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MM-VLBI with ALMA

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ABSTRACT

This memo reviews the requirements for using the ALMA array as a part of a global VLBI array at millimeter wavelengths. ALMA can be outfitted for VLBI at modest cost and should be planned with this capability in mind, as it may be more difficult to retrofit at a later date. The essential features required in the ALMA design are discussed.

1. Introduction

VLBI observations at short millimeter wavelengths are required to resolve the compact radio components associated with active galactic nuclei. These components are optically thick at longer wavelengths, or obscured by scattering, as in the case of SgrA*.

Large new telescopes planned for completion in the next 10 years provide a powerful new platform for millimeter and submillimeter VLBI. The atmospheric phase corrections required for successful operation of millimeter arrays on baselines of several km also enable phase coherent VLBI observations with 20 μarcsec resolution. This is sufficient to resolve structure on the scale of an accretion disk around a massive black hole in the nearest quasars. At 10 Rs the intensity distribution is distorted by the black hole.

The increased sensitivity will also enable more refined studies of SgrA*, the dynamics and chemistry of SiO maser emission evolved stars, maser emission associated with IRc2 at the center of the Orion-KL nebular, and molecular absorption against bright galactic and extragalactic systems.

2. New Telescopes

Large millimeter telescopes which could be used in a future millimeter VLBI Array are listed in Table 1. New telescopes included here are the Atacama array (ALMA), the Large Millimeter Telescope (LMT) which is collaboration of the University of Massachusetts and Mexico's National Institute of Astrophysics, Optics and Engineering, the California array (CARMA) which is the merger of the BIMA and OVRO arrays, and the Smithsonian Astrophysical Observatory Submillimeter Array (SMA). The GBT can also be used at 3mm wavelength.

Figure 1 & 2 show the *uv* tracks for 3C273 and SgrA* for this new millimeter VLBI array (MMVLBA) at a wavelength 1.3 mm. The array provides significantly better *uv* coverage for low declination and southern sources than the existing mm VLBI networks. The beam has a size of 20 μarcsec at 1.3 mm and is roughly circular for both northern and southern sources. The sparse *uv* coverage can be greatly improved for continuum studies by exploiting multi-frequency synthesis (MFS) across the wide bandwidths available in the new telescopes.

Table 1: MM-VLBI Antennas.

Name	Location	Latitude	Longitude	Effective Diameter (m)
IRAM	France	44.6	-5.9	33
Pico Veleta	Spain	36.9	3.4	30
ALMA	Chile	-23	68	96
SEST	Chile	-29.1	70.7	10
LMT	Mexico	19.0	97.3	50
CARMA	California	37	118	30
SMA	Hawaii	19.7	155.5	19
NOBEYAMA	Japan	35.8	-138.5	25

The geometric mean equivalent diameter is 35 m. Since all these telescopes are being built with low antenna noise on good high sites, it is reasonable to assume that a system temperature around 100 K will be obtained at 1 to 3 mm wavelength. Assuming a 250 MHz bandwidth, the RMS sensitivity is about 0.5 mJy in 1 min. This is about 20 times better than currently obtained with a system temperature of 200 K, an average diameter of 15 m and a bandwidth of 64 MHz. The brightness sensitivity is about 10^7 K at 1 mm.

3. Phase coherent Millimeter VLBI

The path length fluctuations due to atmospheric water vapor cause a serious loss of coherence in VLBI experiments. For the new millimeter array telescopes, it is anticipated that a combination of fast switching between source and calibrator, and phase correction from water-vapor measurements will be able to correct for atmospheric phase fluctuations, so that phase coherent aperture synthesis images can be obtained using baselines of several km. The new millimeter arrays are being designed to include this capability. If these corrections are successful, then the same techniques at each telescope, or phased array, in the proposed MMVLBA will provide phase coherent aperture synthesis images with a resolution of 20 μarcsec at 1.3 mm. Most of the calibrators will themselves be resolved, so that self-calibration will be required to obtain the structure of the calibrators. The

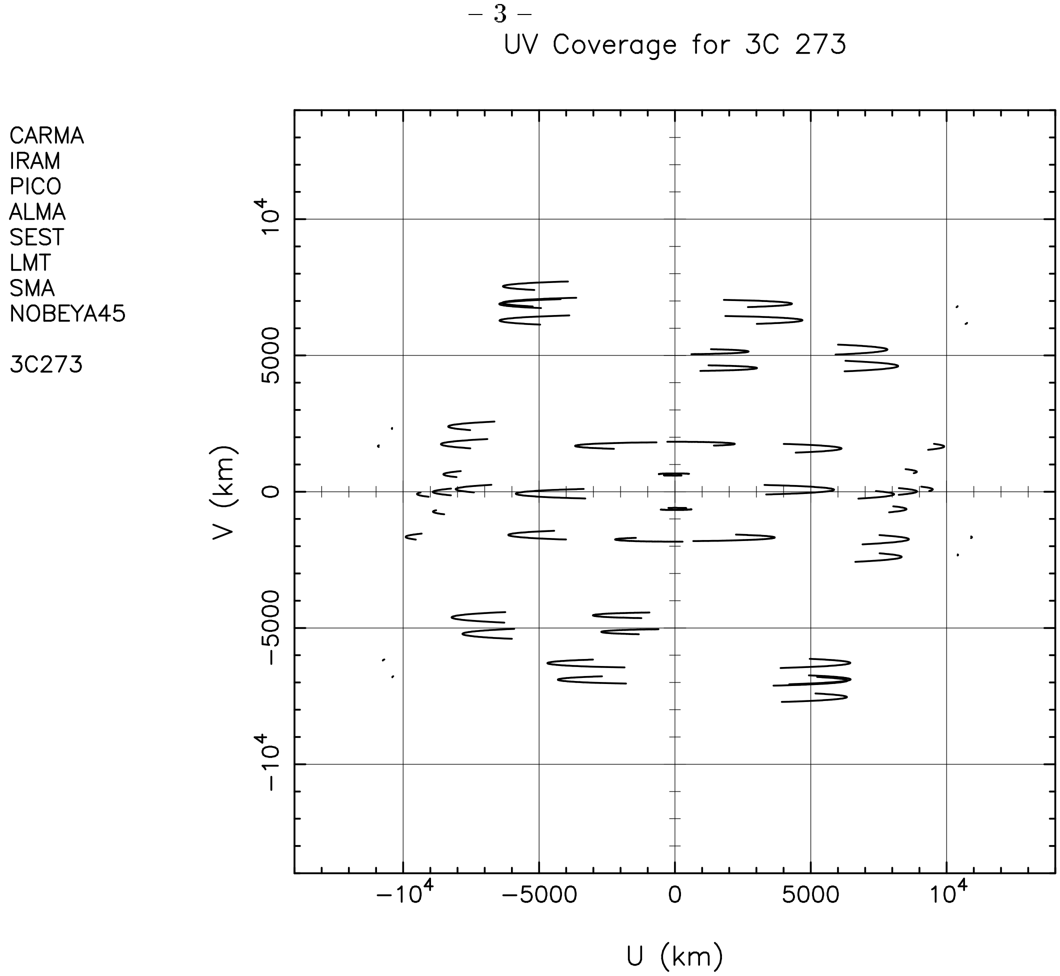

Fig. 1.— uv tracks for 3C 273 ($\delta = +03^o$) with the proposed millimeter VLBI array.

calibrator with its known structure, and correction for the atmospheric phase can then be used as a phase reference for the unknown source.

4. Design Considerations

The VLBI system must use a hydrogen maser, or other very coherent phase reference for all the LO's in the IF downconversion, and for the time standard. The coherent integration time is currently limited by the atmosphere; if atmospheric phase correction is successful, the hydrogen maser stability will become the limiting factor. Phase stable electronics must be used in the LO chain into a wide bandwidth recording device. A built-in test tone generator to inject a phase stable signal into the front end receivers would be nice, but not essential once the phase stability of the ALMA VLBI system has been established. Observing modes should include array phasing,

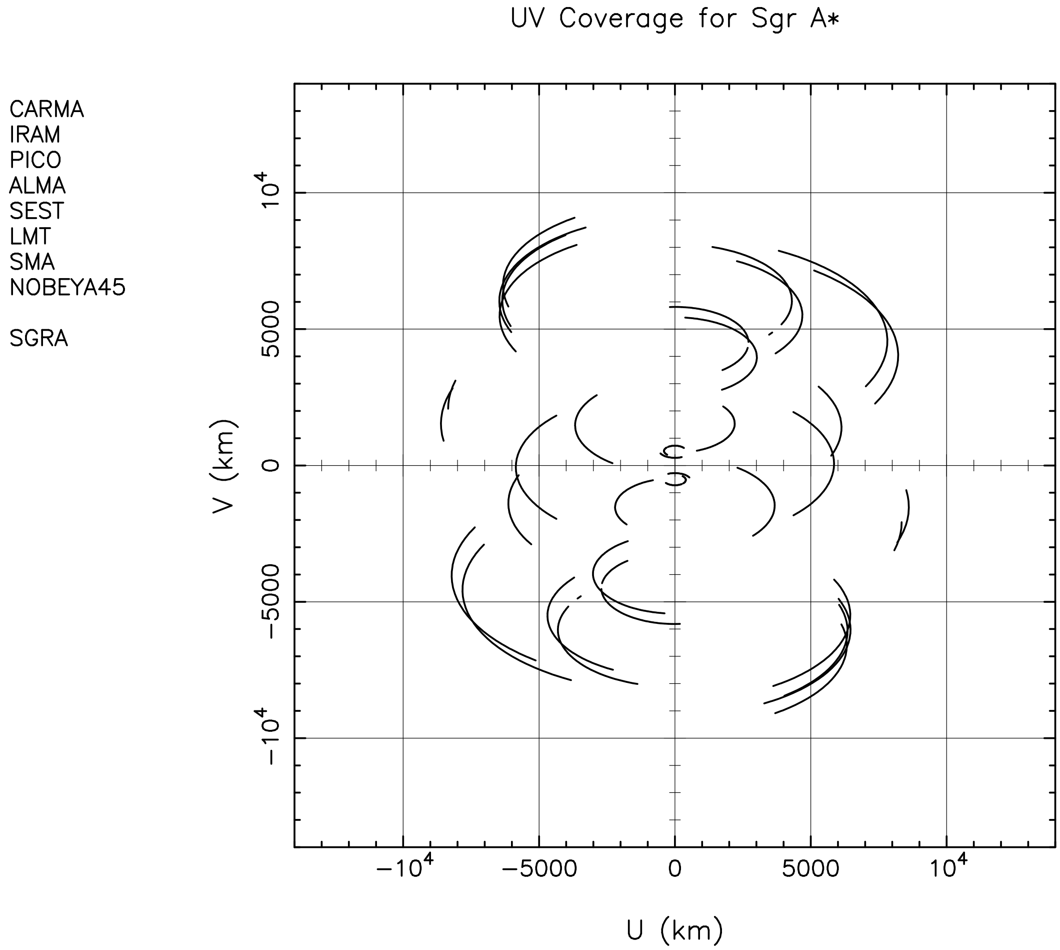

Fig. 2.— uv tracks for SgrA* ($\delta = -30^o$) with the proposed millimeter VLBI array.

dual polarization and rapid switching from local to VLBI modes. Multiple phased arrays are required for simultaneous observations of different target sources or observing frequencies, such as multiple SiO transitions, or simultaneous 800 micron and 3 mm continuum observations. Multiple phased arrays will be also important for avoiding FOV problems with sparse array configurations. For both MFS and for observations of multiple spectral lines, we want to select the recorded bandwidth from several windows across the available bandwidth.

5. Operational Model

Operational issues which need to be addressed include: 1) Who will organize future mm VLBI experiments and install and maintain the VLBI terminals at participating stations? 2) the interaction of UT scheduling with dynamic scheduling.

6. Array Phasing

For VLBI the phase correction must be applied before the IFs are summed, e.g. as a phase offset to the LO. This is different from the data correction envisioned for ALMA observations. The phase might be derived some combination of: i) WVR, ii) selfcal on strong target source, iii) rapid switching to nearby reference source.

We must also measure the phasing efficiency in order to calibrate the data. It is best if the ALMA correlator allows correlation of the summed antenna IFs with a reference antenna. This gives a direct measure of the effective gain of each phased array. Alternatively, the phasing efficiency can be derived from measurement of the relative phase of each antenna in each phased array, as measured for example on baselines to a reference antenna, and, in addition, a measurement of the weight, or contribution of the IF from each of the phased array antennas to the summed output into the VLBI recording system. The ALMA correlator should support local correlations simultaneous with VLBI recording.

7. Polarization

ALMA front ends provide dual linear polarizations. VLBI observations are usually made in circular polarization to correlate with other VLBI stations. If the relative phase of the dual polarizations is well determined, the linear polarizations can, in principle, be combined at the telescope before recording to correlate with other stations. Alternatively, a single linear polarization could be recorded and correlated with circular with some loss in SNR - which may degrade the detection of weak VLBI fringes. Dual linear polarization could become the default mode for future mm VLBI experiments. Many VLBI experiments would benefit from dual polarization observations. Although this is not currently available at many stations, it is a desirable goal. It seems easiest to record both linear polarizations.

8. Recording Medium and Bandwidth

Recent developments in VLBI recording technology are showing the way to economical multi-Gbps VLBI recording. Several systems, including Mark 4, Mark 5, S3 and K4, now exist or are being developed to support at least 1 Gbps recording; in addition most, if not all, of these systems will support the recently adopted VLBI Standard Interface (VSI) specification which mandates support of 1-Gbps on a single 80-pin connector. As a result, it seems sensible to base future mm-VLBI working on multiple channels each of 1-Gbps data rate. It is clear that by 2007 multi-Gbps recording systems will be available (mostly built in increments of 1-Gbps) for $20-40K/Gbps. This cost level places something like an aggregate data rate of 8 Gbps within economical reach. Media costs are also coming down to levels which are economically viable for fairly sustained multi-Gbps operations. For example, industry projections are that disc drives will be available for $0.30-0.50/GB within the next 4 years or so; projections for the cost of tape media are in the same ball park.

Since it appears that VLBI recording systems will be available in economical 1-Gbps increments, a good match for future mm-VLBI channel bandwidth would be 250 MHz using 2-bit Nyquist sampling. This also seems a reasonable match to the sort of multi-GHz bandwidths used by ALMA. The primary work needed will be digital signal combiners, plus the digital and/or analog filters and samplers to break these larger native channel bandwidths into multiple 250-MHz subchannels. It is recommended that ALMA provide one VSI-compatible connector carrying 1-Gbps data for each 250 MHz subchannel.

Although few, if any, current correlators can handle a 250 MHz channel bandwidth, it is clear that at least some correlators can be economically upgraded to support this operating mode. A preliminary study at Haystack Observatory, for example, has shown that the Mark 4 correlators can be upgraded to support this mode of operation with the upgrading of only the 'station unit' component of the correlator system, along with a modest investment in software upgrades. Other correlators may be similarly upgraded.

Developments in high speed sampling and fiber link VLBI techniques are showing remarkable progresses. The Japanese group are completing a 2 Gbps recorder and developing 10 Gbps transfers using IT networks. By 2010, these techniques will be available with a reasonable cost, and should be considered.

9. References

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