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Article

# Millimeter-Wave Monitoring of Active Galactic Nuclei with the Africa Millimetre Telescope

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**Abstract:** Active galactic nuclei are the dominant sources of gamma rays outside our galaxy and are also candidates for the source of ultra-high energy cosmic rays. In addition to being emitters of broad-band non-thermal radiation throughout the electromagnetic spectrum, their emission is highly variable on timescales from years to minutes. Hence, high-cadence monitoring observations are needed to understand their emission mechanisms. The Africa Millimetre Telescope is planned to be the first mm-wave radio telescope on the African continent and one of few in the southern hemisphere. Further to contributing to the global mm-VLBI observations with the Event Horizon Telescope, substantial amounts of observation time will be available for monitoring observations of active galactic nuclei. Here we review the scientific scope of the Africa Millimetre Telescope for monitoring of active galactic nuclei at mm-wavelengths.

**Keywords:** active galactic nuclei; millimeter-wave astronomy; mm-VLBI; monitoring

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## 1. Introduction

Active galactic nuclei (AGN) and more particularly the subclass of blazars have been a major topic of research throughout the electromagnetic spectrum for the past fifty years. Despite significant progress in understanding the blazar phenomenon [1], many open questions remain. Several apparent differences could be attributed to their non-spherical structure and the orientation of the highly relativistic jets relative to the line of sight [2]. Still, the underlying particle acceleration and emission processes remain a matter of current research. Connected to the more than one hundred years of quest for the sources of the highest-energetic cosmic rays, hadronic emission scenarios are tested, e.g., [3,4], and recent coincident gamma-ray and neutrino detections point in that direction [5]. Even though, hadronic emission scenarios are not uncontested, as also the leptonic synchrotron self-Compton (SSC) model [6] is highly successful in explaining the broad-band spectral energy distribution (SED) for blazars, see e.g., [7]. AGN are variable on all time scales: from optical quasi-periods of several years [8] down to gamma-ray flares lasting only minutes [9] and even limiting the size of the emission region to be smaller than 20% of the gravitational radius of the central black hole [10]. This motivates intensive efforts for monitoring the variability of AGN across the electromagnetic spectrum.

Following recent positive developments of astronomy in Africa in general [11] and Namibia in particular [12], the Africa Millimetre Telescope (AMT) project aims to build a mm-wave radio telescope in Namibia [13]. It will be the first telescope of its kind on the African continent and one of only few in the Southern hemisphere. The proposed site for the AMT is Mt. Gamsberg (23.34° S, 16.23° E) in the Khomas Highlands of Namibia, at a height of 2347 m a.s.l. At very similar latitude to ALMA, this site offers exceptional observing capabilities at 3 mm (100 GHz) throughout the year as well as strong though seasonal capabilities at 1.3 mm (230 GHz) and 0.8 mm (345 GHz), for the latter particularly suited during June through August [13]. The AMT will re-purpose the refurbished structure of the SEST telescope [14] and shall (initially) employ receivers for 3.5 mm and 1.3 mm (86 GHz and 230 GHz), possibly extended to 0.8 mm (345 GHz). One of the main scientific drivers for the AMT are observations of the ‘shadows’ of the black holes at the centres of our Milky Way, Sagittarius A\*, and of the radio galaxy M 87 at 3.5 mm and 1.3 mm within the Event Horizon Telescope (EHT) network [15]. The shadow of the black hole at the centre of M 87 has recently been imaged for the first time by the EHT [16]. Initial simulations for Sagittarius A\* indicate a significant improvement in image quality and, hence, angular resolution by adding the AMT to the EHT [17]. Still, EHT observations will only make use of a small fraction of the available observation time on the AMT, allowing for high-cadence monitoring observations of AGN to be conducted in addition.

## 2. Scientific Rationale

Particularly because of their high variability, monitoring of AGN is crucial to obtain a complete picture of their variability patterns and to understand the underlying phenomena in these enigmatic objects. Across all accessible wavelength regimes, monitoring campaigns are being conducted; besides the all-sky monitoring in X-rays by MAXI, aboard the International Space Station, and *Swift*-BAT, in high energy gamma rays by AGILE-GRID and *Fermi*-LAT and in ultra-high energy gamma rays by HAWC, targeted monitoring of AGN is conducted particularly successfully by optical telescopes, e.g., SMARTS [18], GASP [19] of the WEBT [20], and the Steward Observatory blazar monitoring program [21], radio telescopes, e.g., OVRO [22], UMRAO [23], and Metsähovi [24,25], and the imaging atmospheric Cherenkov telescopes (IACTs) in the very-high energy gamma rays. VERITAS and MAGIC pursue long-term blazar monitoring [26,27] and FACT [28,29] was built for the purpose of blazar monitoring [30–32], even with the idea in mind to set up a world-wide network for continuous monitoring [33]. In the southern hemisphere, the H.E.S.S. telescopes conduct very-high energy gamma-ray monitoring of AGN [34,35]. These IACT observations are regularly complemented by optical monitoring in  $R_C$ - and  $B_C$ -bands by the robotic KVA [36] and ATOM telescopes [37,38].

It has long been established by very long baseline interferometry (VLBI) at up to 43 GHz (7 mm) that the high energy gamma-ray emission as measured by CGRO-EGRET is coincident with the appearance of new VLBI features (‘knots’) [39]. Later, this was underpinned with the observation of a gamma-ray flare coincident with a new VLBI knot in the radio galaxy M 87 [40]. In this context, there have been long-standing programs VLBI flux and morphology monitoring of AGN like MOJAVE in the northern hemisphere at 15 GHz (2 cm) [41], TANAMI in the southern hemisphere at 22 GHz (1.3 cm) [42], and VLBA-BU-BLAZAR in the northern hemisphere at 43 GHz (7 mm) [43]. Further, single-dish flux monitoring has been conducted at up to 43 GHz with the 100 m Effelsberg telescope within F-GAMMA [44,45] and with APEX at 345 GHz (0.87 mm) [46]. Polarimetric monitoring at 86 GHz and 229 GHz (3.5 mm and 1.3 mm) has been conducted in the northern hemisphere at the IRAM 30 m telescope within the POLAMI programme [47–49]. Further, multi-wavelengths monitoring campaigns have been organized, like MARMOT [50]. A recent review of mm-VLBI observations of AGN is given in [51], whereas the major initiative of mm-VLBI monitoring of AGN is conducted by the GMVA [52] at 86 GHz (3.5 mm) and the EHT at higher frequencies. For both initiatives, the only telescopes in the southern hemisphere are (phased) ALMA and APEX (in Chile) and the South Pole Telescope. Whereas the addition of another Southern hemisphere telescope to the EHT is one of the major and obvious scientific drivers of the AMT, complementing the GMVA at 3.5 mm VLBI

and improving the  $u-v$ -coverage of mm-VLBI observations of Southern AGN is a scientific purpose in its own right; with the superior angular resolution of mm-VLBI observations over cm-VLBI the smallest scale structures, closest to the core of AGN can be resolved. Combined with polarization imaging, the ordering and mean direction of the magnetic field at the base of the jet can be determined to distinguish between models of highly ordered helical magnetic fields or turbulent ones (possibly with standing shocks), e.g., [53,54].

Though correlation studies between 5 GHz–8 GHz VLBI flux densities obtained from the Radio Fundamental Catalogue and Fermi-LAT measurements show much stronger correlation for the high energy ( $>100$  MeV) measurements than for the very-high energy ( $>50$  GeV) ones [55], preliminary findings comparing ALMA observations at 230 GHz (1.3 mm) of a sample of 77 AGN from the Fermi-LAT 3FGL catalogue (above 100 MeV) show a significantly higher correlation than comparing the Fermi-LAT flux to 1.4 GHz data [56]. This hints at the mm-wave emission of AGN being more strongly connected to the gamma-ray emission than the cm-wave emission. The AMT will for the first time allow for strictly simultaneous observations of mm-wave and very-high energy gamma-ray emission, due to the close location of the AMT to the H.E.S.S. telescopes, which will allow for unprecedented studies of the emission properties of Southern hemisphere AGN.

One of the major drawbacks of cm radio flux density observations of AGN is that the cm emission is likely produced at different regions of the jet and, hence, for consistent modelling of the spectral energy distribution, these measurements have to be ignored because of the opaqueness of the emission region to cm radio waves due to synchrotron self-absorption. This changes drastically for observations in the mm-regime. Likely for the 3.5 mm (86 GHz) emission but certainly for the 1.3 mm (230 GHz) one, synchrotron self-absorption is negligible and the innermost regions of the jet can be probed. Such observations could test whether mm-wave and (very-)high energy emission are produced co-spatially. In this case, both, spectral as well as temporal studies would be significantly enriched. Not only would the mm-wave flux be useful for constraining AGN emission models, but also temporal correlation of the respective lightcurves would be expected—obeying differences in the electron cooling timescales. The electron cooling timescale for synchrotron emission at 230 GHz is given by

$$t_c(\text{obs}) \sim 40B_G^{-3/2}\delta_1^{-1/2} \text{ days}, \quad (1)$$

where  $B_G$  is the strength of the magnetic field in Gauss and  $\delta_1$  is the Doppler factor in units of 10. It is rather well established that emission of AGN close to the core is produced in confined volumes with  $R \lesssim 10^{16}$  cm, which are moving at relativistic speed  $\beta_\Gamma = \sqrt{1 - \frac{1}{\Gamma^2}}$ , with a bulk Lorentz factor  $\Gamma$ , along the jet. The Doppler factor is defined as  $\delta \equiv \frac{1}{\Gamma(1 - \beta_\Gamma \cos \theta^{\text{obs}})}$ , with  $\theta^{\text{obs}}$  being the viewing angle (with respect to the jet axis) in the observer's rest frame. Considering that neither the magnetic field strength nor the Doppler factor are known and taking into account the possibility for Compton-dominated cooling, resulting in shorter cooling timescales than given in Equation (1), this well motivates monitoring observations with weekly cadence. For emission of visual light, the cooling timescale is shorter by a factor of  $\sim 100$  than given in Equation (1) above. Hence, for co-spatial emission, the optical light curves should lead the radio ones by this difference. Further, if such a time-lag could be established (assuming an independent estimate of the Doppler factor), the magnetic field strength in the emission region could be estimated (as proposed initially for intra-optical time-lags in [57]). The magnetic field is generally believed to play a central role in the launching and collimation of AGN jets and in the acceleration of relativistic electrons. Thus, probing the magnetic field in the mm-emitting region will aid in clarifying its role in the particle acceleration (magnetic reconnection, e.g., [54], vs. shocks, e.g., [58], vs. shear layers, e.g., [59]) and its potential for collimating the jet.

Even if no correlation with identifiable time lag between mm and optical flux is observed, the mm-wave monitoring observations would be highly useful; in case the mm-wave variability would not be correlated to the optical variability of a given AGN, this would indicate different emission regions. Possibly, molecular and dust emissions could not only dominate the infrared part of the spectral energy

distribution but even the mm-wave emission, as observed for some blazars [60]. This, in turn, would drastically help to constrain external photon fields within the AGN as invoked for external-Compton emission models [61].

Obviously, for any significant correlation studies of multi-wavelengths lightcurves, high-cadence monitoring observations are needed as will be supplied by the AMT.

### 3. Summary

Summarizing, there is ample scope for the AMT to have significant impact in the field of (gamma-ray loud) AGN. Particularly, high-cadence single dish monitoring observations at 1–3.5 mm will help to constrain theoretical models of emission mechanisms as well the the site of gamma-ray production. Even more so, 3.5 mm VLBI observations with the GMVA and 1.3 mm VLBI observations with the EHT will help resolving the emission features and hence, foster the understanding of the structure and formation processes of AGN jets.

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### Abbreviations

The following abbreviations are used in this manuscript (in order of appearance):

AGN	Active galactic nucleus
SSC	Synchrotron self-Compton
SED	Spectral energy distribution
AMT	Africa Millimetre Telescope, <a href="https://www.ru.nl/blackhole/africa-millimetre-telescope">https://www.ru.nl/blackhole/africa-millimetre-telescope</a>
ALMA	Atacama Large Millimeter/submillimeter Array, <a href="https://www.almaobservatory.org">https://www.almaobservatory.org</a>
SEST	Swedish ESO Submillimetre Telescope, <a href="http://www.apex-telescope.org/sest">http://www.apex-telescope.org/sest</a>
EHT	Event Horizon Telescope, <a href="https://eventhorizontelescope.org">https://eventhorizontelescope.org</a>
MAXI	Monitor of All-sky X-ray Image, aboard the International Space Station, <a href="http://maxi.riken.jp/top">http://maxi.riken.jp/top</a>
Swift-BAT	Burst Alert Telescope, aboard the Neil Gehrels Swift Observatory, <a href="https://swift.gsfc.nasa.gov">https://swift.gsfc.nasa.gov</a>
AGILE-GRID	Gamma Ray Imaging Detector, aboard the Astro-Rivelatore Gamma a Immagini Leggero satellite, <a href="http://agile.rm.iasf.cnr.it">http://agile.rm.iasf.cnr.it</a>
Fermi-LAT	Large Array Telescope, aboard the Fermi Gamma-ray Space Telescope, <a href="https://fermi.gsfc.nasa.gov">https://fermi.gsfc.nasa.gov</a>
HAWC	High-Altitude Water Cherenkov Observatory, <a href="https://www.hawc-observatory.org">https://www.hawc-observatory.org</a>
SMARTS	Small and Moderate Aperture Research Telescope System, <a href="http://www.astro.yale.edu/smarts/glast">http://www.astro.yale.edu/smarts/glast</a>
GASP	GLAST-AGILE Support Programme, <a href="http://www.oato.inaf.it/blazars/webt/gasp/homepage.html">http://www.oato.inaf.it/blazars/webt/gasp/homepage.html</a>
WEBT	Whole Earth Blazar Telescope, <a href="http://www.oato.inaf.it/blazars/webt">http://www.oato.inaf.it/blazars/webt</a>
OVRO	Owens Valley Radio Observatory, <a href="http://www.astro.caltech.edu/ovroblazars">http://www.astro.caltech.edu/ovroblazars</a>

<sup>1</sup> Any opinion, finding and conclusion or recommendation expressed in this material is that of the authors and the NRF does not accept any liability in this regard.

UMRAO	University of Michigan Radio Astronomy Observatory, <a href="https://dept.astro.lsa.umich.edu/datasets/umrao.php">https://dept.astro.lsa.umich.edu/datasets/umrao.php</a>
IACT	Imaging Atmospheric Cherenkov Telescope
VERITAS	Very Energetic Radiation Imaging Telescope Array System, <a href="https://veritas.sao.arizona.edu">https://veritas.sao.arizona.edu</a>
MAGIC	Major Atmospheric Gamma Imaging Cherenkov, <a href="https://magic.mpp.mpg.de">https://magic.mpp.mpg.de</a>
H.E.S.S.	High Energy Stereoscopic System, <a href="https://www.mpi-hd.mpg.de/hfm/HESS">https://www.mpi-hd.mpg.de/hfm/HESS</a>
KVA	<a href="http://users.utu.fi/kani/1m">http://users.utu.fi/kani/1m</a>
ATOM	Automatic Telescope for Optical Monitoring, <a href="https://www.lsw.uni-heidelberg.de/projects/hess/ATOM">https://www.lsw.uni-heidelberg.de/projects/hess/ATOM</a>
VLBI	Very long baseline interferometry
CGRO-EGRET	Energetic Gamma Ray Experiment Telescope, aboard the Compton Gamma Ray Observatory, <a href="https://heasarc.gsfc.nasa.gov/docs/cgro/cgro/egret.html">https://heasarc.gsfc.nasa.gov/docs/cgro/cgro/egret.html</a>
MOJAVE	Monitoring Of Jets in Active galactic nuclei with VLBA Experiments, <a href="http://www.physics.purdue.edu/MOJAVE">http://www.physics.purdue.edu/MOJAVE</a>
TANAMI	Tracking Active galactic Nuclei with Austral Milliarcsecond Interferometry, <a href="http://pulsar.sternwarte.uni-erlangen.de/tanami">http://pulsar.sternwarte.uni-erlangen.de/tanami</a>
F-GAMMA	FERMI-GST AGN Multi-frequency Monitoring Alliance, <a href="https://www3.mpifr-bonn.mpg.de/div/vlbi/fgamma/fgamma.html">https://www3.mpifr-bonn.mpg.de/div/vlbi/fgamma/fgamma.html</a>
VLBA	Very Long Baseline Array, <a href="https://science.lbo.us/facilities/vlba">https://science.lbo.us/facilities/vlba</a>
VLBA-BU-BLAZAR	VLBA Boston University Blazar monitoring project, <a href="http://www.bu.edu/blazars/VLBAproject.html">http://www.bu.edu/blazars/VLBAproject.html</a>
APEX	Atacama Pathfinder EXperiment, <a href="http://www.apex-telescope.org">http://www.apex-telescope.org</a>
IRAM	Institut de Radioastronomie Millimétrique, <a href="http://iram-institute.org">http://iram-institute.org</a>
POLAMI	POLarimetric monitoring of AGN at Millimetre Wavelengths, <a href="http://polami.iaa.es">http://polami.iaa.es</a>
MARMOT	Monitoring of $\gamma$ -ray Active galactic nuclei with Radio, Millimetre and Optical Telescopes, <a href="http://www.astro.caltech.edu/marmot">http://www.astro.caltech.edu/marmot</a>
GMVA	Global mm-VLBI Array, <a href="https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm">https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm</a>

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