Report on the ESO Workshop

mm-wave VLBI with ALMA and Radio Telescopes around the World

held at ESO Headquarters, Garching, Germany, 27–28 June 2012

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Very long baseline interferometry at millimetre/submillimetre wavelengths (mm-VLBI) offers the highest achievable spatial resolution at any wavelength in astronomy and the inclusion of ALMA into a global network will bring unprecedented sensitivity. The workshop on mm-VLBI reviewed the broad range of science topics, from imaging the event horizon of the black hole at the centre of the Galaxy, through masers in the Milky Way and distant galaxies to jets in radio galaxies. Plans were laid to develop a science case and a European organisation to promote mm-VLBI including ALMA.

The huge potential of very long baseline interferometry (VLBI) at millimetre and submillimetre wavelengths is that it enables the highest resolution imaging currently possible at any wavelength in astronomy. The spatial resolution of an interferometer in radians is given by the ratio of the observing wavelength to the separation of the telescopes. For a wavelength of 1 mm and a separation of 9000 km, this resolution is about 20 microarcseconds. Using ALMA as a phased array to form part of a global VLBI network will offer unprecedented sensitivity at very high angular resolution. This capability will allow the shadow of a black hole, the relativistic jet flows in active galactic nuclei (AGN) and the dusty winds near stellar surfaces to be imaged; and it may potentially even improve measurements of the Hubble constant.

While ALMA is nearing completion and the first observing cycle is under way, astronomers are already thinking ahead along these lines. To discuss the opportunities from a European perspective, over 65 scientists gathered at ESO Headquarters in Garching to attend a one and a half day workshop on mm-wave VLBI with ALMA and other telescopes. In the following report on the workshop, the names of speakers are given in square brackets in the text and all of their talks are linked to the conference webpage[1].

The reason why the millimetre-wave region is so important for ultra-high-resolution imaging is that heterodyne receivers can still be used and quantum effects do not yet limit our ability to do interferometry, as they do at shorter wavelengths. The addition of ALMA offers a leap in sensitivity, thus making many more and weaker sources accessible to ultra-high-resolution studies and greatly improving image fidelity for the brighter objects. Only sources with flux densities above several hundred milliJansky (mJy) have been observable so far; this threshold could be reduced by more than an order of magnitude if ALMA were to be included.

The phasing up of ALMA as part of a VLBI array had been envisaged from the beginning of the project and is incorporated into the system design, but had been deferred on cost grounds, and in the interests of completing the instrument for stand-alone operation. The ALMA Development Steering Committee is now considering a proposal by a team of institutions led by the MIT Haystack Observatory in the USA to upgrade the ALMA correlator and to create the operational infrastructure needed for the efficient phasing of all antennas [Doeleman, Baudry]. This would effectively allow the array to be used as a giant single dish in parallel to its normal interferometric mode. Recording ALMA data and correlating it with those of other (sub)millimetre telescopes would then provide the standard ALMA data products as well as super-high resolution images from the VLBI mode.

ALMA's wide frequency range (35–950 GHz, once all of the planned receiver bands are completed) will enable a broad range of VLBI science to be pursued by astronomers in Europe and around the world. It was therefore timely to bring together interested European astronomers to discuss their scientific interests and ambitions for this new ALMA observing capability. The meeting followed immediately after the Garching ALMA Community Days. The first part of the meeting included reviews of current activities and achievements in mm-VLBI, including the Event Horizon Telescope Collaboration, currently being run by Haystack Observatory, and the Global Millimeter VLBI Array coordinated at the Max-Planck-Institut für Radioastronomie in Bonn. The second part concerned the potential science that will be enabled by a VLBI array including ALMA (Figure 1). The final discussion centred on upcoming developments worldwide. Following

Figure 1. Scientists from all across Europe discussing mm-wave VLBI science with ALMA in the ESO auditorium.

on from the meeting, a science case will be developed, incorporating the ideas presented and discussed.

Approaching the event horizon

One major science case that has been driving the development of sub-mm VLBI has been the possibility of imaging the innermost parts of accretion discs and jets around supermassive black holes and in particular imaging the shadow of the event horizon in the black hole at the Galactic Centre [Falcke, Doeleman]. The shapes and sizes of the shadow and the photon ring surrounding it (e.g., Figure 2) are precisely predicted by Einstein's theory of general relativity (GR), so this observation would provide tests not only of the black hole paradigm but also of GR in its strong-field limit.

The Galactic Centre, Sgr A*, is the most favourable source for this experiment, since the angular size of its black hole shadow on the sky is the largest known and has optically thin millimetre- and submillimetre emission on event horizon scales. Most importantly, the mass of this source has been determined accurately by near-infrared imaging of the stars in the central region of the Milky Way. Ultimately, the mass constraints will improve even further with near-infrared interferometry, especially the GRAVITY project (Eisenhauer et al., 2011). There will be extremely interesting synergies between ALMA VLBI and VLTI in the area of strong-field GR studies [Eisenhauer].

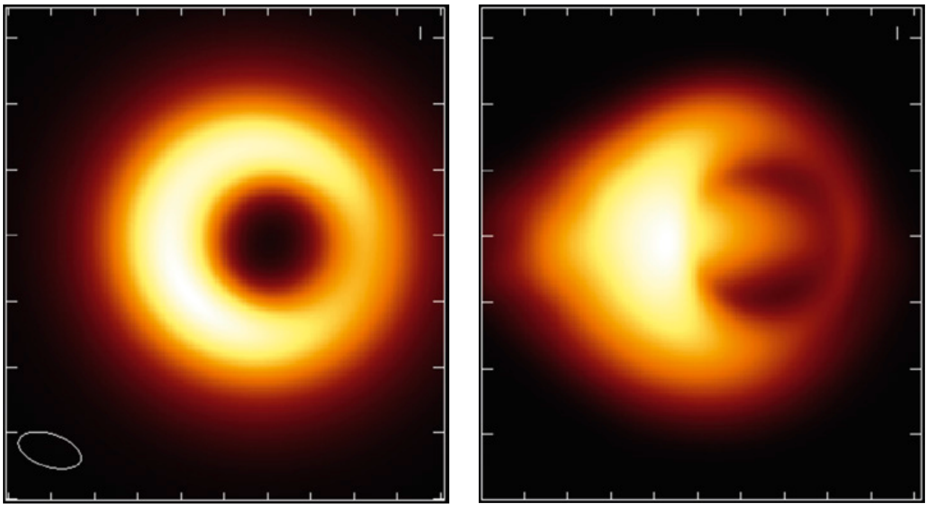


Figure 2. Simulated images at 345 GHz of the black hole in the Galactic Centre using a VLBI array involving ALMA and other telescopes. The input model is based on general relativistic magneto-hydrodynamic simulations of plasma around a Kerr black hole from Mościbrodzka et al. (2009). Left: Face-on orientation; Right: Edge-on orientation. The black hole shadow and photon ring are much more difficult to detect, but still visible in the edge-on case. Figure updated from Falcke et al. (2011).

Powerful jets

The other source of great interest in this respect is the black hole in the central galaxy of the Virgo cluster, M87. This black hole is a thousand times further away, but also a thousand times more massive then Sgr A*, so their event horizons are comparable in angular size. In M87, the radio emission is undoubtedly produced by a relativistic plasma jet (Figure 3). Recent mm-VLBI observations [Krichbaum, Hada] indicate that this jet forms on the scale of a few Schwarzschild radii, thus imposing extreme constraints on all possible models for jet formation. VLBI at 230 GHz and above should ultimately reveal the region where the jet is formed, thereby addressing one of the fundamental problems of astrophysics: jets and discs are ubiquitous in astronomical objects ranging from young stars to supermassive black holes.

Moreover, the study of relativistic jets with VLBI has recently received additional attention in connection with observations of blazars made by the Fermi satellite. Multi-wavelength campaigns suggest that bright gamma flares are directly connected to outbursts and component ejections seen at millimetre wavelengths.

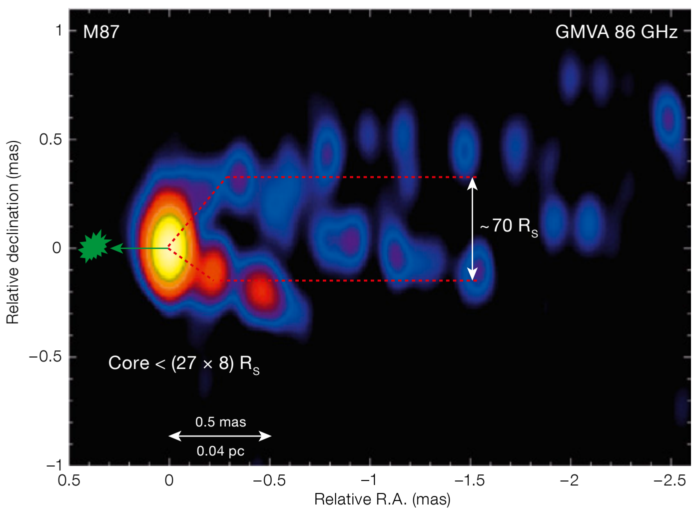
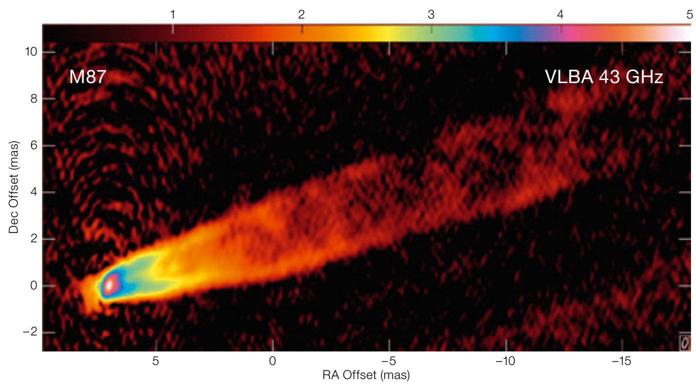


Figure 3. Left: 86 GHz VLBI image of the jet in M87 (from Krichbaum et al., 2007). The jet extends down to some tens of Schwarzschild radii (Hada et al., 2011). Right: A 43 GHz VLBA image from Walker et al. (2008), clearly revealing the limb-brightened structure also seen at 86 GHz.



Surprisingly, these flares seem to come from rather large distances from the black hole, i.e., regions that can still be imaged by mm-VLBI even in more distant sources, where the event horizon is too small to resolve [Giroletti, Orienti].

Masers in stars, star-forming regions and AGN

Another fascinating science driver at millimetre wavelengths is high-brightness line emission. Many of the lines commonly detected by ALMA are produced in extended and diffuse regions with low brightness temperatures and are not detectable at high spatial resolution. This changes, however, when one looks at maser emission or at absorption lines towards compact continuum sources [Impellizzeri].

Well-known examples of maser sources occur in evolved stars, where H_20 and SiO masers provide impressively detailed tracers of the dynamics of the molecular and dusty winds blown away from the old star into the interstellar medium [Colomer, Richards]. Quite a number of maser lines of water and other molecules have frequencies above 35 GHz. (A list of maser transitions relevant to VLBI is given in the contribution by E. Humphreys linked to the conference web page). Some of these transitions are expected to come from the most excited molecules close to the stellar surface (Figure 4). Precise astrometry of masers [Brunthaler] is also needed in the Galactic Centre, where the accuracy of the basic reference frame for calculating stellar orbits is limited by errors in cross-referencing the radio and optical reference frame using SiO masers.

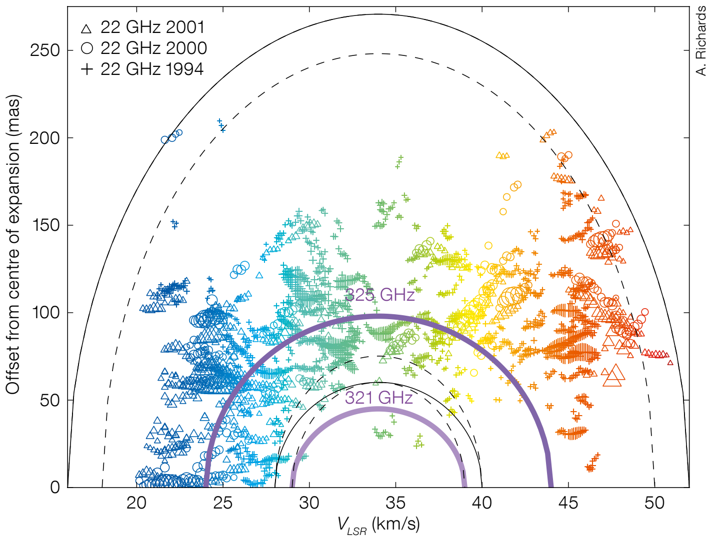


Figure 4. Position–velocity plot showing the observed 22 GHz water vapour emission from the oxygen-rich AGB star IK Tau (colour-coded by velocity), together with the predicted locations of water maser emission at 321 and 325 GHz from models by Malcolm Gray.

Masers are also seen in star-forming regions and young stellar objects, particularly in regions excited by shocks [Goddi]. They may trace radial infall as well as outflow. Again VLBI allows precise measurement of the dynamics of these processes.

A foretaste of the potential of high-resolution maser observations at millimetre wavelengths has been given by the first ALMA test observations of 321 and 658 GHz water masers with two-kilometre baselines (Figure 5). The observations are part of the initial tests on the longer baselines and demonstrate the use of compact spectral line sources for calibration. The targets chosen for these initial tests are well known high-mass star-forming regions, which contain bright maser sources, and analysis of the test data is still in progress. These early results clearly show the potential of ALMA and, in the future mm-VLBI, for high angular resolution imaging of bright maser sources. Additional tests are currently being planned targeting masers

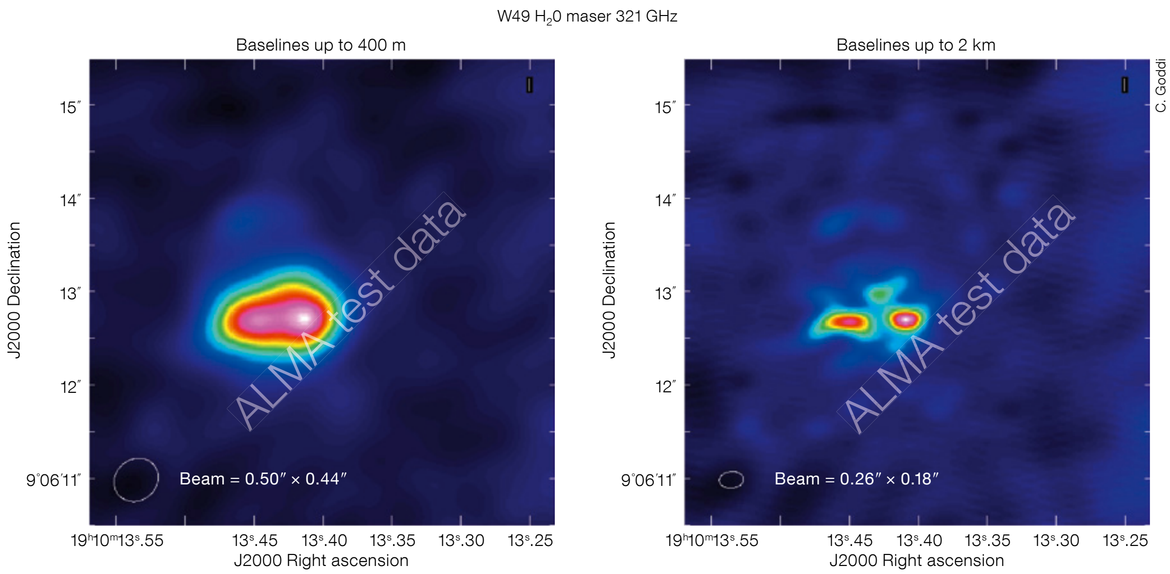


Figure 5. ALMA test observations of water-maser emission from W49N at 321 GHz. Left: baselines up to 400 metres, with a beam of 0.55 by 0.44 arcseconds. Right: baselines up to 2 kilometres with a beam of 0.26 by 0.16 arcseconds.

in late-type stars. A full characterisation of submillimetre maser sources across the sky may also generate an alternative network of (bright) phase calibrators for high frequency observations.

Extragalactic maser sources are also known [Humphreys]. A famous example is the nearby active galaxy NGC 4258, where a warped molecular disc surrounds the central supermassive black hole. VLBI proper motion observations of 22 GHz water masers in the disc have been used to obtain a precise geometric distance to this galaxy, making it a crucial component of the extragalactic distance ladder. Currently the water maser cosmology project is extending this technique to larger distances, thereby providing an independent measurement of the Hubble constant and a direct determination of black hole masses (important for the black hole mass–velocity dispersion relation). Observations of higher frequency water maser transitions (e.g., 183 or 321 GHz) have the potential to improve our understanding of the accretion disc physics and geometry. Particularly intriguing is the speculation that super-masers might exist. In those systems the millimetre-wave emission could be more intense than the well known 22 GHz line and perhaps detectable to greater distances.

Pulsars, microquasars and gamma-ray bursts

Finally, there are many other compact sources that are potential targets for mm-wave VLBI. In particular, transient sources such as supernovae, gamma-ray bursts and microquasars should be very interesting, since the highest frequencies probe the earliest phases of any eruption.

At first sight, pulsar science is an unexpected field for ALMA, since the radio spectra of pulsars are usually very steep. Nevertheless, there is some indication of spectral flattening at millimetre wavelengths and a phased ALMA should be able to observe pulsed emission [Kramer]. Of particular interest would be searches for pulsars in the Galactic Centre, where low-frequency pulses suffer from huge dispersion and scattering, to the extent that they become undetectable. An optimally located pulsar could, e.g., measure the black hole mass to one part in a million and provide independent tests of GR.

Organisational challenges

VLBI inherently requires many telescopes to operate together. While the ALMA phasing project is under way, other millimetre telescopes will also be needed to act as part of a global array. Existing activities at 3 mm (the Very Long Baseline Array and the Global Millimeter VLBI Array) and at 1 mm (the Event Horizon Telescope project) have laid the groundwork for future coordinated observations. Some of the most outstanding science goals, like imaging the black hole shadow, are unlikely to be achieved with just a few baselines. As ALMA reaches full operation, there will be financial pressures to close down existing facilities, but on the positive side, new facilities are emerging such as the Large Millimeter Telescope (LMT) in Mexico [Hughes] and the Long Latin American Millimeter Array (LLAMA) in Argentina [Cseh]. In Europe, the Northern Extended Millimeter Array (NOEMA) project, an upgrade of the Institut de Radioastronomie Millimétrique (IRAM) Plateau de Bure Interferometer is going ahead [Bremer] and large single dishes (IRAM 30-metre, Effelsberg, Sardinia Radio Telescope, Yebes, Onsala and Metsähovi) will play an important role at 3 and 7 mm wavelengths. In the USA, the Very Long Baseline Array (VLBA) is crucial, as well as the Combined Array for Research in Millimeter-wave Astronomy (CARMA) [Brinkerink], the Submillimeter Telescope (SMT) and Submillimeter Array (SMA) at higher frequencies.

Overall the meeting demonstrated that European astronomers have a broad range of science interests beyond the initial key projects that will be addressed by a phased ALMA facility alone and in coordinated mm-VLBI observations. This might, for example, be organised following the established examples of the European VLBI Network (EVN) supported by the Joint Institute for VLBI in Europe (JIVE) [van Langevelde], as well as the Global Millimeter VLBI Array. The inclusion of ALMA and the extension to higher frequencies will bring a very substantial improvement in data quality, but also an extra level of complexity, such as a yet-to-be achieved form of dynamic scheduling to take account of changing weather conditions.

The community's enthusiasm about the groundbreaking possibilities offered by mm-VLBI with ALMA was clearly evident during the workshop: some of the expected science results may indeed become transformational. There was general agreement at the conclusion of the meeting that, from a European perspective, the ultimate goal of the planning process should be a facility accessible to the general user, with time made available through open competition.

On the way towards this goal, the scientific needs of the user community for mm-VLBI with ALMA need to be compiled as a necessary input to the approval process for the ALMA phasing project. Some of the technical challenges of this project are being addressed by the international multi-partner phasing-project led by the Haystack Observatory: the task for the nascent European ALMA VLBI user community is to organise itself to prepare for the successful use of this exciting new capability.

The meeting was co-sponsored by ESO and Radionet3, an EU Integrated Infrastructure Initiative to coordinate access, development and training for radio astronomy facilities in Europe[2].

References

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Links

[1] Workshop webpage: http://www.astro.ru.nl/mmVLBI2012
[2] Radionet3: http://www.radionet-eu.org