SFSU

Engineering Experimentation Laboratory

Title: *The Event Horizon Telescope and First Black Hole Image: Measurement Techniques and Devices*

Subject: ENGR 300 Open-Ended Project

Abstract: In April of 2019, the first ever actual image of a black hole was released and celebrated as a monumental achievement in astronomy, physics, data science, engineering, and many other fields. The Event Horizon Telescope project consisted of over 200 of the brightest minds in science and before this collaborative effort, black holes were just a theory. These groundbreaking results are the product of many different branches of science utilizing a number of different apparatuses scattered across the globe, as well as pioneering data manipulation techniques. The influence of this magnificent accomplishment reaches professionals in the space science community while simultaneously captivating enthusiasts and those interested in nearly any STEM field.

Authors:

Name	Signature	Date
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Created by Prof. Dipendra K. Sinha 2006

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1. Introduction

1.1 Overview/ Purpose:

The Event Horizon Telescope (EHT) research team used the latest radio telescope technology and data processing methods to capture the first image of a black hole. This interdisciplinary project brought many researchers with different skills together, from astronomers to programmers. Moore's Law states that the overall power of data processing doubles every 2 years, and this project demonstrates truly how fast technology is developing. The researchers are still continuing the development of the EHT to get an even clearer and more accurate picture.

1.2 Ground-Based Radio Telescopes

An optical telescope brings visible light together, focusing and amplifying it to make images available for analysis using different instruments. These telescopes magnify light that is from the visible range of the electromagnetic spectrum which helps us observe details of an object that the naked eye cannot see because of distance. The three main types of optical telescopes (refractor, reflector, and catadioptric telescopes) use lenses, mirrors, or a combination of the two.

Similarly, radio telescopes bring together weak radio light waves, focuses it, and amplifies it to be analyzed. Radio telescopes are generally used to observe and study radio waves that naturally occur from stars, galaxies, black holes, and other astronomical phenomena. These telescopes can also be used to "transmit and reflect radio light off of planetary bodies" (NRAO). Radio telescopes observe the longest light wavelength which range from 1 mm to 10 m long.

1.2.1 Radio Telescope Components

The radio telescope consists of a radio receiver and an antenna system; the antenna system and the receiver work to detect the radio-frequencies. The receivers used in radio telescopes are the most sensitive in the world, due to the extremely weak amplitude of the radio signals we receive from space. This is also why radio telescopes are the largest telescopes in use today (NRAO).

1.2.2 Data Processing

According to the National Radio Astronomy Observatory, radio telescopes observe many frequencies at the same time, then computers divide these frequency bands into several thousand different channels spanning a wide range of frequencies. The telescope remains pointing at the radio source to be able to detect the faintest signals over time, the computers may then add the waves together while also removing random noise interference from our own radio signals in a data processing technique called "interferometry".

1.2.3 Limitations

Several limiting factors include its ability to form a clear image, defined by a value known as angular resolution. In regard to radio waves, a radio telescope's ability to have a desirable angular resolution depends on the wavelength of what we are observing divided by the size of the radio telescope antenna. So, in order to get a very clear, finely-detailed image, the angular resolution calculated above must be a very small number. However, radio wavelengths are much longer than visible light wavelengths, being as small as millimeters long and as long as 10 meters, so even with the largest of antennas available, the angular resolution we would get would be no better than simply looking at the night sky with our own eyes. In order to get finely detailed images of distant objects like the black hole, the antennas of our radio telescopes must be more massive than is currently possible.

To get an image of the black hole at the center of M87, we would need a telescope the size of the Earth. The EHT project found a solution for this problem however, through the use of arrays of radio telescopes, which are synchronized together so they act like one giant, Earth-sized telescope. Connected together like this, they were able to collect data used for the finely detailed images of objects like the black hole, although very costly to do so, as fiber optic cables were used to connect the arrays together and synchronize them (NRAO).

1.3 Black Holes

Black holes are made up of matter packed into a small space, creating an extremely strong gravitational field (not even light can escape this gravitational pull). Black holes form out of large stars that died in a supernova explosion. According to NASA.gov:

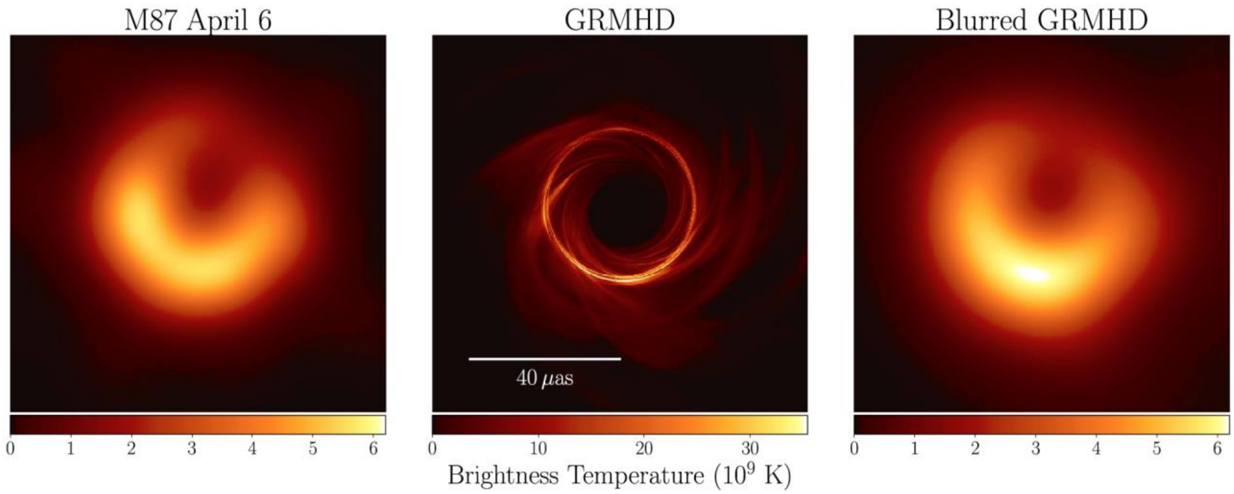
> "As the surface of the star nears an imaginary surface called the 'event horizon,' time on the star slows relative to the time kept by observers far away. When the surface reaches the event horizon, time stands still, and the star can collapse no more - it is a frozen collapsing object. There are two types of black holes, "stellar mass" black holes are generally 10 to 24 times as massive as the Sun. Most stellar black holes, however, lead isolated lives and are impossible to detect...
>
> On the other end of the size spectrum are the giants known as 'supermassive' black holes, which range from millions to tens of billions of times as massive as the Sun. Astronomers believe that supermassive black holes lie at the center of virtually all large galaxies, even our own Milky Way. Many aspects of black holes have always been, and still are a huge mystery."

Black holes are so incredibly dense and massive that they create a gravitational pull that is so strong, not even photons, which travel at the speed of light, can escape its pull. Thus, no visible light can escape from black holes, which is why they appear black. However, the collapse of the black hole leaves traces of radiation, which includes radio waves. This is how radio telescopes like those used in the Event Horizon Telescope array are able to get a clear picture of a supermassive black hole (NRAO).

1.4 Event Horizon Telescope

The Event Horizon Telescope was the first project to be able to capture and image a black hole. Using an array of eight ground-based radio telescopes they captured this image, showing the first visual evidence of a supermassive black hole and its shadow.

> "This breakthrough was announced today in a series of six papers published in a special issue of *The Astrophysical Journal Letters*. The image reveals the black hole at the center of Messier 87 [1], a massive galaxy in the nearby Virgo galaxy cluster. This black hole resides 55 million light-years from Earth and has a mass 6.5 billion times that of the Sun" (EHT).



Left panel: an EHT 2017 image of M87 from Paper IV of this series. Middle panel: a simulated image based on a GRMHD model. Right panel: the model image convolved with a 20 mas FWHM Gaussian beam. Although the most evident features of the model and data are similar, fine features in the model are not resolved by EHT.
Source: The EHT Collaboration et al.

To describe what the image is showing, the EHT collaboration states: "The asymmetric ring is produced by a combination of strong gravitational lensing and relativistic beaming, while the central flux depression is the observational signature of the black hole shadow," (EHT).

Since the black hole itself is pitch black and cannot be seen, the image shows its shadow, as predicted by the Theory of General Relativity. Supermassive black holes are extremely small, which is why it has been difficult to see them up until now.

The EHT team describes how these radio telescopes were able to collect the data:

> “Although the telescopes are not physically connected, they are able to synchronize their recorded data with atomic clocks — hydrogen masers — which precisely time their observations. These observations were collected at a wavelength of 1.3 mm during a 2017 global campaign.
>
> Each telescope of the EHT produced enormous amounts of data — roughly 350 terabytes per day — which was stored on high-performance helium-filled hard drives. These data were flown to highly specialised supercomputers — known as correlators — at the Max Planck Institute for Radio Astronomy and MIT Haystack Observatory to be combined. They were then painstakingly converted into an image using novel computational tools developed by the collaboration.”

The international collaboration continues to improve the Very Long Baseline Interferometry (VLBI) capabilities at short wavelengths. They linked the radio dishes around the globe “to create an Earth-sized interferometer”, have been used to collect data on the emission regions of two supermassive black holes with the largest “apparent event horizon” (EHT). By linking all the radio telescopes around the world, they created a virtual telescope.

1.5 Goals of the Experiment

While getting a digital photo of a black hole was a major breakthrough for the Event Horizon team and the physicists who worked on it, it was not the only goal of the experiment. According to the official website for the Event Horizon telescope, “A long standing goal in astrophysics is to directly observe the immediate environment of a black hole with angular resolution comparable to the event horizon” (EHT). This obviously includes gaining a photo of the event horizon first but doesn’t stop there.

The goal was to use these findings and observations to prove some of the basic tenets of general relativity. One of these is solving the dynamics of different types of matter as they get closer to a black hole. How is the matter affected by going at nearly light speed? What kind of effect does a black hole have on the gravity surrounding it? Being able to directly observe a black hole will open up new avenues in physics in terms of understanding the nature and specifics of black holes.

Another goal of this experiment was to improve the current Ground Based Radio Telescopes so EHT and other projects could produce more accurate and detailed observations of black holes. So a secondary goal to achieving the main goal is to improve the sensitivity and range of the very-long-baseline interferometry (VLBI) which is discussed further in section 2.2, so that we will eventually be able to catalog and study many black holes that can now be observed using these techniques.

2. Experimental Details

2.1 Methods

The theory and approach of this project were to use VLBI with a very high sampling rate to collect an immense amount of data and then fit geometric and GRMHD models developed from simulations to that data. They analyze the data to find which model it is consistent with to ascertain certain features and attributes about the black hole, such as spin magnitude, orientation, and direction. All of this analysis used to characterize the black hole are reliant on the amount and quality of data collected, as well as the simulation models and comparison image libraries.

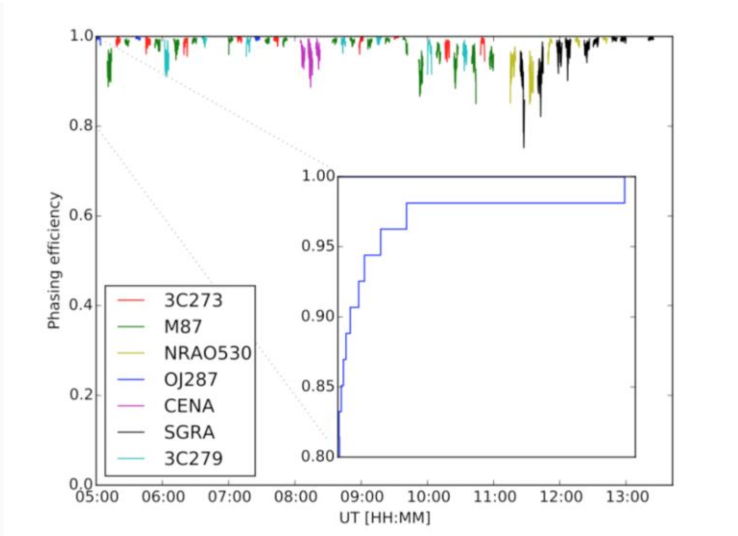
2.1.1 Data Collection

Increasing the range of frequencies to increase the sensitivity of the EHT was accomplished by capturing more radio waves from the black hole at different sites. These observations require high speed computers and systems with higher capacity disk drives, and recent technology advancements have allowed the researchers to do this allowing a higher recording rate.
Each dish telescope “samples analog data from a radio receiver and feeds the formatted digital data to a data recorder”(EHT).

Several different types of digital backend were used: DBE1 system, the Digital Baseband Converter (DBBC) system, the ROACH Digital Backend (RDBE), and R2DBE (ROACH2 DBE). “The R2DBE samples and processes data at a rate of 16 gigasamples-per-second, perfectly matched to the recording data rate of the Mark6 digital recorder, the latest generation of EHT VLBI Data Recorder”(EHT). The data was stored in recorded disk packs and they were all sent to two central locations for correlation. “Among other advantages, software correlation clusters are scalable, and the programs are easily customized ” (EHT).

2.1.2 Increase in Telescope Aperture

For many types of telescopes, increasing the area/aperture allows more data to be captured which will produce a higher resolution image. Similarly, to radio telescopes, increasing the size of the dishes in the array increases the sensitivity of the EHT. Larger dishes will allow the photons that were emitted by the hot gases near the black hole able to be recorded on Earth. Due to high costs, several of the locations used a collection of antennas rather than one large dish. The collaboration describes, “Like the EHT they (antennas) are interferometers, but they operate on local short baselines up to hundreds of meters, rather than thousands of kilometers as for the EHT, and their dishes are connected by cables. To use these sites as EHT stations, the small dishes must be electronically phased together, which allows their collecting area to be combined.” Increasing the total area thus increases the total collecting area, meaning more data will be produced.



The measure of the operational quality of a phased array system is the "phasing efficiency" , which ideally should be greater than 90% for typical EHT sources. The plot here shows the phasing efficiency of SWARM over a track during the 2016 EHT campaign.
Credit: Primiani et al., 2016, JAI, Vol 5, No. 4 (2016), page 13.

2.1.3 Building a Larger Array

As more telescopes are added to the telescope array further away, more detailed features of the emissions become recognizable. The researchers have been adding more telescopes working towards having a footprint the size of Earth. The EHT has been able to reach a resolution better that 60 microarcseconds, the equivalent of observing an orange on the moon. The "angular resolution of a baseline is given by λ/D, where D is the projected separation between the antennas. We also refer to this calculation by λ/B to specify that D is the Baseline, the separation of EHT sites used for Very Long Baseline Interferometry". By observing shorter wavelengths and increasing the distances between telescopes, a more detailed/finer angular resolution can be observed. They describe, "future EHT observations may be able to obtain a resolution as fine as 1.5 Schwarzschild radii" (EHT). Schwarzschild radii is used to describe the event horizon of a black hole. The resolutions of different telescopes are shown in the table below.

Baseline	Resolution at 230 GHz	Resolution at 345 GHz
LMT - SMT	140 µas/ 14 R_{Sch}	93 µas/ 9.3 R_{Sch}
Hawaii - SMT	58 µas/ 5.8 R_{Sch}	39 µas/ 3.9 R_{Sch}
Hawaii - ALMA	28 µas/ 2.8 R_{Sch}	19 µas/ 1.9 R_{Sch}
Plateau de Bure - South Pole	23 µas/ 2.3 R_{Sch}	15 µas/ 1.5 R_{Sch}

Table showing the resolution (both in Microarcseconds and Sgr A* Schwarzschild Radii) achievable on Sgr A* with current and future EHT baselines.

The astronomers use the term “uv coverage” and that refers to “projected baseline lengths and orientations for which data are obtained. As the Earth rotates, the projection of each baseline in the plane normal to the direction to the source changes such that each baseline sweeps out an arc in the uv plane. Each location in the uv plane corresponds to one Fourier component of the image on the sky. The ability to reconstruct the sky image improves with increasing uv coverage.’’

2.1.4 Additional Considerations

Like many other ground-based telescopes, weather is a huge factor in gathering clean data. At the distance and resolution scales that the EHT is using, water droplets, dust clouds, and other seemingly insignificant atmospheric phenomena can produce huge observational error. The EHT array was exposed to weather ranging from the desert, polar regions, tropics, and mountains allowing all erroneous data to be accounted for and removed from the final image. Some devices used measured the opacity and transmittance of the sky because those indicate the ability of electromagnetic waves to pass through the atmosphere and to the receivers. Constantly monitoring weather also helped to minimize signal decay and observe complete waves.

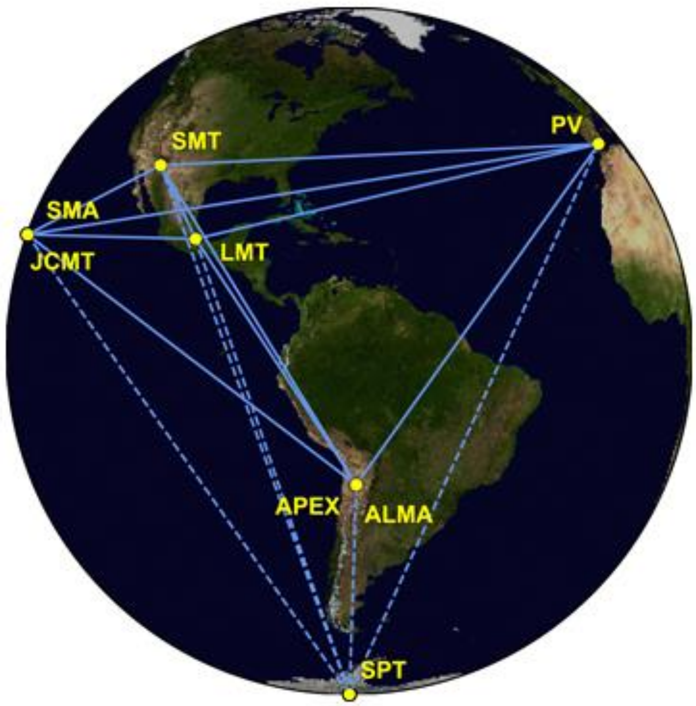
2.1.5 Imaging Algorithms

The EHT baselines sampled only a limited range of frequencies, and the measured visibilities potentially held large calibration uncertainties. To combat this, imaging algorithms known as CLEAN and Regularized Maximum Likelihood (RML) were used to produce plausible images that fit the constraints of the data. While CLEAN is an inverse-modeling approach that deconvolves the functions from the Fourier-Transformed data, RML is a forward approach that searches for an image that fits the data, and also favors specified parameters for said image. Three separate pipelines of algorithms and parameters were used, and the images generated were averaged from these three pipelines.

2.2 Apparatus

2.2.1 Radio Telescopes Involved

In order to create a wide enough aperture, an array of 8 stations in 6 locations, as shown below. The 8 stations are the SMT or the Submillimeter Telescope, which is a part of the Arizona Radio Observatory, the APEX or the Atacama Pathfinder EXperiment, the IRAM 30-meter telescope, the JCMT or the James Clerk Maxwell Telescope, the LMT or the Large Millimeter Telescope, the SMA or the Submillimeter Array, the ALMA or the Atacama Large Millimeter/Submillimeter Array, and the SPT or the South Pole Telescope.



The Locations of the 8 EHT Stations, As Seen From the Equator.
Source: iopscience

Observations were performed over four days, as a series of scans ranging from 3-7 minutes in length. Signals in both polarizations and at two adjacent frequency bands were converted to baseband, then digitized and recorded. The process of linking all of the ground-based radio telescopes was referred to as VLBI or the Very Long Baseline Interferometry, and focused on collecting short wavelengths in order to create an accurate photo. While in the past the equipment for recording data was all in analog, all of the bases shown below record in digital using a unit called the DBE or the “Digital Back End” which is fixed to single dish telescopes and “samples analog data from a radio receiver and feeds the formatted digital data to a data recorder” (EHT). The most advanced of these DBE’s is the ROACH2 DBE, which stands for Reconfigurable Open Architecture Computing Hardware and is now currently at all of the EHT sites shown below.

The DBE can process data at a speed of 16 gigasamples per second, which matches the abilities of the main digital recorder using the array, the Mark6, a data recorder designed for VLBIs. The last key component of the apparatus is the storage system for all of the data that has been recorded. Each individual digital recorder has 32 hard disk drives assigned to store the information that is grouped into modules of 4 with each module having 8 drives attached. Each site consequently has 4 Mark6 units, each with their own drives attached, which can process data at a rate of 64 gigabits/sec.

2.3 Interdisciplinary Collaboration

2.3.1 Professions

Due to the massive nature of the project, people were required to work on Instrumentation, Data Collecting and Processing, Data Analysis, Near Horizon Science Utilization, Beyond Horizon Science Utilization, and Products and Publications. These topics span from purely theoretical calculations (Beyond Horizon and Near Horizon) that create models and simulations so that the team could have a better idea of what they were looking for, to software analysis (Data Analysis and Data Collection and Processing) which worked with computing teams to sift through the data recorded and to put them together, to practical engineering of machinery (Instrumentation) which focused on testing the arrays, building them, monitoring them and developing any technologies as needed. There were over 200 researchers that all contributed to the project, from countries in Africa, Asia, Europe and North and South America (MIT).

In addition to the astronomers and physicists that worked on the project, there was also engineers, administrators and computing teams all working in tandem (ESO). Also, there were groups of people who work on maintaining and building the arrays, as well as building the software needed to process the data and the correlators that help combine the data together. Not only were there scientists with PhDs and postgraduate students working on the project, but also undergraduates as well.

2.3.2 Organizations

Thirteen total institutions were crucial to the development of the EHT, among them were the NSF, ERC (The European Research Council), and other agencies in East Asia. The NSF (National Science Foundation), "directly funded more than $28 million in EHT research, the largest commitment of resources for the project" (NSF) .This money went towards the funding of independent investigators, interdisciplinary scientific teams and radio astronomy research facilities. Among the many groups that contributed were the Institutional Board and Representatives for the EHT project, which included Academia Sinica Institute of Astronomy and Astrophysics, University of Arizona, University of Chicago, East Asian Observatory, Goethe-Universitaet Frankfurt, Institut de Radioastronomie Millimétrique, Large Millimeter Telescope, Max Planck Institute for Radioastronomy, MIT Haystack Observatory, National Astronomical Observatory of Japan, Perimeter Institute for Theoretical Physics, Radboud University, and the Smithsonian Astrophysical Observatory (EHT).

This project was a global effort using not only the radio telescopes of many different countries but also the funding and the manpower from those same countries as well. As such, all of the above listed institutions had one or more representatives on the Institutional Board. There were also numerous other donors than the ones listed, both independent and institutional.

3. Results and Discussion

3.1 Outcomes
The resulting image was consistent with the shadow of a black hole as predicted by General Relativity. The black hole was found to be circular in shape with a brighter southern section, rotating clockwise with a mass of M = (6.5 ± 0.7) 10^9 solar masses.

3.2 Other Interpretations
A shadow can be generated by many objects that lie outside of the predictions of General Relativity. Naked Singularities, Boson Stars, Gravastars. Some of these objects are incompatible with the data generated by the EHT but are still viable alternatives to black holes.

3.3 Future Projects
Several telescopes are slated to join the worldwide array in their continuing research on black holes. Future use of the EHT array and the data it provides may show us finer details such as stability, shape, and depth. They hope that eventually they will be able to answer such questions as, "How some supermassive black holes, including M87's, launch such bright plasma jets. Understanding how gas falls into and feeds black holes could also help solve the mystery of how some black holes grew so quickly in the early universe" (Temming).

In addition, it could also be used to, "Find pairs of supermassive black holes orbiting one another — similar to the two stellar mass black holes whose collision created gravitational waves detected in 2015 by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO). Getting a census of these binaries may help researchers identify targets for the Laser Interferometer Space Antenna, or LISA, which will search from space for gravitational waves kicked up by the movement of objects like black holes." (Temming)

4. Conclusion and Perspectives

4.1 Conclusions Drawn
The photo of the black hole taken was able to add proof for the general relativity theory due to the fact that the bright ring shown in the photo, known as the lensed photon orbit, matched closely with the calculated and theorized size that a 6.5 billion solar mass black hole should have. The mass of the black hole is also contained within its photon orbit, which strongly supports the existence of supermassive black holes.

4.2 Criticisms
The researchers used technologically advanced data collection and processing methods and employed an array of radio telescopes. The data was compared with an extensive library of synthetic images produced by several different modelling techniques and theories. The most probable place for criticism in this project is that we are still only certain to a very high degree that the image produced accurately reflects reality. When more independent projects can reproduce the same image of M87* or other black hole candidates using different techniques then our certainty will be that much greater.

5. References

1. The EHT Collaboration et al. 2019. “First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole.” ApJL, 875, Pp. 1. Publisher's Version

2. The EHT Collaboration et al. 2019. “First M87 Event Horizon Telescope Results. II. Array and Instrumentation.” ApJL, 875, Pp. 2. Publisher's Version

3. The EHT Collaboration et al. 2019. “First M87 Event Horizon Telescope Results. III. Data Processing and Calibration.” ApJL, 875, Pp. 3. Publisher's Version

4. The EHT Collaboration et al. 2019. “First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole.” ApJL, 875, Pp. 4. Publisher's Version

5. The EHT Collaboration et al. 2019. “First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring.” ApJL, 875, Pp. 5. Publisher's Version

6. The EHT Collaboration et al. 2019. “First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole.” ApJL, 875, Pp. 6. Publisher's Version

7. The Event Horizon Telescope Collaboration et al. “IOPscience.” *IOPscience*, 2019, iopscience.iop.org/journal/2041-8205/page/Focus_on_EHT.

8. The Event Horizon Telescope Collaboration et al. “Event Horizon Telescope.” *Event Horizon Telescope*, 2019, eventhorizontelescope.org/.

9. Information@eso.org. “ESOblog: Photographing a Black Hole A Story of Overcoming Differences between People and Telescopes.” *Www.eso.org*, 2019, www.eso.org/public/blog/photographing-a-black-hole/.

10. Kellermann, Kenneth I. “Radio Telescope.” *Encyclopædia Britannica*, Encyclopædia Britannica, Inc., 28 Sept. 2016, www.britannica.com/science/radio-telescope.

11. Mackenzie, Ashley. “What Are Optical Telescopes Used for?” *Sciencing*, 2 Mar. 2019, sciencing.com/optical-telescopes-used-for-6370484.html.

12. MIT News Office. “Astronomers Capture First Image of a Black Hole.” *MIT Washington Office | Massachusetts Institute of Technology*, 2019, dc.mit.edu/newsletter.

13. NASA Science Directorate. “Black Holes.” *NASA*, NASA, 2018, science.nasa.gov/astrophysics/focus-areas/black-holes.

14. NRAO. “Black Holes.” *National Radio Astronomy Observatory*, public.nrao.edu/radio-astronomy/black-holes/.

15. NSF Public Affairs, NSF. “Astronomers Capture First Image of a Black Hole.” *NSF*, 2019, www.nsf.gov/news/news_summ.jsp?cntn_id=298276.

16. Temming, Maria. “How Scientists Took the First Picture of a Black Hole.” *Science News*, 11 Apr. 2019, www.sciencenews.org/article/event-horizon-telescope-black-hole-picture.