Practical Optical Interferometry

Imaging at Visible and Infrared Wavelengths

Optical interferometry is a powerful technique to make images on angular scales hundreds of times smaller than is possible with the largest telescopes. This concise guide provides an introduction to the technique for graduate students and researchers who want to make interferometric observations, and acts as a reference for technologists building new instruments. Starting from the principles of interference, the author covers the core concepts of interferometry, showing how the effects of the Earth's atmosphere can be overcome using closure phase, and the complete process of making an observation, from planning to image reconstruction. This rigorous approach emphasises the use of rules-of-thumb for important parameters such as the signal-to-noise ratios, requirements for sampling the Fourier plane and predicting image quality. The handbook is supported by web resources, including the Python source code used to make many of the graphs, as well as an interferometry simulation framework, available at www.cambridge.org/9781107042179.

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Practical Optical Interferometry

Imaging at Visible and Infrared Wavelengths

DAVID F. BUSCHER
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Principal symbols, functions and operators

$\boldsymbol{B}_{ij}$	baseline vector between telescopes i and j
$F(\boldsymbol{u})$	coherent flux of object at spatial frequency $\boldsymbol{u}$
F_{ij}	coherent flux of fringes measured between telescopes i and j
F_i	flux measured through telescope i
$\mathcal{F}$	Fourier transform operator
$I(\boldsymbol{\sigma})$	object brightness at angular coordinate σ
$i(x)$	fringe intensity at coordinate x
i_p	fringe intensity at pixel p
$\mathrm{jinc}(x)$	$J_1(x)/x$ where J_1 is the order-1 Bessel function of the first kind
P_{ij}	power spectrum of fringes measured between telescopes i and j
r_0	seeing coherence length (Fried parameter)
$\hat{\mathbf{S}}_0$	direction of the phase centre
SNR	signal-to-noise ratio
$\mathrm{rect}(x)$	rectangular ‘top-hat’ function
s_{ij}	spatial frequency of fringes between telescopes i and j
T_{ijk}	triple product (bispectrum) of fringes measured on telescopes i, j and k
t_0	seeing coherence time
$\boldsymbol{u} = (u, v)$	projected baseline coordinate in wavelengths
$V(\boldsymbol{u})$	complex visibility of object at spatial frequency $\boldsymbol{u}$
V_{ij}	complex visibility of fringes measured between telescopes i and j
$\delta(\boldsymbol{x})$	Dirac delta function
η_i	complex gain coefficient for telescope i
γ_{ij}	complex visibility degradation for fringes measured between telescopes i and j
λ	optical wavelength

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Λ_p	integrated classical intensity in pixel p
ν	optical frequency
Ψ	complex wave amplitude
σ	standard deviation
$\boldsymbol{\sigma} = (l, m)$	angular coordinate with respect to phase centre

List of abbreviations

ALMA	Atacama Large Millimeter/submillimeter Array
AMBER	Astronomical Multi-BEam combineR
AO	adaptive optics
APD	Avalanche Photo-Diode
BSMEM	BiSpectrum Maximum Entropy Method
CCD	charge-coupled device
CHAMP	CHARA Michigan Phase tracker
CHARA	Center for High Angular Resolution Astronomy
COAST	Cambridge Optical Aperture Synthesis Array
DFT	discrete Fourier transform
ESO	European Southern Observatory
FFT	fast Fourier transform
FITS	Flexible image transport system
FLUOR	Fibered Linked Unit for Optical Recombination
FWHM	full width at half maximum
LBT	Large Binocular Telescope
MROI	Magdalena Ridge Observatory Interferometer
NPOI	Navy Precision Optical Interferometer
OIFITS	optical interferometry FITS
OPD	optical path difference
P2VM	pixel-to-visibility matrix
PIONIER	Precision Integrated-Optics Near-infrared Imaging ExpeRiment
PSF	point-spread function
PTI	Palomar Testbed Interferometer
resel	resolution element
RMS	root mean square
SNR	signal-to-noise ratio
SUSI	Sydney University Stellar Interferometer

SVD	singular value decomposition
V2PM	visibility-to-pixel matrix
VEGA	Visible spEctroGraph and polArimeter
VLA	Very Large Array
VLTI	Very Large Telescope Interferometer

Foreword

I was honoured and delighted when David Buscher invited me to write an introduction to his new book. I have long felt that there is a desperate need for an authoritative and accessible book on the techniques of optical and infrared interferometry and David has filled this major gap in the literature with this excellent piece of technical and scientific writing.

For the radio astronomer, interferometry is the bread and butter of how much of the discipline has to be undertaken. Radio, and nowadays millimetre and submillimetre, astronomers are brought up with the concepts of amplitude and phase, Fourier inversion and so on, which has always been something of a barrier to the wider appreciation of these disciplines by optical astronomers, who until recently scarcely had to bother about phase at all. The understanding of aperture synthesis imaging in all its variants became a black-belt sport for the initiates and this discouraged the typical astronomer from taking the plunge.

But this is no longer reasonable or acceptable. The possibilities opened up by optical and infrared synthesis imaging are enormous, as David makes clear in this book. Angular resolution of a milliarcsecond or better can now be routinely provided by the most advanced optical-infrared interferometers and will undoubtedly result in important new discoveries and much improved tests of theories of Galactic and extragalactic objects.

This is where David's book comes in. He offers a rigorous, but accessible, introduction to the necessary theoretical and experimental tools needed to understand and apply the techniques of optical synthesis imaging. The result is that the effort needed to understand the key concepts by those new to the field, or who are still put off by the apparent complexity of the techniques, is made very much less forbidding. There is so much remarkable astrophysics lurking

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below the 1 milliarcsecond threshold that it is only a question of time before optical-infrared interferometry becomes a standard tool of the trade. David's excellent exposition makes this feasible for all astronomers and I warmly recommend this book to all of them.

Malcolm Longair
October, 2014

Preface

Optical interferometry uses the combination of light from multiple telescopes to allow imaging on angular scales much smaller than is possible with conventional single-telescope techniques. It is increasingly recognised as the only technique capable of answering some of the most fundamental scientific questions in astronomy, from the origin of planets to the nature of the physical environments of black holes.

Interferometry is an established technique at radio and millimetre wavelengths, with instruments such as the VLA and ALMA being the workhorses at these wavelengths. The development of interferometry in the optical (which we take here to include both visible and infrared wavelengths) has lagged behind that of radio interferometry due both to the extreme precision requirements imposed by the shorter wavelengths and to the severe effects of the Earth's atmosphere. For many years, the use of optical interferometry for scientific measurements was limited to the specialists who designed and built interferometric instruments.

At the beginning of the twenty-first century, the first "facility" optical interferometers such as the VLTI, the CHARA array the Keck Interferometer came online, with the aim of broadening the use of interferometry to the wider community of astronomers who could use it as a tool to do their science. As part of this expansion, organisations in Europe and the USA began to hold summer schools to provide an introduction to the theory and practice of interferometry to astronomers new to the topic. A number of times after giving lectures at these schools, I have had students come up to me wanting to find out more about some 'well-known' interferometric idea that I have mentioned in my talk. Often I have had to reply that there is no one place in the literature which provides this further information.

While a lot of the knowledge has been built up by the community involved in the development of optical interferometry, much of it is not written down, or is scattered over multiple separate papers. The most useful single reference on the topic is provided by the course notes from the 1999 Michelson Summer School (Lawson, 1999), but of necessity it cannot cover the decade and more of developments in interferometry since its publication. Knowledge relevant to optical interferometry is also available in radio-astronomy textbooks (a good example is *Interferometry and Synthesis in Radio Astronomy* (Thompson *et al.*, 2008)), but finding it requires the reader to have an existing understanding of which elements of radio interferometry are relevant in practice to optical interferometry. This is because, although the same physical principles apply at both radio and optical wavelengths, many concerns which are important to the practice of interferometry in one wavelength regime do not arise in the other.

This book is mainly aimed at enabling the newcomer to optical interferometry to get 'up to speed' on the topic, providing a basic reference on the fundamental concepts applicable to present-day optical interferometry. It aims to give simple rules-of-thumb to allow a quick understanding of what is important, but also shows how a more rigorous understanding of more detailed aspects can be derived, without necessarily giving detailed derivations in all cases. The ideas are presented assuming a mathematical background at the level required for an undergraduate physics course, including concepts such as complex exponentials and random walks. Where possible, examples from the literature are given in order to relate the more abstract ideas to their practical roots.

The main intended audience for this book is students and researchers in astronomy who want to use an interferometer as a tool for doing science. This book concentrates on the most 'mainstream' application of interferometry, which is loosely termed 'imaging': this can range from measuring a few parameters of an object's appearance based on a simple model (for example measuring a diameter of a star under the assumption that it is round) to true 'aperture synthesis', reconstructing model-independent images of the object under study.

In the interests of brevity, less is said here about interferometric techniques such as nulling, polarimetry and astrometry that have undoubted scientific potential, but are less mature in their application, and as a result less readily available as a science tool for non-expert users. These techniques are evolving rapidly, and the consensus as to the best way to make them work is still quite fluid. Any useful discussion of these topics would need to cover all the possible directions of development in these modes of interferometry and might still not cover the key ideas which will turn out to be of importance to their successful establishment.

A second and overlapping audience for this book is students, instrumentation scientists and engineers who want to work on developing and building new instrumentation for interferometry. Interferometry is clearly on an upward arc, with new initiatives such as the Planet Formation Imager (`http://www.planetformationimager.org`) gaining support from a wide scientific user base. These initiatives will require the efforts of a new generation of scientists and technologists who are well-versed in the existing ideas of interferometry, but are also able to see beyond these techniques to understand what can make interferometry even more useful in the future. This book will hopefully provide a small stepping stone for such people.

Acknowledgements

I would like to thank my wife for her encouragement to take the idea for this book forward and her support for and patience with the process of writing it. The majority of the book's diagrams were drawn by Fran Harwood-Whitcher, who turned my rough scrawls into models of clarity. Karen Scrivener was instrumental in getting the necessary permissions for the images borrowed from other publications. James Gordon, Malcolm Longair, Aglaé Kelerer and Alex Wells read drafts of the manuscript and provided helpful comments and discussion. I am grateful to my colleagues at the Cavendish Laboratory for providing a stimulating work environment and the sabbatical which allowed me to get this book started. My editor, Vince Higgs, gave helpful advice along the way, and my colleagues in the worldwide interferometry community provided me with gentle and useful reminders that I really ought to finish this book. I would like to thank my mother for instilling me with an appreciation of the rewards of learning and teaching, and my father for his infectious enthusiasm for ideas and their practical application; the combination of these values in many ways provided the origin for this book.