PROCEEDINGS OF SCIENCE

Preparatory studies for the Africa Millimetre Telescope

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The Gamsberg Mountain and the H.E.S.S. site are both located within the Khomas highlands and have been identified as potential sites for the Africa Millimetre Telescope (AMT). Precipitable water vapour (PWV) in the atmosphere is the primary source of opacity and noise from atmospheric emissions, when observing at millimetre to sub-millimetre wavelengths. This study aims to establish the PWV content and meteorological conditions at the potential sites of the AMT using Global Navigation Satellite System (GNSS) measurements. Using conservative specifications and potential dish sizes of 13, 14, and 15 m for the AMT, the System equivalent flux density (SEFD) and Signal to Noise ratio (S/N) to the reference stations ALMA and NOEMA were also assessed from simulated observations of M87* and Sgr A*. The EHT window PWV had a 25^{th} percentile of 12.21 mm at the H.E.S.S. site and 7.54 mm at the Gamsberg Mountain. The simulated results of M87* and Sgr A* showed the 15 m and 14 m dishes at the Gamsberg Mountain to have the lowest SEFD, with the performance of the 13 m dish being comparable to the 15 m dish at the H.E.S.S. site. For M87* and Sgr A* observations, the 13 m dish at Gamsberg Mountain achieved a higher average S/N output for the ALMA–AMT baseline than the 15 m dish at the H.E.S.S. site. For M87*, the S/N output from Gamsberg Mountain was higher for the NOEMA–AMT baseline, with the 13 m dish providing 41 additional minutes of S/N≥4 compared to the 15 m dish at H.E.S.S. For Sgr A*, the AMT at Gamsberg Mountain achieved the highest S/N for the ALMA–AMT baseline, yielding an additional 1h32 of S/N≥4 for the 13 m dish compared to the 15 m dish at the H.E.S.S. site. The PWV and simulation results indicate that the Gamsberg Mountain is the more suitable site for the AMT.

High Energy Astrophysics in Southern Africa (HEASA2025)
16-20 September, 2025
University of Johannesburg, South Africa

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1. Introduction

The Event Horizon Telescope (EHT) is a network of antennas across the globe that operates at 230 GHz (1.3 mm) and is used as a Very Long Baseline Interferometry (VLBI) array to image supermassive black holes (SMBHs). SMBHs are found in the centre of galaxies and have masses ranging from millions to tens of billions of solar masses [1]. In 2017, the network with 7 antennas at 5 geographical sites and 8 antennas at 6 geographical sites across the globe observed Messier 87* (M87*, where the "*" always signifies a black hole located at the center of the galaxy) and Sagittarius A* (Sgr A*), respectively, between 5 April and 11 April [2, 3]. The image of M87* was released in 2019 [2], and that of Sgr A* in 2022 [3]. The release of these images prompted the next phase for the EHT, which is to dynamically image SMBHs and further improve the angular resolution of the images, and add more robustness to the network. However, to make dynamical images, more antennas need to be added to the current configuration of the EHT. The Africa Millimetre telescope (AMT) is one such antenna planned to be built in the Khomas highlands of Namibia [4]. The telescope was previously planned to be of a 15 m diameter dish [4, 5] but has since been designated to be either of a 13 m, 14 m, or 15 m in diameter, with the frontend and backend specification still to be confirmed. Two potential sites have been identified within the Khomas highlands for the AMT: these are the High Energy Stereoscopic System (H.E.S.S.) observatory site and the Gamsberg Mountain, with the sites separated by a distance of approximately 30 km. Precipitable water vapour (PWV) is the primary source of opacity at millimetre to sub-millimetre wavelengths. It is defined as the amount of water vapour in the atmospheric column above a location, equivalent to the amount of liquid precipitation that would result if all the water vapour in the column was condensed [6]. The presence of PWV causes phase delays on millimetre and submillimetre astronomical signals, which may lead to a decline in performance on millimetre and submillimetre long baseline interferometers if not corrected [7].
This study investigates and compares the PWV obtained from GNSS measurements at the proposed sites for the AMT, namely the Gamsberg Mountain and the H.E.S.S. site. Furthermore, the study outlines the performance of the AMT at these sites when conducting VLBI observations with the EHT. Finally, the study concludes by identifying the more suitable site of the two potential AMT sites. This paper is the third in a series of three papers that comprise a thesis. The results from the first two papers ([8] and [9]) will therefore only be summarised.

2. GNSS-derived PWV, temperature & pressure

Figure 1 shows the timeline and periods over which GNSS station data was taken at both the H.E.S.S. site and at the Gamsberg Mountain. As can be seen, Gamsberg Mountain GNSS data was taken over a short period (approximately 2 months). For this reason, Gamsberg Mountain long-term data was estimated from the H.E.S.S. site GNSS data using the methods described in [8]. The EHT window refers to the annual period, typically occurring during March and April, when the EHT carries out its scheduled observational campaign. For this reason, a study was carried out to establish the PWV content primarily for the EHT window at both sites [8]. Table 1 shows the mean and percentiles of PWV at the H.E.S.S. site and at the Gamsberg Mountain as determined in [8]. The mean PWV was found to be 16.61 mm and 11.19 mm at the H.E.S.S. site and at

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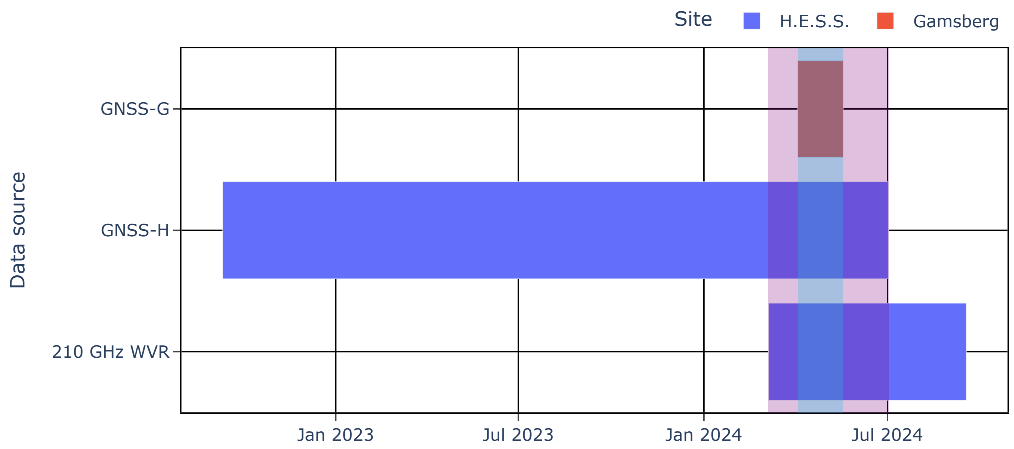

Figure 1: Period over which data measurements were obtained from the H.E.S.S. site and the Gamsberg Mountain by various instruments.

Table 1: GNSS-derived PWV percentiles determined at the H.E.S.S. site and at the Gamsberg Mountain during the EHT window over two years between 2022 and 2024.

Site	25% [mm]	50% [mm]	75% [mm]	Mean [mm]
H.E.S.S. (HE)	12.21	16.62	20.80	16.61
Gam (GB)	7.54	11.20	14.67	11.19

the Gamsberg Mountain, respectively. Individual EHT antennas only participate in observations under the best local conditions mainly considering the PWV among other conditions. The best conditions correspond to the 25^{th} percentile, with values of 7.54 mm for the Gamsberg Mountain and 12.21 mm for the H.E.S.S. site, respectively. The GNSS stations at both stations are also

Table 2: Pressure and temperature measured at the H.E.S.S. site and estimated for the Gamsberg Mountain at 25^{th} percentile.

AMT Site	P_g [mbar]	T_g [K]
Gam (GB)	770.13	288.98
H.E.S.S. (HE)	819.50	291.04

coupled with a weather station which measures temperature t_g and pressure p_g. Table 2 shows the 25^{th} percentiles of t_g and p_g obtained at both sites.

3. GNSS-derived PWV validation

To assess the validity of the GNSS-derived PWV data, a comparison to PWV measurements from a 210 GHz Water Vapour Radiometer (WVR) was conducted, as shown in [9]. The 210 GHz

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WVR was installed next to the GNSS station. PWV data measured simultaneously by both instruments for the period indicated in purple in Figure 1 were analysed. PWV data from both instruments were found to be 98% correlated and a mean PWV offset of 0.15 mm was found between the instruments. The 0.15 mm PWV offset is essentially negligible and suggest that the 210 GHz WVR and GNSS station PWV data are equivalent.

4. AMT performance during EHT+AMT simulated observations

Simulated EHT+AMT observations of M87* and Sgr A* were conducted using the SYnthetic Measurement creator for long Baseline Arrays (SYMBA). SYMBA is a synthetic data generation pipeline for VLBI observations [10]. SYMBA can recreate EHT observations by providing an input general relativistic magnetohydrodynamics (GRMHD) model image, such those of M87* [11] or Sgr A* [12], and applying noise corruptions to the models. SYMBA requires site information input such as the PWV, surface pressure P_g, temperature T_g, and the phase coherence time at each of the antenna participating in the simulated observations. Since observations at each site will only be triggered under the best conditions, the 25^{th} percentile PWV was used as input for both sites as given in Table 1. The P_g and T_g input for both the H.E.S.S. site and Gamsberg Mountain is given in Table 2. The Phase coherence insitu measurements for both sites were not available at the time, and for this reason, a conservative C_t value of 3 seconds was used for both sites as was done by [10]. Furthermore, SYMBA also requires antenna specifications input such as the diameter D_{tel}, the reciever temperature T_r and the effective apperture area $AE_{230\,\mathrm{GHz}}$ of each antenna participating in the observation. The T_r for the AMT at the H.E.S.S. site and at the Gamsberg Mountain was adopted as 330 K and 270 K, respectively. At both sites, D_{tel} options of 13, 14 and 15 m were considered with a $AE_{230\,\mathrm{GHz}}$ of 0.51. Antenna specifications and site information recorded at the individual EHT stations during the 2017 EHT observations were used as input for the other EHT stations. Both the antenna specification and site information are provided by [10]. Since ALMA and NOEMA are the most important reference stations for fringe detections, only information from these stations were included in the analysis.

4.1 Simulated EHT+AMT observations

The simulated station information during the simulated observations of M87* are shown in Figure 2. The two lowest SEFD values for the AMT were given by the 15 m and 14 m at the Gamsberg Mountain, while the 13 m dish at the Gamsberg Mountain nearly matches the SEFD of the 15 m at the H.E.S.S. site. The 13 m and 14 m options at the H.E.S.S. site offer the worst performance for the AMT during the simulated observations of M87*. Therefore, to achieve performances even remotely comparable to those at the Gamsberg Mountain, the AMT at the H.E.S.S. site would require a dish size of at least 15 m. For the EHT, only fringe detections with S/N $\geq$ 4 among the EHT baselines are considered significant. Therefore, the duration of S/N $\geq$ 4 of the AMT baseline to the reference stations ALMA and NOEMA during observations was obtained. Figure 3 show the baseline S/N to the reference stations ALMA and Figure 4 that to reference station NOEMA from both the H.E.S.S. site and the Gamsberg Mountain for the different potential diameters of the AMT during the simulated observations of M87*. As can be seen in Figure 3, a S/N ratio of more than 4 was achieved by the ALMA-AMT baseline with the AMT at both sites, for all potential diameters

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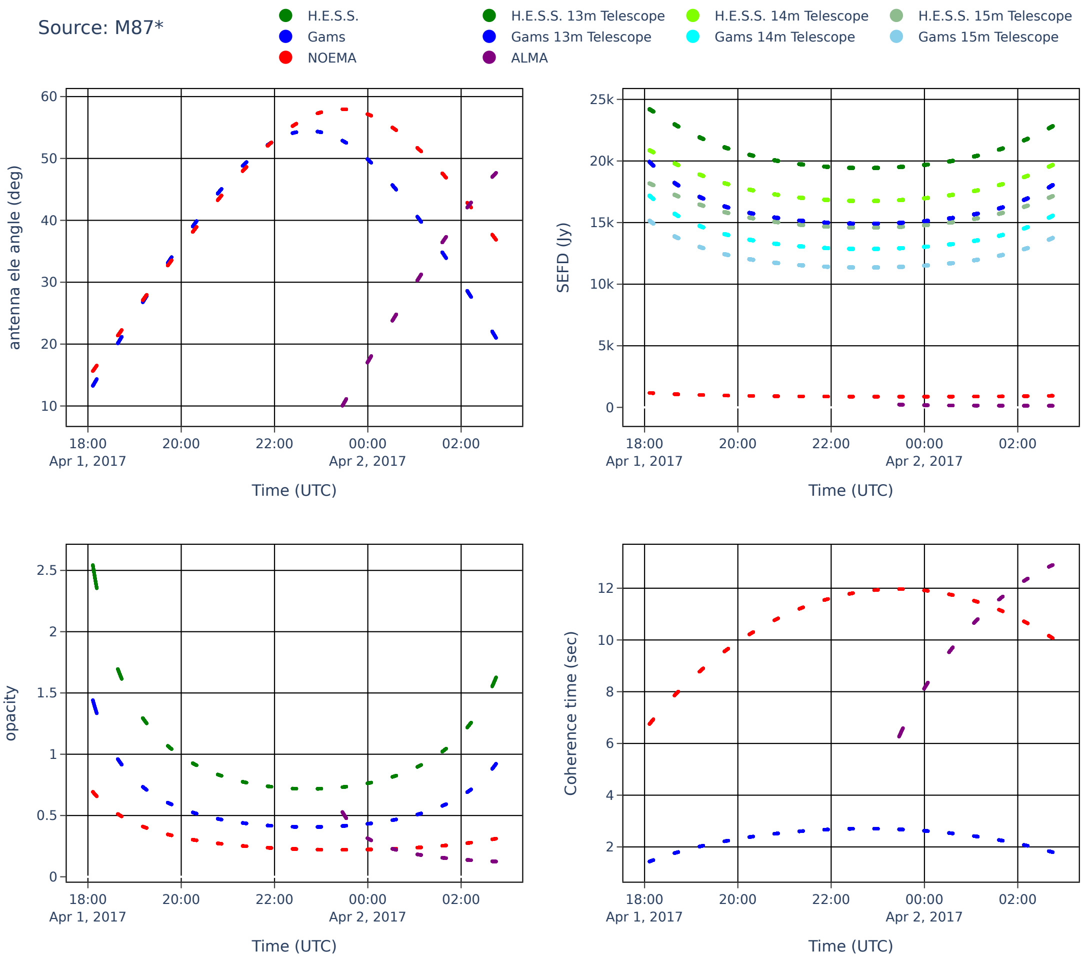

Figure 2: Simulated antenna and site information during observation of M87*.

of the AMT for the full duration of the observations of 3h14. Moreover, the 13 m diameter at Gamsberg Mountain exhibited a higher S/N than the 15 m diameter at the H.E.S.S. site on the baseline with ALMA.

As can be seen in Figure 4, the NOEMA-AMT baseline achieves a low S/N ranging between 3.6 to 4.6 for all possible diameters of the AMT at both sites. The highest S/N of at least 4 or above is achieved between 19h00 UTC and 22h30 UTC, after which the S/N drops below 4. This indicates that the NOEMA-AMT baseline, despite having a low S/N, will be crucial in the first half of observations of M87*, after which the ALMA-AMT baseline could take over as the NOEMA-AMT baseline S/N decreases below 4. The 13 m diameter at the Gamsberg Mountain also provides a longer duration of 1h39 during which the S/N ≥ 4 for the NOEMA-AMT baseline, compared to all AMT dish diameter options at the H.E.S.S. site.

For Sgr A* observations, it was found that constructing the AMT at Gamsberg Mountain with the smallest available antenna option of 13 m guarantees at least an additional 1h32 of observing time per night, with an S/N ratio ≥ 4, compared to the 15 m option at the H.E.S.S. site for the ALMA–AMT baseline.

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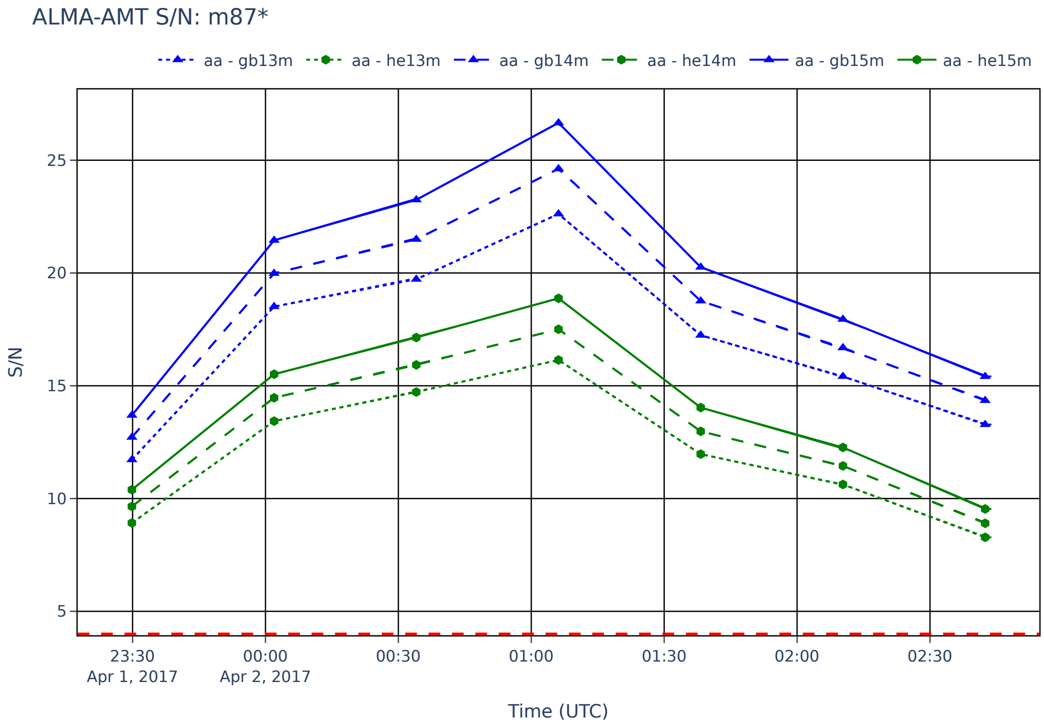

Figure 3: The S/N of the ALMA-AMT baseline during the observations of M87* from both the H.E.S.S. site and the Gamsberg Mountain with the various potential dish diameters for the AMT.

5. Conclusions

Under the best conditions, represented by the 25^{th} percentile, the PWV values were found to be 12.21 mm at the H.E.S.S. site and 7.54 mm at Gamsberg Mountain. A high correlation of 98% and an offset of 0.15 mm was calculated between the PWV obtained from the 210 GHz WVR and that from the GNSS station. The validation results indicated that the GNSS station can be used with high accuracy to determine the PWV with minimum offset from traditionally utilised instruments such as the 210 GHz WVR.
For the NOEMA-AMT baseline, the 13 m at the Gamsberg Mountain provided 41 minutes more observing time with the S/N $\geq$ 4 than the 15 m at H.E.S.S. site during the simulated observation M87*. Similarly, For Sgr A* it was found that a 13 m AMT dish at the Gamsberg Mountain would provide an additional 1h32 of observing time with S/N $\geq$ 4 over a 15 m at the H.E.S.S. site. The simulated observations found that the AMT at Gamsberg Mountain offered the best overall performance when compared to the AMT at H.E.S.S. site.
In conclusion, while building the AMT at the H.E.S.S. site may save costs associated with the construction of the observatory, it is evident from the PWV data and the simulation results that the best site among the two potential sites for constructing the AMT is the Gamsberg Mountain.
Phase coherence is an important aspect of mm-wave radio astronomy, as it significantly influences the signal. This study utilised a conservative estimated value of 3 seconds at both sites. Such a

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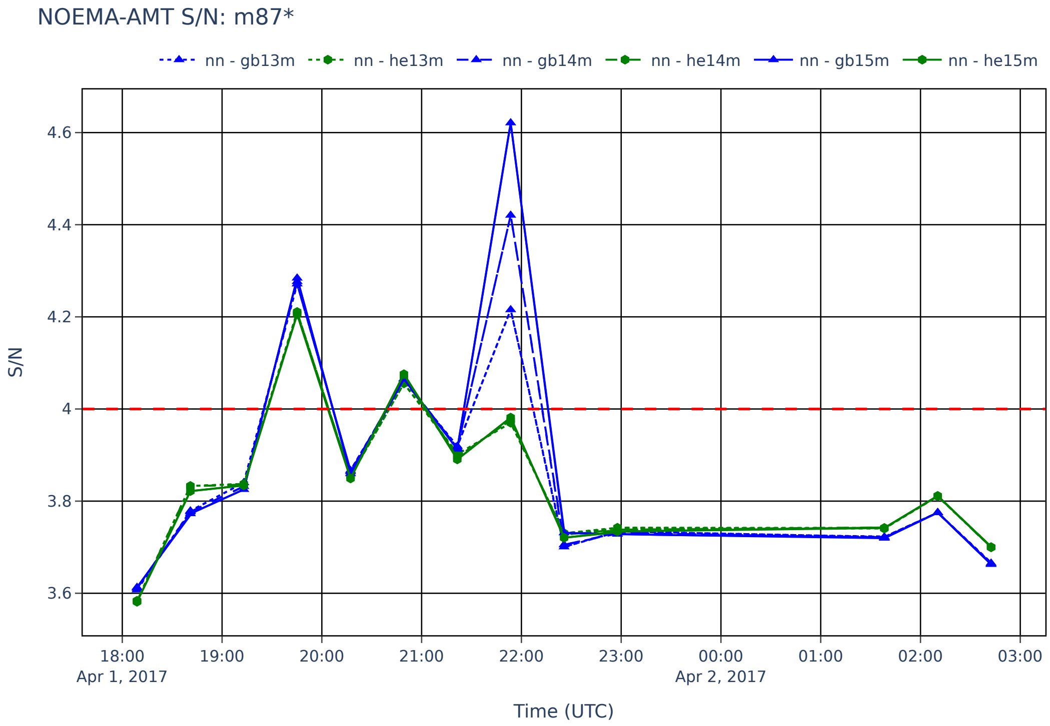

Figure 4: The S/N of the NOEMA-AMT baseline during the observations of M87* from both the H.E.S.S. site and the Gamsberg Mountain with the various potential dish diameters for the AMT.

value will have a significant impact on the simulated results, leading to poor performance of the AMT. For this reason, a phase coherence study was recommended and commissioned to establish the phase coherence at both sites.

Acknoweledgments

This work was and is supported by multiple institutions including the South African Radio Astronomy Observatory (SARAO) through Dr Roelf Botha and the National Autonomous University of Mexico (UNAM) through Prof. Stanley E. Kurtz and his collaborators in CONACyT-NRF Project 291778./. We also thank the Nevada Geodetic Laboratory (NGL) for processing and presenting the GNSS tropospheric products used in this study. This work has been partially supported by the ERC Synergy Grant BlackHolistic and H2020-INFRADEV-2016-1 project 730884 JUMPING-JIVE.

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