Transactions on Computer Science and Intelligent Systems Research
ISSN: 2960-1800, eISSN: 2960-2238 | Volume 7
TPCEE 2024

High-Resolution Imaging of Radio Interference

Zhujia Kuang
Chongqing Yucai Secondary School, Chongqing, 400050, China
Sharon0830@126.com

Abstract. In recent years, the advancement of radio astronomy has played a critical role in the exploration of space. The development of large-scale radio telescopes, such as the Five-hundred-meter Aperture Spherical Telescope (FAST) in China, has enabled astronomers to capture high-resolution images of celestial bodies and improve people's understanding of the universe. However, challenges remain in achieving higher precision and sensitivity in astronomical observations. This review paper provides an overview of the fundamental principles, methodologies, and applications of radio interferometers, particularly focusing on their ability to enhance the resolution of astronomical images through synthetic aperture technology. The paper discusses the structural components of radio telescopes and details the operation of radio interferometers, including their application in Very Long Baseline Interferometry (VLBI). By examining the technological developments in VLBI and space VLBI, this paper highlights their contributions to astronomical observations and explores future directions for radio interferometry research. Future research may consider further improving the capabilities and applications of high-resolution radio imaging.

Keywords: Radio interferometry; VLBI; FAST; high-resolution imaging; astronomical observations.

1. Introduction

In recent years, with the attention of various countries to the field of aerospace, many countries have made remarkable progress in astronomical observations, and have built high-performance telescopes and launched satellites. China's Five-hundred-meter Aperture Spherical Telescope (FAST) is one of the most representative astronomical devices.

FAST is a single-aperture radio telescope capable of receiving electromagnetic signals from tens of billions of light-years away. Radio telescopes play a fundamental role in astronomical research by receiving radio waves with wavelengths greater than 1 millimeter (radio waves). The core components of a radio telescope include antennas or antenna arrays, feeds, high-sensitivity receivers, information logging devices, data processing and display systems, clock systems, and environmental detection systems [1]. When radio waves from celestial bodies are reflected by the radio telescope's parabolic antenna, they are focused on the feed oscillator. After that, the signal enters the high-frequency amplifier, and the high-frequency signal is changed into an intermediate frequency signal through a mixer, and then converted into a low-frequency signal, and finally the information carried by the radio wave is obtained through the detector and recorded or processed by a computer. As a radio telescope composed of multiple antenna systems, radio interferometers have become an important tool in astronomical research and have important significance for the development of radio telescopes because they can improve their resolution through synthetic aperture technology [1, 2].

The purpose of this review is to provide a comprehensive analysis of the current state of radio interferometry, focusing on the advancements made by instruments like FAST and VLBI.

2. Principles, Methods, and Applications of Radio Interferometer Direction Finding

Figure 1 presents captured images of the FAST, showcasing its structure and scale. Figure 2 illustrates the structural layout of FAST, detailing the main components that contribute to its functionality. Figure 3 depicts the dual antenna interference setup used in radio interferometry. This diagram explains the principle of wave superposition, where signals received from two antennas are combined to enhance resolution and sensitivity. It also emphasizes the role of phase adjustment in achieving high-precision observations in radio astronomy.

Figure 1. Captured images of FAST [3]

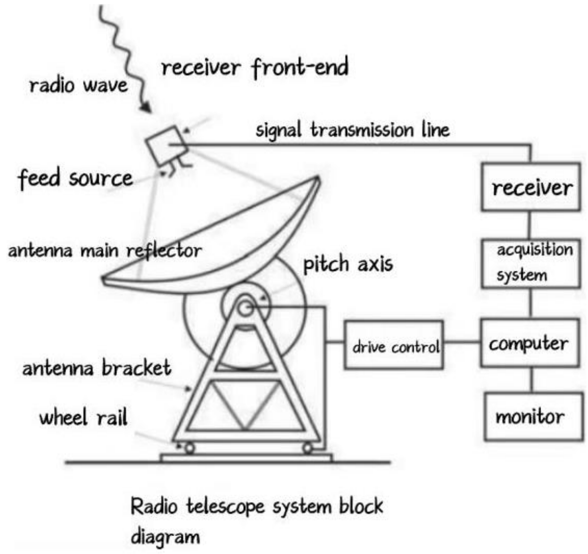

Figure 2. Structure diagram of FAST (Photo/Picture credit: Original)

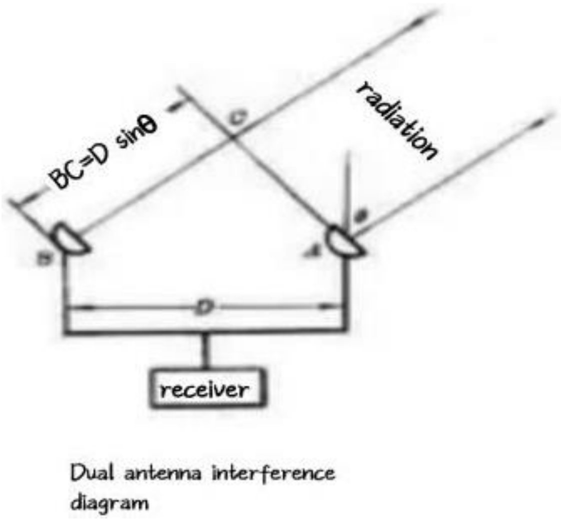

Figure 3. Dual antenna interference diagram (Photo/Picture credit: Original)

The principle of radio interference is based on the principle of wave superposition, which means that when multiple telescopes observe the same object at the same time, the celestial signal they receive is fed into the interferometer through a transmission line.

The interferometer can superpose the signals received by different telescopes after adjusting the phase and amplitude. Then through the calculation and processing of the interferometer, people can obtain high-resolution and high-sensitivity celestial images and data. So astronomers use the principle of wave interference to build radio interferometers. Radio interferometers are usually arranged with two equally sized antennas spaced apart and connected by a cable [4]. This technique allows people to extract useful signals from noise more efficiently; The very long baseline interferometer, usually made by several radio telescopes thousands of kilometers apart, greatly improved the resolution, allowing the resolution of the radio band to be higher than that of the optical band for the first time. However, radio interferometers also use the same principle as optical interferometers, and play an important role in the measurement of radio source location and angular diameter. For example, the simplest interferometer consists of two antennas separated by a certain distance. The resolution of the interferometer depends on the distance between the two antennas, while the "receiving area" depends on the size of the antenna. The resolution of radio today is thousands of times higher than other wavelengths, revealing the cores of radio objects more clearly. Figure 4 shows the flow of delay and delay rate in VLBI. The diagram illustrates how signals from multiple telescopes, separated by vast distances, are processed to determine the time difference and delay rate, enabling high-resolution imaging of distant radio sources.

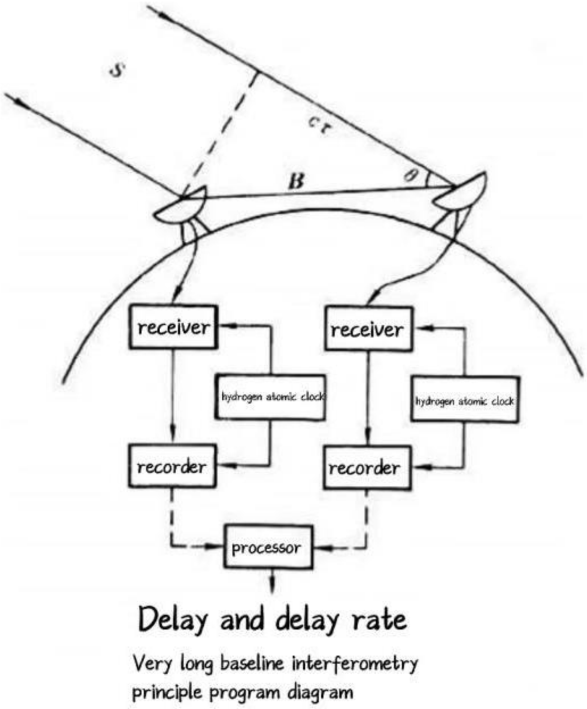

Figure 4. The delay and delay rate flow of VLBI (Photo/Picture credit: Original)

The principle and application of VLBI technology, as well as the advantages and application fields of VLBI network and EVLBI technology of the Chinese Academy of Sciences.

Application of VLBI technology: VLBI technology can observe distant radio sources and spacecraft and measure their space position and parameters.

Space VLBI: Space VLBI further expands the observation range and improves the resolution by sending the radio telescope to space. Real-time data processing: Through EVLA technology, the relevant processing of observation data can be carried out in real time, greatly reducing the data transmission and processing time.

3. Radio Astronomical Interferometry

3.1. Principle of Measurement

VLBI is a method of astronomical interferometry used in radio astronomy [4]. It allows multiple telescopes to observe a single object at the same time, simulating the effect of a giant telescope with a size equivalent to the maximum distance between the telescopes. The original very long baseline interferometry was proposed in 1931 by Martin Ryle and some other people. The measurement principle is: the radio telescopes at both ends of the baseline each receive the signal of the same radio source with an independent time standard (hydrogen clock, etc.), record it on tape, and then send the records of the two tapes together to the processor for related processing, and find the difference of the time when the two same signals reach the baseline at both ends (referred to as delay) and the relative delay rate (referred to as delay rate). The bases of very long baseline interferometry are time synchronization and phase synchronization. Time synchronization is the time consistency between the two observing antennas, and phase synchronization is the consistency between the phases of the received frequency signals, which is time synchronization. Very long baseline interferometry is to record the signals of the two stations after mixing on the tape of each station (there is no common clock, but each station has its clock, and the time mark signal is also recorded on the tape). After the observation, the tapes of the two stations are sent to the processing system for data playback and related processing. In this way, as long as the source can be seen at the same time, the length of the baseline is virtually unlimited. The measurement method has different solutions according to different waves. First of all, the projected electromagnetic wave will be accurately reflected in the public focus. At the same time, using a rotating paraboloid as a mirror is easy to achieve in-phase focusing, so most radio telescope antennas are paraboloids. If the mean square error between the surface of a radio telescope and an ideal paraboloid is less than $\lambda/16 \sim \lambda/10$, the telescope can generally operate efficiently in radio bands with wavelengths greater than λ. The second is the observation of meter waves or long meter waves, which can be made of metal mesh mirrors; For centimeter-wave and millimeter-wave observation, a smooth and accurate metal plate (or coating) is needed as a mirror. Finally, the radio waves projected by the celestial body and concentrated at the telescope's focus must reach a certain people level before they can be detected by the receiver. The level of detection technology requires that the people's weakest level should generally reach 10 ~ 20W. The RF (Radio Frequency) signal people is first amplified 10 to 1000 times at the focal point and converted to a people frequency (intermediate frequency), and then transmitted by cable to the control room for further amplification, detection, and finally recorded, processed, and displayed in a manner suitable for a particular study.

3.2. Observation Equation

People can assume that the direction of the observed radio source (declination δ, right ascension λ) is known. The basic observation equation relating the coordinate differences (Δx, Δy, Δz) between the positions of the two radio telescopes and the observed quantity in the geocentric Cartesian coordinate system is given by: C + cosine omega delta (sin lambda - cos lambda) + = - cos the delta cos lambda - cos the delta sin lambda - sin the delta z + c (+ t), where c is the speed of light; The second term on the left is the rotation term, ω is the angular velocity of rotation, and the appropriate approximation is substituted into the calculation; Is the observation error; +t represents the part of the delay that comes from the instrument. The above formula assumes that all necessary corrections have been made, including pole shift, diurnal pole shift, precession, nutation, propagation medium, station, and tide load. Otherwise, there must be corresponding undetermined parameters in the observation equation.

The observation accuracy of the delay is very high, which has reached 0.1 milliseconds, and the corresponding distance is 3 cm. Moreover, this method is a purely geometric measurement, basically not involved, and the distance measured is only limited by the earth itself. As a result, this technique can be used to measure the entire globe with centimeter-level accuracy. The observed radio sources are quasars outside the Milky Way, very far away, their self-motion is not greater than 0.0001 "per year, the accuracy of the radio source position has been better than 0.01", but also higher, the reference coordinate system is very stable, is so far the best inertial reference system can be used. Observation is completely free from meteorological conditions and can work all day. Regarding reference frames, people can simply divide them into two categories. First, is the celestial reference system. Second, the Earth reference department. According to the principle of relativity, the position of any star in the universe needs a reference frame, and the observed data are the relative positions obtained according to the reference frame. Different observation distances have different reference systems. Generally, the observation within the solar system is based on the Earth reference system, and the observation outside the solar system is based on the celestial reference system.

3.3. Reference System

The celestial reference system is as follows:

Origin: Solar system center of mass.

Equator: J2000.0 Flat equator.

Right ascension origin: J2000.0 dynamic vernal equinox. Its establishment and maintenance are achieved through the radio source coordinate table.

The earth reference system is as follows:

Origin: Earth's center of mass.

Scale: Scale within the framework of relativity.

Direction: 1984.0 International Bureau of Time (BIH) direction.

Time change of direction: No overall rotation of the crust.

4. The Role of Radio Interferometers

Radio interference technology enables people to extract useful signals from noise more effectively, greatly improving the resolution, so that the resolution of the radio band is higher than the optical for the first time, today's radio resolution is thousands of times higher than other bands and can reveal the core of radio objects more clearly; The successful development of synthetic aperture technology makes the radio telescope to have convenient imaging ability. The synthetic aperture radio telescope is equivalent to the camera working in the radio band. For example, as early as 1920, stellar interferometers were used to measure the angular diameters of bright stars [5].

5. Conclusion

This paper has examined the fundamental principles, methodologies, and applications of radio interferometry, with a particular focus on the contributions of FAST and VLBI to the field of radio astronomy. The paper began by exploring the significance of radio telescopes, specifically FAST, which, with its unparalleled ability to detect electromagnetic signals from billions of light-years away, has set new benchmarks in radio astronomy. The study highlighted the operational mechanisms of radio telescopes, from the reception of radio waves by parabolic antennas to the processing and recording of signals.

The discussion then shifted to the principles of radio interferometry, emphasizing the technique’s reliance on wave superposition and synthetic aperture technology to achieve high-resolution imaging. By combining signals from multiple telescopes, radio interferometers can significantly improve the resolution and sensitivity of observations. VLBI, in particular, was explored as a method that allows for precise measurements of celestial objects by simulating a giant telescope with baselines thousands of kilometers apart. This technique not only enhances resolution but also plays a crucial role in the measurement of radio source locations and angular diameters.

The paper also addressed the applications and advancements of VLBI, including its use in space VLBI, which expands observational capabilities beyond Earth-based telescopes, and the integration of real-time data processing technologies such as EVLA. These developments represent significant strides toward achieving even higher resolutions and more accurate astronomical observations.

In conclusion, the advancements in radio interferometry, particularly through technologies like VLBI and the development of instruments like FAST, have had a profound impact on radio astronomy. These innovations have expanded our ability to observe and understand the universe with unprecedented clarity. As the field continues to evolve, future research should focus on further refining these technologies and exploring new applications in both theoretical and applied astronomy.

References

[1] Li Y., Li Y. China's Eye on the Universe: Brightening the View of the Cosmos. Youth Science Expo, 2021, (07): 1-3.

[2] Dian D. The Listener of the Vast Universe: China’s Eye. Children's Science & Technology, 2018, (03): 30-31.

[3] Xinhua News. Exploring the Vast Sky: China’s Eye Provides 'Chinese Wisdom' for the World Astronomy. Xinhua News, 2024, 4 (17). Accessed on 2024/8/25. Available at: http://www.news.cn/politics/20240417/94db6a6cf5004149957318e8dd0013bb/c.html.

[4] Liu F. Analysis of Influencing Factors in Interferometer Direction Finding. Wireless Interconnection Technology, 2022, 19 (07): 3-4+9.

[5] Hey J. S., Parsons S. J., Phillips J. W. Fluctuations in Cosmic Radiation at Radio Frequencies. A Source Book in Astronomy and Astrophysics, 1900–1975. Cambridge, MA: Harvard University Press, 1975: 774-776.