State-of-art Facilities and Prospect of Radio Telescopes

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Abstract. The radio telescopes play a crucial role in astrophysical observations; hence it is necessary to discuss about the significance, structure, and applications of radio telescope and analyse the difference between the state-of-art radio telescopes (FAST and SKA) based on present information. Specifically, the background and present conditions as well as the history of radio telescopes will be introduced initially. Subsequently, the significance of radio telescope will be explained, including structure and application of radio telescopes. Subsequently, the doubts on FAST and SKA and strengths of them will be clarified. Eventually, the problems and limitations about radio telescope and the future prospect will be discussed. Overall, these results shed light on offering suggestions for future development of galaxy and cosmology observations.

Keywords: radio astronomy, radio telescope, astronomical observation.

1. Introduction

Human's desire for astronomical observation and research comes from the original curiosity about the Sun, the Moon, and the stars in the sky; the realistic needs for climatic and agricultural purposes. Since the modern times, with the development of optical telescopes, the instruments for astronomical observation shifted from human eyes to optical telescopes, and radio telescope in early 20th century. In January 1610, physicist Galileo made his telescope of magnification of 33 [1, 2]. This is a large development in the astronomical instruments, and Galileo's telescope actually provided images that are better than expected [1]. In the same year, Galileo observed the Saturn's ring. The invention of optical brought the astronomy into a new era. As time goes by, scholars found that not only visible light but also electromagnetic waves at other frequency could also provide significant information about celestial bodies; the traditional optical telescopes had numerous limitations in astronomical observations and there needed to be a revolution in observation instruments. In the year of 1937, the first radio telescope was invented, and this event created the radio astronomy.

Contemporarily, radio telescope technology has made significant progress. In 1963, Arecibo telescope was built; in 1974, Hulse and Taylor found an unusual pulsar system which has changing period by using the Arecibo telescope. Subsequently, the system was later identified as binary radio pulsar. This discovery help Taylor and Weisberg use the rate of orbit energy loss to indirectly prove the existence of gravitational wave, which was a milestone [3, 4]. In 2016, Five-hundred-meter Aperture Spherical radio Telescope was settled in Guizhou, China. Compared to Arecibo telescope, it can form illustrated area of diameter 300m at different regions on the reflective antenna (which enables FAST to cover more areas) by adjusting the reflective aluminium boards through the change in crossed nodes of the cable-net [5]. Fig .1. shows the schematic diagram of FSAT and the geographical location of FAST. In 1993, the project Square Kilometre Array launched and the telescope will be completed in 2024 and used in 2030. At 2030, it will be the largest and the most sensitive radio telescope array in the world, which can cover the frequency from 70MHz to 25GHz, and its array of single antennas spread for about 3000 kilometres [6], which mean its observational range, the resolution ratio, and sensitivity will be the best.

FAST is the largest spherical radio telescope and SKA is the largest radio telescope array; their general function is similar but there are some differences between them. This paper will explain the significance, structure, and application of radio telescope respectively. The rest part of the paper is organized as follows. Firstly, this paper will introduce the history of radio astronomy and radio telescope; in this section, this paper will explain more about some landmark radio telescopes or radio telescope arrays including the Arecibo telescope, FAST, and SKA. Secondly, this paper will discuss the significance of radio telescope, including the general structure of the radio telescope and their applications and present observations. In the third section which is the last section of the main body, this paper will demonstrate the limitations and future prospects of present radio telescopes respectively. At the end of the paper, this paper will summarize all the three points that have been discussed.

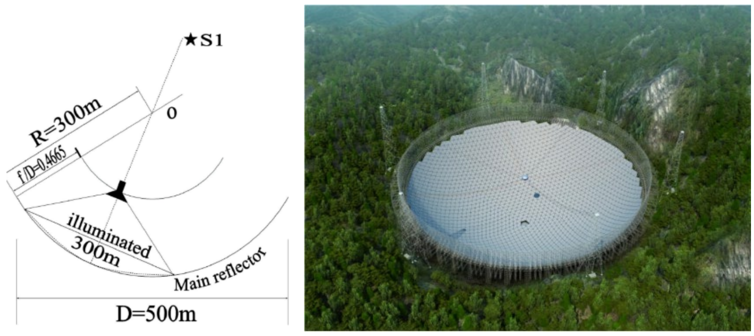

Fig.1 FAST optical geometry, right: FAST 3-D model [5].

2. The history of radio astronomy and radio telescopes

In 1932, Karl Jansky from America found that the radio noise would increase when the antenna directed closer to the Milky Way, and the noise would maximize when the antenna directly to the Sagittarius direction. Karl found that the period of the electromagnetic wave was about 23 hours and 56 minutes [7]. It is considered that the strange and periodic electromagnetic came from the Galaxy especially from the Galactic centre. This event lifted the curtain on radio astronomy and radio telescope. In 1974, Hulse and Taylor found the existence of binary radio pulsar and indirectly proved the existence of gravitational waves by using the Arecibo radio telescope. In 1965, Penzias and Wilson found the existence of cosmic microwave background using a large radio antenna. In 1963, Ryle came up with the idea of very long baseline interferometry and designed the first aperture synthesis radio telescope which used the idea. This idea enabled scientist to use radio telescope array to decrease the resolution angle:

$$\theta = \frac{1.22\lambda}{D} \tag{1}$$

where, θ is the resolution angle, λ is the wavelength of the electromagnetic wave that are observed, and D is the calibre of the telescope. What did Martin do is to split the single telescope into radio telescope array in which each single telescope can act as a part of the whole single array and this design can drastically increase the calibre of the whole large telescope (array), which will lead to the reduction of the resolution angle, θ, and the dramatical reduction of resolution angle means the huge increase in the resolution ratio. This design is also used in the latest radio telescope array—SKA, which help the radio telescope array to increase the sensitivity drastically. Generally, this design solved a hard problem in radio astronomy, which enabled people to build more smaller single radio telescopes which need lower level of technology, make the telescopes into an array, and get observation results that are more precise. Besides, the single spherical aperture radio telescope is also developing fast. In 2016, the FAST program is completed in Guizhou, China. The single telescope has found hundreds of pulsars since its completion.

3. Significance and State-of-art applications

3.1 Radio telescopes' general structure

Fig. 2. can clearly show the mechanical structure of a radio telescope, mainly consist of a curved face reflector, a feed source which is also the receiver, and information processing system. The right image shows the general pattern of electromagnetic wave reflection on a radio telescope's antenna. Seen from Fig. 2, it can be known that the electromagnetic wave beam will be focused which can enhance the intensity of electromagnetic waves in observations. The sensitivity of a radio telescope is in accord with the formula:

$$S_{min} \propto \frac{T_{sys}}{A\sqrt{\tau \Delta f}} \tag{2}$$

Here, S_{min} is the minimum sensitivity of the telescope, T_{sys} is the receiving system's temperature, τ is the observation time, Δf is the bandwidth, and A is the area of the antenna. From this formula it can be known that the larger the area of antenna is, the smaller the minimum sensitivity is. The telescope become more sensitive when S_{min} become smaller. The relationship between sensitivity and antenna is because the bigger the reflective area is, the stronger the intensity of electromagnetic wave received is, and therefore the more sensitive the radio telescope is. The shape of the reflective antenna will also affect the reception of electromagnetic waves. In Fig. 3. and Fig. 4. it can be observed that the paraboloid can reflect the electromagnetic waves to one point, its focus, hence the work of reception and design of feed source can be relatively easy such as in FAST; while the sphere can only reflect the beans into on line, which will make the design of feed source extremely complicated such as in the Arecibo telescope. Therefore, most of the antennas of modern radio telescopes are designed to be paraboloid. As shown in Fig. 2, the radio telescope can focus the electromagnetic waves on one point. Fig. 3 gives the reflection pattern of paraboloid.

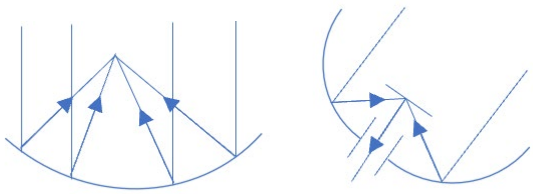

Fig.2. The sketch of reflection pattern of radio telescope.

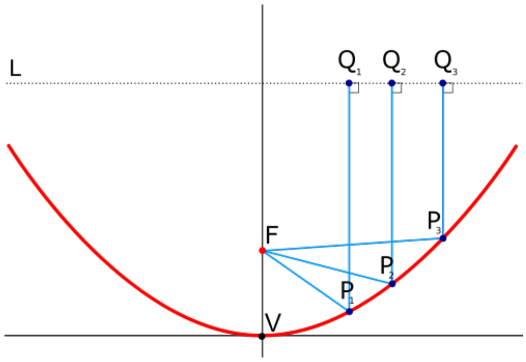

Fig.3. The reflection pattern of paraboloid [8].

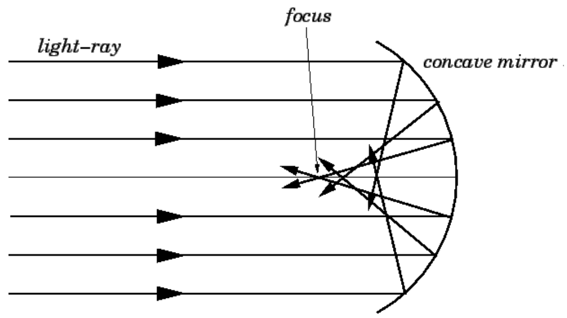

Fig.4. The reflection pattern of sphere [8].

The answer to the question why the antennas of radio telescopes are enormous lies in the formula Eq. (1). As mentioned in Eq. (1), λ is the wavelength that are received. Radio telescope, as its name, receives electromagnetic waves the wavelengths of which are far larger than the visible light, thus the λ will be large. In order to limit the resolution angle thus increase the resolution ratio, the calibre, D, of the radio telescope must be larger than traditional optical telescopes. At the same time, the range of frequency of radio telescopes is much larger than the traditional telescopes so it can provide more information about the celestial bodies in detail.

As mentioned earlier, the aperture synthesis technique can make the calibre of a single radio telescope to become the calibre of the whole radio telescope array which is only limited geographically and drastically increase the resolution ratio. This advantage cannot be shared with traditional optical telescopes so the radio telescopes are very significant and cannot be replaced. Meanwhile, because the total area of antennas of a radio telescope array is also very large, the telescope array will be very sensitive. The telescope array can also lower the level of technology required for a single telescope.

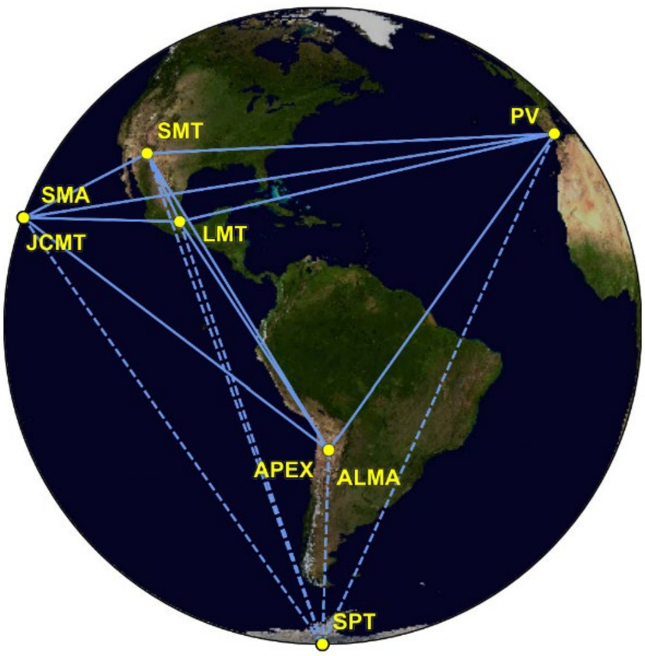

Fig.5. 8 telescope (array) which took part in the observation of M87 black hole and gave the image of the black hole [9].

3.2 Application of radio telescopes and present observation

The most famous recent event about observation of black hole is the 2019 image of the black hole in the centre of M87. This project included radio telescope array such as the ALMA and the Sub-Millimetre Array.

As illustrated in Fig. 5. it can be seen that the telescopes used in EHT program. The EHT actually used very-long-baseline interferometry, which came from Martin Ryle's idea. Besides, this achievement is based on the radio research on the centre of M87 galaxy since the discovery of radio jet in M87 in 1918 [9]. In 2000, Frazer N. Owen and his research group analysed the centre of M87 and gave a 90cm (presented in Fig. 6) image of the centre of M87 with the help of Very Large Array and historical observation and analysis in 74, 321, and 327MHz [10].

This research revealed the inner structure of the core of M87, gave the competitive relationship between the hot cluster gas and the central black hole in M7, and laid an important foundation for the direct imaging of the central black hole in M87. From these studies it can be directly seen that the profound influence of radio telescope on the domain of astrophysics and astronomy.

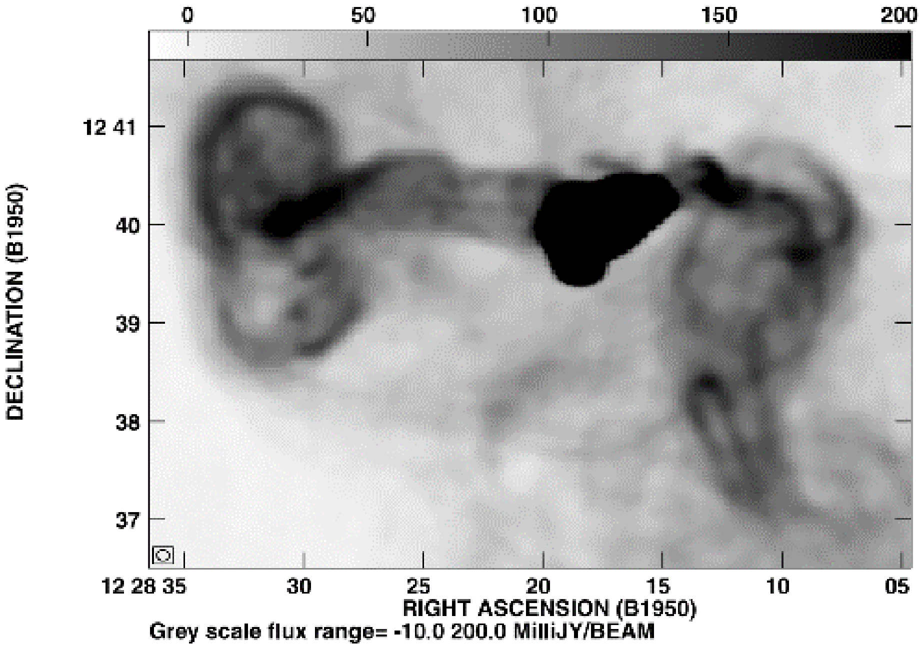

Fig.6. 90 cm image of central part of Virgo A/M87 [10].

4. Comparison between single radio telescope and telescope array.

In order to compare single telescopes and telescope arrays I will take FAST and SKA as example. Although FAST and SKA both use radio telescope, there are big differences between them. Firstly, their collecting areas are different. SKA is an array of radio telescopes, so the total reflective area can reach 0.4 Km^2 for the SKA_LOW (for observations of lower frequency) in Australia [11]. FAST is a single radio telescope, i.e., it has reflective area of 0.25 Km^2 which is far smaller than that of SKA_LOW. According to Eq. (2), if the A is larger the minimum sensitivity will be smaller, which means that SKA_LOW will be more sensitive than FAST when observing electromagnetic waves in lower frequencies. Secondly, the array properties make SKA have smaller resolution ratio: according to Eq. (1), the telescope with larger calibre has smaller resolution ratio; SKA_MID's max baseline reaches 150 km, and SKA_LOW's max baseline reaches 65km [11], while FAST only have calibre of 300m, which means SKA will be much more precise. Thirdly, The SKA_MID can observe electromagnetic wave up to 15GHz, while FAST can only reach the frequency up to 8GHz [5], which means that the range of frequency observed for SKA is much wider than that of FAST. From the three points it can be known that SKA is better choice among most of domains. FAST also has its own advantages. Firstly, SKA_MID (for observations of middle frequency) only have reflective area of 0.032km^2 [11], which is much smaller than that of FAST, hence FAST will be more sensitive than the SKA_MID according to Eq. (2). Secondly, which is also very significant, as a single telescope, FAST cost far less fund and time period to construct because the total workload for the single surface than for the numerous small antennas of SKA. From the five points it can be drawn that single radio telescopes represented by FAST are more likely to be a substitution of telescope arrays represented by SKA with a few domains stronger when there is a fund and time shortage. In short terms, for better observation and research, when the fund is sufficient, telescope arrays such as SKA should be more tended to build because the arrays have better performances in resolution radio and sensitivity which are important in observations.

5. Limitation and Future prospects

The biggest problem of radio telescope is that the telescope's resolution ratio is low because of the long wavelength of the electromagnetic wave. Therefore, it is a good way to increase the resolution ratio is to use the very-long-baseline interferometry technique, which can increase the resolution ratio drastically and this goal must be done with the international scientific cooperation. The single radio telescope has the problem that the cost is pretty high to build a telescope similar to FAST and the technical requirements are also tough. In addition, the telescope array faces the issues of bid data analysis.

With the completion of SKA, the radio astronomy will definitely keep developing to new levels. For now, the single radio telescope is very important because it can collect the signal and deal with the information from observation easily. With the development of technology, the data processing capacity will be enhanced and the energy consumption will decrease. As a result, radio telescope array might be used more widely in order to participate in international programs (e.g., EHT) and explore space in greater detail.

6. Conclusion

In summary, this paper discusses radio telescope from the perspective of history of radio telescopes, significance of radio telescope (radio telescope's general structure and state-of-art application), comparison between FAST and SKA, state-of-art observations using radio telescopes, and limitation and future prospects of radio telescope. Specifically, this paper gives the features of FAST and SKA with respect to each and this evaluation may suggest that the way to choose radio telescopes to construct. In the future, radio telescope arrays may be used more widely with the development of data processing technology which will enable people to take their understanding of the universe to a new level. Overall, these results offer a guideline for the construction choice and development direction of radio telescope and radio astronomy.

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