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Aperture Synthesis at Optical Wavelengths

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Abstract: Optical stellar interferometers have demonstrated milli-arcsecond resolution with few apertures spaced tens of meters apart. Results from the area of stellar angular diameters with implications for emergent fluxes, effective temperatures, luminosities and structure of the stellar atmosphere, dust and gas envelopes, binary star orbits with impact on cluster distances and stellar masses, relative sizes of emission-line stars and emission region, stellar rotation, limb-darkening, and astrometry have been published. However, in order to obtain snapshot images, many-apertures would be required, for a better sampling of the incoming wavefront. The coherent imaging thus achievable improves the sensitivity with respect to the incoherent combination of successive fringed exposures, heretofore achieved in the form of optical aperture synthesis. For efficient use of a multi-aperture imaging interferometer, this can be done with pupil densification, a technique also called hypertelescope imaging. When equipped with a coronagraph, this can be used for imaging of exo-planet transits across a resolved star. The capabilities of such a technique can be envisaged through a simulated image carried out recently by Surya et al. [1]. This lecture is aimed to describe some of these techniques and methods.

1 Introduction

Conventional mode of imaging in optical astronomy cannot achieve resolution better than 1 arcsecond or so, which is comparable to the diffraction-limit of a telescope with an aperture of 10 cm. This degradation is due to 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) preventing the complete utilization of the resolving capabilities of large telescopes. The optical interferometric imaging, triggered in 1970 by Labeyrie [2], with the introduction of stellar speckle interferometry 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 [3 and references therein]. Further development in hardware technology has made it possible to compensate in real time the wavefront perturbations, particularly in infra-red wavebands, by incorporating a controllable phase distortion in the light path, which is opposite to that introduced by the atmosphere.

The angular resolution capabilities in astronomy differ across the electromagnetic spectrum, it is limited with the diameter of the single aperture. The resolution

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improves if the baselines are extended by using diluted aperture interferometry, which combines signals to obtain information that could not be supplied by either of the signals individually. The optical interferometry using a pair of small telescopes was built in 1975 by Labeyrie [4], which was followed by Grand Interferometre de deux Telescopes (GI2T) using a pair of moderate sized telescopes [5, 6]. This had made it possible to obtain a very high resolution of the order of a few milli-arcseconds. This technique has addressed subjects such as star surface imaging, close binaries, circumstellar environment, etc. The methods and technology of interferometry in infrared wavebands in atmospheric windows have also been established.
Aperture synthesis technique measures, instead of measuring the image directly, its Fourier components which form the required image after Fourier inversion. At present, several interferometers using diluted apertures equipped with adaptive optics system have been successfully producing results [7 and references therein]. A new array based on the concept of densified pupil imaging is being built in France [8]. This article discusses the present scenario of long baseline interferometry.

2 Optical interferometry

In an 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. This method is very useful to find the angular diameters of stars and binary star orbits. An algorithm based on least square method to obtain plots and the orbital parameters was developed at IIA. The normal equations are solved using Cracovian matrix elimination technique, which finds out the constants, a, h, b, g, and f, as well as for plotting the apparent ellipse (see Figure 1),

$$\begin{bmatrix} \sum x_i^4 & 2\sum x_i^3 y_i & \sum x_i^2 y_i^2 & 2\sum x_i^3 & 2\sum x_i^2 y_i \\ \sum x_i^2 y_i^2 & 2\sum x_i y_i^3 & \sum y_i^4 & 2\sum x_i y_i^2 & 2\sum y_i^3 \\ \sum x_i^3 y_i & 2\sum x_i^2 y_i^2 & \sum x_i y_i^3 & 2\sum x_i^2 y_i & 2\sum x_i y_i^2 \\ \sum x_i^3 & 2\sum x_i^2 y_i & \sum x_i y_i^2 & 2\sum x_i^2 & 2\sum x_i y_i \\ \sum x_i^2 y_i & 2\sum x_i y_i^2 & \sum y_i^3 & 2\sum x_i y_i & 2\sum y_i^2 \end{bmatrix} \begin{bmatrix} a \\ h \\ b \\ g \\ f \end{bmatrix} = - \begin{bmatrix} \sum x_i^2 \\ \sum y_i^2 \\ \sum x_i y_i \\ \sum x_i \\ \sum y_i \end{bmatrix}$$

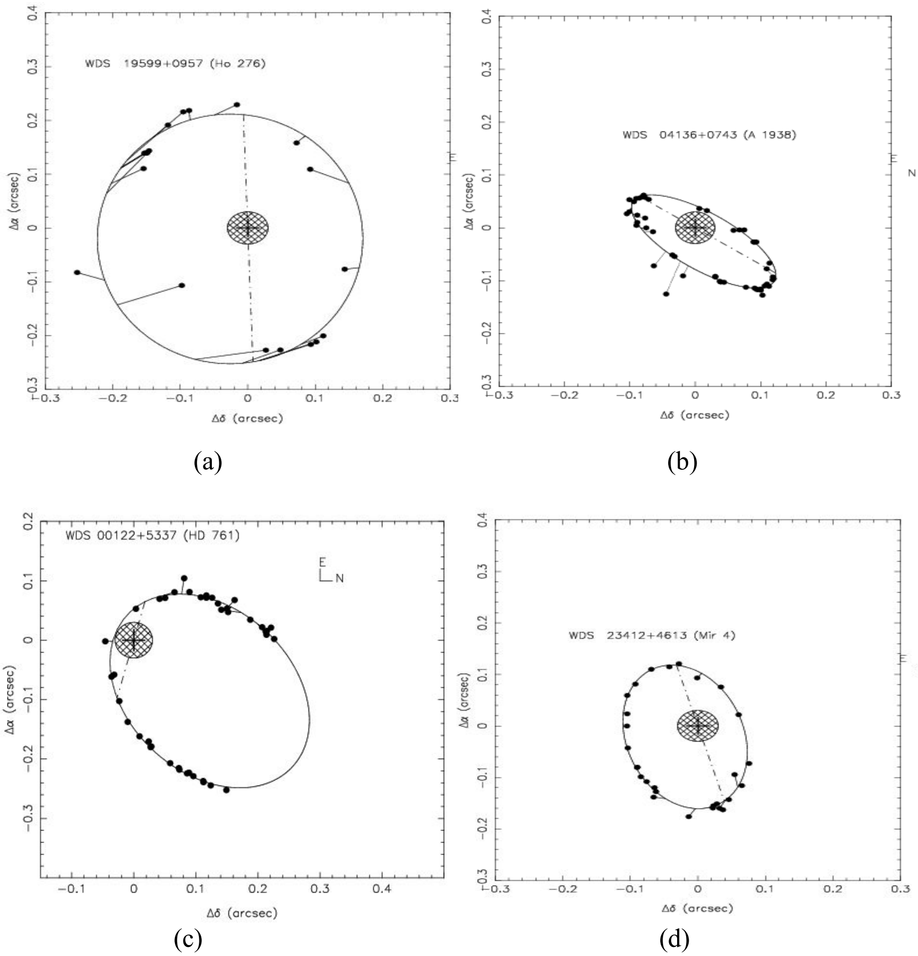

Figure 1: Plotting orbits of the close binary stars: (a) WDS 19599-0957 = Ho276 (HD 189340) in which 18 interferometric data were used between 1961 and 2000, (b) WDS 04136+0743 = A1938 (HD 22690) where 36 interferometric data were used between 1975 and 1995, (c) WDS 00122+5337 =Bu 1026AB (HD 761) , in which 36 interferometric measurements between 1975 and 2000 were taken into account; speckle interferometric data date back to 1975, covering about half the resolution, and (d) WDS 23412+4613 = Mir 4 , where 29 interferometric data were used between 1980 and 2000.

The two major limitations of optical interferometry are atmospheric turbulence and limited response time of interferometer. Due to the small wavelength of the signals the interferometer should be fast enough to respond to them. To overcome this problem, adaptive optics systems, 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. This procedure is implemented in Keck Interferometer as well as VLTI. Optical interferometry faces many drawbacks, such as (i) many phase cells over the pupil, hence, the size of the telescope becomes limited to the size of the Fried's parameter, (ii) short atmospheric coherence time; interference pattern should be detected in a few milliseconds to avoid smearing due to turbulence, (iii) the light from the source must be gathered within short time, or the source will move from the field of vision, (iv) optical delay lines, high speed photodetectors with high-level storage and processing capabilities and frequency-stabilized lasers to measure continually changing delay line lengths, (v) mechanical stability of telescopes, (vi) beam recombination (pupil or in image plane), (vii) limited u-v coverage, and (viii) limited accuracy on amplitude and phase estimates.

Table 1: Optical/IR Interferometers

Facility	Telescopes	Apertures (m)	Maximum Baselines (m)
CHARA (USA)	6	1	350
COAST (UK)	5	0.40	20
GI2T (France; closed)	2	1.5	65
IOTA (USA; closed)	3	0.40	38
ISI (USA)	3	1.65	85
Keck (USA)	2	10	60
LBT (USA)	2	8.4	22
MIRA (Japan)	2	0.25	4
NPOI (USA)	3	0.12	35
PTI (USA)	3	0.40	110
SUSI (Australia)	2	0.14	640
VLTI (ESO)	4 + 4	8.2 (Main) 1.8 (Auxiliary)	120

CHARA – Center for High Angular Resolution Astronomy
COAST – Cambridge Optical Aperture Synthesis Telescope
GI2T – Grand Interferometre a 2 Telescopes
IOTA – Infrared Optical Telescope Array
ISI – Infrared Stellar Interferometer

LBT – Large Binocular Telescope
MIRA - Mitaka optical and Infrared Array
NPOI - Navy Prototype Optical Interferometer
PTI - Palomar Testbed Interferometer
SUSI – Sydney University Stellar Interferometer
VLTI – Very Large Telescope Interferometer

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 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). To note, the visibility is a measure of contrast of the fringes and phase measures the location of the fringe crest relative to the optic axis.
Labeyrie [3] 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 and the spectra are recorded at short-exposure using a photon counting detector. Following its success, several such interferometers have been developed (see Table 1); in some cases, large mirrors are employed.

3 Aperture synthesis

Since an interferometer using two apertures cannot provide the information on the phase structure of the object, some of the set up described in the Table 1 are employing the services of several telescopes for obtaining the same. 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 telescope. 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. 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. According to the van Cittert-Zernike theorem [9], if the number of samples of the coherent function can be made large, the spatial frequency spectrum of the object can be reconstructed. A single interferometer with a fixed baseline measures one Fourier component of sky brightness within the envelope pattern of the instrument. So, by sampling the source's complex visibility function at particular intervals in the baseline, one can obtain brightness distribution from the Fourier transform of visibility function. As the Earth rotates, the length and orientation of interferometer baseline changes. Due to this u-v-plane samples in an elliptical way during a 24-hr period, a large number of ellipses can be traced by changing the interferometer spacing till source is not varying with time. The spacing between the telescopes can be changed by moving one of the telescopes along a rail track. This method is called earth rotation aperture synthesis. Arrays of telescopes connected in pairwise are called as aperture synthesis arrays. At optical 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.

4 Hypertelescope imaging

The hypertelescope involves the blossom of huge flower-like instruments, which requires to incorporate many apertures. 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. Due to the non-availabiity of the adaptive phasing, including also active alignment, which in principle provide a good Strehl ratio for the interference function, the speckle imaging mode simulations, based on the algorithm developed by Surya and Saha [10] may relax both the pointing and the gondola alignment tolerances. One can add to the Kolmogorov turbulence in the simulations some misalignment aberration. For a realistic tolerances of gondola tip/tilt in the speckle mode (calculating the speckle autocorrelation may suffice for that, given the long computer time needed for triple correlations [11]).
The simulations of hypertelescope imaging on various objects by Surya et al. [12] suggest to try with a transiting planet, little or not resolved, crossing the disk of a well resolved star. Several such exo-planets have been discovered by photometry in the recent years, but not in the form of a resolved image. They provide periodic eclipses, which may become feasible to observe with hypertelescopes, even perhaps the 57 m Ubaye prototype [8], which is less difficult than obtaining exo-planet images with coronagraphy. The speckle imaging may be another possibility, in spite of the lower dynamic range expected than with adaptive optics.

5 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 radio interferometers in use have led to several new discoveries. Optical interferometry, though a relatively new field, also has several new findings to its credit. The new generation interferometers with phased arrays of multiple large sub-apertures would provide larger collecting areas and higher spatial resolution simultaneously. With these interferometers, many secrets of the universe will be unveiled. Development of an hypertelescope with many primary mirror elements, can in principle, provide enough resolved elements in snapshot imaging and morphological information on the faint extragalactic sources.

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