The first image of the Milky Way's central black hole and the unique enhancement Africa could offer future tests of gravity

AUTHORS:
Roger Deane[1,2]
Iniyan Natarajan[1]

AFFILIATIONS:
[1]Wits Centre for Astrophysics, University of the Witwatersrand, Johannesburg, South Africa
[2]Department of Physics, University of Pretoria, Pretoria, South Africa

CORRESPONDENCE TO:
Roger Deane

EMAIL:
roger.deane@wits.ac.za

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Significance:

The Event Horizon Telescope (EHT) Collaboration recently released the first images of the supermassive black hole in the heart of the Milky Way galaxy. The ring size and shape in these images are consistent with Einstein's general theory of relativity. The location of this black hole in southern skies and its rapidly changing appearance mean that expanding the EHT into Africa is critical to optimally utilise this unique gravitational laboratory in the future. Leveraging our southern African geographic advantage will turn images into high-fidelity movies – a game-changing milestone for precision tests of gravity with the next-generation EHT.

Introduction

Astronomers use a wide range of telescopes to study the universe, tuning into different parts of the electromagnetic spectrum to explore diverse astrophysical phenomena. Our eyes are sensitive to light that has a wavelength of approximately 500 nanometres. This is the region in which traditional, so-called 'optical' astronomy is carried out with facilities such as the Southern African Large Telescope in Sutherland. The choice of wavelength and telescope depends on the physical properties of the astronomical source of interest, e.g. hot gas at billion-degree temperatures is best studied at shorter wavelengths like X-rays. The recently launched James Webb Space Telescope will revolutionise our view of the infrared universe with a sensitivity significantly surpassing that of the Hubble Space Telescope. Another critical aspect of a telescope is the sharpness with which it can make out small details in a distant object. In this Commentary, we discuss a global network of radio telescopes known as the Event Horizon Telescope (EHT), observing light with a wavelength of 1 millimetre (mm), synthesising a much larger, earth-sized virtual telescope to achieve the sharpest detail attainable in astronomy. The primary objective of the EHT is to make images of supermassive black holes, behemoths that lie at the centres of galaxies and possess masses that range from about a million to ten billion times the mass of our own Sun.

Very long baseline interferometry

The technique that enables this worldwide network of antennas to function is called radio interferometry. Its development won Martin Ryle the Nobel Prize in Physics in 1974 and it underpins the operation of the future Square Kilometre Array. The smallest structure a telescope can see, or 'resolve' in astronomical parlance, is known as its angular resolution θ. It depends directly on the wavelength of light that is observed, λ_{obs}, and inversely on the telescope's diameter, d_{tel}:

$$\theta = \lambda_{obs}/d_{tel}.$$

The angular resolution can be made finer (enabling one to discern sharper details) by either decreasing λ_{obs} or increasing d_{tel}. In practice, it is impractical from an engineering and cost perspective to increase d_{tel} beyond a few hundred metres at most. To overcome this limitation, astronomers use the technique of interferometry in which signals from two or more elements (also referred to as antennas or stations), separated by a distance D, are combined according to the principle of interference of waves to achieve an effective angular resolution of λ_{obs}/D.[1] Such a synthesis of an 'aperture' (i.e. any element that collects light) of effective diameter D is achieved by carrying out the observation for several hours, letting the rotation of the earth relative to the sky fill in the 'holes' or 'gaps' in this virtual telescope, in a process known as earth rotation aperture synthesis, devised by Martin Ryle and others in the 1950s.

In connected-element interferometry, the signals received by the individual stations are transferred almost instantly and combined coherently in real time. This is a significant challenge and expensive to achieve if the stations are separated by hundreds or thousands of kilometres. In such cases, temporal synchronisation is achieved using precise and independent atomic clocks that record the times of reception of the signals at the individual stations. This practice is known as very long baseline interferometry (VLBI).

The EHT is one such global VLBI network that operates at millimetre wavelengths to achieve an angular resolution that subtends 20 microarcseconds, which is approximately 100 million times smaller than the full moon's apparent diameter on the sky. At these short wavelengths, turbulent precipitable water vapour in the atmosphere absorbs and scrambles the incoming wavefronts of light.[1] Hence, millimetre-wave observatories are established at high-altitude sites with dry atmospheric conditions (Figure 1).

Also seen in Figure 1 is an example of the EHT digital backend which is present at every EHT station. After the electromagnetic waves are focused by individual antennas onto the cryo-cooled receivers, amplified, down-converted, filtered and digitised, the Petabytes of recorded digital signals are then transported to the two correlators in the USA and Germany. A correlator combines the signals from individual stations coherently and outputs the data in a format required by radio data processing algorithms. This completes the signal path in this virtual earth-sized telescope, enabling images of faraway black holes to be reconstructed. A notable aside is that each digital backend includes four Reconfigurable Open Access Computing Hardware (ROACH2)[2] boards, originally designed with significant involvement from South African engineers and the South African Radio Astronomy Observatory (formerly SKA Africa). The ROACH2 boards (which still bear the SKA Africa logo, Figure 1) are therefore a critical component in the EHT signal processing pipeline.

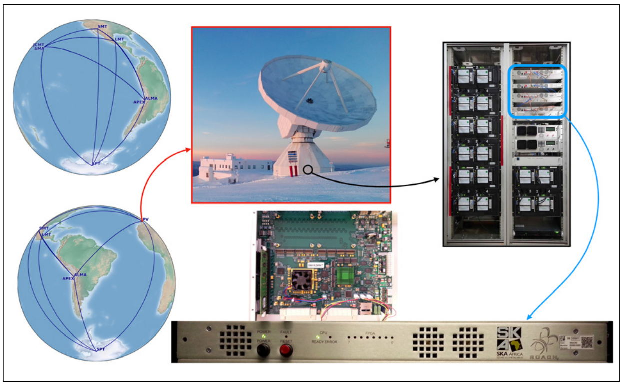


Image credits: SARAO, IRAM, EHT Collaboration

Figure 1: The 2017 EHT network as viewed from the centre of the Milky Way (left). The IRAM Pico Veleta 30-metre antenna in Spain (top middle), with the EHT VLBI backend deployed at all EHT stations (top right), which include South African developed ROACH2 digital backend boards (bottom).

Sgr A* observations with the EHT

In April 2017, the EHT observed the supermassive black hole at the heart of the Milky Way, known as Sagittarius A* (Sgr A*) at a wavelength of 1.3 mm for five nights using eight radio telescopes situated at six geographical locations. These data were correlated at the Max Planck Institute for Radio Astronomy in Germany and the Haystack Observatory at the Massachusetts Institute of Technology in the USA. Following correlation, two calibration pipelines were deployed to correct for instrument imperfections and stabilise the signal to produce the data used for the remainder of the analysis.[3]

After five years of analysis, the first Sgr A* images were published in May 2022 (Figure 2).[4] The images are redolent of the images released by the EHT Collaboration in 2019 of the supermassive black hole at the centre of the galaxy M87 (M87*)[5], with a fiery ring surrounding a dark region corresponding to the shadow of the black hole. For both M87* and Sgr A*, the measured ring diameters on the sky agree remarkably well with predictions based on general relativity.

What causes the ring-like signature in these images? Hot ionised gas surrounding a black hole radiates as it orbits the black hole attracted by its immense gravitational pull. Any radiation that passes through the event horizon of a black hole, the boundary from which not even light can escape, is lost forever to the observable universe. Depending on the angle of approach of the light and the distance at which it passes the black hole, the curvature of the local spacetime bends its path around the black hole in different directions and to different extents. As a consequence, a region slightly larger than the event horizon at the centre appears dark, while the light bent around the black hole shines all around it, resembling a bright ring.

Though in theory any black hole surrounded by hot radiating plasma must be visible to the observer, even the nearest, most massive black holes cast exceedingly small shadows and rings on the sky, owing to their large distances from the earth. To image them with sufficient angular resolution required the assembly of the EHT.

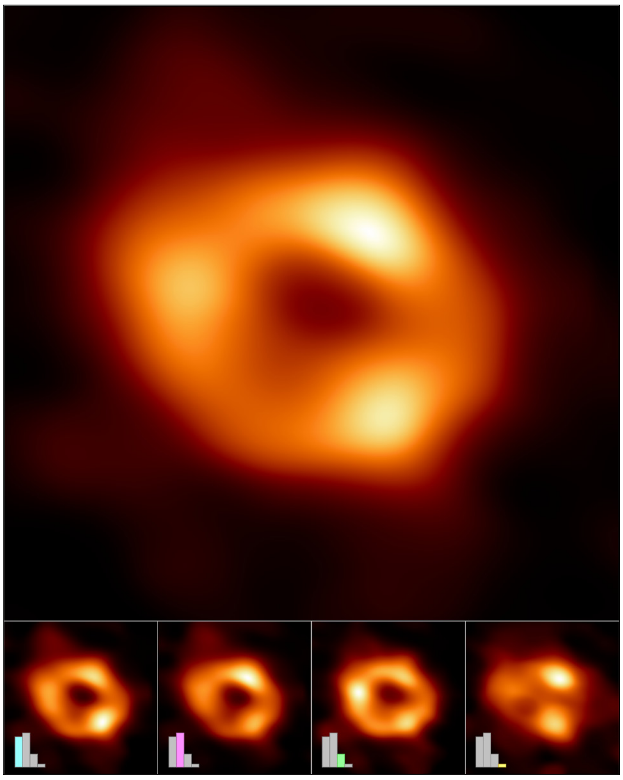
Imaging challenges

Four methods were used to reconstruct images from the raw data output from the correlator. Thousands of images were created, all of which are consistent with the Sgr A* data.[6] Two of these methods are regularised maximum likelihood algorithms, conceptually different from the third, an implementation of the CLEAN algorithm used in radio astronomy for almost 50 years. The fourth is a cutting-edge, fully Bayesian imaging method that produces the full set of images that are consistent with the data.[7]

Compared with M87*, Sgr A* poses additional imaging challenges due to the fact that the source structure evolves rapidly. M87* is ~1500 times more massive than Sgr A* and light takes a few weeks to complete one orbit around M87* while it takes only a few minutes to orbit Sgr A*. This results in rapid variations in the observed source structure for Sgr A* on timescales of minutes, which violates a fundamental assumption made by conventional imaging methods in radio interferometry – that the source does not change during the observation. A completely novel approach had to be developed to account for the variability in order for these algorithms to work.[8]

Another significant challenge to imaging was the fact that Sgr A* is located at the heart of our own galaxy. Because the earth is located in the gaseous disk of the Milky Way, to observe the centre we have to peer through 27 000 light-years of gas and dust that constitute the interstellar medium. The free electrons in the interstellar medium along our line of sight to the Galactic Centre scatter the light from Sgr A*, causing the images to appear fuzzy and blurred. New theoretical and stochastic models of scattering were developed to mitigate these effects while imaging[6].

Optimising the four imaging methods to reconstruct the Sgr A* images required validation on synthetic data sets generated from known geometric models with the variability and scattering characteristics of actual EHT observations. An overwhelming majority of the final Sgr A* images obtained via this optimal imaging process display a prominent ring structure, with the ring size being consistent across imaging methods and parameters. The images were classified into four clusters or modes, with the first three modes comprising over 95% of the images displaying ring-like features, with a small fourth set showing non-ring morphologies (Figure 2). The modes vary in the brightness distribution pattern around the ring, which is a consequence of the sparsity of observing stations and the intrinsic variability of Sgr A*.[6] The averaged image in the top panel retains the features most commonly seen in the different clusters, while suppressing those features that appear infrequently.



Source: Reproduced from Figure 3 of EHT Collaboration et al.[4]

Figure 2: Image of the supermassive black hole Sagittarius A* located at the centre of our galaxy. The main image (top) was produced by averaging together thousands of images created using different computational methods — all of which accurately fit the EHT data. The images are clustered into four groups based on similarity of features (bottom). The bar graphs show the relative number of images belonging to each cluster, with their heights indicating the relative contribution of each cluster to the main image.

Astrophysical implications

The EHT Collaboration developed a large library of simulations representing 200 general relativistic magneto-hydrodynamical models of black hole physics. These fiducial models vary in the strength and structure of the magnetic fields surrounding the black hole, brightness of the outflow region, the inclination angle with respect to the line of sight, and the black hole spin.[9]

All fiducial models were tested against 11 constraints derived from the 230 GHz EHT observations, as well as prior observations of Sgr A* at lower radio frequencies (86 GHz), infrared, and X-ray wavelengths. None of the models passes all 11 constraints, displaying greater variability than warranted by the data in combination with the other constraints. Excluding the strict constraint on variability, the data prefer models of a 'face-on' (rather than highly inclined) shadow, with a prograde spin (with the disk-like accretion flow swirling in the same direction as the black hole spin), reasonably efficient jet outflow (motivating future studies), and ordered magnetic fields that impact the dynamics of the accretion flow.

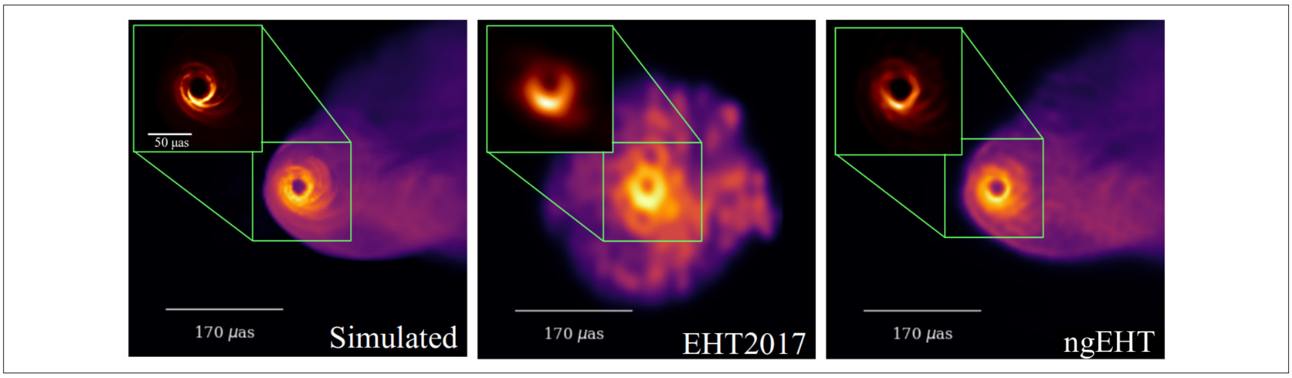
To compare with theories of gravity, we have to convert the measured morphological properties of the images to a common physical scale so that various physical properties of the black hole may be estimated.[10] This is accomplished by calibrating the measured ring diameter d_{ring} to a quantity called the angular gravitational radius θ_g, which is directly related to the size of the event horizon. A suite of 100 data sets generated from general relativistic magneto-hydrodynamical simulations with known θ_g values was used to perform this calibration. Applying the outcome of this process to the measured ring diameters for Sgr A* yields a θ_g value consistent with theoretical predictions and an estimated mass of $4^{+1.1}_{-0.6}$ million times the mass of the Sun.

The above measurements are consistent with what is expected for a Kerr black hole, defined as a black hole that is fully described by its mass and spin. As all astrophysical black holes are expected to be Kerr black holes, quantifying the potential deviations from the Kerr metric is necessary to understand how gravity operates in the vicinity of black holes. Using a calibration data suite consisting of 145 synthetic data sets, generated from both Kerr and non-Kerr models, the EHT Collaboration calibrated the expected shadow sizes against the measured ring diameters for Sgr A* and estimated the deviation from the Kerr metric to be within 10%.[11] Together with the deviation metric derived for M87*[12] and for two gravitational-wave events detected by LIGO/Virgo for stellar-mass binary black holes[13], we find that the same black hole metric is consistent over eight orders of black hole mass, as predicted by general relativity, proving Einstein correct yet again.

Africa's potential role in future black hole imaging

Three new stations have been added to the global EHT network since the 2017 observing campaign, with the goal of expanding this array by a further six to ten additional stations spread across the earth towards the end of this decade. This expanded array is referred to as the next-generation EHT (ngEHT).[14] Each additional station in the ngEHT contributes an increasingly larger number of new measurements. The locations of these new sites determine how the gaps in the virtual earth-sized telescope are filled. Therefore, carefully positioning them around the world, minimising any large gaps such as those found in Africa, can significantly improve the quality of the images (Figure 3). Improved images contribute directly to improved tests of general relativity and to new insights on the role of magnetic fields in the jet launch and accretion process. Promising studies have also been made to complement the ngEHT with space-based stations, but that is likely decades into the future.[16,17]

Establishing observatories around the planet must also take practical constraints and costs into consideration, including road and power



Source: Reproduced from Figure 4 of Blackburn et al.[14]

Figure 3: Snapshot of a general relativistic magneto-hydrodynamical simulation of M87[15] (left). Image reconstructed using the 2017 EHT array (middle). Image reconstructed using the proposed ngEHT array at both 230 and 345 GHz (right) recovering both the ring and the jet with far superior contrast and fidelity.

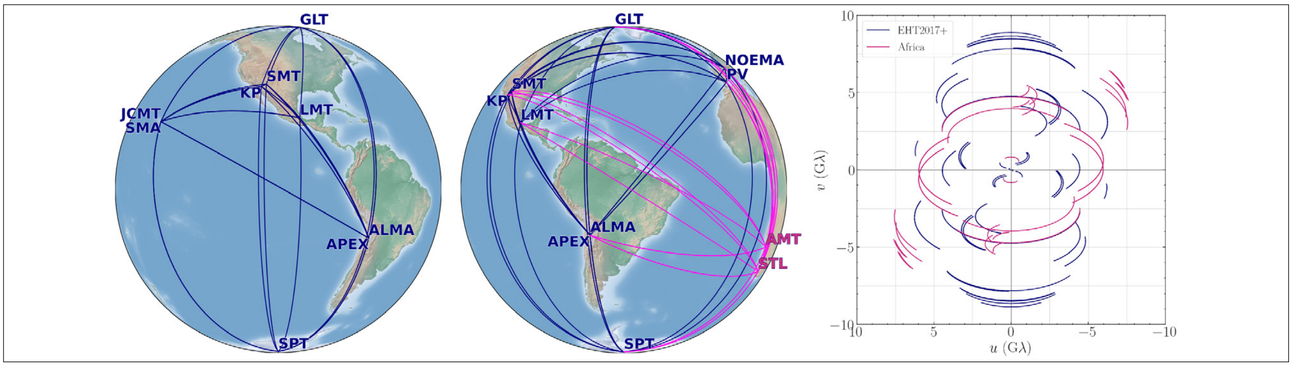


Figure 4: Locations of existing (EHT2017+, blue) and proposed (pink) EHT stations in Africa (left, middle). Baseline coverage of Sgr A* observation during one night in April (right). The (u, v) coordinates represent projected baseline vectors for each pair of antennas in units of the observing wavelength. As the earth rotates, an individual baseline will trace out an arc. The blue arcs correspond to the baselines formed by EHT2017+ and the pink arcs correspond to the baselines contributed by the African stations.

availability. South Africa has well-established infrastructure protected by legislation at its astronomical sites and boasts world-class astro-engineers at the forefront of their craft (an example being the EHT's use of the ROACH2 boards). Moreover, as with palaeoanthropology, there are contributions to astronomy that can only be made from southern African soil, especially in the case of the ngEHT. The Galactic Centre lies in the southern sky, passing directly above us here in southern Africa, which is optimal for astronomical observations. New technology such as a cutting-edge simultaneous multi-frequency receiver design and the phase-transfer technique[18] enables EHT stations to be located at relatively low-altitude sites (1500–2500 m) where atmospheric conditions are not as pristine as at the South Pole or above 5000 m in the Chilean Andes. This means well-established astronomical sites in the country can be used, decreasing project costs by a substantial factor.

Figure 4 shows the number of new baselines added to the existing EHT array by the introduction of two potential stations in Africa: (1) the Africa Millimetre Telescope (AMT)[19] located at Gamsberg in Namibia, and (2) a millimetre-wave telescope located at Sutherland (STL) in South Africa, as an example site that holds this strategic geographic advantage alongside established infrastructure. The baselines formed by AMT and STL with existing EHT stations contribute to improved angular resolution along different directions for both major EHT targets – M87* and Sgr A*. Figure 4 demonstrates this by plotting the *uv*-coverage (a plot showing where the gaps in the virtual telescope are filled) of this enhanced array during an example Sgr A* observation. Crucial new baselines of different lengths at different orientations are introduced by the African stations, enabling enhanced angular resolution and contrast ratio of the resultant images. Potentially just as important are the unique, approximately north-south oriented short baselines ($\sim$1000 km) added to the array by the intra-African baselines between Namibia and South Africa. This currently missing information could be important in connecting black hole shadows to larger-scale features such as jets. Moreover, by better constraining the large-scale emission with these short baselines, we improve the optimisation and performance of the imaging algorithms to produce the shadow images. Clearly, Africa offers this new black hole imaging enterprise distinct and unique value towards fundamental tests of gravity and understanding how relativistic jets are launched from black holes.

However, deeper, more equitable involvement by African countries and researchers in large-scale international scientific collaborations has the potential to make societal contributions of a broader nature. As has been demonstrated with the MeerKAT telescope, the precursor to the Square Kilometre Array, the impact of innovative mega-projects on human capacity and technology development is profound.[20] Perhaps a deeper legacy of African EHT stations would be to spur further innovation, inspire local youths to excellence, and foster greater equality in science collaboration between the Global South and the rest of the world.

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