

## The Africa Millimetre Telescope

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It is believed that supermassive black holes are found in the centres of galaxies, including the Milky Way. Still, only indirect evidence has been gathered for the existence of these enigmatic objects that are predicted by the general theory of relativity. With the Event Horizon Telescope, a Very Long Baseline Interferometry network of millimetre-wave (radio) telescopes, it will be possible to directly image the ‘shadow’ of the event horizon of the black hole at the centre of the Milky Way, Sgr A\*. Although the Event Horizon Telescope utilises an extensive network of telescopes, there is a huge gap in the coverage of the  $u - v$ -plane for these observations across Africa.

We discuss the benefits of adding the Africa Millimetre Telescope to the Event Horizon Telescope and present Mt. Gamsberg in Namibia as the best site for this new and first mm-wave telescope in Africa.

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## 1. Imaging the Black Hole at the centre of our Galaxy (Sgr A\*)

The general theory of relativity is still largely untested in the strong-field limit. Certainly, the best objects to pursue such tests are supermassive black holes (SMBHs) and the nearest one, which is also the largest in apparent diameter, is located at the centre of the Milky Way, Sgr A\*. Currently, we can only infer from indirect evidence that Sgr A\* is a SMBH. However, by utilizing Very Long Baseline Interferometry (VLBI) techniques at millimetric wavelengths, one should be able to achieve sufficient angular resolution to directly image the ‘shadow’ of the event horizon of Sgr A\*, which has an angular size of about  $50 \mu\text{arcsec}$  [1]. For further details see [2] and references therein.

Recent observations of Sgr A\* at 43 GHz [3], 86 GHz [4, 5], and 230 GHz [6] are starting to resolve the source. The observation of non-zero closure phases indicates possible substructure in the plasma emission around Sgr A\*. These indications and the aforementioned possibility to directly image Sgr A\* have given rise to the Event Horizon Telescope project.

## 2. The Event Horizon Telescope

The Event Horizon Telescope (EHT)<sup>1</sup> is an initiative to create a global mm-wave VLBI network that will achieve a resolution of 12–20  $\mu\text{arcsec}$  and therefore have sufficient resolution to image the  $\sim 50 \mu\text{arcsec}$  ‘shadow’ of the event horizon of Sgr A\*.

The millimetre VLBI campaign, scheduled for April 2017, will be the first with the required resolution and sensitivity to image the event horizon of Sgr A\* and the SMBH at the centre of M87. The following telescopes will be part of this network: the Atacama Large Millimeter/submillimeter Array (ALMA)<sup>2</sup> in Chile, the James Clerk Maxwell telescope (JCMT)<sup>3</sup> and the Submillimeter Array (SMA)<sup>4</sup> in Hawaii, the Submillimeter Telescope (SMT)<sup>5</sup> in Arizona, the Large Millimeter Telescope (LMT)<sup>6</sup> in Mexico, the South Pole Telescope (SPT)<sup>7</sup> at the South Pole, and the IRAM 30 m telescope<sup>8</sup> in Spain. In the following years, observations are also planned with the Northern Extended Millimeter Array (NOEMA)<sup>9</sup> in France and the Greenland Telescope (GLT)<sup>10</sup> in Greenland. More details about the EHT [6] and BlackHoleCam<sup>11</sup> projects are given in a recent and extensive overview, including their motivation and anticipated observational results [7].

Although the EHT already constitutes an impressive VLBI network of mm-wave radio telescopes, their spacial distribution is clustered around the Americas, thus limiting its capabilities.

<sup>1</sup><http://www.eventhorizontelescope.org>

<sup>2</sup><https://www.eso.org/sci/facilities/alma.html>

<sup>3</sup><http://www.eaobservatory.org/jcmt>

<sup>4</sup><https://www.cfa.harvard.edu/sma>

<sup>5</sup>[http://aro.as.arizona.edu/smt\\_docs/smt\\_telescope\\_specs.htm](http://aro.as.arizona.edu/smt_docs/smt_telescope_specs.htm)

<sup>6</sup><http://www.lmtgtm.org>

<sup>7</sup><http://pole.uchicago.edu>

<sup>8</sup><http://www.iram-institute.org/EN/30-meter-telescope.php?ContentID=2&rub=2&srub=0&ssrub=0&sssrub=0>

<sup>9</sup><http://www.iram-institute.org/EN/noema-project.php?ContentID=9&rub=9&srub=0&ssrub=0&sssrub=0>

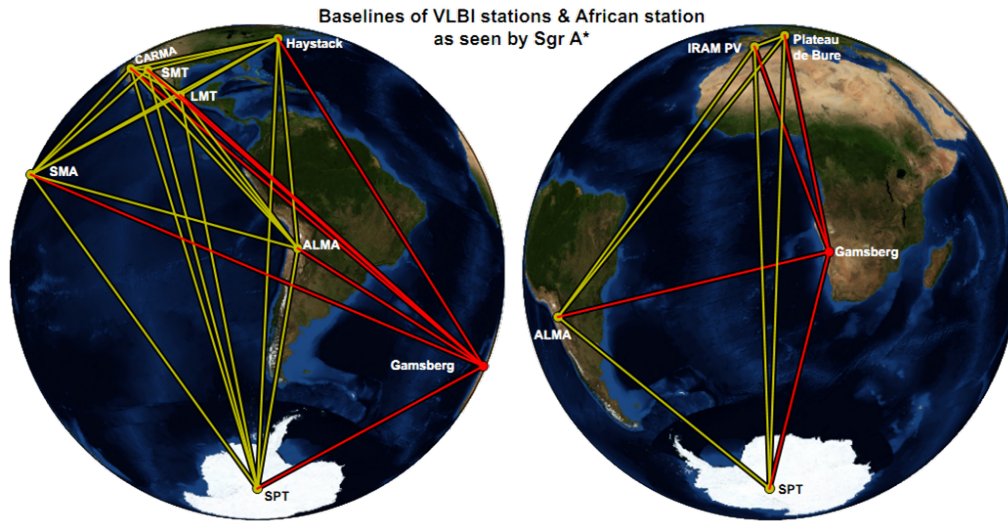
<sup>10</sup><https://www.cfa.harvard.edu/greenland12m>

<sup>11</sup><https://blackholecam.org>

Significant improvement can be achieved by adding a single mm-wave radio telescope in Africa, nominally called the Africa Millimetre Telescope.

### 3. The Africa Millimetre Telescope

Adding the Africa Millimetre Telescope (AMT)<sup>12</sup>, a single mm-wave radio telescope on the African continent, to the EHT network will significantly increase the coverage in the  $u-v$ -plane (see fig.2). This will greatly improve the imaging capabilities of the EHT and, hence, advance its capabilities to directly image the ‘shadow’ of Sgr A\*. In particular, it will enable the ‘Eastern sub-array’, including the IRAM 30 m telescope, NOEMA, SPT, ALMA, and AMT to perform imaging observations, thus adding a significant amount of daily observing time of Sgr A\* to the EHT (see fig. 1 on the right). As shown in fig. 1, the AMT will have common baselines for observations of



**Figure 1:** Baselines of the current EHT VLBI network (in yellow) and additional baselines provided by the AMT (in red). Note: the Combined Array for Research in Millimeter-wave Astronomy (CARMA) ceased observations in 2015, *IRAM PV* denotes the IRAM 30 m telescope on Pico del Veleta, *Plateau de Bure* denotes NOEMA, and *Gamsberg* denotes the AMT.

Sgr A\* with all the high-sensitivity telescopes (the IRAM 30 m telescope on Pico Veleta, NOEMA, ALMA, and the LMT) as well as with all the other EHT telescopes. The  $u-v$ -plane coverage of the current EHT configuration is presented in figure 2; included is the improvement in coverage by adding the AMT.

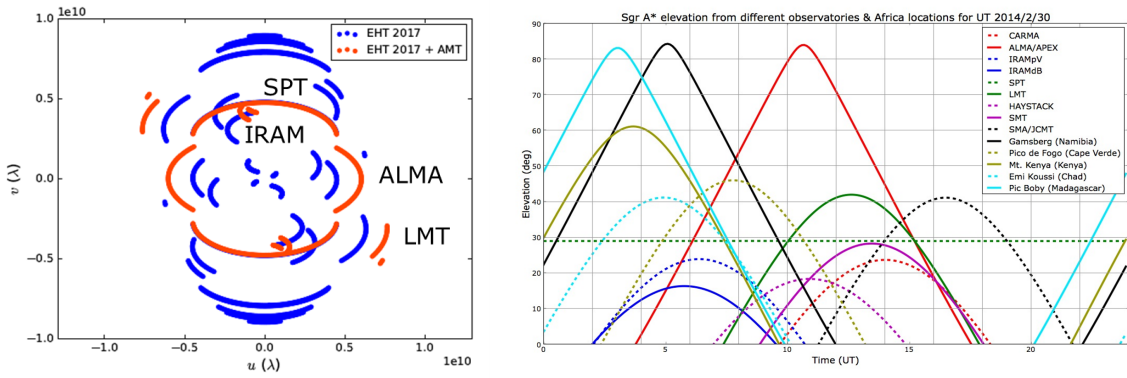
It is proposed that the AMT consists of a commercially available 12–16 m diameter antenna with 40–50  $\mu\text{m}$  RMS surface accuracy and with 4–5 arcsec pointing accuracy. The AMT will support 1.3 mm / 230 GHz and 0.8 mm / 345 GHz band receivers. It is also suggested that the AMT supports centrimetric radio receivers in the 6–2 cm / 5–15 GHz bands. The latter receivers would allow the AMT to participate in the African VLBI Network (AVN)<sup>13</sup> [8] presently under

<sup>12</sup><http://www.ru.nl/amt>

<sup>13</sup><http://www.ska.ac.za/science-engineering/avn>

construction and with the European VLBI Network (EVN). The power consumption is estimated to be  $\sim 30$  kW and an off-grid ‘green power’ solution like HIPERSENSE<sup>14</sup> is proposed.

Potential sites on the African continent where Sgr A\* can be observed at elevation angles  $\geq 40^\circ$  and that are at sufficiently high altitude to ensure an average precipitable water vapour column of less than 6 mm include sites on Mt. Kilimanjaro ( $\geq 4,300$  m a.s.l.) in Tanzania and the Sani Pass in the Drakensberg mountains in Lesotho ( $\geq 3,050$  m a.s.l.). However, primarily because of temporal overlap in visibility of Sgr A\* with the mm-wave telescopes in the Americas, the western-most site, Mt. Gamsberg (2,347 m a.s.l.) in Namibia has been chosen as the primary site for further investigations. Additional supporting arguments for this site are that the land is owned by the Max-Planck Society, and that the government of Namibia is very encouraging of astronomy development.



**Figure 2:**  $u - v$ -plane coverage of the current EHT configuration depicted in blue and the additional coverage to be added by the AMT indicated in red.

**Figure 3:** Elevation of Sgr A\* observations from different observatories and possible locations in Africa for the AMT for UT 2014/02/30. Note the remarkably symmetric curves for ALMA/APEX and the Gamsberg (Namibia) as for their similar latitudes.

Based on simulations of the reconstructed EHT image of the black hole ‘shadow’ of Sgr A\* [9], simulations including the AMT at Mt. Gamsberg were conducted. These simulations indicate that, in the  $u - v$ -plane coverage limited case of long integration times, the AMT will prove invaluable for reconstructing the image of the ‘shadow’ of the black hole. Details will be published in a forthcoming article [10].

Besides these prospects for the use of the AMT within the EHT network, there is ample scope for further science applications, such as single-dish mm-wave observations for flux density monitoring and studies of molecular emission lines, and (cm-wave) VLBI observations as part of the African and European VLBI Networks (AVN and EVN).

#### 4. Mt. Gamsberg as a site for the AMT

For decades Mt. Gamsberg (2,347 m a.s.l.) in the Khomas Highlands in Namibia has been known as an excellent site for astronomy, both for the number of photometric nights [11], and for seeing conditions comparable to the ESO site at La Silla in Chile [12]. Subsequently, it was chosen

<sup>14</sup><https://hipersense.eu>

as the planned site for the 2.2 m diameter telescope of the southern observatory of the MPI for Astronomy [13] and was later considered as a possible site for the Southern African Large Telescope (SALT)<sup>15</sup> [14]. It was even proposed to establish an inter-African astronomical observatory and science park on the mountain [15]. Despite the quality of the site, none of these projects has ultimately used Mt. Gamsberg. However, from 1972 [16] through to 1986 [17], professional astronomical observations were conducted using a 50 cm cassegrain telescope and, since 2010, an association of amateur astronomers has operated a 28'' (71 cm)  $f/4.4$  telescope at the site [18, 19].

Physically, the site itself is a flat tabletop mountain with 2.3 km<sup>2</sup> of area available for many astronomical instruments. The geographic coordinates of the site are 23.34° S and 16.23° E, only 0.32° different in latitude to ALMA. Hence, similar high elevation observations of Sgr A\* will be possible as indicated in fig. 3.

Some site characterization of Mt. Gamsberg has been undertaken previously. It was determined that there is a relatively low annual average wind speed of  $23.3 \pm 1.0 \text{ m s}^{-1}$  at 200 mbar (i.e. approximately 12 km a.s.l.), below the limits set for adaptive optics techniques [20]. The average wind speed, 2 m above ground level, was measured to be as low as  $4 \text{ m s}^{-1}$  and estimated to be  $5.4 \text{ m s}^{-1}$  at a height of 10 m above ground level [21], showing that the site has the low wind speeds necessary to achieve the required high pointing accuracy for a large mm-wave radio telescope.

The latter site investigation campaign by ESO and the MPI for Astronomy in 1994–1995 also measured the yearly average precipitable water vapour column on photometric nights to be 5.2 mm, with the maximum monthly average of 6.7 mm in December 1994 and the minimum monthly average of 2.5 mm in August 1994 [22]. In addition, the precipitable water vapour has been interpolated from satellite observations for comparison purposes at the altitude and geographical location of the Mt. Gamsberg site [23]. The results indicate the exceptional capabilities for observations up to 3 mm / 100 GHz throughout the year. In addition, strong but seasonal capabilities for observations at 1.3 mm / 230 GHz, which is the observational band of the EHT, and at 0.8 mm / 345 GHz, particularly around the southern winter months of June through to August are indicated. Admittedly, for simultaneous co-observing with, particularly, the northern hemisphere instruments, observations need to be scheduled in fall or spring, which will still allow for observations with low absorption by water vapour at 1.3 mm. Also, most EHT sites have suitable weather for observations up to 345 GHz under normal winter conditions [24].

## 5. Conclusion and Outlook

We have shown that the Africa Millimetre Telescope (AMT) will be a valuable addition to the EHT and have presented arguments supporting locating the AMT on Mt. Gamsberg in Namibia.

As outlined in Section 4, Mt. Gamsberg has long been regarded as a world-class astronomical site. Namibia, in general, has excellent astronomical sites: the country has successfully hosted the High Energy Stereoscopic System (H.E.S.S.) telescopes<sup>16</sup> since 2004, about 30 km from Mt. Gamsberg (see e.g. [25]), and was ranked the best site for scientific potential during the bid to host the

<sup>15</sup><http://www.salt.ac.za>

<sup>16</sup><https://www.mpi-hd.mpg.de/hfm/HESS>

Cherenkov Telescope Array (CTA)<sup>17</sup> [26] but the bid was unsuccessful [27]. Still, Namibia attracts attention for astronomy because of the quality of its sites. In addition, the support for astronomy in Namibia currently is excellent [28]. The University of Namibia and Radboud University recently signed a Memorandum of Understanding (MoU) to facilitate the development of the AMT.

In the near future, a geodetic observing station will be installed on Mt. Gamsberg in collaboration with the Hartebeesthoek Radio Astronomy Observatory (HartRAO)<sup>18</sup>. This station, designed and built by HartRAO, will initially consist of a Global Navigation Satellite Systems (GNSS) reference station, a Met-4 meteorology unit, an anemometer and a seismometer. Data from this station can be used to complete a detailed characterisation of the site, in particular the determination of the precipitable water vapour in the atmosphere. The automated station is independently powered by solar PV with batteries, and also includes a communications device for data transfer.

The initial estimate of the capital investment needed to build the AMT, including the antenna, various cm- and mm-wave receivers, VLBI equipment, infrastructure and software is about 10 million Euros. Since governmental funding schemes at this level would introduce a significant latency to the project, a fund-raising campaign seeking alternative sources of funding, e.g. foundations and/or philanthropists, is underway.

It is anticipated that the AMT will be fully operational within two years after funding and permits are secured.

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<sup>17</sup><https://www.cta-observatory.org>

<sup>18</sup><http://geodesy.hartrao.ac.za>

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