An ALMA Beamformer for VLBI and Phased Array Science

Shep Doeleman[1], John Webber[2], Rich Lacasse[2], Ray Escoffier[2], Makoto Inoue[3], Walter Alef[4], Mareki Honma[5], Neil Nagar[6], Alain Baudry[7], Jonathan Weintroub[8], Rurik Primiani[8], Jeff Kern[2], Joseph Greenberg[2], Alejandro Saez[2], Alan Whitney[1], Geoff Crew[1], Roger Cappallo[1]

[1]MIT Haystack Observatory, [2]NRAO, [3]ASIAA, [4]MPIfR, [5]NAOJ, [6]U. Concepcion, [7]U. Bordeaux & ESO, [8]Harvard-Smithsonian CfA

Abstract

Phasing all of the 12m ALMA dishes together will enable the array to function as a single telescope with an effective aperture of ~85m diameter. In conjunction with other (sub)mm wavelength facilities, a phased ALMA will serve as the high sensitivity anchor for (sub)mm VLBI arrays capable of resolving super massive black holes on Schwarzschild radius scales. At longer wavelengths (7/3mm), inclusion of ALMA in existing VLBI networks will enable high sensitivity AGN and astronomical maser studies. A phased ALMA will also be a sensitive pulsar/transient observatory with the ability to search for shallow spectrum pulsars towards the Galactic Center and study known high frequency magnetars with sub-ns time resolution. A detailed plan and design has been developed with resources for implementation now secured by an international group. Work will begin in Fall 2011 with a target of first phased array science projects to be carried out with ALMA within 3 years.

Event Horizon Science

- Previous epochs of 1.3mm VLBI (2007, 2009) confirm existence of ~4 Schwarzschild radius structure in SgrA*, the super massive black hole at the Galactic Center.
- New VLBI results show strong evidence for time variability of this compact structure (Fig 1; Fish et al, ApJ, v727, L36, 2011).

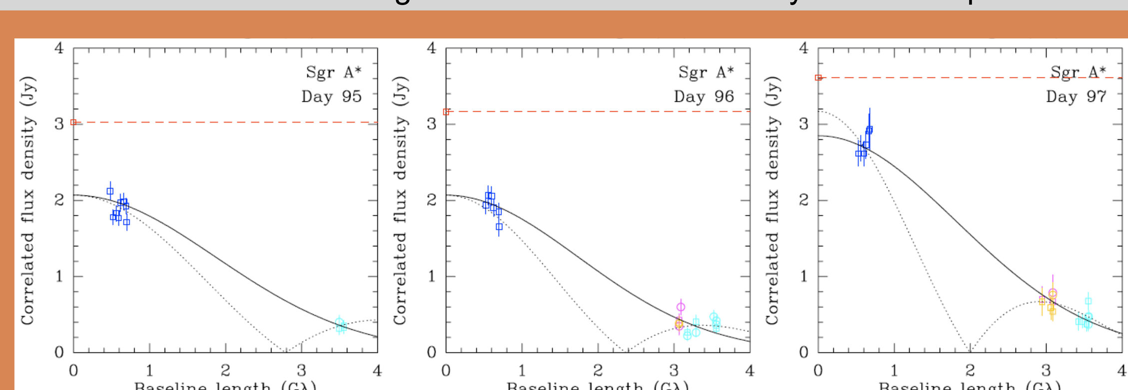

Fig. 1: Correlated flux density vs Baseline length for the April 2009 1.3mm VLBI observations of SgrA*, which used a three-station array: ARO/SMT, CARMA, JCMT. The solid black curve shows a 43μas Gaussian model of the compact emission for SgrA*, while the dotted lines show ring models. On days 95, 96 the structure and flux density of SgrA* was stable, while on day 97 the flux density of SgrA* increased on all VLBI baselines, indicating a brightening on scales of a few Schwarzschild radii.

Assembling an Event Horizon Telescope (EHT)

- Including ALMA in current (sub)mm VLBI arrays increases sensitivity by x10 and doubles angular resolution.
- By monitoring VLBI 'closure' phases, ALMA-anchored VLBI arrays can track hot-spots in the SgrA* accretion flow (Fig 2).
- New arrays can place tight constraints on spin and inclination of the SgrA* black hole (Broderick et al, ApJ, v735, 110, 2011).
- As more (sub)mm dishes join the VLBI array (anchored by a phased ALMA), true imaging of SgrA* becomes possible (Fig 3).

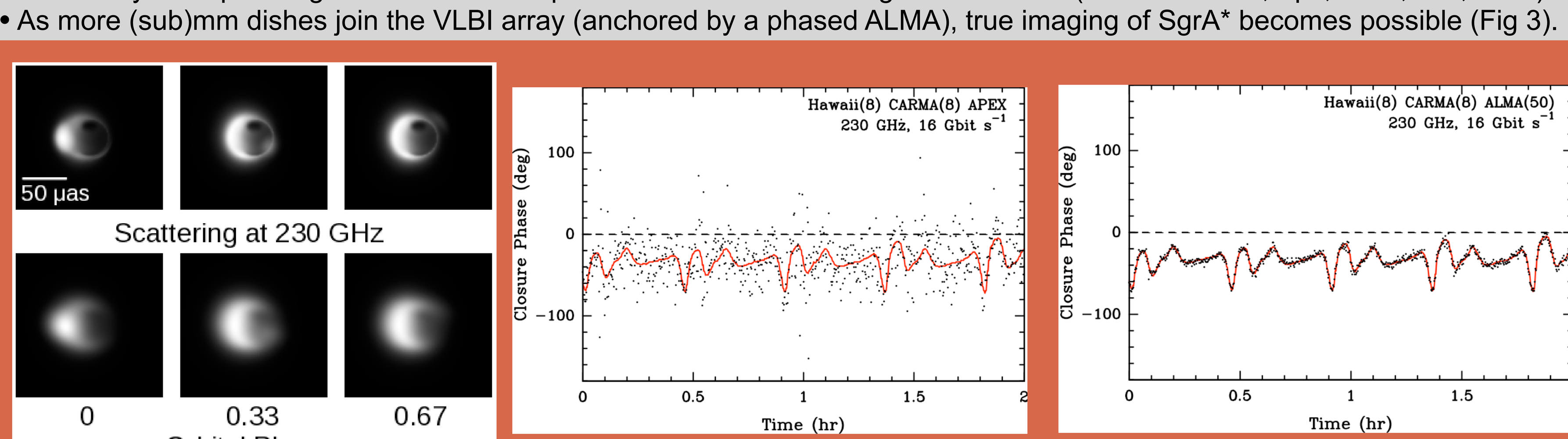

Fig. 2: Simulation of a hot spot at the Innermost Stable Circular Orbit of SgrA* with a 27 minute period exhibits clear and periodic closure phase signatures on the Hawaii-CARMA-Chile triangle of VLBI baselines. Left: the model at 3 orbital phases with full GR ray tracing and radiative transfer. Middle: closure phase of model (red) and simulated 10s points using a single Chilean dish. Right: Same plot but using 50 ALMA dishes phased together. The raw sensitivity of ALMA enables high dynamic range sampling of such orbiting hot spots, which can explain the observed submm variability of SgrA*. Timing of these orbital periods can be used to estimate black hole spin (Doeleman et al, ApJ, v695, 59, 2009; Fish et al, ApJ, v706, 1352, 2009).

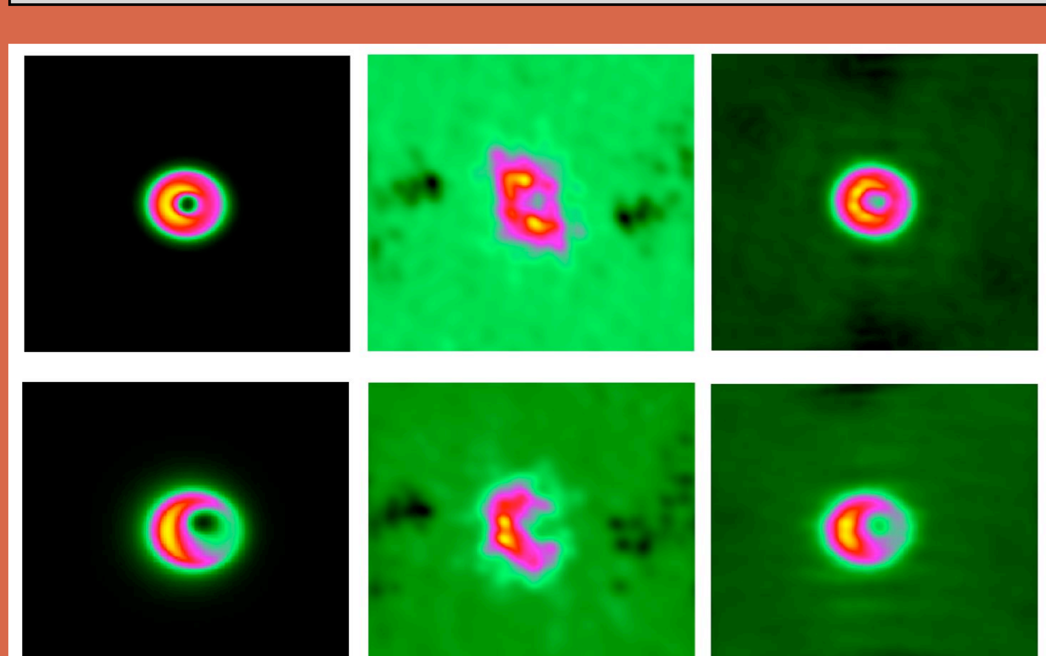

Fig. 3: Imaging an Event Horizon. Because of its high sensitivity, all VLBI baselines to ALMA will be sensitive enough to detect SgrA* on short integration times, allowing many telescopes to join EHT observations. By 2014, the EHT should consist of 7 VLBI sites, and up to 13 stations could be possible by adding telescopes at key sites (e.g., South Pole). With more telescopes, imaging can be used to discern signatures of strong gravity, and specifically to measure the size and shape of the predicted black hole 'shadow'. Left panels are SgrA* models (~40 Rsch across); middle panels show image reconstructions using a 7-station VLBI array; right panels show image reconstructions using 13 stations. Models from Broderick&Loeb (*MNRAS*, **367**, 905, 2006) and Noble & Gammie (*CQGra*, **24**, 259, 2007).

Diverse Science with a Beamformed ALMA

- Using ALMA as a large aperture will allow searches for pulsars near SgrA* at 7/3mm. Detection of a pulsar orbiting SgrA* would allow exquisite tests of GR (Pfahl & Loeb, ApJ, v615, 253, 2004).
- Observations of magnetars at sub-ns resolution will address questions of B field decay and particle acceleration.
- Continuum VLBI within multiple ALMA bands (7/3mm) will enable high fidelity imaging for AGN jet studies, including polarimetric observations, in conjunction with existing VLBI arrays (EVN, GMVA, VLBA).
- Phased ALMA opens a rich spectral window for high sensitivity and high resolution VLBI maser studies, including multiple molecular lines (SiO, water, HCN, methanol) as well as atomic recombination line masers (e.g., MWC 349).

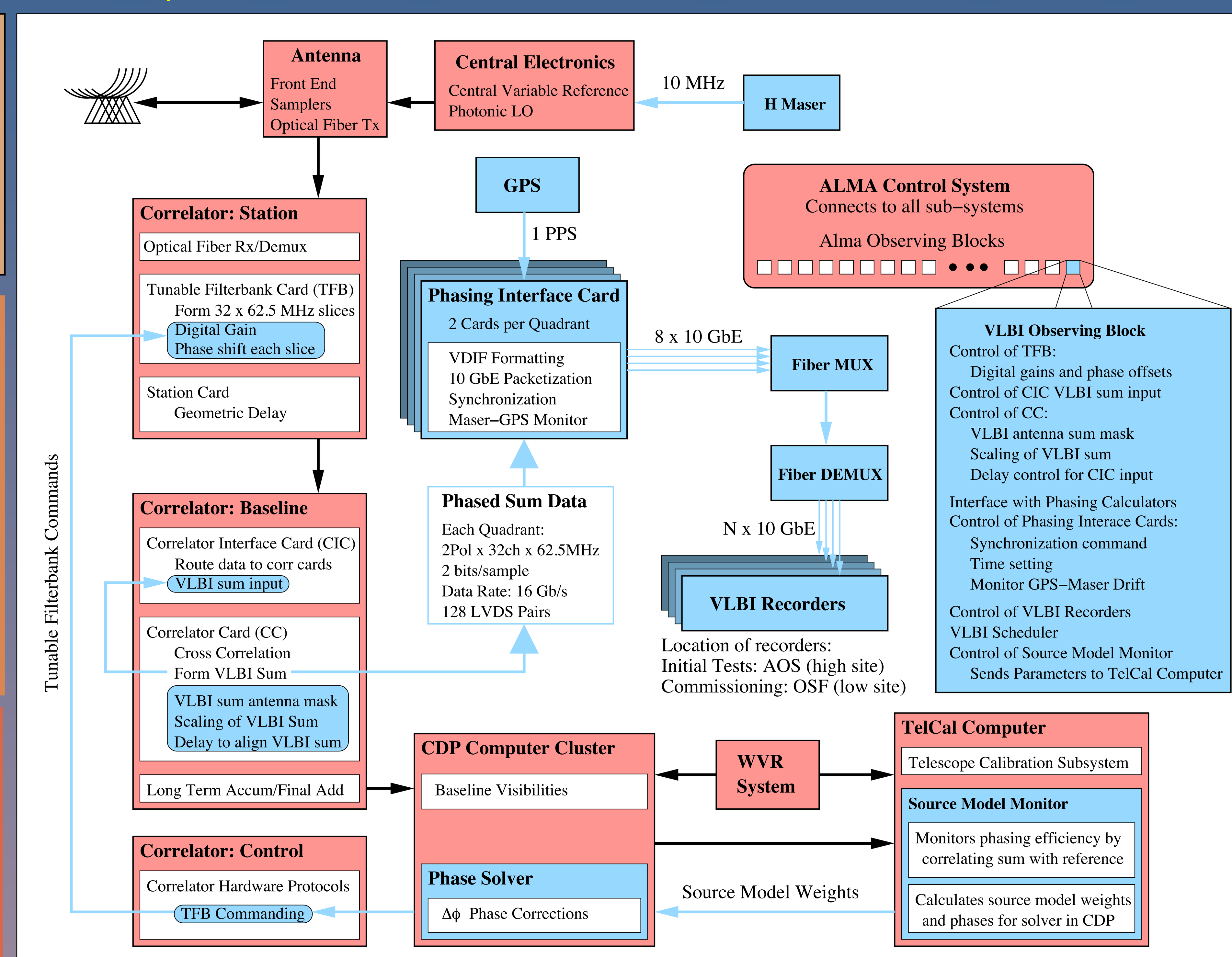

Fig. 4: The detailed design for the ALMA Beamformer. All blocks shown in orange are existing elements of the ALMA system, and blue blocks (and arrows) show elements of the Beamformer system.

ALMA Beamformer Design

The basic principle for phasing ALMA is similar to adaptive optics: phase corrections are made for each antenna, which allow signals from each element in the array to be coherently summed. An important design concept is the use of all (n)(n-1)/2 baselines available from the ALMA correlator to solve for the (n-1) antenna phases. Using the full 8GHz BW of ALMA and both polarizations, the signal-to-noise for each antenna phase for SgrA* observations (SgrA*~3 Jy at 230GHz) will be ~850, resulting in negligible phasing coherence losses. This high-snr regime holds for sources with flux density down to 100mJy.

The ALMA correlator already contains the logic to form a coherent sum across all the array antennas. The loop to solve for the necessary antenna phase offsets starts in the correlator, where cross correlation data for all ALMA baselines is sent to the Correlator Data Processing (CDP) computers. There, a solver uses source model information (and Water Vapor Radiometer data for faint sources) to determine antenna phase corrections on ~10 second time scales. These offsets are routed through the Correlator Control computer to the Tunable Filter Bank (TFB) cards, which are also housed in the ALMA correlator system. The TFBs can impose the desired phase shifts for each antenna, which closes the phasing loop. The phased sum data (computed in parallel with the interferometric array data) is sent to a new ALMA correlator card (Phasing Interface Card - PIC) that formats the phased sum for VLBI recording using 10Gb Ethernet protocols. The data are then sent via optical fiber to the ALMA Operations Support Facility (OSF) for recording. A Hydrogen maser frequency standard provides the stable reference required for VLBI.

Project Status/Planned Schedule

- **2008-2010:** Phasing Architecture designed in consultation with ALMA technical teams.
- **Jan 2011:** Endorsement by ALMA Board, International MRI proposal submitted to NSF.
- **Aug 2011:** Project recommended for funding by NSF, work begins.
- **2011-2013:** New hardware (PIC - Fig 4) designed and fabricated, ALMA VLBI software functional, VLBI recorders installed.
- **2013-1014:** Hydrogen maser installed, VLBI software complete, hardware tested, first VLBI observations with phased ALMA.
- **2014-2015:** Commissioning and availability of ALMA phasing system to community.