

Astronomical Intensity Interferometry

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Abstract: The development of astronomy relies heavily on advances in high-resolution imaging techniques. With the growing demand for high-resolution astronomical observations, conventional optical interferometry has gradually revealed various limitations, especially in coping with atmospheric phase fluctuations and long baseline observations. However, intensity interferometry is becoming an important method to overcome these challenges due to its high robustness to atmospheric phase fluctuations and its excellent performance in long-baseline observations. In this paper, the basic principles and key technologies of intensity interferometry are systematically described, and the remarkable potential of this technique for improving angular resolution and detection sensitivity is comprehensively discussed in light of the recent advances in modern photon detector and signal processing techniques. The results show that the intensity interferometry technique is capable of realizing high-precision observation of long-range and low-brightness targets, especially in the field of exoplanet detection, which shows a wide range of application prospects. In the future, with the continuous development of telescope arrays and adaptive optics, the intensity interferometry technique is expected to further promote the precision and breadth of astronomical observations, and provide new opportunities for revealing the mysteries of the universe.

Keywords: intensity interferometry; astronomy; high-resolution observations; photon detection; angular resolution; exoplanet detection



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1. Introduction

Advances in imaging techniques with higher spatial resolution have driven the development of photonics. Optical imaging techniques with microarcsecond resolution reveal the fine structure of the surface of the source and its surroundings and enable detailed observations of exoplanets and their atmospheric features, as well as the complex dynamics and material distribution of active galactic nuclei. The application of these techniques to studies exploring habitable planets and extraterrestrial life outside our solar system has become a central frontier of modern photonics. Since the first exoplanet was discovered by astronomers using the radial velocity method in 1995 [1], over 5500 exoplanets have been discovered to date [2]. Currently, Kepler [3–5] and TESS [6], which are based on the transit method, and the recently launched PLATO [7], ARIEL [8], and LUVOIR [9] exploration missions are being implemented. Additionally, the CSST coronagraph [10], which utilizes the direct imaging method for detection and the Euclid [11] and ROMAN [12] projects, which use the gravitational microlensing method, have been employed in exoplanet detection. However, the current exoplanet detection methods still face several challenges in accurately measuring the mass, orbital parameters, and direct imaging of exoplanets. These detection methods often encounter limitations due to optical interference, optical path

differences, and atmospheric turbulence when detecting distant targets and weak signals, making it difficult to achieve high-resolution observations. Therefore, the resolution must be improved to enhance the ability to capture weak signals.

Achieving such high resolution usually requires constructing interferometers with baseline lengths of several kilometers. Although amplitude interferometry has made remarkable achievements in astronomical observations over the past decades [13–15], its high stability requirements hinder the construction of telescope arrays with kilometer-long baselines, a key to achieving microarcsecond imaging [16]. Furthermore, combining long baselines and short wavelengths makes it difficult to precisely control the optical path difference in amplitude interferometry. Therefore, scientists have explored a more robust technical approach—intensity interferometry (II), which is insensitive to atmospheric phase fluctuations and has efficient observation capabilities over long baselines, solving these problems.

The research background and origin of II can be traced back to the combination of quantum and classical theories. Quantum theory was proposed by Roy Glauber, while the early classical theory was first described by Robert Hanbury Brown and Richard Q. Twiss in 1952 [17]. II was initially proposed to accurately determine the angular diameter of stars. The technique essentially used the correlation of photon intensities received by two independent detectors, overcoming the limitations of conventional optical interferometers regarding atmospheric perturbations and mechanical stability. Thus, II significantly improves the accuracy of astronomical measurements, providing a crucial observational tool for modern astronomy.

As quantum optics and photon statistics rapidly develop, scientists have begun to extensively examine the quantum properties of light and the correlations among photons. In 1956, Hanbury Brown and Twiss first verified the correlation phenomenon between photons in two coherent light beams through a pioneering experiment, which provided strong experimental support for the quantum theory of light [18]. In the experiment, the coherent light beams were separated and subsequently recombined. Photodetectors were used to accurately record the arrival times of photons, thereby measuring the temporal correlation between the photons. The success of this experiment spearheaded photon correlation studies and inspired a series of important subsequent experiments. Subsequently, Hanbury Brown and Twiss designed and built the Narrabri Stellar Intensity Interferometer (NSII) in Australia. The setup was equipped with two 6.5 m-diameter telescopes. The telescopes were mounted on a 188 m-diameter circular orbit and could be moved freely along the orbit to ensure that signals could be sent promptly and maintain a fixed baseline while tracking stars over long periods [19]. In 1974, Hanbury Brown successfully measured the angular diameters of 32 stars using NSII, achieving a measurement accuracy of less than 0.4 milliarcseconds. This precision significantly improved over previous measurements and provided important observational data for further research on stellar physics [20].

Although the II technique has important application prospects in astronomical observation, its development is constrained by its detector performance and signal processing system capability, leading to significant deficiencies in the frequency bandwidth and signal sensitivity. Recent advancements in photonic detectors [21] and modern signal processing techniques [22,23], as well as the development of large-scale light collectors (e.g., the Cherenkov telescope array (CTA) [24]), have renewed interest in the astronomical applications of II. The sensitivity of intensity interferometers can be significantly enhanced to enable observations with higher angular resolution by utilizing modern photonics techniques.

With the development of astronomy, especially the increased demand for high-resolution observations, traditional interferometric techniques face many challenges. This study systematically explores the applications of II in modern astronomy, particularly its potential for exoplanet detection. By combining recent technological advances and examples from various astronomical projects, we demonstrate how II can overcome the limitations of traditional techniques and provide new solutions for future high-precision astronomical observations.

2. Principles of Intensity Interference

Intensity interference is an advanced technique that connects multiple optical telescopes or photon collectors electronically to measure intensity fluctuations of celestial light for high-resolution image reconstruction [25]. As illustrated in Figure 1, multiple telescopes with segmented primary mirrors are linked together, forming an array where the interference baselines among the telescopes enable precise measurements of the light intensity. The technique utilizes the second-order correlation property of light intensity to achieve intensity interference in the system, avoiding the use of delay lines through timestamps formed during the detection process [26]. The basic working principle covers several complex and highly coordinated steps, which include key stages from photon acquisition [27] and signal processing [28] to aperture synthesis [29]. In these stages, various optical elements first collect photon signals from celestial objects and convert them into usable interferometric data. The interferometric data are then subjected to sophisticated mathematical processing and integration, ultimately generating high-resolution astronomical images.

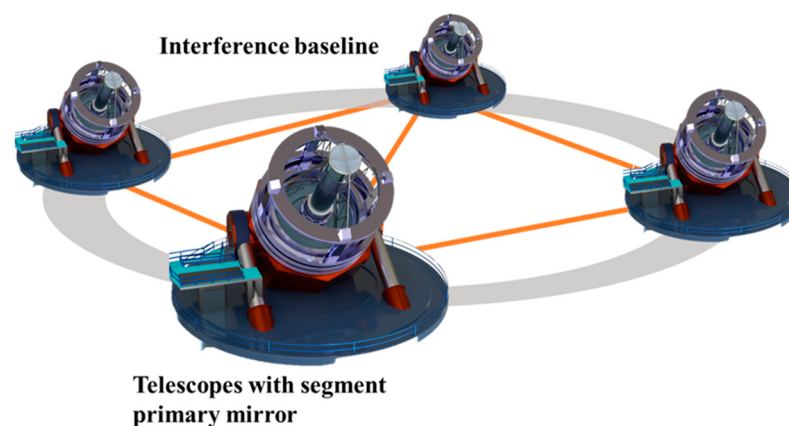


Figure 1. Intensity interferometry system.

2.1. Photon Acquisition and Signal Processing

Hanbury Brown and Twiss [30,31] showed that hot light sources (such as stars) exhibit aggregated signals of photons on short baseline or time scales. This idea was later popularized by Glauber [32] as the second-order correlation function $g^{(2)}$:

$$g^{(2)}(\tau, b) = 1 + e^{-2|\tau|/\tau_c} |\gamma(b, l_c)|^2. \quad (1)$$

where τ is the detection time difference, τ_c is the coherence time of the light source, γ is a complex spatial coherence function dependent on the spatial separation b between detectors, and l_c is the effective spatial coherence length of the light source. This correlation, which is characterized independently of the optical phase of the light, is the basis for intensity interferometry and is insensitive to first-order noise. The spatial correlation $g^{(2)}(\tau = 0, b)$ provides insights into the physical shape and intensity distribution of the light source. On the other hand, the temporal correlation $g^{(2)}(\tau, b = 0)$ sheds light on the emission mechanism of the source, helping to distinguish between coherent sources, like laser light, and incoherent sources, like thermal light [33].

First, multiple telescopes observe the same light source simultaneously, each equipped with a highly sensitive photon detector. Each detector records the light intensity signals from the target celestial object and transmits them to the signal processing unit to perform time cross-correlation calculations. The light intensity signal measured by each detector is a time-averaged product of the amplitude of the electromagnetic wave and its complex conjugate, expressed as

$$\langle I(t) \rangle = \langle E(t)E^*(t) \rangle, \quad (2)$$

where $I(t)$ is the optical intensity, $E(t)$ is the electric field strength, $E^*(t)$ denotes the complex conjugate of the electric field intensity, and $\langle \cdot \rangle$ denotes averaging over time.

A basic dual-telescope intensity interferometer is described in detail in this study. The device consists of two optical telescopes, each equipped with a photon detector. The light intensity signals measured by Detectors 1 and 2 are analyzed through cross-correlation calculations:

$$\langle I_1(t)I_2(t) \rangle = \langle E_1(t)E_1^*(t) \cdot E_2(t)E_2^*(t) \rangle. \quad (3)$$

When dealing with chaotic light (i.e., light with a Gaussian amplitude distribution), both the real and imaginary parts of the light intensity signal are Gaussian random variables, following the Gaussian moment theorem [34,35]. This property allows all higher-order correlations of a Gaussian variable to be expressed as a product of its lower-order correlations [36]. An important overlooked point in the above equation is that, generally, the complex electromagnetic fields E do not commute. Therefore, in the general case, the order of the terms cannot be rearranged. In the case of chaotic light, however, the cancellation of cross-terms between random relative phases allows this reorganization [37]. Thus, for linearly polarized light [38], the cross-correlation function of the light intensity measured by the intensity interferometer can be expressed as follows:

$$\langle I_1(t)I_2(t) \rangle = \langle I_1 \rangle \langle I_2 \rangle + |\Gamma_{12}|^2, \quad (4)$$

or

$$\langle I_1(t)I_2(t) \rangle = \langle I_1 \rangle \langle I_2 \rangle (1 + |\gamma_{12}|^2), \quad (5)$$

where $|\Gamma_{12}|^2$, the second-order correlation function, corresponds to $\langle I_1 \rangle \langle I_2 \rangle |\gamma_{12}|^2$, γ_{12} represents the mutual coherence function between the positions of the two telescopes, and $|\gamma_{12}|^2$ represents the square of its mode. This cross-correlation between E_1 and E_2 is as follows:

$$\Gamma_{12}(\tau) = \langle E_1(t + \tau)E_2^*(t) \rangle. \quad (6)$$

Or, for greater clarity, with respect to the integration time T :

$$\Gamma_{12}(\tau) = \frac{1}{T} \int_0^T E_1(t + \tau)E_2^*(t)dt. \quad (7)$$

It is important to note that if $E_1(t + \tau)$ and $E_2(t)$ are uncorrelated, the integral will approach zero as T increases; however, this behavior will not hold true if they are correlated.

Furthermore, by defining the intensity fluctuation ΔI as

$$\begin{aligned} \Delta I_1(t) &= I_1(t) - \langle I_1 \rangle \\ \Delta I_2(t) &= I_2(t) - \langle I_2 \rangle \end{aligned} \quad (8)$$

we obtain the expression for the correlation between intensity fluctuations:

$$\langle \Delta I_1(t)\Delta I_2(t) \rangle = \langle I_1 \rangle \langle I_2 \rangle |\gamma_{12}|^2. \quad (9)$$

In this context, $|\gamma_{12}|$ represents the classical visibility, defined as the ratio of the difference between the minimum and maximum intensities $I_{\max}$ and $I_{\min}$ in an amplitude interferometer:

$$V = |\gamma_{12}| = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \quad (10)$$

This visibility thus ranges from 0, indicating complete destructive interference fringes, to 1, which occurs when $I_{\min} = 0$.

Note that the $|\gamma_{12}|^2$ measured by the intensity interferometer is always positive. However, because the temporal resolution of the electronics in practical operations is consider-

ably lower than the optical coherence time, the signal is diluted, making the measurable correlation extremely small. Therefore, highly precise photon statistical techniques must be employed with large-area photon flux collectors to obtain reliable measurement results [39].

2.2. Optical Aperture Synthesis

Optical aperture synthesis is a high-resolution imaging technique that integrates observational data from multiple telescopes to reconstruct images of celestial objects. This method simulates a larger aperture virtual telescope through the combined observations of multiple telescopes, precisely capturing the target object. This technique is similar to interferometry in radio astronomy [40,41] in the sense that both rely on baselines, i.e., distance vectors between the telescopes. By measuring the interference signals along these baselines, the Fourier transform components of the brightness distribution of the target source's surface can be obtained. These components are inverted and synthesized, resulting in a highly accurate image of the object [42]. This method significantly improves the spatial resolution and overcomes the limitations imposed by the aperture of a single telescope, making it a crucial tool in modern astronomical research [43–45].

For the two telescope locations r_1 and r_2 , the electric field strengths are $E(r_1)$ and $E(r_2)$, respectively. Their coherence function Γ_{12} is defined as

$$\Gamma_{12} = \langle E(r_1)E^*(r_2) \rangle, \quad (11)$$

where $\langle \cdot \rangle$ denotes time averaging, and $E^*(r_2)$ denotes the conjugate complex of $E(r_2)$.

According to the Van Cittert–Zernike theorem [46–48], the coherence function $\Gamma(u, v)$ at a given baseline is part of the Fourier transform of the surface intensity distribution of the light source $I(l, m)$:

$$\Gamma(u, v) = \iint I(l, m)e^{-2\pi i(ul+vm)} dldm, \quad (12)$$

where (l, m) is the angular coordinate position of the target, and (u, v) is represented by the projection of the separation vector $r_1 - r_2$ between the telescope pairs onto the vertical plane of the observation line, for optical wavelengths λ , $r_1 - r_2 = (u\lambda, v\lambda)$.

By sampling the (u, v) plane by interferometry at multiple baselines and orientations, the image of the light source can be reconstructed. The resolution of the reconstructed image is equivalent to that of a virtual telescope with a diameter equal to the longest baseline. The Fourier inversion is expressed as

$$I_v(l, m) = \iint V(u, v)e^{2\pi i(ul+vm)} dudv. \quad (13)$$

where $V(u, v)$ is the normalized value of $\gamma(u, v)$.

Fourier inversion ensures that a continuous image is recovered from discrete frequency-domain data. The accuracy of this process relies on the density of coverage in the (u, v) plane and the quality of the observational data. During the observation process, the layout of the telescope array and the motion of the celestial objects affect the degree of coverage of the (u, v) plane, which affects the final image's resolution and clarity. For large telescope arrays, such as the CTA, high-density coverage of the (u, v) plane can be achieved through numerous telescopes and prolonged observations, resulting in high-quality image reconstruction [49].

2.3. Comparison of Intensity Interferometry with Other Interferometric Techniques

Interferometric techniques in astronomy play an important role in improving imaging resolution. Due to the fluctuating nature of light, the resolution of optical imaging is limited by the diffraction limit. Especially in the case of direct imaging, the Abbe diffraction limit will limit the maximum resolution of the telescope [50,51]. To break through this limit, scientists have proposed a variety of interferometric techniques, mainly including amplitude interferometry [52] and intensity interferometry. Traditional amplitude interferometry

(e.g., very long baseline interferometry, VLBI [53]) relies on phase coherence among multiple telescopes, and although it can achieve very high angular resolution, its application is limited in the optical band due to the difficulty of keeping the phase information stable [54]. Intensity interferometry, on the other hand, relies on the correlation of photon intensities without the need for phase synchronization, and thus has the advantage of being easier to operate under large baseline conditions.

Rotondo [55], in 2004, pointed out that intensity interferometry can achieve high-precision astronomical observations without the need for precise phase synchronization and has great potential for application, especially under large baseline conditions, but detector sensitivity and signal processing capabilities still need to be improved due to the limited signal strength. On this basis, Bojer et al. [56], in 2022, conducted a quantitative comparison between intensity interferometry and amplitude interferometry, especially analyzing their performance in solving the small-angle stellar separation problem. Their study found that, despite the weaker intensity interferometry signal, its larger numerical aperture was able to compensate for the lack of signal in astronomical observations of very small angular separations (e.g., in the problem of the angular separation of neighboring stars) and even outperformed amplitude interferometry in large baseline conditions, making it suitable for ultra-high resolution observing tasks. With advances in detector technology, the signal processing efficiency of intensity interferometry has improved significantly, bringing it back to prominence as an important tool in astronomy. A comparative analysis of the two techniques provides a clearer understanding of their respective strengths and limitations and reveals the great potential of intensity interferometry for future applications in astronomy. Table 1 summarizes the performance of amplitude interferometry, intensity interferometry, and aperture synthesis techniques in astronomy.

Table 1. Comparison of different interferometry techniques.

Technique	Advantages	Disadvantages	Resolution	Representative Achievements
Amplitude Interferometry	Achieves high resolution through phase synchronization; especially effective in radio wavelengths and for weak signal detection (e.g., VLBI).	Requires precise phase synchronization; especially challenging in optical wavelengths due to atmospheric and instrumental instabilities.	High resolution, but limited in optical wavelengths due to phase synchronization issues.	VLTI, Keck Interferometer, LBTI
Intensity Interferometry	Does not rely on phase information; suitable for large baselines and high-frequency optical wavelengths; modern detector technology enhances signal processing efficiency, especially for high-angular-resolution observations.	Weaker signal, particularly under low photon flux conditions; limited by photon degeneracy effects; less advantageous for short baselines.	Achieves very high resolution under large baseline conditions, especially effective for small angular separations.	NSII, CTA, AGIS
Aperture Synthesis	Combines multiple telescopes into an effective aperture, simulating a large telescope to achieve extremely high angular resolution (e.g., EHT).	Requires complex synchronization and data processing; expensive infrastructure; especially challenging for high-frequency and precise calibration tasks.	Extremely high resolution, scalable with baseline length, ideal for imaging extreme astronomical objects.	VLA, ALMA, LBTI, VLBI

Although intensity interferometry techniques have shown shortcomings in some scenarios, their potential in the high-frequency band and at large baselines cannot be ignored. With the advancement of detector technology and the optimization of signal processing algorithms, intensity interferometry is expected to play a more important role in astronomical imaging missions. Meanwhile, the possibility of combining amplitude interferometry with intensity interferometry can be further explored in the future to complement its strengths to meet the needs of different observation missions.

3. Key Technologies of II

3.1. Design of the System Baseline

Improving the spatial resolution of astronomical telescopes is key to exploring celestial objects' morphology and internal structure details. According to the Rayleigh criterion [57,58], the spatial resolution θ can be defined as $\theta = 1.22\lambda/D$. This indicates that the resolving power θ of an optical system depends on the wavelength of light λ and is limited by the aperture size D of the system. Therefore, increasing the aperture of the telescope directly improves the resolution of the system [59–61]. However, the actual angular resolution of the telescope is constrained by the cost and feasibility of technical implementation. Additionally, the perturbations caused by atmospheric turbulence on telescope observations significantly limit their performance [62]. The angular resolution often fails to surpass the limit of atmospheric seeing, thus restricting the aperture of the telescope from being infinitely large. To overcome these limitations, modern astronomy employs optical interferometry to improve the spatial resolution of telescopes through aperture synthesis interferometry (ASI) [63,64]. In optical interferometry, the baseline length—the maximum separation distance between two or more telescopes—determines the system's resolution. The longer the baseline, the higher the resolution of the system, which can overcome the limitations of a single telescope aperture and achieve higher observational accuracy.

In advanced astronomical research, the baseline configuration of the telescope array ensures the performance and observational capability of the optical interferometric system [65]. The baseline design directly affects the system's resolution and determines the flexibility of the telescope array, the diversity of observational targets, and the accuracy of the data [66]. The different lengths and configurations of baselines in the telescope arrays have their own unique functions and effects [67,68]: the long baseline design enables the telescope to capture finer celestial details by significantly increasing the spatial resolution, whereas the short baseline optimizes the sensitivity and responsiveness of the system, contributing to the efficient observation of celestial structures on larger scales. Moreover, the flexibility and diversity of the baselines determine the adaptability of the telescope arrays in response to different observational objectives and scientific requirements. By optimizing the baseline design, astronomers can achieve higher-quality observations in different bands and observing conditions [69].

The classical Narrabri intensity interferometer system comprises two telescopes with a 6.5 m diameter, enabling accurate measurements in the order of a few milliarcseconds [70]. The NSII's baseline configuration of up to 188 m allows it to be used primarily to measure the angular diameters of stars, especially those with high brightness. In addition, the system effectively withstands wavefront aberrations caused by atmospheric turbulence by measuring the correlation of light intensity rather than phase information. Modern Cherenkov telescope arrays [71–73], such as VERITAS [74], HESS [75,76], and MAGIC [77], despite focusing primarily on gamma-ray astronomy rather than the traditional fields of optical or infrared astronomy, can still be adapted for intensity interferometry with high sensitivity and high temporal resolution through different array designs and baseline layouts (Table 2). The very energetic radiation imaging telescope array system (VERITAS) consists of four 12 m-diameter telescopes distributed over a range of about 100 to 200 m with a flexible baseline layout. Although VERITAS does not directly measure phase, it can achieve high-precision intensity interferometry by analyzing variations in light intensity observed across its complex array of telescopes. By studying the spatial correlations of

these intensity variations, VERITAS can provide insights into the source structure with high temporal accuracy. The high-energy stereoscopic system (HESS) includes four imaging atmospheric Cherenkov telescopes (IACTs) with a baseline length of 120 m. The multi-telescope array structure of HESS equipped with highly sensitive photomultiplier tubes (PMTs) allows it to perform intensity interferometry by capturing and comparing intensity fluctuations rather than direct phase measurements. This enables the high-resolution exploration of astrophysical sources through intensity correlations. Similarly, the major atmospheric gamma imaging Cherenkov (MAGIC) telescopes, with their two 17-m mirrors separated by an 85 m baseline, are well-suited for intensity interferometric observations. Their high temporal resolution and photon count rate make them particularly effective for detecting and analyzing the spatial structure of gamma-ray sources. These capabilities demonstrate the potential of Cherenkov telescope arrays to contribute significantly to the field of intensity interferometry, despite their primary focus on gamma-ray detection.

Table 2. Technical parameters of the main telescope arrays.

Abbreviation	Number of Apertures	Aperture Diameter	Longest Baseline
NSII	2	6.5 m	188 m
VERITAS	4	12 m	109 m
HESS	4	10.4 m	120 m
MAGIC	2	17 m	82 m

3.2. Photon Collection

3.2.1. Telescopes and Optical Systems

In astronomy, it is crucial for capturing weak celestial signals, and its accuracy depends on the photon flux's magnitude. To effectively reduce statistical noise, higher photon fluxes that typically require telescopes with large apertures are necessary. Thus, using small telescopes for II appeared impractical because of their limited flux collection capacity (the 6.5 m flux collector used by NSII was already larger than any other optical telescope at the time [70]). Moreover, the key to constructing large-intensity interferometers is the deployment of multiple large telescopes or optical flux collectors distributed over several square kilometers. This distributed configuration expands the area over which the signal is received and enhances the ability of the device to capture weak photon streams, thereby improving measurement accuracy and efficiency.

The Cherenkov telescope array (CTA) [78,79] is a new generation of high-energy gamma-ray observatories. It consists of multiple large reflectors equipped with highly sensitive photodetectors that capture the faint Cherenkov radiation produced by gamma rays interacting with the atmosphere and convert it into analyzable electronic signals. To enable effective interferometric observations, these telescopes are distributed over several hundred meters, forming an extensive interferometric baseline. The layout of the CTA is meticulously designed to optimize the collection area and sensitivity required for such large flux collector arrays. The entire CTA network spans several square kilometers, with maximum distances between the telescopes reaching up to two or three kilometers, providing a substantial baseline for realizing high-resolution intensity interferometry.

When observing at short optical wavelengths, the CTA can achieve high-precision intensity interferometry with spatial resolutions approaching 30 microarcseconds (μas). This capability allows the CTA to resolve finer details of astronomical objects than traditional telescopes, showcasing its potential for groundbreaking research in optical stellar astronomy [80]. In 2007, S. Le Bohec et al. [81] demonstrated the feasibility of applying intensity interferometry in modern very-high-energy gamma-ray observatories using VERITAS (Figure 2). VERITAS is configured with four 12 m-diameter imaging atmospheric Cherenkov telescopes (IACTs) with baseline lengths ranging from 34 to 109 m, providing numerous independent interferometric baselines. This configuration enabled initial tests

of intensity interferometry at gamma-ray observatories, laying the groundwork for future experiments. On this basis, in 2020, Abeysekara et al. [60] successfully solved the problem of the high optical path accuracy requirements of conventional optical amplitude interferometry (OAI) by II using VERITAS. They measured the angular diameters of ϵ Orion and β Canis Major with results of 0.631 ± 0.017 mA sec and 0.523 ± 0.017 mA sec, respectively, which not only agree with the NSII results of the 1960s but also drastically reduce the observation time. The II technique is more efficient than OAI because it does not require complex optical path control and can utilize multiple telescopes to obtain multiple baseline data. Although the sensitivity is still insufficient in observing faint stars and is interfered by background light, it is expected to be further enhanced by improvements in the future and extended to large arrays such as the CTA.



Figure 2. The VERITAS array [60].

In addition, in 2024, Abe et al. [82] upgraded the MAGIC-II system to utilize a four-channel real-time GPU-based correlator to successfully measure the angular diameters of 22 stars in the 425 nm band, including 9 stars for which measurements were available and 13 stars for which no measurements had been made. The system demonstrated an accuracy comparable to the existing optical interferometers, while offering great operational flexibility and efficiency. It was shown that by further incorporating the CTA, the measurement sensitivity could be significantly improved over a longer baseline range, providing a new tool for high-resolution imaging in astronomy. However, the system still faces signal-to-noise and sensitivity challenges in detecting fainter targets, and further hardware performance enhancement is needed. Although there is still room for improvement of the current intensity interferometry technique in terms of hardware performance and measurement sensitivity, its application in modern astronomical equipment, such as the CTA, has demonstrated great potential and paved the way for a wide range of future applications in astronomical observations.

3.2.2. Detectors

In II, detector performance is a key factor in determining measurement accuracy. Detectors with high efficiency and fast response characteristics can not only reduce the dependence on large aperture mirrors, but also significantly improve the data acquisition speed. Photomultiplier tube (PMT), as a mature detector technology, realizes high-gain photon amplification based on the photoelectric effect and secondary electron emission, which is particularly suitable for use in low-light environments. In optical astronomy, focal plane cameras in Cherenkov telescopes are often equipped with numerous PMTs as optical “pixels”. These detectors and subsequent electronics are optimized for triggering and recording weak transient Cherenkov light. In contrast, II requires only one pixel, and in some telescopes (such as HEGRA [83] and MAGIC [84]), the central camera pixel is specifically designed to support experimental requirements, with its function unaffected by other pixels. However, although PMTs possess high gain in excess of 10^6 and fast response on the nanosecond scale, their quantum efficiency is relatively low, typically not exceeding

30%. In II technology, the quantum efficiency directly affects the sensitivity of the system, so optimizing the detector design becomes one of the key tasks to improve the II accuracy.

In order to make up for the lack of quantum efficiency of PMT, new detection technologies, such as the Geiger-mode avalanche photodiode (G-APD) [85] and single-photon avalanche diode (SPAD) [86], have been gradually introduced into II applications. The G-APD not only maintains the high gain and broadband characteristics similar to those of PMT, but also achieves a quantum efficiency of about 60%, which is far better than that of the traditional PMT. This high efficiency makes the G-APD significantly improve the detection sensitivity under low-light conditions, especially in scenarios that require long time accumulation of signals in II technology, and the G-APD is better able to capture the weak light intensity changes. In addition, the G-APD has a lower noise level, which is also an important advantage for it in II applications. Similar to the G-APD, SPAD technology has made significant progress in recent years in improving the sensitivity and time resolution of photodetectors. The SPAD is capable of operating with high reverse bias close to the avalanche breakdown voltage, which enables single-photon-level detection capability with a time resolution at the picosecond level. This excellent time resolution makes the SPAD outstanding for II experiments that require high-precision time resolution [87]. Combined with a modern time-to-digital converter (TDC), the SPAD can achieve millions of counts per second, opening up new possibilities for highly time-resolved II applications.

Meanwhile, the design and optimization of avalanche photodiodes (APDs) in recent years have further advanced the development of II technology. Wang and Mu et al., in 2022, further enhanced the performance of APDs in II technology by optimizing their structures and materials. Their proposed silicon–germanium material-based APD achieved a gain-bandwidth product of 845 GHz by employing a SACM structure and a nonlocal field model, successfully solving the tradeoff between bandwidth and noise. This design not only reduces the noise, but also enhances the sensitivity of the detector, making it more widely used in II technology, especially in the scenarios of multi-channel detection and high-precision measurement. In addition, the introduction of low-voltage three-terminal APDs effectively reduces the power consumption, further enhancing their utility in complex II systems. Jinwen Song et al., in 2023, proposed an APD based on a Ge/Si heterostructure, which improves the light absorption efficiency through the design of subwavelength periodic hole arrays while maintaining high gain and bandwidth. This technique shows great potential in II applications, especially in large-scale astronomical observatories, such as the Cherenkov telescope array (CTA), which can effectively capture and analyze small-intensity variations in celestial radiation signals. Compared to traditional PMTs, this APD not only has higher light absorption efficiency but also has obvious advantages in high-speed response and low power consumption, making it suitable for large-scale, long-duration observation scenarios. Although the dark current problem of this design still needs to be further solved, it has significant application prospects in improving the measurement sensitivity and accuracy. Future research should continue to focus on improving the quantum efficiency, bandwidth, and gain of the detector to meet the demand for higher-precision interferometry, and special attention should be paid to optimizing the design for achieving low noise and low power consumption in complex systems. Continued advances in these technologies will lead to greater breakthroughs in the application of II technology in large-scale astronomical observation equipment.

3.3. Intensity Interferometric Imaging

Intensity interferometric imaging is a high-resolution imaging technique applied to astronomical observations. By analyzing the temporal correlation of the light intensity emitted by celestial bodies, information about the surface structures can be obtained. Unlike conventional amplitude interferometers that rely on direct measurements of phase information, intensity interferometers use statistical methods to indirectly infer phase information, thereby reconstructing images of celestial objects. Although this technique has achieved remarkable results in its initial application to stellar diameter measurements,

its full potential requires further exploration. With the development of modern image reconstruction techniques, especially the advancement of phase retrieval algorithms and numerical optimization methods [88,89], extracting high-resolution images from intensity interferometric data is feasible. These methods can reveal the detailed structure of celestial objects and accurately detect the separation of binary star systems, activity on the stellar surface, and other complex astronomical phenomena. Intensity interferometric imaging has gained prominence in contemporary astronomical research owing to its ability to extend observational capabilities. It can explore the fine and complex structures in the universe, providing a unique and powerful tool for astronomers.

3.3.1. Phase Reconstruction

The retrieval of phase information is a central challenge in various branches of the physical sciences, especially during image formation [90,91]. Considering that II only provides amplitude information without capturing phase information, this limitation leads to image blurring and information loss because phase information contains spatial structure and details about the object. Therefore, phase retrieval can achieve high-resolution and high-quality imaging. Phase retrieval algorithms and techniques have been widely applied to reconstruct the complete information of objects [92–95].

II, developed by Hanbury Brown and Twiss in the 1950s, solved the problem of conventional interferometry being highly sensitive to path differences by measuring the correlation of photon arrival times [95–98]. However, the imaging capabilities of this method are limited by the inability to recover the Fourier phase. Since then, scientists have continued to explore ways to improve the accuracy and application range of the SII technique. In 2016, Zampieri et al. [99,100] significantly improved the accuracy of phase recovery by applying the II technique to the Cherenkov telescope array. By measuring the zero-baseline correlation (ZBC) and combining observations at different baseline positions, they efficiently optimized their observing strategy to improve the accuracy of stellar angular diameter measurements to 0.5–0.6 milliradians in a short integration time. The optimization of this technique lays the foundation for further research. In 2020, Acciari et al. [101] optimized the observing strategy and integration time of the Cherenkov telescope array and succeeded in observing previously fainter stars, although signal-to-noise ratios and long baseline observing times remain limiting factors.

Meanwhile, in 2020, Paul M. Klaucke's team [102] successfully solved the problem of II's inability to recover Fourier phase by upgrading the Southern Connecticut Stellar Interferometer (SCSI) to a triple-baseline system, introducing triple correlation. They obtained significant correlation peaks in observations of objects such as Vega, demonstrating that the triple correlation system can effectively improve observing efficiency. To further enhance efficiency, the team suggested adopting a multi-wavelength detection technique, using a narrow-band filter with a bandwidth of 0.1 nm to distribute photons to 10 detection pixels. It is expected that each pixel will be able to receive about 7×10^5 photons during a 10 h observation period, thus realizing effective phase recovery. If the SCSI system is applied to a 2 m aperture telescope, the signal-to-noise ratio is expected to improve by a factor of 10, allowing the phase information of a bright star (e.g., Sirius) to be recovered in a single night of observation. This combination of technical improvements in both phase recovery techniques and multi-wavelength detection offers significant potential to enhance the accuracy and efficiency of imaging with intensity interferometry, overcoming key challenges that have historically limited its practical application. Although the II technique has made significant progress in terms of accuracy and observing range, the research still faces challenges in terms of the signal-to-noise ratio and observing time [103]. Future work will focus on further improving the measurement capability through technical advancements and the optimization of observing conditions.

3.3.2. Image Reconstruction

In optical interferometry, the observed signals usually behave as complex visibilities containing amplitude and phase information that reflect the spatial frequency characteristics of the observed object. In the case of known transfer functions, image reconstruction can be synthesized from complex visibility data [104,105]. However, due to the sparse coverage of the u - v plane, image retrieval algorithms have to perform Fourier interpolation in conjunction with the a priori information to compensate for the missing data and some of the Fourier phase information [106,107]. Especially in low signal-to-noise ratio data processing, optical interferometry makes image synthesis more complex than radio interferometry due to its sparse u - v coverage and nonlinear effects. This requires optimizing the initial solution and strategy to cope with the nonconvex optimization problem [108].

In the 21st century, with the advancements in photodetector technologies, such as CCD and complementary metal oxide semiconductor (CMOS), intensity interferometry and scattering interferometry techniques have gained renewed attention, driving the adoption of these techniques in large-scale projects, such as the CTA and AGIS, which have achieved sub-milliarcsecond measurement accuracies, greatly expanding the range of interferometric applications. In addition, in recent years, the Wiener-Khinchin telescope, based on spatial intensity self-correlation imaging, has broken through the phase limitation by means of random phase modulation, realizing wide-band, high-resolution imaging, and showing good application prospects [109].

In particular, a broad-spectrum optical synthetic aperture imaging method based on spatial intensity interferometry proposed by Chunyan Chu et al. [110] in 2023 effectively solves the problems of the phase fluctuation sensitivity and narrow bandwidth of traditional optical interferometric imaging at long baselines. The method reconstructs the object image through spatial intensity autocorrelation measurements and combines it with a phase recovery algorithm to overcome the errors induced by phase fluctuations. In addition, the sub-aperture array design introduced in the study realizes diffraction-limited imaging with a single exposure over a wide spectral range, which significantly improves the photonic efficiency. Simulation and experimental results showed that the method could achieve high-resolution imaging at 100 nm spectral width with inter-sub-aperture optical range differences of up to 69λ . Nevertheless, the optical synthetic aperture method still needs to cope with the problems of u - v plane sparse coverage and nonlinear effects during image reconstruction [111]. Similar to radio interferometry, the problems of spectral loss and side-flap interference in sparse aperture arrays still affect the imaging sharpness. Although the method of Chu et al. improves the stability of the system and significantly enhances the photon efficiency through an array of spatially randomized phase modulators (SRPMs), the inhomogeneity of the spectral coverage may still lead to degradation of the imaging contrast. Future research will focus on further optimizing the synthetic aperture array design to enhance the image reconstruction performance, especially for applications in wider spectral range and signal-to-noise ratio enhancement.

4. Conclusions

The development of II has been revitalized by significant advancements in photon detection and signal processing systems, making it a promising technique for high-resolution imaging applications in photonics. Recent breakthroughs in photonic detector technology, such as APDs and SPADs, have drastically improved the sensitivity and temporal resolution of II systems. These enhancements allow II to overcome previous limitations in photon collection and signal accuracy, which were major challenges in earlier implementations. Moreover, the integration of modern computational methods for data analysis and phase recovery algorithms has enabled the better reconstruction of high-resolution images, furthering II's applicability to long-baseline interferometry and large-aperture optical systems. The continuous improvement of adaptive optics and the design of large-scale photon-collecting arrays offer significant opportunities to refine II techniques for broader applications. These developments in photonic technologies will not only enable II to meet

the growing demands of high-precision measurements but also ensure its compatibility with emerging telescope arrays and imaging systems. By enhancing both the angular resolution and sensitivity of II, these innovations promise to expand the capabilities of optical imaging, making II a valuable tool in the field of photonics for future observational and experimental research.

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