The progress of astronomical telescopes: principals, state-of-art facilities and applications

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Abstract: An astronomical telescope is the main instrument utilized to obtain data on celestial bodies and the universe. In this review, the development of astronomical telescopes and their scientific contributions are demonstrated based on information retrieval. The historical development of telescopes shows a trend of increasing aperture and the appearance of various telescopes, from ground to space, detecting electromagnetic radiations from radio waves to gamma-rays. With the invention of radio telescopes, astrophysicists became able to investigate the distant stars and thus the universe's evolution. Besides, the launch of rockets and satellites made space telescopes possible. Free from the block of the atmosphere, space telescopes allow scholars to conduct observations on faint objects and obtain more precise data of previously detected stars. The exponential growth of radio telescopes and periodic upgrades of instruments on space telescopes provide opportunities to test theories, e.g., the general theory of relativity and dark matter, understand galaxies' formation and evolution, and search for exoplanets, etc. To further boost the development of astronomical telescopes with a larger aperture and wider frequency range, both technical inventions and financial support are necessary. These results shed light on the future development of astronomical telescopes.

1. Introduction

The first telescope, using lenses to focus lights (called refractor later), was invented in 1608. Galileo Galilei is the first person to use telescopes to observe celestial bodies. Later, Isaac Newton built the first telescope based on an array of mirrors, and reflectors became widely used. Due to the size-limit of refractors and other reasons, reflectors dominate modern astronomical telescopes [1]. In the 20th century, various telescopes developed, collecting electromagnetic waves ranging from radio waves to gamma-rays. The fast advances in telescopes answer previously unresolvable questions about the universe and stimulate new questions. Despite its fast growth, the astronomical telescope has always been a limited resource, with the number of nights of observation demanded by researches far greater than the nights available [2]. The development of astronomical telescopes is critical to the understanding of the universe.

Optical telescopes in space have advantages over those on the ground mainly because of atmospheric opacity [1]. Scholars have designed and launched plenty of space telescopes, e.g., Hubble Space Telescopes (HST), Kepler space telescope, Gaia space telescopes, TESS, DAMPE, WMAP, PSP, etc. Among them, HST served a mission for over three decades and is probably the most important space telescope. Five servicing missions upgraded instruments on HST and expanded its capacity [3]. On the other hand, radio telescopes experienced exponential growth after their invention [1]. The five hundred-meter aperture spherical radio telescope (FAST) in China has the largest aperture. With the deployment of FAST, detection of pulsars, exoplanets, molecular masers, and distant galaxies will be aided [4].

The rest of the paper is organized as follows. Sec. 2 introduces the principles of astronomical telescopes and discusses the trend in the development of telescopes. Subsequently, the historical development of radio telescopes is illustrated in Sec. 3. As an example of a radio telescope, FAST and its potential applications are analyzed in detail in Sec. 3. Next, space telescope and HST are discussed in Sec. 4, with key projects conducted using HST, servicing missions, and replacing its instruments described in detail. The impact of HST and its future are also mentioned. Finally, the future development of telescopes and the importance of this review are given in Sec. 5.

2. Principles of astronomical telescopes

Telescopes employ a combination of lenses or mirrors to collect electromagnetic radiation and bring it to a focal point, i.e., one can observe and study distant stars, nebula, or other light-emitting objects from images produced by telescopes. Telescopes that use lenses to form an image are called refracting telescopes, or refractors, while those using mirrors are called reflecting telescopes or reflectors. The earliest telescope, invented in the Netherlands in 1608, used lenses, but most astronomical telescopes since the 20th century have been reflectors. Compared to refracting telescopes, reflectors take advantage of parabolic mirrors, reducing spherical aberration and avoiding chromatic aberration [1]. Most importantly, refracting telescopes have a maximum physical size limit of about 1 meter as lenses with larger sizes would bend themselves under gravity. Therefore, scholars choose to design reflectors for the need for a larger aperture.

Telescopes can be classified by the wavelength of light they collect. Thereinto, optical telescopes (detect visible light) and radio telescopes are mostly common. Other types, Gamma-ray telescopes, X-ray telescopes, Ultraviolet telescopes, Infrared telescopes, and Submillimeter telescopes, have been developed since the beginning of the 20th century. Some telescopes detect signals other than electromagnetic waves. Telescopes can be classified by location as well, and the two major types are ground telescopes and space telescopes. Ground telescopes are influenced by atmospheric electromagnetic opacity. Gamma rays, X-rays, ultraviolet light, infrared light are barely observable from the Earth's surface. Visible light is observable but with atmospheric distortion. In contrast, the atmosphere is opaque for radio waves (see Fig. 1). Thus, space telescopes designed and launched are often optical telescopes, with some X-ray, Gamma-ray, and other types of telescopes, while most radio telescopes are on the ground.

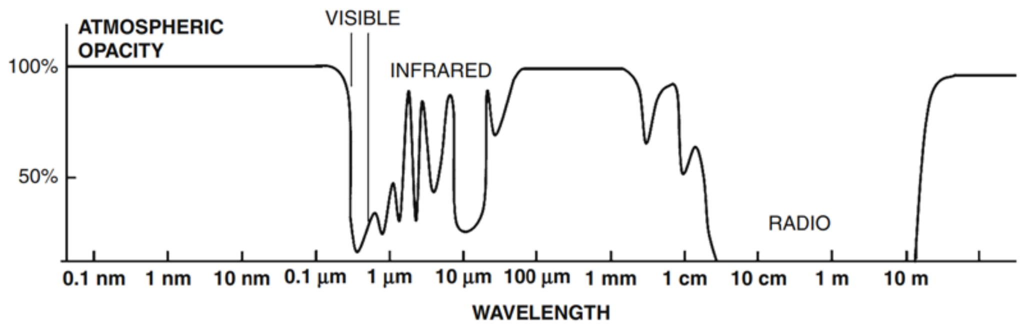

Figure 1. the atmospheric opacity for electromagnetic waves of different wavelengths [1]

This article mainly focuses on radio telescopes and space optical telescopes because these two types provide a large amount of data with high precision for most astrophysical research. One of the most criteria in designing telescopes is the resolving power, usually indicated by the angular resolution. For radio telescopes, the resolving power is directly related to the aperture of the antenna; for optical telescopes, the resolving power is directly related to the aperture of the objectives. The following formula gives the Rayleigh criterion for the angular resolution limit [5]:

$$\sin \alpha = 1.22 \frac{\lambda}{D} \tag{1}$$

where α is the angular resolution limit, λ is the wavelength of light gathered, and D is the aperture of the primary mirror or antenna. Light gathering power of telescopes is proportional to the square of the aperture [5] given by:

$$P = \frac{D}{D_p}^2 \tag{2}$$

where P is the gathering power compared against a human eye, D is the aperture, D_p is the diameter of an adult pupil.

Angular resolution limit and light gather power are the two most important criteria of a telescope, and both of them increase with aperture. Thus, the trend in designing and building astronomical telescopes sees an increase in aperture.

3. Radio telescopes and FAST

3.1 Development of Radio telescopes

Radio telescopes began when Karl Guthe Jansky discovered radio emission from the Milky Way in 1931. Radio telescopes have developed into various types because radio waves, which travel through the universe with little distortion, are easy to handle with [6]. Directional antenna arrays or large stationary reflectors with moveable focal points are generally used to detect radio waves at wavelengths of 30 meters to 3 meters (10–100 MHz) . Parabolic "dish" antennas predominate the detection at shorter wavelength [7]. The dishes are single monolithic collectors. The arrays have a number of separated receptors over large areas in the aperture plane that first sample the wave front and then combine these signals electronically to form an image [1]. The criteria, e.g., angular resolution, sensitivity, frequency range, survey speed, and field of view, determine the design of radio telescopes. The sensitivity has been growing exponentially since the invention of radio telescopes, and Harwit concluded that the for science, exponential growth is the normal mode of growth (illustrated in Fig. 2) [1], which implies that field that has not kept growing exponentially has now faded away. To maintain the growth, technical inventions are needed in addition to refining existing technology.

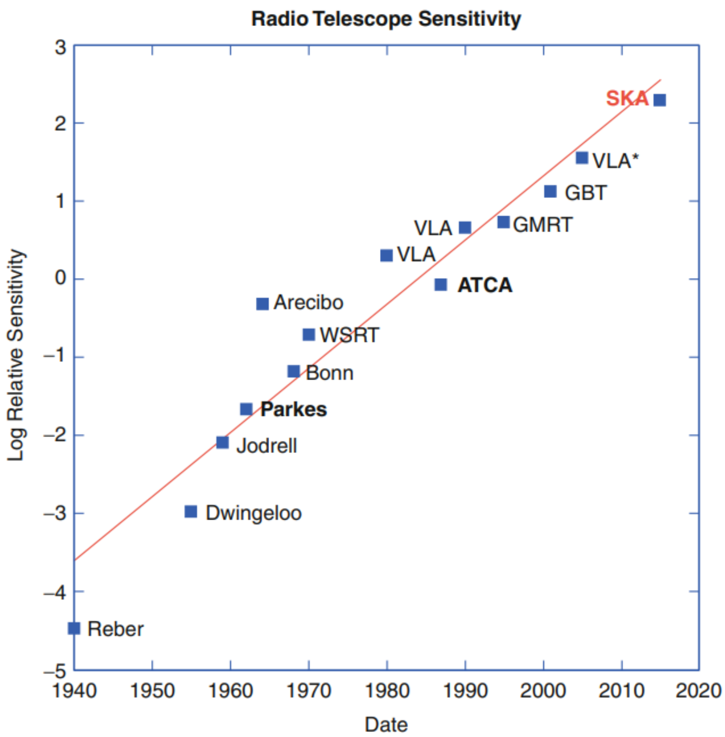

Figure 2. Radio telescope sensitivity vs. time

The log of the relative continuum point source sensitivity are taken and plotted against time. The data are based on sensitivity of telescopes when first deployed or after major upgrades. VLA* (now called the Jansky VLA) is the upgrade of EVLA. The proposed sensitivity for telescope SKA is shown (SKA has not yet been built) [1].

Very long baseline interferometers (VLBI) are an important technical invention in 1967, which enabled receiving elements that are separated by a large distance to be operated with enough coherence [1]. As a result, the Very Long Baseline Array (VLBA) provides the highest angular resolution among any ground or space telescopes.

Table 1. Main technical specification of FAST [8]

Spherical reflector	Radius = 300 m, Aperture = 500 m
Illuminated aperture	Dill = 300 m
Focal ratio	f/D = 0.4611
Sky coverage	zenith angle 26.4° (full gain) 26.4°-40° (with a maximum gain loss of 18%)
Frequency	70 MHz – 3 GHz
Sensitivity(L-Band)	A/T~2000 m^2/K
Resolution(L-Band)	2.9'
Multi-beam (L-Band)	beam number = 19
Slewing time	<10 minutes
Pointing accuracy	8"

3.2 FAST

In 2020, the Five hundred meter aperture spherical radio telescope (FAST) opened to use. FAST is located in the Guizhou Province of southwest China. Due to its large aperture and geographic location, it will increase the sensitivity of VLBA by order of magnitude upon its joint to the network.

Thanks to its high-resolution power, sensitivity, and large sky coverage, FAST is a powerful tool for surveying hydrogen lines in distant galaxies (large redshift), detecting weak emission pulsars, and searching for extraterrestrial intelligence (SETI) [4]. Owing to its wide frequency range, FAST is also useful in surveys of the molecular masers in galaxies [4]. Table 1 shows a list of the major specifications of FAST.

3.3 Pulsars

While according to the theoretical prediction, around 60 thousand pulsars in the galaxy are observable, only about 2600 pulsars are known [4, 9]. Moreover, the number of double pulsar binary and rare types of pulsars is small, but the discoveries are around the limit of detecting instruments [4]. FAST high sensitivity and large sky coverage would enable discoveries of more pulsars and increase the precision of measurement of known pulsars. Such improvements would allow better determination of pulsars' properties, their evolution, and chance to test the predictions of General Relativity.

3.4 Molecular clouds

Since the birth of millimetre radio astronomy in the 1960s, the spectral lines of various organic molecules have been detected in the interstellar medium. FAST can make surveys of molecular radio emissions in both our galaxies and in distant, high redshift galaxies, which enables the detection of more mega-masers and the understanding of the relation between mega-masers and galaxy activity and type [4].

3.4 Search for extra-terrestrial intelligence (SETI).

Because radio waves transmitted through space with the least distortion, using radio waves would be the only practical way to communicate with distant civilizations. SETI teams search sun-like stars using the largest available telescopes, and Table 2 shows the possible performance of 4 radio telescopes in SETI and that of FAST.

Table 2. Comparison of radar ability of four telescopes [4]

Transmitter power EIRP (MW)	Parks		Bonn		Arecibo		FAST	
	range (ly)	# of stars	range (ly)	# of stars	range (ly)	# of stars	range (ly)	# of star
10			1		1.8		2.7	
100	1.4		3		5.8	1	8.7	2
1,000	4.5	1	9	1	18	12	27	40
10,000	14	5	28	45	58	390	87	1,300
100,000	45	173	90	1,430	185	12,000	280	40,000
1,000,000	140	5,480	280	45,200	583	328,000	870	1,100,000

4. Space telescope and Hubble Space Telescope (HST)

4.1 Launch and maintenance

The notion of space telescope appeared early in the 1920s, but the first space telescope was not launched until the 1960s using rockets. In 1990, HST was launched into low Earth orbit and remained in operation. So far, it is possibly the most well-known space telescope. Its design has flexibility and extensibility, which, combined with periodic refurbishment in orbit and replacing and upgrading systems on it, makes HST a symbol of ingenuity in people’s learning of the universe. The Space Telescope Science Institute (STScI) is responsible for selecting Hubble's targets and processing the resulting data, while the Goddard Space Flight Center (GSFC) is committed to controlling the spacecraft [10].

4.2 Major projects and scientific impact

HST has helped people learn about the universe. At the time of HST’s launch, characterization of the universe was very different than now. With the universe thought to be expanding at decreasing rate, the expansion rate undetermined, exoplanets not been seen, and black holes at the centers of galaxies not detected [10]. HST was designed, fund, and launched for three original, specific goals [10].

Determine the Hubble constant, with uncertainty less than 10%. It met this goal by observing the standard candle objects beyond out galaxy. After servicing mission 4, the Hubble constant could be determined to be 3%. The observations strongly suggest an accelerating universe, which changed people’s understanding of the cosmological parameters.

Determine the properties of the intergalactic medium.

The “Medium Deep Survey”, surveying galaxy demographics.

The three early projects were completed long ago, and HST brought about discoveries and new questions well beyond the original goals. With upgrades in instruments, new projects were proposed and conducted, focusing on deep universe observation.

Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS). This is referred to as the largest project in the history of Hubble, aiming to investigate evolution of galaxy in the early age of the universe and the very first seeds of cosmic structure at less than one billion years after the Big Bang. It is designed to survey the galactic evolution from z=8 to 1.5 through deep imaging of more than 250,000 galaxies [11].

Frontier Fields program aimed to advance the knowledge of early galaxy formation. With the help of gravitational lensing to see the "faintest galaxies in the distant universe", the program explores high-redshift galaxies in blank fields. It focuses on galaxies of z=5 to z=10. The earliest, most distant galaxies known has just been detected by HST through WFC3, a new camera installed during servicing mission 4. They show the 13.8-billion-year-old universe (at large redshifts between 8-10) as it was just 5 hundred million years after the big bang [12].

Cosmic Evolution Survey (COSMOS), designed to probe the formation and evolution of galaxies and explore the evolution's relation with both cosmic time (redshift) and the local galaxy environment [13].

HST paves a path to the investigation of early galaxy formation and evolution. It has also been a crucial tool in the discovery of exoplanets. Its observational data in five servicing missions have helped constraining the nature of dark energy. The publication of journals can also illustrate the influence of HST. Based on Hubble data, over 15,000 papers have been published in peer-reviewed journals, and in late 2009, there were 287,000 citations based on HST data [10, 14].

4.3 Missions and expanded capabilities

Up to now, there have been five manned servicing missions to HST to repair and replace instruments, enhancing the observatory (depicted in Fig. 3). The first mission in 1993 installed corrective optics. In June 1990, Hubble returned its first images, but the image quality was far below the expected, revealing a flaw in its primary mirror that prevented the mirror from focusing. Analysis of flawed images indicates that the mirror had been polished to the wrong shape, causing spherical aberration, severely impacting the observation of faint objects and making cosmological programs impossible [15, 16]. Allen Commission was established to find out the origin of the error and concluded that a reflective null corrector was the cause. After calculating the error in the conic constant of the primary mirror, the Corrective Optics Space Telescope Axial Replacement (COSTAR) system was designed and fit onto the HST to correct the spherical aberration for FOC, FOS, and GHRS in 1993, during the first servicing mission [16]. By 2002, those instruments requiring COSTAR were all replaced by instruments with their own corrective optics, so COSTAR was removed (seen from Fig. 4). Mission 2 in 1997 replaced the GHRS with NICMOS and FOS with NICMOS to reduce the thermal noise from the instrument. Mission 3A in 1999 replaced all gyroscopes and a fine guidance sensor. Mission 3B in 2002 replaced the FOC with ACS. Mission 4 in 2009 repaired ACS and STIS systems and installed WFC3 and COS. WFC3 allowed the Hubble constant H0 to be determined to 3% and enabled HST to detect the earliest, most distant galaxies known [10]. The instruments on the HST are illustrated in Fig. 5.

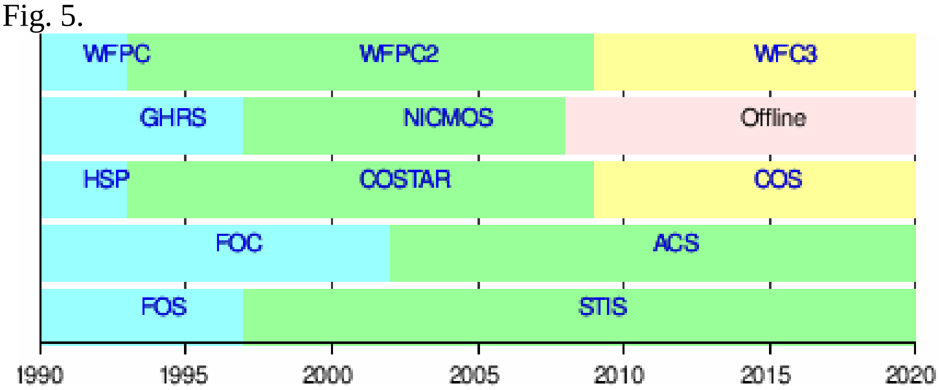

Figure 3. The image shows the upgrades of instruments on HST [17]

Figure 4. Optical evolution of Hubble's primary camera system.

Image on the left show spiral galaxy M100 as seen with WFPC1 in 1993, before corrective optics. Image on the middle depicts the same galaxy seen with WFPC2 (after correction)in 1994, and image on the right is that seen with WFC3 in 2018[18].

4.4 Future of HST

Although there is no direct replacement to HST now due to its wide wavelength coverage, there will be a day when HST no longer conducts observations. The James Webb Space Telescope (JWST) is the possible successor to HST, but it currently faces budget uncertainties. JWST would also have a different priority in its mission than HST does. It is expected to detect more distant stars in the early Universe, so its coverage would be 0.6–28.5 μm [20].

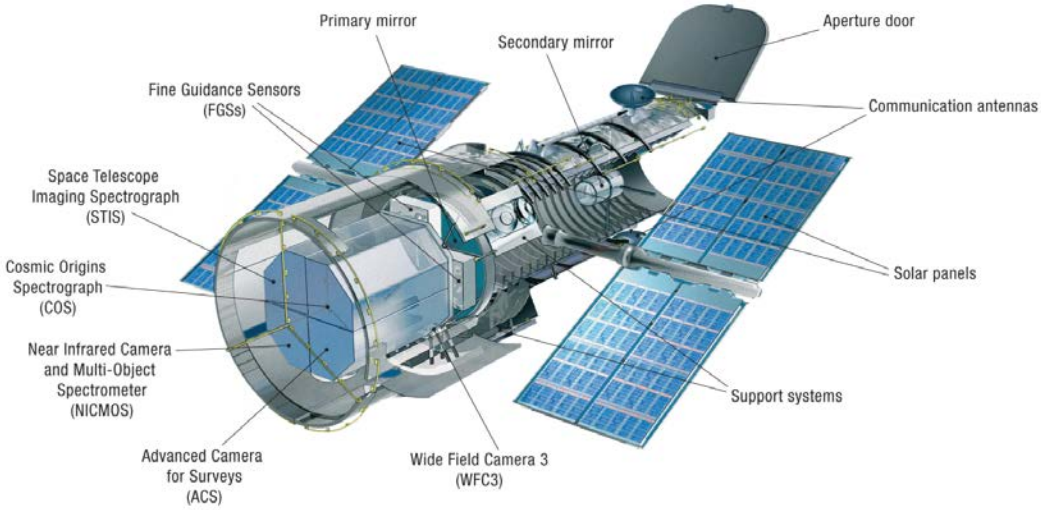

Figure 5. The locations of Hubble's instruments inside the telescope [19]

5. Conclusion

In summary, this paper discusses the development of astronomical telescopes and analyses two state-of-the-art telescopes, FAST and HST. In detail, historical progress and important criteria in telescope design are introduced primarily. Subsequently, the development of the radio telescope is analysed, with FAST, the radio telescope having the largest aperture, and its application described in detail. Then, the 30 years of operation and maintenance of HST are demonstrated, and the scientific impact of HST is overviewed. This paper clarifies the importance of the progress of telescopes in the understanding of the universe. With advances in telescopes (e.g., increasing aperture and frequency range), unaddressed questions in astrophysics could be answered, but such advances require technical innovations and budget. Choosing to financially support the development of a ground telescope or space telescope is also a topic in the debate. The summary of the progress of astronomical telescopes offers a guideline for the future development of the telescope.

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