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The Global Millimetre VLBI Array

Current Capabilities and Future Enhancements

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Abstract. The Global Millimetre VLBI Array (GMVA) is a high-resolution, high-sensitivity radio astronomical instrument operating at millimetre wavelengths. The GMVA, leveraging the phased ALMA and additional continental and global arrays, has recently achieved significant advancements in sensitivity and resolution. This paper presents the current capabilities of the GMVA, explores recent scientific achievements, and discusses ongoing enhancements to hardware and calibration techniques, aiming towards the next-generation very long baseline interferometry (VLBI) with the inclusion of future arrays such as the ngVLA.

1. Introduction

Millimetre wavelength very long baseline interferometry (mm-VLBI) has revolutionized our understanding of relativistic jet dynamics, black hole environments, and high-energy astrophysical processes. The Global Millimetre VLBI Array (GMVA), including the phased Atacama Large Millimetre/submillimetre Array (ALMA) since 2017, now operates at wavelengths of 7 mm and 3.5 mm, complemented with the Event Horizon Telescope (EHT) which also includes ALMA and operates at 1.3 mm and 0.85 mm, providing unprecedented angular resolution and sensitivity. The recent upgrade of the IRAM NOrthern Extended Millimetre Array (NOEMA) telescope has also notably enhanced the sensitivity of mm-VLBI arrays (see Kim et al. 2023 for the exemplary enhancement in the observations of BL Lac).

The operations of the GMVA are based on a Memorandum of Understanding[1], signed in 2003, following earlier efforts by the Coordinated mm-VLBI Array (operated by the MIT/Haystack Observatory). The agreement reserves blocks of time for 3-mm VLBI observations, with schedules set at least six months in advance, and issues open calls for proposals aligned with existing cm-wavelength VLBI deadlines. The proposals are reviewed collaboratively by designated schedulers and observatory representatives, who determine the observation schedule. The original signatories included the U.S. National Radio Astronomy Observatory (NRAO), Institut de Radioastronomie Millimétrique (IRAM) in France and Spain, Max-Planck-Institut für Radioastronomie (MPIfR) in Germany, Onsala Space Observatory in Sweden, and the Metsähovi Radio Observatory in Finland.

The GMVA provides coordinated, high angular resolution and high sensitivity observations in the 3 mm band (85–95 GHz), significantly enhancing the capabilities of stand-alone Very Long Baseline Array (VLBA) or High Sensitivity Array (HSA) operations. The array comprises eight VLBA antennas with 3-mm receivers, the Green Bank Telescope (GBT), the IRAM 30 m telescope, the phased NOEMA, the MPIfR 100 m Effelsberg telescope and other facilities in Europe, Asia and Greenland (see Fig. 1 and Table 1). Proposals involving phased ALMA must be submitted to both the GMVA and ALMA (this may be changed in the future to avoid 'double jeopardy' for proposers). GMVA observations are scheduled bi-annually in Session I (April–May) and Session II (September–October), with individual proposals being combined into dedicated blocks to optimise resources. Note that starting in 2025, the GBT will be shut down from May to September each year.

Standard GMVA data acquisition is performed at 4 Gbps in DDC mode and correlation is performed at the MPIfR DiFX correlator in Bonn, with data provided to the principal investigator in `uv-fits` format. Since 2024, the array has increased the recording capacity of the GMVA from 4 Gbps to 16 Gbps for several stations. In the future, the array will continue to upgrade to higher bandwidths for increased sensitivity.

The present sensitivities of the array, following the GMVA webpage[2] are described in Table 1. For proposing, sensitivity calculations are supported by tools such as

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[1] See text in `https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/mou.html`

[2] See `https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/`

Fig. 1: World map with the GMVA array. Included are as well telescopes operating at 3 mm which have observed jointly with the array (in grey). Map created with `worldmapgenerator.com`, telescopes images from their institutional web pages or Wikipedia.

the GMVA Sensitivity Calculator[3] and EVN Observation Planner[4]. A cartoon with the telescopes operating at present at 3 mm wavelength is shown in Fig. 1.

Deadlines for GMVA proposals are around 1 February (for the Sep-Oct session) and around 1 August (for the Apr-May session of the following year). Multi-epoch and out-of-session proposals are possible. Proposals must be prepared using the NRAO Proposal Submission Tool[5] (PST), with special registration required for all proposers. Proposals involving ALMA must follow its guidelines[6] and deadlines. The GMVA imposes technical restrictions, detailed in the Technical Guidelines[7], and proposers must quantitatively justify their observing plans, especially for faint targets (e.g., flux densities ≤ 100 mJy). Additional facilities operating at 3.5 mm may be requested, and it is the responsibility of the Principal Investigator to arrange these[8]. GMVA data are archived and made available to the public one year after the correlation release, according to NRAO standards.

2. Science Results and Observational Capabilities

The main scientific goals of mm-VLBI are to probe the collimation and acceleration mechanisms of relativistic jets, to understand the connection between black holes and

[3] See `https://www3.mpifr-bonn.mpg.de/cgi-bin/mobs.cgi`

[4] See `https://planobs.jive.eu/`

[5] For detailed information, see `https://science.nrao.edu/observing/call-for-proposals`

[6] See `https://almascience.nrao.edu/proposing/proposers-guide`, note that there are specific requirements such as font size (minimum 12 point for ALMA and 11 point otherwise), text modification to ensure proposer anonymity (not required for GMVA/NRAO), and a recommended 4 page scientific justification format

[7] See `https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/tech.html`

[8] Note that the participation of the LMT (50m) is based on separate proposals to be submitted to the LMT; see `https://www.lmtobservatory.org`. The availability of the Large Millimetre Telescope (LMT) is limited and local night observations (4–13 UT) are preferred. For the (phased) Australia Telescope Compact Array (ATCA) and Mopra telescopes, additional proposals are also required to the Australia Telescope National Facility, again with different proposal deadlines from the GMVA, see `https://www.atnf.csiro.au/observers/apply/applications.html`.

Table 1: GMVA Antenna and Receiver Properties at 3.5 mm (adapted from the GMVA webpage), in *italics*, other 3-mm telescopes not affiliated to the GMVA

Station name	Diameter [m]	T_{sys} [K]	Gain g_i [K/Jy]	η [%]	SEFD [Jy]	Comment
GBT	100	130	0.98	35	133	for nighttime observing
Effelsberg	80 (eff.)	140	0.14	7.7	1000	-
NOEMA (12×15 m)	52 (eff.)	70	0.42	70	163	phased array, dual-band receivers 3/1.3 mm
Pico Veleta	30	100	0.15	60	654	dual-band receiver 3/1.3 mm
Yebes	40	100	0.10	22	990	dual-band receiver 7/3 mm
VLBA (8×25 m)	25	115	0.028	16	4100	g_i range is (0.01−0.04) K/Jy
KVN (4×21 m)	21	150	0.05	40	3000	for each 21 m dish, multi-band receiver 13/7/3/2 mm
Onsala	20	130	0.049	43	2650	-
Metsähovi	14	150	0.010	18	15000	-
GLT	12	170	0.032	78	5312	-
APEX (prelim)	12	170	0.032	78	5000	dual-band receiver 3/1.3 mm
ALMA (37×12 m)	71 (eff.)	70	1.02	71	69	phased array, changing configuration
ARO (prelim)	12	170	0.032	78	5000	-
ATCA (6×22 m)	47 (eff.)	150	0.12	unk.	1450	phased array, supports only 1 Gbps, 5 dishes at 3 mm
Mopra	22	300	0.068	49	4400	dual linear feeds
LMT (prelim.)	50	200	0.39	55	513	double side band
Haystack	37	125	0.16	45	780	-
JCMT	15	80	0.038	unk.	170	

Notes: The SEFD is the system-equivalent flux density. The values for APEX and Arizona Radio Observatory (ARO) have been set equal to GLT, pending more detaled measurements. "unk." stands for unknown by the writers of this contribution. Baseline sensitivity measurements give the following detection limits: for Effelsberg, sensitivities range from 20 to 300 mJy; for NOEMA, from 8 to 125 mJy; for GBT, from 8 to 111 mJy; and for ALMA, from 8 to 80 mJy. The array sensitivity (1σ) improves significantly depending on the stations included, with values of 0.087 mJy/hr for the Europe+VLBA configuration, 0.052 mJy/hr for Europe+VLBA+GBT, and 0.029 mJy/hr for Europe+VLBA+GBT+ALMA. These values scale by $\exp(\tau A)$, where τ is atmospheric opacity, and $A = 1/\sin(\text{elevation})$ is air mass. For $\tau = 0.1$ and $A = 2$, the factor is about 1.22. Weather conditions, phase stability and atmospheric coherence time impose additional constraints as these parameters can vary between 10 and 180 seconds. In particular, due to antenna pointing accuracy, calibration and phasing of ALMA and NOEMA, the typical VLBI duty cycle is about 0.5. Consequently, for each hour of on-source VLBI observation, two hours of actual observing time are required. The assumed parameters include the MK6 recording system in 4096-16-2 (DDC) mode with single polarisation, a 512 MHz bandwidth per polarisation, 10,s integration time (typical coherence time), 7σ detection threshold, and 2-bit sampling. Sun avoidance limits for telescopes are: NOEMA 32°, APEX 30°, LMT 20°, ALMA 15°, and Effelsberg, Metsähovi, Onsala, Pico Veleta, Yebes, and VLBA 5°. In addition, daytime observations close to the Sun at 3 mm are affected by atmospheric turbulence and sensitivity loss, so it is recommended to avoid observations of sources too close to the Sun. As a reminder, $\mathrm{SEFD}_i = T_{\mathrm{sys},i}/g_i$, $\sigma_{ij} = {\eta_c}^{-1}(\sqrt{\mathrm{SEFD}_i \cdot \mathrm{SEFD}_j})/(\sqrt{2\Delta t \Delta\nu})$, where $\eta_c = 0.64 \quad (1\mathrm{bit})$ and $\eta_c = 0.88 \quad (2\mathrm{bit})$.

their associated jet structures, and to study high-energy emission processes and neutrinos (for recent progress in the VLBI-neutrino connection see e.g., Kadler et al. 2016 and Ros et al. 2020, for future prospects, see Kovalev et al. 2023 and the ERC MuSES project, see Kovalev 2024). This synergy between VLBI and high-energy observations provides a more complete picture of jet physics, from the innermost regions close to the black hole to the far-reaching relativistic outflows (see Blandford et al. 2019 and references therein). In particular, mm-VLBI allows for the resolution of structures close to the event horizon, providing insights into the jet formation and launching (see e.g., Krichbaum et al. 2010, 2012, 2014). In particular, it is investigated whether the jet launching regions are magnetically dominated (MAD) or not (SANE), and the associated dynamics of these outflows (see Tchekhovskoy, Narayan & McKinney 2011).

Recent GMVA observations, such as the imaging of the black hole shadow in Messier 87 (M 87, Lu et al. 2023, see Fig. 2, complementing earlier observations by the Event Horizon Telescope et al. 2019 at 1.3 mm wavelength) and transversely stratified jet structures in sources such as 3C 84 (Paraschos et al. 2024), have demonstrated the capabilities of the GMVA. See sect. 2.1 for further details. The integration of the phased ALMA in the array has proven transformative, markedly enhancing sensitivity and angular resolution. This advancement has facilitated the observation of more intricate jet features and magnetic field structures. Such progress was achieved following the successful implementation of ALMA phasing (refer to Matthews et al. 2018 for further details).

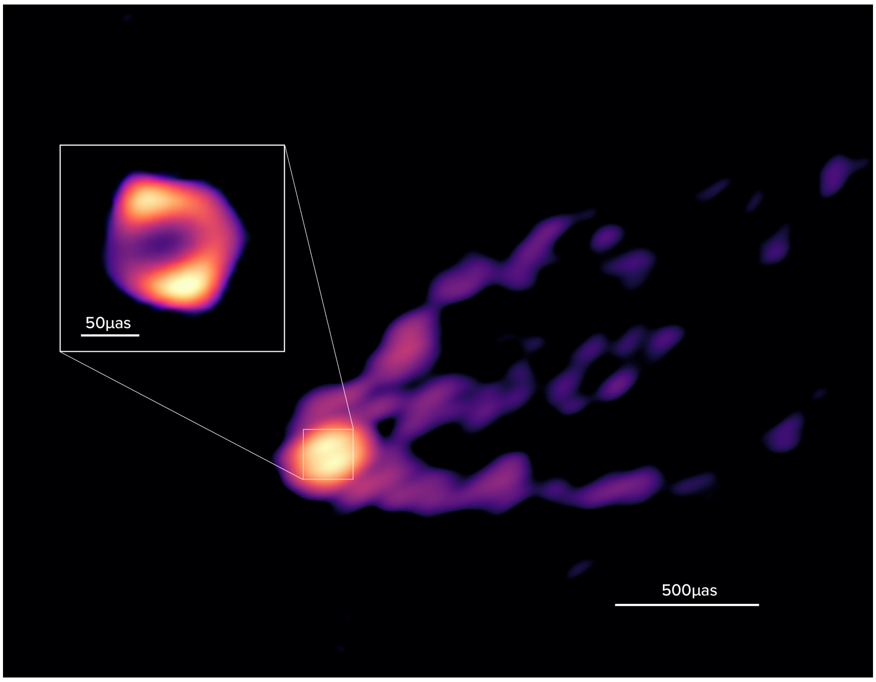

Fig. 2: GMVA highlight: this image shows the jet and shadow of the black hole at the centre of the M 87 galaxy together for the first time. The observations were performed by the GMVA including phased ALMA in April 2018, reaching angular resolution of 50 μas. The new observations also revealed that the black hole's ring, shown here in the inset, is 50% larger than the ring observed at shorter radio wavelengths by the EHT. This suggests that in the new image we see more of the material that is falling towards the black hole than what we could see with the EHT. The scientific rendition of this image and additional information is provided in Lu et al. (2023). Illustration taken from the MPIfR Press Release 2023/6.

2.1. Recent Scientific Results

The GMVA provides high-resolution imaging of active galactic nuclei (AGN), revealing the innermost structures of jets and accretion processes around supermassive black holes. Common themes across several studies include the investigation of magnetic field strengths and jet dynamics and collimation mechanisms at sub-parsec scales. The data consistently reveal features such as precessing jets, recollimation shocks, and polarisation structures that support jet formation models linked to black hole spin and accretion states. The observations also reveal significant Faraday rotation and synchrotron self-absorption effects, which are key to studying the environment around AGN nuclei. For details in the related science, see some recent reviews such as Blandford et al. (2019) and Boccardi et al. (2017).

These findings advance our understanding of jet physics by resolving structural transitions (e.g., collimation breaks), tracing helical magnetic fields, and linking variability in radio and gamma-ray emissions to localized jet phenomena like shocks or bending. Below is a source-specific summary of the recent results obtained with the GMVA. The resolutions reached are in the range of (50 to 60)μas, and the apparent speeds range from (0.055 to 0.22)c for 3C 84 or below 1c in M 87 to values of about 3c in J1924−2914, (3 to 10)c in BL Lac, above 5c in NRAO 530, about 10c in 3C 454.3, and above 10c in 3C 273 and OJ 287.

Most sources appear to have magnetic field dominated dynamics. Recent publications provide these features: helical fields in OJ 287; values of mG to tens of mG on parsec scales for OJ 287, 3C 454.3, 3C 273, and BL Lac. Higher estimates are given for 3C 84 (a few G) and NRAO 530 (3000 to 30000 G), and NGC 1052 (10^4 G). Note that these values are given for different regions in the black hole neighbourhood, sometimes in the jet, sometimes at the edge of the Schwarzschild radius, please see the corresponding publications for more details.

Most of the imaging work has been performed with the CLEAN algorithm, but usually this was compared with regularised maximum likelihood algorithms such as `Resolve`[9] (see e.g., Junklewitz et al. 2015, 2016, Arras et al. 2019, and Kim et al. 2024), `DoG-HiT` (Müller & Lobanov 2022), and `smili` (Akiyama et al. 2017a, 2017b), which provide higher resolution and fidelity. Advanced calibration pipelines such as `rPICARD` (Janßen et al. 2019) and `GPCAL`[10] (Park et al. 2021) improved the data quality, particularly for BL Lac (see 4 for technical developments).

Classically, parameterisation from the structure of sources observed with a radio interferometer has been performed by fitting Gaussian functions in the image plane to the observed visibilities using the Levenberg-Marquardt nonlinear least squares minimisation technique, e.g., in `difmap` (Sheperd et al. 1997). As an example of recent method developments, and inspired by the EHT efforts, but also applicable to modelling any other features observed with mm-VLBI (e.g. jet features), a new Bayesian image reconstruction method, `THEMIS`, has been developed by Broderick et al. (2020) to address the challenges of interpreting mm-VLBI. `THEMIS` offers a full Bayesian treatment, providing posterior distributions for images and allowing rigorous analysis of their statistical significance. In addition, it can directly incorporate modelled features, as demonstrated by the successful reconstruction and characterisation of the photon ring in the EHT images of M 87,

[9] See `https://gitlab.mpcdf.mpg.de/ift/resolve`
[10] See `https://github.com/jhparkastro/gpcal`

but also in the EHT observations of 3C 279 (Kim et al. 2019).

The synergies with the space-VLBI RadioAstron mission (Kardashev et al. 2013) yielded joint studies (e.g., OJ 287 and 3C 84), and also with the Event Horizon Telescope (NGC 1052, 3C 84, M 87, NRAO 530, or J1942−2914).

Further sources have been studied with the GMVA in earlier years, but we will not report about those here thoroughly (see for that directly the concerning papers on OJ 287 also in Dey et al. (2020) and Hodgson et al. (2016), BL Lac as well in Casadio et al. (2021) and Rani et al. (2015, 2016), NGC 315 in Boccardi et al. (2021), 3C 111 in Schulz et al. (2020), 3C 279 in Kim et al. (2020), TXS 2013+370 in Traianou et al. (2020), Sgr A* in Issaoun et al. (2019), Brinkerink et al. (2019) and Lu et al. (2016), 3C 84 also in Kim et al. (2019), CTA 102 in Casadio et al. 2019, M 87 as well in Kim et al. 2018, NRAO 150 in Molina et al. (2016), NGC 1052 in Baczko et al. (2024, 2016), Cygnus A in Boccardi et al. (2016), Mrk 501 in Koyama et al. (2016), PKS 1502+106 in Karamanavis et al. (2016), or S5 0716+714 in Rani et al. (2014). Here are some highlights from the most recent results (corresponding references at the end of the paragraph).

NGC 1052 (B0328−084) Millimetre-VLBI provides access to the otherwise obscured centre of the active galaxy NGC 1052, exploring jet formation and magnetic fields. The observations reveal a compact region near the SMBH, consistent with theoretical jet-launching models like Blandford-Znajek, which require strong magnetic fields. The magnetic fields estimates at the very centre range from 200 G to 8.3×10^4 G. The size of the jet base, combining GMVA observations and EHT data modelling, resolve the jet base's size (43 μas, i.e., ∼250 Schwarzschild radii) and identify structural features supporting jet expansion. For more information, see Baczko et al. (2016, 2024).

OJ 287 (B0851+202) Observations with GMVA and ALMA resolved a twisted and compact jet structure, potentially indicative of a precessing jet. The VLBI core was identified at the southeast end, while an extended feature with a conical shape suggested possible oblique shocks. The magnetic field structure is consistent with a helical configuration, aligning with a binary supermassive black hole model. See Zhao et al. 2022), Gómez et al. (2022), and Lico et al. (2022).

3C 84 (B3 0316+413, NGC 1275, Perseus A, 4C +41.07, OE 427, CTA 022, DA 097, NRAO 132) High-resolution imaging revealed a double nuclear structure in this nearby radio source. The data suggest a bent, stratified jet with significant magnetic field ordering near the core. Polarimetric analysis highlighted equipartition conditions and steep synchrotron spectra, indicative of advection-dominated accretion flows. Observations also confirmed a possible spine-sheath jet structure. See Paraschos et al. (2024, 2022) and Oh et al. (2022).

3C 454.3 (B 2251+158, 4C +15.76, OY 185, DA 586, NRAO 701) Multi-frequency studies uncovered synchrotron self-absorption features, with magnetic fields varying across regions. Observations identified a quasi-stationary component (C) linked to recollimation shocks, while a moving jet component (K14) enhanced emission during gamma-ray flares. The bending jet structure aligns plasma flows with the line of sight. See Traianou et al. (2024) and Jeong et al. (2023).

M 87 (PKS 1228+126, Virgo A, NGC 4486, 3C 274, 4C +12.45, DA 325, NRAO 401) The GMVA resolved M 87's black hole shadow and extended jet simultaneously. Imaging at 3.5 mm wavelength revealed a thicker, ring-like structure with bright spots suggesting gravitational lensing. A spine-sheath structure was confirmed, with evidence of accretion-driven winds augmenting jet emission close to the black hole. See Lu et al. (2023), and Kim et al. (2024).

3C 273 (B1226+023, 4C 02.32, ON 044, CTA 053, DA 324, NRAO 400) The quasar's inner jet exhibited a transition from parabolic to conical collimation at scales beyond the sphere of gravitational influence. The break in collimation suggests external factors influencing jet expansion. Observations confirmed structural transitions consistent with theoretical jet formation models. See Okino et al. (2022).

BL Lacertae (B3 2200+420, OY 401, DA 571) During a flaring state, high-resolution imaging showed a helical jet morphology. Improved sensitivity from NOEMA participation facilitated detection of polarized knots and brightness temperatures consistent with relativistic beaming. Ridge-line analyses supported a sinusoidal jet pattern, suggesting underlying magnetic field dynamics. See Kim et al. (2023).

NRAO 530 (PKS 1730−130) This quasar exhibited some of the strongest magnetic fields measured in AGNs. Faraday rotation measurements between 7 and 1.3 mm wavelengths indicated high particle densities near the jet base. The precessing jet behavior and observed spectral features align with theories of dynamic jet launching influenced by black hole spin. See Lisakov et al. (2024).

J1924−2914 (TXS 1921−293, OV −236) This blazar displayed a clockwise bending jet morphology across frequencies from 13 cm to 1.3 mm wavelengths (two orders of magnitude). Commensal EHT imaging revealed toroidal magnetic fields, supporting ordered magnetic field configurations in the jet base. These findings corroborate models of jet launching in AGNs. See Issaoun et al. (2022) for details in the morphology and for further theoretical references.

3. Current Capabilities and Upcoming Methods

3.1. Array Expansion and Hardware Enhancements

The GMVA operates with an extended network of telescopes, including VLBA, IRAM, KVN, and ALMA. The integration of new receivers with higher data bit rate (up to 16 Gbps) is underway, aiming to standardize 4 GHz bandwidth across all stations.

Since its inception in 2003, the GMVA has steadily improved its capabilities by increasing the bandwidth of the available data bit rate, improving the hardware of its various telescopes, implementing more efficient correlation modes, and adding new telescopes to the array.

The Korean VLBI Network was first successfully tested in September 2014 and has been regularly participating in observations, on a best-effort basis, since May 2016. The fourth antenna of the array, PyeongChang, joined in April 2024.

The biggest step forward in sensitivity, together with the more recent NOEMA upgrade (fringes in September 2020), came with the completion of the ALMA phasing project (Matthews et al. 2018), but also with the addition of antennas to selected experiments. ALMA started regular observations in April 2017. Haystack was scheduled for May 2022 and April 2023, but no data have been correlated.

The Greenland Telescope (GLT) first got fringes at 3 mm wavelength with the GMVA in March 2018 (data published in Lu et al. 2023), and has participated since then regularly in the sessions of the array.

The Large Millimetre Telescope (LMT) in Mexico was scheduled for observations in May 2022, but withdrew observations before they started, no fringes were found at 3 mm to the antenna in April 2023. No further joint observations were possible. Fringes between the LMT and the VLBA were obtained at 3 mm already in April 2015 (Ortiz-León et al 2016)

Mopra and ATCA successfully participated in selected experiments in May 2022, April 2023 and April 2024. ATCA had already got 3 mm fringes with the KVN in September 2013 (see Rioja et al. 2014).

The James Clerk Maxwell Telescope (JCMT) on Hawaii successfully joined GMVA observations in May 2023 and May 2024.

Since October 2024, the APEX telescope in Chile has been a regular member of the array, providing a factor of 3 improvement in north-south resolution that was previously only available when phased ALMA was granted (first in April 2017).

It is planned that the Italian VLBI telescopes which are developing a three-band (13/7/3 mm) receiver, namely, Medicina, Sardinia, and Noto, will join the GMVA in the near future.

A promising development in high-frequency VLBI in Europe is the planned construction of the Wetterstein Millimetre Telescope (WMT) near the Zugspitze in the German Alps (see Kadler et al. these proceedings) at an altitude over 2600 m above sea level, as part of the LEVERAGE project to extend the new-generation Very Large Array to east and the SKA-mid to the north. The WMT would also join the GMVA.

Looking to observing modi (see below), the implementation of multi-band receivers at Effelsberg and APEX, particularly the multi-band receivers in both telescopes, will further augment the array's capabilities. More details on these hardware developments, both in the receivers (frontend) and the electronics and recording (backend) are provided in Sect. 4.2.

Efforts towards a new era of the EHT are also considering the addition of 3 mm observations to the 1.3 mm observations. The form and manner in which this will be implemented is beyond the scope of this publication (see Issaoun et al. 2023 for more details).

3.2. Frequency Phase Transfer (FPT)

One of the critical advancements in millimetre-wavelength VLBI is the deployment of frequency phase transfer (FPT) techniques. These significantly boost dynamic range and image fidelity, enabling 3-mm observations to rival or surpass those at 1.3 mm (EHT). Initially formulated at the MPIfR (Middelberg et al. 2005), FPT is particularly effective at wavelengths shorter than 13 mm and has been successfully implemented at the Korean VLBI Network (KVN; Rioja et al. 2015).

FPT enhances sensitivity and dynamic range in VLBI imaging, achieving astrometric accuracy up to one microarcsecond. These improvements have broad implications for black hole physics, cosmology, stellar astrophysics, and transient phenomena (Dodson et al. 2017).

A workshop held in Bonn in 2022 (Dodson et al. 2023) emphasized the development of a global FPT VLBI network. Currently, the KVN operates multiband shared-optical-path (SOP) receivers, which are being replicated or developed across Europe, Asia, and Australia (Han et al. 2013, Rioja & Dodson 2020). The aim is to achieve unparalleled resolution and sensitivity at 13, 7, and 3.5 mm wavelengths (KQW bands). To ensure alignment of capabilities and goals, formalized coordination through technical and science working groups is being advocated (Venturi et al. 2020).

Global FPT VLBI introduces several critical enhancements. It extends coherence time and reduces phase noise at millimetre wavelengths, facilitating high-precision imaging and astrometry. Positional accuracy improves with longer baselines and higher signal-to-noise ratios, supporting transformative scientific applications.

FPT VLBI offers groundbreaking opportunities in astrophysical research. In black hole physics, it enables unprecedented studies of event horizons, magnetic fields, and disk-jet interactions (Lu et al. 2023, Mizuno et al. 2018). The technology is also crucial for investigating transient phenomena such as tidal disruption events and gravitational wave counterparts, alongside probing the dynamics of binary supermassive black holes (Quercellini et al. 2009).

Despite these advancements, challenges remain in standardizing multiband receivers and optimizing backend processing equipment. Collaborative efforts among observatories are necessary to address recording rates, extend frequency ranges, and ensure compatibility across institutions (Rioja et al. 2015).

The workshop summarized in Dodson et al. (2023) highlighted the immense potential of FPT VLBI to redefine VLBI operations and its significant contributions to astrophysical research. Establishing a coordinated global network is a pivotal step toward realizing these capabilities (Dodson et al. 2017). A near-in-time formation of working groups and development of strategic roadmaps will be instrumental in advancing this field, ensuring that the technology's scientific promise is fully realized.

A detailed description of the FPT technique and the expected improvements in VLBI science is provided in Lobanov (these proceedings). Additional details on the progress of the FPT technique at the MPIfR in the framework of the ERC funded M2FINDERS program are provided in Zensus et al. (these proceedings).

4. Future Directions

The development roadmap for the GMVA includes deploying enhanced digital backends, new receiver technologies, and calibration pipelines (e.g., `rPICARD` and `polsolve`, see below) to enable faster and more accurate data processing. With the addition of new facilities like the ngVLA (Murphy et al. 2018), the GMVA will extend its reach to frequencies beyond 100 GHz, opening new frontiers in mm-VLBI science.

4.1. Software developments

A summary of the recent software developments for VLBI data processing and analysis, with a focus towards millimetre wavelengths, is provided in Janßen et al. (2022).

Concerning data processing, this was traditionally performed in the Astronomical Image Processing System[11]) AIPS (Greisen 2003) or the Haystack Observatory Postprocessing System[12] (HOPS), this has been enhanced at present with the CASA[13]-based python Radboud PIpeline for the Calibration of high Angular Resolution Data (`rPICARD`[14], Janßen et al. 2019), and with a developed HOPS, i.e., `eht-HOPS`[15] (Blackburn et al. 2019).

VLBI arrays typically use circular polarization (via quarter-waveplates) because calibrating linear feeds is complicated by varying feed-angle rotations at different antennas. Mixed-polarization observations, where some telescopes use linear polarization, create visibilities that are harder to analyze and incompatible with the `FITS-IDI` format. This issue affects the geodetic array VLBI Global Observing System (VGOS), some EVN, and mm-VLBI observations involving phased ALMA (i.e., the EHT and the GMVA). To address this, mixed polarization data are converted to a circular basis using the `PolConvert`[16] (Martí-Vidal et al. (2016) program before release to the PI. This development was essential for the game-changing quality of ALMA, as described above. Continuing in this line, for advanced polarisation calibration, Martí-Vidal et al. (2021) developed `polsolve`[17], a python package which introduced advanced capabilities such as simultaneous multi-source calibration, nonlinear modelling of instrumental polarization, and self-calibration to improve accuracy in wide-band, high-dynamic-range observations.

As already mentioned above, the traditional CLEAN methods for imaging (in `AIPS` or `difmap`[18] (Shepherd 1997), new software packages are available in the market, with a focus on regularised maximum likelihood (e.g., `eht-imaging`[19], Chael et al. 2016, 2018 ; `smili`[20], Akiyama et al. 2017a, 2017b).

4.2. Hardware developments

4.2.1. Frontend

In a radio telescope, the frontend refers to the part of the system that collects and amplifies incoming radio signals from space. It typically includes the antenna, low-noise amplifiers and sometimes initial frequency conversion stages. The goal of the frontend is to collect signals with minimal noise and prepare them for further processing. In VLBI, heterodyne receivers are used, i.e., receivers that use frequency mixing to convert a received signal to another frequency, known as an intermediate frequency (IF), for easier processing.

At present, several telescopes are developing SOP multi-band receivers, including the GMVA antennas in Yebes, Metsähovi, Onsala, and further antennas with the potential to join the array, such as Medicina, Noto, and the Sardinia Radio Telescope. These will follow the scheme by the KVN, covering the wavelengths 13, 7, and 3.5 mm (Yebes can already perform dual-band observations, while the KVN also reaches 2 mm in a four-band suite). Effelsberg is also joining this effort, with the present development of a receiver covering these three bands. The

[11] See the cookbook at `http://www.aips.nrao.edu/cook.html`
[12] See `https://www.haystack.mit.edu/tech/vlbi/hops.html`
[13] The Common Astronomy Software Applications package, see `https://casa.nrao.edu/`
[14] See `https://bitbucket.org/M_Janssen/picard`
[15] See `https://github.com/sao-eht/eat`
[16] See `https://github.com/marti-vidal-i/PolConvert`
[17] See `https://github.com/kettenis/casa-poltools/blob/master/polsolve.py`
[18] Available at `ftp://ftp.astro.caltech.edu/pub/difmap/difmap.html`
[19] See `https://github.com/achael/eht-imaging`
[20] See `https://github.com/astrosmili/smili`

design choice departs from the Korean design, and foresees a coaxial receiver for the 13 mm and 7 mm wavelengths (i.e., K_a and Q bands), and a detached 3 mm (i.e., W-Band) receiver, all in the same Dewar. These developments in Effelsberg, funded by the Max Planck Society and supported by the ERC M2FINDERS project (see Zensus et al. these proceedings), are expected to be commissioned during 2025.

Commissioning of N3AR in APEX and FPT tests in progress
Dual-band options at shorter wavelengths including the 3 mm band are also under development, this is already possible at the IRAM-30m telescope on Pico Veleta, and is being deployed in NOEMA, among other telescopes. Following this development, the MPIfR radio telescope has recently developed the 3 mm receiver N3AR and installed it at APEX. N3AR uses a dichroic mirror to reflect frequencies below 120 GHz into N3AR and allow the high frequencies to pass to the Nasmyth receivers, including the 1.3 mm nFLASH redceiver, and 0.35 mm SEPIA receiver band, among others, making dual-band observations possible.

At the time of writing, we can report that the first light of the N3AR receiver took place in early October 2024, and APEX successfully participated in the October 2024 GMVA session (from 11 to 13 October). A commissioning observing run to test the dual-band observing mode and the options to apply the FTP between 3.6 mm and 1.2 mm, between APEX and Pico Veleta, was performed on 20 November 2024, provided fringes and showed that after solving the phase wrap the technique works for this intercontinental baseline. Further details will be reported in G.-Y. Zhao et al. (in prep.). Converging efforts are underway and will be reported in S. Issaoun et al. (in prep.).

4.2.2. Backend

The backend processes the signals from the frontend. It performs tasks like digitization, filtering, frequency channelization, and data formatting. It also involves recording or transmitting the processed data to be correlated or analyzed. A Digital Baseband Converter (DBBC) significantly enhances the performance of radio telescopes by enabling efficient signal digitization and processing. Unlike traditional analog systems that are constrained by noise and physical limitations, present developments such as the DBBC4 (see Tuccari et al. 2023b, these proceedings) digitizes signals across ultra-wide bandwidths, preserving their integrity and reducing the effects of analog distortion. For example, the DBBC4 can process input bands up to 32 GHz, capturing data from multiple frequency ranges simultaneously, which is critical for the GMVA and the EHT. The digitisation of the signal closer to the antenna using modular elements minimises analog signal degradation over long cable runs. By combining ultra-wide bandwidth processing, reduced analog noise, and AI-assisted optimization, developments such as the DBBC4 represent a transformative leap for VLBI, not only for mm-VLBI, but also for geodesy or for systems like BRAND (see Alef et al. 2023, Tuccari et al. 2023a, and Rahimi et al. these proceedings), which offer multi-band capabilities in cm-wavelengths.

The GMVA has paved the way for the bandwidth upgrade by conducting the first 16 Gbps observations in April 2024. It has logistically arranged the sharing of Mark 6 recording media with the neighbouring EHT observing campaign.

5. Conclusion

The GMVA is a cornerstone of high-resolution millimetre radio astronomy, providing transformative insights into the physics of relativistic jets, black hole environments, and high-energy astrophysical phenomena. By exploiting advances in array sensitivity and implementing state-of-the-art calibration techniques, the GMVA has consolidated its role in addressing fundamental questions about jet collimation, magnetohydrodynamic processes, and accretion dynamics.

Recent achievements of the GMVA include high-resolution imaging of AGN cores, resolution of magnetic field structures and jet-base dynamics, and multi-band observations linking radio features to gamma-ray and X-ray variability. The imaging of the black hole shadow and jet structure in M 87 stands out as a highlight, illustrating the potential of mm-VLBI to probe event horizon-scale physics. Similarly, the detection of helical magnetic fields in OJ 287, stratified jets in 3C 84 and the detailed study of magnetic field intensities in NRAO 530 underline the unique capabilities of the array. Further magnetic field studies using the improved polarisation calibration techniques now available promise new and exciting results.

Technological advances, including the development of frequency phase transfer (FPT) techniques, multi-band receivers, and digital backends, are critical to maintaining and expanding the capabilities of the GMVA. The implementation of FPT not only improves sensitivity but also enables astrometric accuracy in the microarcsecond range, paving the way for groundbreaking measurements in cosmology, galactic dynamics and black hole physics. The ongoing deployment of dual- and multi-band receivers at facilities such as Effelsberg and APEX, as well as upgrades to digital processing systems such as the DBBC4, are key milestones along this path.

Looking forward, the synergy between the GMVA and facilities such as the EHT and the future ngVLA promises to expand the science emerging from mm-VLBI. This will open new frontiers in mm-VLBI science, including the study of transients, gravitational wave counterparts and binary supermassive black holes. The continued development of advanced software pipelines for calibration and imaging will further enhance the GMVA's scientific output.

In summary, the GMVA's unparalleled sensitivity and resolution have established it as a leading instrument for the study of the most compact non-thermal emitting sources in radio astronomy. Its ongoing hardware and software improvements, coupled with its integration into global arrays, position it to address some of the most pressing questions in modern astrophysics, from the formation and dynamics of relativistic jets to direct imaging of black hole event horizons.

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