ALMA Phasing Project Incremental Acceptance Report

ALMA-05.11.00.52-0005-A-REP

2015-09-17

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Change Record

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Chapter 1

Introduction

1.1 Purpose

This document provides an overview of the current status of work by the ALMA Phasing Project (APP) on its path towards full acceptance. It is intended to support an "Incremental Acceptance Review" of the APP progress as described in Chapter 2.1.

1.2 Scope

This document is limited to providing summaries of completed items, discussions of work in progress and attempts to identify outstanding issues. The reference documents (Section 1.3) and other exhibits should be consulted for full particulars.

1.3 Reference Documents

The following documents (Table 1.1) contain additional information, are referenced in this document, and should be consulted for further, more detailed information.

1.4 Acronyms

ACS ALMA Common Software

ADS ALMA Department of Science

ALMA Atacama Large Millimeter/submillimeter Array

APEX Atacama Pathfinder EXperiment (telescope)

APP ALMA Phasing Project

APS ALMA Phasing System

AOS Array Operations Site

ASDM ALMA Science Data Model

BL Baseline (correlator)

CAI Correlator Antenna Input

CAN Controller Area Network

CARMA Combined Array for Research in Millimeter Astronomy

Table 1.1: Reference Documents

Reference	Document Title	Document ID
[RD1]	Implementation Plan	ALMA-05.11.10.01-0001-A-PLA
[RD2]	Acceptance Review for the H-Maser S/N 59 - Plan	ALMA-05.11.21.01-0005-A-PLA
[RD3]	Acceptance Review for the Recorders, Optical Fiber Link System, Correlator Upgrades and the Phasing Interface Card Assembly	ALMA-05.11.00.52-0001-A-PLA
[RD4]	APP Computing Management Plan	ALMA-05.11.60.01-0001-B-PLA
[RD5]	APP Update to Corr/Control Design	ALMA-05.11.61.01-0001-A-DSN
[RD6]	APP Update to TelCal Design	ALMA-05.11.62.01-0001-A-DSN
[RD7]	APP Commissioning and Science Verification Plan	ALMA-05.11.10.01-001-A-PLA
[RD8]	APP Phasing Efficiency Status Report	ALMA-05.11.63.03-0001-A-REP
[RD9]	APP VLBI Fringe Status Report	ALMA-05.11.63.03-0002-A-REP
[RD10]	APP Mark6/OFLS/PIC Acceptance Report	ALMA-05.11.50.03-0001-A-REP
[RD11]	Current Status of PolConvert	not assigned
[RD12]	Summary of the First APP CSV Mission: 2015 January 6-13	ALMA Technical Note 16
[RD13]	Summary of the Second APP CSV Mission: 2015 March 24-30	ALMA Technical Note 17
[RD14]	Summary of the Third APP CSV Mission: 2015 July 28 - August 3	ALMA Technical Note 18
[RD15]	EOC Program Report for EOC Week ending 05 August 2014	EOC ARC Memo 13
[RD16]	APP Requirements Version 2.1 (`APP_requirements_2.1_21APR13.xlsx`)	not assigned
[RD17]	APP Detailed Test Procedures Version 1.3	ALMA-05.11.00.52-0002-A-PRO
[RD18]	Observational Modes Supported by the ALMA Correlator	ALMA Memo #556
[RD19]	APP VOM Input and SSR Design	ALMA-05.11.61.01-0002-A-DSN (in preparation)

https://wikis.alma.cl/bin/view/AIV/EOCMemos
https://almascience.nrao.edu/documents-and-tools/alma-technical-notes/

CASA Common Astronomy Software Applications

CCC Correlator Control Computer

CDP Correlator Data Processor

CDR Comprehensive/Critical Design Review

CFP Call For Proposals

CSV Commissioning and Science Verification

DiFX Distributed FX *(VLBI Software Correlator)*

DSO Director Science Operations

EHT Event Horizon Telescope

EOC Extension and Optimization of Capabilities

FDM Frequency Division Mode

GUI Graphical User Interface

ICD Interface Control Document

ICT Integrated Computing Team

IRAM Institute de Radioastronomie Millimétrique

JAO Joint ALMA Observatory

JCMT James Clerk Maxwell Telescope

JIRA Not an acronym; a truncation of Gojira, which is Japanese for Godzilla

LAN Local Area Network

LO Local Oscillator

LORR Local Oscillator Reference Receiver

LTA Long Term Accumulator

MIT Massachusetts Institute of Technology

OSF Operations Support Facility

OFLS Optical Fiber Link System

OPT Observing Preparation Tool

OT Observing Tool (same as OPT)

PDR Preliminary Design Review

PIC Phasing Interface Card

RID Review Item Discrepancy

rms Root Mean Square

RMS Root Mean Square

SB Scheduling Block

SCO Santiago Chile Office

SFI (ALMA) Single-Field Interferometry (observing mode)

SMA Submillimeter Array

SMT Submillimeter Telescope (Observatory)

SNR Signal to Noise Ratio

SSR Science Software Requirements

TDM Time Division Mode

TFB Tunable Filter Bank

TFINT Test Facility INTerferometry

UTC Coordinated Universal Time

VEX VLBI EXperiment file

VLBA Very Long Baseline Array

VLBI Very Long Baseline Interferometry

VOM VLBI Observing Mode

WVR Water Vapor Radiometer

Chapter 2

Current Status

2.1 Context

The APP is in transition from a "phase one" which involved implementation of the basic capabilities, to a "phase two" in which those capabilities are to be merged with the Observatory for use in Cycle 4. Phase one was very much about delivering the Hardware and Software capabilities as spelled out in the Implementation Plan (see [RD1]). At that time, we knew what work was necessary for the technical capability, but many of the details of fully integrating the APS into Observatory operations were not clear. It was also envisioned that the work would be complete by August of 2015, with a concluding "Acceptance" review towards the end of the project. For a number of reasons (none of which are particularly important here), phase one activities had to be extended past the original project timeline, but are now nearing completion.

As phase one activities are nearing completion, we are now entering "phase two", with a view towards an offering of a phasing capability in Cycle 4. Some of this is work that was envisioned in the original project, if only in vague way, and some of it is new work to meet the current realities.

An overview of the current software status of the APP is presented in Section 4. At this time, the Hardware work for the project (and a significant number of other deliverables, such as ICDs) have already been Accepted (see [RD2] and [RD3] and follow-up in Section 3). Likewise, most of the necessary Software tasks generally were carried out as planned ([RD4]) and designed ([RD5] and [RD6]), and are relatively complete in Cycle 3. Therefore, even though a phasing capability is not to be offered in Cycle 3, it makes eminent sense to complete an Acceptance of that software at this time (rather than wait a year until the Cycle 4 Acceptance).

Finally, the Scientific Validation of the software is also largely complete; but according to the APP Commissioning and Science Verification (CSV) Plan (see [RD7]), we need to Validate our work against project requirements. This process is partially complete but still ongoing. We expect to complete these outstanding validations as a part of the Cycle 4 Acceptance (in roughly a year's time). By that point, the work of the APP should be properly integrated, and remaining work can be viewed as additional, desirable enhancements for a future Cycle. This is detailed in Section 5.

Recently, the ALMA EOC team (which has overseen the CSV of the APP) has transitioned to a tighter integration within ADS and direct oversight by the DSO. Thus this document (and surrounding Review) may function as a convenient point to identify CSV work satisfactorily completed and work in progress, to be completed by Cycle 4 (or as appropriate, in a later Cycle).

2.2 General Status At This Review

At this time, we have fully implemented a VLBI Observing Mode (VOM) which can adequately phase the entire ALMA array ([RD8]). This observing mode has been used in VLBI experiments to obtain fringes to a number of peer observatories on other continents in bands 3 and 6 ([RD9]), most recently in July/August of this year. The correlation and analysis of these data is not yet complete, but is proceeding satisfactorily.

Our attention has turned (briefly) from development of the technical capabilities to support of the programmatic aspects required for support of VLBI observations in Cycle 4. The requirements for the OT to allow VLBI proposals have been finalized (tracked under `ICT-5575`). A "friend" of VLBI at JAO has been appointed (Violette Impellizzeri) with whome we are actively working to finalize the remaining items necessary for the CFP next March, and full operations at the start of Cycle 4. Section 6 provides a list of anticipated "final" deliverables for APP in an approximate timeline. Since the development for some of these will occur well after the Cycle 4 candidate is captured, it is likely these features will not become available until Cycle 5.

2.3 A Comment about Sub-Arrays

One point about the VOM that should be emphasized is that it is not currently safe to operate in the subarray paradigm. That is, there are low-level interactions between subarrays that require special handling (for code is not in place) to avert interference of one observation with the other. Since it is generally desirable to operate the VOM with as many antennas as possible, this is not a significant issue for operations. However it bears repeating, as it is likely to be forgotten.

The APP project was conceived at a time when sub-arrays were expected in the future (indeed, the future is now), and the design was made compatible with sub-arrays to the extent possible. However, some of the operational aspects of VLBI render it somewhat inconsistent with subarrays, *e.g.* the scans must be executed at a fixed time, and there is no provision for that in the current subarray implementation. Additionally, a VLBI observation would naturally want to observe with maximum sensitivity and therefore would want to use all viable antennas, leaving none for other observations. Operationally, this is not expected to be an issue.

Chapter 3

Hardware Acceptance Residual Items

The hardware acceptance was conducted in two portions. The Hydrogen Maser was accepted sometime after its installation ([RD2]). The remaining hardware items took longer to install and test and were later accepted ([RD3]).

At this point there are two outstanding RIDs remaining from that review as shown in Table 3.1.

***Table 3.1:** APP Review Item Discrepancies, Open/Unresolved*

Key	Summary	Assignee	Document Title
APPRID-60	H-Maser and level of HW self-protection	Shep Doeleman	ALMA Phasing Project Hydrogen Maser Maintenance Plan
APPRID-63	ICD Between ALMA Phasing Project And ALMA Backend ALMA-05.11.10.00-50.00.00.00-A-ICD is not approved by both parties to the interface	Andrea Araya	ICD Between ALMA Phasing Project And ALMA Backend

The first is waiting on information from the vendor (T4Science).

The remaining hardware-related items we are aware of are essentially "maintenance items":

- Repair of the damaged LAN port on the OFLS DeMux unit. (A trip to supervise this planned for late November.)
- Maintenance on the Maser to be conducted by the vendor, T4Science (in December).
- Anticipated upgrade of embedded Mark6 recorder software (minor enhancements and bug fixes, sometime in 2016).

Chapter 4

Software Development Status

4.1 Development Process

Software development was partitioned into ICT tasks following CDR (May 2013) and merged with the ALMA release schedule more-or-less as planned ([RD4]). The features as described there were migrated to the ICT JIRA more-or-less one-to-one as ICT JIRA tasks, and the work was assigned to APP developers as planned. There were immediate complications in that the observatory was working through a number of operational issues (power and labor), and it was requested that we delay integration of some features for one or two releases since the resources would not be available at JAO to follow the original plan. The first features were integrated in Release 10.4 and the most recent ones appear in Release 2015.6. Since APP is an "online" capability, its supporting features are only introduced into the "even" releases. (The "odd" releases are intended for "offline" parts of the software system only.) These are detailed in Sections 4.2 through 4.6.

We found it quite important to support phase B testing at the OSF. In the event 3 missions to Chile were mounted during 2014 as shown in Table 4.1. During these missions, two or three of the APP developers would travel to both the SCO and the OSF in order to help verify the softare. Work was exclusively executed within Engineering time (daylight hours) and except for a few tests, with a relatively small array operating with band 3 receivers.

Table 4.1: *APP Software Missions*

Dates	Title and Link
Jan 15, 2014 - - Jan 29, 2014	APP Software Verification Mission: Phasing System https://ictwiki.alma.cl/twiki/bin/view/Control/AppMissionChile012014
Jul 7, 2014 - - Jul 13, 2014	APP Software Verification Mission: VLBI data path https://ictwiki.alma.cl/twiki/bin/view/Control/AppMissionChile072014
Oct 15, 2014 - - Oct 28, 2014	APP Software Verification Mission: Full Phasing Loop and ASummer https://ictwiki.alma.cl/twiki/bin/view/Control/AppMissionChile102014

The full particulars of each mission are to be found in detail on the corresponding wiki pages. However the main goals of each were usually achieved, and we present those along with a discussion of the tasks completed in the following sections. In addition to the wiki pages, the particulars of each ICT task are detailed on the appropriate JIRA task ticket. We reproduce certain summary information for each ticket, but do not include the details. The reader is referred to the appropriate pages of the JIRA for more information (http://ictjira.alma.cl/browse/ICT-<number>).

In most cases, the tasks listed arose as either part of the original design, adjustments to the design or bug fixes to planned features. There are a few additional tasks listed (tagged with the APP label for tracking purposes) which arose from other considerations (*e.g.* bugs or performance issues) and are very relevant to the VOM execution.

In the tables that follow covering the ICT tasks,

Key the ICT task name

Summary the title of the task

Status is with respect to the work flow: **submitted** (by reporter), **accepted** (by developer), **in progress** (by developer), **implemented** (by developer), **verifying** (by phase B tester), **resolved** (by testing), **validating** (within phase C), **or closed** (whether validated, resolved or rejected)

Resolution depending on type of testing—**verified** for relatively simple, straightforward items, or **validated** for more complex features requiring significant AOS testing by the commissioning team. Items may also be **rejected**, discarded as **duplicate** of some other task, or merely **unresolved**.

Fix release requiring the fix (for simplicity, we list only the earliest release that was repaired). **NA** stands for "not applicable" and **NYS** is "not yet scheduled"

Created calendar date of creation

The work proceeded as spelled out in [RD4], with (for the most part) APP developers doing the phase A implementation and integration into the releases as shown. The phase B testing was cooperatively performed between APP developers and software operations team members—the former where necessary, the latter as much as possible. Finally the phase C testing was jointly carried out APP, EOC, and software operations teams, and evaluated by the APP team. For details on each task, consult the individual JIRA tickets. Those important for Validation are also discussed more thoroughly in Section 5.

Finally, release nomenclature changed over the course of this work. Release naming shifted from *Major.Minor* to *Year.Number* for better coordination with the underlying ACS software releases.

4.2 AppMissionChile012014: Releases 10.4 and 10.6

The initial APP tasks were deployed in `R10.4`, branched Sep 30, 2013. These consisted of tasks to create the VOM (as a class derived from the "Standard Interferomety Mode") and some necessary changes to certain lower level interfaces. These tasks are listed in Table 4.2. There was, however, no useful functionality in this new VOM without the addition features of `R10.6`, branched Dec 27, 2013, as shown in Table 4.3.

Table 4.2: *ALMA-10.4*

Key	Summary	Status	Resolution	Fix	Created
ICT-310	VOM: InterferometryController	Closed	Verified	ALMA-10.4	2013-05-24
ICT-315	LTA protocol changes to support antenna sum	Closed	Verified	ALMA-10.4	2013-05-24
ICT-317	TFB commands to support phasing	Closed	Verified	ALMA-10.4	2013-05-24
ICT-726	Retrieve and apply TelCal calibrations in the ExecState component.	Closed	Verified	ALMA-10.4	2013-06-25
ICT-966	VOM: VLBI Observing Mode interfaces	Closed	Verified	ALMA-10.4	2013-07-23

Notably, these include the new `PhasingController` and the necessary ASDM and `TelCal` changes to create the "slow" phasing loop. With these capabilities in place, the first mission was organized in order to exercise the phasing loop using the AOS hardware. While it was originally hoped that we would be able to test the phasing loop in a software simulator, in practice that proved

Table 4.3: ALMA-10.6

Key	Summary	Status	Resolution	Fix	Created
ICT-301	Device: Hydrogen Maser	Closed	Verified	ALMA-10.6	2013-05-24
ICT-302	Device: VLBI Optical Fiber Link System	Closed	Verified	ALMA-10.6	2013-05-24
ICT-311	VOM: PhasingController	Closed	Verified	ALMA-10.6	2013-05-24
ICT-313	VOM: Control of Antenna CAI-63	Closed	Verified	ALMA-10.6	2013-05-24
ICT-314	VOM: DataCapturer support for CalAppPhase	Closed	Verified	ALMA-10.6	2013-05-24
ICT-321	TelCal: Phase Solver (Prototype/Simple)	Closed	Validated	ALMA-10.6	2013-05-24
ICT-854	CDP support for slow phasing loop	Closed	Verified	ALMA-10.6	2013-07-11
ICT-967	ObservationControl interface to support phasing system	Closed	Verified	ALMA-10.6	2013-07-23
ICT-1994	Adding the CalAppPhase table to ASDM data model	Closed	Verified	ALMA-10.6	2013-12-10
ICT-2162	APP CAN commands possibly overlapping	Closed	Verified	ALMA-10.6	2014-01-08
ICT-2177	ObservationControl:: setAppPhaseParameters general execution problems	Closed	Verified	ALMA-10.6	2014-01-10
ICT-2293	NodeImpl::startSubscanSequence is invoked too late when using subscan sequences	Closed	Fixed	ALMA-10.6	2014-01-25
ICT-2310	TFB phase adjustments not resetting between observations	Closed	Fixed	ALMA-10.6	2014-01-28
ICT-2311	Inconsistencies in APP phase corrections relative to delays	Closed	Fixed	ALMA-10.6	2014-01-28
ICT-2312	Add APP scripts to science scripts path	Closed	Verified	NA	2014-01-28
ICT-2326	TMCDBAccess reports NullPointerException when retrieving a AntennaBaselineName giving a CAI from an antenna if at least one antenna in the configuration doesn't have its CAI defined	Closed	Verified	ALMA-10.6	2014-01-29
ICT-2586	Unknown CDP exception during VLBITestObs	Closed	Fixed	ALMA-10.6	2014-03-06

too difficult to accomplish on the (rather tight) project timeline. Thus it was very important to verify that the basic design was working as anticipated.

In addition, several of the hardware devices were deployed in the software at this time. This would allow the hardware to be operated through the software as soon as delivered.

The explicit goals of this mission were to:

- Test new VLBI Observing Mode and consolidate prototype observing script
- Test BL Correlator interaction and data flow using new protocols
- Test and exercise slow phasing loop (Control-Corr-Telcal)
- Correct any issues found in preparation for the first CSV campaign later this year
- Involve OSF staff with details of APP software and operations.

All goals were met. In addition, a number of issues were identified in the course of the mission. New "bug fix" tasks were created to address these, and they appear in Table 4.3. At one additional issue (ICT-2586) was found during regression testing following the mission; this was also fixed. Finally, in ICT-2312 it was worked out how to capture VLBI script development in a sensible way outside the release cycle.

4.3 AppMissionChile072014, Releases 10.8 and 2014.2

With the basic phasing system in hand, we turned our attention to the VLBI backend. All of the APP hardware (Maser, OFLS, Recorders, PICs, and supporting cabling) was delivered in the first half of 2014. Significant software capability was introduced into Releases R10.8 (branched Apr 7, 2014) and 2014.2 (branched Jun 16, 2014) to support this hardware.

A second software verification mission was designed to verify the new software and hardware and to provide the final testing to complete the hardware on-site acceptance. The goals of the mission as spelled out on the mission page were:

- Integrate critical VLBI data path hardware with the software infrastructure.
- Verify VLBI Observing Mode VLBIController (control of VLBI devices).
- Verify VLBI Observing Mode PhasingController improvements (slow phasing loop).
- Correct any issues found in preparation for the first CSV campaign later this year
- Capture sample data for testing TelCal multi-channel average solution modes
- Record sample data for test VLBI correlations and checking ALMA interferometry phases
- Involve OSF staff with details of APP software and operations.

Indeed, these goals were all met. A portion of the sample data recorded during the mission was subsequently correlated within the ALMA Recorders as well as back at Haystack (see [RD9] and [RD10]).

4.4 AppMissionChile102014, Release 2014.4

The final software verification mission was timed to correspond to phase B of R2014.4 (branched Sep 22, 2014) and also as a mission of opportunity during the long-baseline campaign. This release contained the final piece of significant functionality—the "fast" loop (ICT-319, as shown in Table 4.6). That the baselines were longer than usual was an issue for combining the "slow" and "fast" loops but it was not a problem for the "fast" loop testing.

The formal goals of this mission were to:

- Verify VLBI Observing Mode VLBIController (control of VLBI devices)

Table 4.4: ALMA-10.8

Key	Summary	Status	Resolution	Fix	Created
ICT-303	Device: VLBI Recorder	Closed	Verified	ALMA-10.8	2013-05-24
ICT-312	VOM: VLBIController	Closed	Verified	ALMA-10.8	2013-05-24
ICT-316	PIC control interfaces	Closed	Verified	ALMA-10.8	2013-05-24
ICT-323	TelCal: Phase Solver (Advanced)	Closed	Verified	ALMA-10.8	2013-05-24
ICT-324	ICT-323 TelCal: Efficiency Monitor	Closed	Verified	ALMA-10.8	2013-05-24
ICT-326	VEX to XML	Closed	Verified	ALMA-10.8	2013-05-24
ICT-1003	PIC diagnostics interface and ObservationControl Implementation	Closed	Verified	ALMA-10.8	2013-08-01
ICT-2305	TelCal Simple Solver Antenna Index Error	Closed	Verified	ALMA-10.8	2014-01-27
ICT-2306	TelCal Simple Solver zero phase corrections	Closed	Verified	ALMA-10.8	2014-01-27
ICT-2317	TelCal adjust time in CalAppPhase table	Closed	Verified	ALMA-10.8	2014-01-28
ICT-2329	Avoid array destruction requirement after using VOM	Closed	Verified	ALMA-10.8	2014-01-30
ICT-2446	Device: Hydrogen Maser Upgrade	Closed	Verified	ALMA-10.8	2014-02-10
ICT-2449	cdp disables residual delay corrections with an incorrect mechanism	Closed	Validated	2014.4	2014-02-11
ICT-2630	Add support for VLBI devices to CONTROL Master	Closed	Verified	ALMA-10.8	2014-03-13
ICT-2747	ICT-323 Refine quality calculation	Closed	Verified	ALMA-10.8	2014-03-31

Table 4.5: 2014.2

Key	Summary	Status	Resolution	Fix	Created
ICT-2294	CDP support for sum antenna scaling	Closed	Validated	2014.4	2014-01-25
ICT-2295	VOM: Advanced PhasingController	Closed	Validated	2014.4	2014-01-25
ICT-2584	CDP support for sum antenna delay/phase correction	Closed	Validated	2014.4	2014-03-05
ICT-2803	PIC control implementation	Closed	Verified	2014.2	2014-04-07
ICT-2994	Device: VLBI Recorder Upgrade	Closed	Verified	2014.2	2014-05-14
ICT-3124	VLBIDeviceResource status handling is incorrect	Closed	Verified	2014.2	2014-06-09
ICT-3355	PICController: CCC container crash while getting apply VDIF header status	Closed	Verified	2014.2	2014-07-11

- Verify VLBI Observing Mode PhasingController improvements (slow+fast phasing loop)
- Test TelCal multi-channel average solution modes
- Install (done) and test final two recorders
- Record sample data for test VLBI correlations and cross-checking ALMA interferometry phases and absolute timing
- Prepare for hardware acceptance (workmanship inspections, power measurements, documentation)
- Make progress on general 2014.2/2014.4 issues (CORR subarrays, with remote support from Rodrigo and J)
- Correct any issues found in preparation for the first CSV campaign early next year
- Coordinate upcoming commissioning activities
- Involve OSF staff with details of APP software and operations

These goals were generally met. However, there were a number of puzzles in the behavior of the system which were not understood at the time. (It was difficult to separate issues of the phasing system itself from those induced by the longer baselines. That analysis is still incomplete.) As usual a few issues were resolved and fixed in the course of the mission as shown in Table 4.6.

Table 4.6: *2014.4*

Key	Summary	Status	Resolution	Fix	Created
ICT-319	Phase updates for fast loop	Closed	Validated	2014.4	2013-05-24
ICT-2539	Parallelize APP CAN commands	Closed	Verified	2014.4	2014-02-25
ICT-2834	Per Spectral Window phase solutions	Closed	Verified	2014.4	2014-04-11
ICT-3640	Update PIC control implementation to latest ICD	Closed	Validated	2014.4	2014-09-12
ICT-3697	Fast phasing loop processing thread stopping too early	Closed	Verified	2014.4	2014-09-24
ICT-3841	VLBIRecorder communication should be tollerant to recorder failures after system startup	Closed	Validated	2014.4	2014-10-18
ICT-4299	LTA DownloadSumScalingData takes longer than it used to	Closed	Verified	2014.6	2015-01-08

4.5 Remaining Cycle-3 Features

During the EOC week of Dec 16, 2014, we carried out some follow-up testing with remote support from the OSF Software Operations staff in preparation for the first commissioning mission planned for early January, 2015 (see Table 5.1 of Section 5). Release R2014.6 (branched Dec 19, 2014, Table 4.7) which was destined to become the Cycle-3 candidate, was important to APP as the team was now pivoting to commissioning activities (band 6, during EOC time at night). Since it is inconvenient to switch software releases far outside of normal Engineering hours, it was thus imperative to be able to conduct phasing studies and VLBI experiments with the release under test by EOC. In the event that switch (by EOC) did not actually happen until after the January mission.

The R2014.6 tasks are listed in Table 4.7. Note that since this was the Cycle-3 candidate, a few post-R2014.6 improvements were developed in the testing branches (R2015.2 and R2015.4) and subsequently patched onto R2014.6. Thus all APP tasks available (for continued testing) in the 201509-Cycle3-ON are now fully listed in Tables 4.2 through 4.7.

Most of these features were planned for R2014.6 and are relatively minor enhancements aimed towards completion of the planned mode, for example software methods to allow GUIs to be created to monitor the VOM. However, three of them are signficant modifications and were introduced in later releases and backported to R2014.6 for the afore-mentioned reasons. Two of them (ICT-4460 and ICT-4461) were created in the weeks following the January mission as a result of identifying a serious issue with the delay processing in the CDP spectral processing software. A third (ICT-5401) bug fix took several months to nail down, and was ultimately fixed as a result of corrections to correlator software and firmware to allow sub-array processing as needed for Cycle 3.

ICT-3863 was originally thought needed as a code enhancement to the VOM. Additional study relevealed that the required WVR calibrations were already captured in the `ExecState` system and thus could were easily accessible by the observing script.

***Table 4.7:** 2014.6*

Key	Summary	Status	Resolution	Fix	Created
ICT-318	Phase update query interface	Closed	Validated	2014.6	2013-05-24
ICT-2296	Provide access to VOM methods for Array Status GUI	Closed	Validated	2014.6	2014-01-25
ICT-2835	Phasing efficiency	Closed	Validated	2014.6	2014-04-11
ICT-3398	VOM: Dynamic timeouts for TelCal results in PhasingController	Closed	Verified	2014.6	2014-07-22
ICT-3846	TELCAL does not calculate APP solutions if no comparison array is defined	Closed	Fixed	2015.2	2014-10-21
ICT-3850	CDP sum antenna scaling should consider current sum mask	Closed	Verified	2014.6	2014-10-21
ICT-3861	Revert phase update in VLBIObsControlHelper if phase download/apply fails	Closed	Verified	2014.6	2014-10-24
ICT-3862	Optional slow loop phase reset between subscan sequences	Closed	Validated	2014.6	2014-10-24
ICT-3863	Remember WVR coefficients between consecutive CORR subarrays	Closed	Validated	NA	2014-10-24
ICT-3865	AppVomMode.isEnabled does not skip phase applications	Closed	Validated	2014.6	2014-10-26
ICT-3953	Deliver source models to TelCal	Closed	Verified	2014.6	2014-11-10
ICT-4255	PICController: PIC state dead end in PIC_STARTUP	Closed	Verified	2014.6	2014-12-23
ICT-4460	Add option to disable CDP baseband delays	Closed	Validated	2014.6	2015-02-04
ICT-4461	Add phasing support for multiple channel averages	Closed	Verified	2015.2	2015-02-04
ICT-4481	DelayEvents subarray-specific variables are not reset at subarray creation	Closed	Verified	2015.2	2015-02-06
ICT-4810	CONTROL/VLBI/cppContainer container crashes during reconnectSocket	Closed	Cannot Reproduce	2015.4	2015-03-29
ICT-5401	Phase jumps in AppScanSequence at start of subscans	Closed	Fixed	2015.6	2015-06-18

4.6 Cycle 4 Features

Through most of 2015, the emphasis of the APP team has been on commissioning the VOM capabilities rather than development. As the working team is small, a pivot to commissioning implies a suspension of significant development. Thus the number of tasks introduced into the software this year is comparatively small, see Table 4.8. There are four relevant releases in 2015: R2015.2 (branched Mar 28, 2015), R2015.4 (branched Jun 3, 2015), R2015.6 (branched on or shortly after Oct 12, 2015) and R2015.8 (to be branched Dec 16, 2015).

Table 4.8: *2015.2, 2015.4, 2015.6 or 2015.8*

Key	Summary	Status	Resolution	Fix	Created
ICT-3812	cross cdp nodes fail to obtain auto-data	**Accepted**	Unresolved	2014.6	2014-10-14
ICT-4449	CCC is using uncorrected coarse delays in TFB phase calculation	**Accepted**	Unresolved	2014.6	2015-02-03
ICT-4286	Use the array observation schedule to allocate phase adjustments	**Implemented**	Unresolved	2015.2	2015-01-06
ICT-5118	NullPointerException in VLBIControllerImpl constructor if it fails to retrieve PIC Controller resource/component	**Closed**	Verified	2015.4	2015-05-09
ICT-4583	TELCAL / SSR: reduce overheads added to executions due to waiting for WVR results	**Resolved**	Validated	2015.6	2015-02-25
ICT-4656	increase maximum number of channel average regions from 10 to 32	**Implemented**	Unresolved	2015.6	2015-03-05
ICT-5575	Enable VLBI projects in the OT	**In Progress**	Unresolved	2015.6	2015-07-15
ICT-3852	CDPMaster integration timeout when using 32 spectral windows	**Accepted**	Unresolved	2015.8	2014-10-22

In addition to these tasks, there are a few that (at the time of this report) are in an active, but unscheduled state, as shown in Table 4.9.

Table 4.9: *Active, Unscheduled Issues*

Key	Summary	Status	Resolution	Fix	Created
ICT-325	VLBI observation scripts (VEX2VOM v1.0)	**In Progress**	Unresolved	NA	2013-05-24
ICT-3954	Add VLBIObservingMode support to SSR	**In Progress**	Unresolved	NA	2014-11-10
ICT-4815	Porcupine pattern in cross correlations	**Submitted**	Unresolved	None	2015-03-30
ICT-5693	setAppSumParameters parameter out of range exception	**Submitted**	Unresolved	None	2015-08-03

ICT-3812 refers to an investication of some clear mis-behavior with the CDP processing nodes. It should be resolved before Cycle 4; but it is perhaps not urgent to resolve.

In the process of understanding the “delay” problem ([RD8]) a related problem was found with normal interferometric observations. ICT-4449 was created to address this—it labelled with APP since the two modes share some infrastructure, and fixing one might break the other.

ICT-4286 is implemented, but awaiting testing by the Software Ops Team.

ICT-4583 addresses a general efficicency issue within the `TelCal/SSR` infrastructure. The issue (as far as APP is concerned) was addressed separately. However, it labelled with APP since addressing the remaining issues could cause problems for the VOM.

ICT-4656 will become closed for the BL correlator in R2015.6. For consistency, the ACA correlator will pick up the change in R2015.8 (in a new task ICT-6043), but that is irrelevant (since the APS does not work on the ACS correlator). This will allow better performance on bright sources, and remove residual coherence losses due to the baseband delay issue to the level of negligibility.

ICT-5575 is in active development by the OT team to allow VLBI observations in Cycle 4. It is believed that all the relevant requirements are now adequately specified by the Science Team.

ICT-3852 is possibly fixed through work on an unrelated issue, ICT-4359. Additional testing is required to find out if the problem recurs.

Two of the unscheduled tasks, ICT-325 and ICT-3954 cover the two halves of the work required to run the VOM from scheduling blocks, rather than from a manual-mode observation script. This work must be demonstrated before December 1, and may be assigned to R2015.8. However, these are SSR scripts and historically have not been as tightly coupled to the release process.

The other two issues, ICT-4815 and ICT-5693 refer to bugs just observed during the most recent commissioning campaign. Investigation and resolution should proceed later this year or early next.

4.7 Residual Software Items

For completeness, we list a number of rejected tasks in Table 4.10. We present a brief discussion of each one.

Table 4.10: *Rejected Tasks*

Key	Summary	Status	Resolution	Fix	Created
ICT-320	Phasing Simulation	Closed	Rejected	NA	2013-05-24
ICT-327	Advanced VLBI Scripts (VEX2VOM v2.0)	Closed	Rejected	NA	2013-05-24
ICT-604	Add CalAppPhase table to ASDM data model	Closed	Duplicate	None	2013-06-14
ICT-3042	CDPMaster aborting VLBI observations	Closed	Duplicate	None	2014-05-23
ICT-3528	Decrease inter-subscan time for VLBI subscan sequences	Closed	Rejected	NA	2014-08-19
ICT-3866	General slow phasing loop issues	Closed	Rejected	NA	2014-10-26
ICT-4315	polY-only VLBI observation produces zero TelCal phases	Closed	Rejected	NA	2015-01-11
ICT-4801	Update the CalAppPhase ASDM to allow for empty comparison arrays	Closed	Rejected	None	2015-03-27

As mentioned previously, our original notion was to build a sophisticated phasing simulator (ICT-320) to allow testing of the system in offline environments. We managed to do a significant amount of testing in the `IntTest` test suite environment and so such a simulator became unnecessary.

It was originally thought that supporting test scripts (*e.g.* such as are ultimately found in the `SSR` module) would be released with the incremental software, and so a number of tasks were created to capture the incremental test development (*e.g.* ICT-327). In the event, however, the test scripts have lived in the `CVS` script area and therefore are developed outside the release process.

ICT-604 was the original ticket for work that was ultimately accomplished under ICT-1994. Similarly, ICT-3042 reported a bug that had already been reported (and was ultimately fixed) under ICT-2171.

The inter-subscan time is driven by the dump duration in the correlator. While the inter-subscan time is invisible to normal observations, this data does appear in VLBI experiments which record continuously. At one time, the inter-subscan time was fairly long and that had sufficient implications for phasing efficiency that ICT-3528 was created to fix this. However, before this task could be implmented, certain improvements were made (notably parallelizing the download of TFB phases) and so the current inter-subscan time restrictions were deemed acceptable for all cases except perhaps for "fast" loop applications. Even in that case, it is acceptable to drop an application which collides with CAN bus activities within this inter-subscan time, and thus this feature is not required and therefore rejected.

ICT-3866 was created to track the strange behaviors first observed in the third software verification mission. There were a number of issues to untangle; some of which disappeared without a clear explanation, some of which were suspiciously plausible for attempts to phase on very long baselines, and one of which was ultimately addressed by ICT-5401. ICT-3866 was thus closed after it had served its purpose with no directly-associated code fixes.

While it is possible to specify operation with only X polarizations in the correlator, it turns out it is not possible to use only the Y polarizations. ICT-4315 was created when we discoved this and found problems in `TelCal` processing. However, investigation showed that the problem was there by design and rather avoidable.

ICT-4801 was created to create a defect in the ASDM specification where comparison antennas were effectively marked as obligatory, but not actually made so by the VOM. This produced no operational consequences except that the ASDM would be mal-formed in no comparison antennas were in fact designated. Since this fix wound up being an interface change (made at a time when other issues with development tools supporting the ASDM created serious problems), and since the problem could be resolved operationally by a runtime check enforcing the selection of comparision antennas, we ultimately chose to write-off the associated development work and to reject this task.

Finally, the remaining tasks tagged with the APP label are shown in Table 4.11 and are worthy of some explanations.

Table 4.11: *Cycle 5 or Later*

Key	Summary	Status	Resolution	Fix	Created
ICT-304	GUI: VLBI Hardware Status Panel	**In Progress**	Unresolved	NA	2013-05-24
ICT-305	GUI: TelCal Results Display	**In Progress**	Unresolved	NA	2013-05-24
ICT-306	GUI: CCC phase updates	**In Progress**	Unresolved	NA	2013-05-24
ICT-307	GUI: VLBI Observation Status	**In Progress**	Unresolved	NA	2013-05-24
ICT-965	QuickLook support for CalApp-Phase	**Accepted**	Unresolved	NYS	2013-07-23
ICT-1734	APP Device Alarms	**In Progress**	Unresolved	NA	2013-11-05
ICT-2833	Source modeler	**In Progress**	Unresolved	NYS	2014-04-11
ICT-4594	Move H-Maser management to AOSTiming controller	**Accepted**	Unresolved	NYS	2015-02-27

The original plan of development included provision for "operator" GUIs to show current status of the VOM activities and to allow manual adjustments as required. It was thought that such GUIs might be started early in the development process and available for the developers as an aid to debugging *&c.* . ICT-304, ICT-305, ICT-306 and ICT-307 were created to capture the four essential parts of such a GUI.

In the event, however, separate resources to develop the GUIs were not available, and the schedule too tight to allow this plan to reach fruition. An additional complication was that the `QuickLook` GUI architecture was found to be not entirely satisfactory and it thus did not make sense to try to develop GUIs that would be dead-on-arrival. ICT-965 was captured to assist with this integration.

On the other, hand, it turned out that the `CorrGUI` (which was never intended to be a general-use GUI) turned out to provide much of the developmental support that was required. Likewise, the access methods created to **eventually** support the APP GUI functionality turned out to be adequate for the developers using relatively simple Python scripts.

At this time, the plan is that (as developer time allows) tie these simple scripts into a more friendly Python prototype such as supporting scientists might use during a VLBI observation. If this prototype is found to be useful, it could be more properly, and easily integrated into the `OMC` operator GUI.

ICT-1734 reflects work that was completed by APP to allow automatic notification of issues surrounding the APP hardware. The completed work specifies normal operating limits and testing intervals for a number of monitor points. However, the alarm system itself has been found wanting and the final disposition of this task awaits resolving the issues with the alarm system.

ICT-2833 captures the `TelCal` work necessary to implement the modelling of sources with structure. This work is non-trivial, and moreover, for ease of use, it needs to be integrated with the ALMA Archive such that structural information about a given source should be naturally picked up from the Archive rather than via some *ad hoc* APP mechanism. At this time, protocols exist in the VOM in order to activate source-model-informed phasing, but the implementation is necessarily incomplete. It seems unlikely that the functionality could be provided in time for Cycle 4, but it should be feasible to roll this out in Cycle 5 as desired.

ICT-4594 concerns the ownership of the Maser software device. Normally software is deployed in ACS containers, and the Maser is currently run from the so-called VLBI container which hosts the other required software. However while the Maser runs all the time and is now intended to be in routine use by ALMA, such is not the case for the VLBI processes (which are only truly needed when VLBI observation are made). This issue was created to move the Maser to the same container as is used by the `AOSTiming` system. This would allow the VLBI container to be disabled when not needed. (Of course, that would disable monitoring of the VLBI equipment, which should then perhaps be powered-off.) This is certainly not a critical item.

4.8 New Development

Finally, it should be pointed out that since the time VLBI was designed sub-arrays have been implemented and, with Cycle 3 are to become the standard operating mode for the observatory. There are a number of reasons why the existing design will not operate with concurrent observations as allowed in the sub-array paradigm. A full discussion is captured on the `CONTROL` wiki. A short description of the issues is as follows:

- There is an APP requirement to start an observation at a fixed UTC time. With concurrent subarrays CONTROL is not anymore deciding when an observation will start. . . .
- The control of PIC cards is not related to any subarray and as such these commands can potentially be issued at any given moment by the `PICController` module. There could be conflicts. . . .
- The timing of phase adjustments within a subscan becomes more complicated if there is other CAN bus traffic. . . .
- The implementation of `CCC/WVREvents` assumes only one subarray is in use. . . .
- Data rate limitations get more complicated when using multiple subarrays; currently VLBI assumes use of all bandwidth resources. . . .
- The "sum" antenna is `CAI-63` and if that antenna is actually used by some other array, activating VLBI would break that observation. . . .

There may be operational work-arounds for some of these issues, or with minor development, they could be resolved. This is something to consider for post-Cycle 4 development.

A second development item concerns baseband delays. As discussed in [RD8], these are normally handled in the CDP processing nodes. However, that prevents `TelCal` from delivering phase solutions that are correct at the point of application. The APP project has been directed to study this issue and recommend a better solution. If such can be identified, and if resources for the word are to be made available, this could be implmented in a later observing Cycle.

Chapter 5

Commissioning Status

5.1 Context

A Commissioning and Science Verification (CSV) plan for the APP was formally approved by the APP Board in 2013 ([RD7]). The CSV plan laid out a series of tests intended to validate the fully integrated components of the APS, including hardware, software, observing modes, and recording modes through on-sky observations. These tests were designed to: (1) insure that the APS meets all of the formal APP requirements designated for verification through CSV [RD16] and [RD17]; and (2) to demonstrate that the APS produces robust, scientifically valid data whose characteristics are well understood and documented. Specific CSV deliverables or "end products" (7 in total) were laid out in §1.6 of [RD7], and include scripts and reports documenting compliance with the two aforementioned goals. This Chapter provides a status report on APP CSV, including progress toward satisfying the above requirements and providing the necessary deliverables.

Table 5.1: *APP Commissioning Missions*

Dates	Title and Link
Jan 5, 2015 - - Jan 14, 2015	APP Commissioning Campaign: First VLBI fringes https://ictwiki.alma.cl/twiki/bin/view/Control/AppMissionChileCommissioning01
Mar 23, 2015 - - Mar 31, 2015	APP Commissioning Campaign: Validate phasing system https://ictwiki.alma.cl/twiki/bin/view/Control/AppMissionChileCommissioning02
Apr 14, 2015 - - Sept 14, 2015	APP Off-site Commissioning: Phasing system tests https://ictwiki.alma.cl/twiki/bin/view/Control/AppNonMissionCommissioning03
Jul 28, 2015 - - Aug 3, 2015	APP Commissioning Campaign: Intercontinental Fringe Tests with Phasing System https://ictwiki.alma.cl/twiki/bin/view/Control/AppMissionChileCommissioning04

5.2 Overview of APP CSV and Activities to Date

Chapter 3 of the APP CSV Plan ([RD7]) laid out a set of 14 tests to be carried by the APP team at ALMA (see also Table 5.3, discussed below). The tests are divided into three phases (0, 1, and 2), which represent, respectively, activities classified as pre-commissioning, commissioning, and science verification. Phase 0 CSV tests (§ 3.1 of [RD7]) were designed to complement APP I&T activities and to allow testing of the VOM and APS data products prior to the commencement of full-scale, dedicated commissioning activities. Phase 1 tests (§ 3.2 of [RD7]) include targeted on-sky observations ultizing APS software and hardware to permit complete testing and characterization of all APS components. Phase 1 also includes initial VLBI tests with the APS. Finally, Phase 2 (§ 3.3 of [RD7]) is geared toward full-scale science verification and involves intercontinental VLBI observations spanning several hours with multiple partner sites in Band 3 and 6, followed by correlation and post-correlation analysis.

Table 5.2: *APP-Related EOC Memos*

Date	Memo No.	Title
06 Nov 2014	EOC Memo 23	ALMA Phasing Project (APP) Acceptance Review for the H-Maser S/N 59– Minutes
29 Mar 2015	EOC Memo 30, ALMA Tech. Note 16	Summary of the First ALMA Phasing Project (APP) Commissioning and Science Verification Mission: 2015 January 6-13
04 Sep 2015	ALMA Tech. Note 17	Summary of the Second ALMA Phasing Project (APP) Commissioning and Science Verification Mission: 2015 March 24-30
14 Sep 2015	ALMA Tech. Note 18	Summary of the Third ALMA Phasing Project (APP) Commissioning and Science Verification Mission: 2015 July 28 - August 3

https://wikis.alma.cl/bin/view/AIV/EOCMemos
https://almascience.nrao.edu/documents-and-tools/alma-technical-notes/

As per the recommendations of the APP Board (APPRID-47), the CSV plan designated a subset of tests as "desirable but not mandatory" (see Table 3.1 of [RD7]) in order to minimize risks associated with dependence on external resources whose availability could not be guaranteed. In addition, some minor deviations from the original APP CSV plan have been necessary in order to allow the most efficient use of ALMA array time and to allow tests to be adapted as experience was gained with real-life, end-to-end operation of the phasing system. These are explicitly noted in the discussion that follows.

Table 5.3: *Status of APP EOC-Time Tests*

CSV Test #	CSV Hours⋆	Total hours requested	Status
0A	0†	2	Completed (§5.3.1)
0B	0†	12	Ongoing (§5.3.1)
0C	0**	2	Waiver requested (§5.3.2)
0D	0§	12	Future observations needed (§5.3.3)
0E	3⋆	1	Completed (§5.3.4)
1A	12⋆	12	Completed (§5.4.1)
1B	0♠	2	Completed (§5.4.2)
1C	0♠	5	Completed (§5.4.3)
1D-0	0**	3	Waiver requested (§5.4.4)
1D-1	0**	2	Waiver requested (§5.4.4)
1E	0**	8	Waiver requested (§5.4.4)
1F	8	2	Analysis ongoing (§5.4.5)
2A	4	20	Analysis ongoing; new observations needed ((§5.5.1)
2B	12	30	Analysis ongoing; new observations needed (§5.5.2)
Total	39	113	

⋆ Total array time, including overheads for set-up and software installation.
† Test used data acquired during APP software testing, not CSV.
**Test not mandatory; waiver requested.
§ Proposed to combine with Tests 2A and 2B.
♠ Tests carried out in software testing time, or synergistic with 2A/2B test time already accounted.

CSV for the APP officially commenced in 2015 January following the formal acceptance of all APP hardware. To date there have been three full-fledged APP CSV campaigns (Table 5.1) whose objectives and outcomes have been described in detail in a series of ALMA Technical Notes (Table 5.2). Daily work logs, observing logs and scripts, and assorted plots and notes from each mission are also available through the ICT wiki pages listed in Table 5.1. Outside of the regularly scheduled missions, some additional "off-site" CSV observations have also been conducted by the APP through coordination with ALMA EOC personnel and ALMA engineering staff. Results and logs from these tests are posted on a separate wiki page (see Table 5.1). Key CSV milestones to date have included:

- Successful demonstration of both the fast and the slow phasing loops for arrays of up to 51 antennas
- Demonstration that the phasing system meets phasing efficiency requirements in Bands 3 and 6 in all four independent correlator quadrants, both polarizations
- Successful VLBI fringe detection on intercontinental baselines (>5000 km) with phased ALMA in Bands 3 and 6

Further details are provided below.

So far 39 on-sky hours have been used for CSV testing by the APP, out of a total of 113 hours requested in the formal CSV plan (see Table 5.3). To this point, APP CSV activities to date have been carried out during ALMA EOC weeks through coordination with the ALMA EOC lead, A. Remijan. However, because the ALMA EOC group formally disbanded as of 2015 September 30, future APP CSV activities will be coordinated through DSO L. Nyman.

In the discussion that follows, §5.3-5.5 provide a status summary of progress toward meeting the objectives of the full set of CSV tests specified in the formal APP CSV plan. When applicable, references are provided to documents or web pages containing more detailed test results and discussion. Areas requiring future work are also highlighted. §5.3-5.5 are thus intended to provide an overview of the progress of CSV toward demonstrating the scientific functionality of the APS. In §5.6, we specifically address the set of formal APP requirements that has now been verified as a result of CSV testing, while in §5.7 we summarize the status of the complete list of "end products" to be delivered by APP CSV. Finally, in §5.8 we list remaining tasks and priorities leading up to full APP acceptance.

5.3 Phase 0: Pre-Commissioning Activities

5.3.1 Tests 0A and 0B: "Commensal" Observing

APP CSV Tests 0A and 0B (§3.1 of [RD7]) were designed to permit testing of the VOM and verification of APS data products prior to the commencement of full-scale, dedicated commissioning runs. Originally, the APP envisioned that this could be accomplished through routine "commensal observing"—i.e., piggyback observations where the APS would be operating, but where ALMA EOC staff would be in control of the array and the content of the schedule blocks.

In practice, commensal observing of this type was not possible owing to the fact that nearly all routine test observations conducted by ALMA personnel (e.g., DelayCal measurements) are executed in TDM mode rather than the FDM mode required for APS operations. Furthermore, during late 2014 and early 2015, non-APP activities at ALMA frequently employed different software releases than the one containing the latest APS developments. For these reasons, a slightly different approach was adopted.

Because Tests 0A and 0B are not dependent on APP hardware, the APP was instead able to fulfill the goals of these tests through analysis observations obtained as part of APP software testing beginning in 2014 October. Analysis of these observations has demonstrated that:

- VOM execution blocks can be routinely executed successfully in Bands 3 and 6
- Use of the APS does not introduce any artifacts or corruption of the visibilities in SFI data compared with unphased FDM SFI data

- The APS produce valid ASDM data that can be read and analyzed using standard CASA tasks
- The phased sum signal appears in place of the antenna assigned to "CAI63" in the archived ASDM file
- The ASDM file generated from VOM observations contains a CalAppPhase.xml table containing phasing information (including the list of phased antennas and a measure of the phasing efficiency).
- The polarization properties of the SFI data generated by the APS are indistinguishable from those generated by standard (unphased) FDM observations.

In addition, these tests were used to establish the optimal subscan duration and phasing correction application intervals for different bands and observing conditions.

Status: Ongoing. Observations of the type used for Test 0B will continue to be accumulated as part of periodic APS regression testing (see §3.3.4 of [RD7]) and will be used to monitor the health and stability of the APS up through final acceptance and handover to ALMA. These data will also be used to conduct an analysis of phasing stability as a function of baseline length.

5.3.2 Test 0C: Polarization Characterization with a Beacon

CSV Test 0C proposed to characterize the polarization properties of the APS using a calibration beacon. However, such a beacon has not yet been installed at ALMA and is unlikely to be available in time for use in CSV testing. This test was designated as "desirable but not mandatory" in the approved CSV plan.

Status: No data obtained. Waiver of test requested.

5.3.3 Test 0D: Polarization Characterization with Astronomical Sources

Test 0D requires observations of calibrator sources with sufficient parallactic angle coverage to allow determination of polarization D terms. Observations in support of this test were planned for 2015 March but could not be completed because of inclement weather ([RD13]). In view of the progression of of APP CSV since March, the objectives of this test could instead be fulfilled through VLBI observations obtained as part of CSV Tests 2A and 2B (§5.5.1 and 5.5.2) rather than through separate ALMA-only observations.

Status: No data obtained. Can be combined with Tests 2A and 2B.

5.3.4 Test 0E: APP Maser Test

Verification of the performance of the hydrogen maser was conducted through a series of on-sky tests in 2014 July. Results are summarized in [RD15] and documented on JIRA, CSV-3107.

Status: Analysis completed. Objectives satisfied. No further testing planned.

5.4 Phase 1: Commissioning Tests

5.4.1 Test 1A: Stepped Scans with Closure Phase Tests

During a "step scan" test, antennas are systematically added to or subtracted from the phased array, permitting evaluation of how the correlated amplitude and the phasing efficiency scale with the number of phased antennas in the array. In theory, the correlated amplitude should increase as $\sqrt{N_A}$, where N_A is the number of phased antennas. Deviations from this trend provide a measure of overall phasing efficiency.

Step scan tests have now been performed during several CSV sessions, and the results have been used to perform a detailed analysis of phasing efficiency of the APS (see §3.2 [RD13] and [RD8]). In practice, the originally proposed closure phase analysis of these data is not possible owing to the fact that the baseband delay corrections of the unphased comparison antennas are not the same as those applied to the phased sum (see [RD12] and [RD13]).

Status: Analysis completed. Objectives satisfied. No further observations required.

5.4.2 Test 1B: Single-Dish Spectroscopy of an Astronomical Line Source

Observations of bright astronomical line sources (including CO and SiO maser sources) were undertaken with the APS during both the January and the July-August CSV campaigns. Analysis of these data has demonstrated that:

- the frequency specifications in each of the four independent correlator quadrants are accurate and consistent
- the line placement within the band (and within a particular TFB channel) is as expected given the frequency specification syntax used by the VOM

Analysis of the line observations also allowed a demonstration of the feasibility of phasing up on a bright line source without any modifications to the standard "continuum" mode of operation of the phasing system (see Figure 2 of [RD13]).

Status: Objectives partially satisfied. Additional analysis ongoing.

5.4.3 Test 1C: Inter-Quadrant Fringe Test

APP requirements specify that all four correlator quadrants shall operate independently. Performing zero baseline fringe tests between different quadrants therefore provides a mechanism to verify the robust and independent operation of each quadrant. This was demonstrated in [RD10].

Status: Analysis completed. Objectives satisfied. No further observations required.

5.4.4 Tests 1D-0, 1D-1, 1E: VLBI Between ALMA Antenna and an OSF Antenna

CSV Tests 1D-0, 1D-1, and 1E specified a series of VLBI experiments to be performed between ALMA and an independent ALMA antenna parked on a pad at the OSF. During the first APP CSV campaign in 2015 January, an ALMA antenna was available at the OSF on pad PM01. A set-up was devised whereby this antenna was operated in conjunction with the two-antenna correlator TFINT, which was running a special two-antenna build of software release R2014.4. The TFINT set-up was able to record a single TFB channel, providing a total bandwidth of 32 MHz.

To permit the desired VLBI tests, a quartz crystal that had been used previously to monitor the hydrogen maser at the AOS was deployed as a time standard. This crystal had been brought down in advance of the EOC week, acclimated, and installed at the OSF. To provide a second independent time standard, a spare LORR was also installed to bring down the maser reference signal from the AOS. This signal suffered too much 1/f noise to be usable for the LOs, although it did suffice to provide a measure of the crystal frequency drift.

Single-dish observations were successfully carried out with the OSF antenna, and valid VLBI data were successfully recorded on the AOS-OSF baseline, including spectral line measurements of the SiO maser toward Orion Source I that were applicable to Test 1B (§5.4.2). However, attempts to obtain VLBI fringes between the OSF antenna and ALMA AOS antennas were unsuccessful. Pointing issues with the OSF antenna were suspected as a probable cause of this failure (see Figure 1 of [RD12]).

A repeat of the OSF VLBI tests was planned for the second APP CSV campaign in 2015 March, but had to be canceled owing to inclement weather (see [RD13]). By the time of the third APP CSV mission in 2015 July, the TFINT set-up had been disassembled because of competing ALMA needs for the hardware resources that were being deployed. Because of these factors, the APP instead opted to meet the objectives of Tests 1D-0, 1D-1, and 1E through VLBI observations conducted between ALMA and APEX (see §5.4.5). Allowance for this contingency was specified explictly in the CSV Plan.

Status: Objectives satisfied through alternate CSV tests. No further observations planned.

5.4.5 Test 1F: VLBI between Phased ALMA and APEX

The first VLBI fringe tests between ALMA and APEX were conducted on 2015 January 13 in Band 6. Despite the rather short baseline involved (∼2 km), this represented a true VLBI tests since both ALMA and APEX were operating with completely independent electronics, backends, and frequency standards.

Following the January mission, fringes were successfully obtained on the ALMA-APEX data with a high SNR, representing VLBI "first light" for ALMA ([RD12]). This success demonstrated:

- All hardware components of the APS are working as expected
- The ALMA array position is know sufficiently accurately for VLBI
- The DiFX (Deller, 2011) zoom band mode provide a viable path to correlation between data from ALMA and other peer VLBI stations, which in general employ different sampling rates.

Because of issues with the application of baseband delays during the January mission, ALMA was effectively operating as a single antenna during these tests. (See [RD12] for details). However, VLBI fringes with *phased* ALMA have since been demonstrated on much longer baselines between phased ALMA and the IRAM 30-m antenna in Band 6 (Figure 6 of [RD13]), as well as between phased ALMA and six of the stations of the VLBA (Figure 5 of [RD14]). Additional VLBI data were also recorded on a baseline between ALMA and APEX in Bands 6 and 7 during the July-August CSV campaign. Correlation of these data is pending and will be used in support of CSV Test 2B (§5.5.2) as well as for testing polarization purity and the APP's PolConvert software.

Status: Analysis of existing data ongoing.

5.5 Phase 2: Science Verification

5.5.1 Test 2A: Global Band 3 Observing

The first global VLBI campaign involving ALMA and peer sites observing at 3 mm (Band 3) took place on 2015 August 1 as part of the third APP CSV campaign ([RD14]). The partner stations included the eight antennas of the VLBA equipped with 3-mm receivers as well as the Effelsberg antenna. Targets included two bright quasars and two evolved stars expected to have bright SiO maser emission.

The global Band 3 VLBI observations taken during the third CSV campaign were significantly impacted by a non-APP issue that affected the timing synchronization of the antenna station cards that has since been resolved (see ICT-5401). As a consequence of this issue, the phased ALMA array was limited to 7 antennas throughout these observations (see [RD14] for details).

Despite the station card issue, correlation of a short segment of data on one of the target sources has confirmed the detection of VLBI fringes on the baselines between phased ALMA and all of the six operating VLBA sites (see §4.7 of [RD14]). (Two of the VLBA sites were down because of hardware issues and two sites are not equipped with Band 3 receivers). Correlation of the full 4-hour data set, including the Effelsberg baselines, is currently ongoing at Bonn.

Despite the station card issue, data obtained for Test 2A are expected to be suitable for satisfying most of the objectives of this test. Once the fully correlated data products are available, additional analysis will be undertaken, including:

- Closure phase analysis on various baseline triangles
- Stability analysis of the phasing system over the course of the 4-hour session
- PolConvert processing of the data to test algorithms for conversion of linear to circular polarization
- Imaging analysis to verify the expected sensitivity and resolution resulting from including phased ALMA in the VLBI array

Additional Band 3 observations will likely be required to provide data with sufficient parallactic angle coverage for rigorous testing of PolConvert (see [RD11]).

Status: Analysis ongoing. Additional observations will likely be required.

5.5.2 Test 2B: Global Band 6 Observing

The first global VLBI tests involving ALMA and peer sites operating at 1.3 mm (Band 6) took place on 2015 March 30, during the second formal APP CVS mission. This mission overlapped with an ongoing worldwide EHT observing campaign, during which several VLBI stations around the world were conducting coordinated 1.3-mm observations. Although ALMA did not participate in EHT science observations, the EHT campaign provided an ideal opportunity to perform VLBI fringe tests with ALMA for the first time on intercontinental baselines.

During the March observations, two short scans were obtained on baselines between ALMA and three other VLBI stations, including the IRAM 30-m antenna, and SMT, and CARMA. So far, fringes have been successfully detected on the baseline between ALMA and the IRAM 30-m antenna (Figure 6 of [RD13]). A more detailed analysis, as well as correlation of the remaining baselines, is ongoing.

A second set of Band 6 global VLBI campaigns was conducted during the third APP CSV mission in 2015 July. Unlike the previous Band 6 tests, these campaigns were organized specifically for APP CSV. Participating partner sites included the SMA, the JCMT, and APEX. Two four-hour sessions were carried out on back-to-back nights (July 30 and 31). Target sources on both nights comprised bright quasars. Further details are summarized in [RD14].

Data from these two Band 6 sessions were impacted by the same station card synchronization issue described in §5.5.1. However, effects were mitigated during the second session by limiting the ALMA array to 7 phased antennas (all sharing two station cards). Consequently, the data from the second session are expected to be suitable to satisfying most of the objectives of this test. Correlation and analysis of these data is pending, with objectives similar to those described for the Band 3 VLBI data (§5.5.1). Additional Band 6 VLBI observations will likely be required to provide data with sufficient parallactic angle coverage for rigorous testing of PolConvert (see [RD11]). The large east-west separation of participating VLBI stations during the July-August campaign precluded tracking of a single source over multiple hours.

Status: Analysis ongoing. Additional observations will likely be required.

5.6 APP Requirement Satisfaction

Formal APP requirements ([RD16] and [RD17]) included a number of requirements designated for verification or partial verification through CSV. This subset of requirements is summarized in Table 5.4 (see also [RD7]). Column 4 of Table 5.4 lists the set of CSV tests relevant to verification. The subsections that follow explicitly summarize progress toward satisfying each of these requirements.

Note that a number of them were deemed already satisfied in the Maser Acceptance ([RD2]) or Hardware Acceptance testing ([RD3]). These specifically include APP0010, APP0020, APP0030, APP0050, APP0060, APP0070, APP0080, APP0090, APP0100, APP0110, APP0120, APP0130, APP0170, APP0180, APP0190, APP0200, APP0210, APP0220, APP0230, APP0240, APP0250, APP0260, APP0270, APP0280, APP0290, APP0300, APP0310, APP0320, APP0330, APP0340, APP0350, APP0370, APP0390, APP0400, APP0410, APP0420, APP0430, APP0440, APP0450, APP0460, APP0470, APP0480, APP0490, APP0500, APP0510, APP0520, and APP0530. Since some of these were marked for coverage under the CSV plan ([RD7]) we discuss them explicitly in the sections that follow.

The missing requirement serial number APP0380 was discarded prior to PDR.

Table 5.4: APP Requirements Verifiable During Commissioning

Req. #	Baseline Requirement	Comments	CSV Test #
APP0010	**Frequency Reference:** All ALMA LOs shall be phase-locked to a common frequency standard.	Requires a maser.	0E, I&T
APP0020	**Spectrum:** The APP shall be capable of processing 8 GHz of input spectrum per polarization.		0A, 0B, 0D, 1A, 1B, 1C, 1D-1, 1E, 1F, 2A, 2B, I&T
APP0030	**Polarization:** The APP shall generate dual-polarization signals	Needs to correlate with circular polarization data from other stations. ALMA observes linear polarization in most bands.	0A, 0B, 0D, 1A, 1B, 1C, 1D-1, 1E, 1F, 2A, 2B, I&T
APP0040	**Polarization Purity:** The APP shall not introduce more than 3% polarization leakage.	Needs to correlate with circular polarization data from other stations. ALMA observes linear polarization in most bands.	0A, 0B, 0C, 0D, 1A, 1B, 1C, 1E, 1F, 2A, 2B
APP0100	**Environments:** The APP system shall be operable whenever ALMA is.	APP should not by itself restrict ALMA operations; performance of APP is only as required by, e.g., AP0140 and APP0150.	0A, 0B
APP0140	**Phasing Efficiency (stability):** The APP phasing efficiency shall be as stable as the atmospheric coherence timescale of the median antenna of the array.	The APP should not make things worse than the atmospherics. If a set of antennas is well behaved (and some are not) the phasing system should phase up the stable ones and discard the noisy ones. Phasing efficiency is real/theoretical.	0A, 0B, 0D, 1A, 1B, 1C, 1D-1, 1E, 1F, 2A, 2B
APP0150	**Phasing Efficiency (quality):** The phasing system shall achieve 90% of the theoretical SNR expected for a compact 4 Jy source at 230 GHz operated with 15 antennas with baselines less than 2 km with no more than 0.8 mm precipitable water vapor and mean rms path fluctuations no more than 0.125 mm.	These are based on the design study with data from May 2012. We expect to do much better than this, but a tighter requirement must either be simulation-driven or must await availability (to us) of observations with more antennas.	0A, 0B, 0D, 1A, 1B, 1C, 1D-1, 1E, 1F, 2A, 2B
APP0190	**Correlator Configuration:** The antenna summed data shall be provided as CAI-63.		0A, 0B, 0D, 1A, 1B, 1C, 1D-1, 1E, 1F, 2A, 2B, I&T
APP0430	**Band Support:** Band 3 and 6 receivers shall be fully supported.	Band 3 support is required to support early commissioning tests even for measurements that only require Band 6.	0A, 0B, 0D, 1B, 1C, 1D-0, 1D-1, 1E, 1F, 2A, 2B
APP0450	**IF Frequency:** The APP system shall support faithful programming of the IF band specified by the VEX file.	ALMA and EHT stations must be band-compatible.	1B, 1C, 1D-1, 1E, 1F, 2A, 2B, I&T
APP0460	**TFB Tunings:** The TFB channel placement shall be capable of being made compatible with the 2^n MHz sampling schemes of traditional VLBI.	Spacing/alignment is at MHz intervals, where $n \geq 5$. The per antenna LO offsetting shall result in frequency alignment of the sums.	1F, 2A, 2B, I&T

Table 5.4: *APP Requirements Verifiable During Commissioning (cont.)*

Req. #	Baseline Requirement	Comments	CSV Test #
APP0470	**Observing correlator:** The ALMA correlator shall operate in a single Nyquist sampled, single region frequency division mode covering the full 2 GHz bandwidth on each quadrant.	This is a standard correlator mode which has already been commissioned (Mode 13). We shall verify that the correlator is indeed in this mode.	0A, 0B, 0D, 1A, 1B, 1C, 1D-1, 1E, 1F, 2A, 2B, I&T
APP0490	**Antenna Participation:** The phasing system shall be capable of phasing up an array consisting of an arbitrary odd number of antennas <64.	Subarrays are not currently supported by ALMA, but the implementation should not preclude phasing a subarray when that capability is made generally available.	0A, 0D, 1A, 1B, 1C, 1D-1, 1E, 1F, 2A, 2B, I&T
APP0500	**Antenna 63:** The antenna assigned to CAI-63 shall be part of the observing array but omitted from the phased sum.	The "CAI-63" input to the correlation matrix shall be used as an input for the phased sum. The auto- and cross-correlation of this input against others shall be used to demonstrate that the phasing is working correctly.	0A, 0B, 0D, 1A, 1B, 1C, 1D-1, 1E, 1F, 2A, 2B, I&T
APP0510	**Log archival:** Information necessary for the post-observation (VLBI) correlation and analysis shall be archived.	Necessary for calibration.	1B, 1C, 1D-0, 1D-1, 1E, 1F, 2A, 2B, I&T
APP0520	**Independent systems:** The phasing and recording systems shall be operated separately.	Necessary for calibration–i.e., the phasing system must be operable even if the sum data are not recorded; the recorders may record data even if the phasing system is not active.	0A, 0B, 0D, 1A, 1B, 1C, 1D-0, 1D-1, 1E, 1F, 2A, 2B, I&T
APP0530	**Independent Quadrants:** The APP system shall support independent operation of the four correlator quadrants.	Each quadrant and VLBI backend is essentially an independent data stream and there is no reason to introduce coupling between them.	1B, 1C, 1D-1, 1E, 1F, 2A, 2B, I&T

5.6.1 APP0010: Frequency reference

Requirement: *All ALMA LOs shall be phase-locked to a common frequency standard. Requires a maser.*

Results: Following the installation of the hydrogen maser at the AOS and collection of several weeks of monitoring data, ALMA EOC began using the maser as a frequency standard the week of 2014 July 29, during an ongoing long baseline campaign. On-sky test observations executed with the maser at that time (§5.3.4) confirmed the stability of phases over time (fluctuations were consistent solely with effects of atmospherics) and confirmed that no detectable broadening of spectral line sources occurred after switchover to the maser.

References: A full report detailing on-sky testing with the maser is available in [RD15].

Status: Satisfied

5.6.2 APP0020: Spectrum

Requirement: *The APS shall be capable of processing 8 GHz of input spectrum per polarization.*

Results: This is trivially verifiable from inspection of APS data sets. Technically, because the correlator mode used by the APP is an FDM rather than a TDM, the APS records 1.875 GHz (rather than 2.0 GHz) of bandwidth per polarization in each of the four correlator quadrants.

References: N/A

Status: Satisfied

5.6.3 APP0030: Polarization

Requirement: *The APS shall generate dual-polarization signals.*

Results: This is trivially verifiable from inspection of APS data sets. As per specifications, the APS generates and records dual linearly polarized signals in each of the four ALMA basebands.

References: N/A

Status: Satisfied

5.6.4 APP0040: Polarization purity

Requirement: *The APP shall not introduce more than 3% polarization leakage.*

Results: Testing this requirement requires solving for polarization D terms using APS SFI data and application of the APP's PolConvert software to the post-correlation VLBI data products (Martí-Vidal et al. 2014). Preliminary testing has been undertaken with existing CSV data sets ([RD11]). However, full verification will require VLBI-mode observations of calibrators with well characterized polarization properties and good parallactic angle coverage. Such data could not be obtained during the July-August CSV campaign because the large east-west separation of participating VLBI stations precluded tracking of a single source over multiple hours ([RD14]).

References: Martí-Vidal et al. 2014; [RD11]; [RD14]

Status: Unresolved If necessary, the APP shall request scheduling of an additional CSV campaign in 2016 March to insure this requirement is satisfied.

5.6.5 APP0100: Environments

Requirement: *The APP system shall be operable whenever ALMA is; APP should not by itself restrict ALMA operations.*

Results: VLBI mode observations can be executed whenever ALMA is operational, provided that a compatible software version is running. ALMA SFI data products (ASDM files) are recorded whenever VLBI mode observations are executed. This has been routinely verified throughout previous CSV campaigns. Because compatibility with subarray was explicitly *excluded* from APP requirements, the APS has not yet been tested when ALMA is operating with subarrays.

References: [RD12], [RD13], [RD14]

Status: Satisfied

5.6.6 APP0140: Phasing efficiency (stability)

Requirement: *The APP phasing efficiency shall be as stable as the atmospheric coherence timescale of the median antenna of the array.*

Results: The improvement in phase coherence as a result of application of both the fast and the slow phasing loops has now been demonstrated in all four correlator quadrants, both polarizations, in Bands 3 and 6. Antennas can be manually removed from the phased array during an APS observation, although the phasing system does not have a mechanism to automatically discard bad antennas.

References: Figures 1 and 2 of [RD13] (stability of the slow phasing loop); ICT-319 (performance of the fast loop); Figure 3 of [RD13] (performance of the fast and slow loops combined).

Status: Satisfied

5.6.7 APP0150: Phasing efficiency (quality)

Requirement: *The phasing system shall achieve 90% of the theoretical SNR expected for a compact 4 Jy source at 230 GHz operated with 15 antennas with baselines less than 2 km with no more than 0.8 mm precipitable water vapor and mean RMS path fluctuations no more than 0.125 mm.*

Results: The phasing efficiency of the APS has been studied extensively using data sets obtained between 2015 March and September. Results are presented in [RD8]. Based on the conclusions of this memo, the APP phasing efficiency quality requirement is satisfied. No further improvements in phasing efficiency are likely to be feasible without significant additional development efforts.

References: [RD8]

Status: Satisfied

5.6.8 APP0160: Phasing efficiency (monitoring)

Requirement: *The phasing system shall monitor the efficiency of its solutions.*

Results: The phasing efficiency is by design monitored through the output of `TelCal` to the ASDM. Several methods are routinely used to access this in real-time (`TelCalSpy` is familiar to commissioning scientists; and there are several scripts to demonstrate the interfaces for the construction of more convenient GUIs for better monitoring support).

References: [RD5] and [RD6]

Status: **Satisfied**

5.6.9 APP0190: Correlator configuration

Requirement: *The antenna summed data shall be provided as CAI-63.*

Results: As per design, the phased sum antenna is assigned to correlator antenna input (CAI) 63 and appears in ASDM data sets with the label of whatever physical antenna it has replaced at that input location, along with the alternative designation "APP001". This is trivially verifiable from inspection of APS data sets obtained during previous CSV campaigns.

References: N/A

Status: **Satisfied**

5.6.10 APP0360: Experiment session

Requirement: Each VLBI session shall be described in a manner compatible with existing VEX file systems in use at 3 mm and 1.3 mm observatories that are expected to participate in VLBI observations with ALMA.

Results: During the July/August campaign, observations at both 3 mm and 1.3 mm were executed and correlated using VEX files generated by the current version of `SCHED`.

References: [RD9] and [RD14].

Status: **Satisfied**

5.6.11 APP0430; Band support

Requirement: *Band 3 and 6 receivers shall be fully supported.*

Results: During the first CSV campaign in 2015 January, it was recognized that phasing efficiency requirements were being met only in Band 3 and only in a single polarization and a single correlator quadrant. This was traced to the manner in which various delays are applied to the data used to form the phased sum signal. During normal ALMA operations, front-end delay corrections (which are stable and have typical values of ∼100-500 picoseconds) are optimized to baseband 1, polarization X in Band 3. Delay corrections for the other bands and baseband/polarization combinations are then performed in the CDP at the same time that a residual geometric delay correction is applied. When the APS is operating, ALMA's TelCal computer uses the data corrected by the CDP to compute a phasing solution to be applied to the TFBs. However, data uncorrected for the front-end delay are used to form the Phased Sum in the LTA hardware, because the signals to the phased sum are captured between the front end and the application of the CDP correction. Documentation on the ALMA delay system available to the APP at the time of CDR did not explicitly specify that the delay correction (fringe-stopping) is performed in software rather than hardware, nor was this well-known even to experts in the community. Therefore, the consequences for the APS as originally designed went unrecognized prior to CSV.

To provide a workaround for this delay problem, the APP team devised a solution whereby the baseband delay corrections are turned off during APS operations. At the same time, the number of channel averages was increased to 8 within each baseband, and the phasing software was modified to independently calculate a phasing solution for each of these channel averages. This approach effectively solves for and removes the gross delay across each of the basebands.

Through CSV testing following these changes, the APS has been shown to be fully operational in Bands 3 and 6 and to meet phasing efficiency requirements in all four correlator quadrants in both bands ([RD14], [RD8]). Further CSV testing of this capability with up to 32 channel averages per baseband is desirable, but to date has been precluded by an ALMA limitation of $\leq$10 channel averages.[1]

References: [RD12], [RD13]

Status: Satisfied

5.6.12 APP0450: IF frequency

Requirement: *The APP system shall support faithful programming of the IF band specified by the VEX file.*

Results: The tunings for band 3 and band 6 have been specified for use in the OT during Cycle 4. These tunings were tested in the July/August campaign and fringes were found, establishing the point of the requirement. Reorganization of the scripting to the SB/`VEX2VOM` paradigm will rearrange the underlying code (and it should be re-tested), but that is beyond the scope of this requirement.

References: [RD9], [RD14]

Status: Satisfied

5.6.13 APP0460: TFB tunings

Requirement: *The TFB channel placement shall be capable of being made compatible with the* 2^n *MHz sampling schemes of traditional VLBI.*

Results: At the time of CDR, ALMA specifications called for the availability of up to 32 spectral windows (one per TFB) in each of the four correlator quadrants. However, during APP CSV testing, it was discovered that when a significant number of ALMA antennas ($\gtrsim$15) is used for high bandwidth observing, at most two spectral windows can be employed simultaneously within a single baseband without triggering system timeout errors. This issue is documented in ICT-3824 and ICT-3852. Despite this limitation, the APP has since demonstrated that correlation of VLBI on baselines between ALMA and stations that use different sampling rates is still possible through the judicious choice of frequency specifications and the use of zoom bands during correlation.

Incidentally, the underlying reason for the "timeout" preventing operation with 32 spectral windows may have been fixed—we will not know for sure until testing begins in earnest with the Cycle 4 candidate.

References: ICT-3824; ICT-3852; [RD9]; § 4 of [RD13]; § 4.1 of [RD14]

Status: Request for waiver. Current limitations of the ALMA BL correlator preclude fulfillment of this requirement as written. Note that the frequency setups for Cycle 4 preclude using the fruit of this in any case.

5.6.14 APP0470: Observing correlator

Requirement: *The ALMA correlator shall operate in a single Nyquist sampled, single region FDM mode covering the full 2 GHz bandwidth on each quadrant.*

Results: As per design, VOM observations are executed exclusively in an FDM mode that attains the largest allowable bandwidth per quadrant achievable in FDM (1.875 GHz with full polarization). This is a standard ALMA correlator mode.

References: [RD18]

Status: Satisfied

[1] This limitation is expected to be removed in late 2015 (ICT-4656). Operation with up to 32 channel averages has already been confirmed by the APP in simulation.

5.6.15 APP0490: Antenna participation

Requirement: *The phasing system shall be capable of phasing up an array consisting of an arbitrary odd number of antennas <64.*

Results: The APS has been shown through CSV to be operable with an arbitrary (odd) number of phased antennas between 1 and 51 ([RD8]). (That largest array operated with 53 antennas.) To date, an array of >51 antennas has not been available during CSV testing. If feasible, the APP shall demonstrate APS operations with 63 antennas during a future CSV campaign. However, in practice, this number of antennas may not be available as a result of maintenance or other ALMA testing. In any case this exceeds the number of available antennas to be allowed in Cycle 4 configurations.

References: [RD8]

Status: Satisfied.

5.6.16 APP0500: Antenna 63

Requirement: *The antenna assigned to CAI-63 shall be part of the observing array but omitted from the phased sum.*

Results: The phased sum antenna, assigned to CAI 63, appears as a normal antenna in the ALMA SFI data recorded in ASDM format during VOM observations. The auto- and cross-correlation products associated with this antenna can be analyzed in a manner identical to the other standard antennas within the data set. An operational script (`getCAI63.py`) is in routine use by the operators to ensure that the array created for the VOM does not include CAI 63.

References: N/A

Status: Satisfied

5.6.17 APP0510: Log archival

Requirement: *Information necessary for the post-observation (VLBI) correlation and analysis shall be archived.*

Results: Extensive logging information, including script execution logs, shift logs, and CCC container logs, are recorded whenever the VOM is executed. For all CSV missions to date, relevant logs are archived as attachments to the respective mission wiki page (see Table 5.1).

References: See Table 5.1.

Status: Satisfied

5.6.18 APP0520: Independent systems

Requirement: *The phasing and recording systems shall be operated separately.*

Results: The "−I" flag of the VOM allows recording of VLBI mode data with no phasing corrections applied. Conversely, the "−V" flag turns off VLBI recording but preserves archiving of ordinary SFI data. Both of these options have been exercised successfully during CSV testing.

References: [RD19]

Status: Satisfied

5.6.19 APP0530: Independent quadrants

Requirement: *The APP system shall support independent operation of the four correlator quadrants.*

Results: CSV tests have verified that during VLBI mode observations, the four correlator quadrants can be tuned independently to arbitrarily specified frequencies (subject to the constraints of the ALMA receivers and LO system) and that phasing corrections can be applied to an arbitrary subset of the four quadrants.

References: [RD8], [RD9].

Status: Satisfied

5.7 Final CSV Outcomes

As described in §1.6 of the APP CSV Plan ([RD7]), the final outcome of CSV should be a set of seven "end products" (*i.e.* , deliverables). These end products are each listed below, together with a brief summary of their status.

Product 1: *An APP system whose functionality for VLBI has been demonstrated in Bands 3 and 6*

Status: As described above, APP CSV testing to date has demonstrated working phasing system in both Bands 3 and 6. Intercontinental VLBI fringes have been demonstrated in both bands ([RD9], [RD13], [RD14]). This outcome will be met in full upon completion of prescribed CSV testing procedures (see [RD7] and §5.3.1-§5.5.2 above).

Product 2: *A verification matrix showing the performance of the APS against the benchmarks specified in the APP Requirements Document [RD16],[RD17].*

Status: Progress achieved through toward meeting formal APP requirements is described in §5.6. Upon completion of CSV testing, this information will be summarized as a verification matrix.

Product 3: *Reports detailing all tests performed as part of CSV activities and the performance characteristics derived from these tests.*

Status: Reports from CSV testing to date are presented in the following memoranda: [RD8], [RD9], [RD12], [RD13], [RD14], [RD15].

Product 4: *A set of software scripts used to perform CSV tests.*

Status: Observing scripts and shift logs for all APP test observations performed to date are available through the mission wiki pages listed in Table 5.1. All operation scripts are in the CSV python script path element `/groups/science/scripts/APP`.

Product 5: *Correlated visibility data from science commissioning tests that are made publicly available.*

Status: Once full correlation of APP VLBI data is complete and the data have been analyzed and vetted, the APP will consult with JAO regarding which, if any, of these data are appropriate for public release. The appropriate mechanism for dissemination will also be discussed with JAO.

Product 6: *Documents describing operations procedures for use of the APP for science operations*

Status: Such documents will be prepared in consultation with the designated "Friend of VLBI" in advance of the ALMA Cycle 4 proposal call in 2016 March.

Product 7: *An automated regression testing script that can be used following CSV to verify the robustness of APP hardware and software*

Status: Such a regression test has already been prepared by the APP team and is in routine use by ALMA personnel (`https://ictwiki.alma.cl/twiki/bin/view/SoftOps/WeeklyRegTestVLBI`). Depending on time available, it is exercised every few weeks. Reports are posted (by release) at `https://ictwiki.alma.cl/twiki/bin/view/SoftOps/SoftwareTestReports`.

5.8 Remaining CSV Tasks

As described in the preceding sections, analysis of portions of the data obtained during previous CSV campaigns remains ongoing. Major outstanding tasks include the following:

- Analysis of phasing stability as a function of baseline length (§5.3.1)
- Additional testing of the APP's PolConvert software (§5.5.1, §5.6.4)
- Correlation of additional Band 3 and 6 global VLBI data obtained to date (§5.5.1, §5.5.2, [RD13], [RD14], [RD9])
- Imaging and closure phase analysis of global VLBI data sets (§5.5.1, §5.5.2)
- Preparation of documentation describing the use of APS for routine science observations at ALMA
- Acquistion of additional VLBI data with the APS suitable for polarization analysis and testing of PolConvert (§5.3.3, §5.6.4, [RD11])
- Tests of the phasing system with up to 32 channel averages per baseband (§5.6.11)

The APP anticipates requesting additional ALMA array time in 2016 March to carry observations needed to complete APP CSV. During March the APP expects peer VLBI sites to be staffed and available for Band 6 testing, thus greatly simplying the logistics of such testing. The target date for completion of all APP CSV activities is 2016 July 31.

The exact number of hours required is **TBD,** but appears to be well within the margin suggested by Table 5.3

Chapter 6

Remaining Project Deliverables

6.1 Road to Cycle 4

In this section we attempt to capture status of the APP project from the perspective of identifiable deliverables in the coming year on the path to Cycle 4.

Various requirements and action items were captured on SCIREQ following OBSMODE4:

- `http://ictjira.alma.cl/browse/SCIREQ-262` **(closed)** Propose Band 6 setup for Cy4 VLBI. (Tested in July.)
- `http://ictjira.alma.cl/browse/SCIREQ-263` **(open)** APP to revisit handling of baseband dependent delays. This is a study topic contingent on funding, due Nov 2.
- `http://ictjira.alma.cl/browse/SCIREQ-264` **(closed)** Friend of VLBI role. (Violette Impellizzeri)
- `http://ictjira.alma.cl/browse/SCIREQ-265` **(open)** Friend of VLBI work on operational procedures. The due date for this was September 30, but more information is needed (from higher levels) before these procedures can be finalized.
- `http://ictjira.alma.cl/browse/SCIREQ-266` **(open)** APP documentation acceptance. Due date is Dec 1. Documentation for proposers can be available in that time frame, but the full commissioning of the capability is not likely to be complete at that time.
- `http://ictjira.alma.cl/browse/SCIREQ-267` **(open)** Standard supporting documentation for CFP needs. Due date is Dec 1. This should be feasible.
- `http://ictjira.alma.cl/browse/SCIREQ-268` **(open)** Fraction of antenna's within a radius required for VLBI. Due date is Dec 1. There is no requirement on radius—VLBI will work in any configuration. However, small configurations are better and we will attempt to quantify that by the due date.
- `http://ictjira.alma.cl/browse/SCIREQ-269` **(open)** Demonstrate operational end-to-end execution of VLBI SB. Due date is Dec 1. This is the `VEX2VOM` tool coupled with the OT tool enhanced for VLBI.
- `http://ictjira.alma.cl/browse/SCIREQ-270` **(open)** Discuss Ph1m with respect to VLBI proposals with Gautier and Maurizio. This was due July 15, and it is not clear APP is involved.

In addition to those requirements, the APP team has identified the following items to be concluded in the next year (*i.e.* by Cycle 4 start):

- **Python GUI** We expect to have this available for use during the remaining commissioning activities next year.

- **[RD5]** Revised Corr/Control Design document to reflect "as built".
- **[RD6]** Revised TelCal Design document to reflect "as built".
- **Final Commissioning Report** Addressing APP requirements considered unfulfilled with this review. These were summarized in Section 5.8

One point about the VOM that bears restating is that it does not currently safe to operate in the sub-array paradigm. That is, there are low-level interactions between sub-arrays that require special handling (for code is not in place) to avert inteference of one observation with the other. Since it is generally desirable to operate the VOM with as many antennas as possible, this is not a significant issue for operations. However it bears repeating as it is likely to be forgotten.

6.2 Beyond Cycle 4

The funding of the APP project is uncertain. At this time, we expect to study a number of topics and develop some code to address a number of existing issues in the coming year, and expect to support their integration into Cycle 5. However, the exact implementation plan is somewhat uncertain at this time (conditional on funding).

Briefly, these include

- **Source Modeler** Work on ICT-2833 has been started, but will not be completed until sometime next year. Achieving proper integration to the ALMA Archive (which should supply source structure data) is one issue which needs to be sorted out. This depends on the proper resolution of SCIREQ-96 (Source structure in the SC database), currently in progress.
- **Baseband Delay** We have been tasked to study alternatives to the current implementation which results in unusable comparision antennas, and marginally compromised phased antennas. Depending on the outcome of the study, we anticipate some corrective development, assuming resources for the work can be located.
- **Band 7 Operation** The original proposal called for operation in band 7. The code base installed will support this, but some commissioning work will be required to tune up the capability if it is to be offered.
- **Tunable Spectral Windows** The original design called for placing TFBs to properly align with channelized back ends. It is believed that operation with multiple spectral windows may become possible during the next year. If so, then some development work on the VLBI correlator (*e.g.* DiFX) may be required to fully reap the benefit of this capability.
- **Co-operation with Sub-arrays** The design of the VOM predated the implementation of subarrays. Now that the latter are working, it is possible to revisit some of the implementation details to see if the VOM can be run in a sub-array.

Bibliography

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