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Very Long Baseline Interferometry Techniques and Their Applications in Radio Astronomy Research

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Abstract. Radio astronomy plays a crucial role in advancing the understanding of space objects by utilizing radio waves, allowing us to observe phenomena and celestial bodies that are otherwise invisible when using traditional optical telescopes. This technique, called Very Long Baseline Interferometry (VLBI), combines signals from different radio telescopes to give a much clearer picture. This paper talks about how VLBI works, including how it picks up signals, measures time delays, and fine-tunes these signals. It's especially useful for taking pictures of black holes and studying space jets, and it was crucial for the Event Horizon Telescope project. The research shows that VLBI improves how well it can see space and helps us learn about extreme conditions in the universe. Although there are challenges with sensitivity and handling the data, future improvements in technology and expanding into space could help us understand the universe even better. This study gives new ideas and directions for making VLBI technology better.

Keywords: VLBI; Radio Astronomy; Black Holes; Event Horizon Telescope.

1. Introduction

Radio astronomy is a field of astronomy that focuses on observing celestial objects that emit radiation within the radio wave spectrum, making it fundamentally different from optical astronomy. It is capable of detecting objects and phenomena that are invisible with optical methods.

Pulsars are dense stars that spin rapidly, exhibiting physical conditions far beyond what can be replicated in any Earth-based laboratory. A research team led by Dr. Wang Peng and Professor Li Di from the National Astronomical Observatories, part of the Chinese Academy of Sciences, conducted an in-depth investigation into the Fermi-LAT unassociated source 3FGL J0318.1+0252. This effort led to the discovery of an extremely faint millisecond pulsar (MSP) using the FAST telescope [1]. Utilizing a radio ephemeris, a thorough analysis of a decade's worth of Fermi-LAT data revealed strong gamma-ray pulsations from PSR J0318+0253, thereby validating the discovery. This accomplishment represents the first collaboration between FAST and the Fermi-LAT team, as well as FAST's inaugural confirmation of a newly discovered MSP. Further analysis across multiple bands determined that PSR J0318+0253 is the faintest high-energy MSP identified in radio wavelengths so far, with a spin frequency of 192.68 Hz and a spin-down power of 5×10^{33} $\mathrm{erg\ s}^{-1}$. PSR J0318+0253 may exhibit a spectral turnover near 350 MHz, a rare characteristic among MSPs, which may be linked to its surrounding environment or could provide insight into its intrinsic emission processes. This finding underscore FAST's exceptional capability in pulsar detection, showcasing the remarkable potential of modern large-aperture radio telescopes [1].

Stars are approximately blackbody radiation sources, with radiation covering a relatively narrow frequency range, concentrated from ultraviolet (UV) to infrared (IR) bands, depending on the star's temperature. Therefore, most bright stars appear very faint at radio frequencies. However, radio telescopes can detect radio galaxies, pulsars, quasars, and interstellar gas, among other celestial bodies that exhibit significant radiation in radio bands, providing extensive information about the structure and evolution of the universe.

Through radio astronomy, scientists can study supernova remnants, active galactic nuclei, and star-forming regions. One key goal of radio astronomy is to locate supernova remnants (SNRs) within the

Milky Way. Although over 1,000 SNRs are estimated to exist in the galaxy, less than 400 have been discovered so far. To address this gap, scientists used the Global Star Formation View (GLOSTAR) survey and identified over 150 candidate SNRs through continuous imaging in the 4-8 GHz range by the Very Large Array (VLA). The research methods included measuring the total flux density and linear polarization flux density of the candidate SNRs and determining their spectral indices through spectral analysis. Results indicated that three out of four candidate non-thermal sources were confirmed as SNRs [2].

This not only complements optical astronomy but also reveals many cosmic phenomena that are difficult to detect in other bands, greatly enriching the understanding of the universe [1]. The radio window spans wavelengths from 1 mm to 60 m, which is much larger than the optical window and contains more cosmic information. Electromagnetic radiation emitted by various celestial bodies at different wavelengths contains different physical information, such as the temperature, state, structure, composition, and evolution of these bodies [3].

Very Long Baseline Interferometry (VLBI), a radio interferometric technique used in radio astronomy, processes observational signals from different astronomical telescopes through a correlator, forming a virtual radio telescope with a diameter equivalent to the distance between multiple telescopes [4, 5].

The Atacama Large Millimeter/submillimeter Array (ALMA) is made up of 66 radio telescopes and is located in the high Atacama Desert of northern Chile. Sitting at 5000 meters (about 16,000 feet) above sea level, this location is ideal for observing the universe because it's above much of the Earth's atmosphere which can block certain signals.

ALMA is amazing for astronomers because it helps them see very detailed views of stars and galaxies being formed, explore the center of the galaxy, and even watch planets forming around other stars. It works by catching light that is between radio and infrared wavelengths, which is a type of light that's hard to detect because water vapor in the air absorbs it. The dry air and high altitude where ALMA is located let it pick up these faint signals from space [6].

The array consists of multiple antennas, including 54 with a diameter of 12 meters (39 feet) and 12 with a diameter of 7 meters (23 feet). All these antennas combined cover more than 6600 square meters (71,000 square feet). They can be moved around to different positions, which allows astronomers to either focus in closely for more detail or spread out for a wider view [6].

There's also a special part of ALMA called the Atacama Compact Array (ACA), which has 12 smaller antennas and four larger ones. This part is used for taking pictures of big things in space, like huge clouds of gas. It can be adjusted to get a better view of objects that are way up north or down south in the sky [6].

The clarity of the images ALMA can get depends on how the antennas are set up and what kind of light they're looking at. When the antennas are placed close together, they can see fine details at certain wavelengths; when they're spread far apart, they can zoom in even more to see very small features in space [6].

2. Very Long Baseline Interferometry (VLBI)

2.1. Components of VLBI

The Very Long Baseline Interferometry system primarily consists of antennas, receivers, data recording terminals, atomic clocks, a time synchronization system, and associated processing systems. Electromagnetic wave signals from radio sources are focused onto the antenna feed by a parabolic reflecting antenna surface, where they are converted into high-frequency electrical signals and transmitted to the receiver. The receiver amplifies these high-frequency signals and mixes them down to intermediate-frequency baseband signals, enabling them to be recorded on data recording terminals. Atomic clocks provide a high-frequency and highly stable frequency reference, offering precise recording times for the data, while the time synchronization system ensures that different sources of time are compared to a uniform standard time. The correlator processes and analyzes the recorded observational signals, obtaining interferometric images, differences in time delays between signals, and rates of time delay.

Traditional radio interferometers use a common local oscillator and real-time correlation processing, thus requiring electrical connections between units. VLBI overcomes the limitations brought about by the necessity of electrical connections in traditional radio interferometers. Each unit in VLBI uses its independent local oscillator, with a highly stable hydrogen maser signal serving as the frequency standard. The intermediate frequency signals of each unit are converted to baseband signals, then digitized and recorded on magnetic tape for post-correlation processing. On Earth, the maximum distance between VLBI units can reach the diameter of the Earth (13,000 km). If VLBI units are launched into space (as in space VLBI), the distance between units can be further increased to tens of thousands of kilometers or even more.

2.2. Physical Principles

Achieving higher angular resolution is a key goal in contemporary observational astronomy, as it enables a more detailed understanding of the structures of astronomical objects. Across all wavelengths of electromagnetic radiation, angular resolution (often termed "beam size" in radio astronomy and "diffraction limit" in optical astronomy) is determined by Equation (1):

$$\theta \approx \frac{\lambda}{D} \tag{1}$$

In this context, θ represents the minimum angle that the telescope can distinguish, λ corresponds to the wavelength of the electromagnetic waves being observed, and D denotes the telescope's diameter. To attain a higher angular resolution at a specific wavelength λ, a larger telescope is required. Nevertheless, building larger telescopes poses significant technological and financial challenges, and there are practical limitations to the size of a single telescope [5].

Interferometry offers an alternative approach to achieving high angular resolution by simulating a large telescope that cannot be constructed as a single unit (Fig. 1). Within the entire electromagnetic spectrum, radio interferometry has effectively created a synthesized telescope of considerable size [7].

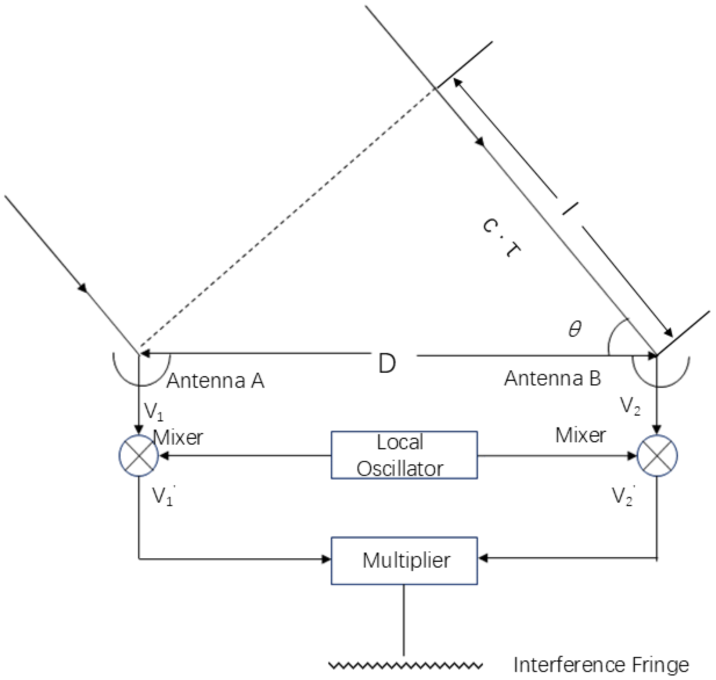

Figure 1. Diagram of Signal Reception and Processing.

The radio sources measured by VLBI are very distant from Earth, and the electromagnetic waves they emit can be approximated as plane waves. In an ideal state, the true value of the time delay difference τ, the baseline vector $\vec{b}$ formed by two antennas, and the angle θ between the direction of the radio source and the baseline can form the observation equation, Formula 1:

$$\tilde{\tau} = \frac{1}{c}|\vec{b}| \cos\theta \tag{2}$$

Formula 1. In an ideal state, the observation equation is formed by the true value of the time delay difference τ, the baseline vector $\vec{b}$ formed by two antennas, and the angle θ between the direction of the radio source and the baseline. c is the speed of light.

Since the distance from the radio source to Earth is much greater than the length of the baseline, the radio source's waves are almost parallel when entering both telescopes, thus θ is nearly the same for both telescopes [4].

2.3. Calibration Techniques

Due to the different locations of antennas, calibration is necessary. By measuring the same deep-space radio source, the distance and direction between two telescopes can be determined with high precision. The distance between the telescopes is determined by the time delay difference of the radio signals reaching the antennas of both telescopes, while the direction between the telescopes is determined by the angle between them and the direction of the radio source. During calibration, various factors such as bandwidth, integration time, antenna aperture and efficiency, antenna noise temperature, receiver noise temperature, signal-to-noise ratio, and the position and flux density of the radio source are considered to select the appropriate radio source for observation [8].

Different positions of antennas lead to geometric delays, and atmospheric conditions as well as observational equipment also affect measurements.

Moreover, in very long baseline interferometry, link delays caused by cables and frequency converters are among the important errors, so they need to be calibrated to obtain the true geometric delays. Current calibration techniques involve injecting equidistant point frequency signals, i.e., phase calibration signals, into the front-end receiver. During correlation processing, the phase of the phase calibration signal is extracted, and by calculating the group delay variation curve, accurate link delays can be obtained for calibration. In general, in VLBI observations, only the relative changes in link delays are of concern, and absolute link delays are eliminated through differential observations. Calibrating absolute link delays helps eliminate errors and enhance accuracy, and precise measurements of UT1, station clock offsets compensation, and maintenance diagnostics also require calibration of absolute link delays.

3. Application

VLBI plays a crucial role in the observation of black holes. Firstly, through the Event Horizon Telescope (EHT), VLBI technology achieved unprecedented resolution, successfully capturing the first image of the supermassive black hole at the center of the M87 galaxy. This accomplishment not only provided a direct observation of the black hole's shadow and its surrounding accretion disk structure but also served as important evidence in validating Einstein's theory of general relativity [9].

The EHT is a network of radio telescopes distributed across the globe. By combining data from multiple VLBI stations worldwide, the EHT project creates a unified array with an angular resolution capable of observing objects as small as the event horizons of supermassive black holes. The observational targets of this project include the two black holes with the largest apparent angular diameters as seen from Earth: the black hole at the core of the supergiant elliptical galaxy Messier 87, and Sagittarius A* located at the center of the Milky Way galaxy [9].

Additionally, VLBI is employed to investigate the intricate details of black hole jets, utilizing high-resolution imaging to resolve the relativistic jets surrounding black holes and to uncover their physical mechanisms and dynamic processes. Ground-based millimeter-wave VLBI is capable of detecting the shadows of the two supermassive black holes, Sagittarius A* and M87. Incorporating smaller telescopes in space into the array could enhance the overall resolution and fidelity of the images produced, which may be pivotal in understanding why some black holes generate powerful jets while others do not. At the same time, achieving higher-resolution imaging of M87’s underlying structure could provide insights into the initial stages of jet formation.

The additional resolution provided by space VLBI will also improve the study of jet collimation in active galactic nuclei [10]. VLBI technology has played a key role in resolving black hole accretion processes, enabling observation of accretion disks and accretion flows near black holes, and studying the dynamics of matter near black holes. These applications not only deepen the understanding of black holes but also provide important observational data and theoretical support for astrophysical research [10].

4. Conclusion

This paper discusses VLBI, a technique used in radio astronomy to study space. It explains how VLBI works, including how it picks up signals, measures the time it takes for these signals to travel, and adjusts the system to get clearer images. The paper highlights VLBI's importance in creating high-quality images of space, studying black holes, and analyzing the jets that come from these black holes. It also talks about how VLBI played a key role in the Event Horizon Telescope project, which managed to take the first-ever picture of a black hole and helped us learn more about these massive space objects.

The paper concludes that VLBI is crucial for radio astronomy as it enhances the clarity of space observations and aids in studying extreme space phenomena like black holes. However, it also points out challenges, such as the difficulty in capturing very weak space signals and the complexity of data handling and synchronization during observations from different locations. The paper suggests that future research should focus on improving VLBI’s sensitivity and precision, possibly extending its use into space for even better results. It hopes that these advancements will lead to more discoveries and further the development of radio astronomy.

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