A Submillimeter VLBI Array

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Abstract. A VLBI array operating at $\lambda$ 1.3 mm and 0.8 mm is being designed using existing submillimeter telescopes as ad-hoc stations. Initial three station $\lambda = 1.3$ mm observations of SgrA* and other AGN have produced remarkable results, which are reported by Doelemans elsewhere in this proceedings. Future observations are planned with an enhanced array which has longer baselines, more stations, and greater sensitivity. At $\lambda = 0.8$ mm and on the long baselines, the array will have about a 20 $\mu$as angular resolution which equals the diameter of the event horizon of the massive black hole in SgrA*. Candidate single dish facilities include the Arizona Radio Observatory Submillimeter Telescope (SMT) in Arizona, the Caltech Submillimeter Observatory (CSO) and the James Clerk Maxwell telescope (JCMT) in Hawaii, the Large Millimeter Telescope (LMT) in Mexico, APEX and APEX in Chile, and the IRAM 30 m in Spain; interferometers include the Submillimeter Array (SMA) in Hawaii, the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in California, IRAM PdBI Interferometer in France, and the Atacama Large Millimeter Array (ALMA) in Chile. I will discuss the techniques we have developed for phasing interferometric arrays to act as single VLBI station. A strategy for detection of short (10s) time-scale source variability using VLBI closure phase will be described.

1. Introduction
It is widely accepted that most galaxies harbor supermassive black holes (SMBH) at their centers. The closest SMBH candidate is SgrA* at the center of our Galaxy—since it has the largest angular size scale of any SMBH it is a compelling example for observation. Infrared observations made with adaptive optics on the VLT and the Keck 10 m telescope have been used to measure the orbits of a number of stars bound to Sgr A* with periods as short as 15 years ([1],[2],[3]). From these orbits the central mass has been determined to be about $3.9 \times 10^6 M_\odot$. Further, the mass density must be greater than $10^{22} M_\odot$ pc$^{-3}$ because lack of proper motion of Sgr A* implies that $>10\%$ of the mass must be tied to Sgr A*, which has a size $<1$ AU [11]. Barring a few really exotic explanations this mass is most likely in the form of a black hole [12]. The Schwarzschild radius ($R_{\text{sch}}$) for this black hole is about $1.2 \times 10^{12}$ cm or 10 $\mu$as. The closest approach among the stellar orbits now measured is about 45 AU ($560 \times R_{\text{sch}}$).

The relativistic gas in the accreting envelope of Sgr A* is the probable origin of the emission at submillimeter wavelengths. Theoretical calculations ([4],[5],[6]) show that the general relativistic ray paths are highly curved and lead to a severely distorted image with a central shadow. The size of the expected image is about 50 $\mu$as and the symmetry of the image is sensitive to the viewing angle of the accretion disk and the spin of the black hole.

The spectral energy distribution of SgrA* peaks in the submillimeter wavelength part of the spectrum. Submillimeter Array (SMA) results [13] show that the peak is near 0.8 mm.
The observed angular size of Sgr A* vs wavelength (source is elliptical; two solid lines indicate the major and minor axes with a $\lambda$ squared dependence characteristic of plasma scattering). At wavelengths longer than several millimeters the apparent angular size is dominated by the image blurring induced by interstellar scattering in the ionized plasma in the inner galaxy. The data points at 1.4 mm and 3.5 mm suggest that the true source size may be in the range of 50-100 $\mu$as (see [7], [8], [9]). Figure from [15]. Reference [10] has an updated form of this figure, which integrates the results from the 1.3 mm VLBI observation of April 2007.

Observations made at or shorter than this wavelength offer the possibility of observing emission originating close to the event horizon because theoretical models predict the emission to be highest there, and the plasma to be optically thin. At radio wavelengths the image of Sgr A* is blurred by the turbulence of the ionized gas in the inner galaxy. The fluctuations in the index of refraction due to this turbulence broaden the image to about $10 \times (\lambda/1\text{mm})^2 \mu$as, as shown by the interferometric data in figure 1.

Hence $\lambda \sim 1$ mm is ideal for VLBI on the Galactic center because the flux density is high, the emission is relatively unaffected by scattering in the intervening medium, and the opacity is small enough to observe close to the event horizon. Sgr A* is obscured by dust in the optical region. In the near infrared, interferometric baselines of 10 km would be required. The GRAVITY instrument using adaptive optics on the VLTI will be capable of astrometry with 10 $\mu$as accuracy, thereby tracing motions in the Galactic Center to a few $R_{\text{sch}}$ [16]. In the X-Ray region a space interferometer, MAXIM, is being considered [17].

2. Extending VLBI to the submillimeter
By extending Very Long Baseline Interferometry to submillimeter wavelengths, it is possible to obtain sufficient resolution to directly probe the emission from the SMBH in the Galactic Center on event-horizon scales, and also higher mass SMBHs in nearby galaxies such as M87. The resolution of an interferometric array is $0.7\lambda/D$, where D is the longest baseline length. Hence for $\lambda = 0.8$ mm and $D = 5000$ km, the resolution is about 20 $\mu$as.

The shortest wavelength at which the VLBA can be used is 3 mm, because of the surface accuracy limitation of its antennas. At shorter wavelengths telescopes must be combined on an ad hoc basis to make VLBI images. Candidate single dish facilities include the SMTO (HHT) in Arizona, the CSO and JCMT in Hawaii, LMT in Mexico, ASTE and APEX in Chile, and the IRAM 30 m in Spain; interferometers include the Submillimeter Array (SMA) in Hawaii, CARMA in California, IRAM PdBI Interferometer in France, and ALMA in Chile. A more comprehensive list of candidate submillimeter VLBI stations, and their salient characteristics is shown in table 1. VLBI is progressively more difficult at shorter wavelengths because the coherence time shortens due to the effects of the atmosphere and atomic frequency standards that control the signal recording at the remote independent stations. Also, at wavelength shorter
than about 0.8 mm, atmospheric transparency is a severe problem due to water vapor, and the likelihood of sufficiently good weather at multiple sites is small.

A preliminary successful observation has been carried out at 1.4 mm wavelength using the IRAM PdBI and 30 m antennas to form a single 1200 km baseline [7]. In 2007 this result was substantially extended with a 3-station experiment with \( \lambda = 1.3 \) mm, and including stations on Mauna Kea (JCMT), California (one CARMA dish) and Arizona (SMT) [10]. The longest baseline in this experiment was 4,500 km, corresponding to a fringe spacing of 60 \( \mu \)as.

**Table 1.** Characteristics of telescopes suitable for use as submillimeter VLBI stations.

| Station   | Location       | A (m\(^2\)) | \( \lambda \) (mm) | BW (GHz) | Polarization | Maser? |
|-----------|----------------|-------------|---------------------|----------|--------------|--------|
| SMA       | Mauna Kea      | 226         | 1.3 ; 0.8           | 2        | 0.8 only     | yes    |
| JCMT      | Mauna Kea      | 177         | 1.3 ; 0.8           | 3        | 0.8 only     | (yes) |
| CSO       | Mauna Kea      | 79          | 1.3 ; 0.8           | 4        | 0.8 only     | (yes) |
| Hawaii\(^2\) | Mauna Kea   | 482         | 1.3 ; 0.8           | 3        | 0.8 only     | (yes) |
| CARMA-1\(^3\) | Cedar Flat, CA | 85         | 1.3               | 4        | no           | yes    |
| CARMA-8\(^4\) | Cedar Flat, CA | 680     | 1.3               | 2        | no           | yes    |
| SMTO      | Mt. Graham, AZ | 79         | 1.3 ; 0.8           | 4        | 1.3 ; 0.8    | yes    |
| LMT       | Mexico         | 804         | 1.3               | 4        | 1.3          | no     |
| ASTE      | Atacama, Chile | 79          | 1.3               | 2        | no           | no     |
| APEX      | Atacama, Chile | 113        | 1.3 ; 0.8          | 4        | 1.3 ; 0.8    | no     |
| ALMA-10   | Atacama, Chile | 1131       | 1.3 ; 0.8          | 4        | 1.3 ; 0.8    | no     |
| IRAM PdBI | Plateau de Bure\(^5\) | 1060 | 1.3 ; 0.8         | 4        | 0.8          | yes    |
| IRAM 30 m | Pico Veleta\(^6\) | 707      | 1.3               | 1        | 1.3          | yes    |

1. The maser reference for all Mauna Kea facilities is at the SMA
2. The “Hawaii” station represents the phased sum of six SMA dishes, plus CSO and JCMT.
3. CARMA-1 is a station with just a single 10.4 m CARMA dish.
4. CARMA-8 is a station using a phased array sum of eight CARMA dishes (six are 10.4 m)
5. Interferometer with six 15 m dishes, located in France
6. 30 m single dish located in Spain

When using an interferometer optimally as a VLBI station it is preferred that all of the available collecting area be used. At the Submillimeter Array (SMA) on Mauna Kea, we are building a phased array processor to enable it to contribute to VLBI with its full collecting area and half of its bandwidth (1 GHz). The SMA has fiber connections to the co-located single dish facilities, the Caltech Submillimeter Observatory (CSO) and the James Clerk Maxwell Telescope (JCMT); this cooperative facility is called the Extended SMA (eSMA). It is possible in principle to aggregate all the eSMA collecting area to form a “Mauna Kea” VLBI station. The resulting equivalent aperture of 25 m approaches that of the IRAM dish in Pico Veleta, Spain. Figure 2 shows the location of these facilities, and summarizes the available collecting area.

Mauna Kea is an excellent site for 1.3 mm (230 GHz) and 0.8 mm (345 GHz) astronomy, and has the potential to provide the longest baselines for VLBI imaging for the medium term future, until a VLBI capable facility becomes available in Chile. The SMA to US West coast baselines can deliver close to the 20 \( \mu \)as resolutions promised by VLBI.

3. **The SMA phased array processor and VLBI recording system**

The SMA normally operates as interferometric array. The signals from its eight elements are brought together and cross correlation pairs are formed. These so called “fringe visibilities” are
Fourier transformed to form an image. To be able to use all of the SMA elements together as a single element in a VLBI array, the signals from the SMA elements must be appropriately delayed and phase shifted before being coherently combined. The combined signal is equivalent to that from a single telescope having the full area of the array. The digital electronics necessary to carry out this signal combination is called a phased array processor.

The design [20] uses fast processing and sampling hardware which has been developed at UC Berkeley. The Berkeley hardware consists of iADC boards based on Atmel Corporation analog to digital converters for sampling and processing boards based on Xilinx Virtex II Pro Field Programmable Gate Arrays (FPGA) for data processing (“iBOB” boards). Berkeley’s Center for Astronomy Signal Processing and Electronics Research (CASPHER) group [18] has applied the BWRC hardware specifically to reducing the design cycle time of radio astronomy instrumentation. They have developed a library of radioastronomy-specific functions that are available for quick application to particular instrumentation needs [19]. The Berkeley hardware and libraries are also used by MIT-Haystack Observatory to develop the new Digital Back End (DBE) for the Mark5b+ VLBI data storage terminal.

Figure 3 shows a schematic of the eight-antenna SMA VLBI phased array processor. This initial system is limited to eight antennas because doing so made for an elegant design in the context of the natural multiples of ADC channels in the CASPER hardware. So when either the CSO or JCMT are included in the eight antenna sum, a single SMA antenna will be dropped for each. Analog IF signals with 1 GHz bandwidth are tapped from the SMA IF electronics and are processed by an analog pre-processor, which amplifies to the correct power level. The preprocessor also includes custom anti-alias filters. Two contiguous 512 MHz Nyquist sub-bands with center frequencies of 768 MHz and 1280 MHz respectively are derived for each antenna. A programmable analog eight-channel phase shifter implemented with broadband quadrature hybrids (Werlatone Corp) and four-quadrant vector multipliers (Analog Devices) modulates both the required phase correction, and the the secondary phase rotation required for doppler correction onto these sub-bands before they are sampled at a rate of 1 GSample s$^{-1}$ to eight-bit precision.
The delay correction and four-channel sum is implemented using the CASPER iBOB FPGA hardware. Each iBOB board can accept four 500 MHz analog inputs, so two are needed to sample eight channels. The coherent sum of each set of four antennas is communicated via 10 Gbit s$^{-1}$ serial links to a downstream iBOB processor board where the two groups are summed coherently to form the eight-antenna signal needed for VLBI. This board also houses a customized version of the Mark5b DBE design, and the data are routed directly to the Mark5b+ data storage terminal. The entire arrangement is replicated for the second 500 MHz IF block to meet the needs of 1 GHz bandwidth VLBI.

Real-time calibration of the programmed phase and delay in the presence of perturbations due to atmospheric effects represents a significant challenge. Since the SMA’s geometry is well known, some of this information can be directly communicated to the VLBI processor. Systematic delays, though, are different for the SMA correlator than for the VLBI system, and because the SMA works on 82 MHz bandwidth chunks, the delay and phase corrections are not computed in the SMA system to adequate precision to correct a 500 MHz bandwidth block.

Thus the VLBI processor will be equipped with a dedicated real-time XF correlator, implemented in another of the CASPER FPGA processing engines, the BEE2. The antenna data in the phased array processor is communicated using the 10 Gbit s$^{-1}$ serial data links to the correlator. The correlator computes the complex cross-power visibility spectrum for each of seven antennas with respect to that antenna which forms the phase reference. A straight line fit to the phase part of the visibility spectrum determines the slope and the offset, which respectively represent the delay and phase corrections required to align that antenna’s signal with the reference. The delay and phase corrections are fed back in real to the phased array summer, allowing for adaptive self-calibration of the phased array processor while the array is

**Figure 3.** Block diagram of the VLBI phased array processor system implemented with Berkeley’s CASPER FPGA hardware.
pointed at the target source.

The phased array processor being developed for the SMA includes technology which we expect to be useful at other interferometers such as CARMA and the Plateau de Bure Interferometer (PdBI). We are in contact with staff at both facilities for technical interchange. The phasing of the ALMA array will require a different technological approach, because the digitization of signals in the antennas means that analog IF tap points are not available at a central location. Implementation of an ALMA phased array and VLBI processor is an important longer term goal of our efforts.

4. Detecting flaring and time-variable structures

Non-imaging algorithms have been developed to detect time variable structures in SgrA*. The methods described briefly here are discussed in detail in reference [21]. There are a number of reasons for an alternative to the imaging approach. For example, Earth rotation aperture synthesis assumes a static source structure, while models of SgrA* suggest substantial time variability may be present on short time- and small angular scales. In any case the sparse UV coverage typical in a submillimeter VLBI observation is not well suited to inversion into the image plane. The technique uses interferometric closure quantities as robust observables (i.e. they are insensitive to atmospheric and instrumental gain variations), and is motivated by models in which an orbiting hot spot is embedded in an accretion disk ([5], [6]). Simulations using these rotating hot spot models, and based on arrays with stations selected from those suggested in section 2, show that the signature of periodicity can be detected using currently available $\lambda = 1.3$ mm 4 Gbit s$^{-1}$ VLBI technology to a 10 s time resolution. The potential for detecting these signatures will be substantially improved when 16 Gbit s$^{-1}$ VLBI bandwidths and large collecting areas from telescopes such as ALMA become available in a few years. The closure signature is shown to be sensitive to the black hole spin. A few representative results using closure phase, taken from reference [21] are presented here.

In the figures in this section, the solid red line shows the predicted closure phase in the absence of noise, while the dots model an actual noisy observation, with each point representing 10 s of coherently integrated data. Plots are presented for a variety of station locations and, in the case of interferometers, collecting areas at a given station. The collecting area in the case of arrays models whether or not interferometers at those locations are phased. Bandwidth in VLBI is measured in terms of the data storage rate in Gbit s$^{-1}$; the simulations illustrate the expected improvement in SNR at higher data rates.

![Figure 4](image1.png)  
*Figure 4.* Closure phase for JCMT-SMTO-CARMA1 triangle with 4 Gb/s bandwidth

![Figure 5](image2.png)  
*Figure 5.* Closure phase for JCMT-SMTO-CARMA1 triangle with 16 Gb/s bandwidth

The first four figures model arrays of North American telescopes only and are thus considered...
to be “small triangles”. Figure 4 is a simulation for a triangle with stations consisting of the JCMT on Mauna Kea, the SMT on Mt. Graham in Arizona, and a single CARMA dish in Cedar Flat, CA. The VLBI array operated with a data rate of 4 Gbit s\(^{-1}\), which is equivalent to an observation with a sky bandwidth of 1 GHz and 2-bit VLBI data samples. Both the data rate and the stations correspond closely to the experiment which was run in April 2007 [10]. Figure 5 considers the same stations as figure 4, however the data rate is 16 Gbit s\(^{-1}\), corresponding to a 2 GHz IF bandwidth as well as dual polarization, and 2-bit sampling.

![Figure 6](image6.png) ![Figure 7](image7.png)

**Figure 6.** Closure phase for Hawaii-SMTO-CARMA8 triangle with 4 Gb/s bandwidth

**Figure 7.** Closure phase for Hawaii-SMTO-CARMA8 triangle with 16 Gb/s bandwidth

In figures 6 and 7, the Hawaii and the California stations now include the collecting area made possible by a phased array instrument retrofit. In the case of Mauna Kea, an effective 23 m aperture results from the phased sum of six SMA dishes, plus the JCMT and the CSO. In the case of California, eight CARMA dishes are phased up to produce an effective 27 m aperture. Again, two cases are presented, 4 Gbit s\(^{-1}\) and 16 Gbit s\(^{-1}\). The periodicity evident in the red line is measurable with 10 s integrations, perhaps marginally so in figure 4 but improving significantly with increases in collecting area and bandwidth. Reference [21] discusses the use of autocorrelation functions, which are applied to the closure phase measurements, and have the potential to improve the detectability of the periodicity.

![Figure 8](image8.png) ![Figure 9](image9.png)

**Figure 8.** Phase closure for Hawaii-CARMA8-ALMA10 triangle with 16 Gb/s bandwidth

**Figure 9.** Phase closure for Hawaii-CARMA8-ALMA10 triangle with 16 Gb/s bandwidth and a=0.9

Figures 8 and 9 both demonstrate the effect of including a Chilean station, in this case a
10-element phased array of ALMA dishes. The large North-South extent produce a greater amplitude in the closure phase periodic signature. Apparent asymmetry in the source results in a net offset in the closure phase signature. The asymmetrical structure in the source is due to lensing and opacity effects. In figure 8 the drift in closure phase offset due to projection effects over the course of an observation is clearly shown. Figure 8 models the case of a non-rotating black hole, figure 9 shows the case of a strongly rotating black hole. Models of SgrA* suggest that a spinning black hole is generally associated with a more spatially compact source, and this results in lower amplitude closure phase fluctuations and greater SNR on longer baselines. Thus the closure-phase technique has the potential to probe the fundamental parameters of the black hole, such as its spin.

5. Conclusions
Observations of SgrA* made in April 2007 have shown the potential of \( \lambda = 1.3 \text{ mm} \) VLBI to probe the Galactic Center on event-horizon scales. This work demonstrates both the feasibility of the technique, and illustrates the benefits available through improving the sensitivity of the VLBI array. In the coming years we plan to improve sensitivity in three ways. First, by increasing the bandwidth at each station, second by having a greater number of stations, and third, by aggregating the collecting area at stations which operate normally as local interferometers through the use of phased arrays. With improved sensitivity and detections on at least three baselines, techniques using closure quantities have the potential to detect short time scale variability in the source with 10 s resolution. Our team aims to observe SgrA* again in the first half of 2009 with an improved VLBI array.

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