Analysis of the Principle and Observations for State-of-the-Art Telescopes

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Abstract: As a matter of fact, the advancement of astronomical technology has enabled unprecedented observations of the universe in recent decades. With this in mind, this study explores the principles, instrumentation, and landmark discoveries of three major state-of-the-art telescopes, i.e., FAST, the Event Horizon Telescope (EHT), and the James Webb Space Telescope (JWST). To be specific, each facility represents a unique approach to astronomical observation, from large single-dish radio detection to global interferometry and deep-space infrared imaging. FAST has revolutionized pulsar and FRB research, while the EHT captured the first image of a black hole, confirming predictions of general relativity. At the same time, JWST is unravelling the early universe and characterizing exoplanet atmospheres. According to the analysis, comparative analysis highlights the complementary strengths of these observatories and discusses the technological and observational limitations they face. Overall, the study concludes with prospects for future telescope development and the broader significance of these facilities in advancing cosmic understanding.

1 INTRODUCTION

The telescope stands as one of humanity's most pivotal inventions in the quest to understand the universe. Since Galileo Galilei first turned a rudimentary telescope skyward in the early 17th century, the field of astronomy has undergone revolutionary developments (Tyson, et al., 2016). Telescopes have evolved from simple optical instruments to highly sophisticated arrays and space-based observatories that observe electromagnetic radiation across the entire spectrum. They have enabled the discovery of planets, stars, galaxies, and cosmic phenomena that were previously beyond the reach (Durrant, 2019). The ability to look deeper into space not only expands the understanding of celestial bodies but also offers insights into the fundamental laws governing the universe (Trimble, 2018).

In recent decades, technological advancements have led to the construction of large-scale and high-precision telescopes, significantly enhancing the observational capabilities. Notably, the Five-hundred-meter Aperture Spherical Telescope (FAST), the Event Horizon Telescope (EHT), and the James Webb Space Telescope (JWST) represent the forefront of this astronomical leap. These facilities offer diverse methodologies: from radio wave detection and very-long-baseline interferometry (VLBI) to near- and mid-infrared imaging. Each one plays a vital role in different areas of astrophysical research, such as the detection of fast radio bursts (FRBs), black hole imaging, and deep field cosmology (Smith, 2020; Jiang, et al., 2019).

The Event Horizon Telescope gained global attention in 2019 when it produced the first direct image of a black hole's event horizon in the M87 galaxy, marking a watershed moment in both astronomy and general relativity (Event Horizon Telescope Collaboration, 2019). Similarly, FAST has been instrumental in detecting new pulsars and fast radio bursts, while JWST, launched in 2021, is unveiling the structure of the early universe and characterizing exoplanet atmospheres with unprecedented clarity (Gardner, et al., 2006; Smirnov, 2011).

The motivation behind this study is to synthesize and analyse the operational principles, technological frameworks, and groundbreaking findings of these three flagship observatories. While they differ in design, objective, and location—ground-based vs. space-based—they are all united in the pursuit of understanding cosmic origins and mechanisms. This

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paper first presents an overview of different telescope types and their observational targets. It then delves into the design, instrumentation, and observational outcomes of FAST, EHT, and JWST. The subsequent sections compare their strengths and limitations and discuss the future prospects of telescope technology.

This structured analysis not only highlights the individual accomplishments of each facility but also underscores the synergistic nature of modern astronomical research. By integrating radio, optical, and infrared data, scientists can approach cosmic phenomena from multiple angles, facilitating a more comprehensive understanding of the universe.

2 DESCRIPTIONS OF TELESCOPES

Telescopes are instruments designed to collect and magnify electromagnetic radiation from distant celestial objects, enabling astronomers to observe phenomena beyond the naked eye. They can be broadly categorized based on the portion of the electromagnetic spectrum they observe and their physical design. The two primary categories are optical telescopes and radio telescopes, with newer subcategories including infrared, ultraviolet, X-ray, and gamma-ray telescopes.

Optical telescopes operate in the visible spectrum and are commonly divided into refracting and reflecting types. Refracting telescopes use lenses to bend light, while reflecting telescopes use mirrors. The Hubble Space Telescope, for instance, is a space-based optical telescope that has contributed significantly to the understanding of galaxy formation and expansion.

Radio telescopes, on the other hand, detect radio waves emitted by cosmic sources such as pulsars, quasars, and interstellar gas clouds. These telescopes typically feature large parabolic dishes, like FAST, which is the largest filled-aperture radio telescope in the world. Arrays of radio telescopes can also function together through interferometry, as exemplified by the Event Horizon Telescope, to achieve extremely high resolution.

Infrared telescopes detect heat signatures and are especially useful for observing objects obscured by interstellar dust or located at great distances. The James Webb Space Telescope operates primarily in the near- and mid-infrared ranges, allowing it to look back to the earliest epochs of the universe and study the atmospheres of exoplanets (Wright, 2008).

Each telescope type is specialized to observe different phenomena and contributes uniquely to the understanding of the universe. Optical telescopes are ideal for studying stars and galaxies; radio telescopes uncover pulsars and cosmic microwave background radiation; and infrared telescopes probe the cold, dust-enshrouded regions of space. Together, these instruments offer a comprehensive toolkit for modern astronomical research.

3 FAST

The Five-hundred-meter Aperture Spherical Telescope (FAST), located in Guizhou Province, China, is the world's largest filled-aperture radio telescope. Commissioned in 2016 and fully operational since 2020, FAST represents a significant advancement in radio astronomy. Its massive dish, spanning 500 meters in diameter and composed of 4,450 triangular panels, enables it to collect weak radio signals from distant cosmic sources with unprecedented sensitivity. The principle is listed in Fig. 1 (Nan, et al., 2011).

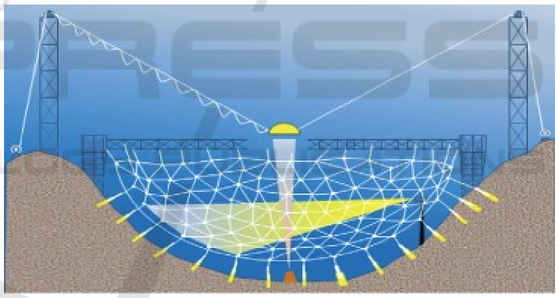

Figure 1: Working principle of FAST telescope (Nan, et al., 2011).

FAST operates in the frequency range of 70 MHz to 3 GHz and employs an active surface capable of adjusting to different observational configurations. Its design allows the feed cabin, suspended by cables, to move and align with different sky positions, effectively simulating a smaller parabolic dish across a vast spherical surface. This provides FAST with a remarkably wide field of view and high sensitivity to low-frequency radio emissions (Li, et al., 2018; Nan, et al., 2011).

A major scientific contribution of FAST is its role in pulsar detection. Since its commissioning, FAST has discovered over 500 new pulsars, significantly enriching the known pulsar population. These discoveries are vital for understanding stellar evolution, neutron star physics, and for potential use in gravitational wave detection via pulsar timing arrays (Wang, et al., 2021). In addition, FAST has detected multiple fast radio bursts (FRBs), including both repeating and non-repeating types, contributing to the ongoing investigation into the origins and mechanisms of these mysterious cosmic phenomena (Zhang, et al., 2022).

The facility also supports research in interstellar medium studies, galaxy evolution, and dark matter exploration through neutral hydrogen line observations. FAST's high precision and sensitivity have positioned it as a cornerstone of international radio astronomy collaboration.

Despite its strengths, FAST faces some limitations. Due to its fixed location and single-dish design, its sky coverage is limited to within 40 degrees from the zenith. Nonetheless, its unparalleled sensitivity ensures its continued relevance in time-domain astronomy and low-frequency surveys. Ongoing upgrades and software improvements are aimed at enhancing observation efficiency and data processing throughput.

4 EHT

The Event Horizon Telescope (EHT) is a groundbreaking international collaboration aimed at imaging black holes by creating an Earth-sized virtual telescope through Very Long Baseline Interferometry (VLBI). This array links multiple radio observatories across the globe to achieve angular resolutions fine enough to observe the event horizon of supermassive black holes. The EHT operates in the millimeter waveband, specifically around 230 GHz (1.3 mm), which allows it to penetrate the gas and dust surrounding black holes (Event Horizon Telescope Collaboration, 2022).

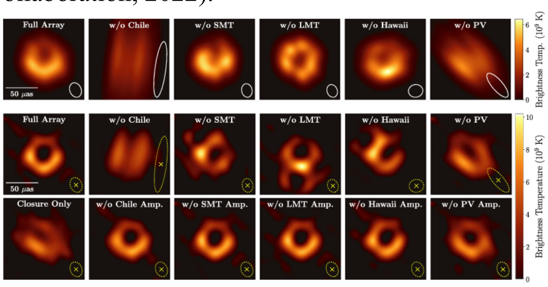

Figure 2: Images of black hole from EHT (Event Horizon Telescope Collaboration, 2022).

A major milestone in EHT's history was the capture of the first image of a black hole's event horizon in the M87 galaxy in 2019. This image confirmed key predictions of Einstein's General Theory of Relativity, particularly the shadow caused by gravitational lensing near the event horizon. In 2022, the EHT collaboration followed up with an image of Sagittarius A*, the supermassive black hole at the center of the own Milky Way as seen from Fig. 2 (Event Horizon Telescope Collaboration, 2022). These accomplishments mark the first time humans have directly observed black hole silhouettes, offering empirical insights into extreme gravitational environments.

The EHT's instrumentation relies on synchronized atomic clocks at each participating observatory and collects petabytes of data, which are then transported to centralized processing facilities for correlation and image reconstruction. The sparse sampling of the Fourier space is addressed through sophisticated algorithms, such as regularized maximum likelihood and Bayesian methods, allowing for the generation of high-fidelity images (Fish, et al., 2014).

The global array includes facilities such as the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile, the South Pole Telescope, and the James Clerk Maxwell Telescope in Hawaii. The project's success is heavily dependent on weather conditions and precise synchronization across the network, making observational campaigns complex and infrequent.

Despite these challenges, the EHT has opened new frontiers in astrophysics by directly probing the innermost regions of black holes. Its ongoing upgrades aim to improve resolution, increase the number of participating telescopes, and extend observation to multiple frequencies. These improvements will enhance the ability to study black hole dynamics, jet formation, and accretion physics, making the EHT a cornerstone in the study of high-energy astrophysical phenomena (Steinhardt, et al., 2021).

5 JAMES WEBB SPACE TELESCOPE (JWST)

The James Webb Space Telescope (JWST) is a space-based infrared observatory that represents the next generation of space telescopes, following the legacy of the Hubble Space Telescope. Launched in December 2021 and positioned at the second Lagrange point (L2), approximately 1.5 million kilometres from Earth, JWST operates in a thermally stable environment shielded from solar and terrestrial radiation. This unique vantage point allows it to achieve extremely sensitive observations in the near- and mid-infrared spectrum (Pontoppidan, et al., 2022).

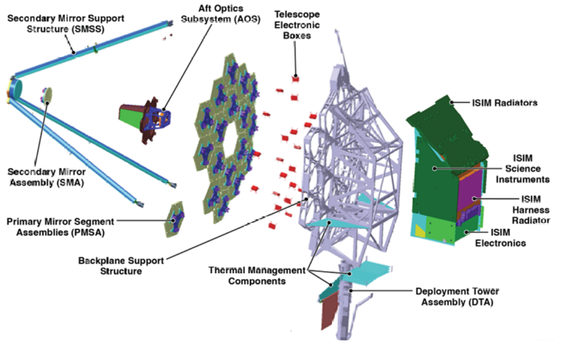

Figure 3: The telescope components of JWST (McElwain, et al., 2023).

JWST's primary mirror consists of 18 hexagonal segments coated with gold to optimize infrared reflection, collectively forming a 6.5-meter aperture as given in Fig. 3. Its instruments include the Near Infrared Camera (NIRCam), Mid-Infrared Instrument (MIRI), Near Infrared Spectrograph (NIRSpec), and Fine Guidance Sensor/Near InfraRed Imager and Slitless Spectrograph (FGS/NIRISS), which together enable high-resolution imaging and spectroscopy across a wide spectral range (McElwain, et al., 2023).

One of JWST's core scientific goals is to study the formation of the earliest galaxies, providing a glimpse into the epoch of reionization. Through deep field observations, JWST has already detected candidate galaxies at redshifts greater than 13, suggesting their formation within the first few hundred million years after the Big Bang. These discoveries offer new insights into galaxy evolution and the nature of the early universe.

Another major objective is exoplanet characterization. JWST employs transit spectroscopy to analyze the atmospheres of exoplanets, identifying chemical compositions, cloud structures, and potential biosignatures. Observations of systems like TRAPPIST-1 and WASP-96b have already yielded significant data on atmospheric water content and molecular features.

JWST is also instrumental in stellar and planetary formation studies, capturing detailed images of star-forming regions like the Carina and Orion nebulae. By penetrating dense clouds of gas and dust, JWST provides crucial data on protostar development and protoplanetary disk dynamics. These observations help bridge the gap between star formation and planetary system evolution.

Despite its breakthroughs, JWST faces limitations such as finite mission lifespan, cooling system constraints, and a lack of in-orbit servicing capabilities. However, its impact on astronomy is transformative. Ongoing and future programs aim to maximize its scientific output, with coordinated campaigns alongside ground-based observatories and upcoming missions like the Nancy Grace Roman Space Telescope.

JWST's unprecedented capabilities make it a cornerstone of 21st-century astronomy, pushing the boundaries of human knowledge about the cosmos. Its role in addressing fundamental questions regarding the origin of galaxies, stars, and potentially life-bearing planets marks a new era in observational astrophysics.

6 COMPARISON, LIMITATIONS, AND PROSPECTS

The three telescopes analysed in this paper—FAST, EHT, and JWST—represent different designs, operating environments, and observational objectives as listed in Table 1. FAST is unparalleled in its sensitivity to low-frequency radio waves, allowing it to discover numerous new pulsars and fast radio bursts. Its massive single-dish design offers a wide collecting area but limits sky coverage and angular resolution. EHT, in contrast, uses a global network of telescopes to achieve high spatial resolution capable of imaging the event horizon of black holes. However, it is limited to very specific high-frequency observations under stringent atmospheric conditions. JWST, as a space-based infrared observatory, overcomes atmospheric interference entirely and captures light from the early universe. It has enabled transformative discoveries in galaxy formation and exoplanetary atmospheres.

Table1: Comparison of the telescopes

Parameter	FAST	EHT	JWST
Wavelength	Radio(0.1-3GHz)	Submillimeter	Infrared(0.6-28μm)
Strength	High sensitivity	Ultra-high resolution	Atmospheric-free IR
Limitations	Limited sky coverage	Weather-dependent	Fixed mission lifespan

While each telescope has unique strengths, they also share common limitations. FAST, though sensitive, lacks the resolving power for detailed imaging. EHT has limited temporal coverage due to logistical coordination and weather dependence. JWST faces constraints on operational lifespan, data transmission rates, and solar shielding degradation.

Nonetheless, these instruments are complementary: FAST excels at survey science, EHT focuses on extreme gravity, and JWST offers deep spectral analysis. Future advancements may include hybrid systems combining radio and optical/infrared capabilities, space-based interferometers for high-frequency VLBI, and AI-driven data processing. These innovations will enhance sensitivity, resolution, and survey efficiency. Multi-messenger astronomy, integrating gravitational waves and neutrino detections, will also expand the scope of observational astronomy. Collectively, these developments promise deeper insights into cosmic origins, structure, and evolution.

7 CONCLUSIONS

To sum up, this study analysed the principles, instrumentation, and contributions of three cutting-edge telescopes: FAST, EHT, and JWST. These facilities represent a leap forward in observational capacity, from detecting faint radio emissions and capturing black hole silhouettes to observing the early universe in the infrared spectrum. The study compared their capabilities and limitations, highlighting their complementary roles in modern astronomy. Looking ahead, innovations in telescope design and data integration promise to further unravel the mysteries of the cosmos. The continued development and deployment of such observatories are vital for advancing both theoretical and applied astrophysical science.

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