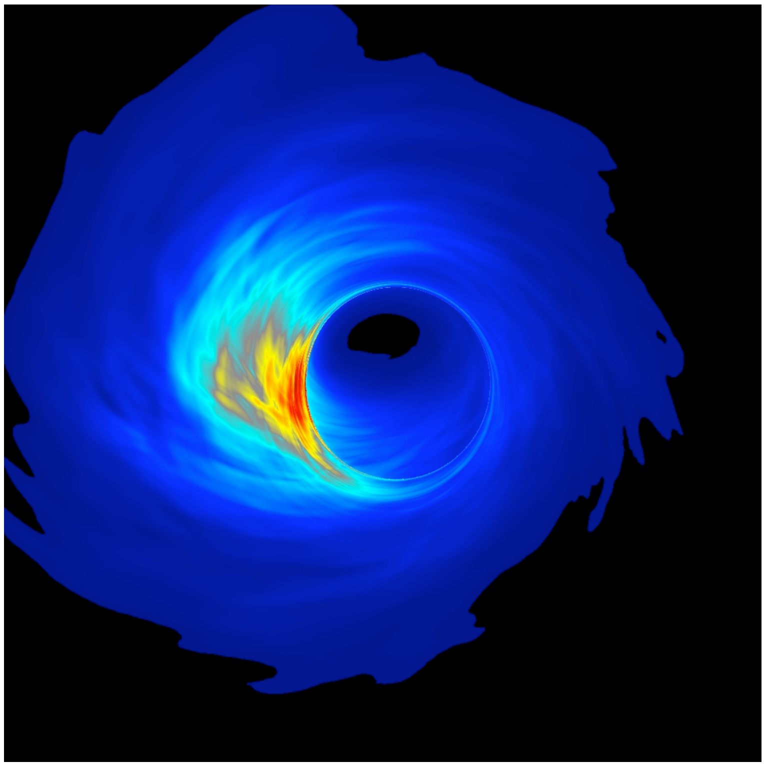
Phasing ALMA for (sub)mm-VLBI Observations

Enabling an Event Horizon Telescope



A proposal for consideration by the ALMA Board
Submitted by a collaboration including:

MIT Haystack Observatory
Harvard-Smithsonian Center for Astrophysics
National Radio Astronomy Observatory
National Astronomical Observatory of Japan

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Executive Summary

A long-standing goal in astrophysics is to directly observe the immediate environment of a black hole with angular resolution comparable to the Event Horizon. Realizing this goal would open 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 an event horizon, and fundamental black hole physics (e.g., spin). *Steady long-term progress on improving the capability of Very Long Baseline Interferometry (VLBI) at short wavelengths has now made it almost certain that this goal will be achieved within the next decade.* The most compelling evidence for this is the recent observation using 1.3mm VLBI of Schwarzschild radius scale structure in SgrA*, the 4 million solar mass black hole candidate at the center of the Milky Way (Nature, v.455, p.78, 2008). This new 1.3mm VLBI detection confirms that short wavelength VLBI of SgrA* can and will be used to directly observe an Event Horizon.

Of all the sites that will join mm/submm VLBI arrays in the coming years, the most essential (indeed the *sine qua non*) is ALMA. With its 50+ dishes (most 12m in diameter) it represents the single largest collecting area of any submm telescope. Any VLBI baseline that includes ALMA will easily detect SgrA*, even over the longest distances. Thus, ALMA single-handedly ensures that the VLBI array will be capable of functioning as a single instrument. No other facility can assume this synthesizing role.

This document outlines a project to implement VLBI capability at ALMA that will phase up all the array dishes. Major elements of the project include:

- Software integration of a VLBI observing mode
- Development of a digital VLBI backend to process ALMA correlator output
- Software to solve for delays and phases to coherently sum all antenna signals
- Procurement/installation of a VLBI frequency reference (e.g., hydrogen maser)
- Illumination of optical fibers that link the AOS to OSF for transfer of VLBI data
- Procurement/installation of VLBI recorders at the OSF site
- Tests to ensure that the ALMA LO is sufficiently stable for VLBI

This project has been conceived by an international group including members from MIT, NRAO, Harvard-Smithsonian CfA, and NAOJ, which has worked together to establish a baseline design and preliminary estimates of required effort and support. We will seek funding to support all activities and hardware associated with implementation of the phased VLBI capability, including any support from ALMA staff. Personnel resources to execute the major development tasks will primarily be drawn from the university-based groups. Nevertheless, access to ALMA-specific expertise and knowledge will be necessary, primarily in the area of software integration of the VLBI mode with ALMA systems. To ensure that this support does not impact the ALMA construction schedule in any way, we will coordinate our project plan carefully with ALMA management, and phase our tasks to match ALMA resource availability.

This proposal requests approval from the ALMA Board for this project to become a sub-system of ALMA to be designed, built, and integrated as outlined herein. While some details of the project require further study, our in-depth initial assessment indicates the technical plan is sound and the timeline reasonable, with no high-risk technical hurdles.

VLBI Science with ALMA

We will not discuss at length the science case for enabling VLBI at ALMA, but will point out that a detailed discussion of using (sub)mm-VLBI to image super massive black holes on Schwarzschild radii scales is presented in a White Paper submitted to the ASTRO 2010 US Decadal Review Committee:

http://www8.nationalacademies.org/astro2010/DetailFileDisplay.aspx?id=106

This White Paper also covers the exceptional promise of (sub)mm-VLBI using ALMA to probe the jet-launching region of the nearby AGN, M87, whose well-studied relativistic jet is powered by a ~6.4×10^9 Solar Mass black hole. In addition to the topics covered by this white paper, (sub)mm-VLBI opens up a part of the spectrum that is rich in molecular and atomic maser transitions. Many of these maser lines exhibit bright and spatially compact emission, providing unique probes of dynamics and physical conditions in proto-stellar and evolved star environments.

Introduction

Phasing all the ALMA dishes together to allow ALMA to act as a single large VLBI aperture will require the array to operate in a specialized mode and provide a specialized data product. New software to monitor and control this observing mode will have to be written, as will lower level software for sub-system tasks necessary while doing VLBI. Post processing software must be coded to calculate the antenna-based phases and delays to create a coherent sum of all antenna signals. On the analog hardware side, tests of the Local Oscillator and IF systems will have to be carried out to ensure that the absolute phase stability is sufficient for VLBI. It is already known that the Central Variable Reference currently in use will have to be upgraded for VLBI operations. An entirely new digital sub-system will accept phased sum output from the ALMA correlator and process the data for recording on the new generation of hard-disk based VLBI recorders (the Mark5c recorder). These recorders will be located at the OSF and linked to the AOS by optical fibers via the planned AOS-OSF fiber bundle.

These tasks comprise a significant effort, but several key factors make this project tractable, relatively low risk, and able to be implemented with minimal impact to ALMA construction. *First*, the most significant new hardware system, the digital signal-processing block to convert the coherently summed data to VLBI format, can be designed and built by non-ALMA personnel. Members of our team have already developed digital VLBI backends with much of the functionality required, and these prototype backends were used to make the successful SgrA* detections using 1.3mm VLBI. *Second*, both ALMA correlators were designed from the outset such that all the firmware and design hooks necessary to sum the signals from all antennas already exist -- the summed signal is already available from hardware connectors on the correlator. *Third*, though the software element of the project is complex, it can be phased in over time so that initial VLBI experiments will require only skeletal software support, with full software support coming in the later stages of the project. We emphasize that our goal is to secure non-ALMA funds to support all the effort described in this document, including required software development. *Finally,* members of our team have developed a coherent phasing system for the submm apertures on Mauna Kea (CSO, JCMT, SMA) that has already been used to obtain VLBI detections at 1.3mm on long baselines.

Requirements of the ALMA Phasing System

In normal operation ALMA will use a geometric model to bring the array into approximate phase coherence. Modeled delays are applied to compensate for path length differences to all the antennas based on array layout and observing details. Modeled differential Doppler frequency shifts are applied to each antenna to remove phase drift as a function of time across the array.

The VLBI phasing system will solve in real-time, for *residual* delays and phases to this model. These residuals are due primarily to the atmosphere above the array as well as instrumental effects. The atmosphere contributes to the delays and phases through rapid changes in delay as turbulent cells drift over the array. Such turbulence results in an atmospheric 'coherence time' during which the array can be expected to remain sufficiently phase stable for coherent VLBI summation of all antenna signals. As an example of how long a coherence time one might expect, we show in Figure 1 the fringe-rate spectrum of a detection made at 230GHz between two 10m CARMA dishes (100m baseline) in April 2009. The width of the fringe rate spectrum is ~5mHz, implying a coherence time of ~30 seconds. It is expected that at the ALMA site, coherence will be at least this good for much of the time (see M.A. Holdaway, MMA Memo Series, #169, 1997).

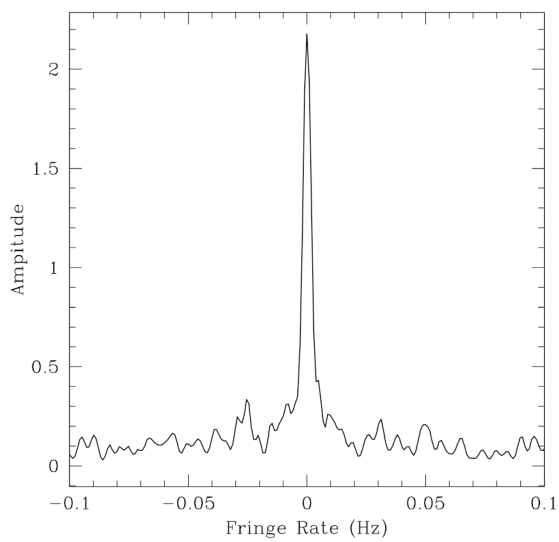

Figure 1: Fringe rate spectrum of 230GHz detection between two 10m CARMA dishes in April 2009.

The width of the fringe-rate spectrum can be used to find the expected magnitude of delay and phase corrections that will be incurred over 10 seconds (Table 1). For a spread in fringe rate (due to atmospheric delay changes) of ~25mHz, the residual phase at an antenna will change by 90 degrees, but the total change in delay to that antenna would only be ~1ps. It is important to note that a 1ps delay corresponds to a phase difference of only ~3 degrees over the full 8GHz of the ALMA IF, resulting in negligible loss in the coherent sum. Therefore, delay corrections due to the atmosphere will be made over long time scales (>100 seconds). However, the phase corrections will have to be made on much shorter time scales (1-10 seconds) to track atmospheric conditions as they change across the array.

Delay Rate (ps/s)	Fringe Frequency (mHz)	ΔPhase (cycles/10sec)	Phase Slope Deg/8GHz/10sec	ΔDelay (ps/10sec)
1.1	250	2.5	32	11
0.1	25	0.25	3.2	1.1
0.02	5	0.05	0.64	0.2

Table 1: Magnitude of delay and phase corrections over 10 second periods due to atmospheric conditions that produce various spreads in fringe-rate (at 230GHz).

General Operation and Design of the ALMA Phasing System

Figure 2 shows a high level block diagram of proposed VLBI operations at ALMA. In this diagram, all pink blocks are existing ALMA systems/hardware, and blue blocks indicate new systems/hardware to be built, developed, or procured. The fundamentally new operation in VLBI mode is to use all the baseline correlations formed in the ALMA correlator to solve for phase and delay corrections, which are then applied to each antenna *in real time* in order to coherently phase the array. In Figure 2, the points at which these corrections are applied are shown in red-outlined boxes.

A VLBI-quality frequency standard (a Hydrogen maser in Fig. 2) provides a 5/10MHz stable tone to the ALMA LO system. This tone locks the Central Variable Reference and the entire photonic LO reference in the Central Electronics system, which is distributed to the antennas. Once in the Antenna Electronics system, the first LO is synthesized and the IF directly sampled. In the Antenna Electronics, the FLOOG (First LO Offset Generator) synthesizers are used to make the phase corrections required to phase the array, and the samplers (one for each polarization) are used to implement the extra-fine (15.625ps step) delay corrections. In the Station Electronics Block, a bulk delay correction (16ns resolution) is made in the Station Cards, and a fine delay correction is made in the Tunable Filter Bank cards (0.25ns steps). The correlator produces normal ALMA data products, which are transferred to the CDP computers for processing (FFT, Quantization Correction, Normalization, and Integration). At this point new phasing software (most probably not directly coded by ALMA personnel) will use the data from the CDP to solve for phase ($\Delta\phi$) and delay ($\Delta\tau$) corrections, which are ultimately used to modify the settings for the FLOOG, IF samplers, Filter Bank cards, and Station cards.

In parallel with the normal data sent to the CDP, the ALMA correlator will also form the coherent sum of all the antennas. The favored option at this point is to run the ALMA correlator in a standard Frequency Division Mode (FDM) in which the summed signal is channelized into 62.5MHz slices. Each quadrant of the correlator will provide 2 GHz BW in each of two polarizations for a total potential aggregate bandwidth of 16GHz. When Nyquist sampled and quantized to 2 bits, this represents a total VLBI data rate of 64Gbits/sec. This summed output will be sent to a new hardware system called the VLBI Digital Backend, where it will be processed using real-time DSP to produce data in 10

Gigabit Ethernet (10GbE) packets suitable for recording on the current generation of VLBI recorders. The VLBI backend will use a 1PPS signal from the GPS receiver to ensure synchronicity with other VLBI stations around the globe. At this point it is assumed that the VLBI recorders, which use banks of hard disks, will be located at the OSF. If provision can be made to locate them at the lower site, pressure containers for each recorder would not have to be built, and personnel can change out hard-disk modules during night-time observations.

Flux density thresholds for VLBI observations will make it very likely that target sources will be bright enough to obtain phasing solutions in real time. Thus, there will not usually be a requirement to slew to phase calibrator sources. Based on experience with phased array summing of submm apertures on Mauna Kea, the cadence for determining phase and delay solutions will be approximately every 10 seconds. However, provision should be made for cases where it is necessary to determine phase and delay solutions on a calibrator source, then re-point on the target source, slewing back and forth on ~10 second time scales. In addition, during normal VLBI observations, ALMA must apply normal geometric and differential Doppler tracking (lobe rotation), which will serve to bring all the antennas to a virtual plane orthogonal to the observing direction.

<u>Sub-System Details</u>

1. **VLBI Observing Block – ALMA Control Computer(ACC)**
   A VLBI Observing Block will have to be defined to orchestrate all the operations required for VLBI within the ALMA Control Computer.
2. **Hydrogen Maser**
   The maser produces a stable 5/10MHz reference signal that drives the Local Oscillator system. During normal operation it requires ~200W of power and should operate within specifications if housed in the temperature controlled environment of the AOS electronics room. A battery back up system will allow the maser to operate for ~18 hours if power is lost. The maser produces monitor information that can be used to diagnose problems, and can receive a limited set of commands to change settings, all through a standard 1GbE interface. Initial VLBI operation will not require ACC control of the maser, but a final implementation of the VLBI mode will require a software interface to allow ALMA control/recording of these signals. *Our group has received funds to purchase a hydrogen maser, which can be used at ALMA.*
3. **Central Variable Reference**
   The CVRs currently in use at ALMA are not sufficiently low noise for VLBI and a different CVR will have to be used. The most straightforward option is to upgrade from the currently employed commercial Agilent synthesizers (E8257D) to a model with lower phase noise (E8257D with option 'UNX'). This would require *no new software* as the interface to the current Agilents would be sufficient. A second option is to design a new CVR, and that would require a new software interface for monitor and control. This second option would incur NRE costs, but would result in a system that is less expensive to duplicate and is tailored to VLBI specifications. In sum, there is a commercial plug-in

replacement solution for the CVR that will provide initial VLBI capability while we evaluate the option to build a new in-house version.

4. **First LO Offset Generator (FLOOG) and IF Samplers**
   As described in the section above on 'Requirements', the FLOOG for each antenna will be used to implement phase corrections on time scales of 1-10 seconds. For VLBI operation, no fundamentally new software is required to set the FLOOG and Sampler settings, but the values used to set the parameters for each of these systems will have to be modified based on the calculated phase and delay corrections for each antenna. The software that currently determines the FLOOG and sampler settings will have to be modified to accept additional input from the phasing algorithm and to generate new settings.
5. **Correlator**
   Most of the firmware to form the coherent sums over up to 64 antennas is already built into the ALMA correlator. What is required, though, is setup of an antenna mask that will control which antennas are combined into the sum. This will be specified within the VLBI Observing Block. In Figure 2, the correlator has been broken up into two parts: the station electronics and the baseline electronics. The station electronics includes the TFB cards (see below) and the Station cards. Both these correlator sub-systems are used in the normal ALMA data flow as well as for VLBI coherent summing. The baseline electronics includes the correlator planes, the Long Term Accumulator and Final Adder Cards, and also combines signals from all 64 stations into a coherent sum for VLBI. The aggregate output of each correlator quadrant will be 64 channels, each 62.5MHz in bandwidth. Each channel is 8 bits wide resulting in 64 x 8 = 512 LVDS pairs (1024 pins) from each correlator quadrant.
6. **Station Cards**
   The Station Cards in the Station Electronics Block of the Correlator will implement the bulk delay corrections, and will have to receive new settings based on the derived delay solutions. As with the FLOOG and Samplers, the basic software to control the Station Cards need not change, just the ability to change the settings communicated to the cards. In normal operation, the Station Card delay will likely only be set once per scan, with the delay changes to keep the array phased implemented in the Tunable Filter Bank Cards and Samplers.
7. **Tunable Filter Bank Cards (TFB)**
   The TFB cards will implement the fine delay corrections, so the software that controls these cards needs to be able to accept new inputs from the phasing software and generate modified setting values. In addition, the TFB cards may be used to implement a polarization specific phase adjustment to allow the two linear polarizations to be combined into RCP and LCP. It is not envisaged that the existing control interface to the TFB's would need change in order to carry out these tasks. Finally, application of gains for each antenna prior to summing will be implemented within the TFB's, and the control software will have to receive these new scalar gains and set the TFB's. This last requirement *does* require modifications to the TFB control software and/or correlator firmware.
8. **CDP**
   Currently, the CDP performs several post-correlation processing steps as shown

in Figure 2. It is not yet clear which of these steps are required to produce data suitable for determining phase and delay corrections. Thus, some of these steps may be removed from the normal data processing flow for VLBI observations to minimize computing load. The VLBI Observing Block will be tasked with any required setup of the CDP. In addition, depending on computing load, the phasing algorithms may be run on the CDP computers (see requirement below).

9. **Phasing Algorithm**
   The heart of the phasing system will be a software package that takes as input the normal baseline data products from the ALMA correlator, solves for residual delays and phases at each antenna, and then outputs these solutions to the ALMA Control Computer. The computation involved will be a real-time Global Fringe Fitting, which will use interferometric closure techniques. For example, if N antennas are to be summed within ALMA, then there will be ½(N-1)(N-2) independent closure phases (interferometric phase summed around a triangle of baselines). Since we seek to solve for (N-1) phases (one reference antenna need not be solved for), the problem is an over-constrained one that is amenable to standard least-squared techniques. The intent is to perform this function on-board the CDP computers, but should computing resources sufficient for normal ALMA operations *and* phasing algorithms not exist on the CDP, data from the CDP will have to be ported to a separate computing platform. A software interface between the phasing software and the ACC will have to be established. WVR data should be incorporated into the phase/delay solutions in real-time, so provision for a software and hardware link from the WVR system to the Phasing Algorithm computer will have to be set up.
10. **VLBI Digital Backend**
   The single largest new hardware system to be added to ALMA for VLBI observations is the VLBI Digital Backend (VDBE). This will primarily be DSP hardware that accepts phased sum data from the ALMA correlator using existing hardware connections and processes the data for recording. The VDBE will have a defined software interface (most likely 1GbE) for communication/control. The ALMA VLBI system will require an interface to communicate with the VDBE in order to set up VDBE modes and monitor some limited diagnostic data. It is not envisaged that the VDBE will have many modes. The VDBE will require a hardware input from the GPS 1PPS signal for synchronization. Since installing ¼ wave plates in front of each ALMA receiver to convert the linear feeds to circularly polarized feeds (the VLBI standard) is not likely to be feasible except for Band 7, it is planned for the digital backend to implement this conversion. The Digital Backend will accept as input up to 2048 LVDS pairs from the 4 correlator quadrants (see aggregate output in point #5 above).
11. **VLBI Recorder**
   The VLBI recorders accept 10GbE input lines from the VDBE. In the initial implementation of VLBI at ALMA, the recorders can operate in an autonomous but synchronous way in which a pre-loaded schedule on the recorders will turn recording on/off based on UTC time tags. A synchronous schedule specified as part of the VLBI Observing Block will orchestrate the rest of the ALMA system during VLBI operations. As VLBI operations continue, it may be preferable to

have the VLBI Observing Block fully control the recorders. In any event, the recorders communicate via a 1GbE link and have a specified software interface for control and monitoring that will need to accept and send input to the ALMA control software.

Estimates of Required Resources

At this stage, both NAOJ and MIT/CfA intend on proposing for funds to support this project. As submission of these funding proposals is pending approval of the project by the ALMA Board, it is premature to layout a detailed work breakdown structure. However, we have estimated below, the personnel time that would be required for the main project elements. Of the resources below, only a fraction will be required from ALMA personnel. Our best estimate at this stage is that 2 FTE years of ALMA software support would be required over the first 3 years of the project, and an additional ~1-2 FTE years of support from ALMA correlator and LO personnel over that same period.

1. **Software**
   The ALMA Software IPT has been apprised of this project, the design and details known so far. Their estimate is that the full integration of VLBI capability into the ALMA software environment would require 6-10 FTE years over the next 3-5 years. Discussions with the Software IPT indicate that a phased approach to the software may be possible, with support for initial observations requiring only a portion of the full effort, and implementation of the final software support after nominal ALMA operation is established. We envisage most of the software effort to come from new staff or other non-ALMA personnel, but clearly there would be some effort required on the part of ALMA software staff to coordinate and consult on the VLBI initiative.
2. **VLBI Digital Backend**
   The initial approach for the backend will be to use the newly developed ROACH hardware platform from the CASPER group. These boards are general purpose FPGA platforms that utilize the Virtex5 chip family. MIT Haystack Observatory is already collaborating with NRAO on a single-dish VLBI Digital Backend that uses the ROACH board. This new design will serve as the starting point for a backend tailored for use at ALMA. It is likely, given the large number of LVDS pairs to be received from the ALMA correlator, that a new board capable of aggregating the LVDS inputs onto a smaller number of data lines will be designed and built. We estimate a total of 6-8 FTE years for this effort, with the work started by MIT/CfA/NAOJ, but with increased participation by NRAO experts in ALMA correlator architecture as work on the ALMA correlator is completed. This subsystem should be completed within 3 years.
3. **Hydrogen Maser:**
   Funds for this component are already available, but installation will require interaction with the ALMA Front End IPT and the Site IPT. We estimate a total of ½ FTE year for all maser issues, largely borne by non-ALMA personnel.

4. **Phasing Algorithm Software:**
   This sub-system will operate on normal ALMA data products to solve for residual delay and phase offsets in quasi real-time. The algorithms themselves can be developed largely in isolation from ongoing ALMA software efforts, but integration with the ACC will require interaction with the ALMA software IPT. We estimate 3-4 FTE years for this effort. If a separate computing platform is required for this, then a software interface for data input and solution output will have to be developed.
5. **Optical Link from AOS to OSF:**
   The data from the VLBI Digital Backend will be in 10GbE packets. These data will be wave division multiplexed onto a single fiber and sent to the OSF for recording on Mark5C data recorders. Commercial solutions to illuminate fiber at the required data rates (up to 64Gb/s) already exist and it is expected that costs will come down considerably over the next 2-3 years. Therefore, we estimate an effort of 1 FTE year to engineer and implement a solution after the fibers have been installed.
6. **LO Components and Testing:**
   The additional requirement on the LO system (over and above nominal ALMA operation) is that the stability of the maser reference be maintained throughout. Should an element of the LO degrade or corrupt the stability of the reference, VLBI will not be possible. Based on the ALMA system specifications, it is expected that the LO system will be sufficiently stable for VLBI once the current CVRs are upgraded to a low noise model synthesizer. See point #3 in 'Sub-system Details' above. But tests to confirm LO stability will be required, and it may still be advantageous to design and build a separate CVR that meets the VLBI phase noise requirements. We estimate 3 FTE years for all LO issues and expect that half of this effort will require intimate knowledge of the ALMA LO system, and the other half expert knowledge of VLBI requirements. To confirm proper conversion from linear to circular polarization in the Digital Backend, it will be desirable to assemble a helix antenna to illuminate several ALMA antennas with a phase stable reference tone near 1.3mm wavelength.
7. **Project Management:**
   The FTE year estimates in items **1-6** above include the need for *strict adherence* to formal ALMA Project Management practices. It is understood that this project will establish an ALMA sub-system and must, therefore, produce ALMA-style documentation and will be subject to ALMA review. For this reason we will also budget an additional 3 FTE years over the project specifically for project management. The optimal location at which to base these project management FTE's will be determined by all the collaborating institutes in consultation with ALMA management.

VLBI Sub-System Ownership and Observing Policy

The hardware to be developed within this project will be tailored specifically for use at ALMA. Furthermore, in all future (sub)mm-VLBI arrays ALMA will play a leading role. Therefore, it is planned for the VLBI sub-system hardware to revert to ALMA ownership, and to remain with ALMA for use by the global astronomy community, after a period of testing and commissioning.

The VLBI Sub-System is conceived to be a new and important capability for ALMA, which should be accessible to the broad astronomy community. Because of the necessarily complex logistics involved in mounting global (sub)mm-VLBI observations, it is reasonable to assume that ALMA will negotiate with other (sub)mm-VLBI sites on observing windows and allocation of time for science projects. At longer wavelengths (>1.3mm), ALMA could join VLBI observations through participation in already existing networks (e.g., VLBA, GMVA). At shorter wavelengths (<=1.3mm), where established networks do not yet exist and organization of global arrays presents particular challenges (e.g., weather and mutual observing windows with other submm facilities), observations may focus on specific scientific targets. The Event Horizon Telescope (EHT), for example, is an international initiative that is planning to use submm-VLBI to study the SgrA* and M87 super massive black holes, and could serve as a coordinating body for the shortest wavelength VLBI networks.

Collaboration on this Project

At the moment, the principal collaborators on the project are CfA, MIT, NRAO, and NAOJ, but as the project moves forward, other institutes may contribute to the effort. As an example, we are in discussions with MPIfR (Bonn) regarding several aspects of the project and their potential contributions.

Estimated Timeline (2010 – 2014)

	2010	2011	2012	2013-2014
Control Software	Define Interfaces	Code skeletal control of LO, and first iteration of VLBI Observing Block	Code feedback loop for phasing control.	Add control of all VLBI elements.
VLBI Backend	Simulate circular polarization reconstruction and re-clocking algorithms. Establish signal interface with correlator.	Complete and simulate overall design.	Complete firmware and hardware. Testing.	Install sub-system at AOS. Testing
Phasing Software	Test algorithms for phase/delay solving. Use SMA data for testing.	Design overall software system.	Tests of phasing system with ALMA data	Full integration with ALMA control system.
Local Oscillator	Tests of LO components in lab. Order 3 new Agilent E8257D with UNX option.	Tests of LO system on-site as part of full system. Design of new CVR.	Helical antenna test tone for LO injection tests and polarization purity tests.	
Optical Link			Procure and install hardware to illuminate fiber for VLBI data transfer.	Integrate with ALMA control system.
Hydrogen Maser	Order maser for ALMA site.	Install maser at AOS.		Tie in to ALMA control with software switch for alternate reference.

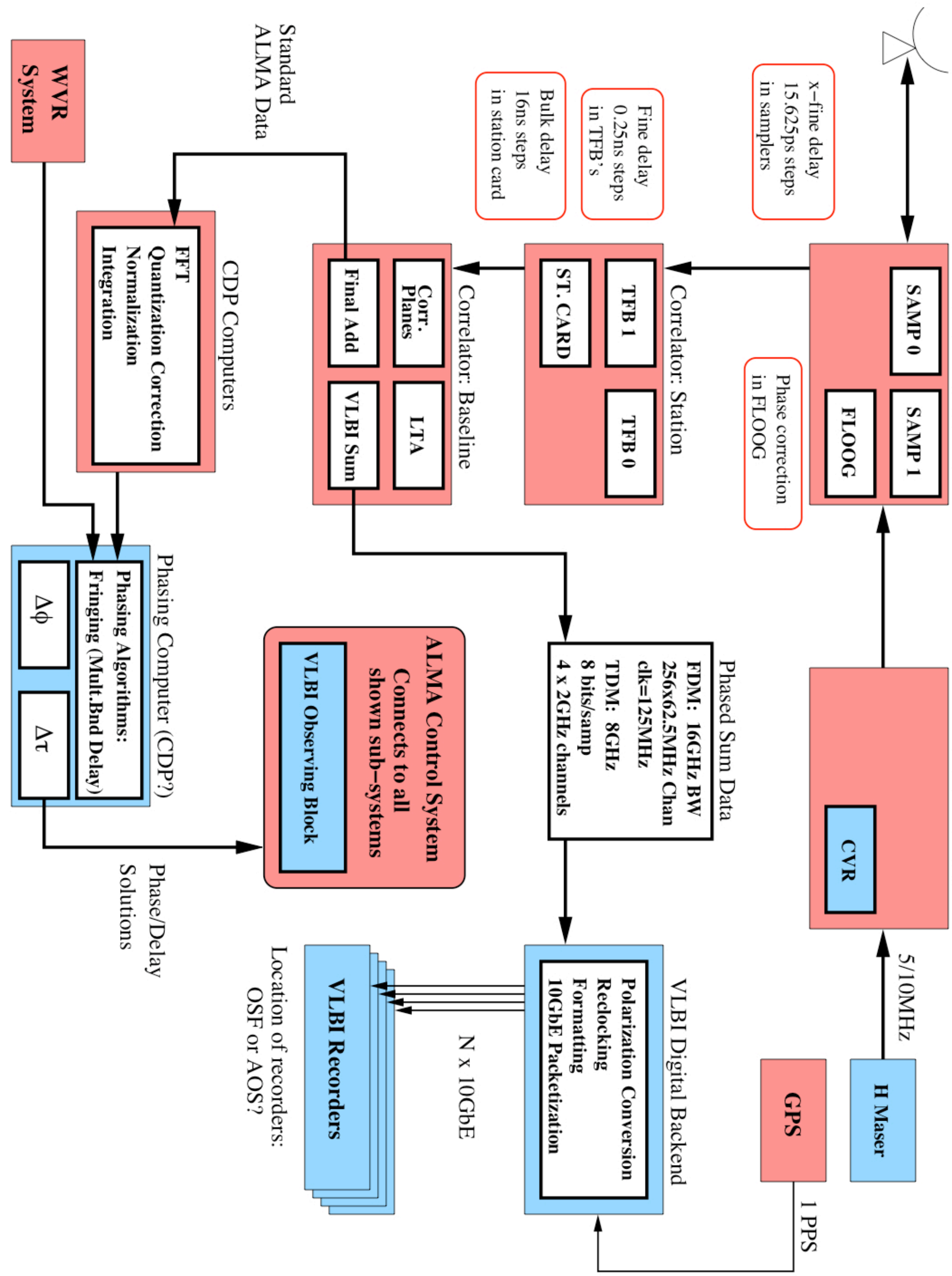

Figure 2: Functional Block Diagram of Phasing System for ALMA VLBI Operations.