Final report: ALMA Phasing Project Augmentation

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1 Background

The ALMA Phasing Project (APP) significantly enhanced ALMA capabilities by creating an in-phase observing mode that is enabling for very long baseline interferometry (VLBI) and other observations that exploit the large *collective* aperture of the ALMA array. As of this writing, VLBI observations have been successfully conducted as part of the Cycle 4 observing campaign.

1.1 Phasing ALMA

The ALMA Phasing Project (APP) provides a means to coherently phase up to 61ALMA dishes, enabling the array to operate effectively as a large single aperture. This new capability, designed to operate in parallel with standard ALMA interferometric observing modes, allows ALMA to address key scientific questions of broad impact and offers a significant additional functionality for the global astronomy community. Additional details are provided in Attachment 1.

VLBI observations fundamentally differ from standard ALMA observations insofar as the data at each participating VLBI site must be stored and later transferred to a central VLBI correlation facility for processing. Recording the full bandwidth from each ALMA dish is infeasible, so the APP phase-corrects data streams from all ALMA antennas in near real-time and forms a single coherent sum that is then captured on a high speed VLBI recorder, time-referenced to the new hydrogen maser.

In conjunction with other (sub)mm wavelength facilities, a phased ALMA serves as the high sensitivity anchor for (sub)mm VLBI arrays capable of resolving super-massive black holes on Schwarzschild radius scales. Recent observational results from 1.3mm VLBI have resolved structures near the Event Horizon of the black holes powering Sgr A*, the radio source at the center of the Milky Way, and M87, the giant elliptical galaxy in the Virgo cluster. Phased ALMA is transforming these observations, opening a new window on the study of General Relativity in the strong field regime, accretion and outflow processes at the edge of a black hole, the existence of event horizons, and fundamental black hole physics (e.g., spin). The ability to phase ALMA will also leverage Global VLBI arrays at longer wavelengths (currently commissioned for 3mm) in pursuit of science objectives that require the highest angular resolution and, with a modest additional investment, will provide a high sensitivity aperture for pulsar timing studies.

1.2 Scope of NSF MRI effort

Support and funding for the APP comes primarily from a $2.7M NSF Major Research Instrumentation (MRI) award, "Development of an ALMA Beamformer for Ultra High Resolution VLBI and High Frequency Phased Array Science." The NSF proposal included a commitment to $1.3M of in-kind contributions from the international APP team, ASIAA, NAOJ, MPIfR, and the University of Concepcion, representing all the ALMA regions and partners.

Led by MIT Haystack observatory in consultation with cognizant ALMA personnel and other members of the APP consortium, the APP provided ALMA with:

- A new hydrogen maser timing source with related support equipment
- Software to effect all aspects of the phasing observation
- Phasing interface cards for the correlator with supporting firmware and microcontroller software
- An optical link to convey data from AOS to OSF
- A VLBI data recording system at OSF.

In addition, the APP team provided all system integration functions, including commissioning, as well as Project Management support for the technical effort (but insufficient to support the ALMA processes). A brief summary of the proposed timeline, extracted from the MRI proposal, is shown in Figure 1.

	2011-12	2012-13	2013-14	2014-15
ALMA Software	-VLBI Observing Blk -Hardware protocols -CDP phase solver -Phase corr in TFBs.	-Software Ctrl of PICs -Digital Gain in TFBs	-VLBI recorder cntrl. -H-Maser control -TelCal source model -Start GUI	-GUI complete -Integration Testing
PIC/ Firmware	-ALMA Correlator Firmware mods. -PIC design, fabrication, testing	-PIC Respin -PIC Firmware -PIC production run and testing	-PIC installation and integration -GPS install and buffer design	-Commissioning tests
VLBI Software Correlator	-Hardware specs -Operational software to link with Haystack Systems	-ALMA algorithms -Integrate mmVLBI software -High frequency tests -Purchase hardware.	-ALMA algorithms fully tested on initial test data. -Finish operational software	-Process data from commissioning tests.
Optical Link		-Specify design and procure hardware.	-Install and integrate fiber systems	-Software integration.
Hydrogen Maser			-Ship maser to AOS. -Install maser.	
VLBI Recorder		-Buy 4Gb/s recorders (Mark5c) -Buy media	-First VLBI tests with recorders at AOS. -Buy 16Gb/s recorders.	-Recorders at OSF.
Integration Testing Commission			-Full phasing tests. -VLBI tests at 3mm.	- VLBI tests at 1/3mm. -Commission observations.
Project Management	-Start off meeting -PDR -Documentation	-Technical Advisory Committee Mtg. -CDR -Documentation	-Integration planning mtg. -Documentation	-Commissioning mtg. -Documentation -Reports

Fig 1. Work breakdown of the NSF-funded Major Research Instrumentation task for APP. The tasks in red were subsequently modified because (a) the digital gain activity was made obsolete by design changes, (b) the Mark 5c recorders were replaced by more capable Mark 6 recorders, and (c) the GUI proved unnecessary.

A subsequent funded extension of the MRI award added several additional tasks:

- **Identify approach to delay correction.** Severe degradation of the phasing efficiency observed in early commissioning was found to be caused by a large residual delay correction applied by the correlator downstream of the APP phasing loop. An adequate workaround was implemented that had the drawback of compromising the delays applied to the standard ALMA data. Under this task, a robust approach to this problem .approach has been identified under an ALMA NA Cycle 3 Study award. First steps toward implementation are being carried out under an active ALMA NA Cycle 4 Study award, and full implementation is proposed under a pending ALMA NA Development proposal.

- **Provide a post-processing solution to mismatched sampling rates.** ALMA specifications support 32 spectral windows, which is what is needed to properly align the 62.5MHz slices from the Tunable Filter Banks (TFB) with 3mm VLBI standard channels. However, ALMA has not yet been able to offer more than 2 spectral windows. This liability is a blocking issue for 3mm observations with existing VLBI networks that require a high degree of channelization.

- **Complete the post-processing polarization correction capability.** For VLBI, the orthogonal linear polarizations recorded by the APP at ALMA need to be converted to LCP/RCP for compatibility with 1mm and 3mm VLBI networks. We note that the first successful 1.3mm VLBI fringes between APEX-ALMA were obtained on crossed Circular vs Linear polarized recordings. This work had been delayed by the lack of obtain appropriate test data.

- **Upgrade the Observing Tool**

An extensive commissioning campaign produced the first VLBI fringes in January, 2015, in collaboration with the APEX facility (see the NRAO March 5, 2015 press release). After resolving a thorny problem with residual delays, efficient phasing was demonstrated in March, 2015.

Upon completion of the science commissioning of APP, all elements of the phasing system were transferred to the ALMA Executives in order that the capability may be made available to the broad radio astronomy community. The APP consortium delivered to ALMA all necessary documentation, test instrumentation, and available spare parts to enable ALMA to assume responsibility for maintenance and continued development of ALMA VLBI.

The first science VLBI observations were obtained in Cycle 4, in April of 2017.

1.3 Scope of ADF-funded effort

After initiation of the MRI effort project, it became clear that additional funds would be needed to offset costs incurred by JAO and the ALMA organization, as well as costs incurred by the APP implementing organizations to meet ALMA's the stringent project management requirements with respect to processes such as commissioning, documentation, and software integration. The APP Augmentation was awarded from the ALMA Development Fund (ADF) to meet that need, initially dividing $520K roughly evenly between the implementing APP team, led by MIT Haystack Observatory, and NRAO/JAO in-house activities. The initial Haystack budget of $259.9K was later reduced by $25K to $234.9K in order to support the Product Assurance activities of Bob Treacy at NRAO.

The Statement of Work for the requested funding included the following, distributed across the schedule established for the APP:

1. Increase the level of planning, reporting, documentation, system engineering, technical and programmatic review, and product assurance associated with the APP to conform to ALMA standards. Note that this work package directly impacts personnel in the areas of management, system engineering, and integration and test, but also indirectly impacts the subsystem leads through additional documentation and review processes.
2. Manage and allocate contingency funds associated with item #1.

1.4 Activities supported at MIT

MIT was responsible for overall APP Project Management; activities funded under the ADF augmentation were specific to ALMA-driven activities as distinct from technical management of the effort. Personnel funded under the augmentation included the Principal Investigator, Shep Doeleman; the Project Manager, Michael Hecht; and the Software Lead, Geoff Crew.

The work encompassed documentation, including an Implementation Plan; Formal reviews, including preliminary and critical design reviews, acceptance reviews, and test readiness reviews; and support of observation implementation, including participation in OBSMODE and other ALMA planning processes.

Attachment 2, the Detailed Design Description prepared for the CDR, details the deliverables for these tasks.

1.5 Activities supported at JAO

Task implementation at JAO was coordinated by project leader Bernhard Lopez, who provided a primary point-of-contact for the APP Project Management and was not only a valuable adviser to APP, but was instrumental in coordinating reviews, arranging visits, and expediting the documentation process at JAO. Alejandro Saez at JAO provided direct technical support, and without his assistance the APP would not have been possible. Other staff members at JAO were instrumental in supporting the software implementation process, hardware installation and configuration, and configuration management.

1.6 Activities supported at NRAO

NRAO was tasked with implementing APP software elements that effected vulnerable areas of the ALMA control system, and with generally ensuring the integrity of the ALMA software environment. This support was primarily provided by Matias Mora-Klein, but key elements were also provided by Rafael Hiriart and other members of the Socorro team. As mentioned above, Bob Treacy at NRAO provided invaluable Product Assurance support.

1.7 Scope of this report

In addition to the above descriptions and the Attachments, this report contains mandated close-out items, including:

- A compliance matrix depicting contract requirements versus status of deliverables;
- Final accounting (purchase order closure, final invoices ... etc.);
- Disposition of excess materiel;
- Capitalization of U.S. Government assets (if applicable);
- Contract closure (completed or legally terminated);
- Identification of technical and programmatic (schedule and cost) risks and a recommended risk mitigation plan;
- Primary lessons-learned;
- Disposition (archival and/or disposal) of Project records.

2 Compliance Matrix

As part of the management of ALMA-activities, a compliance matrix was submitted in support of the APP hardware acceptance review. This is reproduced on the following pages.

Items marked “open” fell in one of two categories: Tasks assigned to ALMA personnel, or tasks deferred to Commissioning and Science Verification (CSV). All were subsequently closed.

Rqmt #	Requirement	Verification Method	Pass/Fail
APP-XXXXX-XX	APP-provided hardware shall conform to all applicable requirements and guidelines for identification and labeling of ALMA equipment as specified in ALMA-80.02.00.00-016-A-SPE	ALMA personnel to inspect and verify	Open
APP-XXXXX-XX	APP-provided connectors shall conform to all applicable requirements specified in Standard for AC Plugs, Socket-Outlets, and Couplers: ALMA-80.05.00.00-004-B-STD	ALMA personnel to inspect and verify	Open
APP-XXXXX-XX	APP-provided hardware shall conform to all applicable ALMA System Electrical Design Requirements as specified in ALMA-80.05.00.00-005-C-SPE	ALMA personnel to inspect and verify	Open
APP-XXXXX-XX	APP-provided hardware shall conform to all applicable ALMA System EMC Requirements as specified in ALMA-80.05.01.00-001-B-SPE	ALMA personnel to inspect and verify	Open
APP0010	**Frequency reference:** All ALMA local oscillators shall be phase-locked to a common frequency standard.	[RD-04]: See System Block Diagram. Since the maser replaces the Rubidium in the Central LO, all of ALMA is phase-locked to it.	Pass
APP0020	**Spectrum**: The APP shall be capable of processing 8GHz of input spectrum per polarization	[RD-23], Chapter 3: One data path with 2 GHz BW is demonstrated.	Pass
APP0020	**Spectrum**: The APP shall be capable of processing 8GHz of input spectrum per polarization	[RD-07], section 5.1.3: Eight data paths with 8 GHz per polarization are demonstrated.	Pass
		[RD-04]: See System Block Diagram. Each of the 8 data streams handles one polarization with a bandwidth of 2 GHz.	Pass
		RD-23, Chapter 23, shows that one recorder can handle 25% of the requirement, at PAI.	Pass
		RD-07, section 5.1.3, shows that the four recorders can handle 100% of the required spectrum. (AcRv)	Pass
APP0030	**Polarization:** The APP shall generate dual-polarization signals.	[RD-04]: See System Block Diagram. Four of the data streams handle one polarization and the other four the other polarization.	Pass
APP0040	**Polarization purity:** The APP shall not introduce more than 3% polarization leakage .	CSV	Open
APP0050	**Data capture**: The APP shall have the capability to record 64Gbps of data and associated framing data.	[RD-23], Chapter 3: One data path with 8 Gbps of data is demonstrated.	Pass
		[RD-07], section 2.1.4.4: Eight data paths with with an aggregate data rate of of 64 Gbps are demonstrated.	Pass
		[RD-04]: See System Block Diagram. Each recorder handles two data streams of 8 Gbps each.	Pass
APP0060	**Line Replaceable Unit Reliability (LRU):** All installed APP hardware shall satisfy ALMA LRU requirements.	As noted in RD-18, Correlator components have demonstrated reliability exceeding this requirement. Part of the process for obtaining units that are reliable at ALMA is burning them in before shipping. Both the PICs and associated supplies were burned-in in Charlottesville. This is reported in RD-19 (first tab) and RD-05, section 2.3.12.	Pass
		RD-13, section 3.3, documents burn-in tests for the OFLs at NAOJ. This type of testing contributes to meeting this requirement.	Pass
		RD-13, section 3.6 documents that the unit operates with one of the two redundant supplies disabled. This contributes to the LRU's reliability.	Pass
		RD-21, sections 5.1 to 5.5 document link characteristics which are required for reliable operation.	Pass
APP0070	**Environmental:** All hardware permanently installed at AOS/OSF shall meet ALMA altitude/environmental requirements.	All hardware has been installed at AOS/OSF for many months. It has repeatedly satisfied all tests in [RD-05], [RD-07] and [RD-09], thus demonstrating compatibility with altitude and environmental requirements.	Pass
		RD-13, section 3.7, documents a test that verifies sufficient cooling capacity for operation at the AOS.	Pass
APP0080	**Environmental:** The recording systems shall be compatible with operation at OSF altitudes.	The recorders been installed at AOS/OSF for months.	Pass
		Initially two of the recorders underwent stress tests to verify compatibility. See RD-20 for details.	Pass
		Since then, four recorders have repeatedly satisfied tests in and [RD-07] Chapter 2, again demonstrating compatibility with altitude and environmental requirements.	Pass
		RD-20 is dedicated to an extended test of the recorders at altitude to demonstrate that the recorders satisfy this requirement.	Pass
APP0090	**Data transmission:** A high speed data 80Gbps connection shall link the equipment at the AOS to the OSF	[RD-07], section 2.1.4.4: Eight data paths with with an aggregate data rate of of 64 Gbps are demonstrated.	Pass
		(The capability of the system to meet 80 Gbps is covered in section 2.3.)	Pass
		[RD-04]: See System Block Diagram. The data link between the two OFLs is shown to be 80 GbE.	Pass
		[RD-13], section 3.1 describes the testing and results to validate the 80 Gbps requirement.	Pass
	Environments: The APP system shall be operable whenever ALMA	[RD-07]: It is clear from a review of these tests that they are integrated into the ALMA infrastructure and thus the Phasing System is capable of being used just like any other ALMA system.	Pass

APP0100	**Environments:** The APP system shall be operable whenever ALMA is.	All installed equipment meets all relevant ALMA environmental specifications (see Appendix B of this document). Also, there is no mention of any limitations to the delivered equipment in any of the delivered documentation. Therefore, this requirement is met. (See also test #2.)	Pass
APP0110	**Maser status:** The Maser status / health information shall be accessible via a network interface and recorded at least once every 10 minutes.	[RD-29], section 2.3: The status/health information is reviewed prior to each VLBI experiment (actually more often that that).	Pass
		RD-29, section 2.3. During AOS testing, the software was exercised and the status/health data was inspected.	Pass
APP0120	**Maser stability:** The Maser shall be stable to: 10^{-13} Allen Variance for 1 sec integration time and $2x10^{-14}$ for 10 second integration time.	N/A (covered at Maser AcRv)	N/A
APP0130	**Frequency source:** Switching between the ALMA rubidium clock and the APP Maser shall be a manual procedure.	N/A (covered at Maser AcRv)	N/A
APP0140	**Phasing efficiency (stability):** The APP phasing efficiency shall be as stable as the atmospheric coherence timescale of the median antenna of the array.	CSV	Open
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 2km with no more than 0.8mm precipitable water vapor and mean RMS path fluctuations no more than 0.125 mm.	CSV	Open
APP0160	**Phasing efficiency (monitoring):** The phasing system shall monitor the efficiency of its solutions.	N/A This is a software requirement, not due until CSV.	N/A
APP0170	**Phasing data**: Channel average data from all relevant baselines and WVR data shall be available at the baseband cadence.	No verification needed. This capability currently exists at ALMA	N/A
APP0180	**Correlator output:** The correlator shall operate in a mode where it provides to the PICs the antenna-summed data for each quadrant: 2 pol x 32 ch x 62.5 MHz, 2bits / sample, 16Gbps , 128 LVDS pairs	[RD-07], section 2.1.5: Standard Correlator mode 13 is used in this test.	Pass
		No verification needed. This capability currently exists at ALMA in certain modes, including Mode 13 which is used in Test 2.	Pass
APP0190	**Correlator configuration:** The antenna summed data shall be provided as CAI-63.	[RD-05], section 2.3.10.1	Pass
		[RD-04]: See System Block Diagram. The feedback path of the VLBI sum to the VLBI sum input is shown.	Pass
		[RD-14]: See entries for Correlator Card to CI card. These are the feedback to input 63.	Pass
		(See also test #1)	Pass
APP0200	**Correlator self test**: Test capabilities shall be provided by the ALMA correlator to verify correct PIC operation.	[RD-09], sections 2.3.5.3, 2.3.5.4, 2,3,5,6	Pass
		[RD-05], section 2.3.5, 2.3.6.1.1, 2.3.10.1, 2.3.10.2,	Pass
APP0210	**PIC output:** The output format of the PIC phased sum data shall be VLBI Data Format (VDIF) packets	RD-25 (Recorder Command Set) section 6, input_stream command shows that the recorder only accepts the legacy Mark5b format and VDIF. That we were ever able to record is conclusive evidence that we are fully VDIF compliant with our data.	Pass
APP0220	**PIC timing:** A 1pps clock synchronized with the maser shall be supplied to the PIC	[RD-30]	Pass
		[RD-04]: This connection is shown in the System Block Diagram. (See also test #1.)	Pass
APP0230	**VDIF format:** The VDIF packet shall support 8, 16 and 32 channels.	[RD-07], section 2.4	Pass
APP0240	**VDIF encapsulation:** The VDIF packet shall be encapsulated as UDP/IPv4 payload.	[RD-07], section 5.2.1: The recorder is designed to accept only these type of packets. The fact that it accepts the packets from the PICs shows that the PICs meet this requirement.	Pass
APP0250	**Ethernet mtu:** The Ethernet interface shall support jumbo frames.	[RD-07], section 5.2.1: The recorder is designed to accept only these type of packets. The fact that it accepts the packets from the PICs shows that the PICs meet this requirement.	Pass
APP0260	**Ethernet bandwidth**: The Ethernet interface shall be 10Gbps.	[RD-07], section 5.2.1: The recorder is designed to accept only these type of packets. The fact that it accepts the packets from the PICs shows that the PICs meet this requirement.	Pass
APP0270	**Network infrastructure**: The data communication system linking AOS to OSF shall support multiplexing eight 10 GbE bi-directional channels onto a single fiber.	[RD-07], section 5.2.1: 8 channels are demonstrated in this test at an aggregate rate of 64 Gbps. (The bidirectional nature of the link is not needed for phasing, and is documented in	Pass
		[RD-04]: See System Block Diagram. The data link between the two OFLs is shown to be 80 GbE.	Pass
		[RD-13], section 3.1 describes the testing and results to validate the 80 Gbps requirement.	Pass
		[RD-2] states that the design of the two OFLs are identical. This satisfies the bidirectional requirement.	Pass

	channels onto a single fiber.	RD-13, section 3.2, documents a test that uses an attenuator to simulate the AOS to OSF optical link and measures error rate.	Pass
		RD-13, section 3.1 documents a test which demonstrates the full data capacity over 1 fiber.	Pass
		RD-21, sections 5.1 to 5.5 verify that the network infrastructure is operating correctly at ALMA	Pass
		RD-23, sections x to y verify that the link is operating correctly in Charlottesville.	Pass
APP0280	**Data distribution:** The data shall be evenly distributed at 8Gbps over all optical channels.	[RD-07], section 5.2.1 The recorder saw similar, evenly divided, data streams in this test	Pass
		[RD-04]: See System Block Diagram. Eight 10 GbE channels are shown, each driven by identical PICs. Thus the data are evenly distributed.	Pass
APP0290	**Recording system:** The recorders shall be able to record at an aggregate rate of 64 Gbps.	RD-07, section 5.2, shows that the four recorders can handle 100% of the required spectrum. (AcRv)	Pass
APP0300	**Data integrity**: The recording system (recorder + optical fibers) shall capture at least 95% of the data packets.	RD-23, Chapter 3, shows that the dropped packet capture rate at PAI with 30 km of cable is zero.	Pass
		RD-07, Chapter 3, shows that the packet capture rate at site is < $2*10^{-6}$.	Pass
APP0310	**Recorder control:** Commands to the recorders shall adhere to the VLBI Standard Software Interface Specification (VSI-S).	RD-25,Mark 6 command set document, section 1	Pass
APP0320	**Recorder media:** The data shall be recorded to standard disks.	RD-07, section 5.2.2	Pass
APP0330	**Media processing:** The disks shall be shippable for VLBI processing of data.	RD-07, section 5.2.2	Pass
APP0340	**Media insertion:** Reliability of the connectors / cables between the recorder and the module shall be consistent with at least 5 years of operation	RD-31	Pass
APP0350	**Media capacity:** The disk modules will hold a minimum of 9 hours of data.	64 Gb/s * 9hrs *3600s / 8 bits_per_byte = 260 TB. Capacity of recorders is 4 recorders x 32/recorder modules x 3 TB disks = 384 TB, well in excess of the 260 TB.	Pass
APP0360	**Experiment session:** 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.	CSV	Open
APP0370	**Session duration:** The APP system shall support sessions lasting up to 18 hours.	64 Gb/s * 9hrs *3600s / 8 bits_per_byte = 260 TB. Capacity of recorders is 4 recorders x 32/recorder modules x 3 TB disks = 384 TB. So this becomes an straightforward operational issue. Two sets of modules will need to be provided to support a session lasting 18 hours.	Pass
APP0390	**Interscan gap:** The APP system shall support scans separated by a minimum of ***10*** seconds.	[RD-07], section 5.1.2	Pass
APP0400	**Scan duration:** The APP system shall support scan durations between **10** and **900** seconds.	[RD-20], section 3.2	Pass
APP0410	**Experiment scans:** The APP system shall complete at least ***90*** % of scheduled scans.	20, Section 3.2	Pass
APP0420	**Scan scheduling:** The APP system shall support scans scheduled in UTC time and shall start/stop within 2 seconds of the scheduled time.	RD-07, Section 2.3.3.4	Pass
APP0430	**Band support:** Band 3, 6 receivers shall be fully supported.	RD-04: See System Block Diagram. The data path shows no dependence on which receiver is being used. The key is whether the phasing algorithm is able to phase antennas at these bands.	Pass
		RD-07, Section 5.1.3	Pass
APP0440	**Minimum bands:** APP shall support simultaneous use of one to four ALMA frequency basebands	[RD-07], section 5.1.4: Four basebands are recorded in this test. Since the quadrants and recorders are individually controllable (basic ALMA software properties) any number from 1 to 4 is acceptable.	Pass
		[RD-04]: See System Block Diagram. It shows that the system uses one to four Correlator quadrants. A basic property of the ALMA system is that the quadrants can be operated independently. Therefore the requirement is met.	Pass
APP0450	**IF frequency:** The APP system shall support faithful programming of the IF band specified by the VEX file.	RD-07, Section 5.1.3	Pass
APP0460	**TFB tunings:** The TFB channel placement shall be capable of being made compatible with the 2^n MHz sampling schemes of traditional VLBI.	RD-07, Section 5.1.3	Pass
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	[RD-07], section 2.1.5: Test is conducted using such a mode, Correlator mode 13.	Pass
		RD-17 specifies all Correlator modes. APP uses standard mode 13 to satisfy this requirement.	Pass
APP0480	**LO Tuning:** All Antennas shall have the same LO tuning	No verification needed. This is an existing ALMA mode.	Pass
		[RD-07], section 5.1.1: Summing of various numbers of antennas is demonstrated in this test.	Pass

APP0490	**Antenna participation:** The phasing system shall be capable of phasing up an array consisting of an arbitrary odd number of antennas <64.	RD-14, System Block Diagram shows no limitation on the number of antennas except that antenna 63 (counting from 0) is dedicated to correlating the sum of antennas.	Pass
		RD-06, section 3 shows that the summing mask can contain any number of antennas.	Pass
		The "odd" number of antennas comes from the mathematics of summing 2-bit-sampled data. This is enforced in the high level software.	Pass
APP0500	**Antenna 63:** The antenna assigned to CAI-63 shall be part of the observing array but omitted from the phased sum	RD-04: See System Block Diagram. It is also clear that the normal ALMA data path in the Correlator is not disturbed (the phasing system "taps off" the data it needs), so any antenna can be part of the observing array. Omitting antenna 63 from the phased sum is ultimately governed by the high level software.	Pass
APP0510	**Log archival:** Information necessary for the post-observation (VLBI) correlation and analysis shall be archived.	RD-07, section 5.1.6	Pass
APP0520	**Independent systems:** The phasing and recording systems shall be operated separately.	RD-04: The System Block Diagram clearly shows that the hardware is independent. Separate operation is governed by the high level software design.	Pass
		RD-07, section 5.1.5	Pass
APP0530	**Independent quadrants:** The APP system shall support independent operation of the four correlator quadrants.	[RD-07], section 2.2	Pass
BAK-0010	Maser Rack Cabling	N/A	N/A
BAK-0020	CRG 5 MHz input power level	N/A	N/A
BAK-0030	CVR 10 MHz input power level	N/A	N/A
BAK-0040	**1-PPS levels**. Verify that the 1-PPS signal level at the 1-PPS Distributor in the Correlator Room is compliant.	[RD-09], section 2.3.4.2: The waveform is measured in this test.	Pass
COM-0010	**Protocol verification.**	RD-07, section 5.1.7 shows that all protocols are executed in a simulated observation. Analysis of the data shows that the protocols were *successfully* executed	Pass
		RD-05, section 2.3.8 shows that all protocols are executed in a simulated observation with no errors.	Pass
COM-0020	Recorder NTP capability.	RD-07, section 4.2 demonstrates this capability at PAS.	Pass
COR-0010	Items to be delivered as listed in Table 1 of AD-08	The following Transfer Requests show that all required equipment as well as spares were shipped:	Pass
		CV50-14: TLC brackets to OSF (7/28/14)	Pass
		CV43-14: Spare SFP+ cards_Chile FedEx# (6/18/14)	Pass
		CV36-14: 5th PIC/Roach shipment (5/28/14)	Pass
		CV34-14: 4th PIC/Roach shipment (5/12/14)	Pass
		CV30-14: 3rd PIC/Roach shipment (4/23/14)	Pass
		CV29-14: OFLx2 to Chile (4/23/14)	Pass
		CV28-14: ALMA Phasing Project (4/10/14)	Pass
		CV22-14: CORR BIN+LVDS cables to Chile (3/26/14)	Pass
		CV2-14: 1st PIC_RoachII_Chile (1/17/14)	Pass
		CV97-13: APP_GPS_Ant_A4_LVDS. (12/3/13)	Pass
		CV73-13: APP cables and PSU. (9/17/13)	Pass
		CV64-13: Phasing project 1PPS PARTS. (9/16/13)	Pass
		CV45-13: Phasing project PSU model. (4/18/13)	Pass
		Moreover, the system is now fully installed, proving that there are no missing parts.	Pass
COR-0020	PIC assemblies fit in Final Adder slots of correlator bins	All PIC assemblies have been installed in spare Final Adder slots of Correlator bins, proving that they fit.	Pass
COR-0030	**Rack temperature increase** due to PICs	The power dissipated by a PIC, approximately 30 W, is less than 0.06% of the total power dissipated by one quadrant. Therefore the temperature rise is impossible to measure due to noise in the measurement process.	Pass
		[RD-05], section 2.3.11.1: Power dissipated by PIC is measured to be about 30 W.	Pass
		[RD-09], section 2.3.5.3: The temperatures at various points in the racks are measured in this test. The insignificant amount of power dissipated by the PIC makes the temperature rise of the rack due to the pic impossible to measure (30W/4500W)	Pass
COR-0040	Cabling additions	RD-09, section 2.3.4.1 documents an inspection where the correctness of installed cables was visually verified.	Pass
		RD-09 section 2.3.7.4 documents an automated test which would highlight incorrectly installed cables (a few were found this way!)	Pass
COR-0050	**PIC Comm. Ethernet card**: Verify that it is possible to communicate via Ethernet to each ROACH via the Engineering Port Computer	[RD-09], section 2.3.5.2:	Pass
		RD-09 section 2.3.5.5 documents a test in which Ethernet connections to all PICs were used to obtain PIC temperature readings temperature readings. This verifies the Ethernet communication capability.	Pass

COR-0060	Power dissipation	RD-05, section 2.3.11.1 shows the power dissipated in one PIC as measured at PAI.	Pass
COR-0070	**Firmware deliveries**: Verify that the correct microprocessor and FPGA personalities are installed.	RD-09 section 2.3.4.4 lists the installed firmware. Comparison with the CVS repository (:pserver: [user]@cvs-project7.sco.alma.cl:2401:/project7/CVS) shows that these are appropriate.	Pass
ENVI-00040-00 / A	[Operating and non-operating compatibility with] The levels of earthquake acceleration that are likely to occur at the OSF and AOS	This applies only to the maser rack since other equipment was installed in existing racks. It was covered at the Maser AcRv	Pass
ENVI-00050-00 / R	Occurring downtime and time to repair for the equipment must be defined in each sub-system specification.	Covered primarily in RD-18, and also in RD-02	Pass
ENVI-00070-00 / R	[AOS] All ALMA equipment shall be compatible with an ambient air pressure of 550 mbar ± 60 mbar, which corresponds to an air density of 0.7214 kg/m3 (typical average).	[RD-07]: All Correlator hardware as well as the OFL have been installed since July 2014 and have passed all relevant tests in this document at least once and quite a few of them on several occasions. Thus compatibility has been demonstrated by successful operation in the environment. Maser compliance was covered in the Maser AcRv	Pass
ENVI-00121-00 / R	[AOS operating and non-operating compatibility with] Maximum expected Gamma ray dose rates are 3.14 mSv/year	See ALMA Memo 462. All FPGAs are subject to gamma rays. FPGA personality changes due radiation from gamma rays or neutrons were detected at the rate of one every few hours in tests of the ALMA Correlator for the ~10,000 FPGAs in the Correlator TFB boards. ALMA currently ignores this. The additional disruption caused by an additional 8 FPGAs in the PICs will be too minor to be noticed. **We request a waiver.**	Waive
ENVI-00270-00 / R	[OSF] All ALMA equipment shall be compatible with an ambient air pressure of 750 mbar +/- 100 mbar, which corresponds to an air density of 0.96 kg/m3 (typical average).	[RD-07]: Two recorders were installed at the OSF in 2013 and an additional two in August 2014. They have passed all relevant tests in this document and quite a few of them on several occasions. Thus compatibility has been demonstrated by successful operation in the environment. (Also see test #8.)	Pass
ENVI-00311-00 / R	[OSF Operating and non-operating compatibility with] maximum expected Gamma ray dose rates of 1.70 mSv/year.	This applies to the recorders. As stated above for ENVI-00121, FPGA disruptions occur statistically. At the OSF, given the lower elevation and smaller number and smaller physical size of FPGAs, the probability of a disruption is miniscule and can be dealt with in the same way as ALMA deals with this issue in other computers, by rebooting periodically. **We request a waiver.**	Waive
PA-001000-00/	When appropriate, the accompanying documentation shall be in the outer packaging layer and shall include the Acceptance Data Package, which includes the storage, handling, transportation, packing/unpacking procedures and relevant notes of caution and safety procedures.	N/A	N/A
PA-001020-00/	Labeling of shipment containers shall include: 1. nomenclature, model name and serial number (if applicable) of the item; 2. caution/warning notes for dangerous or toxic contents; 3. package orientation arrows; 4. for large items, weight and centre of gravity, handling and lifting points; 5. conditions and instructions for handling and unpacking, and 6. name, address, phone number of sender and recipient.	ALMA personnel to inspect and verify	Open
PA-001030-00/	Labeling of shipment containers shall be permanent and legible and protected against wear.	ALMA personnel to inspect and verify	Open
PA-00240-00/	Each configuration item shall be uniquely identified by serial number.	ALMA personnel to inspect and verify	Open
PA-00250-00/	A serial number shall be permanently affixed to each configuration item using a method appropriate to the item which may be indelible ink, engraving, coded electronically readable chip or a combination of the above or equivalent methods. Serial numbers shall not be hand-written.	ALMA personnel to inspect and verify	Open
PA-00860-00/	The documentation supplied in the Acceptance Data Package shall reflect the “as-built” version of the delivered equipment and shall contain sufficient information for the installation, operation and maintenance of this equipment.	ALMA personnel to inspect and verify	Open
PA-00920-00/	All commercially purchased test and measurement equipment used in the execution of formal acceptance testing shall satisfy the requirements for metrology and calibration specified in Table 4.	We used ALMA test equipment for all tests. We request a waiver.	Waive
SAFD-0050-00/	The essential characteristics, the recognition and observance of which will ensure that electrical equipment will be used safely and in applications for which it was made, shall be marked on the equipment, or, if this is not possible, on an accompanying notice.	ALMA personnel to inspect and verify	Open
SAFD-0060-00/	The designers or brand name or trade mark shall be clearly printed on the electrical equipment or, where that is not possible, on the packaging.	ALMA personnel to inspect and verify	Open
SAFD-0090-00/	that persons are adequately protected against danger of physical injury or other harm which might be caused by electrical contact direct or indirect;	ALMA personnel to inspect and verify	Open

SIT-0010	**Component power dissipation:** Verify power dissipation under normal operating conditions for one or more of each of the following installed components: · Maser rack (3.1.5.1.1) · 1-PPS distributor (3.2.1.1) · Fiber Mux/DeMux (3.3.1.1) · Recorder (3.4.2)	[RD-05], section 2.3.11.2: 1-PPS distributor power is measured.	Pass
		RD-13, section 3.4, documents measured power dissipation which is considerably less than required.	Pass
		Measure the power dissipation of each required module:	Pass
		· Maser rack: N/A (covered in Maser AcRv)	Pass
		· Fiber Mux/DeMux : RD-13, section 3.4	Pass
		· PIC: RD-05, section 2.3.11.1	Pass
		· Recorder: RD-07, Section 5.2.3	Pass
		[RD-13], section 3.4: OFL power is measured	Pass
		[RD-07], section 5.2.3, Recorder power is measured	Pass
SIT-0020	**Correlator upgrade cabling**	[RD-09], section 2.3.5.1, 2.3.7: Visual inspection and built-in tests were both used to verify the cabling.	Pass
		RD-09, section 2.3.3.1 and 2.3.4.1 documents an inspection where the correctness of installed cables was visually verified.	Pass
		RD-09 section 2.3.5.3 and 2.3.5.4 documents an automated test which would highlight incorrectly installed cables (a few were found this way!)	Pass

3 Final accounting

A final accounting, including purchase order closure, final invoices, etc., is provided on the following pages.

SUMMARY STATEMENT WBS 6927676 - CLOSED

Month End May 31 2017

Supervisor: DOELEMAN /SHEPERD SAMUEL **ALMA PHASING PROJECTION AUGMENTATION** **Begin:** 03/04/2013 **End:** 03/03/2016
Authorized Total: $ 234,890.00 **Company:** Mass. Inst. of Technology **Project:** 6927676
Profit Center: P401710 - PROVOST OFFICE-HAYSTACK **Costing Sheet:** Research MTDC Off (HQ Off) 56.00 ON - 4.50 OFF
Sponsor: National Radio Astronomy Observatory **Contract Number:** PO #342941 **Agreement Type:** 12

Description	Budget *(Version 0)*	Current	Fiscal YTD	Cumulative	Unexpended	Commitment	Uncommitted
EXPENSE NET OF REVENUE							
Expenses							
Direct Expenses							
Salaries & Benefits							
Salaries & Wages							
400355 - Research Staff-Off				107,683.84	107,683.84-		107,683.84-
490100 - Correct Alloc S&W On-not MT				6,755.32-	6,755.32		6,755.32
490101 - Correct Alloc S&W Off-not M				6,755.32	6,755.32-		6,755.32-
600100 - Alloc S&W On-not MTDC				6,755.32	6,755.32-		6,755.32-
600101 - Alloc S&W Off-not MTDC				19,546.04	19,546.04-		19,546.04-
TOTAL Salaries & Wages				**133,985.20**	**133,985.20-**		**133,985.20-**
Employee Benefits							
Fund & MTDC Base EB Off Campus							
600205 - EB Off				25,778.32	25,778.32-		25,778.32-
600237 - Res Vac Acc Off				10,354.33	10,354.33-		10,354.33-
TOTAL Fund & MTDC Base EB Off Camp				**36,132.65**	**36,132.65-**		**36,132.65-**
Non Fund & MTDC Base EB							
490205 - Correct EB Res Vac Acc On				33.78	33.78-		33.78-
490216 - Correct Current Yr EB On-				135.11-	135.11		135.11
600226 - EB On-not MTDC				135.11	135.11-		135.11-
600227 - EB Off-not MTDC				6,251.95	6,251.95-		6,251.95-
600238 - Res Vac Acc On-not MTDC				33.78-	33.78		33.78
600239 - Res Vac Acc Off-not MTDC				2,594.57	2,594.57-		2,594.57-
TOTAL Non Fund & MTDC Base EB				**8,846.52**	**8,846.52-**		**8,846.52-**
TOTAL Employee Benefits				**44,979.17**	**44,979.17-**		**44,979.17-**
TOTAL Salaries & Benefits				**178,964.37**	**178,964.37-**		**178,964.37-**
Operating Expenses							
Travel							
420050 - Travel Expenses				83.76	83.76-		83.76-
420070 - Travel-Foreign Expenses				8,082.54	8,082.54-		8,082.54-
TOTAL Travel				**8,166.30**	**8,166.30-**		**8,166.30-**
Materials and Services							
420226 - Materials and Services				8,038.16	8,038.16-		8,038.16-
420314 - Record Project Overrun-not				10.20-	10.20		10.20
490110 - Correct Alloc M&S On-not MT				2,557.59-	2,557.59		2,557.59
490111 - Correct Alloc M&S Off-not M				2,557.59	2,557.59-		2,557.59-
490112 - Correct Alloc Utilities On-				2,974.58-	2,974.58		2,974.58
490113 - Correct Alloc Utilities Off				2,974.58	2,974.58-		2,974.58-
600104 - Alloc M&S On-not MTDC				2,557.59	2,557.59-		2,557.59-
600105 - Alloc M&S Off-not MTDC				12,504.15	12,504.15-		12,504.15-
600106 - Alloc Utilities On-not MTDC				2,974.58	2,974.58-		2,974.58-
600107 - Alloc Utilities Off-not MTD				11,672.85	11,672.85-		11,672.85-
TOTAL Materials and Services				**37,737.13**	**37,737.13-**		**37,737.13-**
Other Direct Charges							
420920 - Postage Mailing and Shippin				2,156.39	2,156.39-		2,156.39-
TOTAL Other Direct Charges				**2,156.39**	**2,156.39-**		**2,156.39-**

SUMMARY STATEMENT WBS 6927676 - CLOSED

Month End May 31 2017

Supervisor: DOELEMAN /SHEPERD SAMUEL **ALMA PHASING PROJECTION AUGMENTATION** **Begin:** 03/04/2013 **End:** 03/03/2016
Authorized Total: $ 234,890.00 **Company:** Mass. Inst. of Technology **Project:** 6927676
Profit Center: P401710 - PROVOST OFFICE-HAYSTACK **Costing Sheet:** Research MTDC Off (HQ Off) 56.00 ON - 4.50 OFF
Sponsor: National Radio Astronomy Observatory **Contract Number:** PO #342941 **Agreement Type:** 12

Description	Budget (Version 0)	Current	Fiscal YTD	Cumulative	Unexpended	Commitment	Uncommitted
Computation							
421900 - Computer Supplies & Periphe				527.81	527.81-		527.81-
TOTAL Computation				**527.81**	**527.81-**		**527.81-**
Budget Direct Costs Summary							
422155 - Budget-To Be Determined	234,890.00				234,890.00		234,890.00
TOTAL Budget Direct Costs Summary	**234,890.00**				**234,890.00**		**234,890.00**
TOTAL Operating Expenses	**234,890.00**			**48,587.63**	**186,302.37**		**186,302.37**
Equipment							
421827 - Equip/Furniture-Minor				15.60	15.60-		15.60-
TOTAL Equipment				**15.60**	**15.60-**		**15.60-**
TOTAL Direct Expenses	**234,890.00**			**227,567.60**	**7,322.40**		**7,322.40**
Indirect Expenses							
Indirect Expenses							
F&A							
490311 - Correct Current Yr F&A Off				309.16	309.16-		309.16-
490312 - Correct Prior Yr F&A On				349.19-	349.19		349.19
490313 - Correct Prior Yr F&A Off				28.06	28.06-		28.06-
600304 - F&A On				349.19	349.19-		349.19-
600305 - F&A Off				7,548.63	7,548.63-		7,548.63-
TOTAL F&A				**7,885.85**	**7,885.85-**		**7,885.85-**
F&A Adjustments							
490319 - Adj CY F&A Off to Spon Base				309.16-	309.16		309.16
600317 - Adj F&A Off to Spon Base/Ra				254.29-	254.29		254.29
TOTAL F&A Adjustments				**563.45-**	**563.45**		**563.45**
TOTAL Indirect Expenses				**7,322.40**	**7,322.40-**		**7,322.40-**
TOTAL Indirect Expenses				**7,322.40**	**7,322.40-**		**7,322.40-**
*** TOTAL Expenses ***	**234,890.00**			**234,890.00**			
Revenue							
Revenues							
Sponsored Revenues							
800600 - Sponsored Billings				234,890.00-	234,890.00		234,890.00
TOTAL Sponsored Revenues				**234,890.00-**	**234,890.00**		**234,890.00**
TOTAL Revenues				**234,890.00-**	**234,890.00**		**234,890.00**
TOTAL Revenue				**234,890.00-**	**234,890.00**		**234,890.00**
TOTAL EXPENSE NET OF REVENUE	**234,890.00**						

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

FINAL REPORT OF EXPENDITURES

National Radio Astronomy Observatory
ATTN: Richard Sakshaug
NRAO Contracts and Procurement
520 Edgemont Road
Charlottesville, VA 22903

Date: May 6, 2016

CONTRACT/GRANT NUMBER	START DATE	END DATE	MIT PROJ. #	ESTIMATED COST
PO #342941	03/04/13	03/03/16	6927676	$234,890.00

STATEMENT OF EXPENDITURES	CUMULATIVE	CURRENT
Salaries and Wages - Off Campus	$107,683.84	($363.65)
Salaries and Wages - On No O/H	$26,301.36	($28.78)
Employee Benefits Summary	$36,132.64	($109.11)
Employee Benefits No O/H	$8,846.52	($8.63)
Indirect Expense Summary	$7,322.40	($11.73)
Travel Expense - Domestic	$83.76	$0.00
Travel Expense - Foreign	$8,082.54	$0.00
Materials and Services	$10,210.15	$212.17
Materials and Services - No O/H	$29,709.17	($32.87)
Computation Expense	$527.81	$0.00
Cost in Excess of Award Total	($10.20)	$342.59
TOTAL --->	$234,890.00	($0.00)

Customer No. 8600037345

Invoice No. 90257533

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Cambridge, Massachusetts 02139

FINAL

Forward to:
CASHIER'S OFFICE NE49-3077
77 Massachusetts Avenue
Cambridge, Mass 02139

DATE March 03, 2016

TO **NRAO Contracts and Procurement**
Attn: Richard Sakshaug
520 Edgemont Road
Charlottesville VA 22903

Make check payable to:
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
See reverse side for wire transfer instructions

For Billing Inquiries send e-mail to:
Billing-Issues@mit.edu

CONTRACT/GRANT NUMBER	CONTRACT/GRANT DATE	AUDIT VOUCHER NUMBER	FOR THE PERIOD	MIT PROJECT NUMBER	ESTIMATED COST
PO #342941		32	02/01/16 to 02/29/16	6927676	234,890.00

STATEMENT OF EXPENDITURE	CUMULATIVE	CURRENT
Salaries & Wages - Off Campus	108,047.49	1,466.60
1alaries & Wages - off No O/H	26,330.14	358.22
Employee Benefit Summary	36,241.75	439.98
Employee Benefits-No O/H	8,855.15	107.46
Indirect Expense Summary	7,334.13	104.64
Travel Expense Domestic	83.76	0.00
Travel Expense Foreign	8,082.54	0.00
Materials and Services	9,997.98	418.75
Materials and Services-No O/H	29,742.04	409.12
Computation Expense	527.81	0.00
Cost in Excess of Award Total	352.79-	352.79-
TOTAL	234,890.00	2,951.98

Z_SB_EXPENDITURE

4 Disposition of excess materiel

No deliverable materiel was purchased under the ADF award.

While it was initially the intention to transfer hardware procured and developed under the MRI award for NSF, at the conclusion of the effort it was determined that JAO has no established mechanism to own property separate from NRAO. NRAO already owned the PIC hardware; the maser and recorders were the property of MIT Haystack Observatory (the latter contributed by ASIAA); and the fiber optic links were the property of NAOJ.

While it is understood that ALMA is responsible for the maintenance and upkeep of these items and the spare components provided, as a matter of expediency, the ownership was retained by the contributing institutions.

Note that the recording media is not part of the instrumentation provided to ALMA, and will be the responsibility of the VLBI users.

5 Contract closure

The following document provides evidence of contract closure:

FW: WBS Element 6927676 – Financial Closeout Documents

Subject: FW: WBS Element 6927676 – Financial Closeout Documents
From: Melanie A Straight <mstrait@mit.edu>
Date: 5/12/2016 2:53 PM
To: "mstraight@haystack.mit.edu" <mstraight@haystack.mit.edu>

From: Jillian Moreira
Sent: Thursday, May 12, 2016 10:51 AM
To: kc-data
Cc: Courtney Bensey; Jennifer Thurow; Melanie A Straight
Subject: WBS Element 6927676 – Financial Closeout Documents

Hi Coeus Data Team,

Attached, please find the Financial Closeout Documents for WBS Element 6927676.

Feel free to contact me with any questions.

Best regards,
Jillian Moreira

Jillian Moreira | Staff Accountant | moreira@mit.edu
MIT Office of the Vice President for Finance | Sponsored Accounting
77 Massachusetts Ave, NE49-3000 Cambridge, MA 02139 | ph. 617-253-2797

Attachments:

Financial Closeout Documents - 6927676.pdf

FORM: VPF/OSP B

PROJECT AUTHORIZATION

VPF Administrator: Jillian Moreira

VPF Close-out of Children to Parent

OSP Administrator: Courtney L. Bensey

Massachusetts Institute of Technology
Office of Sponsored Programs

Final VPF Close-out of Parent/ Account
Increase or Reduction of Project

Account Number: 6927676

Parent Number: 0

Carryforward to/from **(circle one)** Account:

Change in Amount Obligated to Date: No Change $0.00

New Authorized Total: $234,890.00

Fiscal Comments: Close account per email from Jennifer Thurow

Put Account into Term Code 3: Yes

VPF Signature: Dale Turney

5/5/2016

May 6, 2016

National Radio Astronomy Observatory
ATTN: Richard Sakshaug
NRAO Contracts and Procurement
520 Edgemont Road
Charlottesville, VA 22903

MIT Reference: 6927676
Sponsor Reference: PO #342941
MIT PI: Sheperd Samuel Doeleman
Project Title: ALMA Phasing Projection Augmentation

Dear Richard Sakshaug:

VPF

Massachusetts Institute of Technology submits herewith, a Final Report of Expenditures for the period of March 4, 2013 through March 3, 2016. Also enclosed is one (1) outstanding invoice in the amount of $2,951.98. We trust this will facilitate a prompt remittance.

Please feel free to contact the undersigned at 617-253-2496 or by e-mail at dalet@mit.edu if further information is required.

Thank you for your interest in and support of this Research Project.

Sincerely,

Dale Twomey

Dale Twomey
Assistant Manager

Enclosures

Cc:
OSP Administrator: Courtney L Bensey
Administrative Officer: Melanie A. Straight

6 Anticipated Risks

Since the APP effort is complete, all development risks have been retired.

The following list describes potential risks ALMA may face in its utilization of the phasing capability and the upkeep of the equipment and software:

Risk 1: Future modifications to the ALMA software configuration may "break" the phasing code. While regression testing will reveal such problems, the risk is associated with ALMA staff possessing the insight and documentation to fix it. Similar concerns apply to provided hardware:

> *Mitigation:* In addition to extensive documentation, the APP provided (and are continuing to provide) both support and spares. Key hardware components have service contracts or warranties. Current ALMA software personnel have the know-how to repair failures that might occur due to change in software context.

Risk 2: The hydrogen maser, now the primary source for ALMA timing signals, represents a single point of failure, and it is too expensive to justify maintaining a spare. In particular, unless manually shut down, the maser could be damage by an extended loss of power that exceeds the capacity of the battery backup.

> *Mitigation:* The maser is backed by the highest-level service contract offered by the manufacturer. In the event of service interruption, the Rb clock that was previously used as a timing source can be quickly swapped in to replace the maser. Note that the phasing system itself does not require the maser to operate, though the precise timing it offers is essential for the subsequent VLBI correlation. Other uses of the phased signal would still be possible with the Rb clock. ALMA is encouraged to (a) maintain the Rb clock as a backup, and (b) enhance the battery backup as possible with an emergency power system, fuel cell, or other advanced backup capability as the technology becomes available.

7 Lessons learned

While APP encountered a few unexpected technical problems, notably the need for a significant delay correction, the implementation proceeded relatively smoothly. The single largest deviation from plan was a substantial schedule slip derived from the need to mesh software and commissioning activities with the ALMA schedule; This required no-cost extensions to both the MRI and ADF awards.

Overall, the JAO and NRAO staff supporting the APP effort were technically superb and generally responsive except in rare cases where higher priority responsibilities intervened. ALMA is, however, a large endeavor, and a few Lessons Learned may deserve future attention:

- **Visibility into ALMA documentation:** The general instruction to satisfy all ALMA requirements was unrealizable without examining every document in the vast ALMA archive. In the end, APP identified a set of core requirement documents to itemize. For other requirements areas (e.g. electrical codes), APP requested a professional inspection in lieu of a requirement validation process. This strategy proved to be satisfactory.
    - *Recommendation:* Consider investing in an effective index into ALMA documentation. With respect to requirements in particular, a process of expert inspection to complement the compliance matrix would be helpful to future projects.
- **Legacy documentation:** Despite (or possibly because of!) the extensive document archive, certain characteristics of the ALMA design from the development period were not well understood and had to be discovered empirically. A notable example for APP was the larger-than-expected residual delay.
    - *Recommendation:* Consider consolidating, updating, and reviewing key design documentation.
- **Commissioning and observing time:** As part of the ALMA approval for APP to proceed, it was explicitly stated that phased science observing (specifically Sgr A* and M87 VLBI) could only be done through open competition in the cycle following completion and acceptance of the capability. The APP team, while understandably disappointed, complied rigorously with the policy. But we respectfully suggest that the flexibility to offer discretionary observing time could accelerate the pace of scientific discovery and help attract future large external investments.
    - *Recommendation:* Consider reviewing the policies regarding science utilization of new capabilities.
- **Ticket closure:** Overall, the JIRA ticketing system was an effective way to track tasks. For various reasons having to do with availability of staff rather than technical completion, it proved difficult to close certain tickets. This added unnecessary complexity to the acceptance process.
    - *Recommendation:* Consider a mechanism to purge or force closure of inactive tickets.

8 Disposition of Project Records

All APP documents addressing the design, implementation, and utilization of the phasing capability have been archived in the ALMA document library as specified in 2015-07-15 - ALMA-05.11.00.52-0003-A-LIS - APP CIDL. A concise list appears on the following pages. Phasing software is separately documented under the ALMA software acceptance process.

*	Description	Type	File Name	Date	Document Number	EDM Status	Comment
	CIDL	LIS	APP_CIDL_10DEC14.xlsx	12/10/14		Draft	
	Verification Plan and Matrix	PLA	APP_rqmts_verification_ plan_3DEC2014.docx	12/3/14		Draft	
	Compliance Matrix	PLA	APP AcRV_Compliance_Matrix_04DEC14.xlsx	12/4/14		Draft	Extracteed from Verification Matrices for review purposes only
	Acceptance Review Plan	PLA	2014-12-05 - ALMA-05.11.00.52-0001-A-PLA - APP_HW_AcceptanceReview_Plan_signedNW_signedBLO.pdf	12/5/14	ALMA-05.11.00.52-0001-A-PLA	Draft	
	System Level						
X	APP Integration and Test Plan	PLA	APP I&T Plan V2.2 08APR14	4/8/14		N/A	
	ALMA Memo 584	ALMA Memo	ALMA Memo 584.pdf	11/19/08	584	Released	IN EDM - RELEASED
X	Interface Control Document Between ALMA Phasing Project and ALMA Site	ICD	2014-10-14 - ALMA-05.11.10.00-20.00.00.00-A-ICD - ICD APP and ALMA Site.pdf	8/9/13	ALMA-05.11.10.00-20.00.00.00-A-ICD	OK to release	IN EDM - DRAFT
X	Interface Control Document Between ALMA Phasing Project and ALMA Backend	ICD	2014-12-01 - ALMA-05.11.10.00-50.00.00.00-A-ICD - ICD APP and ALMA BE.pdf	10/7/14	ALMA-05.11.10.00-50.00.00.00-A-ICD	OK to release	IN EDM - RELEASED
X	Interface Control Document Between ALMA Phasing Project and ALMA Correlator	ICD	2014-10-08 - ALMA-05.11.10.00-60.00.00.00-A-ICD - ICD APP and CORR.pdf	10/8/14	ALMA-05.11.10.00-60.00.00.00-A-ICD	OK to release	IN EDM - DRAFT
X	Interface Control Document Between ALMA Phasing Project and ALMA Computing	ICD	2014-09-29 - ALMA-05.11.00.00-70.35.25.00-A-ICD - ICD APP and COMP	10/7/14	ALMA-05.11.00.00-70.35.25.00-A-ICD	OK to release	IN EDM - RELEASED
	Transportation Plan	PLA	2013-06-04 - ALMA-05.11.10.01-0004-A-PLA - ALMA Phasing Project Transportation Plan MH.pdf	6/4/13	ALMA-05.11.10.01.0004-A.2-PLA	Released	IN EDM - RELEASED
X	Hazard Analysis and Safety Compliance Plan	PLA	ALMA-05.11.10.01-0003-A.2-PLA.pdf	5/17/13	ALMA-05.11.10.01-0003-A.4-PLA	Released	IN EDM - RELEASED
X	Product Assurance Plan	PLA	2013-05-17-ALMA-05.11.10.01.0002-A-PLA-ALMA Phasing Project Product Assurance Plan MH.pdf	5/17/13	ALMA-05.11.10.01.0002-A-PLA	Released	IN EDM - RELEASED
X	ALMA Phasing Project Reliability and Maintainability Report	REP	2013 May 17 Reliability ALMA-05.11.10.03-0002-A.4-REP.pdf	5/17/13	ALMA-05.11.10.03-0002-A-REP	OK to release	IN EDM - RELEASED
X	APP Failure Modes and Effects	GEN	ALMA-05.11.10.00-001-A-GEN APP Failure Modes and Effects	5/11/10	ALMA-05.11.10.00-001-A-GEN	OK to release	IN EDM - RELEASED
	ALMA Phasing Project Maintenance Manual	MAN	2014-12-08-ALMA-05.11.10.05-0001-A-MAN.pdf	12/8/14	ALMA-05.11.10.05-0001-A-MAN	Draft	IN EDM - NEEDS SIGNATURE MATRIX
	ALMA Phasing Project System Level BOM	BOM	2014-11-26 - ALMA-05.11.10.12-0001-A-BOM - APP Syst Level BOM.doc	11/26/14	ALMA-05.11.10.12-0001-A-BOM	OK to release	IN EDM - DRAFT
	APP Update to Corr/Control Design	DSN	ALMA-05.11.61.01-001-A-DSN.pdf	5/16/13	ALMA-05.11.61.01-001-A-DSN	**Released**	IN EDM - RELEASED
	APP Mark6 Recorder/OFLS PAI Test Report	REP	ALMA-05.11.40.03-0001-A-REP.pdf	11/24/14	ALMA-05.11.40.03-0001-A-REP	OK to release	IN EDM - DRAFT
	APP Mark6/OFLS/PIC Acceptance Report	REP	ALMA-05.11.50.03-0001-A-REP.pdf	11/30/14	ALMA-05.11.50.03-0001-A-REP	OK to release	IN EDM - DRAFT
	APP Certificate of Compliance	GEN	2014DEC02 ALMA-05.11.00.06-0001-A-GEN.pdf	12/2/14	ALMA-05.11.00.06-0001-A-GEN	OK to release	IN EDM - DRAFT
	APP Tests on Absolute Timing	REP	ALMA-05.11.61.03-0001-A-REP.pdf	12/1/14	ALMA-05.11.61.03-0001-A-REP	OK to release	IN EDM - DRAFT
	Workmanship inspection report	REP	2014-12-04 - ALMA-05.11.10.90-0001-A-REP - APP Hardware Workmanship Inspection Report.docx	12/4/14	ALMA-05.11.10.90-0001-A-REP	Draft	IN EDM - DRAFT
	APP VLBI Operation Manual		To be compiled from low-level manuals				
	Recorder						

X	Mark6 Recorder command set	MAN	Mark6_command_set-Release1.1	10/10/14		Draft	
	Mark6 Recorder Test procedures	PRO	ALMA-05.11.50.02-0002-A-PRO.pdf	11/18/14	ALMA-05.11.50.02-0001-A-PRO	OK to release	IN EDM - DRAFT
	APP Mark6 Recorder Module Test Report	REP	ALMA-05.11.53.03-0001-A-REP.pdf	11/21/14	ALMA-05.11.53.03-0001-A-REP	OK to release	IN EDM - DRAFT
	Mark6 Reliability and Power Requirements Study	MEMO	Mark6_memo_006.pdf	11/24/14		N/A	
	Getting Started with your Mark6	MAN	Getting_started_with_your_Mark_6-1.01.pdf	11/20/13		Draft	
	Mark6 Users Guide	MAN	M6_Users_manual-Release-1.0.pdf	11/19/13		Draft	
	Mark6 Usage Examples	MAN	Mark6_usage_example-Release-1.0.pdf	11/14/13		Draft	
	Mark6 Maintenance manual	MAN	Mark6_Maintenance_Manual_memo_007.pdf	12/10/14		OK to release	
	Certificates of Conformance		See Summary of Properties memo				
	MTBF and reliability studies		See Summary of Properties memo				
	Optical Fiber Link System						
	Optical Fiber Link System Prototype Test Report	REP	ALMA-05.11.40.03-0002-A-REP.pdf	4/24/13	ALMA-05.11.40.03-0002-A-REP	OK to release	IN EDM - DRAFT
	Optical Fiber Link Installation and Test Report	REP	ALMA-05.11.40.03-0003-A-REP.pdf	12/4/14	ALMA-05.11.40.03-0003-A-REP	OK to release	IN EDM - DRAFT
	OFL System Design	DSN	ALMA-05.11.40.01-0001-A-DSN.pdf	4/24/13	ALMA-05.11.40.01-0001-A-DSN	OK to release	IN EDM - DRAFT
	Operation manual	MAN	OFL_operation_manual.pdf	12/4/14	ALMA-05.11.40.05-0001-A-MAN	OK to release	IN EDM - DRAFT
	Maintenance manual	MAN	OFL_maintenance_manual.pdf	12/2/14	ALMA-05.11.40.05-0002-A-MAN	OK to release	IN EDM - DRAFT
	Bill of Materials		See system Design Report				
	Drawings		N/A - COTS				
	CAD files		N/A - COTS				
	Startup, shutdown, and monitoring procedures		See Operation Manual				
	Manufacturers' Manuals		N/A (Have Japanese version)				
	Manufacturer's test reports		N/A				
	Certificates of Conformance		N/A				
	Analyses		N/A				
	MTBF and reliability studies		See OFL System Design, System Reliability manual				
	Correlator Upgrades (General)						
	APP Correlator Modification Description	REP	APP_Correlator_mods_V1.0_26APR13.pdf		ALMA-05.11.30.03-0003-A-REP	OK to release	IN EDM - DRAFT
	Upgrade plan to add PIC and 1-PPS distributor to 64-stn Correlator	PLA	2012-05-30 - DA48 OSF Signal Path Connectivity Test Data Report.pdf	4/9/14	CORL-05.11.00.01-0001-A-PLA	Released	
	Sum Data LVDS Cable List	LIS	2013-12-13-PIC_Sequence_Nrs_short.xls	12/13/13	ALMA-05.11.30.03-0004-A-LIS	OK to release	IN EDM - DRAFT
	Miscellaneous Cables List	LIS	2014-06-06-NRAO_APP_Misc_Cables.xlsx	6/6/14	ALMA-05.11.30.03-0005-A-LIS	OK to release	IN EDM - DRAFT
	Symmetricon GPS Inspection Report	REP	2013SEP12 ALMA-05.11.35.91-0001-A-REP.pdf	9/12/13	ALMA-05.11.35.91-0001-A-REP	OK to release	IN EDM - RELEASED
	APP Correlator Upgrades Acceptance Report	REP	2014-11-24-ALMA-05.11.30.03-0001-A-REP.doc	11/24/14	ALMA-05.11.30.03-0001-A-REP	OK to release	IN EDM - DRAFT
	Correlator Upgrades PAI Test Report	REP	2014-11-25-ALMA-05.11.30.03-0002-A-REP.doc	11/25/14	ALMA-05.11.30.03-0002-A-REP	OK to release	IN EDM - DRAFT
	Correlator Upgrades Manual	MAN	2014-12-05-ALMA-05.11.31.05-0001-A-MAN.pdf	12/5/14	ALMA-05.11.31.05-0001-A-MAN	OK to release	IN EDM - DRAFT
	Correlator Upgrades Maintenance Manual	MAN	2014-12-01-ALMA-05.11.30.05-0001-A-MAN.pdf	12/1/14	ALMA-05.11.30.05-0001-A-MAN	OK to release	

	Symmetricon GPS Manual	MAN	GPSManual.pdf	9/1/10		N/A	
	Report on Detection and Correction of Radiation Induced Events in Integrated Circuits of the ALMA Correlator High Site (updated)	REP	CR_Correlator_Nov2014.pdf	11/27/14		N/A	
	PAS Test Report		ALMA Inspection only, see Acceptance RD07/RD09				
	Phasing Interface Card Assembly						
	PIC Assembly Bill of Materials	BOM	ALMA-05.11.34.12-0001-A-BOM .xlsx	11/16/14	ALMA-05.11.31.12-A-0001-BOM	OK to release	IN EDM - DRAFT
	PIC Assembly Misc Cables	DWG	2013-04-22-ALMA-05.11.31.11-0004-A-DWG.pdf	4/22/13	ALMA-05.11.31.11-0004-A-DWG	OK to release	IN EDM - RELEASED
	PIC Assembly Check-out Logs	REP	PICLog.xls	11/16/14	ALMA-05.11.31.03-0001-A-REP	OK to release	IN EDM - DRAFT
	Inspection Reports	REP	2013 Apr 4 ALMA-05.11.31.91.0001-B-REP 2013 Apr 4 ALMA-05.11.31.91.0002-A-REP ... 2013 Apr 4 ALMA-05.11.31.91.0008-A-REP	4/4/13	ALMA-05.11.31.91.0001-B-REP ALMA-05.11.31.91.0002-A-REP ... ALMA-05.11.31.91.0008-A-REP	OK to release	IN EDM - RELEASED
	Maintenance manual	MAN	See Correlator Upgrades Maintenance Manual				
	Phasing Interface Card Manual	MAN	Included in Correlator upgrades manual		See ALMA-05.11.31.05-0001-A-MAN		
	Installation procedures		See *Maintenance Manual*				
	Test procedures		See *Correlator Upgrades PAI Test Report* and *APP Correlator Upgrades Acceptance Report*				
	Startup, shutdown, and monitoring procedures		See *Maintenance Manual*				
	Operation manual		N/A				
	Manufacturers' Manuals		See GPS manual (at ALMA on CD)				
	Test data report		See *Correlator Upgrades PAI Test Report; APP Correlator Upgrades Acceptance Report; PIC Assembly Check-out Logs*				
	MTBF and reliability studies		See *Reliability and Maintainability* report				
	Phasing Interface Card (PIC)						
	PIC Bill of Materials	BOM	2013-04-22-ALMA-05.11.31.12-0002-A-BOM.xls	4/22/13	ALMA-05.11.31.12-A-0002-BOM	OK to release	IN EDM - DRAFT
	PIC Assembly Block Diagram	DWG	2013-04-22-ALMA-05.11.31.11-0001-A-DWG.pdf	4/22/13	ALMA-05.11.31.11-0001-A-DWG	OK to release	IN EDM - RELEASED
	PIC Schematic	DWG	2013-04-22-ALMA-05.11.31.11-0002-A-DWG.pdf	4/22/13	ALMA-05.11.31.11-0002-A-DWG	OK to release	IN EDM - RELEASED
	PIC PCB Files	DWG	2014 Sep 23 ALMA-05.11.31.11-0005-B-DWG.pdf	9/23/14	ALMA-05.11.31.11-0005-B-DWG	OK to release	IN EDM - RELEASED
	PIC PCB Files, manufacturing files	DWG	ALMA-05 11 31 11-0005-B-DWG.zip	4/10/13	*ALMA-05.11.31.11-0005-B-DWG*	OK to release	ATTACHED
	ROACH FPGA Requirements and Specifications	SPE	2013-04-10-ALMA-05.11.31.15-0002-A-SPE.pdf	4/10/13	ALMA-05.11.31.15-0002-A-SPE	OK to release	IN EDM - DRAFT
X	Interface Control Document Between C167 Microprocessor and ROACH2 FPGA	ICD	2014-10-16-ALMA-05.11.10.49-0005-A-ICD	10/16/14	ALMA-05.11.10.49-0005-B-ICD	OK to release	IN EDM - RELEASED
	ZDOK to QXH Adapter						

	PIC Assembly ZDOK to QXH Adapter BOM and Assembly	BOM	2013apr22 ALMA-05.11.31.12-A-0003-BOM .pdf	4/22/13	ALMA-05.11.31.12-0003-A-BOM	OK to release	IN EDM - DRAFT
	PIC Assembly ZDOK to QXH Adapter Sche	DWG	2013-04-22-ALMA-05.11.31.11-0003-A-DWG.pdf	4/22/13	ALMA-05.11.31.11-0003-A-DWG	OK to release	IN EDM - RELEASED
	PIC Assembly ZDOK to QXH Adapter PCB	DWG	2013 apr 22 ALMA-05.11.31.11-0006-A-DWG.pdf	4/22/13	ALMA-05.11.31.11-0006-A-DWG	OK to release	IN EDM - RELEASED
	PIC Assembly ZDOK to QXH Adapter PCB Manufacturing Files	DWG	ALMA-05.11.31.11-0006-A-DWG.ZIP	2/15/13	*ALMA-05.11.31.11-0006-A-DWG*	OK to release	ATTACHED
	TTL to LVDS Converter Card (TLC)						
	TLC BOM	BOM	2014-09-30 - ALMA-05.11.35.12-0001-A-BOM - TLL-LVDS BOM.pdf	9/30/14	ALMA-05.11.35.12-0001-A-BOM	OK to release	IN EDM - DRAFT
	PCB Files and Spec for Fab	DWG	2014Sep30 ALMA-05.11.35.11-0002-A-DWG.pdf	9/30/14	ALMA-05.11.35.11-0002-A-DWG	OK to release	IN EDM - RELEASED
	Schematic	DWG	2014Sep30 ALMA-05.11.35.11-0001-A-DWG.pdf	9/30/14	ALMA-05.11.35.11-0001-A-DWG	OK to release	IN EDM - RELEASED
	PCB artwork files	DWG	2014Mar21 ALMA-05.11.35.11-0002-A-DWG.zip	3/21/14	*ALMA-05.11.35.11-0002-A-DWG*	OK to release	ATTACHED
	Power						
	ATX Power Supply BOM	BOM	2013-04-26-ALMA-05.11.31.12-0001-A-BOM.xls	4/26/13	ALMA-05.11.34.12-0001-A-BOM	OK to release	IN EDM - DRAFT
	Mechanical						
	ATX Brackets	DWG	ALMA-05.11.34.11-0002-A-DWG.pdf	6/24/13	ALMA-05.11.34.11-0002-A-DWG	OK to release	IN EDM - RELEASED
	ATX PSU Panel	DWG	ALMA-05.11.34.11-0003-A-DWG.pdf	6/24/13	ALMA-05.11.34.11-0003-A-DWG	OK to release	IN EDM - RELEASED
	TLC Panel	DWG	ALMA-05.11.34.11-0005-A-DWG.pdf	5/15/14	ALMA-05.11.34.11-0005-A-DWG	OK to release	IN EDM - RELEASED
	Bin Fiber Support	DWG	ALMA-05.11.34.11-0004-A-DWG.pdf	8/8/13	ALMA-05.11.34.11-0004-A-DWG	OK to release	IN EDM - RELEASED
	Test Fixture						
	Test Fixture Black Hole System Diagram	DWG	picsystemdiagram.pdf	4/11/14		N/A	
	Other relevant documents						
X	CDR Final Report	REP	2013-06-19 - ALMA-05 11 10 03-004-A-REP - ALMA APP Critical Design Review Final Report.pdf	6/19/13	ALMA-05 11 10 03-004-A-REP	Released	IN EDM - RELEASED

	Other material available for review on demand						
X	Configuration summary		APP Workbook				
	Material to be delivered or discussed at Acceptance Review						
na	*Training requirements and plan*		TBD				
na	*Training materials*		TBD				
na	*Hazard Analysis, including electrical*		TBD				
	Known or suspected Liens						
	Mark6 Maintenance Manual						
	Mark6 s/w release 1.2						
	cables I,j on quadrant 4 polarization y						
	maser - gps cable swap to distributor?						
	anything TBD from verification matrix						

9 Attachment 1: Phasing ALMA

Matias Mora ; Geoffrey Crew ; Helge Rottmann and Lynn Matthews
" Phasing up ALMA ", *Proc. SPIE* 9152, Software and Cyberinfrastructure for Astronomy III, 915219 (July 18, 2014); doi:10.1117/12.2057053; http://dx.doi.org/10.1117/12.2057053

Phasing up ALMA

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ABSTRACT

With the completion of the ALMA array, Development Projects are being initiated to expand the observatory's technical capabilities. The ALMA Phasing Project is one of the early ones, with the main goal of adding Very Long Baseline Interferometry (VLBI) observation capabilities. This will enable ALMA to join observations with other millimeter observatories having VLBI data capabilities around the globe. ALMA would therefore become the most powerful millimeter VLBI station yet.

A minimal impact approach has been taken to cause as little overall work overhead at the observatory as possible and integrate seamlessly with existing infrastructure. New hardware elements and software features are being delivered in incremental cycles to the observatory, adhering to existing workflows.

This paper addresses one of the main software challenges of this project and its implementation: the continuous phasing corrections of the ALMA antenna signals. As antenna signals are summed during the online processing for correlation after the observation, a phased array is a key requirement for successful VLBI observations. A new observing mode that inherits all of the existing interferometry functionality is the cornerstone of this development. Further additions include new correlator protocols to modify the data flow, new VLBI specific device controllers, online phase solvers and observation metadata adaptations. All of these are being added to existing ALMA Software subsystems, taking advantage of the modular design and reusing as much code as possible.

The design has included a strong focus on simulation capabilities to verify as much of the functionality as possible without the need for sparse telescope time. The first on-site tests of the phasing loop using the ALMA baseline correlator and antennas were performed in early 2014, and the hardware is expected to be completely installed by the middle of the same year.

Keywords: software engineering; software design scalability; radio-antennas array; very long baseline interferometry; phasing algorithms

1. INTRODUCTION: THE ALMA PHASING PROJECT

The Atacama Large Millimeter/submillimeter Array (ALMA) is the largest ground-based astronomy facility to date. ALMA consists of 66 antennas located on the Chajnantor plateau in northern Chile. The antennas are located at 5000m altitude at the Array Operations Site (AOS), while science operations and data storage are placed at 3000m at the Operations Support Facility (OSF). The array was designed to operate in configurations of one or more subarrays of antennas and to correlate their signals in the FXF baseline correlator. At the same time the correlator design left the open possibility to be extended to incorporate online phasing of antenna signals and their combination into a coherent sum, while still computing the usual correlation of signals. This coherent sum may then be recorded and delivered to a VLBI correlator (in fact, a DiFX correlator [1]) for processing in concert with the signals from other millimeter and sub-millimeter telescopes distributed throughout the globe.

Timing precision and stability are vital requirements for all VLBI stations; therefore the existing time reference will need to be replaced. Another essential requirement is the online phase adjustment of signals from

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the individual antennas to produce a coherent sum, effectively allowing the entire collecting area of ALMA to function as a single large aperture.

An international consortium is currently working in the context of an ALMA Development Project to implement this capability and turn ALMA into the most sensitive millimeter VLBI station yet. The ALMA Phasing Project (APP) will open up a broad variety of science cases, which are introduced in [2].

While the project implementation touches on many different components of the ALMA system, as briefly reviewed in Section 2, this paper will focus on the phasing loop. The adaptation of the correlator hardware to support the phasing mode and add a VLBI formatting backend was presented in [3]; and the initial concepts of the phasing system were described in [4]. We will present the software design that introduces a new VLBI Observing Mode and other elements of the phasing system throughout multiple subsystems (Sections 3, 4 and 5). The actual implementation is being delivered in incremental releases to the observatory as described in Section 6. Finally, Section 7 presents the first preliminary results on the main ALMA array.

2. APP SYSTEM DESIGN

The latest ALMA Phasing Project system block diagram is shown in Figure 1. It divides the system into three main sections: (1) the high precision timing reference (Maser); (2) the phasing system; and (3) the VLBI data backend.

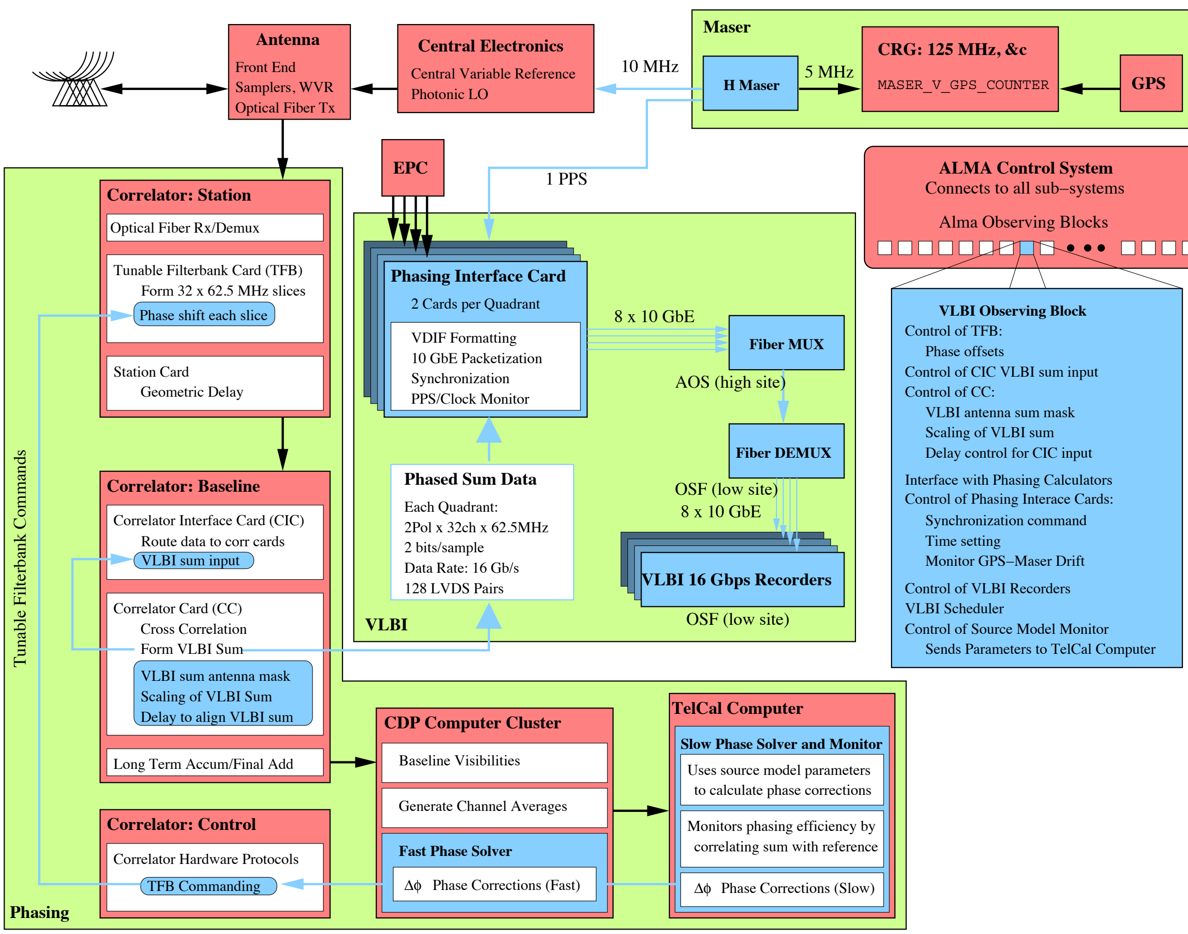

Figure 1. ALMA Phasing Project system block diagram. This shows how the existing ALMA system is being modified by the APP. Objects in pink currently exist, objects in blue are new, and the green backgrounds group related components of the system. *(source: [5])*

New hardware devices are being delivered as part of the project: a Hydrogen Maser that will replace ALMA's current $5MHz$ Rubidium time reference; one Phasing Interface Card (PIC) per baseband and per polarization (8 in total) to format and timestamp the data for VLBI purposes; fiber (de)multiplexer units to send the eight $10GbE$ data streams from the correlator at the AOS to the storage system at the OSF; and four Mark6 VLBI recorder units to record the output data at $16Gbps$ per baseband. In addition some existing cards in the correlator have been adapted to support the phasing system. Specifically, the Correlator Cards now have a special mode to compute the sum of an arbitrary group of antennas and to feed the result back into the Correlator Interface Cards, while at the same time passing it on to the corresponding PIC. In this mode the sum signal effectively replaces an antenna signal by turning a switch for one specific antenna input*. The phase adjustments are done through registers in the existing Tunable Filter Banks (TFB), which provide a way to offset the phase on 32 sub-bands of $62.5MHz$ bandwidth each with a precision of 1/4096 of a 360° turn.

The VLBI data generated by ALMA have to match the data produced at other VLBI stations. Traditionally the latter have used spectral channels with frequency widths different from those that ALMA uses for its sub-bands. Therefore the subdivision of ALMA's $2GHz$ bandwidth into spectral windows must be done with VLBI requirements in mind. This typically results in some loss of bandwidth as a reasonable compromise to a common VLBI tuning at all observatories.

The VLBI Observing Mode software component acts as the glue for the entire system. It commands and monitors new devices, coordinates the phasing loop and operates the recorders. Phasing corrections are separated into two time scales: *slow* (results applied on the order of once every 10 seconds) and *fast* (on the order of once per second). The slow loop processes the channel averaged signal to determine phase corrections relative to a reference antenna. The fast loop compensates for delays measured by water vapor radiometers (WVR) installed on each antenna. In both loops phase offsets are sent to the Correlator Control Computer, which applies the cumulative phase on the TFBs for the next processing round. A more detailed outline of the phasing loop will be presented in Section 3.

The data output of a VLBI observation consists of two main parts: (1) the regular ALMA data and metadata stored normally in the ALMA Archive; and (2) the summed signals that were captured by the VLBI Recorders. The ALMA Archive data can provide valuable calibration and other information about the VLBI observation, such as characterizing the phasing system performance, and eventually be processed as regular data for non-VLBI science purposes. Note that as a consequence of the summed signals being fed back into the correlation, this data will also form part of the ALMA Archive data.

3. VLBI OBSERVING MODE AND THE PHASING LOOPS

The ALMA online software architecture features a number of subsystems running on top of a distributed control framework [6]. Most notably of our interest: Scheduling subsystem (handles antenna arrays and executes scheduling block queues); Control (controls antenna, centralized timing and frequency oscillator instruments and implements higher level observing modes); Correlator† (controls the correlator hardware and processes/formats its output); and Telescope Calibration (TelCal, produces online calibration results). The end-to-end ALMA Software can be used in a fully simulated mode, which is based on low-level hardware communication simulators in the Control and Correlator subsystems [7,8]. Therefore the entire system can be exercised before being integrated with the actual hardware and delivered to the observatory.

All of the APP online software was designed to fit inside existing software subsystems. The general APP software interaction diagram is shown in Figure 2, with the VLBI Observing Mode as a centerpiece. The observation starts with the PI's planning at the top of the figure. A VLBI observing run is typically broken into several sessions of approximately 12 hours duration. Each such session is described by a VLBI Experiment (VEX) file, which is common for all involved VLBI stations and provides a UTC time tagged schedule that all agree to execute. ALMA is commanded through observation scripts, embedded in scheduling blocks; a utility to convert VEX files to a regular ALMA input is provided within the scope of the APP.

*We will hereafter use "sum antenna" to refer to the coherent sum that is returned into the Correlator Interface Cards, replacing an actual antenna input.

†We will hereafter refer to the software subsystem as "Correlator", while using lower case "correlator" for the actual hardware correlator.

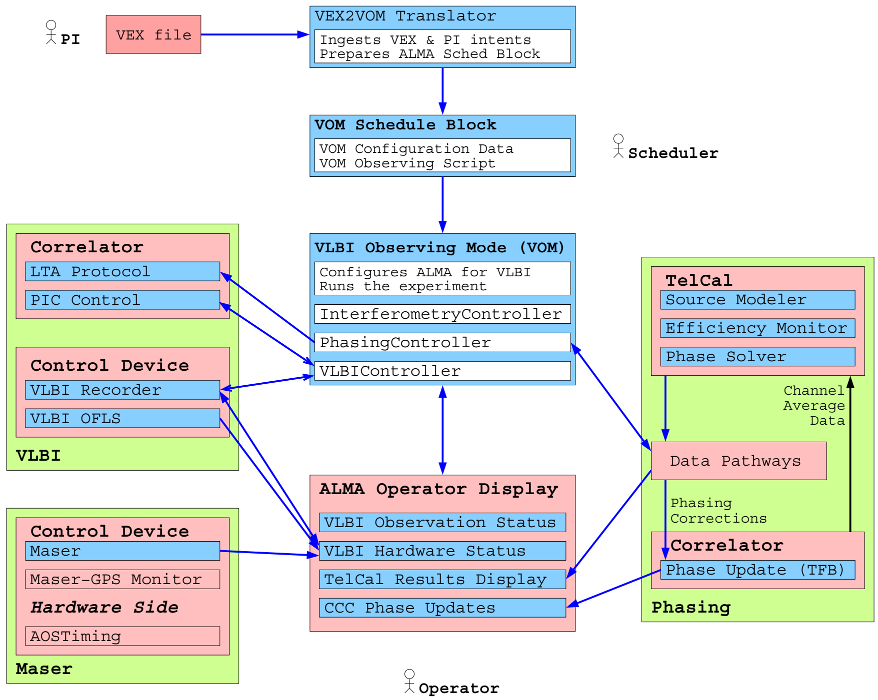

Figure 2. ALMA Phasing Project software interactions diagram. This shows the new software components added by the APP. Objects in pink currently exist, objects in blue are new, and the green backgrounds group related components of the system.

A simplified view of the phasing loop, centered on the involved software pieces is shown in Figure 3. The data stream from the antennas enters the correlator, where the sum is calculated and fed back into the Correlator Interface Cards, where the baseline product for all inputs is calculated. The correlator output is processed by the Correlator Data Processor cluster and further sent out to the Archive and the TelCal subsystem. TelCal calculates the phase results based on the received data and sends the results to Control. From there corresponding phase adjustments can be commanded back to the Correlator Control Computer and applied to the TFB cards. At the same time fast phase corrections calculated by the Correlator Data Processor cluster are being applied.

A VLBI session is divided into several VLBI scans, while ALMA operates on its own scan sequences and sub-scan sequences. For the APP it is of interest to record data continuously during a VLBI scan, while simultaneously getting phase results from TelCal in regular intervals for the slow phasing loop. Since TelCal calculates results once per scan and Correlator outputs data on a sub-scan basis, a decision was made to represent a VLBI scan as an ALMA scan-sequence, with each scan containing one single sub-scan. Figure 4 shows a timeline with the aforementioned scan concepts and phase correction paths. Both the slow and fast phasing loop results are applied within sub-scans. VLBI data flowing from the correlator through the PICs are continuous, only disrupted by punctual phase jumps corresponding to phase application times. Note that once the system is *phased-up*, all of these corrections should be relatively small ones.

The Control subsystem implements observing modes for distinct types of observations, most notably Single Dish Observing Mode and Interferometry Observing Mode (IOM). It was identified early on that VLBI observations can essentially be carried out with the IOM functionality, plus a limited amount of modifications, most notably:

- Observations start on a predefined UTC time (the same for all VLBI stations).
- The *sum antenna* signal is represented as a fake antenna that only exists at the correlator level as a signal input. It must be given special handling, since there are no other controls or data associated with it that

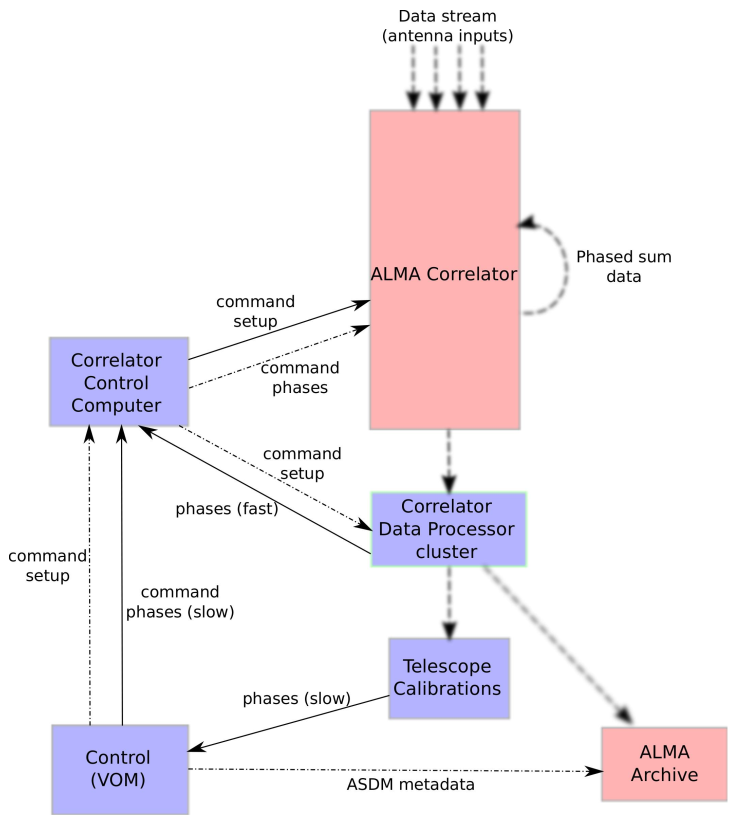

Figure 3. Simplified view of the phasing loops, based on Figure 1. Software elements are shown in blue. Bold/segmented arrows represent the binary data stream from the antennas to TelCal and the ALMA Archive; other arrows represent control data and commands.

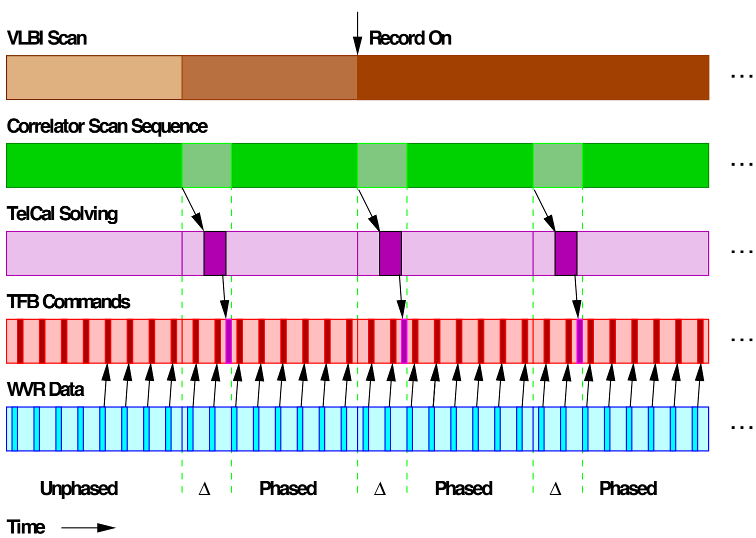

Figure 4. Scans in the phasing system. Each VLBI scan is partitioned into ALMA scans for correlation and *slow* timescale processing in TelCal. Water vapor phase adjustments are calculated by the Correlator software and applied on a *fast* timescale within ALMA scans.

the rest of the system expects. The output data of the sum signal must be associated in the metadata to an arbitrary antenna (not in the array), located close to the array center and flagged as "sum antenna".

- The phasing loop must be controlled, i.e. results must be received from TelCal and adjustments commanded to Correlator on a per scan basis.
- The VLBI backend (i.e. PICs and recorders) must be commanded accordingly on a per VLBI-scan basis.

As a coordinating centerpiece for VLBI observations the VLBI Observing Mode (VOM) has been added to the Control subsystem. It is an extension of the existing IOM, inheriting all of its interfaces and implementations, while adding the above described functionality (see Figure 5). The VOM is effectively initiating the phasing system, as configured by the observation script, by commanding both TelCal (Section 4) and Correlator (Section 5) to start the corresponding processes. To provide certain domain modularity the VOM delegates most of its additions to two new controller modules: the Phasing Controller, in charge of coordinating the phasing loop; and the VLBI Controller, in charge of commanding VLBI devices. This separation allows optionally running observations with or without phasing, and with or without VLBI data recording (e.g. for unphased single-dish recording).

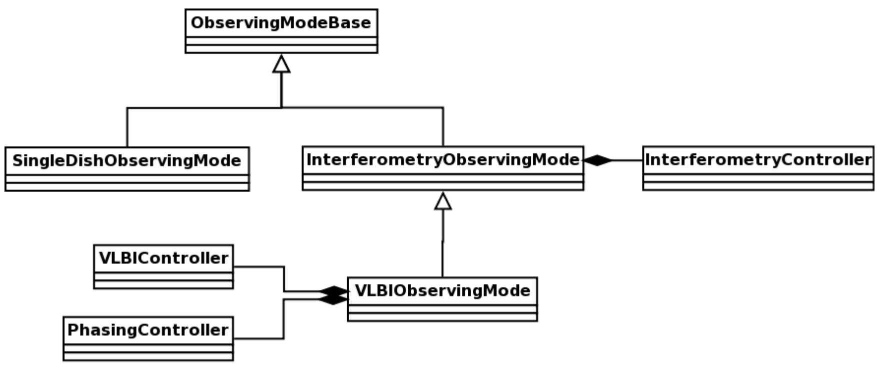

Figure 5. Observing modes class hierarchy. The VLBI Observing Mode adds a new layer of specialization through the VLBI Controller and Phasing Controller, while inheriting all functionality from the Interferometry Observing Mode.

The Phasing Controller has certain dynamic control over the following antenna sub-groups of the main array, based on measured phasing performance (see Section 4 for details on how these are used in TelCal):

- Phased Array: The subset of the array which is included in the sum and will receive phase corrections. Commanded as an antenna mask to the Correlator Cards.
- Reference Antenna: A member of the phased array which is used to fix the array phase by being assigned zero phase in the solution. Preferentially it should be close to the geometric array center.
- Comparison Array: Antennas not included in the phased array which may be used to calculate the efficiency of the phased sum by analyzing their individual cross-correlations with the sum antenna signal. In a perfectly phased system, this correlation amplitude scales as the square-root of the number of antennas in the phased array; in an unphased system, it is comparable to any single antenna; and otherwise, it is somewhere in between.

4. TELESCOPE CALIBRATION

Calibrations in the ALMA Software are performed by the Telescope Calibration (TelCal) software subsystem. The particular data calibration process(es) depend on the calibration intent commanded as part of the observation specifications. For phasing purposes new calibration intents specify what type of phase calculation is needed, which are then produced by a new calibration engine. One intent (*active*) indicates that the object being observed is bright enough to solve for the phases between antennas. The other (*passive*) indicates that no useful phase solution is likely to result from a fainter object, and therefore the phases previously obtained on a strong calibrator source should be used.

The data input to TelCal are channel averages of the spectral data. These will have been defined in the spectral specification for the ALMA observation which will itself have been constructed from the VEX file for the entire observation. The latter defines a number of VLBI channels which must overlap at all stations so that the VLBI correlation can be made between stations (see Section 2). For ALMA this means that the (up to 32) channel averages TelCal sees may not be optimal for the phase solution if the source is not bright enough. Thus TelCal may be instructed to further average these data prior to solving for the phases.

In any case, the calculation is a least-square phase solution for per antenna phases using the measured baseline phases. Prior to solving, any existing phase ambiguities caused by 2π wrapping of the phases over time must be removed. This is done by calculating the closure phases on all baseline triangles and subtracting any multiples of 2π. The algorithm is adapted from the self-calibration routines used in AIPS[9].

By default, the algorithm assumes the target to be an unresolved point source, which ideally is expected to have a phase of zero on all baselines, regardless of length. If the object being observed has an extended structure, there are adjustments to the phase solution which TelCal must take into account. That is, rather than having a zero phase relative to the reference antenna, each antenna should have a phase predicted by the structure of the source (specified by a source model) and the current geometry of the array. From the residuals of the least-squares fit (and possibly other criteria), one may construct a normalized *quality* for each antenna. This may be used to identify antennas which are not usefully contributing to the coherent sum. In addition, TelCal calculates phasing sum *efficiencies* from each cross-correlation of the sum antenna signal with antennas in the comparison array. The VOM can then decide to modify the phased array composition and reference antenna based on the overall phasing efficiency and individual phasing qualities. For example, an antenna could be performing relatively poorly (low quality) due to atmosphere conditions if it is too far away from the array center; the overall sum amplitude may be improved by removing this antenna from the phased array.

The calculated phase solutions are sent to the Correlator software as soon as available, which in practice is a few seconds into the following scan. The time it takes to close the loop will mainly depend on the amount of binary data that is being transmitted, which in turn largely depends on the number of antennas and the degree of spectral averaging of the ALMA data; the TelCal calculation itself is on the order of milliseconds and can be neglected. Current estimates are about 8 seconds for a full 64 antennas array with no spectral averaging of the data.

As can be noted in Figure 4, TelCal phase corrections are applied after the next scan has already started. Therefore the slow loop analysis for the next scan must be restricted to the data after the last phase correction. Some fraction of the data from the beginning of each scan is therefore flagged to be ignored by TelCal since it was commanded to the previous phase solution. The amount of unflagged data needed, and therefore the optimal scan duration will then depend on the brightness of the object being observed and can be estimated prior to the observation.

ALMA observation metadata are stored in the Archive database using a format defined by the ALMA Science Data Model (ASDM)[10], which consists of a collection of related XML tables. TelCal output data are in general sent back to the Control subsystem through ASDM table rows, to be used during the online process and later stored as part of the observation metadata. APP adds one new table containing all relevant information about TelCal's phase calculations, such as the phased array, reference antenna, comparison antenna(s), phase results, qualities, efficiencies, application times, etc.

5. BASELINE CORRELATOR AND THE FAST PHASING LOOP

The Correlator software subsystem is divided into two distinct areas: (1) the Correlator Control Computer (CCC); and (2) the Correlator Data Processor (CDP) cluster. While the CCC receives instructions from the Observing Mode and configures the correlator accordingly, the CDP cluster receives the correlator lags output and applies an FFT (to obtain the visibility spectral data) and other post-processing, aggregation and formatting of the data, which are finally sent out to the Archive. Channel averaged spectral data are simultaneously generated and sent back to TelCal (see Figure 3).

The fundamental change in the CCC software is to provide access to the new command protocols that configure the phased sum in the Correlator Cards and adjust phases in the TFBs. These are new CAN commands and commanding logic that have been built into existing CCC components and can be called from the Observing Mode through the regular high-level interfaces. Phase corrections are expanded and applied on a per sub-band basis during sub-scans as soon as received (see timeline in Figure 4). The existing CCC simulation has been extended to support all new CAN commands and behave close to the real hardware. This has allowed for end-to-end software tests of the phasing system before the actual integration on the ALMA correlator, which is a unique and precious resource.

Since the data stream is split off to the Phasing Interface Cards before reaching the CDP cluster, any processing done in the CDP will not be visible in the VLBI recorded data, while affecting the data analyzed by the TelCal phase solver. The implied differences have been carefully considered to avoid a data distortion. For example, in normal interferometry observations the CDP adds residual delays that are too fine to be applied in the TFB cards; in phasing mode these corrections would produce wrong phase results in TelCal.

There are other special consideration for the sum antenna that are corrected without affecting the phased array: it does not have any associated geometric or baseband delays, and the correlator will not calculate quantization scaling factors for it. The CDP can calculate special scaling factors based on the factors of all antennas included in the sum, effectively scaling the sum signal in a meaningful way for TelCal to obtain accurate visibilities. In terms of delays we actually want a fixed delay on all baselines containing the sum antenna signal corresponding to the time it takes the correlator to produce and feed back the sum (exactly 24 clock cycles, or $192ns$).

The CDP also receives regular WVR data updates from all antennas and can apply online corrections to the data in the form of baseline delays. However, since this would again be omitted by the VLBI recorded data, phased observations must apply these corrections as antenna phase shifts in the TFB cards on a per antenna basis. This is the motivation for the fast phasing loop, in which the CDP sends phase corrections per antenna back to the CCC to be applied on a faster time scale, while being added up with the slow phasing loop offsets and other delays.

6. RELEASE CYCLES AND SYSTEM INTEGRATION

It is important to note that this project is being implemented at the same time as ALMA is transitioning from construction to full operations. The overall APP system design was largely driven by a least impact approach on existing infrastructure and resources. The delivery of technology to the observatory is coordinated within the regular workflows. In particular, the software release process is structured in incremental feature driven release cycles of about 3 months [11]. A release cycle consists of three parts: (1) software development and unit testing by the developer; (2) integration/regression testing and system verification by the Integration and Release Management team; and (3) science validation by the science commissioning team. A collection of incremental releases is finally accepted for a specific observation cycle, about once a year.

The APP software system was therefore divided into individual features that are tracked through the observatory's JIRA system and a dedicated agile Kanban board [12]. Features were scheduled in a way that allowed a meaningful verification of APP capabilities and match the required hardware delivery schedule. This scheme has proven to be specially significant in the mitigation of risks associated to the introduction of external features to the ALMA Software.

The software development and testing have been greatly assisted by the simulation modes of both the Control and Correlator subsystems. TelCal has an offline processing mode which is also quite valuable. These allow exercising the entire code in user space and finding high level problems within one or among different subsystems. Every software release is first exercised in a completely simulated environment running all software subsystems inside a standard test environment, similar in layout to the actual deployment at the observatory.

Automated builds, unit tests and integration tests in a simulated environment for the development branch of the Control and Correlator subsystems are executed every night on a Jenkins build server. An integration test specific to the VOM has been added to this test suite. The TelCal subsystem provides an offline mode to exercise the calibration engines with spectral data on disk. While this is an excellent tool for algorithm development, it does not exercise the communication with other parts of the system. On the other hand, a complete online simulation environment sends data to TelCal; but this is data based on generated spectra that are meaningless to the calibration engines. These limitations have posed a challenge to the integration of the TelCal part of the phasing loop with the rest of the system.

Another critical part of software releases and maintenance is regression testing, which ensures that existing functionality is not impacted by the changing code base [13]. This becomes specially important for the VOM as it is expected to be used only occasionally (at most a few times a year). This implies that changes in common software could severely impact the VLBI portion of the system without being noticed until the next VLBI campaign. Therefore the APP has defined a dedicated regression test that exercises the VOM and all underlying software and hardware. This test is executed periodically as part of the regular regression test suite at the observatory. As with other regression tests, this one is evolving as more features become available. During construction of the VOM, this regression test is also useful to obtain data under the different, seasonal atmospheric conditions at ALMA.

The first APP features were released in September 2013, with the first on-site verification campaign, focused on the slow phasing loop, taking place in January 2014. A second campaign to verify the VLBI recording data path is planned for July 2014.

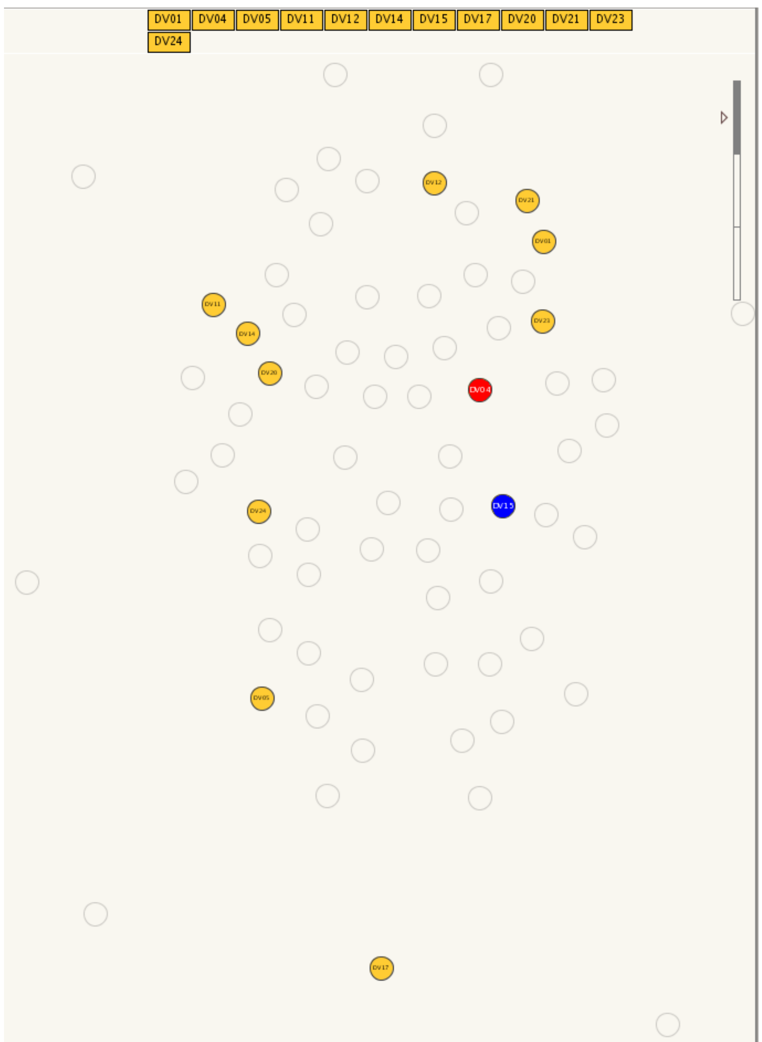

Figure 6. Geographical distribution of an array of twelve 12-meter ALMA antennas in the internal cluster, used for APP software testing on January 29th 2014. The longest baseline was approximately 260m. Antenna DV04 (in red) was used as the reference antenna; DV15 (in blue) was used as comparison antenna; all others were part of the phased array.

7. EXPERIMENTAL RESULTS

During January 2014 a first verification campaign of the phasing system took place at the ALMA site. The outcome of this campaign was an integrated slow phasing loop, with all elements in the various software subsystems properly communicating.

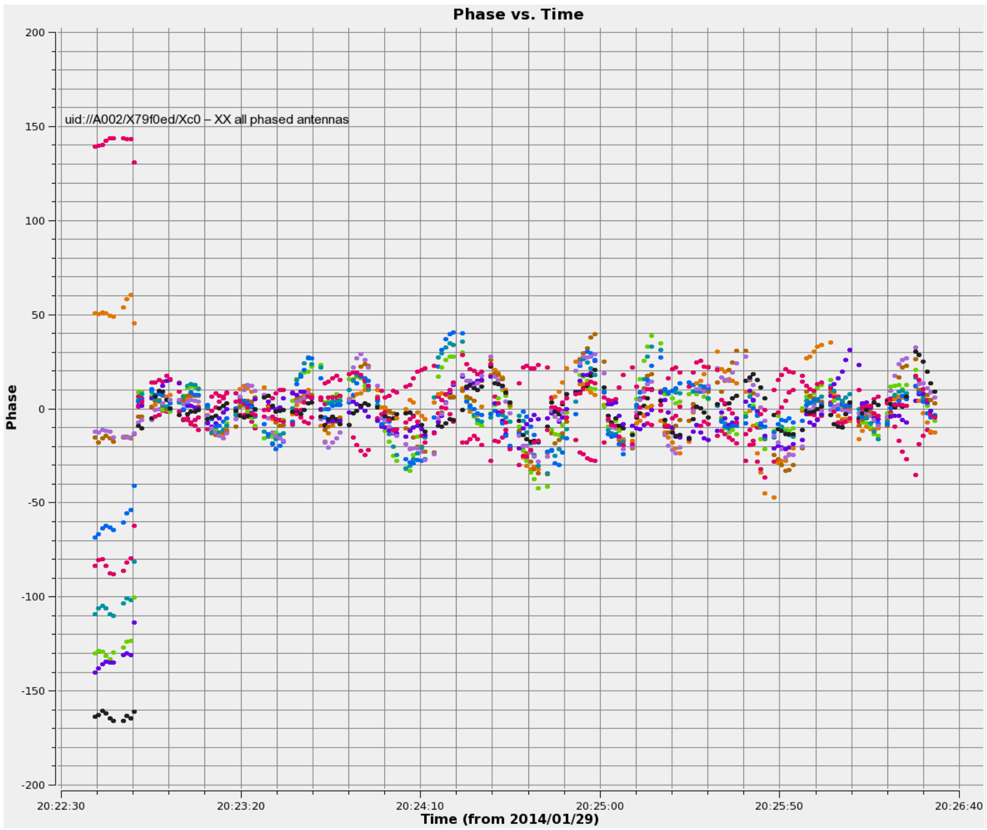

Figure 7. ALMA Band 3 ($86GHz$) observations of the quasar 3C454.3 using an early version of the APP phasing software. Shown are phases as a function of time for baselines between the reference antenna and the antennas in the phased array. Each color represents a single baseline in the XX polarization product. In this example there are 30 sub-scans, each with a 6-seconds duration and 1-second integrations. *(plotted with CASA)*

Figure 6 shows the geographical distribution of the array used to obtain the results further described; we used a subset of the antennas that were available, and the arrangement included a range of baselines. Figure 7 shows a plot of phase as a function of time for baselines between the reference antenna and each of the antennas in the phased sum (X polarization) during a Band 3 observation of the quasar 3C454.3. The data points (available for each 1-second integration) are grouped in 6-seconds sub-scans, with a slight gap in between. A similar plot in Figure 8 shows the data for the Y polarization. In both cases, phases are random on the 10 baselines in the first sub-scan, and also in the first part of the second sub-scan. During the second sub-scan, the phasing commands are applied, and thereafter, the phasing loop drives the phases to cluster around zero phase difference with the reference antenna. The unphased comparison antenna phase(s) (not shown) are meanwhile slowly varying.

Other successful verifications during this campaign included:

- Decomposition of the sum signal into the expected signals from each individual antenna in the phased array.
- Coherent cross-correlations between antennas in the phased array and the sum signal, delayed by the expected $192ns$.

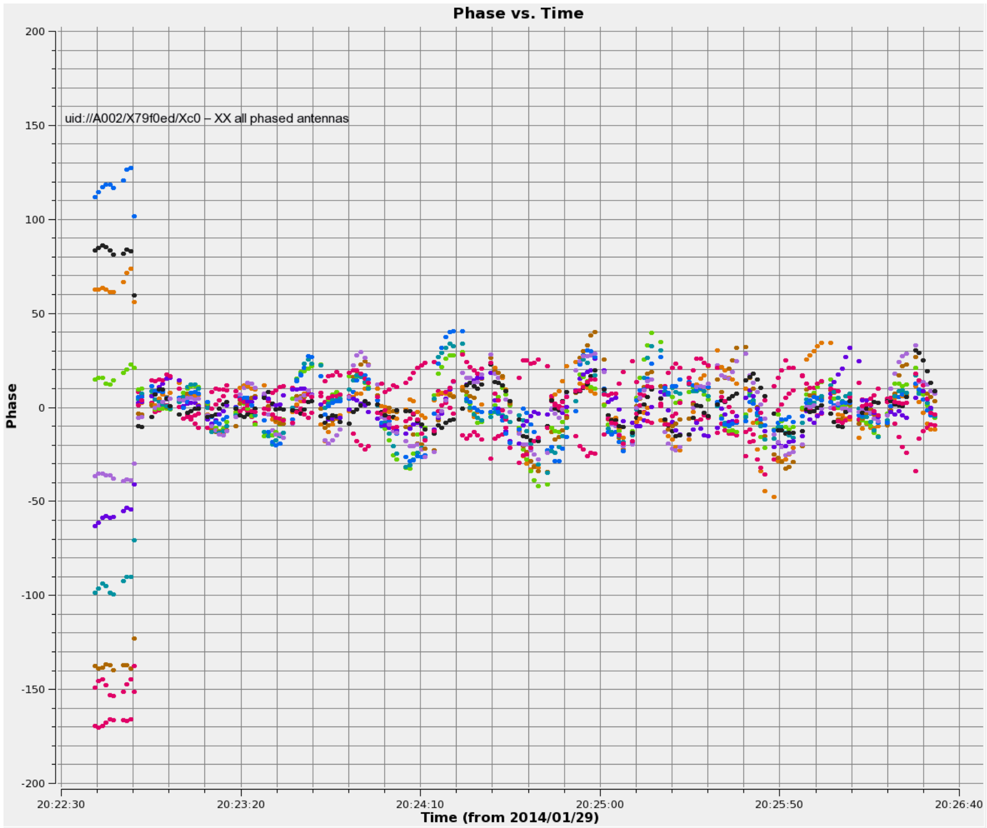

Figure 8. Same sample as in Figure 7, for the YY polarization product. *(plotted with CASA)*

- Acceptable phase solutions of one phase per antenna, relative to the zero-phase reference antenna.

Observations were done in both Band 3 and 6, with up to 30 antennas at a time on a number of sources of varying brightness. The length of the sub-scan, and hence the latency of phase corrections is determined by a number of factors. In these initial tests, TelCal required 5 integrations in order to consider a phase solution worth attempting. In the event these sources were bright enough that restriction may be relaxed in the future.

The Band 3 observations are in general easier to make than Band 6 observations due to the lesser impact of atmospheric delays caused by tropospheric water vapor. The introduction of the fast loop will allow Band 6 observations at times of higher atmospheric water vapor content, as this loop will drive the phases towards zero independently, and on a faster timescale than the TelCal (slow) loop. Once the full system is in place, we will then be in a position to consider tuning the phasing loop parameters based on required (ALMA) spectral resolution, source brightness, and atmospheric conditions.

8. CONCLUSIONS

We have presented the overall phasing system as implemented as part of the ALMA Phasing Project, which will enable ALMA as a VLBI station. As one of the first ALMA Development Projects, the APP has had to overcome a variety of challenges related to interfacing with an observatory that is still in transition from development to full operations. The APP formulated its own set of external requirements, adapted to the overall ALMA framework. The unique hardware and software systems developed for the APP are being implemented incrementally at ALMA in a manner designed to insure that they do not impact normal ALMA operations.

Many of the software design aspects were driven by the existing subsystems, requiring close coordination with each of them. From the technical point of view this process can be considered as a proof of the overall flexibility and modularity of the ALMA Software system, since it has been possible to add all the required features without changing the existing system in fundamental ways, and most importantly isolating the changes into modules that only get used in VLBI mode.

While the phasing loop has been successfully exercised at the telescope in Chile there are a number of features and improvements that are still underway, most of them are scheduled for releases later in 2014. Among the most important ones:

- The fast phasing loop for water vapor corrections to improve phase stability with poor weather.
- Support for multiple channel averages and source models in TelCal.
- Scaling and delay correction for the sum antenna in the CDP.

The ALMA Phasing Project successfully passed its Critical Design Review in May 2013 and is well underway in its implementation phase. All new hardware elements have been delivered to the observatory, as have the general control and calibration software aspects. Further software improvements and ancillary observation tools will be delivered as science commissioning activities progress in late 2014 and early 2015. The APP is centered on providing the technical capabilities for VLBI observations; the arrangements to offer these capabilities to the science community are rather complex because of the fundamental differences compared to the traditional ALMA observation model, and fall outside of the scope of this project.

Given the flexibility built into the design (e.g. separate Phasing and VLBI controllers), subsequent ALMA development projects could build upon this base to either enhance the VLBI capabilities (e.g. eVLBI), enhance the phasing system (improved algorithms), or use these to create entirely new capabilities (e.g., commensal observing for pulsar searches).

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10 Attachment 2: Detailed Design report from CDR

Detailed Design Report: ALMA Phasing Project

Release 1.0

Authors: Michael Hecht, Project Manager

Revision Date: April 30, 2013

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Applicable Documents

APP CDR Plan (ALMA-05 11 10 01-0001-A-PLA)

APP Project Plan

APP Requirements Document

ALMA-VLBI Operational Model

APP Computing Management Plan (ALMA-05.11.60.01-001-A-PLA)

Back End ICD (2013-03-25-ALMA-05.11.10.49-50.00.00.49-A-ICD)

Site ICD (2013-04-22-ALMA-05.11.10.49-20.00.00.49-A-ICD)

Correlator ICD (2013-04-22-ALMA-05.11.10.49-60.00.00.49-A-ICD)

Computing ICD (2013-04-22-ALMA-05.11.10.49-70.00.00.49-A-ICD)

High Angular Resolution and High Sensitivity Science with a Beamformed ALMA (science_case-20130328.pdf)

JAO cost impact assessment associated with the ALMA Phasing Project (ALMA-05.11.00.00-0001-A-STD)

Reviews: Definitions, Guidelines, and Procedure (ALMA-80.09.00.00-001-D-PLAALMA)

General Safety Design Specification (ALMA-10.08.00.00-003-B-SPE)

System Technical Requirements (ALMA-80.04.00.00-005-B-SPEALMA)

System Electrical Design Requirements (ALMA-80.05.00.00-005-C-SPEALMA)

System Electromagnetic Compatibility (EMC) Requirements (ALMA-80.05.01.00-001-B-SPEALMA)

Product Assurance Requirements (ALMA-80.11.00.00-001-D-GENALMA)

Environmental Specification (ALMA-80.05.02.00-001-B-SPEALMA)

Operations Plan (ALMA-00.00.00.00-002-A-PLAALMA)

Seismic Design Specifications for ALMA-AOS and ALMA-OSF (SYSE-80.10.00.00-002-B-REP)

ALMA Interface Management Plan (ALMA-80.07.00.00-001-D-PLA)

Mark6 Users Manual (draft)

APP Optical Fiber Link system design (ALMA-05.11.40.01-0001-A-DSN)

Phasing Interface Card Manual (ALMA-05.11.31.05-0001-A-MAN)

Polarization Conversion for ALMA Phasing (55-PolarizationWhitePaper.pdf)

APP post-processing: From recorded data to uncalibrated data (APP_Post-Processing.pdf)

1 Document Overview & Scope

The ALMA *Reviews Definitions, Guidelines, and Procedure* calls for a *Detailed Design Report* (DDR) to be delivered as part of the Critical Design Review (CDR) documentation package.

The DDR is defined as "an executive summary of the documents submitted for CDR review, including special remarks, recommendations and conclusions, and including deviations from the original plans and specifications."

As an external development, funded independently by the contributing partners with an augmentation from the ALMA Development Fund, the ALMA Phasing Project (APP) does not precisely follow the process defined for ALMA developments.

The content of this document differs from that described in the guidelines with respect to subsystem specifications. In particular:

- APP hardware requirements are defined at the functional level (See the APP Requirements Document), augmented by interface control documents (ICD) as well as various ALMA documents that describe environmental constraints, safety procedures, etc. However, in response to the high level of maturity of the APP hardware, there has ben no explicit effort to develop hardware specifications at the subsystem level distinct from those presented in the design and description documentation. Correspondingly, there is no "assessment of the design to meet the subsystem specification" as called for in the guidelines. This departure from practice has been approved by the ALMA system engineer.
- APP software specifications follow ALMA practice in being fully traceable to functional requirements, extensively documented at the design level rather than deriving from detailed specifications (see APP Computing Management Plan).

The DDR addresses the following topics:

- The evolving programmatic context of APP
- An overview of the submitted document package
- Changes since Preliminary Design Review (PDR) in the Project Plan, Requirements document, and ICDs
- Project status (Management, design, and ALMA interface)
- Summary of the design

2 Programmatic Context

2.1 Compliance with ALMA Board conditions

On November 15, 2012, the ALMA Board approved implementation of the ALMA Phasing Project, subsequent to the following conditions (emphasis and numbering added):

> ***The project plan presented at the CDR is modified*** *such that:*
>
> 1. *The tasks and associated resources (costs, FTEs, timeline) required from the JAO and Executives to outfit ALMA as a VLBI station, are well determined and agreed between the consortium and the observatory;*
> 2. *An ALMA-VLBI operations model explicitly addressing the impact on ALMA operations (costs, FTE, timeline) is agreed between the consortium and the observatory;*
> 3. *Commissioning avoids observation of the primary targets identified in the science case.*
>
> *There will be no allocation of guaranteed time. Proposals for this capability from this consortium, or a broader collaboration, will be subject to the normal ALMA proposal review process.*

The APP Project Plan presented as part of this package has been modified to reflect condition #3 (observation of primary targets) and the denial of guaranteed time. Condition #1 is addressed in a JAO document, *JAO cost impact assessment associated with the ALMA Phasing Project*, in signature cycle as of this writing. Condition #2 is addressed by the *ALMA-VLBI Operational Model*, submitted for discussion by the APP PI to the ALMA Chief Scientist.

2.2 The "McKinnon plan"

Clarification of the relationship between the APP, the Event Horizon Telescope (EHT) experiment, and a global short wavelength (<=1.3 mm) VLBI network was requested at the APP PDR and in other forums. ALMA-NA Project Director Mark McKinnon subsequently proposed the following roadmap (excerpted from the ALMA-VLBI Operational Model):

- Phase I: Completion of the APP. This is an engineering project that will provide basic VLBI capability at ALMA.
- Phase II: Event Horizon Telescope Experiment (EHTE). The EHTE is an international science project to observe supermassive black holes with 1.3mm and 0.8mm wavelength VLBI. The EHTE is organizing VLBI networks in these wavebands and will serve as the pathfinder for general VLBI capability in ALMA Bands 6 & 7.
- Phase III: Roadmap for a Global mm-VLBI Network. This phase will plan development for an international mm-VLBI capability that builds on experience of existing VLBI arrays and the EHTE.
- Phase IV: Establish Global mm-VLBI Network. In this phase, the roadmap of Phase III is implemented with support, schedule and participants to be discussed. Memoranda of Understanding (MoU)'s for the Global Network will likely be required in order to coordinate activity with other mm/submm facilities.

2.3 Implementation Approach

The APP team proposed the following implementation approach, described in detail in the APP Project Plan:

Project Implementation Responsibility: While APP represents the substantive efforts of a multinational consortium, MIT Haystack Observatory (MIT/HO) is responsible for overall implementation, with software and integration & test responsibility delegated to NRAO under the direction of the MIT/HO Project Manager. APP Principal Investigator Shep Doeleman has delegated day-to-day management of APP to MIT/HO Project Manager Michael Hecht.

Cost and Schedule Management: APP is a short duration, cost-capped project. APP utilizes critical path management, with all participating institutions managing performance against cost and schedule. Monthly management reviews are the primary forum for aggregating these performance metrics. Reserves are released by a process requiring top-level approval.

Safety and Product Assurance: Minimizing disruption to the ALMA development and observation schedule as well as risk to the ALMA facility is a primary APP emphasis. A designated Product Assurance manager coordinates with an ALMA counterpart to ensure (a) a robust and fault-tolerant design, (b) the maximum degree of isolation from critical ALMA components, and (c) a high fidelity test program.

Configuration Management: Configuration Management is a two-tiered system, comprising change control, version control and notification for code and documents. The first tier addresses documents requiring ALMA concurrence, which are maintained through the ALMA EDM system and subject to ALMA change control processes. The second tier are internal APP documents, maintained on a wiki with version tracking, and with change control effected by concurrence of the Project Manager (PM), Principal Investigator (PI), and cognizant engineers. Code configuration is managed through a parallel but similar process utilizing the ALMA CVS.

Reviews and Reporting: Reviews are attended by all cognizant APP partners, designated ALMA personnel, and an independent review board. In addition to monthly management reviews (MMR), the key review gates are the preliminary and critical design reviews (PDR, CDR), an incremental software design review (ISDR), and a test readiness review (TRR).

Risk Management: The Project System Engineer maintains a risk list, whose status is reviewed on a monthly basis as part of the Monthly Management Review. Individual risks will be rated for severity and likelihood, and resolution will be peer reviewed and documented.

Risk, Problem and Failure Management: In addition to Action tracking, the APP Project Manager maintains logs of risks, liens, changes, and significant problems and failures encountered during development. Status is presented at major reviews.

Test Philosophy: Testing is incremental at the component, module, subsystem, and system levels as appropriate. Software and electronics will be tested in a simulation of the ALMA configuration at the NRAO Central Development Lab at Charlottesville, VA and at OSF.

Transitioning capability to ALMA: The APP system engineer will coordinate with a designated ALMA counterpart to ensure that ALMA has all documentation, code, tools, and parts to maintain, operate, and continue development of the phasing system after commissioning.

Summary of Delivered Products: APP will deliver the following to ALMA(a) All hardware and software (including source code) needed to phase ALMA; (b) Services, in the form of support for integration and commissioning, as well as training for subsequent operation; (c) Science and technology data products, in the form of reports, publications and publicly available data; (d) Complete documentation; and (e) Any outreach and education products developed under APP.

2.4 Relationship to JAO

Subsequent to PDR, an APP team traveled to Chile to meet with key personnel at JAO, OSF, and APP, with the goal of agreeing on APP procedures, defining interfaces, and generally establishing relationships with ALMA personnel. Important outcomes of these meetings include:

- Establishment of points-of-contact in all areas of the project.
- Agreement on cost guidelines and a basis of estimate of APP impact on JAO (see JAO Cost Impact Assessment).
- Agreement on an architecture for managing software delivery and integrating it into the ALMA software infrastructure (See Computing Management Plan).
- Agreement on an approach to VLBI operations (see ALMA-VLBI Operational Model)
- Full and quantitative discussion of ALMA interfaces at OSF and AOS (see APP ICDs for Back End, Site, Correlator, and Computing)
- Agreement on an approach to this CDR (see APP CDR Plan)

2.5 Science Case

The Science Case for ALMA VLBI both justifies the APP requirements and informs implementation of the roadmap spelled out in the "McKinnon Plan." A draft of that case has been assembled with contributions from numerous members of the community and posted to solicit the broadest possible comment prior to publication (*see High Angular Resolution and High Sensitivity Science with a Beamformed ALMA*).

3 The CDR Document Package

As of this writing, the tables below itemize the documents submitted to the CDR Review Board, available either as individual documents in a hierarchical wiki or in a single compressed (ZIP) file. Note that certain file names may change as documents are updated. Documents and presentations from the PDR are included for completeness and for reference of new Review Board members. Note that the agenda is to be found only on the wiki.

Updates to key PDR documents are also provided: Project Plan release 1.2 (under *Project Management*), which responds to ALMA Board conditions; APP Functional Requirements release 2.1, (under *Design/Requirements & Specifications*), which now includes Verification detail; ICDs for Back End, Site, Correlator, and Computing (under *Design/ICDs*), replacing the single ICD provided at PDR; and a new resource-loaded Gantt chart (under *Project Management*) reflecting a significant replan that resulted from discussions with ALMA.

Overviews of the four new hardware subsystems to be delivered are listed under the *Design* heading. These include the maser, the optical fiber link, the PIC, and the Mark 6 recorder, as well as a description of the planned firmware upgrades to the ALMA correlator (APP_Correlator_mods_V1.0).

In subfolders under *Design* are found ROACH FPGA specifications, the aforementioned ICDs, and drawings for the electronic assemblies.

In addition to the new Gantt chart, a snapshot of the project can be assessed from the APP_Organizer, provided in Excel format and containing tabs for Action Items, Liens, Risks, Changes, and Problems, as well as the information in the tables below.

Important new plans have been created for Integration and Test, which includes requirements verification, as well as Commissioning and Science Verification. These are found under *Plans and Procedures*.

A computing management plan as well as technical descriptions of the three key subsystems to be modified (correlator & control update, TelCal update, and DiFX post-processing update) are provided under *Software*, as well as a description of the planned polarization correction strategy.

A *Product Assurance and Safety* infrastructure has recently been developed, with emphasis on complying with ALMA requirements in those areas. The overall plan is provided, as well as short reports on a number of required compliance areas (reliability and maintainability, transportation, hazard analysis, test/maintenance equipment) that will be fleshed out subsequent to CDR. Several reference documents are also provided.

For CDR, *Build* documentation is limited to Bills of Materials. Test and reliability reports for the optical fiber link and the maser are also provided under *Reports*.

In response to the conditions of ALMA Board approval, a JAO cost assessment and a VLBI operations model are provided under *ALMA Board Deliverables*.

A full description of RFA responses resulting from the PDR are provided under *RFA Closure*.

Finally, in addition to the Science Case referenced above, several scientific papers addressing the promise of a beamformed ALMA are provided under *Science*.

	File Name	Description
CDR Material (Board Access)		
	Agenda	*(Part of web page)*
	ALMA Review Guidelines.pdf	*ALMA Review Guidelines*
	ALMA-05 11 10 01-0001-A-PLA - 2013-03-19 - ALMA Phasing Project CDR Plan.pdf	*APP CDR Plan*
CDR Documentation Package		
	Documentation_Package_26APR13B.zip	*Zip file of all documents*
	Detailed Design Report	*(Incomplete)*
Project Management		
	APP_2.9_24APR13_Plan C.mpp	*Resource-loaded schedule (Microsoft Project format)*
	APP_2.9_24APR13_Plan C.pdf	*Gantt chart*
	APP_Organizer_26APR13.xls	*Actions, risks, liens, problems, changes, etc. (Excel format)*
	APP_Project_Plan_1.2_25APR13.pdf	*Project Plan 1.2 (updated for CDR)*
Design		
	16Gbps_paper.pdf	*Mark 6 recorder description*
	Mark6_users_manual_draft.pdf	*Mark 6 user manual*
	Mark6_command_set-Rev3.04_draft.pdf	*Mark 6 command set*
	2013-04-23-ALMA-05.11.31.05-0001-A-MAN.pdf	*PIC Assembly Manual*
	ALMA-05.11.40.01-0001-A-DSN.pdf	*Optical Fiber Link design*
	APP_Correlator_mods_V1.0_25APR13.pdf	*Correlator modifications*
	Installation_Operation_and_Maintenance_User_manual_iMaser_T4S-MAN-0012_1_7emc-2.pdf	*Maser manual*
	maser_dspl.pdf	*Maser configuration at ALMA*
Requirements and Specifications		
	APP_requirements_2.1_25APR13.xlsx	*APP Functional Requirements*
	2013-04-10-ALMA-05.11.31.15-0002-A-SPE.pdf	*ROACH FPGA requirements and specificaitons*
ICDs		
	2013-03-25-ALMA-05.11.10.49-50.00.00.49-A-ICD.pdf	*Back End ICD*
	2013-04-22-ALMA-05.11.10.49-20.00.00.49-A-ICD.pdf	*Site ICD*
	2013-04-22-ALMA-05.11.10.49-60.00.00.49-A-ICD.pdf	*Correlator ICD*
	2013-04-22-ALMA-05.11.10.49-70.00.00.49-A-ICD.pdf	*Computing ICD*
Drawings		
	2013 apr 22 ALMA-05.11.31.11-0005-A-DWG.pdf	*PIC PCB files*
	2013 apr 22 ALMA-05.11.31.11-0006-A-DWG.pdf	*ZDOK to QXH Adapter PCB Files*
	2013-04-22-ALMA-05.11.31.11-0001-A-DWG.pdf	*PIC Assembly Block Diagram*
	2013-04-22-ALMA-05.11.31.11-0002-A-DWG.pdf	*PIC Schematic*
	2013-04-22-ALMA-05.11.31.11-0003-A-DWG.pdf	*PIC ZDOK to OXH Adapter Schematic*
	2013-04-22-ALMA-05.11.31.11-0004-A-DWG.pdf	*PIC Assembly miscellaneous cables*

Plans and Procedures		
	2013-04-24-ALMA-05.11.10.01-0001-A-PLA.pdf	*Integration and Test Plan*
	APP_CSV_Plan_draft_22-April-2013.pdf	*Commissioning and Science Verification (CSV) Plan*
Software		
	ALMA-05.11.60.01-001-A-PLA.pdf	*Computing Management Plan*
	55-PolarizationWhitePaper.pdf	*Polarization White Paper*
	ALMA-05.11.61.01-001-A-DSN.pdf	*Correlator and Control Update Design*
	ALMA-05.11.62.01-001-A-DSN.pdf	*TelCal Update Design*
	APP_post-processing.pdf	*Post-processing (DiFX) design*
Product Assurance & Safety		
	2013 apr 19 APP Product Assurance Plan ver A.4.pdf	*Product Assurance Plan*
	2013 apr 19 APP Reliability Report ver A.3.pdf	*Reliability and Maintainability Report*
	2013 apr 25 APP Transportation Plan ver A.1.pdf	*Transportation Plan*
	Hazard_Analysis_Safety_Plan_placeholder.docx	*Placeholder (MSWord)*
	Test_Maintenance_Equipment_placeholder.docx	*Placeholder (MSWord)*
referenced shipping docs		
	2008.1.22-CORL-60.00.00.00-017-A-PLA.pdf	*Correlator shipping plan (2008)*
	2009-04-27-BEND-50.01.00.00-013-A-PLA.pdf	*Band end shipping plan (2009)*
	2009.04.09-CORL-60.00.00.00-061-B-SOW.pdf	*Correlator packing and shipping SOW (2009)*
	2011-01-13-BEND-50.01.00.00-071-A-SOW.pdf	*Back end photonics packing and shipping (2011)*
Build		
	APP BOM 2013Apr19.xls	*APP Bill of Materials (BOM) - draft (Excel format)*
	2013-04-26-ALMA-05.11.31.12-0001-A-BOM.xls	*PIC Assembly BOM (Excel format)*
	2013-04-22-ALMA-05.11.31.12-0002-A-BOM.xls	*PIC BOM (Excel format)*
	2013apr22 ALMA-05.11.31.12-A-0003-BOM .pdf	*ZDOK to ZXH Adapter BOM and assembly (Excel format)*
	Assembly_Procedures_placeholder.docx	*Placeholder (MSWord)*
	Critical_Items_Spares_List_placeholder.docx	*Placeholder (MSWord)*
Reports		
	ALMA-05.11.40.02-0001-A-xxx.pdf	*Optical Fiber link prototype test report*
	Maser white paper MTBF 130131.pdf	*Maser reliability report*
Science		
	science_case-20130328(1).pdf	*Community Science Case for APP*
	Doeleman_2008_Nature_SgrA.pdf	*Doeleman et al., Nature (2008)*
	Doeleman_2012_Science_M87.pdf	*Doeleman et al., Science (2012)*
	Fish_2011_ApJL_SgrA.pdf	*Fish et al., Astrophys. Journal Lett. (2011)*
	Lu_2012_ApJL_1924-292.pdf	*Lu et al., Astrophys. Journal Lett. (2012)*
RFA Closure		
	RFA_Closure_worksheet_26APR13.xlsx	*RFA Closure Worksheet*
	Supplemental-RFA-responses.pdf	*RFA responses too long for the worksheet*
ALMA Board Deliverables		
	Board statement of APP approval	*(On wiki page)*
	2013-04-19 - ALMA-05.11.00.00-0001-A-STD APP Cost Impact Assessment.pdf	*JAO Cost and Impact assessment (draft)*
	app_operation_model.docx	*VLBI Operations model (to be used for cost assessment)*

PDR Documents	
PDR_Agenda_18OCT12.pdf	*PDR Agenda*
16Gbps_paper.pdf	*Mark 6 performance*
2012-10-19-xxx-yyy-A-ICD.pdf	*ICD (draft)*
2012-10-24-xxx-yyy-A-PLA.pdf	*Integration and Test Plan (draft)*
2012-10-28-xxx-A-STIP.pdf	*Science Team Implementation Plan*
2012-10-29_ALMA-PhasingPolPlan.pdf	*Polarization Options*
ALMA_Board.pdf	*PDR Review Board membership*
ALMA_Memo_584.pdf	*ALMA Memo 584 describing VLBI support capability*
APP_2.9_29OCT12.pdf	*APP Gantt chart*
APP_Correlating_Simulated_ALMA_Data.pdf	*Simulation of ALMA data correlation*
APP_PDR_Success_Criteria.pdf	*PDR success criteria*
APP_Phased_Sum_Statistics.pdf	*ALMA 2-bit antenna sum statistics*
APP_PhasingAlgorithm.pdf	*Proposed phasing algorithm (draft)*
APP_Project_Plan_1.1_Submitted_11OCT12.pdf	*Project Plan V1.1*
APP_requirements_28OCT12B.xls	*Functional requirements V1.1*
APP_VLBI_Observing_Mode_Design.pdf	*VLBI Observing Mode design*
APP-EHT_Observing_Bands.pdf	*VLBI infrastructure for observing in various bands*
Installation_Operation_and_Maintenance_User_manual_iMaser_T4S-MAN-0012_1_7emc-2.pdf	*Maser manual*
Mark6_command_set-Rev3.03_draft.pdf	*Mark 6 recorder command set*
TEST_report_iM61.pdf	*Maser test report*
PDR Presentations	
01_Shep_Welcome.pdf	*Welcome (Doeleman)*
01_Welcome.pdf	*Welcome (Weintroub)*
02_Scientific_Objectives.pdf	*Scientific Objectives of APP (Doeleman)*
03_Driving_requirements.pdf	*Driving requirements and design studies (Doeleman)*
04_Design_Overview.pdf	*Design overview (Crew)*
05_Hydrogen_Maser.pdf	*Hydrogen maser characteristics (Doeleman)*
06_LO_Testing.pdf	*LO testing & station coherence (Shillue)*
07_Correlator_Upgrades.pdf	*Phasing Interface Card & Correlator Upgrades (Greenberg)*
08_Optical_Fiber_Link.pdf	*Optical Fiber Link (Honma)*
09_Recorders.pdf	*Mark 6 recorders (Rusczcyk)*
10_Haystack_Software.pdf	*Haystack software (Crew)*
11_MPIfR_Software.pdf	*MPIfR software (Alef)*
12_ASIAA_Software.pdf	*ASIAA software (Pradel)*
13_Polarization_Analysis.pdf	*Polarization analysis (Roy)*
14_Integration_Test_Commissioning.pdf	*Integration, test, & commissioning (Lacasse)*
15_Project_Management.pdf	*Project Management (Hecht)*
16_Operations_and_Science_Planning.pdf	*Operations & Science Planning (Doeleman)*
17_Impact_of_the_APP_on_ALMA.pdf	*Impact of the APP on ALMA (Doeleman)*
18_Transition_to_an_ALMA_Facility.pdf	*Transition to an ALMA Facility (Doeleman)*
19_Deliverables_to_ALMA.pdf	*Deliverables to ALMA (Doeleman)*

4 Changes since PDR

4.1 Project Plan

The most significant change in the Project Plan was the response to the ALMA Board acceptance conditions. SgrA* and M87 were dropped from the commissioning plan, as was any reference to guaranteed time for observation. An explicit acknowledgment of the need to assess ALMA impact during and subsequent to APP development was included. Correspondingly, the estimate of ALMA workforce was removed in anticipation of a JAO-led costing exercise.

A change in scope (see below) resulted in removal of the third commissioning activity and deletion of references to Band 7, and a change in ICD resulted in a reference to the 10 MHz maser signal rerouting. References to "Requirements and Specifications" were changed to refer to requirements only, as detailed subsystem specifications were replaced by design descriptions.

In response to RFAs, references were added to the ALMA science staff, and references to software product assurance were removed in response to integration of software acceptance into the ALMA software process. References to optional use of beacon sources and water vapor radiometers were clarified, and it was also clarified that TelCal is a computer application, not a computer. Minor changes were also made in organizational charts and assignments.

All changes are noted in the document Change Log.

4.2 Requirements

The Functional Requirements Document was expanded to include descriptions of verification methods, and a Project descope resulting in dropping the requirement to explicitly support Band 7 (the actual hardware and software is band independent, so this amounts to dropping a commissioning requirement). TBRs were removed and a more general statement about supporting existing VEX formats was substituted for the specific statement about releases. Similarly, a requirement on number of connector insertions was replaced by a more general statement on reliability of the connector.

All changes are noted in the document Change Log

4.3 ICDs

At the request of ALMA System Engineering, the original APP ICD presented at PDR was replaced with four separate ICDs for Back End, Site, Correlator, and Computing. Notable in the Site ICD was seismic safety for the maser. In addition, the Back End ICD discusses the use of the 10 MHz signal from the maser to replace the corresponding signal from the Central Reference Generator (CRG).

5 Project Status

5.1 Management

Since PDR, the APP was approved by the ALMA Board, which triggered the active participation of JAO personnel. This, in turn, allowed working relationships to be established, ICDs to be developed, test and commissioning protocols to be defined, and the Board approval conditions to be addressed. Notably, in contrast to the PDR, JAO is the convening authority for this CDR. ADF funding for NRAO (Socorro) followed shortly after Board approval, completing the APP software team. Partner institutions in Europe and Asia are fully funded and working productively. There have been three significant technical interchange meetings; The APP team visit to ALMA in Chile has been discussed elsewhere. Software meetings have been held at NRAO in Charlottesville, and at MPIfR at Bonn; the latter included the helpful participation of ESO personnel to advise on TelCal development.

Several staff assignments have been made since PDR. Bob Treacy (NRAO) has accepted the role of Product Assurance (PA) and Safety Manager and has set up a PA program. A formal System Engineer still has not been identified; the PM (Hecht) continues to do additional duty in this role, with many of the specific responsibilities distributed among team members. This arrangement seems to work and there are no immediate plans to change it. Under the leadership of the Project Scientist (Vincent Fish), all but a few of the RFAs from the PDR have been resolved with concurrence of the initiator. Lynn Matthews has taken on leadership of Commissioning and Science Verification planning. On the JAO side, Bernhard Lopez has taken on a central role as primary point of contact for APP.

Geoff Crew took on leadership of the software development effort, which was restructured into “features” as a result of meetings with the ALMA software team. In addition to being responsive to the ALMA development environment, this change helped to partition the scheduling process and to improve the workforce distribution among the institutions. A few outstanding architectural problems, notably the method of conversion between circular and linear polarization, have been resolved.

Hardware development continues as projected, and all non-COTS parts have been fabricated. The fiber optic link is nearly complete, recorders will be ordered soon, the maser has already been purchased, and the PIC boards lack only firmware development. ICDs have been worked out down to the levels of racking and cabling. A few specific problems have been resolved, notably the use of the 10 MHz signal from the maser to replace a noisy output of the CRG.

The APP is managed from MIT/HO as described in the Project Plan. The role of management is primarily one of coordination, with each partner institution using its own internal processes. Weekly status teleconferences include Monthly Management Reviews for each institution, and tracking tools have been put in place.

5.1.1 Meeting ALMA Board conditions

On approving the APP, the ALMA Board imposed three conditions to be addressed by CDR.

- The Board required the Project Plan to be modified, removing references to the use of primary science targets for commissioning and to the provision of guaranteed observing time. This condition has been fully met.
- The board asked for an assessment of JAO costs, which has been addressed through a

JAO cost study led by Bernhard Lopez with the support of the APP PM. The resulting report, *JAO cost impact assessment associated with the ALMA Phasing Project*, meets the Board condition.

- The Board also requested an operational VLBI model that would allow an estimate of operating costs in VLBI mode. The APP PI has submitted the *ALMA-VLBI Operational Model* to the ALMA Chief Scientist for discussion. In parallel, ALMA-NA has asked MIT Haystack Observatory to explore the concept of a global 1.3 mm VLBI network.

5.1.2 Project Management Tools and Practices

APP team members communicate and report regularly, using weekly teleconferences, monthly management reviews (MMR) from each institution, formal and informal documentation, occasional technical interchange meetings, and a common document repository for coordination.

Weekly teleconferences are hosted under Webex, with screen-sharing used extensively for presentations such as the MMR or for discussion of documents. Minutes are formally maintained and posted weekly.

APP has selected the MindTouch wiki tool, hosted by MPIfR, as the primary repository of all APP Project documents with the exception of software code. MindTouch is particularly capable in the area of version control, and maintains a readily accessible version history. Uploading is simple, requiring only a brief [optional] description, and files may be uploaded in batch. All APP team members have equivalent access. Leaders of the various work packages defined in the WBS are responsible for maintaining their own pages. By agreement with JAO, a subset of mature documents of particular interest to ALMA (ICDs, for example) are also posted on the ALMA Electronic Document Management (EDM) system.

While key APP team members will have access to ALMA's implementation of the JIRA action tracking tool (used for CDR RIDs, for example), project critial APP items are tracked in an Excel workbook, dubbed the APP Organizer, and updated regularly on the Wiki. The Organizer is maintained by the PM, reviewed in weekly teleconferences, and summarized at major reviews. It includes sheets for assigned actions, risks, liens, and problems as well as compliance matrices for the Project Plan, document preparation, MMR scheduling, etc.

The practice of Monthly Management Reports was initiated after PDR. By the time of CDR, the 5 participating institutions (MIT-HO, NRAO, MPIfR, NAOJ, ASIAA) will have presented five MMRs each. Each MMR reports on accomplishments vs. prior goals; goals for the coming month; progress against schedule, budget, and workforce; change requests; risk updates; problem log updates; RFA retirement; outstanding action items; issues and concerns; and any other technical discussion considered appropriate. Presentations are posted, and reported items are added to the Organizer for tracking. Participation of line management is at the discretion of the reporting institution.

The Project Plan calls for written Quarterly Reports, which were planned to begin in this calendar year (2013). The first report will be extracted from this Design Report; Subsequent quarterly reports will reflect MMRs.

To date, changes to requirements and major changes to design are ratified by the PM and PI after presentation to the team (by teleconference and email). Subsequent to CDR, certain changes will also be brought before the ALMA Change Control Board.

A full resource loaded schedule (Microsoft Project) is maintained and regularly updated. Total FTE commitments have been leveled and checked for consistency with available workforce. After recent adjustments, total workforce in the schedule allows comfortable margin with respect to the FTE levels allocated at each institution.

The Product Assurance program is a recent addition to the APP and it is yet to be determined how this will be tracked and reported.

5.1.3 Design Changes

In addition to changes in Functional Requirements (discussed in Section 5) the APP Organizer tracks significant design changes. Two such changes have been approved since PDR (see *APP Organizer*). One involves a modification of the PIC to cover more channels, in response to RFA #51, in anticipation of future eVLBI usage. Another involves the change from the ROACH-1 to the more capable ROACH-2 platform, triggered by donations of the necessary chips from Xilinx.

5.1.4 Resource loaded schedule

The current schedule is aggressive, targeting completion of APP commissioning and subsequent data analysis and reporting by end of calendar year 2014. At this juncture, ALMA would be declared ready for phased operation in Bands 3 and 6. While sufficient resources exist to accommodate slippage, it is noted here that the EHT 1.3 mm VLBI observations of Sgr A* typically occur in the March; If the McKinnon Plan is to be followed, pathfinder observations by EHT would likely have to be proposed for spring of 2015 or deferred for a full year to spring of 2016.

The critical path flows through PIC firmware development and software commissioning. The latter is a particular risk area, as it must conform to the ALMA software testing cycles in late 2013 and early 2014. These are typically at two-month centers, and are not yet defined for this period.

The major change from PDR (aside from dropping the third, Band 7 commissioning observation) is the "featurization" of the software development process. These features are defined in detail in the Computing Management Plan; 25 groups of features are color coded in the Gantt chart to feed into one of 5 planned software release cycles. Two additional features that are used only for post-observation processing do not need to be submitted to these cycles.

5.1.5 Actions, Liens, Risks, and Problems

Since PDR, 58 actions have been tracked and 49 have been closed. The remaining 9 are expected to close by CDR, with the possible exception of a planned analysis of phasing performance in poor weather using actual observational data. Others outstanding at this writing include identification of bad-weather ALMA data; pricing of a maser service contract; obtaining sign-off from the Chief Scientist on a VLBI operational model; testing a microprocessor interface in the ROACH-2; obtaining a quote and placing an order for Mark 6 recorder hardware; defining a test for dispersive fiber losses; and determining who will implement the code for polarization correction in DiFX.

One lien has been resolved, the cost of seismic outfitting of the maser rack, while two remain open. One of those pertains to costs of supporting the ALMA acceptance process, which remains unclear. The second is a need for an additional 0.5 FTE at MPIfR, which is likely a question of identifying available staff rather than a funding shortfall.

Two project risks have been retired, Mark 6 readiness and a data simulator development delay at ASIAA, while three remain open. The aforementioned manpower shortage at MPIfR and the possibility of burgeoning costs of software acceptance are also reflected in the lien list. The remaining risk is associated with the anticipated loss of CSV personnel at ALMA as it transitions to operational status.

Eight problems have been tracked, all but two closed. Both are minor: An intermittent failure in a test fixture board, and a failure of the first run of a data simulator at ASIAA.

5.1.6 Resolving PDR RFAs

The PDR Review Board chair specified the minimum criteria for closing RFAs, which APP has met or exceeded in all cases. Initially, the 48 RFAs were sorted into three groups: Accept (28), Advisory (16), and Rejected (4). Rejections were only assigned in rare cases where the request was clearly out of scope. Advisory status was assigned when the request was not directly actionable or out of scope but potentially achievable within existing resources. For all Advisory or Accepted FRAs, propositions for closure were sent to the reviewer, providing an opportunity for concurrence or comment within a fixed time period but not requiring such a response.

Closing an RFA requires only a plan of action, not necessarily implementation of that plan. In many cases, the RFA is closed by assignment of an action to be tracked by the project.

At the time of this writing, all but one RFA is either closed or awaiting reviewer concurrence.

5.1.7 APP Safety and Product Assurance

APP has established a Product Assurance (PA) program to ensure compliance with ALMA PA policies while minimizing impact on the ALMA development and observation schedule as well as risk to the ALMA facility. The QA plan includes requirements for testing, reliability analysis, parts and materials qualification, and system safety, and requires ALMA concurrence.

The following ALMA documents have been identified as having concrete, itemized requirements relevant to APP PA. These will be itemized in the next release of the PA plan, and verification that these have been met will be reflected in the next release of the Integration and Test Plan.

- General Safety Design Specification (ALMA-10.08.00.00-003-B-SPE)
- System Technical Requirements (ALMA-80.04.00.00-005-B-SPEALMA)
- System Electrical Design Requirements (ALMA-80.05.00.00-005-C-SPEALMA)
- System Electromagnetic Compatibility (EMC) Requirements (ALMA-80.05.01.00-001-B-SPEALMA)
- Product Assurance Requirements (ALMA-80.11.00.00-001-D-GENALMA)
- Environmental Specification (ALMA-80.05.02.00-001-B-SPEALMA)

The following documents do not have specific, itemized requirements, but are being reviewed for essential reference information:

- Operations Plan (ALMA-00.00.00.00-002-A-PLAALMA)
- Seismic Design Specifications for ALMA-AOS and ALMA-OSF (SYSE-80.10.00.00-002-B-REP)
- Reviews Definitions, Guidelines and Procedure (ALMA-80.09.00.00-001-D-PLAALMA)
- ALMA Interface Management Plan (ALMA-80.07.00.00-001-D-PLA)

6 Design status

6.1 Brief APP Technical Design Summary

The general methods for phasing arrays of antennas are well understood; phasing systems for several mm and submm arrays including the Berkeley Illinois Maryland Array (BIMA), the Owens Valley Radio Observatory (OVRO) array, and the Plateau de Bure (PdeB) array have been implemented to enable VLBI observations (Bower *et al*. 1997, BIMA Memo Series, 52; Torres 2000, Proc. SPIE, 4015: 96-105). These systems were used in early 1.3 mm and 3 mm wavelength VLBI observations of Sgr A* (Krichbaum *et al*. 1998, A&A 335: L106-L110; Doeleman *et al*. 2001, ApJ, 121: 2610—2617). More recent efforts focused on building a beamformer for the Submillimeter Array (SMA) on Mauna Kea, which is now able to coherently sum all the submm apertures on the Hawaiian summit, including the James Clerk Maxwell Telescope (JCMT) and the Caltech Submillimeter Observatory (CSO) for VLBI work (Weintroub 2008, J. Phys. Conf. Ser., 131, 012047). A similar system has been adapted for use at the Combined Array for Research in Millimeter Astronomy (CARMA) with the primary application being 1.3 mm VLBI of Sgr A* and M87.

The following are essential features of the plan for ALMA phasing:

- Correlator upgrades are in parallel with the existing hardware/firmware and do not affect the normal data path
- Only relatively minor software enhancements to the ALMA code base are required.
- All of the phasing corrections are performed in the correlator and supporting computer system with no front-end or Local Oscillator modifications required.
- Development of the system is fault-tolerant in that the critical path involves minimal risk to commissioning
- No new technical development is required for the project (i.e. this plan involves a straightforward implementation of existing technologies).
- The phasing system includes a commercial hydrogen maser to provide a high stability, spectrally pure frequency standard to ALMA for routine operations as well as VLBI.
- ALMA operates normally during VLBI observations so that all of the normal interferometric capabilities of ALMA are available while the VLBI data is being captured.

Additional design detail can be found in the APP Project Plan.

6.2 Hardware design status

New hardware subsystems to be delivered include the maser, the optical fiber link, the PIC, and the Mark 6 recorder, as well as planned firmware upgrades to the ALMA correlator. All of these are at a level of maturity exceeding what is typical for a CDR and, as a result, a Manufacturability Review has been waived. The maser is a commercial item (already procured); the optical fiber link is assembled from purchased components (already integrated and in test); and the PIC is a straightforward electronic design centered around a commercial CASPER ROACH 2 board (already fabricated and integrated, with FPGA firmware and personality under development).

6.2.1 Maser

A Hydrogen Maser supplied by the APP will serve as the frequency reference for the entire ALMA facility. The APP has procured a modern Hydrogen Maser frequency standard (an iMaser 3000, commercially available from T4 Science) to be installed at the AOS. Space for this unit (WxDxH is 60 x 80 x 95 cm, 100kg weight) at the AOS has been identified; it requires 100W in normal operations and has a warrantee extendible in 7-year increments.

This maser provides two 5 MHz and four 10 MHz sine-wave outputs (13 dBm at 50 ohm) and a TTL compatible 1PPS signal. The current Rubidium frequency reference will be retained as a facility backup for the maser, which will enable ALMA to quickly recover from a failure of the maser.

The maser is currently at Haystack Observatory, and is available for shipping to ALMA at any time (it will not be used for Charlottesville testing). Since PDR, the major activity has been to define interfaces, including specific cable runs, and (in response to an RFA) to characterize the signal from the Central Reference Generator (CRG), which is fed by the maser 5 MHz signal. It was found at that time that the 10 MHz signal from the CRG to the Local Oscillator suffers from thermal drift and noise, and is inadequate for VLBI. A plan to replace that signal with the 10 MHz signal directly from the maser was accepted by the ALMA System Engineer. This will make the process of switching back to the existing Rb clock (in the event that the maser suffers a malfunction) slightly more complex. Other signals (e.g., 5MHz, 125MHz, 2GHz) output from the CRG were found to be acceptable.

The outstanding issue with respect to the maser is seismic engineering. The University of Concepcion is familiar with conditions and requirements in Chile, and has taken responsibility for this task.

For additional detail, see *maser_dspl*.

6.2.2 Recorder

The Mark 6 is the latest in a line of digital recorders for VLBI, increasing the recording rate to 16 Gb/s per unit. Four Mark 6 units will be required for APP. Haystack Observatory works closely with the vendor, Conduant, to define the hardware configuration, and the software is provided directly by Haystack. In addition to speed and capacity, the Mark 6 is the first in the line to be based entirely on commodity electronics, and will therefore be easily maintainable.

The Mark 6 is in the final stages of development under another program. Basic specifications have been met and hardware components have been selected. Configuration of the Mark 6 units for APP will require some integration and testing of the software at Haystack Observatory. Procurement of the components is in progress. For the purposes of APP, the Mark 6 is considered a commercial unit and its development is not under review at CDR. Performance characteristics are described in *Mark6_users_manual_draft*.

6.2.3 Fiber Optic links

The Optical Fiber Link system transmits the antenna sum data from the AOS to the OSF. Eight 10 GbE data streams are wavelength- division-multiplexed onto one fiber at the AOS for transmission to the OSF, where it is demultiplexed and routed to the appropriate recorder sub-system. The optical fiber link system(a pair of a transmitter and a receiver) is fully symmetric and the two devices are inter- changeable. The device is a passive participant in the VLBI phasing system, with no packet monitoring capability.

The multiplexor and demultiplexor units have been procured, integrated, and delivered to NAOJ, where it is undergoing network connection and reliabilitytesting. Details of the design are provided in ALMA-05.11.40.01-0001-A-DSN, and test results are provided in ALMA-05.11.40.02-0001-A-xxx.

6.2.4 Phasing Interface Cards (PICs)

The NRAO (Charlottesville) ALMA Correlator group is carrying out PIC development under NSF funding. The PICs serve as the VLBI backend for ALMA, aggregating all coherent sums and formatting the data in a standard VLBI Data Interchange Format (VDIF). Resulting 10 GbE packets are sent to the fiber optic link system for transport to the VLBI recorders at OSF. A maser-derived 1PPS tick (whose alignment with GPS is known) is used by the PICs to ensure synchronization with other VLBI sites around the globe.

The main function of the PIC is to format the phased sum data into frames suitable for recording. It maintains the "look and feel" of the correlator (standard timing signal interfaces, form factor, etc) to simplify software development and mechanical constraints. The PIC includes the standard ALMA Correlator microprocessor and the standard connection to the Correlator Bin Motherboard. The ROACH2 provides the signal processing power, in the form of a large FPGA, for formatting the data.

Prototype PICs have been received at NRAO, including adapters and connectors necessary for testing. Basic acceptance tests have been completed and all ICD details defined. ROACH FPGA firmware is now under development.

A general description is provided in the Phasing Interface Card Manual.

6.2.5 Correlator upgrades

The correlator upgrade is solely for the purpose of directing ALMA data to the Phasing Interface Cards (PIC). It involves a firmware modification to the summing logic in the Correlator Cards, which provides the sum of the antenna signals in the 2-bit format required by the PICs and Correlator Interface Cards (CIC). The new Correlator Card FPGA personality (under development at NRAO) will facilitate the formatting and testing of the output sums. The addition of up to 64 2-bit values is represented with 8 bits using a tree of adder chips. The final 2-bit sum of N antennas is achieved by scaling via a lookup RAM in the Xilinx. This logic is applied to each of the 32 channels to provide the signals sent to the PIC. In the interest of testability, it is possible to substitute pseudo-random data or an incrementing count for the sum data.

The CIC Xilinx personality was modified *before delivery of the fourth quadrant* to accept an alternate input for "antenna 64". The antenna sum will be routed to this alternate input, providing the capability of correlating the sum against any of the other 63 antennas connected to the correlator. This important test feature is useful in evaluating the effectiveness of the phasing..

Approximately 275 LVDS cables will be routed in the existing cable trays in the correlator to transport the sum signals and timing signals to the PICs. The PICs will also be cabled into the multi-drop bus. Two small modules will be added to one of the computer racks to distribute Maser and GPS 1 PPS signals to the PICs. A 1-PPS distributor, a GPS receiver, and a PIC power supply will also be provide

6.3 Software Design status

Code development and testing is distributed among NRAO, Haystack Observatory, MPIfR, and ASIAA. The overall software development is led by MIT-HO, supported by the ALMA Software group at NRAO (Socorro), which is funded from the ALMA Development Fund at a level of 1.5 work years, including a 25% contingency.

Important developments resulting from ALMA Board approval of APP and realized through Technical Interchange Meetings at ALMA and at Bonn include:

- Access to ADC resources including CVS, Twiki, JIRA, and STE
- Management and release integration support
- Construction of remote software development systems.
- Consultation on TelCal and ALMA GUI software development (ESO Grenoble).
- Restructuring of software development in terms of "features" to be validated and integrated into the ALMA core software

6.3.1 Device control

Three new Control Devices (hardware components) are being added to ALMA, each requiring a device software abstraction. The maser runs autonomously, producing status data but requiring no commanding. The PICs reside in the four ALMA correlator quadrants, accepting commands from and providing monitor data to the CCC computer using the same CAN buses as the remainder of the cards in the correlator, but with new protocols. The standard ALMA data process is unaffected, running in parallel to the PIC processing. The data generated by the PIC card in the ALMA correlator (high site) is passed directly to the VLBI recorders (low site) via an optical fiber link. The optical fiber system, like the maser, is always operational, but may produce some health data to be monitored. Aside from some configuration commands, the recorders mostly receive simple scan start/stop commands.

Device Control is under development at MIT-HO.

6.3.2 Observing Mode

The VLBI Observing mode (VOM) is the ALMA observing mode to be used for VLBI operations. The VOM is an enhancement of the existing Single Field Interferometry Observing Mode, adding two new controllers and modifying an existing one. It requires new interfaces, specified through the Interface Definition Language. VLBI mode and phasing mode are implemented in separated controllers, allowing the phasing system to work independently of VLBI observations. See ALMA-05.11.61.01-001-A-DSN for additional description.

Observing Mode is a joint development of MIT-HO and NRAO.

6.3.3 Correlator Development

New commands will be added to the correlator to provide new features (Long Term Accumulator Protocols), support for the PICs, and revisions to the tunable filter bank protocols to facilitate phasing corrections. The correlator side of the phasing loop and the fast loop calculations are also a part of this package. In addition, minor simulation infrastructure changes are provided to support development.

Correlator Development is primarily the responsibility of NRAO, with MIT-HO contributing to the phase update routine.

6.3.4 Phase Solver (TelCal)

Phase Solver is the phasing system that computes and publishes the phasing solutions to be consumed by the VOM and eventually forwarded to the Correlator subsystem. TelCal will also provide in- formation about the quality of the obtained phasing solutions and will respect manual/automatic weighting/masking of antennas.

In parallel with routing data to the recorder, the correlator continues to produce its normal correlation products. Correlated baseline data are transferred to the Correlator Data Processor (CDP) computer cluster, where the complex visibilities are sent to a new phasing software routine coded within the CDP and TelCal systems. This solver routine uses the phases of the baseline visibilities to solve for residual antenna phases ($\Delta\phi$), which are then transmitted to the TFB cards to correct the input antenna signals. The TelCal computer also estimates the phasing efficiency and the atmospheric coherence. To close the feedback loop, the antenna phase solutions are sent to the Correlator Control Computer (CCC), which commands the TFB to apply the solutions.

The phase updates are calculated by the phase solver software, which takes the channel-averaged data from the ALMA correlator and generates periodic phase shift updates. The phase solver is implemented within the TelCal component, which uses these data products for calibration purposes and thus already supports the necessary data interfaces. It generates a linearized solution that the CDP uses to generate fast time scale phase shift commands for the TFB. Finally, the summed product is fed back into the ALMA correlator for a real-time correlation with one selected antenna, which is monitored to determine and report the efficiency of the phase solver in real time and make appropriate adjustments.

Implementation and release of the Phase Solver component will be realized in several steps by incrementally adding in more advanced features. Phase Solver is the responsibility of MPIfR. See *ALMA-05.11.62.01-001-A-DSN* for additional information.

6.3.5 Polarization Calibration

ALMA receivers are dual orthogonal linear polarization, while other VLBI sites record dual circular polarization. Circular polarization avoids getting polarizations crossed during correlation due to parallactic angle differences between VLBI stations.

Polarization calibration will be implemented in DiFX (see Polarization Conversion for ALMA Phasing), and is a joint responsibility of MPIfR and ASIAA.

6.3.6 VLBI Scheduling

To avoid modifications of the existing ALMA Scheduling subsystem, APP software ingests VLBI scheduling instructions in the form of a VLBI Experiment file (VEX), and converts it to an ALMA VOM file. The VEX file contains a description of the configuration of all of the participating VLBI sites, the timing of the scans to be recorded, and other ancillary information. The VOM interacts with the ALMA operators through a new status panel incorporated into their existing displays. Since each session runs synchronously with the remote stations, there is no actual commanding for the operators, except perhaps for extreme contingencies.

In order to better balance workforce, responsibility for VEX to VOM translation was recently transferred from MPIfR to a new staff member at MIT-HO.

6.3.7 Graphical User Interfaces (GUI)

The APP requires enhancements to the existing development and operator GUIs to monitor status of the several components in the APP system and to perform some corrective actions.The GUIs are being implemented at MPIfR

6.3.8 Post-processing (DiFX)

The VLBI Correlator software (DiFX) requires certain enhancements to allow the correlation of ALMA VLBI data. This is not a deliverable to the ALMA software system. DiFX modifications are being provided by ASIAA (see *APP_post-processing.pdf*)

Acronyms

ALMA	Atacama Large Millimeter/Sub-millimeter Array
ALMA-NA	ALMA North America
AOS	(ALMA) Array Operations Site
APP	ALMA Phasing Project
ASIAA	Academia Sinica Inst. of Astron. and Astrophys.
CASPER	Collaboration for Astronomy Signal Processing and Electronics Research
CDR	Critical Design Review
CIC	Correlator Interface Card
COTS	Commercial Off-the-Shelf
CRG	Central Reference Generator
CSV	Commissioning and Science Verification
CVS	Concurrent Versions System
DiFX	Distributed Fourier Transform (Correlator)
EDM	Electronic Document Management
EHT(E)	Event Horizon Telescope (Experiment)
FPGA	Field Programmable Gate Array
FTE	Full Time Equivalent
GbE	Gigabit Ethernet
GPS	Global Positioning System
GUI	Graphical User Interface
ICD	Interface Control Document
ISDR	Incremental Software Design Review
JAO	Joint ALMA Office
LVDS	Low Voltage Differential Signaling
MIT-HO	Mass. Inst. of Tech. Haystack Observatory
MMR	Monthly Management Review
MPIfR	Max Planck Institute for Radio Astronomy
NAOJ	National Astronomical Observatory of Japan
NRAO	National Radio Astronomy Observatory
OSF	(ALMA) Operations Support Facility
PA	Product Assurance
PI	Principal Investigator
PIC	Phasing Interface Card
PDR	Preliminary Design Review
PM	Project Manager
PPS	Pulse Per Second
RID	Review Item Discrepancy
RFA	Request for Action
ROACH	Reconfigurable Open Architecture Computing Hardware
TBR	To be revisited
TRR	Test Readiness Review
VEX	VLBI Experiment File
VLBI	Very Long Baseline Interferometry
VOM	VLBI Observing Mode
WBS	Work Breakdown Structure