Trends in optics and photonics
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Present trends in stellar interferometry

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Abstract

Long baseline interferometry in optical/IR band offer the possibilities for direct measurement of all the basic physical parameters for a large number of stars. Soon after the success of obtaining interferometric fringes of α Lyrae (Vega) by means of two independent telescopes in the early 1970's by Labeyrie [1] followed by the development of Grand Interféromètre à deux télescope (GI2T), an interferometer with a pair of 1.5 meter (m) telescopes on a North-South baseline configuration at Observatoire de la Calern [2], several instruments of this nature are in place [3]. A few of them are employing large telescopes (8-10 m), which are successfully producing results. Concept of hypertelescope using large interferometric arrays of telescopes is also being looked into. Potentials for progress in the direction of developing such an array are expected to provide images, spectra of quasar host galaxies, and exo-solar planets. This article enumerates the present scenario of the current trend and the path to future progress in stellar interferometry using diluted apertures.

1 Introduction

Angular resolution of a telescope is limited by its diameter, which can be improved by extending baselines in the form of a diluted aperture interferometry. Such a method combines signals to obtain information that could not be supplied by either of the signals individually. Although interferometric technique in astronomy began with Fizeau [4], the field lay dormant soon after the measurement of the diameter of α Orionis by Michelson's stellar interferometer [5]. It was revitalized by the intensity interferometry [6] and the pioneer's era ended with the Narrabri intensity interferometer [7] by which 32 southern stars were resolved. Knowledge of atmospheric turbulence and of ways to overcome this degradation has triggered the development of speckle interferometry by Labeyrie [8]. This is a passive method that deciphers diffraction limited spatial Fourier spectrum and image features of stellar objects by counteracting blurring effect caused by the atmospheric turbulence. This method has made impacts in several important fields in astrophysics [9, 10]. Further development in hardware technology has made it possible to compensate in real time the wavefront perturbations, known as adaptive optics, particularly in infra-red wavebands [11]. These efforts have begun to provide further insight into the physics of stars, galaxies, and other celestial objects.

Spectacular progress has been witnessed in the case of the radio interferometry [12] in which very long baseline interferometry (VLBI) is used to obtain milliarcsecond spatial resolution. This caught the attention of astronomers working on optical and infrared (IR) regions, spanning the whole range from 0.35 to 20 μm. Thus a Long Baseline Optical Interferometer (LBOI) came into existence offering unprecedented resolution of the order of a few milliarcseconds. A milestone in observational astronomy was achieved when the interferometric fringes of α Lyrae (Vega) in the visible band were obtained in July 1974, by A. Labeyrie [1] from an interferometer, called Interféromètre à deux télescope (I2T), with a pair of independent telescopes on a North-South baseline configuration at Nice Observatory. These were the first fringes that are obtained by using the concept of merging speckles from both the telescopes. Such a success in synthesizing images impelled astronomers to venture towards ground-based very large arrays. This technique has addressed subjects such as star surface imaging, close binaries, circumstellar environment. Over the years optical interferometry has slowly gained in importance and today it has become a powerful tool. Several such instruments are in operation and in some cases, large telescopes are used. The methods and technology of interferometry in infrared wavebands in atmospheric windows have also been established [13, 14]. The progress in developing the new generation ground- and space-based optical interferometer is noteworthy. In this article, the current trend and the path to future progress in aperture synthesis techniques using large number of telescopes are elucidated.

2 Single aperture synthesis

The concept of aperture mask using two holes on top of the telescope was suggested by Fizeau [4]. In this technique the beams are diffracted by these sub-apertures which produce Young's fringes at the telescope's focal plane. These fringes remain visible in presence of seeing, which allow to obtain high angular measurements of stellar objects. Initial experiment by Stéfan with 1 m telescope at Observatoire de Marseille revealed that the fringes appeared within the common Airy disk of the sub-apertures. But he could not notice any significant drop of fringe visibility. Since the maximum achievable resolution is limited by the diameter of the telescope, he concluded none of the observed stars approached 0.1 arc sec. in angular size. The notable advantages of such an interferometer are: (i) the telescope acts as both collector and correlator, thus the temporal coherence is automatically obtained due to the built-in zero optical path difference (OPD), and (ii) the spatial modulation frequency, as well as the required sampling of the image change with the separation of sub-apertures. Later, this technique was used at the Yerkes refractor by Michelson [15] to measure the diameter of the satellites of Jupiter. Similar experiment has also been conducted by a few others in order to record the fringes [16, 17].

The concept of using three antennae arranged in a triangle was first introduced in radio astronomy [18]. Closure-phases are insensitive to the atmospherically induced random phase errors, as well as to the permanent phase errors introduced by the telescope aberrations in optics. Since any linear phase term in the object cancels out, this method is insensitive to the position of the object but sensitive to any object phase non-linearity. Single aperture aperture synthesis involves observing an object through a non-redundant masked aperture of several holes and recording the resulting interference patterns in a series of short-exposure. Such a mask introduces a series of overlapping two-holes interference patterns projected onto the detector. The fringe patterns contain information about structure of the object at the spatial frequencies from which an image of the same can be reconstructed by measuring the visibility amplitudes and closure phases. This method produces images of high dynamic range, but restricts to bright objects. The instantaneous coverage of spatial frequencies is sparse and most of the available light is discarded.

3 Long baseline optical interferometry

The marked advantage of using independent telescopes is the increase in resolving capabilities. At radio wavelengths, development of long baseline interferometry and very long baseline interferometry (VLBI) had brought high dynamic range images with milliarcseconds resolution. Radio astronomers have produced extra-ordinary images as those of Cassiopeia A and Cygnus A. The major advantages of radio interferometry are: (i) uniform phase over individual apertures, (ii) time integration, (iii) phase stability of delay lines and (iv) electric delay lines.

In Optical interferometry, two different telescopes are used to receive the signals from a distant source, and the primary mirrors are adjusted carefully. The mirrors have to be placed so as to compensate the geometrical delays as one primary mirror receives light from the distant source first. This ensures that both the light waves reach the detector at same time. The output of this is a combination of bright and dark fringes resulting from the interference of two waves. If the source is very small, there will be a high contrast in the fringes but as the size of source increases the contrast of fringes decreases. The resolution of this method depends on the length of baseline rather than diameter of individual mirrors. This setup is, therefore, more cost effective than the large single optical telescope. The fringes which are obtained are examined and the visibility and contrast are converted using Fourier transforms so that the object under observation can be mapped, and all the properties such as magnitude. This method is very useful to find the angular diameters of stars and binary star orbits.

The fringe visibility, $\mathcal{V}$, is derived from the variation of intensity with time. In the above Figure (1) a stellar source in question is at an angle of θ. Due

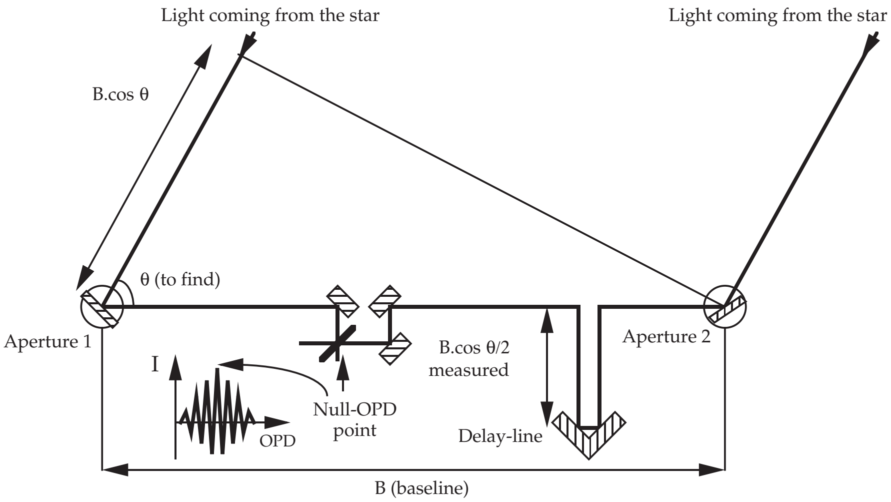

Figure 1: Principle of long baseline interferometry using two telescopes.

to this the effective baseline of the interferometer (is given by projection of the telescope positions onto a plane perpendicular to the source direction) is changed and the signal should travel an extra path of dl to reach right hand telescope (geometric delay $= dl\cos\theta/c$, in which c is speed of light). The signals from both the telescopes should reach the signal intensity detector at same time. For this, geometric delay is compensated using a signal delay component δt (instrumental delay).

The observed visibility function, $\mathcal{V}$, of a point source in the direction of θ is given by,

$$\mathcal{V}(\mathrm{B}_\lambda) = \int I_{int}(\theta) e^{i2\pi\mathbf{B}_\lambda\cdot\mathbf{s}} d\mathbf{s}. \tag{1}$$

in which $\mathrm{B}_\lambda (= \mathrm{B}/\lambda)$ is the baseline in wavelengths from one telescope to another, normalized to the value at the zero frequency and $\mathbf{B}\cdot\mathbf{s}$) the optical path difference (OPD) that is defined by the projection of the baseline vector $\mathbf{B}$ in the pointing direction $\mathbf{s}$ of the incoming light beam; here the integration is over the extent of the source.

By performing inverse Fourier transform of the source visibility function, the source morphology may be recovered,

$$I_{int}(\theta) = \int \mathcal{V}(\mathrm{B}_\lambda) e^{-i2\pi\mathbf{B}_\lambda\cdot\mathbf{s}} d\mathbf{s}, \tag{2}$$

In the Cartesian coordinate system, $\mathbf{x}(= x, y)$, are drawn on the the sky with origin at the field center, where x and y are the Eastward and Northern displacements respectively. In terms of celestial coordinates, $x = -\Delta\alpha\cos\delta$ and $y = \Delta\delta$, in which $\Delta\alpha$ and $\Delta\delta$ are the offsets in right ascension, α and declination,

δ respectively. Thus,

$$I(\mathbf{x}) = \int_{-\infty}^{\infty} \mathcal{V}(\mathbf{u}) e^{-i2\pi \mathbf{u} \cdot \mathbf{x}} d\mathbf{u}. \tag{3}$$

where $\mathbf{u} = u, v$ is the spatial frequency.

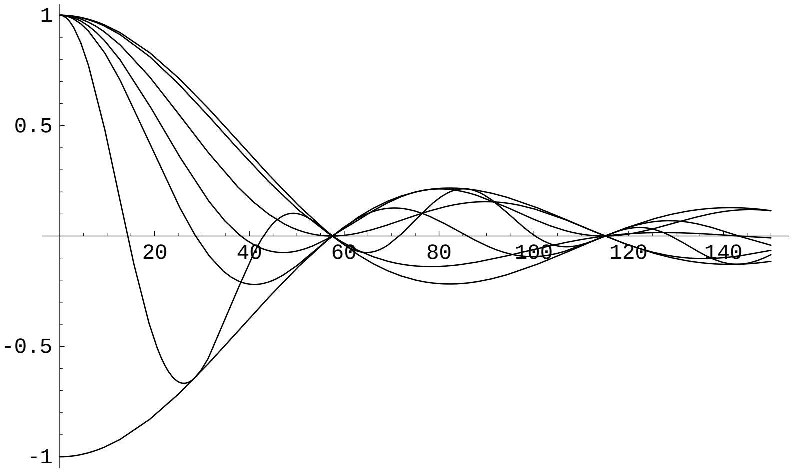

Figure 2: Visibility functions vs interferometer spacing for the case where the source is uniform.

To note, the diffraction-limit of a telescope is dictated by an angle, $\theta_{tel} = 1.22\lambda/D$, in radians, where θ_{tel} is the resolving power of the telescope. In the case of a two element interferometer, the light disturbance from a point source in the focal point is derived as,

$$\begin{aligned} U_{int}(\theta) &= \int_{\mathrm{B}/2-D/2}^{\mathrm{B}/2+D/2} e^{i(2\pi x\theta/\lambda)} dx + \int_{-\mathrm{B}/2-D/2}^{-\mathrm{B}/2+D/2} e^{i(2\pi x\theta/\lambda)} dx \\ &= 2D\cos(\pi\theta \mathrm{B}_\lambda) \frac{\sin(\pi\theta D/\lambda)}{\pi\theta D/\lambda}. \end{aligned} \tag{4}$$

The intensity in the focal point is deduced as,

$$I_{int}(\theta) = 2I_{\mathrm{tel}}(\theta)\left[1 + \mathcal{V}\cos(2\pi\theta \mathrm{B}_\lambda)\right], \tag{5}$$

where I_{tel} is the envelope shape and $\mathcal{V}$ the visibility that is given by,

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}. \tag{6}$$

The equation (5) is the product of the broad envelope of a single-telescope diffraction pattern and the interference term. This term depends on the separation between the telescopes. Figure 2 depicts the visibility curves for uniformly bright circular disks. The frequency of first zero of the function scales inversely with angular diameter of the source.

3.1 Limitations

Optical interferometry faces difficulties from the atmospheric turbulence (a state of the flow of air in which apparently random irregularities occur in the air's instantaneous velocities, often producing major deformations of the flow.), as well as from the limited response time of interferometer. Due to the small wavelengths of the signals the interferometer should be fast enough to respond to them. To overcome this problem adaptive optics which consist of a number of self adjusting mirrors are used to sense the irregularity in the signal and tilt the mirror rapidly. As the number of telescopes increases the complexity of the mirror system also increases as it is necessary to compensate for the numerous beams which contribute to the interference pattern. The noted other drawbacks a stellar interferometer faces are:

- many phase cells over the pupil, hence, the size of the telescope becomes limited to the size of the atmospheric coherence length (Fried's parameter),
- short atmospheric coherence time; interference pattern should be detected in few milliseconds to avoid smearing due to turbulence,
- the light from the source must be gathered within short time, or the source will move from the field of vision,
- optical delay lines, high speed photo-detectors with high-level storage and processing capabilities [19, 20] and frequency-stabilized lasers to measure continually changing delay line lengths,
- mechanical stability of telescopes,
- beam recombination (pupil or in image plane),
- limited $u - v$ coverage, and
- limited accuracy on amplitude and phase estimates.

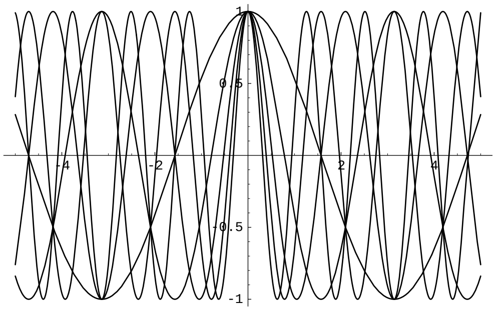

Figure 3: Response of an interferometer to a narrow band source.

Operating an optical interferometer, i.e., finding fringes, measuring their visibility, interpreting the result, is a long and difficult process. It requires accurate alignments, high stability, full control of any effect decreasing visibility. The limitations come from the parameters, viz., (i) precise determination of visibility, (ii) sensitivity in measuring weak sources, (iii) accurate measurement of fringe phases, and (iv) availability of range of baselines. High speed photo-detectors with high-level storage and processing capabilities and frequency-stabilized lasers to measure continually changing delay-line lengths are also required.

Another limitation comes from the bandwidth since a LBOI works in finite bandwidth where the pass-band defines the effective source spectrum, the effect of which is to produce a frequency dispersion. The optical path delay is different for the different frequencies within the band, which can lead to signals being out of phase. The time over which the radiation is considered, the actual time coherency is derived from the Fourier transform of the pass-band used. Figure (3) depicts the response of an interferometer to a narrow band source.

3.2 Initial experiments

Labeyrie [1] extended the concept of speckle interferometry to a pair of telescopes that are run on tracks for variable North-South baseline. It combines the features of the Michelson design and the radio interferometers. These telescopes track simultaneously the same source (star) and send the collected light to the central laboratory where the star images are superposed at the focii in order to produce Young's fringes. The beams from these telescopes are recombined in an image plane after reconfiguring the pupils. Fringed speckles are visualized when a speckle from one telescope is merged with the speckle from other telescope. These fringed speckles are dispersed (see Figure 4) and the spectra are recorded at short-exposure using a photon counting detector. The beam-recombining optical devices were kept on a computer controlled motor driven carriage parallel to the baseline. This carriage moves along the telescopes to maintain constant zero OPD that changes due to diurnal motion, within the coherence length between the two beams.

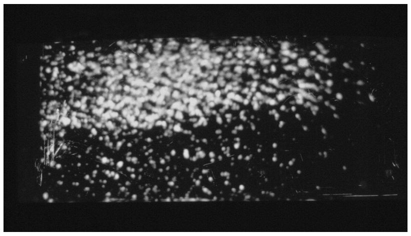

Figure 4: A dispersed image of a fringe pattern across a star taken with GI2T (Courtesy: D. Mourard).

The present recombiner called recombineur pour grand interféromètre (REGAIN) at Grand interféromètre à deux télescopes (GI2T) that comprises of a pair of 1.5 meter telescopes, uses a delay-line featuring a cat's eye reflector with variable curvature mirror. Each Coudé beam coming from the telescopes meets a pupil stabilizer, a field rotator, a wedge prism and the beam combiner [21]. The different chromatic dispersion between the two beams which occur due to the atmospheric dispersion is compensated by using for each beam two prisms that can slide on their hypotenuse, forming, therefore, a plate with adjustable thickness. This thickness is modified every few minutes, following the variation of the altitude of the observed object. The first result came out of the GI2T in 1989, in which Mourard et al. [22] reported resolving the rotating envelope of hot star, γ Cas. The star was observed with a spectral resolution of 1.5 Å centered on Hα. This result demonstrates the potential of observations that combines spectral and spatial resolution.

Another interferometer was developed by Shao [23] at Mt. Wilson observatory, called Mark III interferometer. In this two well-separated siderostat mirrors (to divert the light from the distant object in a single direction) track the target star as the Earth rotates and direct its light into a series of mirrors. Tilt-correction mirrors adjust for disturbances caused by atmospheric turbulence. Delay lines compensate for the geometric delay so that the light in each beam that left the star at the same time arrives simultaneously at the beam splitter, which combines the two beams to produce interference fringes. Both the instruments, I2T and Mark III interferometer have ceased operations.

4 Diluted-aperture synthesis

Aperture synthesis combines signals from a collection of individual telescopes to provide an image with a resolution equivalent to that of a single telescope with a size equal to the maximum distance between the individual antenna. The light collected by an array of separated telescopes yields a measure of the amplitude of the spatial coherence function of the object at a spatial frequency $\mathbf{B}/\lambda$, where $\mathbf{B}$ is the baseline vector and λ the wavelength. For n telescopes, there are $n(n-1)/2$ independent baselines, with, $n-1$ unknown phase errors. In order to make an image from an interferometer, one needs to estimate of the complex visibilities over a large portion of the (u, v) plane, both the amplitudes and phases.

Arrays of telescopes connected in pairwise are called as aperture synthesis arrays. The main theme of array telescopes is to have maximum coverage of uv-plane. The angular resolution of an interferometer entirely depends on the largest possible spacing between any two telescopes and sensitivity depends on the diameter of the telescope's objective lens; the functional components of an optical imaging array is given in Table I. However, in order to have continuous Fourier components all the intermediate spacings are required. The extent of this entirely depends on the design of the systems (concerning the spacings between the telescopes and shape in which they should be arranged). If the source is constant over a extent of observations, then it is not necessary that all the necessary baselines simultaneously exist. Aperture synthesis about study of techniques of getting maximum information from data keeping in view the limitations involved in that particular method.

Table I
Functional components of an optical imaging array

Components	Parameters to consider
Collectors	size, number, array design
Beam transporter	free or guided
Delay compensator	vacuum or air
Beam combiners	number and nature of combiners
Detector	sensitivity, temporal and spectral resolution

The orientation and fringe spacings can be obtained from vector spacing between the aperture pair which is generating fringes. Fringe orientation is normal to the vector and the period is equal to the length of the vector. The orientation and period of fringes are denoted by the spatial frequency (u, v). Visibility is a measure of contrast of the fringes and phase measures the location of the fringe crest relative to the optic axis.

At optical frequencies, even more than at radio frequencies, the calibration of the imaging performance of the system is vital if high-quality images are to be obtained. This requires an assessment of the phase errors associated with each sub-aperture in the array. In astronomy, the compact and high-contrast nature of the objects imaged and the change in interferometer orientation due to the diurnal rotation of the earth permit one routinely to obtain synthetic images of great quality.

In order to measure the closure phase together with the measurements of visibility amplitude, Baldwin et al. [24] have implemented in the visible band by reconstructing an image of an object using Cambridge optical aperture-synthesis telescope (COAST). In addition, two interferometers, namely (i) Keck interferometer [25], and (ii) Very large telescope interferometer [26] are of heterogeneous nature, consisting of large- and medium-sized outrigger telescopes. In these cases, recombining large and small telescopes is a difficult task since the signal-to-noise ratio is determined by the smaller ones. For imaging in the case of the former, the main telescopes are used with outriggers to fill in incomplete parts of the (u, v) plane. It combines phased pupils provided by adaptive-optics for the main telescopes and fast tip/tilt correction on the outriggers. While in the case of the latter, beams are received from the movable telescopes in a central laboratory for recombination and are made to interfere after introducing suitable optical delay-lines. Coudé beams from these apertures are sent through delay-lines operating in rooms at atmospheric pressure but at accurately controlled temperature. Of late, another interferometer, called the Center for High Angular Resolution Astronomy (CHARA) Array, situated at Mt. Wilson, California, USA, is under operation. Equipped with six telescopes of 1 m in diameter, this interferometer is arranged on a Y-shaped configuration with 15 baselines ranging from 31 to 331 meters. It operates at optical (470 - 800 nm, 0.15 mas limiting resolution) and IR (2.0 - 2.5 μm, 0.6 mas limiting resolution) wavebands [27]. Fringes of HR 1017 at 211 m baseline using said interferometer can be seen in Figure (5).

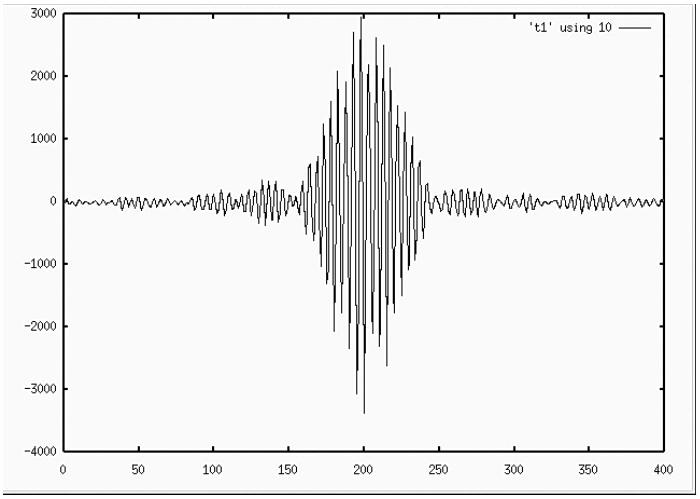

Figure 5: Fringes of HR1017 obtained at 211 m baseline using CHARA interferometer (Courtesy: ten Brummelaar).

Although an interferometer with two apertures cannot recover the complex visibility, but a different kind of interferometer called Large Binocular Telescope (LBT) that is being developed, can provide such a visibility. This instrument will utilize both 8.4-m primary mirrors with a baseline of 22.8 meters. These primary mirrors fitted with adaptive optics systems (AO) are co-mounted on a fully steerable alt-az mounting, thus information in (u, v)-plane can be continuously combined or co-added. The LBT AO system will employ two 91-cm diameter 1.7-mm thick f/15 secondary mirrors with 672 actuators on each mirror operating at 900 or 1000 Hz [28]. This AO system can be used for imaging and/or for nulling interferometric imaging. By nulling, faint objects such as extra-solar planets may be detectable around bright stars. The effect of nulling will suppress a bright star by a factor of $\sim 10^4$ or 10^5. The expectations are that Jupiter-sized planets may be detectable via nulling, orbiting nearby stars, i.e., those within 20-30 light years. Also, the detection of extended protoplanetary disks should also be possible.

5 Road to hypertelescope, a novel concept

A new concept, called hypertelescope, may provide snapshot images having both a high resolution and a high information content. It involves the blossom of huge flower-like instruments, on Earth and in space, which have the potential of extending the angular resolution towards nano-arcseconds at visible wavelengths. Such a method requires to incorporate many apertures to provide direct snapshot images with this high resolution. The possibility of this breakthrough results from a rather modest optical innovation which announces scheme currently developed for achieving such goals is called densified pupil imaging, which can be implemented in the form of imaging interferometric arrays [29].

6 Multi-aperture intensity interferometry

Intensity interferometry, introduced by Hanbury Brown and Twiss [30] in visible waveband had successfully measured the diameter of bright stars and the orbit of binaries [7]. Recent technological developments of detectors and electronics have increased the band pass of detectors, and consequently, the potential sensitivity of intensity interferometry. Also, various gamma ray detection observatories, based on collection of Cerenkov radiation produced in the atmosphere, are potentially making available large collecting area mirrors. Upcoming atmospheric Cerenkov telescope (ACT) projects would consist of up to 100 telescopes, each with $\sim$100 m^2 of light gathering area, and distributed over $\sim$1 km^2. These facilities can offer thousands of baselines from 50 m to more than 1 km and an unprecedented (u, v) plane coverage [31]. Recently developed high altitude gamma ray telescope array (HAGAR), which has seven telescopes, each with seven mirrors of total area 4.4 square meters, installed at the Indian astronomical observatory (IAO) Hanle, India at an altitude of 4300 m above sea level, where seeing is superior to those at lower altitude, offers a possibility of conducting interferometric experiment for the measurements of the stellar diameter wavelength dependence. To note, the total light gathering area of such a system is 31 sq meters, which are deployed on the periphery of a circle of radius 50 meters with one telescope at the center. Each of the seven mirrors in each telescope would be looked at by a UV sensitive photo-multiplier tube. The site has the advantage of being at 4300 m above sea level, where seeing is superior to those at lower altitude.

7 Concluding remarks

Interferometry has the advantage of being cost effective, at the same time giving very high resolution of distant objects in the sky. The technological advancement made it possible to witness the speedy progress of optical interferometry using diluted apertures, which would provide larger collecting areas and higher spatial resolution simultaneously. An important fundamental problem that can be addressed with these instruments fitted with complete adaptive optics systems is the origin and evolution of galaxies. They would be able to provide imaging and morphological information on the faint extragalactic sources such as, galactic centers in the young universe, deep fields, and host galaxies. Development of an hypertelescope with many primary mirror elements project, can in principle provide enough resolved elements in snapshot images to observe galaxies and cosmological deep fields as well. Reviving intensity interferometry may also an option to achieve diffraction-limited imaging over a square-kilometer synthetic aperture.

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