Analysis of the Observations for Three Telescopes: EHT, FAST and LBTI

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Abstract. As technology continuously advances, the telescope technologies available to humans are becoming increasingly refined, leading to the discovery of an ever-growing number of phenomena using these telescopes. This allows for a deeper understanding of the universe one inhabits, with more astronomical phenomena receiving scientific explanations. This article primarily seeks to broaden our knowledge in this area by describing three distinct astronomical telescopes. It introduces the components and detection principles of the Event Horizon Telescope (EHT), FAST, and the Large Binocular Telescope Interferometer (LBTI). Additionally, this study delves into the primary research objectives, pivotal scientific domains, and ongoing projects of these three telescopes. Moreover, at the conclusion of each section, this study discusses their recent observational results or some noteworthy astronomical phenomena. According to the three examples presented in this article, the aim is to enhance people's understanding of astronomical telescopes and to inspire more individuals to take an interest in the advancements of astrophysics.

Keywords: Telescope applications; EHT; FAST; LBTI.

1. Introduction

Starting from 1608, a Dutch manufacturer named Hans Lippershey invented the earliest recorded telescope, leading up to Galileo improving the telescope design for astronomical observations. The use of telescopes expanded over time, and subsequent generations have continuously enhanced the design and structure of the instrument. Today, humans commonly use radio telescopes in astrophysics to explore unknown territories and delve deeper into the study of celestial bodies or phenomena that have already been discovered [1]. Recent astronomical observations have yielded significant findings. For example, in 2019, the EHT captured the inaugural photo of a giant mass BH, presenting a chance for humans to validate Einstein's theory of general relativity [2].

Moreover, there have been recent detections of gravitational waves, with LIGO and Virgo recording numerous binary black hole mergers. These detections serve as evidence for the gravitational waves predicted by general relativity, while also providing a novel method for observing the universe. For example, by employing deep learning techniques to analyze gravitational wave data, and training with noise extracted from LIGO's O1 data and our simulated black hole merger waveforms, we can distinctly identify three confirmed gravitational wave events. Furthermore, after utilizing the trained network to test the 8 gravitational wave events detected in the O2 data, they were clearly marked. Beyond these distinct data points, there are also more than 2000 candidate events [3]. Nonetheless, with the deployment of the James Webb Space Telescope on December 25th, 2021, humanity took a further leap in space exploration. JWST aims to explore various stages of the universe, from the aftermath of the big bang. It will also search for exoplanets similar to Earth with potential for life and delve into the progression of our Solar System [4].

This study will dive into the optical principles of telescopes, using the JWST as a prime example in the second section. From the third to the fifth sections, offering a detailed overview of three distinct astronomical telescopes, discussing their structures, recent projects they've participated in, and their discoveries. Subsequently, using EHT as a case study, addressing the limitations and future outlooks of telescopes.

2. Basic Descriptions

This section mainly describes the optical principles of telescopes, using the famous James Webb Space Telescope as an example, which includes ICS (Imager, Coronagraphs, and Spectrometers), stray-light control and on-board calibration. Both the imager and the spectrometer channels are fed by a single mirror within the IOC. As depicted in Fig. 1, the field of view in the Mid-Infrared Instrument/Micro shutter Imaging Module (MIRIM) is divided into several main segments: imaging, coronagraphy, and low-resolution spectroscopy. Thanks to this design, all scientific tasks rely on just one detector array and a single wheel mechanism. The light is shaped and this wheel carries filters for images, coronagraphs, an assembly prism for the spectrometer, a blank space to measure dark current, and a lens for observing the pupil. The main focal plane is relayed to the detector using a three-mirror camera, assigning distinct parts of the detector for different tasks, namely imaging, coronagraphy, and spectroscopy [4].

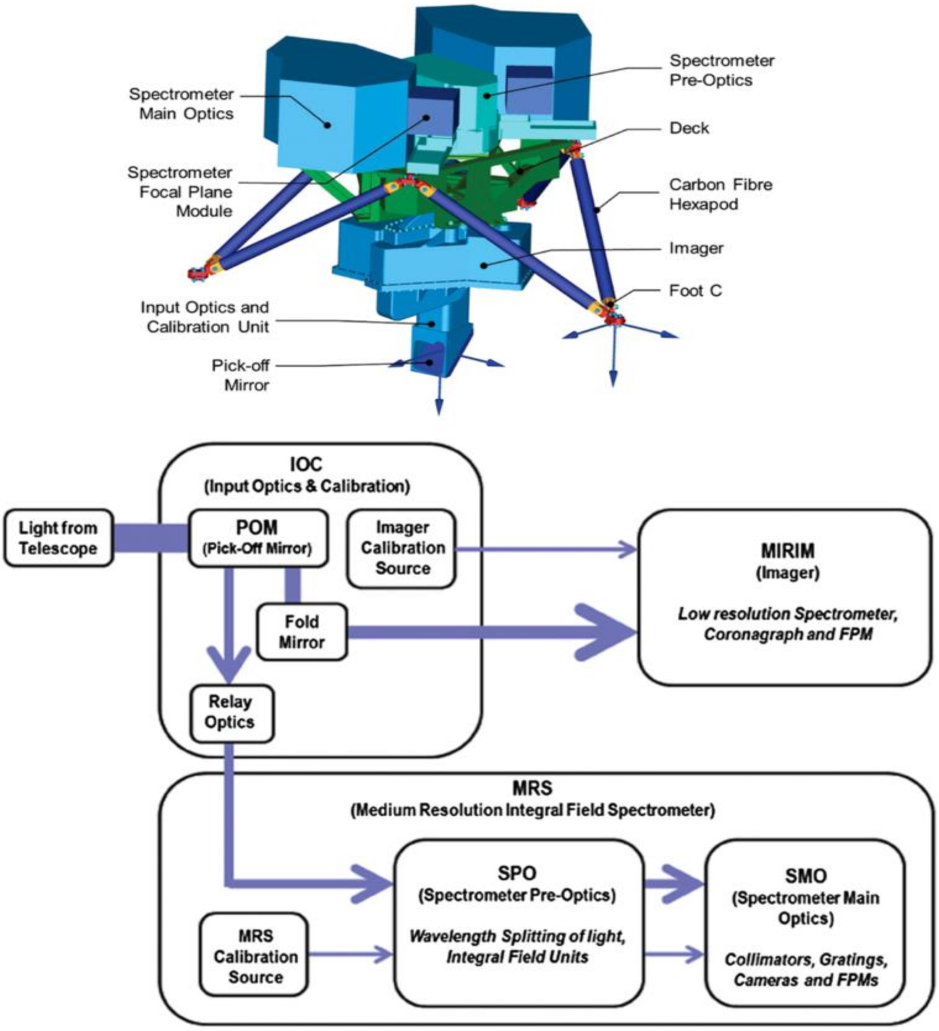

Fig. 1 The light path through the MIRIM module.

Efforts have been made to effectively manage undesired light. Within the telescope optics, the fine steering mirror (FSM) is encircled by a cold stop, forming a protective cold baffle around the primary mirror. Cold pupil stops are incorporated in every instrument module. To avoid shadow effects at the FSM stop, even when there's a slight pupil misalignment, these stops are slightly oversized. This design helps to enhance protection against unwanted light and do not affecting the optical path (seen from Fig. 2) [4]. MIRI needs consistent light sources for timely calibration during astronomical observations. The goal is to quickly capture clear signals to measure how different pixels respond and ensure that this light source stays steady. This helps track how detectors compare when observing regular stars. The light should be even and maintain this consistency for several days [4]. Both the picture-taking (imager) and light-splitting (spectrometer) parts have the same type of calibration light sources. For the light-splitting part, a source is placed and light is directed through a hole in a mirror. For the picture-taking part, its source is in the IOC, and a tiny mirror directs the light.

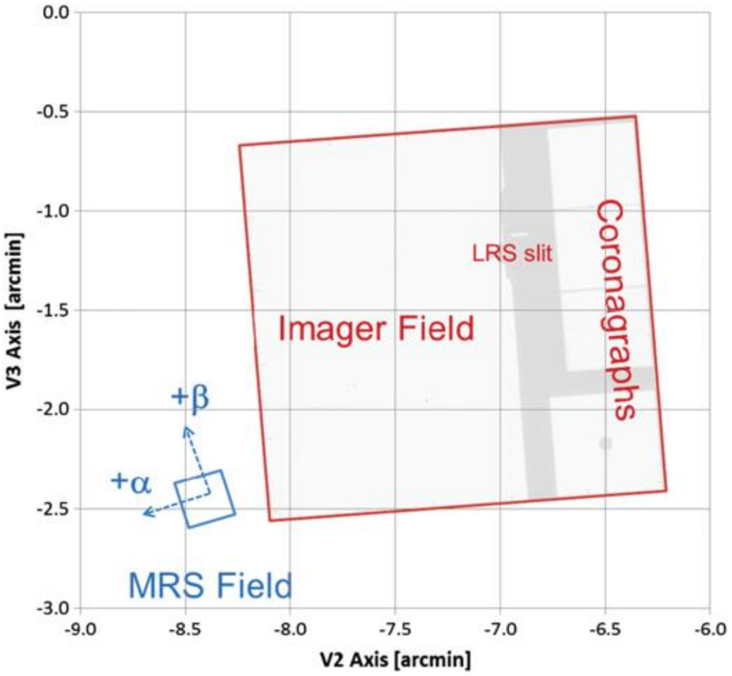

Fig. 2 Locations of the MIRIM and MRS viewing fields on the focal plane of the telescope.

3. EHT

The EHT is a large matrix of synchronized radio telescopes from all over the world to form an Earth-sized interferometer, as shown in Fig. 3. The goal is to closely examine the surroundings of a black hole with an angular resolution comparable to the event horizon and testing general relativity in Einstein's theory in an extreme environment [5, 6]. Besides, understanding accretion around a black hole and realize Jet genesis and collimation are including in the key scientific objectives for event horizon telescope as well [5].

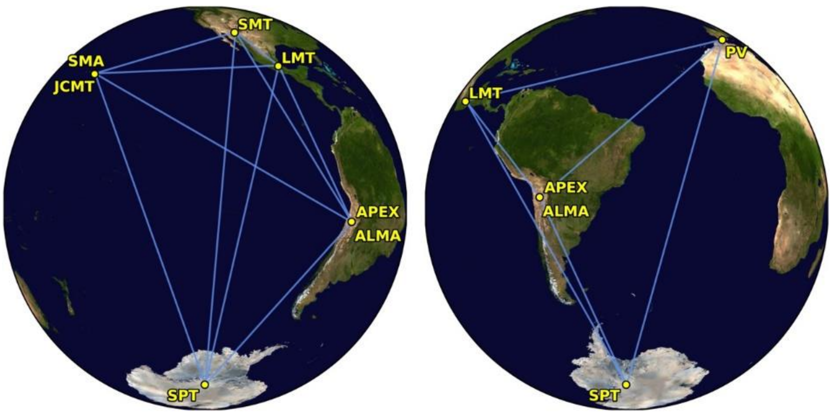

Fig. 3 The 2017 EHT array as seen from Sgr A*.

After discussed about the scientific goals of the EHT, VLBI as the main observational technique used in the event horizon telescope is another interesting point. At first, this method was seen as a tool for radio astronomy to study celestial bodies, but by 1969, it was also employed in geodesy, astrometry, and clock alignment [7].

However, the very long base-line interferometry used in the event horizon telescope is quite different to some other applications that use this technique. It is obvious that the resolution of a telescope can be calculated as lambda divided by the diameter of a telescope (280λ/D) which is about

60 arcsec for a human eye in visible light [8-10]. For simplest interferometry which contains only two antennas, it is insensitive to structures on the sky which is bigger than a wavelength over the distance between these two antennas. In order to overcome this difficulty, antenna arrays are designed to capture various directions and spatial dimensions in the sky. In addition, VLBI uses atomic clock to timestamp the recorded data for achieving required stability and uses global positioning service clocks at different locations to ensure recordings are made simultaneously [7]. The event horizon telescope project enhanced the VLBI technique, using an unprecedented 1.3mm wavelength and increasing the recording rate to 64 Gigabits/second from the usual 2 Gigabits/second. These developments allow for capturing the shadow of supermassive BHs at the event horizon [8].

Moreover, two primary Observing targets of the EHT are Sgr A* and M87, Milky way's central BH and the giant elliptical galaxy, respectively. As human's first discovery of the photo of supermassive BH, M87's appearance has been modeled by using general relativity magnetohydrodynamical (GRMHD) simulation which describes a chaotic, heated, magnetic disk revolving around a black hole called Kerr [9]. The related graph is shown in the Fig. 4.

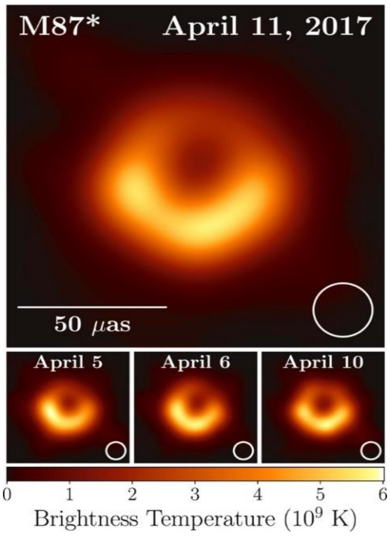

Fig. 4 Top: Sample EHT image of M87* from April 11, 2017. Bottom: Images from various days highlight consistent structure and similarity across days.

While the results of 2017 EHT observations of Sgr A*, the central SMBH in the Milky, suggest intraday structural changes in Sgr A*, reinforcing indications from previous studies across the electromagnetic spectrum. Data gathered on April 7, which happens to be our most comprehensive dataset, consistently points towards a ring-shaped structure and that is quite similar to M87*. Observations from April 6 further corroborate this depiction [10].

Fig. 5 Landscape of FAST, it was built in Qiannan, Guizhou.

4. The FAST

The FAST is a Chinese mega-science project that spent 5.5 years on constructing a single dish radio telescope and completed construction on September 25, 2016, as shown in Fig. 5. In simple terms, a radio telescope has three main parts: a big dish (reflector), a device to catch signals (receiver), and something to move it around (pointing device). This big dish helps catch very faint signals from space, letting us learn about distant parts of the universe. The whole FAST telescope is made up of several parts, like the place it's set up, the active dish, the support for the signal catcher, controls, and a base for observing [11]. The FAST's control and measurement system is split into four sections: central telescope management, time and position references, active dish monitoring and adjustment, and feed support tracking and management [11].

FAST boasts three distinct features. Firstly, it takes advantage of the singular, expansive, and deep Qiannan karst depression for its location. Secondly, its use of an active reflector not only ensures comprehensive polarization and wide bandwidth during observations but also allows the surface to reshape into a paraboloid, correcting ground-level spherical aberration. This design allows for the use of conventional feeding technology. Last prominent feature is that FAST employs a lightweight cable-driven feed support technology. Compared to the impractical Arecibo method of suspending the cabin, FAST internally uses a secondary adjustable system to carry the feed [11]. There are five main scientific goals for the FAST due to the technique and resolution it has: 1) Identify neutral hydrogen at the universe's extremities and recreate an image of its early state, 2) Collaborate with the International VLBI Network to discern the ultra-detailed structures of heavenly entities, 3) perform high resolution radio spectral survey and identify faint signals from space, 4) Discover pulsar, establish a pulsar timing array and contribute to both pulsar navigation and detecting gravitational waves in the future, 5) Find extraterrestrial life [12]. Among these, FAST has advantage of really big aperture on detecting pulsar. The first pulsar found by FAST is called PSR J1900-0134, with properties of pulse period of 1.8 second and a dispersion measure (DM) of 188 pc/cm3 [13]. As the number of pulsars increases, there are some interesting phenomena happens on pulsar, like those whose emissions turned off, or where the emissions shift in phase and much more [13]. Besides, detecting exoplanets is another duty for FAST. Experts compared the frequency range and sensitivity of the FAST radio telescope with exoplanet data from 2011, concluding that FAST is best suited for searching for SPI emissions down to moderate intensities. A central component of FAST's exoplanet research involves conducting numerous targeted repeat observations and polarized surveys. This includes monitoring all detectable star systems within 10 pc, comprising 200 identified stars and the 35 known exoplanets [14].

5. LBTI

The LBTI is a NASA-funded equipment that cooperated with the university of Arizona to study exoplanetary system, located at Mount Graham, as seen in figure 7. LBTI benefits high sensitivity from its two 8 meters telescopes and the adaptive optic systems it has delivers superb wave front quality. However, due to its adaptive secondary design, LBTI boasts a reduced thermal background. Moreover, the fusion of light from the two LBT telescopes allows for exceptional angular resolution, given their 14.4-meter center-to-center distance and a 23-meter baseline [15]. On other hand, LBTI works at mid-infrared wavelength with N-band and L/M-bands, 8-14 microns NOMIC camera and 3-5 microns LMIRCAM camera, respectively. Due to the advantages that it has, LBTI can operates in many modes, such as, high contrast direct imaging, coronagraph, nulling interferometry, aperture masking interferometry, etc. [15]. The HOSTS is a project funded by NASA. Its objective is to survey the mid-infrared radiation originating from exozodiacal dust located in the HZ of surrounding stars that are in their main sequence. This is accomplished using the N-band nulling mode of the LBTI. HOSTS is aimed to provide information to design future space missions for detecting and characterizing exo-Earths (seen from Fig. 6) [16]. One of the most important elements that been studied in the HOSTS is called exozodiacal dust. In our solar system, zodiacal dust is something like small rocky grains left by the collision of asteroids and comets, distributed between near the Sun and the asteroid belt that between Mars and Jupiter. Exozodiacal dust behaves on exoplanet in the same way, so it is essential for astronomer to study this dust and may find some clues to what other planetary system are like. For example, the more asteroid and comets collided with exoplanet, the more exozodiacal dust appears surrounding the exoplanet [17].

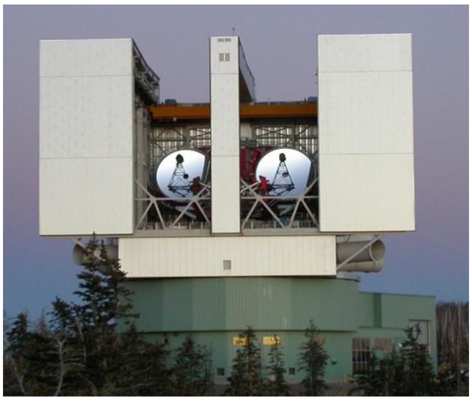

Fig. 6 Large Binocular Telescope Interferometer located at the Graham, Arizona.

The Large Binocular Telescope Interferometer can identify exozodiacal dust. This is due to its ability to conduct nulling interferometric measurements within the N band (8 to 13 μm), which can reduce a star's brightness and pinpoint faint emissions surrounding it. Scientists have statistically analyzed the results of the LBTI/HOSTS survey on exozodiacal dust and compared it with data from Sun-like stars (3 zodis with 1 σ upper limit: 9 zodis, 95% confidence: 27 zodis based on our N band measurements) [18]. It was found that among the 38 observed stars, the data of 10 stars significantly exceeded the expected. These statistical findings can support the verification of upcoming theories about the beginnings and characteristics of exozodiacal dust. Furthermore, in-depth analysis of this dust can deepen our knowledge about its composition and the processes leading to its creation and distribution. Marrying this enriched comprehension of dust creation and distribution in distinct systems with models synthesized after statistics can amplify our ability to forecast habitable zone dust amounts in systems not yet observed [19, 20]. Based on the first statistical results of the HOSTS survey on habitable zone dust around nearby stars, scientists have discovered an interesting phenomenon that suggests the HZs of stars similar to our sun may have more dust than those of early-type stars [21].

6. Limitations and Prospects

As the understanding of the universe deepens, there are naturally some limitations or impacts on telescope technology. At the same time, scientists' new discoveries have enlightened their perspectives and expectations for certain future areas. In this section, the Event Horizon Telescope been used as an example to discuss the limitations and prospects of telescope applications. During the April 2017 observations, the EHT successfully met the criteria for capturing horizon-scale images of BHs in M87 and Sgr A* for the first time. The researchers developed a thorough data analysis procedure, resulting in the inaugural dataset that covered M87 and 3C 279. The 2017 data showed an upgrade in the telescope's network, with it incorporating the ALMA for the first time, moving from its earlier eight sites. While this addition has enhanced the telescope's capabilities, it also brought about analytical challenges due to variations in telescope specifics, climate conditions, sensitivity, site-specific issues, and sampling rates. Moreover, the expanded network resulted in a surge in raw data volume, necessitating consistent and systematic calibration approaches [20]. In the imaging results of Sgr A* by the Event Horizon Telescope, general relativity magnetohydrodynamical simulations often exhibit more variability than observed results. This could potentially be attributed to the absence of modeling for collisionless plasma as a fluid or the omission of radiative cooling in the simulations. Aside from this variability, only a handful of configurations are in alignment with all observational constraints. Our research generally supports theories with potent magnetic dynamics, modest forward spins, an angled viewing perspective, and a significant distinction between protons and electrons in the emission area. Notably, these theories suggest a jet flow that's notably efficient when weighed against the accretion pace. Yet, deeper investigation is essential to thoroughly examine various physical occurrences and grasp their intrinsic fluctuations [10].

For M87, the Event Horizon Telescope aims to delve deeper in future observations to scrutinize the stability, form, and intensity of the shadow with greater precision. A notable trait of M87's supermassive black hole is its expected consistent features over time, given that M87*'s mass isn't predicted to have drastic alterations within human lifespans. Upcoming publications from the research group will elaborate on the image's polarimetric analysis, shedding light on both the accretion pace through Faraday rotation and magnetic flux details. The goal to attain clearer images remains, with strategies like utilizing a shorter 0.8 mm (345 GHz) wavelength, expanding the global telescope network, and tapping into space-based interferometric techniques [9]. Apparently, other telescope has their unique, different types of limitations and outlook on applications as well.

7. Conclusion

To sum up, this article primarily discusses intriguing recent applications of telescopes and introduces the optical design of the James Webb Space Telescope. Subsequently, it delves into three distinct astronomical telescopes: EHT, FAST, and LBTI, along with their recent research involvements. Drawing from the data reports within these projects, the detection results from recent years are elucidated. EHT directly observes the silhouette of potential supermassive black holes using electromagnetic signals. FAST excels in identifying pulsars and exoplanets. LBTI, with its cutting-edge capabilities, provides researchers a deep dive into the birth and development of systems beyond our planet. However, certain geographical and hardware constraints can limit the scope of the telescope's exploration. In the future, scientists are poised to discover new research domains based on the data acquired from telescopes, probe the mysteries of the universe, and enhance the general populace's understanding of the world they inhabit. At the same time, through the telescope examples presented in this article, the hope is to guide more astronomy enthusiasts towards areas or research topics that pick their interest, fueling their passion for astrophysics. For those not specialized in this field, the article aims to broaden their understanding of telescopes.

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