using a 60 s portion of the OJ287 scan using AIPS task `FRING`. High SNR solutions were found for all stations. After applying these corrections to the data, the residual delay rate for the line target Source I was determined using emission from a single strong line channel (channel 900) with 60 s solution intervals.

Because of the high SNR of the detected ^{28}SiO v=1, J=1-0 emission, a few iterations of phase-only self-calibration (AIPS task `CALIB`) were subsequently performed using the data from a single spectral channel (again channel 900) and solution intervals of 20 s. Sample cross-correlation spectra of Source I obtained after applying this full set of preliminary calibrations are shown in Figure 13. High SNR detections were obtained on all baselines in the array, confirming ALMA's ability to function nominally as a VLBI station in Band 1.

5.3.5 Band 9 Testing

As noted in Section 5.1, during 2023 some interest emerged from the community for exploring VLBI feasibility in Band 9. Consequently, this became the first "other" band to be explored following recent APP3 modifications to the VOM. Details are reported elsewhere (Crew & Matthews 2024). Here we simply note that this test case validated our assertions that following the software updates implemented under APP3 (Section 5.2), the only additional work required to add support for any ALMA receiver band (in this case, Band 9) was (i) add it to the regression software; and (ii) sidestep the current lack of OT support for selection of the requested receiver for a VLBI experiment (see Section 5.2). Validation concluded with an on-sky test and the successful demonstration of plausible phasing in Band 9.

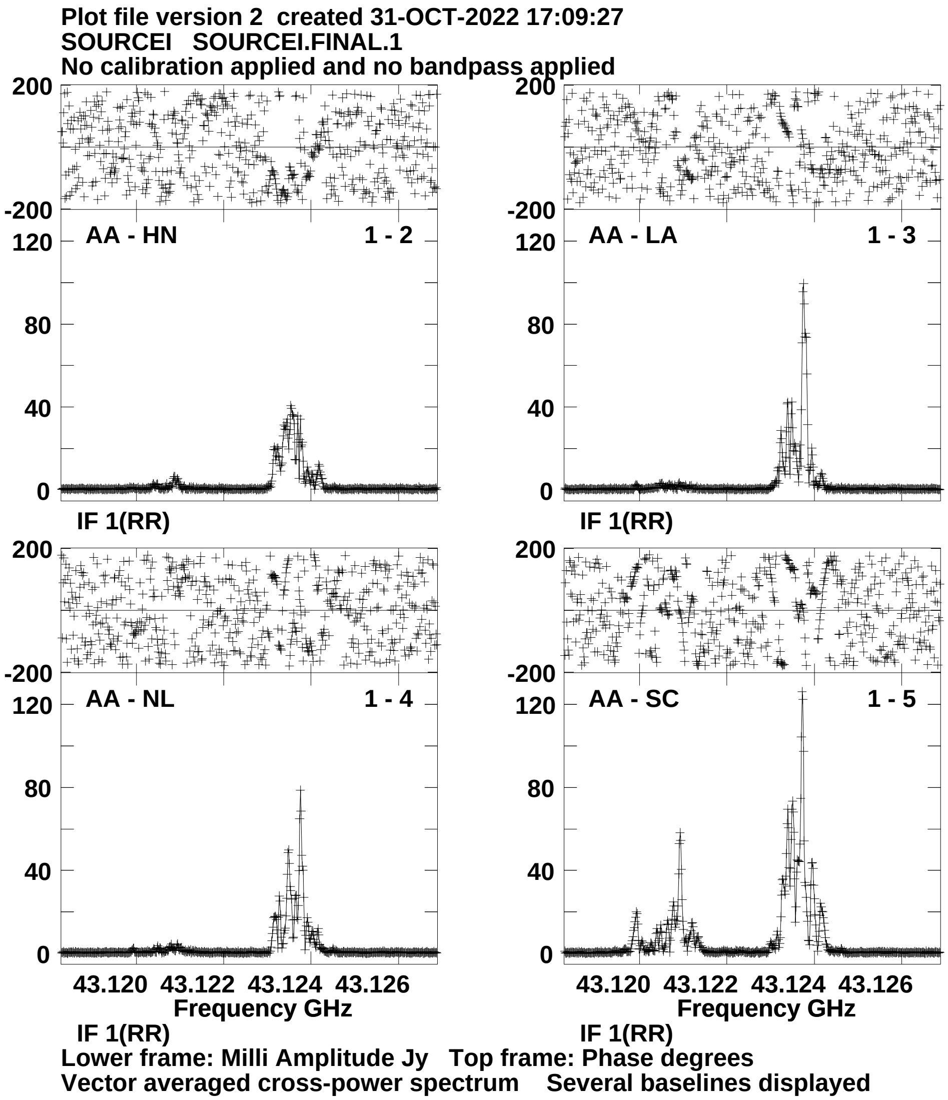


Figure 13: **Band 1 cross-power spectra (Stokes XR) of Orion Source I on select ALMA-VLBA baselines**— Sample Band 1 cross-power spectra of the ^{28}SiO v=1, J=1−0 line in Orion Source I on baselines between ALMA (AA) and several VLBA stations. Station codes are summarized in Table 2. Mixed XR polarizations (labeled 'RR' here) are shown. A preliminary calibration of the delay, delay rate, and phases has been applied (see Text for details). For each panel, phase as a function of frequency is shown along the top, and amplitude (in uncalibrated units) vs. frequency along the bottom. Approximately 4 minutes of data have been vector averaged, obtained starting at 10:27:01 UTC on October, 2022 as part of experiment `TA037B`.

6 Spectral Line VLBI with Flexible Tuning (WBS 2.0)

6.1 Motivation for a More Flexible Spectral Line VLBI Capability

The original ALMA VOM was optimized for the observation of continuum sources. The APP2 subsequently implemented a prototype spectral line VLBI observing capability (offered in Cycle 9 for Band 3 only) that operated within this framework, but its applicability was restricted to a single scientific use case, namely observations of Galactic SiO masers at λ3 mm.

One of the major objectives of APP3 was to finally deliver a versatile and fully flexible spectral line VLBI observing mode. This mode allows VLBI observers to observe any scientifically interesting line that falls within one of ALMA's receiver bands and to optimally place the line(s) of interest within each available baseband. In addition, these upgraded spectral line mode allows the option of three different phase-up methods for the array, depending on the properties of the science target. Achieving these goals required the parallel implementation of flexible tuning options for all ALMA VLBI observing bands, as discussed in Section 5.

6.2 Software Requirements for a Flexible Spectral Line Mode

Array phase-up for spectral line sources at ALMA can in principle be handled in multiple ways, depending on the properties of the science target. For line targets with sufficiently bright continuum emission ($\gtrsim$500 mJy, depending on the band), phase-up of the array using the continuum emission is possible in a manner analogous to a standard continuum experiment. For targets with weaker continuum, or with broad absorption lines, passive phasing (i.e., phasing the array using a nearby continuum calibrator) can instead be used. The mechanics are again analogous to the continuum case, although enabling this option required including provisions for a spectral line observer to select this option in the OT and enter a preferred phasor source and other set-up information. A third option, for targets with sufficiently bright emission lines (i.e., masers), is to phase up the array by directly using the signal from line emission ("active" phasing).

The code to support active phasing on spectral lines was originally developed for Band 3 as part of APP2, but it was done in a manner that allowed future extension to other bands. The required software changes spanned several different subsystems, including the OT, `VEX2VOM`, the SSR code, and the post-processing software PolConvert.

In the case of the OT, the APP3 team worked with the OT programming team to define a series of required modifications. These included:

- A relaxation of the existing spectral setup constraints to allow greater choice in band placement.
- Extension of the existing Band 3 'dopset' capability to all VLBI bands.
- Enabling specification of line rest velocity

- Provision of an entry box to summarize known information about the line target (peak flux density, LSR velocity, linewidth) and the requested correlation parameters.
- Impose a limit of one phased line per baseband.

During phasing operations on continuum sources, each 1.875 GHz ALMA baseband is divided into a series of channel averages (typically 8) and phasing solutions are computed independently for each channel average. However, in the spectral line case, if phase-up using emission on the line itself is desired, the bandwidth of the channel average containing the primary line of interest is modified to cover only the line peak. This eliminates noise from the portion of the baseband containing little or no signal. [The spectral window (SPW) containing the full-resolution spectral data is not affected]. The information needed by the phasing system to define these windows is conveyed via “hint” directives. These are supplied to `VEX2VOM` which then merges information about the observation (from the VEX file) with the SB generated from the OT in phase 2. The hint directives are either suggestions to `VEX2VOM` or explicit expert parameters (EPs). For spectral line VLBI the three relevant EPs are:

`SpecLineList` This is provided by the OT and includes a comma-separated list of source, frequency, bandwidth, as well as observer comments. The OT provides the source as `tmp.vex` since the source name required is only available once the VEX file has been prepared the external VLBI scheduler.

`SpecLineData` This is an alternate name for `SpecLineList`, left over from development of the mode before the OT implementation was completed.

`SpecLineBB1Only` In the Band 1 and Band 3 cases (where only one baseband is currently recorded during VLBI observations) the SPWs for the other basebands may be configured as with normal ALMA spectral line observations with higher spectral resolution and/or narrower observing bandwidths. This directive prevents the channel-average adjustments (used for array phase-up) from being made in those basebands.

6.3 On-sky Testing and Commissioning of the Spectral Line VLBI Observing Mode

6.3.1 Planning and Preparation

In March 2022, as part of the regular Cycle 8 ALMA-EHT VLBI science campaign, the EHT Collaboration (EHTC) decided to include in its observing schedules a few scans on bright SiO line targets with known emission in the ^{28}SiO v=1, J=5−4. This line (with rest frequency 215.59595 GHz) lies within baseband 2 of the standard EHT continuum observing passband. The goal was not maser science, but rather to explore whether such scans could be successfully used for amplitude calibration purposes, via the “template fitting” method that is commonly used in lower frequency VLBI experiments (see, e.g., Reid 1999). Through coordination with JAO and the EHTC, the APP3 team seized this opportunity to further validate the fully flexible spectral line observing mode and to commission spectral line VLBI observing in Band 6 at ALMA.

Two Galactic SiO line sources—the evolved stars VX Sgr (near Sgr A*) and W Hya—were selected as targets based on previous high SNR detections in the ^{28}SiO v=1, J=5−4 line with single-dish telescopes (Clemens & Lane 1983; Jewell et al. 1987) and compatibility with the ALMA-EHT Cycle 8 observing schedule. The coordinates for both stars were updated for the epoch of observation to take into account the source proper motions based on the *Gaia* Data Release 3.

Sky frequencies for ^{28}SiO v=1, J=5−4 line at the time of observation were computed for both targets assuming LSR velocities of 5.3 km s^{-1} for VX Sgr and 42.0 km s^{-1} for W Hya (Rizzo et al. 2021; Alcolea et al. 1999). Based on the previously observed SiO linewidths, phasing bandwidths of 7.2 MHz were used in both cases. Thus the "hint" directives to the APS (see Section 5.3.1) were:

```
global:SpecLineList=VXSGR:215.622241870:7.2:app3test
global:SpecLineList=WHYA:215.579214995:7.2:app3test
```

The two line targets are identified by their names in the VEX file (i.e. VXSGR for VX Sgr and WHYA for W Hya) and the aforementioned hints were placed in the input to VEX2VOM and were converted to EPs in the SBs.

We initially considered inserting "special test" SBs between the planned Cycle 8 science SBs, as shown in Figure 14.

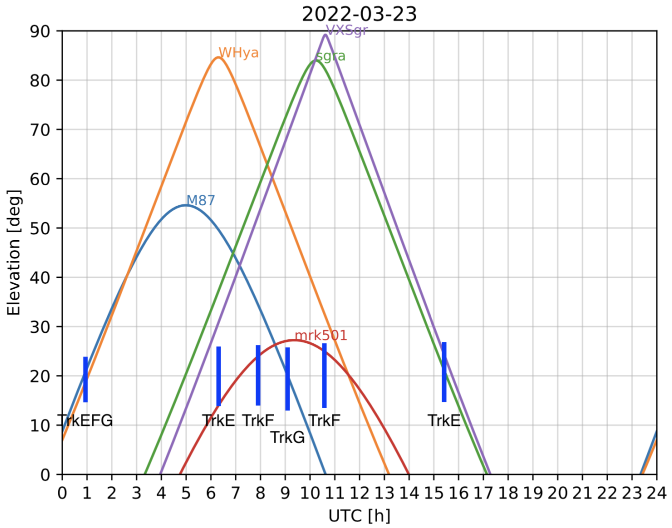


Figure 14: **Band 6 spectral line planning**—Elevation as a function of time for sources in the Cycle 8 Band 6 VLBI SBs. This figure was used to explore slots where test SBs could be inserted in-between regular VLBI science SBs. The blue vertical lines reflect end-points on the E, F and G tracks which were all primarily supporting the EHT's M87 observing project. Credit: H. Messias.

However, a crucial disadvantage of this approach is that the targets would all be at low elevations at ALMA, likely leading to poor performance. Also, the QA2 would be challenging since these scans would not be part of a calibrated session. To avoid these issues, we made a special request to the ALMA Director of Science Operations (DSO) to allow the scans to be inserted into the existing Band 6 VLBI science projects. The request was granted, and several scans were inserted into unused time intervals in some of the observing tracks. Some of the scans were actively phased and others were passively phased and left to "coast" through the spectral line target.

The "fast" phasing mode [which applies water vapor radiometer (WVR) corrections approximately once per second] was used during the March 2022 observations, in addition to the standard (slow) phasing mode. As an example, the log comments for the phasing adjustments to the baseband where the line of interest falls are shown in Figure 15 for the VX Sgr scan scheduled for 13:08:00 UTC on March 22, 2022.[12] Note that this process is pre-checked using the Observing Script Simulator (OSS) during the planning stages when the SBs are built (see Section 7.3).

```
[frame=single,fontfamily=courier,
   xleftmargin=-1.5cm,xrightmargin=-1.5cm]
2022-03-22T13:07:16.825 StandardVLBI performing  VXSGR at 2022y081d13h08m30s, AppMode type fast-abs
. . .
2022-03-22T13:07:16.851 StandardVLBI [Array3-BLC/VLBICalTarget] Insert SpecLine at 215.622 GHz bw 7.2 MHz
. . .
2022-03-22T13:07:16.852 StandardVLBI [Array3-BLC/VLBICalTarget] FS[BB_2] useUSB:true 12GHz:false sbPrf:NONE CFreq: 215100000000.0 (SB)
. . .
2022-03-22T13:07:16.858 StandardVLBI [Array3-BLC/VLBICalTarget] BB_1:  have 1920 fft pts on 8 tfbs, (0.000976563 chbw 0.234375000 tbw) GHz
2022-03-22T13:07:16.858 StandardVLBI [Array3-BLC/VLBICalTarget] BB_1:  cf 215.100000000 dc edge at 216.037500000, eff # chan is 1920
. . .
2022-03-22T13:07:16.864 StandardVLBI [Array3-BLC/VLBICalTarget] ----------------------------------------
2022-03-22T13:07:16.864 StandardVLBI [Array3-BLC/VLBICalTarget]    0 for  240 ch.av 215.803125..216.037500
2022-03-22T13:07:16.864 StandardVLBI [Array3-BLC/VLBICalTarget]  240 for  240 old ch. average 215.568750..215.803125
2022-03-22T13:07:16.864 StandardVLBI [Array3-BLC/VLBICalTarget] | 215.568750 < [ 215.618642 215.622242 215.625842 ] < 215.803125 |
2022-03-22T13:07:16.864 StandardVLBI [Array3-BLC/VLBICalTarget] bot 51 top 182 newc 8 (last 189)
2022-03-22T13:07:16.864 StandardVLBI [Array3-BLC/VLBICalTarget]  422 for    8 new ch. average
2022-03-22T13:07:16.864 StandardVLBI [Array3-BLC/VLBICalTarget]  480 for  240 ch.av 215.334375..215.568750
2022-03-22T13:07:16.864 StandardVLBI [Array3-BLC/VLBICalTarget]  720 for  240 ch.av 215.100000..215.334375
2022-03-22T13:07:16.867 StandardVLBI [Array3-BLC/VLBICalTarget]  960 for  240 ch.av 214.865625..215.100000
2022-03-22T13:07:16.867 StandardVLBI [Array3-BLC/VLBICalTarget] 1200 for  240 ch.av 214.631250..214.865625
2022-03-22T13:07:16.867 StandardVLBI [Array3-BLC/VLBICalTarget] 1440 for  240 ch.av 214.396875..214.631250
2022-03-22T13:07:16.868 StandardVLBI [Array3-BLC/VLBICalTarget] 1680 for  240 ch.av 214.162500..214.396875
2022-03-22T13:07:16.868 StandardVLBI [Array3-BLC/VLBICalTarget] ----------------------------------------
. . .
```

Figure 15: **Log excerpts of the channel average adjustments**—Adjustments to BB_2 for the Band 6 VX Sgr line scan scheduled at 13:08:00 UTC on March 22, 2022.

In Figure 15 one can see that the channel average containing the sky frequency of 215.622 GHz, which is normally 240 channels (FFT points) wide, is reduced to 8 channels for the requested 7.2 MHz bandwidth. (The channels are approximately 1 MHz wide, and the logic rounds up.) After the observation, the channel average that was edited is restored to its original 240 channel width.

6.3.2 Execution

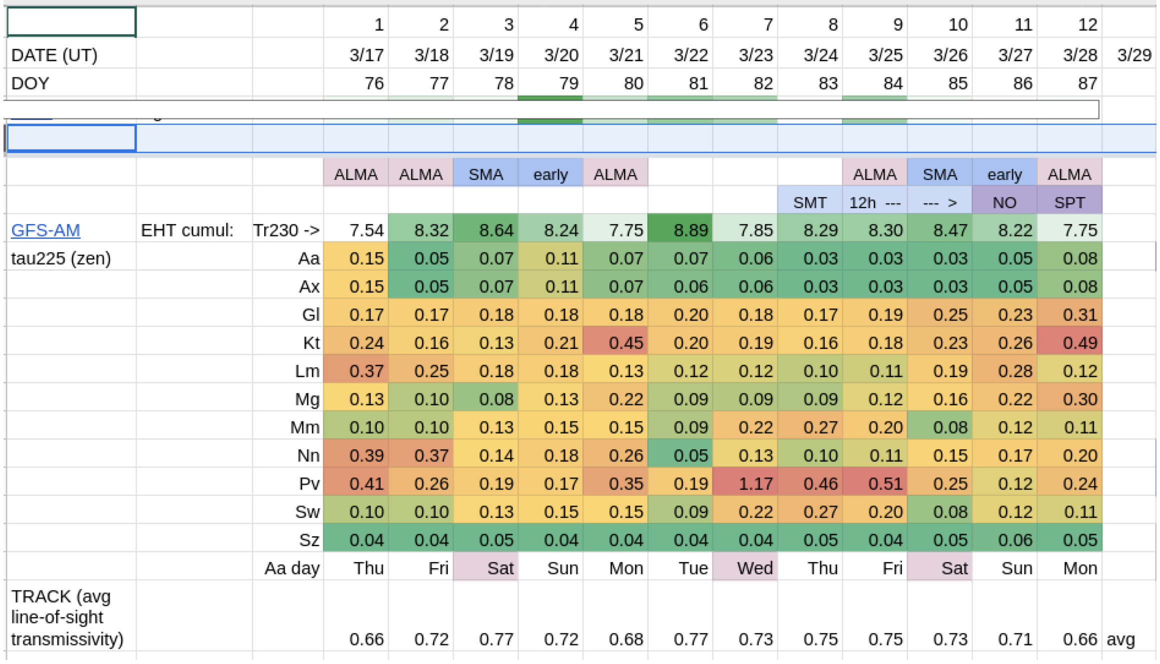
As shown in Table 6.3.2 there were suitable gaps to allow insertion of line scans on either VX Sgr or W Hya in 4 tracks which were observed on March 20 through 27, 2022 (tracks e22c20, e22e22, e22d23 and e22f27, respectively). Conditions at ALMA were generally good (low PWV, low opacity) although there were some periods with high winds (>10 m s^{-1}; see below). Aside from this, there were no technical issues. Weather conditions at the other sites were more variable, as shown in Figure 16.

---

[12] In the log, the basebands are labeled 0...3 instead of 1...4 as Python, C++, and Java are zero-based in their array indexing.

Table 3: Spectral Line Scans in the 2022 ALMA-EHT Campaign

Scan start time	Length	Target	A/P	ExecBlock UID	Comment
track e22c20 -- day 79 -- March 19--20					
2022y079d08h49m00s	60s	VXSGR	A	uid://A002/Xf656ba/X45b8	generally poor weather everywhere[1]
2022y079d13h13m00s	60s	VXSGR	P	uid://A002/Xf656ba/X555f	(same)
2022y079d14h57m00s	120s	VXSGR	A	uid://A002/Xf656ba/X5f99	(same)
track e22e22 -- day 81 -- March 21--22					
2022y081d04h49m00s	180s	WHYA	A	uid://A002/Xf676e4/X1320	(eastern, good weather at Nn)[1]
2022y081d13h08m30s	90s	VXSGR	P	uid://A002/Xf676e4/X2097	correlated with Kt, Mg, Sw, Mm
2022y081d15h32m30s	120s	VXSGR	A	uid://A002/Xf676e4/X2567	correlated with Kt, Mg, Sw, Mm
track e22d23 -- day 82 -- March 22/23					
2022y082d12h50m30s	90s	VXSGR	P	uid://A002/Xf67b94/X3706	better weather at ALMA...
2022y082d15h22m30s	90s	VXSGR	A	uid://A002/Xf67b94/X3cfa	..., but worse everywhere else[1]
track e22f27 -- day 86 -- March 26/27					
2022y086d02h44m00s	120s	WHYA	A	uid://A002/Xf6abb4/X245c	even worse at peers[1]



			1	2	3	4	5	6	7	8	9	10	11	12	
DATE (UT)			3/17	3/18	3/19	3/20	3/21	3/22	3/23	3/24	3/25	3/26	3/27	3/28	3/29
DOY			76	77	78	79	80	81	82	83	84	85	86	87	
			ALMA	ALMA	SMA	early	ALMA				ALMA	SMA	early	ALMA	
										SMT	12h ---	--- >	NO	SPT	
GFS-AM	EHT cumul:	Tr230 ->	7.54	8.32	8.64	8.24	7.75	8.89	7.85	8.29	8.30	8.47	8.22	7.75	
tau225 (zen)		Aa	0.15	0.05	0.07	0.11	0.07	0.07	0.06	0.03	0.03	0.03	0.05	0.08	
		Ax	0.15	0.05	0.07	0.11	0.07	0.06	0.06	0.03	0.03	0.03	0.05	0.08	
		Gl	0.17	0.17	0.18	0.18	0.18	0.20	0.18	0.17	0.19	0.25	0.23	0.31	
		Kt	0.24	0.16	0.13	0.21	0.45	0.20	0.19	0.16	0.18	0.23	0.26	0.49	
		Lm	0.37	0.25	0.18	0.18	0.13	0.12	0.12	0.10	0.11	0.19	0.28	0.12	
		Mg	0.13	0.10	0.08	0.13	0.22	0.09	0.09	0.09	0.12	0.16	0.22	0.30	
		Mm	0.10	0.10	0.13	0.15	0.15	0.09	0.22	0.27	0.20	0.08	0.12	0.11	
		Nn	0.39	0.37	0.14	0.18	0.26	0.05	0.13	0.10	0.11	0.15	0.17	0.20	
		Pv	0.41	0.26	0.19	0.17	0.35	0.19	1.17	0.46	0.51	0.25	0.12	0.24	
		Sw	0.10	0.10	0.13	0.15	0.15	0.09	0.22	0.27	0.20	0.08	0.12	0.11	
		Sz	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.05	0.04	0.05	0.06	0.05	
		Aa day	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	
TRACK (avg line-of-sight transmissivity)			0.66	0.72	0.77	0.72	0.68	0.77	0.73	0.75	0.75	0.73	0.71	0.66	avg

Figure 16: **EHTC Planning Sudoku**—A portion of the planning "sudoku" for the EHT-ALMA Cycle 8 campaign. This is used to assign observing tracks to nights within the observing window. For the current discussion, the most relevant portion is the matrix of τ_{225} estimates (opacity at 225 GHz) based on actual weather or predictions. The colors overlaid on the numerical values indicate the quality of the conditions: good (green), moderately good (yellow), fair (orange).

6.3.3 Correlation

The spectral line data from ALMA and various EHT sites were shipped to Haystack Observatory for correlation following the March 2022 experiment. Owing to resource constraints at the Haystack correlator, we were able to load the 2022 data for only a few stations and to devote a few days of correlation time to processing scans from the experiment prior to the ObsMode 2022 Go/No-go decision. This was sufficient to correlate several sample line scans and adjacent continuum calibrators. The scans selected for correlation were chosen based on source elevation, weather conditions, and other information available from the participating sites.

We deemed the VX Sgr scans from the `e22e22` track to be one of the most promising for initial tests of the Band 6 spectral line VLBI capability As seen in the observing "sudoku" in Figure 16, this track had generally good weather, especially on Mauna Kea, location of the Submillimeter Array (SMA) and the James Clerk Maxwell Telescope (JCMT) stations. The two Arizona stations [the Kitt Peak (KP) 12 m and the Submillimeter Telescope (SMT)] also had acceptable weather, so we proceeded with an analysis with these five stations. Using scans with both of the Mauna Kea sites is valuable since the detection of the line on the short SMA–JCMT baseline provides useful checks prior to searching for fringes on longer baselines.

The first steps of correlation generally require updating the VEX file with information about the Earth rotation parameters and finding fringes on bright continuum calibrators included in the observing track. In the case of the `e22e22` track, J1743−0350 ($\sim$0.96 Jy at 1 mm) and J1924−2914 ($\sim$5.72 Jy at 1 mm)[13] were observed in scans at 12:10, 13:20, and 15:37 UTC, respectively. Thus a short correlation run of these scans along with two adjacent VX Sgr scans was conducted. One of those scans was passively phased (using SgrA* as the phasor), and the other was actively phased. We have also correlated a W Hya spectral line scan and associated continuum calibrators from the `e22e22` session (see below).

The initial correlations used the full 2 GHz band and high spectral resolution (i.e., a large number of FFT points) to adequately sample the narrow maser lines. The adopted channel spacing was internally 0.015625 MHz, but summed to 0.0625 MHz, or $\sim$0.08 km s^{-1}, for output. However, this results in rather large output data set ($\sim$15 GB). After some experimentation, we found it was also possible to use the zoom band of DiFX (Deller et al. 2011) to correlate only the portion of the band containing the line, along with a few surrounding channels, resulting in more modestly sized output files ($\sim$160 MB). A trade-off, however, is that a bandwidth that is too narrow does not allow solving for robust estimates of the instrumental and residual delays (see Section 6.3.4) and may lack a sufficient number of line-free channels for characterizing the noise levels and instrumental response.

An additional note on the correlation of the Band 6 spectral line test is that it was necessary to use a "freqId" parameter to prevent DiFX from correlating "everything possible" (the default). Furthermore, a special procedure was required to convert the raw correlator output into FITS files that could be read by AIPS; since `PolConvert` had not been run, the data remained in a mixed polarization basis, but were relabed for compatability with

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[13] Flux density estimates are based on the SMA Calibrator List `http://sma1.sma.hawaii.edu/callist/callist.html`.

the FITS file format (see Section 4.3.3).

6.3.4 Band 6 Spectral Line Analysis

ALMA Interferometric Data and QA0+ Processing During VLBI experiments with ALMA, a specially designed CASA-based QA0+ script is normally used to generate a series of diagnostic plots from the ALMA single field interferometry (SFI) data. This allows the monitoring of data quality and the effects of changing weather and other factors that can impact system performance. However, the existing script was originally designed to handle continuum experiments, and it was unable to generate prompt diagnostic plots for the spectral line scans at the time of the Band 6 spectral line test. For typical Band 6 continuum VLBI experiments, the EHTC requires all 4 basebands for continuum recording, and high spectral resolution plots are thus typically not of interest. (The spectral resolution in this case is about 1 MHz due to spectral averaging.) In contrast, the spectral line case can use a wide variety of set-ups. Furthermore, in general all four basebands are not used for VLBI. Thus the script needs to collect additional information to produce useful output. Subsequent to the Band 6 spectral line experiment, the QA0+ script was overhauled and it now provides feedback on spectral line scans.

Since the QA0+ script was not operating nominally during the March 2022 test, we instead manually generated some of the same types of diagnostic plots as the updated script will produce in the future in real time. Examples are shown in Figures 17 and 18 for the Band 6 spectral line scans observed as part of the `e22e22` track on March 22, 2022.

During the course of the the `e22e22` track, PWV at ALMA fell from about 1.6 mm (on the first W Hya scan) to about 1.0 mm for both VX Sgr scans. The wind speed was about 2.5 m s^{-1} at the outset, rising to 7.5 m s^{-1} for the (passively phased) VX Sgr scan, and finally to about 11 m s^{-1} for the final (actively phased) VX Sgr scan.

Figure 17 shows that the APS performance on the (180 s) W Hya scan was excellent. As is typically the case, the first correlator subscan (about 16 s duration) is unphased. After that, the phasing corrections generate a 5–6-fold increase in the visibility amplitude (left panel) on baselines between the phased sum and a pair of unphased comparison antennas. For a perfectly phased array this increase in correlated amplitude should scale as $\sim \sqrt{N_{\rm ant}}$ (where in this case, $N_{\rm ant}$=41). Meanwhile the RMS phase fluctuations (right panel) are modest ($\sim \pm 30^\circ$), indicating coherence losses of $\lesssim$13%.

Phasing performance plots for the VX Sgr scans in the same track are shown in Figure 18. For this source we clearly see the effects of wind on the phasing performance. In the earlier scan at 13:08:30 UTC (top panels), winds speeds have risen to $\sim$7 m s^{-1}, and compared with Figure 17, amplitudes are less stable and the RMS phase fluctuations are higher ($\sim \pm 50^\circ$). In the second scan at 15:32:30 UTC where wind speeds reach 11 m s^{-1}, phasing performance is poor despite the use of the WVR-based fast-loop phasing corrections. This implies that wind-induced turbulence (and possibly antenna pointing errors) rather than tropospheric water vapor fluctuations are dominating the phasing efficiency losses. This is consistent with our previous findings that for phasing operations at $\lambda \lesssim$1 mm, phasing efficiency is consistently low ($\lesssim$20%) in wind speeds $\gtrsim$10 m s^{-1}, irrespective of PWV content, and that use of fast phasing corrections does not help to improve the efficiency under such conditions (Crew et al. 2023). Examination of the ALMA SFI data also showed that the

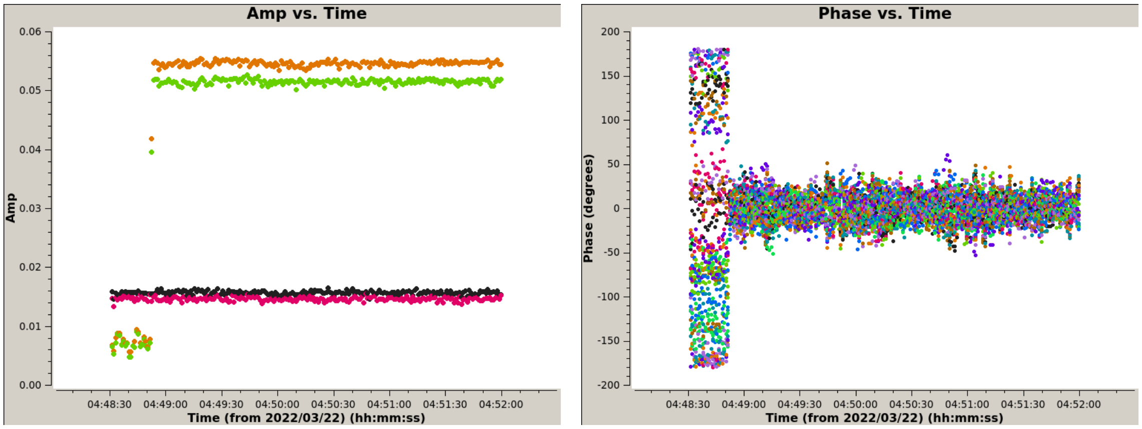


Figure 17: **Amplitude and phase as a function of time for the W Hya scan during the e22e22 track**—Phasing performance on the spectral line source W Hya during the e22e22 track on March 22, 2022 (XX polarization). *Left:* correlated amplitude vs. time on baselines between the phased sum and two unphased reference antennas, DV14 and PM04 (orange and green points), and between the phasing reference antenna and the comparison antennas (black and red points). The first correlator subscan (∼16 s) is unphased; subsequently the phasing corrections generate an increase in the visibility amplitude on baselines to the comparison antennas. *Right:* phase as a function of time on baselines between the reference antenna and antennas in the phased sum. Data source: uid://A002/Xf676e4/X1320.

SiO line was only marginally detected on the individual baselines within the array during this scan, underscoring that the poor quality of the data is tied to the general conditions at the site, not an issue with the phasing software.

6.3.5 Analysis of the Band 6 Spectral Line VLBI Data

Some basic analysis of the Band 6 spectral line VLBI scans was carried out using the HOPS and AIPS post-processing packages. The two packages allow independent and complementary checks of data quality. For example, HOPS uses a different fringe-finding algorithm than available AIPS, one that is nominally may perform better for data with very short coherence timescales (Rogers et al. 1995). It also readily handles mixed polarization data. On the other hand, HOPS lacks the wide diversity of tools available for VLBI data display and inspection that are available in AIPS and it is not designed for handling spectral line experiments (see Hoak et al. 2022).

HOPS Although it is not optimized for handling spectral line cases, quick-look VLBI fringe searches for spectral line targets can be carried out in HOPS using the “passband” feature that restricts processing to the same window used by the APS for phase-up (e.g., 215618.242...215626.242 MHz in the case of our observations of VX Sgr). Figure 19 shows an example of line fringes detected on the ALMA-JCMT baseline using this approach for a scan from the March 2022 experiment. All four (mixed) polarization products are shown.

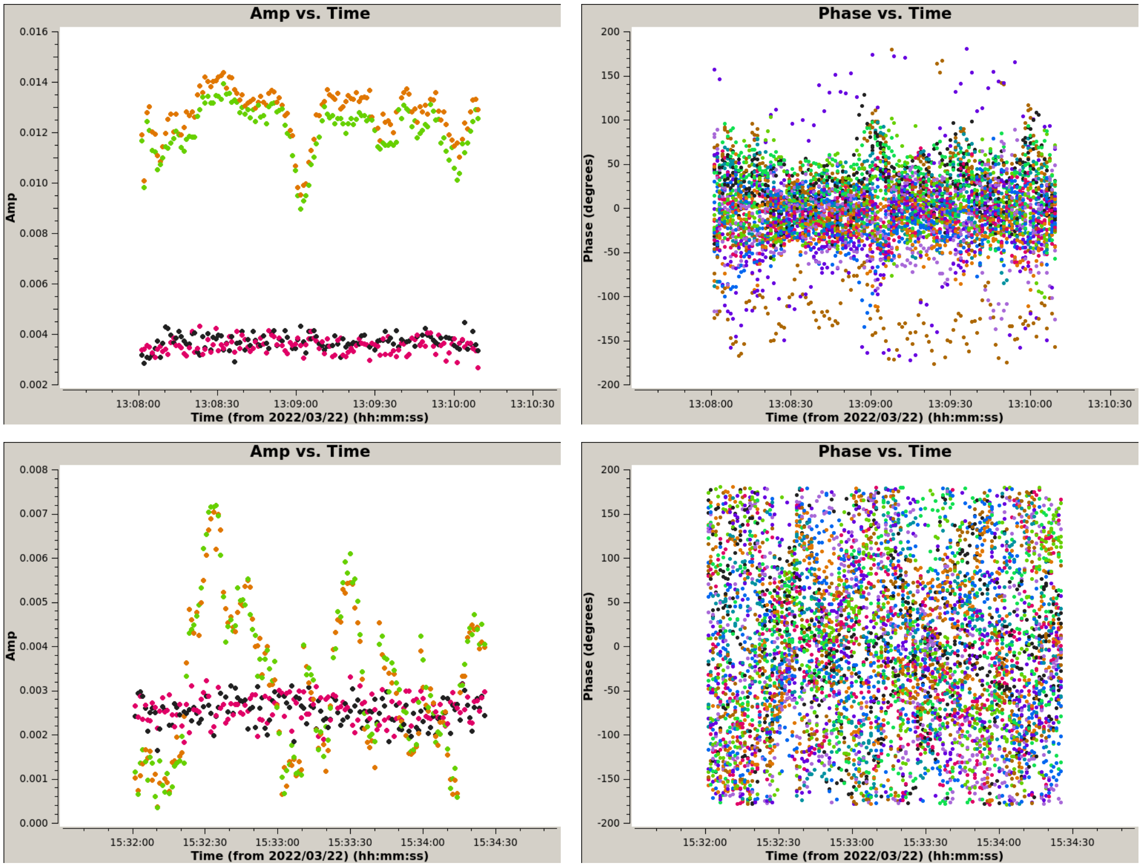


Figure 18: **Amplitude and phase vs. time for the e22e22 VX Sgr scans**—As in Figure 17, but for the SiO line target VX Sgr. The first scan (top panels) is passively phased at the outset (based on phases established during the preceding SgrA* scan) but the correlated amplitude fluctuates during the scan due to the changing atmosphere. Here the wind speed had increased to ∼7 m s^{-1} and phasing performance had deteriorated compared with Figure 17 but remains acceptable. In the final (actively phased) scan (lower panels), wind speed has further increased to ∼11 m s^{-1} and phasing performance has deteriorated significantly. Data source: uid://A002/Xf676e4/X2097 and uid://A002/Xf676e4/X2067.

Figure 20 shows the corresponding ALMA autocorrelation results for this scan. Spectral features are clearly visible in the ALMA-JCMT cross-power spectra at the same frequencies as in the ALMA autocorrelation spectra.

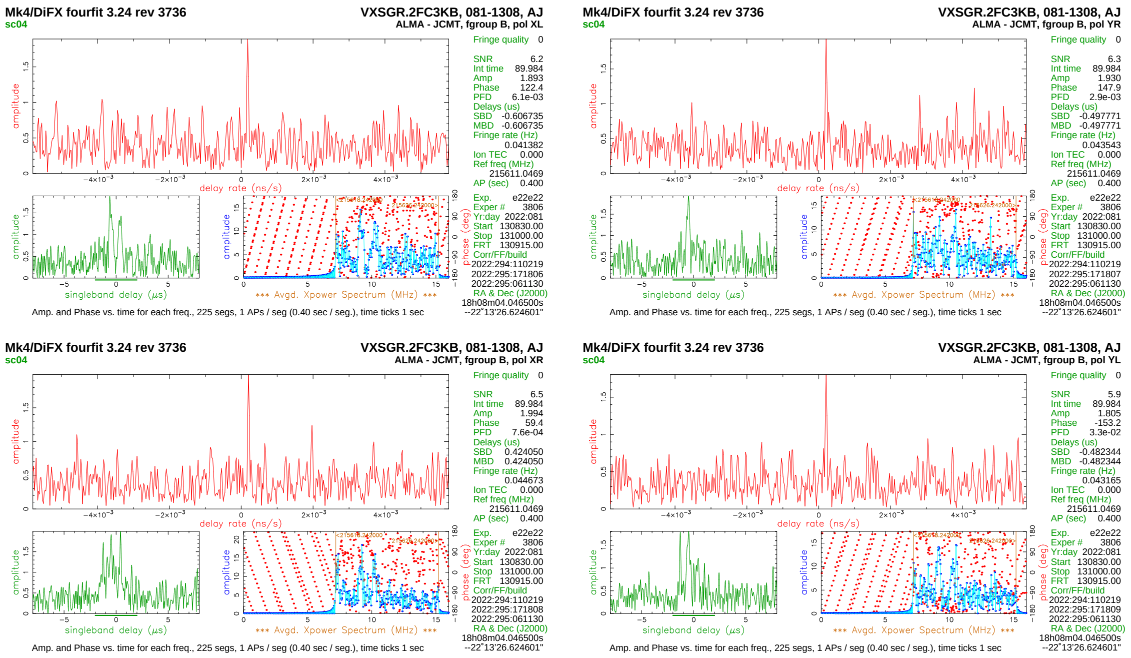
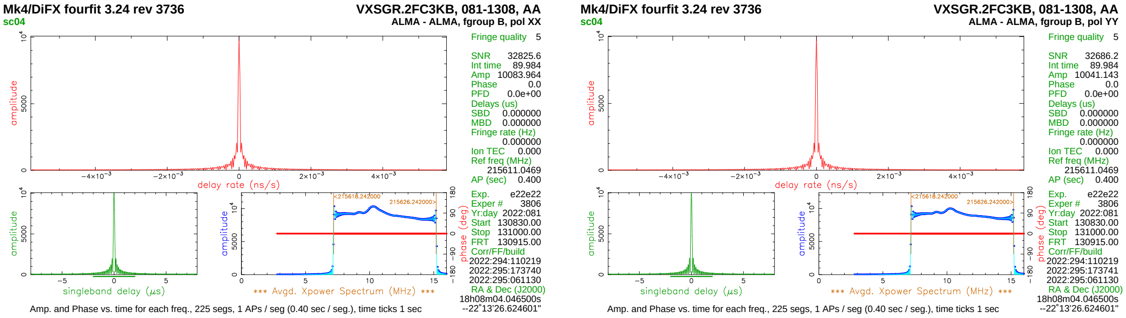


Figure 19: **HOPS quick-look results for VX Sgr on ALMA-JCMT baseline**—HOPS fringe results on the 9448 km ALMA-JCMT baseline for an actively phased Band 6 spectral line scan on VX Sgr, obtained at 13:08:30 UT on March 22, 2022. The frequency passband was restricted to 8 MHz surrounding the ^{28}SiO v=1, J=5−4 line. (Outside of this band, there are phase and amplitude artifacts that should be ignored). The line is detected in the cross-power amplitudes (light blue curves) and phases (red dots) in all four polarization products (lower right sub-panels). Note that JCMT uses circularly polarized signals. Delay rate is shown each red in each of the upper sub-panels. The delay peak (green curve in lower left sub-panels) is relatively broad (up to 4 μs) owing to the intrinsic frequency-dependence of the delay for line sources. The JCMT data are used with permission of P. Friberg and the EHTC.

AIPS To permit an independent validation of the above results and allow additional exploration of the Band 6 line data in AIPS, a FITS file containing five VLBI scans from the `e22e22` track was generated from the DiFX output as described Section 4.3.3. This FITS file included two scans on the line target VX Sgr, two scans on the fringe-finder/bandpass calibrator J1924−2914, and one scan on the continuum source J1743−0350:

```
Scan   Source           UT Timerange        RA(2000.0)     Dec(2000.0)
   1 J1743-0350      12:10:00 - 12:12:00  17:43:58.8561 -03:50:04.617
   2 VXSGR           13:08:30 - 13:10:00  18:08:04.0465 -22:13:26.625
```



```
Mk4/DiFX fourfit 3.24 rev 3736                    VXSGR.2FC3KB, 081-1308, AA
sc04                                        ALMA - ALMA, fgroup B, pol XX
Fringe quality   5
SNR        32825.6
Int time    89.984
Amp      10083.964
Phase          0.0
PFD        0.0e+00
Delays (us)
SBD       0.000000
MBD       0.000000
Fringe rate (Hz)
          0.000000
Ion TEC      0.000
Ref freq (MHz)
       215611.0469
AP (sec)     0.400
Exp.        e22e22
Exper #       3806
Yr:day    2022:081
Start    130830.00
Stop     131000.00
FRT      130915.00
Corr/FF/build
2022:294:110219
2022:295:173740
2022:295:061130
RA & Dec (J2000)
18h08m04.046500s
--22°13'26.624601"
Amp. and Phase vs. time for each freq., 225 segs, 1 APs / seg (0.40 sec / seg.), time ticks 1 sec
```

```
Mk4/DiFX fourfit 3.24 rev 3736                    VXSGR.2FC3KB, 081-1308, AA
sc04                                        ALMA - ALMA, fgroup B, pol YY
Fringe quality   5
SNR        32686.2
Int time    89.984
Amp      10041.143
Phase          0.0
PFD        0.0e+00
Delays (us)
SBD       0.000000
MBD       0.000000
Fringe rate (Hz)
          0.000000
Ion TEC      0.000
Ref freq (MHz)
       215611.0469
AP (sec)     0.400
Exp.        e22e22
Exper #       3806
Yr:day    2022:081
Start    130830.00
Stop     131000.00
FRT      130915.00
Corr/FF/build
2022:294:110219
2022:295:173741
2022:295:061130
RA & Dec (J2000)
18h08m04.046500s
--22°13'26.624601"
Amp. and Phase vs. time for each freq., 225 segs, 1 APs / seg (0.40 sec / seg.), time ticks 1 sec
```

Figure 20: **ALMA autocorrelation spectra for VX Sgr**—HOPS-generated ALMA autocorrelation spectra for the parallel hands (XX and YY) in the same VX Sgr scan and 8 MHz passband as shown in Figure 19. The ^{28}SiO v=1, J=5−4 line is visible in the amplitude vs. frequency plot (blue curves, lower right subpanels).

```
3 J1924-2914        13:20:00 - 13:22:00  19:24:51.0560 -29:14:30.121
4 VXSGR             15:32:30 - 15:34:30  18:08:04.0465 -22:13:26.625
5 J1924-2914        15:37:30 - 15:39:30  19:24:51.0560 -29:14:30.121
```

The stations present included ALMA, the SMT, the Kitt Peak 12 m, the JCMT, and phased SMA. This correlation pass was produced with a total bandwidth of 1.856 GHz (the entirety of baseband 2), and included 32 "IF channels", each comprised of 928 spectral channels, yielding a spectral resolution of 62.5 kHz (~ 0.08 km s^{-1}). The time resolution was 0.4 s. As the SiO v=1, J=5−4 line emission was expected to be confined to IF channel 25, only IFs 24–26 were used for subsequent processing, giving a total bandwidth of 174.0 MHz, centered at 215.53948 GHz.

Since QA2 had not yet been performed on the ALMA SFI data, one consequence of this is that `PolConvert` (which utilizes data products generated from QA2) could not be run on the data, hence they remain in a mixed polarization basis. In addition, the ANTAB tables (text files containing $T_{\rm sys}$ information used for a priori amplitude calibration) were not yet available for ALMA or any of the other participating EHT sites. Owing to these limitations, our analysis focused on fringe detection and other basic data quality checks.

After loading the data into AIPS and applying efficiency corrections to account for the 2-bit quantization, the three IFs of interest were copied out and the remainder of the passband was discarded to reduce the data volume. Subsequently, the reference frequency was reset to the center of the new spectral band (using task `CENTR`) and u, v, w values were appropriately scaled to the new reference frequency.

As described above, the performance of ALMA deteriorated during the `e22e22` experiment owing to an increase in the wind speed. Consistent with this, we see a marked difference in the quality of the ALMA autocorrelation spectra for the two scans on line target VX Sgr (Figure 21). During the earlier scan (at 13:08:30 UT), the ^{28}SiO v=1, J=5−4 line is clearly seen in the phased sum autocorrelation, while in the later scan (15:32:30 UT) shows virtually no hint of a line signal.

Even in the raw, uncalibrated data, the ^{28}SiO v=1, J=5−4 line was clearly detected on the quasi-zero-length baseline between JCMT and the phased SMA at Mauna Kea. This

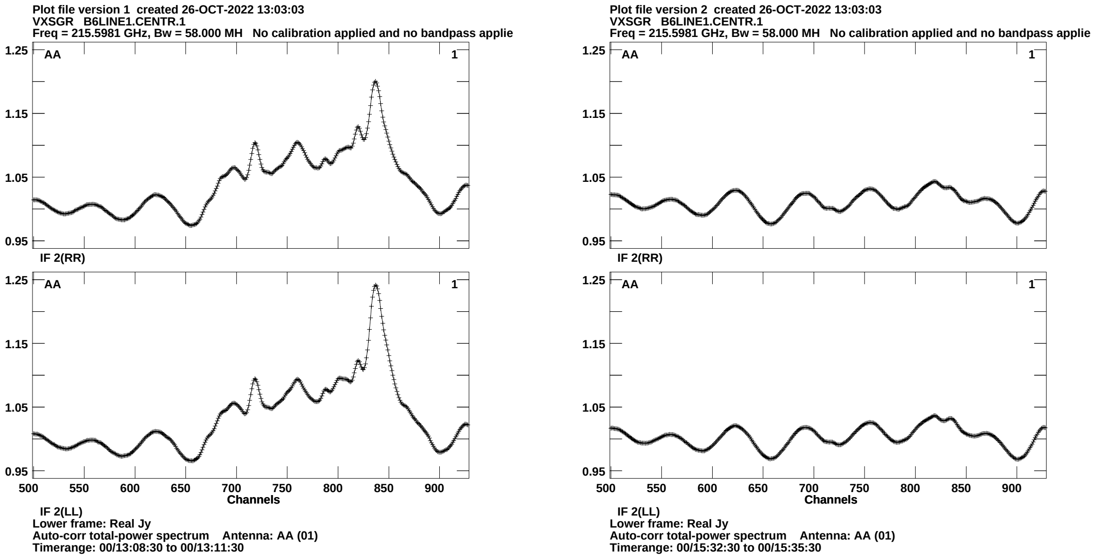


Figure 21: **ALMA autocorrelation spectra for VX Sgr**—ALMA autocorrelation spectra as plotted in AIPS for the two Band 6 VX Sgr scans obtained on March 22, 2022. A 26.75 MHz portion of the band is shown for both parallel hands in each scan (XX and YY, but labeled "RR" and "LL" here). The scan at 13:08:30 UT (left column) clearly shows the ^{28}SiO v=1, J=5−4 line near 215.5 GHz, but the line was undetected in the second scan at 15:32:30 UT (right column) owing to deteriorating weather conditions.

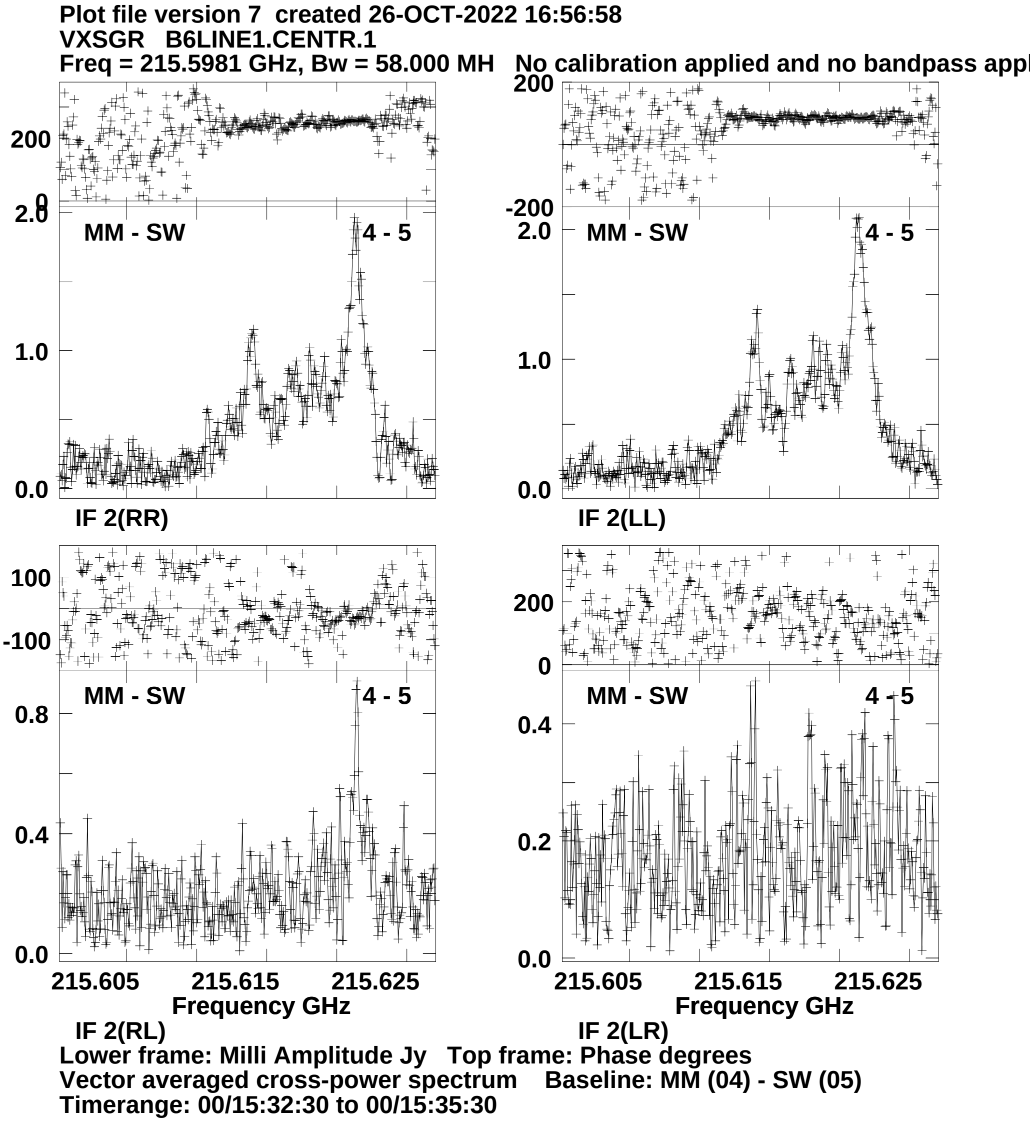


Figure 22: **SMA-JCMT cross-power spectra of VX Sgr**—Raw (uncalibrated) cross-power spectra of the ^{28}SiO v=1, J=5−4 line toward VX Sgr on the trivially short baseline between the phased SMA and JCMT stations on Mauna Kea, HI. All four polarization products are shown. The data are vector averaged over a 2-minute scan obtained at 15:32:30 UT on March 22, 2022. A 26.75 MHz portion of the band is shown surrounding the frequency of the line. For each panel, phase as a function of frequency is shown along the top, and amplitude vs. frequency along the bottom. The JCMT data are used with permission of P. Friberg and the EHTC. The SMA data are used with permission of G. Keeting, J. Weintroub, and the EHTC.

can be seen in the cross-power spectra shown in Figure 22. However, detections were not evident in the raw data on the longer baselines, hence further calibration (fringe-fitting) was required to calibrate the phases as a function of time and frequency.

Because these observations represent (to our knowledge) the first attempts to perform spectral line VLBI at wavelengths shorter than 3 mm on continent-scale baselines, there exists no previously established recipes for calibrating such data. Hence a variety of approaches were explored in AIPS. Owing to the large number of spectral channels in the data set, we found that `KRING` (rather than the more frequently used `FRING`) was more effective for global fringe searches owing to its more efficient use of memory allocation. Use of `KRING` made it possible to fringe search across the entire 174 MHz subband without reducing the spectral resolution. Initially, the calibration scans on J1924−2914 were used to solve for both delay and delay rate. Similar to the methodology adopted by the EHTC for their AIPS calibration pipeline (EHT Collaboration et al. 2019b), the first fringe-finding pass solved for a single solution for all IFs, and a solution interval equal to the entire scan length was adopted. ALMA was used as the reference antenna and good solutions were found for all baselines. These solutions were subsequently applied to VX Sgr (using task `CLCOR`).

After application of this initial set of delay and rate corrections, evidence of detection of the ^{28}SiO v=1, J=5−4 line is clearly seen in the cross-power spectra from the first of the two VX Sgr scans on the continent-scale baselines between ALMA-SMT (7176 km; Figure 23), ALMA-JCMT (9448 km; Figure 24), and ALMA-Kitt Peak (7215 km; Figure 25). Evidence of weaker line detections is also seen on some of the intra-EHT baselines (not shown).

Because J1924−2914 is in a different part of the sky than VX Sgr, the fringe rate on VX Sgr cannot be fully calibrated from this source alone, leading to coherence losses when the data are averaged in time. A common practice in spectral line VLBI is to use the spectral emission in one (or a few) strong line channels to solve for these residual rates. Using AIPS's baseline-based fringe solving algorithm `BLING` with a solution interval of 30 s, we were successfully able to solve for this residual rate on the ALMA-SMT baseline, leading to an additional boost in the SNR of the line fringes on this baseline (Figure 26). This result offers an important demonstration of feasibility of obtaining scientifically meaningful spectral line VLBI measurements at wavelengths as short as 1 mm.

6.4 Description of the Implemented Spectral Line VLBI Observing Mode

As noted above, spectral line VLBI observers can choose between three different methods for phasing up ALMA, depending on the properties of the target (phase-up using the continuum, passive phasing, or phase-up using the line signal itself). To phase up on a bright emission line source, the APS requires specification of a doppler-shifted line frequency (in GHz) and the desired phasing bandwidth (in MHz) for each target. The latter identifies the portion of the baseband where strong signal should be present. These quantities must be provided by the project PI based on the known LSR velocity and linewidth of the target.

While spectral line VLBI tuning options are now fully flexible (subject only to ALMA's inherent tuning restrictions; see Section 4.2), it is also necessary that the selected tunings be commensurate with the capabilities available at peer observatories in terms of IF

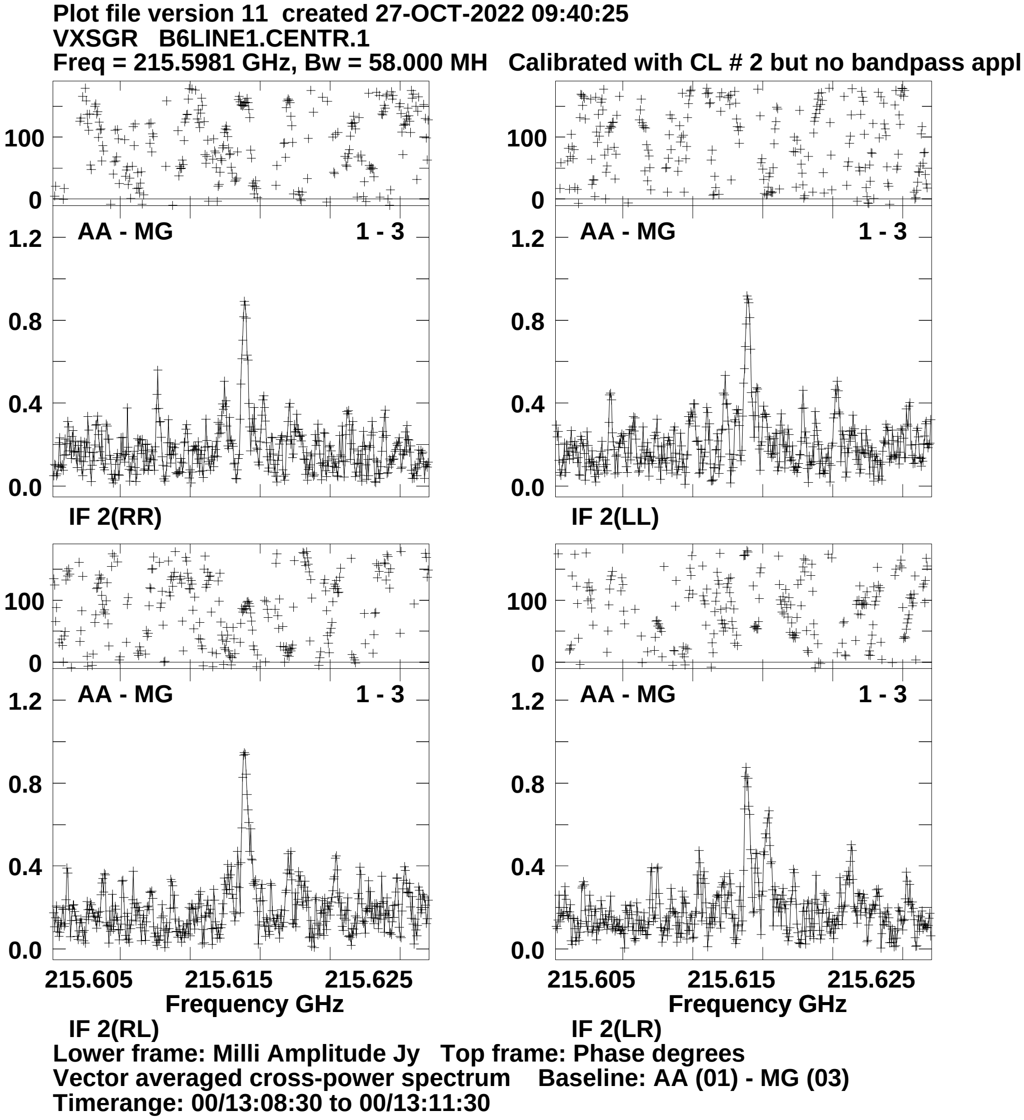


Figure 23: **Band 6 VX Sgr cross-power spectra on ALMA-SMT baseline**— Band 6 cross-power spectra of the ^{28}SiO v=1, J=5−4 line in VX Sgr on the ALMA (AA)-SMT (MG) baseline, obtained after applying initial delay and rate corrections derived from the calibrator J1924−2914. A 26.75 MHz portion of the band is shown surrounding the frequency of the line. The data are vector averaged over a 90 s scan obtained starting at 13:08:30 UT on March 22, 2022. All four (mixed) polarization products are shown. For each panel, phase as a function of frequency is shown along the top, and amplitude (in uncalibrated units) vs. frequency along the bottom. Evidence of detected line emission can be seen in both the amplitudes and in the phase structure in all polarization products. The SMT data are used with permission of D. Marrone and the EHTC.

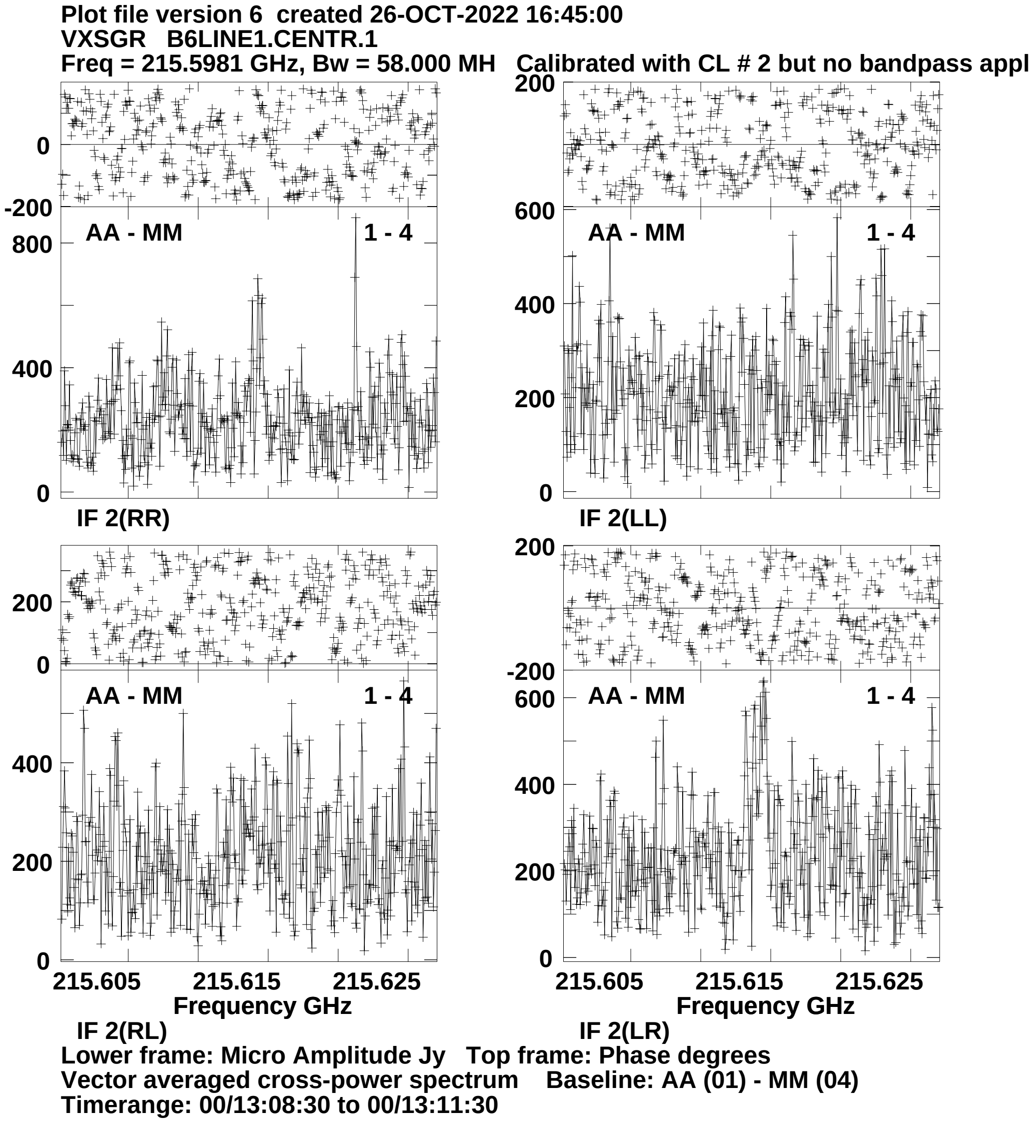


Figure 24: **Band 6 VX Sgr cross-power spectra on ALMA-JCMT baseline**—As in Figure 23, but for the ALMA (AA)-JCMT (MM) baseline. The JCMT data are used with permission of P. Friberg and the EHTC.

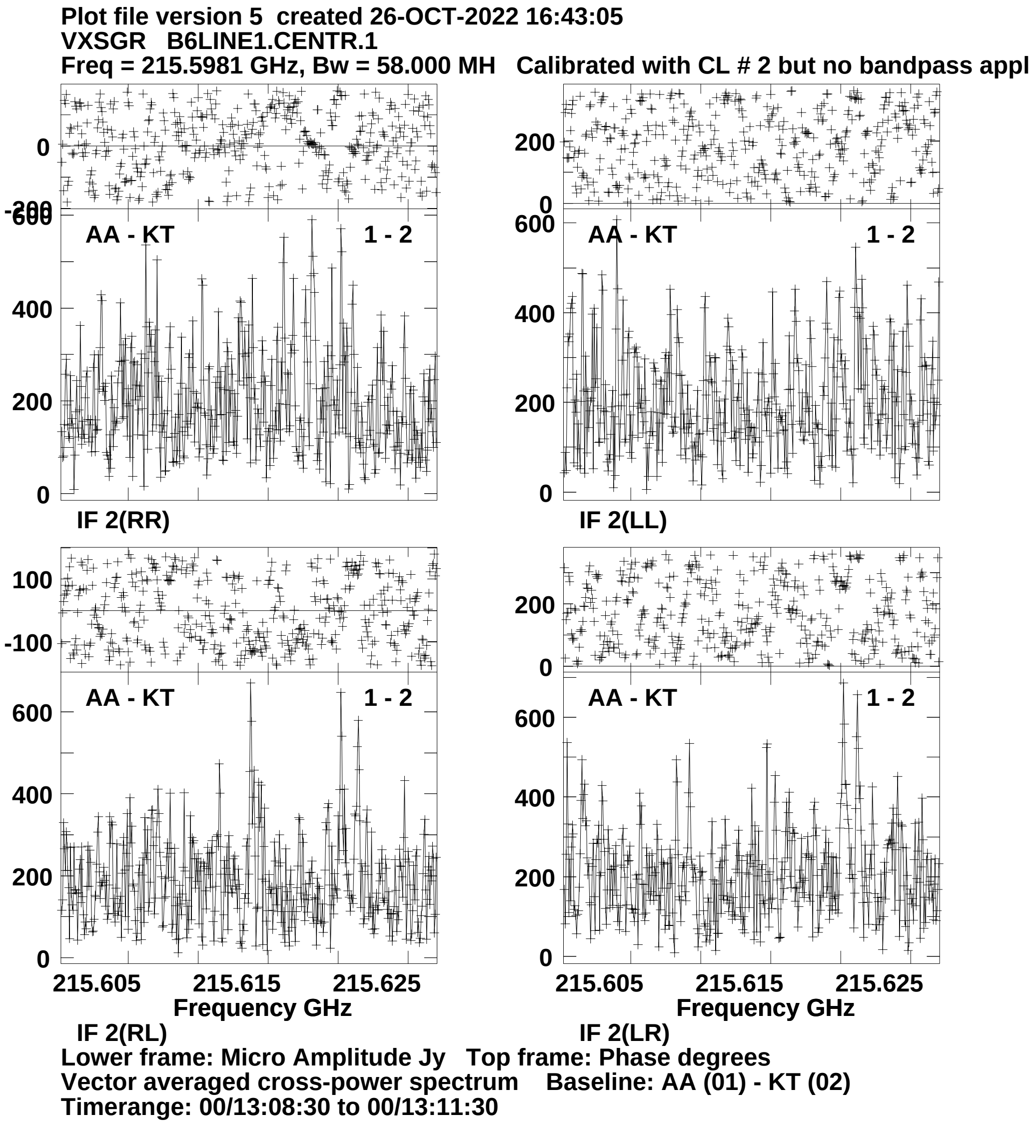


Figure 25: **Band 6 VX Sgr cross-power spectrum on ALMA-KP baseline**—As in Figure 23, but for the ALMA (AA)-Kitt Peak 12 m (KT) baseline. The KP data are used with permission of D. Marrone and the EHTC.

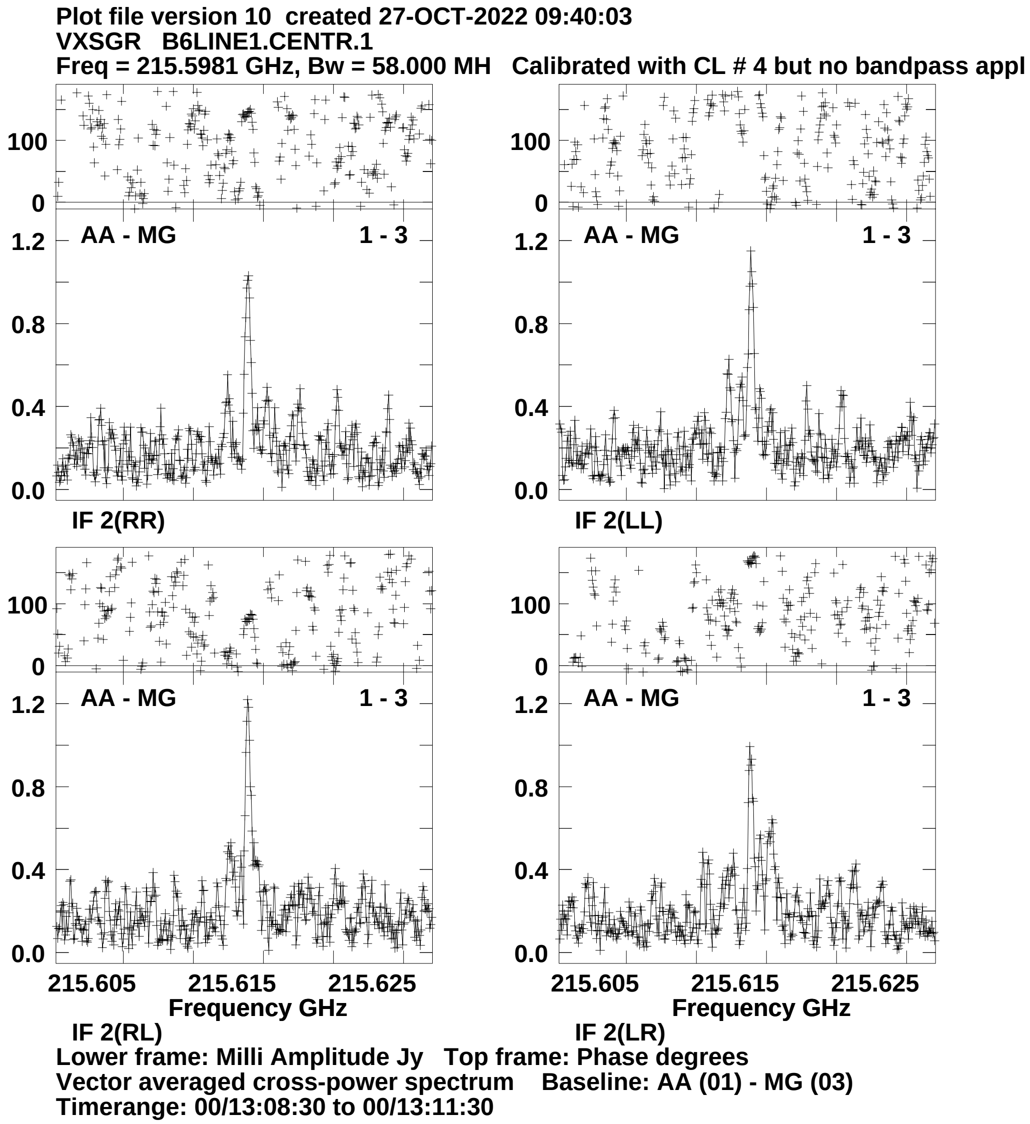


Figure 26: **Delay rate-corrected VX Sgr cross-power spectra on ALMA-SMT baseline**—As in Figure 23, but after solving for the residual delay rate using select line channels. Note the boost in the correlated amplitude compared with the earlier plots. The SMT data are used with permission of D. Marrone and the EHTC.

bandwidth and LO setting, which in some cases are less flexible than ALMA's. Because the capabilities and restrictions of partnering VLBI observatories are constantly evolving (e.g., as a result of upgrades or the commissioning of new telescope sites), after discussion with stakeholders it was decided not to attempt to impose any restrictions or warnings based on the requirements of external sites within the OT itself. Thus the responsibility of ensuring tuning comparability between ALMA and other VLBI partner sites rests with the observer. Links to relevant resources to help observers with this type of planning have now been added to the ALMA Proposer's Guide and the ALMA Technical Handbook.

Regardless of the phasing method used, the updated OT interface for setting up spectral line experiments includes an input box where the observer is asked to supply various relevant details of their VLBI experiment, including estimated flux density of the target, proposed VLBI calibration sources, and the requested VLBI correlation set-up. Additional details regarding the information requested from observers are provided in the ALMA Technical Handbook and Proposer's Guide.

In principle, the spectral resolution of the correlated VLBI data product can be arbitrarily high, depending on the number of points used in the FFT. However, in practice, the data volumes may become prohibitively large if a very fine spectral resolution is requested over the full ∼2 GHz of bandwidth. Thus the correlation parameters requested by the PI should be selected as appropriate for meeting the science goals, while avoid the generation of an excess volume of correlated data products. Guidelines are provided in the ALMA Technical Handbook.

With the Cycle 10 implementation of spectral line VLBI, active phase-up using the spectral line emission from the target can only be performed for a single line within a given baseband. This is a consequence of the manner in which baseband delays are handled at ALMA during VLBI mode observations (see Matthews et al. 2018; Crew & Matthews 2024). In future cycles, it is anticipated that use of an alternative baseband delay handling method (which was developed under APP2) will remove this restriction and enable VLBI observations of multiple lines per baseband (Crew & Matthews 2024 in prep.; Matthews & Crew 2024, in prep.).

In general, standard ALMA SFI data are sent in parallel to the ALMA archive whenever ALMA carried out VLBI or phased array observations. For all basebands being recorded for VLBI, the resulting data will use a specific (FDM) correlator mode with a 1.875 GHz bandwidth and a channel spacing of ∼1 MHz. However, if higher spectral resolution ALMA-only observations of the line (or another line in the band) are desired, spectral line observers have the option to flexibly configure up to three ALMA basebands to obtain ALMA-only observations of the line of interest with a narrower bandwidth and higher spectral resolution than provided in the VLBI baseband. Configurability of these three ALMA-only basebands is flexible, but subject to the same IF/LO limitations as standard (non-VLBI) ALMA spectral line observing set-ups.

7 Other Activities (WBS 4.0)

APP3 efforts covered in this section were undertaken in support of WBS 4.0 of the APP3 project ("Operation and Maintenance of VLBI Capabilities"). Since the original APP was completed, JAO has begun to transition to an operations model for VLBI whereby the ALMA portion of the observations can be conducted autonomously, without requiring support from external VLBI experts. Portions of the below mentioned work were therefore intended to facilitate a complete transition to this mode of operations by the end of APP3, including providing training and documentation to JAO staff and supplying additional tools to reduce the amount of human effort required to plan and operate VLBI campaigns and deliver the resulting data products.

7.1 VLBI Support and Training

Training and knowledge transfer to JAO staff have been a part of all phases of the APP. This has included considerable training of the Astronomers on Duty (AoDs) to support the generation of VLBI SBs, the execution of VLBI campaigns, and the post-processing QA2 effort.

During the period of performance of APP3 our team provided training and support to ALMA staff in the use of all newly developed APS capabilities, as well as on the use and maintenance of the previously existing capabilities, and VLBI-specific software and hardware. We also provided programmatic support for the APS and VLBI at ALMA by performing activities such as monitoring the health of ALMA's Mark 6 VLBI recorders and H maser, creating and responded to JIRA tickets, authoring VLBI and phased array-related content for the ALMA Technical Handbook, Proposer's Guide, and yearly proposal call; answering technical questions from prospective or active APS users; and assisting the Friend of VLBI with VLBI schedules and SB preparation, and the execution of VLBI observations at ALMA.

With the impending close-out of APP3 (and APP2 in August 2024), a significant effort was made to provide training on additional items necessary for full JAO VLBI self-sufficiency. A plan for achieving self-sufficiency was devised by JAO two years ago (with input from the APP3 team) and is available internally through the ALMA Confluence pages.[14] Our efforts in this area included training of the front-line software engineers to be able to handle technical issues associated with the VLBI recorders and disk modules. (Most the external EHT and GMVA sites rely on external experts for recorder support, but this is more problematic for ALMA). As of this writing, all areas in the self-sufficiency plan have been addressed, with the exception of the completion of an overview document that provides pointers to relevant existing documents for every aspect of the APS and ALMA VLBI.

7.2 Binary Storage of Metadata

In 2023 a decision was made to transition to storing metadata in the ALMA Archive in binary (`.bin`) rather than ascii (`.xml`) format to minimize storage volume. The Archive machinery in principle should be able to hand the conversion back and forth between the two formats, but in practice this software had not been thoroughly tested and debugged, and several bugs were identified and fixed late last year by ALMA staff. For the VLBI

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[14] `https://confluence.alma.cl/display/AVLBI/VLBI+Team`

code there was an additional issue in that one of the most important metadata tables, the `CalAppPhase` table, is routinely used during data analysis, and a number of scripts have been developed to parse the table [until now available as ascii text in the eXtended Markup Language (XML)]. Additionally, especially during test observations, information in the `CalAppPhase` table is sometimes needed by the person performing the data analysis, requiring a human readable format. To retain these capabilities in the transition to binary metadata formatting, some adjustments were necessary. At the time of this writing we have implemented a workaround solution, but a stable and permanent operational mode that retains access to the `CalAppPhase` table will not be available until after `p-redosf` is upgraded following the end of Cycle 10. In the interim, VOM operations are using a standalone copy of those codes, together with a script we have created (`vlbi-recover-xml.py`) to perform the conversion after the ASDM data are extracted from the Archive.

7.3 Development of a New SB Verification Tool

As the complexity of VLBI observing options at ALMA has grown, it became necessary to create a new tool (`v2v-common.sh`) to orchestrate the generation of SBs and then verify that the SBs will execute as intended. The `v2v-common.sh` tool also accepts addition inputs from the VLBI Friends who prepare the SBs; these inputs are termed "defines" and are the same for either spectral line or continuum observing.

In the process of preparing VLBI SBs, the observations are simulated using a tool known as the `ObservingScriptSimulator` (OSS). The script execution finishes (both in the simulator and the online code) by providing a log with a short summary, including lists of VLBI and calibration scans that can be used to evaluate timing. Figures 27 and 28 show examples of the planned and "as executed" versions of this summary, respectively, from one of our Band 1 VLBI tests (see Section 4.3.1). The timestamps have been deleted from the "as executed" example since they only refer to when the log report was made. Note that in this example, the simulation had the previous SB ending too late to observe the first science target scan. However, in the actual observation, it finished earlier and the scan was observed. Because this is a relatively common occurrence, the VLBI planners who create the VEX files are generally instructed not to place anything critical in the first scan of an SB. Overall the current OSS has sufficient fidelity to ensure a successful observation, and further improvements in this tool would require large amounts of effort with only minimal gain.

7.4 Regression Tests

VLBI regression tests offer a crucial means of regularly verifying the nominal operation of the APS following software upgrades at ALMA or other major changes. These tests are designed to ensure that the VLBI capabilities that we have worked to develop do not get broken by changes to unrelated software in the complex ALMA system. The APP3 team designed a set of VOM regression tests (for both spectral line and continuum) that can be executed whenever opportunities allow (e.g., during periods of marginal weather, during scheduling gaps, etc.). These tests are ∼10 minutes in duration and the acquired

```
[frame=single,fontfamily=courier,
    xleftmargin=-1.0cm,xrightmargin=-1.0cm]
 SIMULATION_EPOCH = 2022-10-04T10:15:34
  VLBI PrepTime:     5.000    0.000
  VLBI VLBITime:    15.000   20.000
  VLBI   <calib>:   93.756  113.756 [153.000 119.244] PhaseCalTarget on J0407+0742 at 43.168 GHz ref=topo (33s)
  VLBI   <assoc>:   13.596  127.352 [119.244 105.648] AtmCalTarget on IK_Tau at 43.168 GHz ref=topo (13s)
  VLBI    No0018:  524.772  652.124 [105.648 142.740] vlbi IKTAU at 2022y277d10h20m00s (524s/240s/276.384s) (Active  fast-sl1)
  VLBI   <assoc>:   25.596  677.720 [-11.124 -24.720] AtmCalTarget on Orion_Source_I at 43.168 GHz ref=topo (13s)
  VLBI    No0019:  375.372 1053.092 [  7.796 123.708] vlbi SOURCEI at 2022y277d10h27m00s (375s/240s/243.868s) (Active  fast-sl1)
  VLBI   <calib>:   45.756 1098.848 [187.908 154.152] PhaseCalTarget on J0407+0742 at 43.168 GHz ref=topo (33s)
  VLBI   <assoc>:   13.596 1112.444 [154.152 140.556] AtmCalTarget on J0609-1542 at 43.168 GHz ref=topo (13s)
  VLBI    No0020:  466.620 1579.064 [140.556 114.192] vlbi J0609-1542 at 2022y277d10h37m00s (466s/180s/211.872s) (Active  fast-sl1)
  VLBI   <assoc>:   25.596 1604.660 [ 21.936   8.340] AtmCalTarget on J0510+1800 at 43.168 GHz ref=topo (13s)
  VLBI    No0021:  334.404 1939.064 [  8.340 114.192] vlbi J0510+1800 at 2022y277d10h43m00s (334s/180s/211.872s) (Active  fast-sl1)
  VLBI   <assoc>:   25.596 1964.660 [ 21.936   8.340] AtmCalTarget on OJ287 at 43.168 GHz ref=topo (13s)
  VLBI    No0022:  427.464 2392.124 [  8.340 142.740] vlbi OJ287 at 2022y277d10h49m00s (427s/240s/276.384s) (Active  fast-sl1)
  VLBI    No0023:  410.484 2802.608 [  5.134 133.224] vlbi OJ287 at 2022y277d10h56m00s (398s/240s/260.126s) (Active  fast-sl1)
  VLBI   <assoc>:   25.596 2828.204 [  0.000   0.000] AtmCalTarget on J0510+1800 at 43.168 GHz ref=topo (13s)
  VLBI   <after>:  364.380 3192.584 [  0.000   0.000] PolarizationCalTarget on J0510+1800 at 43.168 GHz ref=topo (364s)
  VLBI   <assoc>:   13.596 3206.180 [  0.000   0.000] AtmCalTarget on J0609-1542 at 43.168 GHz ref=topo (13s)
  VLBI   <after>:  364.380 3570.560 [  0.000   0.000] PolarizationCalTarget on J0609-1542 at 43.168 GHz ref=topo (364s)
  VLBI DoneTime:  3550.560 3570.560
  VLBI ExitTime:     0.000 3570.560
  VLBI Finished execution UID is uid://A00/X00/X00
```

Figure 27: **Simulated Timing Summary for experiment TA037B (October 4, 2022)**—Simulated timing report for the final SB of the `TA037B` experiment conducted on October 4, 2022 (see also Section 5.3.1). The second column indicates the type of activity, the third column the time (in seconds) of the activity, and the fourth column is a running total. The remainder of each line provides details on what was done.

```
[frame=single,fontfamily=courier,
    xleftmargin=-1.0cm,xrightmargin=-1.0cm]
  VLBI PrepTime:     5.074    0.000
  VLBI VLBITime:    16.713   21.788
  VLBI   <assoc>:   51.912   73.700 [-111.846 -160.305] AtmCalTarget on Mira at 43.168 GHz ref=topo (48s)
  VLBI    No0017:  128.161  201.861 [  2.271  12.083] vlbi OCETI at 2022y277d10h13m00s (128s/240s/113.805s) (Active  fast-sl1)
  VLBI   <calib>:   50.761  252.622 [131.407  80.773] PhaseCalTarget on J0401+0413 at 43.168 GHz ref=topo (50s)
  VLBI   <assoc>:   25.813  278.435 [ 80.708  54.959] AtmCalTarget on IK_Tau at 43.168 GHz ref=topo (25s)
  VLBI    No0018:  336.502  614.937 [ 54.957   5.159] vlbi IKTAU at 2022y277d10h20m00s (336s/240s/276.384s) (Active  fast-sl1)
  VLBI   <calib>:   41.469  656.406 [138.329  96.988] PhaseCalTarget on J0401+0413 at 43.168 GHz ref=topo (41s)
  VLBI   <assoc>:   31.460  687.867 [ 96.868  65.527] AtmCalTarget on Orion_Source_I at 43.168 GHz ref=topo (31s)
  VLBI    No0019:  347.506 1035.373 [ 65.525   5.595] vlbi SOURCEI at 2022y277d10h27m00s (347s/240s/276.384s) (Active  fast-sl1)
  VLBI   <calib>:   47.609 1082.982 [317.857 270.412] PhaseCalTarget on J0401+0413 at 43.168 GHz ref=topo (47s)
  VLBI   <assoc>:   36.160 1119.142 [270.289 234.252] AtmCalTarget on J0609-1542 at 43.168 GHz ref=topo (36s)
  VLBI    No0020:  449.529 1568.671 [234.250   3.405] vlbi J0609-1542 at 2022y277d10h37m00s (449s/180s/211.872s) (Active  fast-sl1)
  VLBI   <calib>:   52.047 1620.718 [144.596  92.676] PhaseCalTarget on J0401+0413 at 43.168 GHz ref=topo (51s)
  VLBI   <assoc>:   29.357 1650.075 [ 92.544  63.319] AtmCalTarget on J0510+1800 at 43.168 GHz ref=topo (29s)
  VLBI    No0021:  276.552 1926.627 [ 63.316   1.361] vlbi J0510+1800 at 2022y277d10h43m00s (276s/180s/211.872s) (Active  fast-sl1)
  VLBI   <calib>:   44.643 1971.270 [146.606 102.124] PhaseCalTarget on J0401+0413 at 43.168 GHz ref=topo (44s)
  VLBI   <assoc>:   40.577 2011.847 [101.994  61.547] AtmCalTarget on OJ287 at 43.168 GHz ref=topo (40s)
  VLBI    No0022:  343.155 2355.002 [ 61.544   5.224] vlbi OJ287 at 2022y277d10h49m00s (343s/240s/276.384s) (Active  fast-sl1)
  VLBI   <calib>:   56.279 2411.281 [138.267  82.113] PhaseCalTarget on J0401+0413 at 43.168 GHz ref=topo (56s)
  VLBI    No0023:  364.167 2775.448 [ 82.058   5.670] vlbi OJ287 at 2022y277d10h56m00s (364s/240s/276.384s) (Active  fast-sl1)
  VLBI   <assoc>:   36.818 2812.266 [  0.000   0.000] AtmCalTarget on J0510+1800 at 43.168 GHz ref=topo (36s)
  VLBI   <after>:  370.658 3182.923 [  0.000   0.000] PolarizationCalTarget on J0510+1800 at 43.168 GHz ref=topo (370s)
  VLBI   <assoc>:   34.971 3217.895 [  0.000   0.000] AtmCalTarget on J0609-1542 at 43.168 GHz ref=topo (34s)
  VLBI   <after>:  370.477 3588.371 [  0.000   0.000] PolarizationCalTarget on J0609-1542 at 43.168 GHz ref=topo (370s)
  VLBI DoneTime:  3566.597 3588.385
  VLBI ExitTime:     8.836 3597.221
  VLBI Finished execution UID is uid://A002/Xff294f/X531e
```

Figure 28: **Executed Timing Summary for Experiment TA037B (October 4, 2022)**—The actual timing summary for the `TA037B` observation. The format is similar to that of Figure 27.

data can be analyzed quickly using automated scripts. The tests also allow accumulation of statistical information on the quality of phasing performance during different observing conditions. The spectral line tests are available in Bands 1, 3, 6, and 7, while the continuum regression tests are offered in Bands 1, 3, 6, 7, and 9.

7.5 Installation of a New Hydrogen (H) Maser at ALMA

A stable and precise time standard is crucial for VLBI operations. This motivated the replacement of the rubidium clock originally used as a frequency reference at ALMA with a hydrogen (H) maser as part of the original APP (see Matthews et al. 2018). Unfortunately the model iMaser 59 from T4Science that was installed at ALMA suffered a series of failure during the past several years, compromising ALMA's ability to participate in scheduled VLBI observations. (The rubidium clock was kept online as a hot spare, thus regular ALMA observing could continue once it was swapped in). A decision was ultimately made by JAO to replace the original H maser with a newer model. The T4Science iMaser 167 was selected in order to minimize the resources required for integration and maintenance.

APP3 team member G. Crew was a critical part of the team who undertook installation and testing of the new maser. These efforts included software updates needed to support the new maser's use for VLBI. A new device code (`Maser167`) was cloned from the original one (`Maser`) and subsequently modified as needed. This code is used for monitoring of the maser. Additionally it was necessary to adapt the VLBI GUI `AppGui.py` to handle two masers and to adapt offline monitoring scripts to handle the second maser.

While both the new and the original H masers have several dozen monitoring points for the evaluation of general operational health, these do not supply direct information on how well the masers are actually working. That instead requires use of two other methods: examination of Allan Variance (Allan 1966), and monitoring of the maser pulse per second (PPS) output relative to that of a global positioning system (GPS). It is also crucial to measure the drift of the frequency reference so that this information can be included at the time of VLBI correlation. Enabling these tests to be performed and then capturing the relevant information required some modifications to the monitoring software. Additional details about the H maser installation and integration may be found in the Cycle 11 Acceptance Report by Crew & Matthews (2024). A popular-level account of this effort is also available through a documentary video produced as part of this project (see Section 9).

8 Project Management (WBS 1.0)

8.1 Management Practices

Consistent with all phases of the APP, development, engineering, and design activities for the APP3 were conducted in accordance with established Systems Engineering policies, practices, and procedures. As had been done for APP and APP2, the majority of APP3 development efforts were coordinated and reviewed through the ALMA ObsMode process, and the team participated in ObsMode 2022 during the APP3 period of performance. Steps included delivery of a Test Plan, presentation of status updates, and delivery of a document package prior to the Go/No-Go decisions. However, ALMA did not formally convene an ObsMode process in 2023, and instead, APP3 activities were coordinated through the DSO.[15] Following the recommendation of the ALMA Board, APP3 activities were also

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[15] ObsMode for 2023 and future Cycles is in suspension due to the impending WSU.

independently reviewed by a panel of external experts on an annual basis.

For all software development efforts, APP3 adhered to the normal ALMA software delivery process, which is organized around implementation of specific and separable features. The evaluation criteria used for each feature included successful offline testing, successful regression testing, and finally, successful commissioning. A comparison between the list of originally proposed APP features (Figure 1) with the outcomes described in this document demonstrates successful completion of all proposed project activities.

8.2 Documentation

Documentation produced as part of the APP3 included the following:

- A Project Implementation Plan (including quality assurance, safety procedures, and a risk register)
- Monthly "4-Square" Progress Reports (summarizing ongoing activities, changes and updates to the Risk Register, as well as financial information)
- Software Design documentation
- Technical Manuals and Procedures (including updates to the VLBI- and Phased Array-related sections of the ALMA Technical Handbook and ALMA Proposer's Guide)
- Annual Acceptance Test Plans and Reports
- A final Closeout report (this document)

All projected-related documentation expected to be of general or historical interest that has not already been posted publicly will be posted as part of the ALMA Technical Notes Series[16], as will pending documentation from APP2.

9 Broader Impacts (WBS 5.0)

To broaden the impacts of the present work and make its outcomes accessible to a wider audience, our team worked with Nicolás Lira, Education and Public Outreach Coordinator at JAO, on the production of a short documentary video that detailed the installation of the new H maser at ALMA and its integration with ALMA's other VLBI subsystems (see Section 7.5). Lira's video was featured in an NRAO press release.[17]. In addition, the APP3 team worked with MIT Haystack Communications, Outreach, and Education Officer Nancy Kotary to produce a news feature[18] aimed at the general public that summarizes Haystack's long-term role in VLBI development at ALMA, including the work undertaken under APP3, as well as ALMA's critical importance to the (sub)mm VLBI community. This feature was publicized through Haystack Observatory's web page and social media accounts.

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

[17] `https://public.nrao.edu/news/alma-gets-a-new-heartbeat/`

[18] `https://www.haystack.mit.edu/news/alma-maser-2024001/`

10 Looking Ahead

With the completion of APP3, we have effectively exhausted the feasible improvements to the current APS and VOM that can be accommodated within the framework provided by the original ALMA BL Correlator and other ALMA hardware and software systems (see e.g., Matthews et al. 2018; Crew et al. 2023). These enhanced and expanded VLBI capabilities have laid the groundwork for VLBI's continued relevance and importance at ALMA for the remainder of this decade and beyond. One additional capability (subarrays for VLBI) was also considered but was later descoped from APP3 owing to human resource limitations at ALMA and the possible risk of unintended impacts on subsystems used for ALMA SFI observations.

Spurred by the ALMA 2030 Development Roadmap (Carpenter et al. 2018), major new developments are currently underway at ALMA under the umbrella of the WSU. These will include deployment of a new ALMA correlator, whose design requirements include continued availability of VLBI capabilities (Baudry et al. 2021). An architecture for the next-generation ALMA correlator, known as the Advanced Technology ALMA Correlator (ATAC), has now been selected, and the implementation of VLBI within the new correlator is expected to draw heavily on the existing APS infrastructure. Thus the bulk of capabilities developed under APP3 are likely to survive intact in the eventual implementation. Furthermore, VLBI science with the newly commissioned APP3 capabilities on the existing BL Correlator are expected to serve as a pathfinder for future VLBI science that will be enabled once the ALMA2030 vision is fully realized.

11 Summary

APP3 has delivered a series of updates and enhancements to the original APS, leading to the introduction of flexible tuning for VLBI (subject only to ALMA's inherent tuning restrictions), a fully flexible spectral line VLBI observing mode, and the capability for VLBI/phased array operations to be performed (in principle) in any available ALMA receiver band. The project also undertook a range of activities to improve the operation of maintenance of VLBI capabilities at ALMA.

Although VLBI partner networks operating in the equivalent of ALMA Bands 2, 4, 5, 8, 9 and 10 do not yet exist, thanks to the development work undertaken during APP3, all system code now supports phased array and VLBI operations in these bands. Additionally, the use of the spectral line VLBI mode—including the mechanics of phasing the array on a bright line—have been extended to all bands and now accommodate flexible tuning. These new capabilities developed under APP3 were offered to the community for the first time in ALMA Cycle 10. It is anticipated that their availability will serve to increase the range of VLBI science opportunities available at ALMA during the next several years, leading up to the anticipated debut of VLBI capabilities with the next-generation ALMA correlator early in the next decade.

Acknowledgments The authors acknowledge the generous and expert support of the staff at JAO throughout the APP3. The individuals at JAO who have supported us are too numerous to mention without risk of omission, but we wish to particularly call out lead VLBI Friend, Hugo Messias, and SSR software developer Akihiko Hirota; without them, nearly all aspects of APP3 development would have been considerably more difficult. We also received enthusiastic support from the ALMA Director and his senior management team throughout our efforts.

We are grateful for assistance in the planning and scheduling of global VLBI tests from Thomas Krichbaum (MPIfR) and Vincent Fish (MIT Haystack). We also thank the EHTC Management Team for their allocation of telescope time for Band 6 VLBI commissioning observations, and the staff at each of the EHT observing sites who contributed their expertise to making those observations a success. For Band 1 and Band 3 testing we are indebted to Mark Claussen (NRAO) and other members of the VLBA staff for their help with allocation and scheduling of telescope time, coupled with support for schedule preparation, correlation checks of VLBA-VLBA baselines, and module shipping. The GMVA sites at Effelsberg, Onsala, and Yebes also allocated telescope time for Band 3 testing and we express our gratitude to the respective site leads and telescope staff who supported those observations.

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A List of Acronyms and Definitions

AGN Active Galactic Nuclei
AIPS Astronomical Image Processing System
ALMA Atacama Large Millimeter/submillimeter Array
ANTAB Ancillary telescope calibration table introduced by AIPS
AoD Astronomer on Duty
APP ALMA Phasing Project
APP2 ALMA Phasing Project, Phase 2
APP3 ALMA Phasing Project, Phase 3
APS ALMA Phasing System
Archive The software that connects to the ALMA Archive
ascii American Standard Code for Information Interchange
ASDM Archival Science Data Model
ATAC Advanced Technology ALMA Correlator
BB Baseband
BL Baseline (Correlator)
C++ A dialect of C, on which UNIX is based
CASA Common Astronomy Software Applications
CONTRL The tree of software that controls ALMA observations
CSV Commissioning and Science Verification
CVR Commercial unit that generates the LO1 tuning frequency
DDC Digital Down Converter
DiFX Distributed FX *(VLBI Software Correlator)*
DSO Director of Science Operations
EF Station code for Effelsberg Telescope in Germany
EHT Event Horizon Telescope

EHTC Event Horizon Telescope Collaboration
EP Expert Parameters used in SBs
FD Station code for 25 m VLBA antenna in Fort Davis, TX
FDM Frequency division mode **FFT** Fast Fourier Transform—the algorithm used for digital Fourier transforms
FITS Flexible Image Transport System
FLOOG First LO-Offset Generator **FPGA** Field Programmable Gate Array
FTE Full Time Equivalent
ftp File Transfer Protocol
FWHM Full Width, Half Maximum
GMVA Global Millimeter Array
GPS Global Positioning System
GUI Graphical User Interface
HN Station code for 25 m VLBA antenna in Hancock, New Hampshire
HOPS Haystack Observatory Postprocessing System
ICD Interface Control Document
ICT Integrated Computing Team
ICTJIRA The (Atlassian) JIRA system ICT uses
IDL Interface Definition Language
IF Intermediate Frequency—the part of the LSB or USB that is usable
IRAM Institute de Radioastronomie Millimétrique
JAO Joint ALMA Observatory
Java A computing language similar to C, but designed to compile to processor-independent object code
JCMT James Clerk Maxwell Telescope (on Mauna Kea, HI station Mm)
JIRA A truncation of Gojira, which is Japanese for Godzilla
KP Station code for 25 m VLBA antenna at Kitt Peak, Arizona
KT Station code for the 12 m EHT antenna at Kitt Peak, Arizona
LA Station code for 25 m VLBA antenna in Los Alamos, New Mexico
LO Local Oscillator
LO1 The LO that creates the fundamental tuning for upper and lower sidebands
LO2 One of 4 LOs that create the 2 GHz ALMA basebands
LOSolutions The (Java) software used by OT and CONTROL to tune LOs
LSB Lower side band (frequencies below an LO)
LSR Local Standard of Rest
LST Local Sidereal Time
MIT Massachusetts Institute of Technology
MJD Modified Julian Day
MK Station code for 25 m VLBA antenna on Mauna Kea, Hawaii
MPIfR Max Planck Institute für Radioastronomie
NA North America
NL Station code for 25 m VLBA antenna in North Liberty, Iowa
NOEMA Northern Extension of the Millimeter Array IRAM, Plateau du Bure
NRAO National Radio Astronomy Observatory

ObsMode The process whereby Observation Modes are introduced or revised
OFFLINE Refers to the released software that supports observations
ON Station code for 20 m antenna Onsala antenna in Sweden
ONLINE Refers to the released software that performs observations
OSF Operations Support Facility
OSS Observing Script Simulator
OT Observing Tool
OV Station code for 25 m VLBA antenna in Owens Valley, California
PFB Polyphase Filter Bank
PI Principal Investigator
PPS Pulse Per Second
PT Station code for 25 m VLBA antenna in Pie Town, New Mexico
PV The IRAM 30-m telescope on Pico Veleta, near Granda, Spain
PWV Precipitable water vapor
Python The scripting language used at ALMA
QA0+ Quality Assurance (at time of observations, enhanced version)
QA2 Quality Assurance Level 2 (performed prior to data delivery)
R2DBE ROACH (2nd generation) digital back end
RF Radio Frequency
RMS Root Mean Square
ROACH Reconfigurable Open Architecture Computing Hardware
SB Scheduling Block
SC Station code for 25 m VLBA antenna in St. Croix, Virgin Islands
SFI Single Field Interferometry
SMA Submillimeter Array (Mauna Kea, station Sw)
SMT Submillimeter Telescope (Arizona, station Mg)
SNR Signal-to-Noise Ratio
SPW SPectral Window
SPT South Pole Telescope
SSR Science Software Requirements
UNIX The generic name of a computer operating system
USB Upper side band (frequencies above an LO)
UTC Coordinated Universal Time
VEX VLBI EXperiment file
VDIF VLBI Data Interchange Format
VEX2VOM The tool that merges VLBI plans contained within a VEX File with ALMA SB executions
VLA (Karl G. Jansky) Very Large Array
VLBA Very Long Baseline Array
VLBI Very Long Baseline Interferometry
VOM VLBI Observing Mode
WBS Work Breakdown Structure
WSU (ALMA) Wideband Sensitivity Upgrade
WVR Water Vapor Radiometer

XML eXtended Markup Language
YB Station code for Yebes Observatory in Spain