Preface

The angular resolution of a single aperture (telescope) is inadequate to measure the brightness distribution across most stellar sources and many other objects of astrophysical importance. A major advance involves the transition from observations with a single telescope to a diluted array of two or more telescopes separated by more than their own sizes, mimicking a wide aperture, having a diameter about the size of the largest separation. Such a technique, called aperture synthesis, provides greater resolution of images than is possible with a single member of the array.

Implementation of interferometry in optical astronomy began more than a century ago with the work of Fizeau (1868). Michelson and Pease (1921) measured successfully the angular diameter of Betelgeuse (α Orionis), using an interferometer based on two flat mirrors, which allowed them to measure the fringe visibility in the interference pattern formed by starlight at the detector plane. Later, Hanbury Brown and Twiss (1954) developed the intensity interferometry (see Sect. 3.3). Unlike Michelson (amplitude) interferometry, this does not rely on actual light interference. Instead, the mutual degree of coherence is obtained from the measurement of the degree of correlation between the intensity fluctuation of the signals recorded with a quadratic detector at two different telescopes. It measures the second-order spatial coherance, where the phase of the signals in separate telescopes was not required to be maintained. However, it ended with the Narrabri intensity interferometer (Hanbury Brown 1974) that was used to measure the diameter of bright stars and the orbit of binaries and was the first to measure the limb-darkening of a star other than the Sun. The survey of stellar diameters by means of this instrument serves as a resource for the effective temperature scale of main-sequence stars. Important results were obtained for the spectroscopic and eclipsing binaries as well.

Obtaining a diffraction-limited image of celestial bodies was one of the major problems faced by the optical astronomers in the past. This is mainly due to the image degradation at optical wavelengths produced by the atmospheric turbulence. Labeyrie (1970) developed speckle interferometry as one way to overcome the degradation due to atmospheric turbulence. Then technological advances overcame many of the problems encountered by Michelson and Pease (1921) allowing further development of phase-preserving optical interferometry, more nearly analogous to radio interferometry. Labeyrie (1975) developed a long baseline interferometer with two small optical telescopes and resolved several stars. This technique depends on the visibility of fringes produced by the amplitude interferences formed by the light collected by two telescopes allowing the measurement of stars much fainter than was possible with intensity interferometry using the same size telescopes.

Following the publication of the article entitled, 'Modern Optical Astronomy: Technology and Impact of Interferometry – Swapan K Saha, 2002, Reviews of Modern Physics, **74**, 551–600,' several astronomers, particularly M. K. Das Gupta, who along with R. C. Jennison and R. Hanbury Brown developed intensity interferometry in radio wavelengths, had requested me to write a monograph, for which I am indebted to. In fact, I had the opportunity to be associated with him during graduate school days and discussed at length on this topic. This monograph, a sequel to my earlier book entitled, 'Diffraction-limited Imaging with Large and Moderate Telescopes', 2007, World-Scientific, is a dossier of knowledge for every graduate student and researcher, who intend to embark on a field dedicated to the long baseline aperture synthesis. I have attempted to make this book self-contained by incorporating more than one hundred and fifty illustrations and tens of footnotes. This monograph addresses the basic principles of interferometric techniques, the current trend, motivation, methods, and path to future promise of true interferometry at optical and infrared wavelengths. Since the basic principle of aperture synthesis imaging in optical astronomy using interferometry is Fourier Optics, this topic along with several fundamental equations is also highlighted in the appendices.

The progress in the field of radio interferometry is exemplary. The success is primarily because of the possibility to preserve phase information for widely separated dishes by using very accurate clocks and time markers in the data streams. Though the principles of optical interferometry are essentially identical to those at radio wavelengths, accurate measurements are more difficult to make: (i) the irregularities in the Earth's atmosphere introduce variations in the path length that are large compared to the wavelength; (ii) it is difficult to achieve the required mechanical stability of the telescopes to obtain interference fringes at a wavelength of the order of 500 nm. The calibration of the instrumental phase is a formidable task; and (iii) the division of the photons incident on each telescope in an array of optical telescopes to estimate the mutual coherence function or the complex visibility over the different possible baselines in the array leads to serious signal-to-noise problems. Despite the differences in technology between radio and optical interferometers, a common characterization of source properties, such as source visibility is adequate to provide a qualitative and quantitative description of the response of a long baseline interferometer.

Optical interferometry is generally performed within the standard atmospheric spectral windows. It requires several optical functions such as spatial filtering, which allows determination of the Fourier transform of the brightness distribution at the spatial frequencies, photometric calibration, polarization control etc., but the practical limitations imposed on these measurements are severe. An instrument of this nature needs extreme accuracies to meet the demands of maintaining the optical pathlengths within the interferometer, constant to a fraction of a wavelength of light, which constrained Long Baseline Optical Interferometers (LBOI) to smaller baselines ($\sim$100 m); mostly they operate at longer wavelengths (in the near- and mid-IR bands). The practical considerations regarding extraction of the Fourier components became important to look at. The first chapter lays the foundation of the mathematical framework that is required to understand the theoretical basis for Fourier Optics, imaging systems, while the second and third chapters address the fundamentals of optical interferometry and its applications.

Speckle interferometry (see Sect. 4.2), a post-processing technique, has successfully uncovered details in the morphology of a range of astronomical objects, including the Sun, planets, asteroids, cool giants and supergiants. Fueled by the rapid advancement of technology such as computational, fabrication, and characterization, development on real time corrections of the atmospheric turbulence, called 'Adaptive Optics' (AO), has given a new dimension in this field (see Sect. 4.3). Combining with LBOI, it offers the best of both approaches and shows great promise for applications such as the search for exoplanets. At this point, it seems clear that interferometry and AO are complementary, and neither can reach its full potential without the other. The fourth chapter introduces the origin and problem of imaging through atmospheric turbulence, and the limitations imposed by the atmosphere on the performance of speckle imaging. Further, it deals with the AO system including discussions of wavefront compensation devices, wavefront sensors, control system etc.

Interferometric technique bloomed during the last few decades. The new generation interferometry with phased arrays of multiple large sub-apertures would provide large collecting areas and high spatial resolution simultaneously. Over the next decades or so, one may envisage the development of hypertelescope (see Sect. 7.5.2). With forthcoming many-aperture systems, interferometry is indeed expected to approach the snapshot imaging performance of putative giant telescopes, the size of which may in principle reach hundreds of kilometers in space. However, daunting technological hurdles may come in the way for implementing these projects. Chapters 5–7 elucidate the current state-of-the art of such arrays. The various types of interferometric applications, for example, astrometry, nulling (see Sect. 5.1.3), and imaging are also described. These applications entail specific problems concerning the type of telescopes that are to be used, beam transportation and recombination, delay-lines, atmospheric dispersion, polarization, coherencing and cophasing, calibration, and detecting fringes using modern sensors (Chap. 6). Proposed ground and space-based interferometry projects (see Sects. 7.5–7.7) are also discussed.

Image-processing is an art and an important subject as well. A power spectrum (second-order moment) analysis provides only the modulus of the Fourier transform of the object, whereas a bispectrum (third-order moment) analysis (see Sect. 8.2.2) yields the phase reconstruction. The latter method is useful for simulations involving a diluted aperture interferometry. Indeed, it is difficult to incorporate adaptive optics system in a hypertelescope. Observations may be carried out by speckle interferometry, using either a redundant or non-redundant many-element aperture. Deconvolution method can also be applied to imaging covering the methods spanning from simple linear deconvolution algorithms to complex non-linear algorithms.

Chapter 8 discusses the methodology of recovering visibility functions of stellar diameter, ratio of brightness of binary components etc., from the raw data obtained by means of interferometry. Various image restoration techniques are also presented with emphasis on the deconvolution methods used in aperture-synthesis mapping.

Many astrophysical problems, such as measuring the diameters and asymmetries of single stars, observing stars as extended and irregular objects with magnetic or thermal spots, flattened or distorted by rapid rotation, determining the orbits of multiple stars, and monitoring mass ejections in various spectral features as they flow towards their binary companions, resolving star-formation regions, distant galaxies, AGNs, need high angular resolution information. Although a relatively new field, the steady progress of interferometry has enabled scientists to obtain 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. With the recent interferometers, Very Large Telescope Interferometer (VLTI) in particular, disks around several Young Stellar Objects (YSO), a few debris disks, core of a Luminous Blue Variable (LBV) object and a nova, several Active Galactic Nuclei (AGN) have been resolved. Some of these results obtained by means of optical/IR interferometry are enumerated in chapter nine. Also, it contains discussions on the ability of these instruments to obtain information about the accretion disks, winds and jets, and luminosities of components in binary systems.

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Swapan K. Saha

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