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# Charting new territories: high-resolution VLBI exploration of supermassive black holes in active galactic nuclei

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## Abstract

High-frequency Very-Long-Baseline Interferometry (VLBI) offers a distinctive solution for imaging the shadows of black holes and the innermost regions of active galactic nuclei (AGN) jets. The latest technological developments have significantly enhanced VLBI's capabilities, enabling the exploration of fainter sources and the acquisition of high-precision astrometric data. By studying the opacity and polarization properties of emission in the collimation and acceleration regions of extragalactic jets, we can gain insights into the strength and orientation of magnetic fields near the supermassive black hole's event horizon. The deployment of the frequency phase transfer technique promises to further improve the sensitivity and positional accuracy of global VLBI observations at millimeter wavelengths, opening new avenues for investigating the fundamental physics of black holes and relativistic jets.

## A new era for mm-VLBI

The application of Very Long Baseline Interferometry (VLBI) has markedly enhanced our comprehension of active galactic nuclei (AGN) jets over the past few decades. Nevertheless, the underlying mechanisms that drive the formation and extraordinary radiative output of these plasma flows, particularly at TeV energies, remain unclear. These processes are thought to occur in the immediate vicinity of the supermassive black hole, a region that is too compact to be resolved by traditional centimetre-wavelength VLBI observations.

Current VLBI science focuses on several key questions, including the collimation and acceleration of relativistic plasma near black hole engines in both galactic and extragalactic objects; the dynamics of jet opacity and emissions, including high-energy and neutrino emissions; the orientation of magnetic fields and their connections to black holes; the establishment of reference frames using quasar VLBI data; and the study of transient phenomena such as gravitational wave electromagnetic counterparts, fast radio bursts, and gamma-ray bursts.

To investigate the complex, highly magnetised environments in close proximity to the black hole, millimetre (and sub-millimetre) VLBI (mm-VLBI) is a crucial tool (see for an introduction [2]). This technique, enabled by longer baselines and higher frequencies, provides the necessary resolution to gain insight into these previously obscured regions. By overcoming the limitations of centimetre-wavelength observations, mm-VLBI opens new avenues for examining the intricate physics governing AGN jets and their powerful emissions.

Beyond the Very Long Baseline Array, currently, two powerful arrays enable mm-VLBI capabilities. Since 2017, the Event Horizon Telescope (EHT)[1] operates at frequencies of 230 GHz and 345 GHz, as described in [4]. Complementarily, and since the early 2000s, open-sky observations are available at 86 GHz (and, complementarily, at 43 GHz) through the Global mm-VLBI Array (GMVA)[2], see e.g., [11].

The GMVA provides nominal resolutions of approximately 50 $\mu$as, while the EHT achieves higher resolutions down to about 20 $\mu$as. These resolutions enable astronomers to study high brightness-temperature sources, typically of non-thermal origin. Such sources include masers, pulsars (if their spectra are not steep), active galactic nuclei, and the environments surrounding supermassive black holes at their centers.

Recent highlights from GMVA studies benefit from the inclusion of beamformed ALMA since 2017, and include the joint detection of the jet and the black hole shadow in Messier 87 [8], the characterisation of the scattering screen in the Galactic Centre towards the black hole shadow detection [6]. An example of the continous enhancement of the array is given after the addition of upgraded NOEMA (the radio-interferometer operated by IRAM at the Plateau de Bure site) applied to the study of the central region in the compact AGN BL Lac [7]. The synergy with EHT observations by combining 86 GHz and 230 GHz is manifest in studies of nearby galaxies like the study of magnetic fields in 3C 84 [10], and the central black hole region in NGC 1052 [1].

The integration of beamformed ALMA into the Global Millimeter-VLBI Array (GMVA) since 2017 has ushered in a new era of high-resolution astrophysical observations. This has led to significant advancements, including the joint detection of the jet and black hole shadow in Messier 87 [8] and the characterization of the interstellar scattering screen in the Galactic Center, enabling the subsequent detection of its black hole shadow [6].

The ongoing evolution of the array is exemplified by the recent incorporation of the upgraded NOEMA telescope (operated by IRAM at the Plateau de Bure site) into GMVA observations of the central region in the compact active galactic nucleus (AGN) in the radio source BL Lac [7]. This expansion has enabled the combination of 86 GHz and 230 GHz observations with those of the Event Horizon Telescope (EHT), providing unprecedented insights into the magnetic field structures of nearby galaxies. A similar approach has been

[1]See the EHT webpage
[2]For more information on GMVA capabilities and proposal opportunities, see the GMVA webpage.

also applied in the studies for the radio galaxy 3C 84 [10] and for the central black hole region in NGC 1052 [1].

In recent years, the space-VLBI mission RadioAstron, operating at centimeter wavelengths with baselines spanning several Earth diameters, has offered complementary high-resolution capabilities, sometimes surpassing those of the EHT. Successful combined observations with the GMVA have yielded valuable insights, such as the study of the inner region and jet curvature of the blazar OJ 287 [5].

Looking towards the future, we can highlight ongoing enhancements in mm-VLBI technology and methods, including new imaging algorithms, parameter extraction algorithms, and hardware upgrades. Concerning the latter, excellent capabilities are made available by the development of digital baseband converters, such as the DBBC4 [12], and the implementation of the example, frequency-phase-transfer (FPT) technology, as described in a document based on a recent meeting at the MPIfR [3]. FPT allows us to increase the coherence time, and therefore the on-source integration time, from seconds to minutes. The use of FPT offers ultimately a tenfold increase in imaging dynamic range, matching the resolution capabilities of EHT, but with a much more refined image fidelity given the excellent $(u, v)$-coverage provided by a larger number of antennas.

Looking towards the mm-VLBI FPT era, development of new receivers, such as the coming three-band (22/43/86 GHz) designs at Effelsberg, are instrumental for high-precision astrometry and mapping of magnetic fields near black holes. Ongoing projects (e.g., the M2FINDERS program funded by the European Research Council) explore these techniques to achieve 10 $\mu$as accuracy in cosmological measurements. More in detail the M2FINDERS project explores AGN central regions using multi-frequency polarisation VLBI imaging of their compact radio emission. This probes linear scales of less than a few thousand gravitational radii.

Further advancements in VLBI are anticipated with the integration of the ngVLA, improvements in calibration algorithms, and increased bandwidth. The next phase of EHT and the launch of multi-band receivers in the 22–345 GHz range are expected to enhance observational sensitivity and open new possibilities for multi-messenger astronomy.

In sum, mm-VLBI has matured significantly in recent times, providing high-impact results. Future work in VLBI will encompass the study of transient phenomena, polarization mapping near black hole jets, and the inclusion of new telescopes and technologies, moving toward the era of the ngVLA, which plans to observe up to 120 GHz frequency in the late 2030s.

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