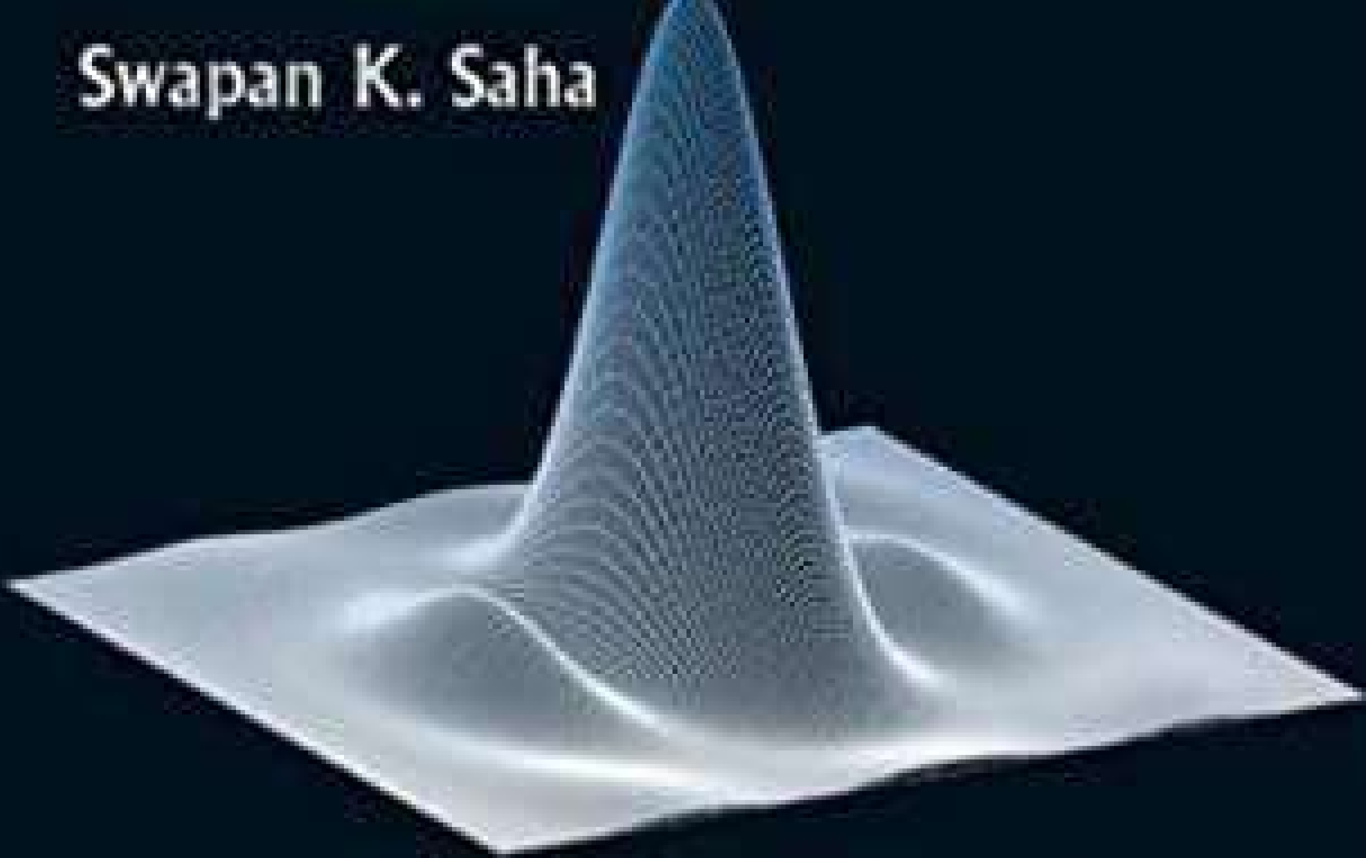
Swapan K. Saha



Diffraction-Limited Imaging with Large and Moderate Telescopes

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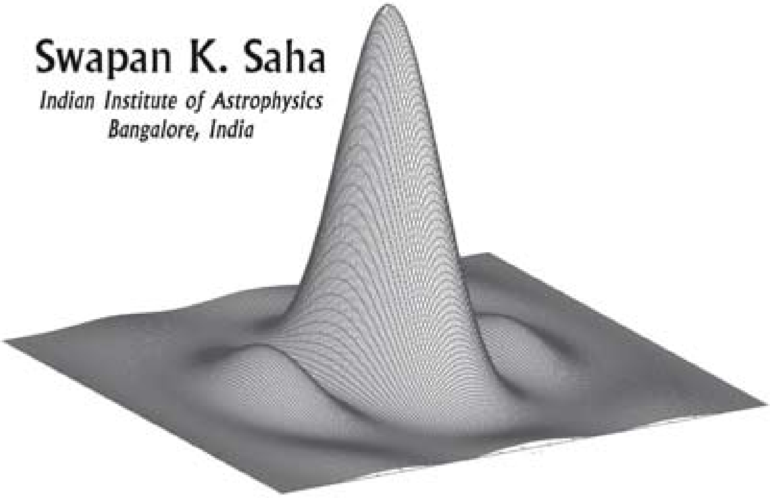
Swapan K. Saha
Indian Institute of Astrophysics
Bangalore, India



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DIFFRACTION-LIMITED IMAGING WITH LARGE AND MODERATE TELESCOPES

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In memory of my wife,
KALYANI

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Preface

Diffraction-limited image of an object is known as the image with a resolution limited by the size of the aperture of a telescope. Aberrations due to an instrumental defect together with the Earth's atmospheric turbulence set severe limits on angular resolution to $\sim 1''$ in optical wavelengths. Both the sharpness of astronomical images and the signal-to-noise (S/N) ratios (hence faintness of objects that can be studied) depend on angular resolution, the latter because noise comes from the sky as much as is in the resolution element. Hence reducing the beam width from, say, 1 arcsec to 0.5 arcsec reduces sky noise by a factor of four. Two physical phenomena limit the minimum resolvable angle at optical and infrared (IR) wavelengths − diameter of the collecting area and turbulence above the telescope, which introduces fluctuations in the index of refraction along the light beam. The cross-over between domination by aperture size ($\sim 1.22\lambda$/aperture diameter, in which λ is the wavelength of light) and domination by atmospheric turbulence ('seeing') occurs when the aperture becomes somewhat larger than the size of a characteristic turbulent element, that is known as atmospheric coherence length, r_0 (e.g. at 10- 30 cm diameter). Light reaching the entrance pupil of a telescope is coherent only within patches of diameters of order r_0. This limited coherence causes blurring of the image, blurring that is modeled by a convolution with the point-spread function (PSF), which prevents the telescope from reaching into deep space to unravel the secrets of the universe. The deployment of a space-bound telescope beyond the atmosphere circumvents the problem of atmosphere, but the size and cost of such a venture are its shortcomings.

This book has evolved from a series of talks given by the author to a group of senior graduate students about a decade ago, following which, a couple of large review articles were published. When Dr. K. K. Phua

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invited the author, for which he is indebted to, for writing a lecture note based on these articles, he took the opportunity to comply; a sequel of this note is also under preparation. This book is aimed to benefit graduate students, as well as researchers who intend to embark on a field dedicated to the high resolution techniques, and would serve as an interface between the astrophysicists and the physicists. Equipped with about two hundred illustrations and tens of footnotes, which make the book self-content, it addresses the basic principles of interferometric techniques in terms of both post-processing and on-line imaging that are applied in optical/IR astronomy using ground-based single aperture telescopes; several fundamental equations, Fourier optics in particular, are also highlighted in the appendices.

Owing to the diffraction phenomenon, the image of the point source (unresolved stars) cannot be smaller than a limit at the focal plane of the telescope. Such a phenomenon can be seen in water waves that spread out after they pass through a narrow aperture. It is present in the sound waves, as well as in the electro-magnetic spectrum starting from gamma rays to radio waves. The diffraction-limited resolution of a telescope refers to optical interference and resultant image formation. A basic understanding of interference phenomenon is of paramount importance to other branches of physics and engineering too. Chapters 1 through 3 of this book address the fundamentals of electromagnetic fields, wave optics, interference, and diffraction at length. In fact, a book of this kind calls for more emphasis on imaging phenomena and techniques, hence the fourth chapter discusses at length the imaging aspects of the same.

Turbulence and the concomitant development of thermal convection in the atmosphere distort the phase and amplitude of the incoming wavefront of the starlight; longer the path, more the degradation that the image suffers. Environment parameters, such as fluctuations in the refractive index of the atmosphere along the light beam, which, in turn, are due to density variations associated with thermal gradients, variation in the partial pressure of water vapour, and wind shear, produce atmospheric turbulence. Random microfluctuations of such an index cause the fluctuation of phase in the incoming random field and thereby, produce two dimensional interferences at the focus of the telescope. These degraded images are the product of dark and bright spots, known as speckles. The fifth chapter enumerates the origin, properties, and optical effects of turbulence in the Earth's atmosphere.

One of the most promising developments in the field of observational

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astronomy in visible waveband is the usage of speckle interferometry (Labeyrie, 1970) offering a new way of utilizing the large telescopes to obtain diffraction-limited spatial Fourier spectrum and image features of the object. Such a technique is entirely accomplished by *a posteriori* mathematical analysis of numerous images of the same field, each taken over a very short time interval. In recent years, a wide variety of applications of speckle patterns has been found in many areas. Though the statistical properties of the speckle pattern is complicated, a detailed analysis of this pattern is useful in information processing. Other related concerns, such as pupil plane interferometry, and hybrid methods (speckle interferometry with non-redundant pupils), have also contributed to a large extent. Chapter 6 enumerates the details of these post-detection diffraction-limited imaging techniques, as well as the relationship between image-plane techniques and pupil-plane interferometry.

Another development in the field of high angular resolution imaging is to mitigate the effects of the turbulence in real time, known as adaptive optics (AO) system. Though such a system is a late entry among the list of current technologies, it has given a new dimension to this field. In recent years, the technology and practice of such a system have become, if not in commonplace, at least well known in the defence and astronomical communities. Most of the astronomical observatories have their own AO programmes. Besides, there are other applications, namely vision research, engineering processing, and line-of-sight secure optical communications. The AO system is based on a hardware-oriented approach, which employs a combination of deformation of reflecting surfaces (i.e., flexible mirrors) and post-detection image restoration. A brief account of the development of such an innovative technique is presented in chapter 7.

The discovery of the corpuscular nature of light, beyond the explanation of the photo-electric effect, by Albert Einstein almost 100 years ago, in 1905, has revolutionized the way ultra-sensitive light detectors are conceived. Such a discovery has far reaching effects on the astrophysical studies, in general, and observational astronomy, in particular. The existence of a quantum limit in light detection has led to a quest, through the 20th century (and still going on), for the perfect detector which is asymptotically feasible. The advent of high quantum efficiency photon counting systems, vastly increases the sensitivity of high resolution imaging techniques. Such systems raise the hope of making diffraction-limited images of objects as faint as $\sim 15-16\ m_v$ (visual magnitude). Chapter 8 elucidates the development of various detectors that are being used for high resolution imaging.

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It is well known that standard autocorrelation technique falls short of providing reconstruction of a true image. Therefore, the success of single aperture interferometry has encouraged astronomers to develop further image processing techniques. These techniques are indeed an art and for most part, are post-detection processes. A host of image reconstruction algorithms have been developed. The adaptive optics system also requires such algorithms since the real-time corrected images are often partial. The degree of compensation depends on the accuracy of the wavefront estimate, the spacing of the actuators in the mirror, and other related factors. The mathematical intricacies of the data processing techniques for both Fourier modulus and Fourier phase are analyzed in chapter 9. Various schemes of image restoration techniques are examined as well, with emphasis set on their comparisons.

Stellar physics is the study of physical makeup evolutionary history of stars, which is based on observational evidence gathered with telescopes collecting electromagnetic radiation. Single aperture high resolution techniques became an extremely active field scientifically with important contributions made to a wide range of interesting problems in astrophysics. A profound increase has been noticed in the contribution of such techniques to measure fundamental stellar parameters and to uncover details in the morphology of a range of celestial objects, including the Sun and planets. They have been used to obtain separation and position angle of close binary stars, to measure accurate diameter of a large number of giant stars, to determine shapes of asteroids, to resolve Pluto-Charon system, to map spatial distribution of circumstellar matter surrounding objects, to estimate sizes of expanding shells around supernovae, to reveal structures of active galactic nuclei (AGN) and of compact clusters of a few stars like R 136a complex, and to study gravitationally lensed QSO's. Further benefits have been witnessed from the application of adaptive optics systems of large telescopes, in spite of its limited capability of retrieving fully diffraction-limited images of these objects. The last two chapters (10 and 11) discuss the fundamentals of astronomy and applications of single aperture interferometry.

The author expresses his gratitude to many colleagues, fellow scientists, and graduate students at Indian Institute of Astrophysics and elsewhere, particularly to A. Labeyrie, J. C. Bhattacharyya, and M. K. Das Gupta (late) for their encouragement and to Luc Damé, A. K. Datta, L. N. Hazra, Sucharita Sanyal, Kallol Bhattacharyya, P. M. S. Namboodiri, N. K. Rao, G. C. Anupama, A. Satya Narayana, K. Sankar Subramanian, B. S. Nagabhushana, Bharat Yerra, K. E. Rangarajan, V. Raju, D. Som, and A. Vyas,

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Swapan K. Saha

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Principal symbols

$\vec{E}$	Electric field vector
$\vec{B}$	Magnetic induction
$\vec{H}$	Magnetic vector
$\vec{D}$	Electric displacement vector
$\vec{J}$	Electric current density
$\vec{r}(=x, y, z)$	Position vector of a point in space
σ	Specific conductivity
μ	Permeability of the medium
ϵ	Permittivity or dielectric
q	Charge
$\vec{F}$	Force
$\vec{v}$	Velocity
$\vec{p}$	Momentum
$\vec{a}$	Acceleration
e	Electron charge
$S(\vec{r}, t)$	Poynting vector
$V(\vec{r}, t)$	Monochromatic optical wave
$\Re$ and $\Im$	Real and imaginary parts of the quantities in brackets
t	Time
κ	Wave number
ν	Frequency of the wave
A	Complex amplitude of the vibration
$U(\vec{r}, t)$	Complex representation of the analytical signal
$I(\vec{x})$	Intensity of light
I_ν	Specific intensity
$\langle\ \rangle$	Ensemble average
$*$	Complex operator

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λ	Wavelength
$\vec{x} = (x, y)$	Two-dimensional space vector
$P(\vec{x})$	Pupil transmission function
$\star$	Convolution operator
$\widehat{\ }$	Fourier transform operator
$\widehat{P}(\vec{u})$	Pupil transfer function
$S(\vec{x})$	Point spread function
$\widehat{S}(\vec{u})$	Optical transfer function
$\lvert\widehat{S}(\vec{u})\rvert^2$	Modulus transfer function
$\mathcal{R}$	Resolving power of an optical system
ω	Angular frequency
T	Period
$\vec{V}_j$	Monochromatic wave vector
j	$= 1, 2, 3$
$\mathcal{J}_{12}$	Interference term
$\Delta\varphi$	Optical path difference
λ_0	Wavelength in vacuum
c	Velocity of light
$\vec{\gamma}(\vec{r}_1, \vec{r}_2, \tau)$	Complex degree of (mutual) coherence
$\vec{\Gamma}(\vec{r}_1, \vec{r}_2, \tau)$	Mutual coherence
$\vec{\Gamma}(\vec{r}, \tau)$	Self coherence
τ_c	Temporal width or coherence time
$\Delta\nu$	Spectral width
l_c	Coherence length
$\vec{\gamma}(\vec{r}_1, \vec{r}_2, 0)$	Spatial coherence
$J(\vec{r}_1, \vec{r}_2)$	Mutual intensity function
$\mu(\vec{r}_1, \vec{r}_2)$	Complex coherence factor
$\mathcal{V}$	Contrast of the fringes
f	Focal length
v_a	Average velocity of a viscous fluid
l	Characteristic size of viscous fluid
R_e	Reynolds number
$n(\vec{r}, t)$	Refractive index of the atmosphere
$\langle\sigma\rangle$	Standard deviation
m_v	Apparent visual magnitude
M_v	Absolute visual magnitude
$L_\odot$	Solar luminosity
$L_\star$	Stellar luminosity

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$M_\odot$	Solar mass
$M_\star$	Stellar mass
$R_\odot$	Solar radius
$R_\star$	Stellar radius
$\langle\sigma\rangle^2$	Variance
k_B	Boltzmann constant
g	Acceleration due to gravity
H	Scale height
n_0	Mean refractive index of air
P	Pressure
T	Temperature
ε	Energy dissipation
$\Phi_n(\vec{k})$	Power spectral density
k_0	Critical wave number
l_0	Inner scale length
k_{l_0}	Spatial frequency of inner scale
$\mathcal{C}_n^2$	Refractive index structure constant
$\mathcal{D}_n(\vec{r})$	Refractive index structure function
$\mathcal{B}_n(\vec{r})$	Covariance function
$\mathcal{D}_v(\vec{r})$	Velocity structure function
$\mathcal{C}_v^2$	Velocity structure constant
$\mathcal{D}_T(\vec{r})$	Temperature structure function
$\mathcal{C}_T^2$	Temperature structure constant
h	Height
$(\vec{x}, h)$	Co-ordinate
$\Psi_h(\vec{x})$	Complex amplitude at co-ordinate, $(\vec{x}, h)$
$\langle\psi_h(\vec{x})\rangle$	Average value of the phase at h
δh_j	Thickness of the turbulence layer
$\mathcal{D}_{\psi_j}(\vec{\xi})$	Phase structure function
$\mathcal{D}_n(\vec{\xi}, \zeta)$	Refractive index structure function
$\mathcal{B}_{h_j}(\vec{\xi})$	Covariance of the phase
$\mathcal{B}(\vec{\xi})$	Coherence function
γ	Distance from the zenith
r_0	Fried's parameter
$O(\vec{x})$	Object illumination
$\left\langle \widehat{S}(\vec{u}) \right\rangle$	Transfer function for long-exposure images
$\vec{u}$	Spatial frequency vector with magnitude u

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$\widehat{I}(\vec{u})$	Image spectrum
$\widehat{O}(\vec{u})$	Object spectrum
$B(\vec{u})$	Atmosphere transfer function
$\mathcal{T}(\vec{u})$	Telescope transfer function
$F\#$	Aperture ratio
F	Flux density
$arg\vert\ \vert$	The phase of ‘ ’
p_j	Sub-apertures
β_{123}	Closure phase
θ_i, θ_j	Error terms introduced by errors at the individual antennae
$\mathcal{A}\delta(\vec{x})$	Dirac impulse of a point source
$\otimes$	Correlation
$\widehat{\mathcal{N}}(\vec{u})$	Noise spectrum
$\left\langle \vert\widehat{I}(\vec{u})\vert^2 \right\rangle$	Image energy spectrum
θ_j	Apertures
UBV	Johnson photometric system
$B(T)$	Brightness distribution

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List of acronyms

AAT	Anglo-Australian telescope
A/D	Analog-to-digital
AGB	Asymptotic giant branch
AGN	Active galactic nuclei
AMU	Atomic mass unit
AO	Adaptive optics
ASM	Adaptive secondary mirror
ATF	Atmosphere Transfer Function
BC	Babinet compensator
BDM	Bimorph deformable mirror
BID	Blind iterative deconvolution
BLR	Broad-line region
CCD	Charge Coupled Device
CFHT	Canada French Hawaii telescope
CHARA	Center for high angular resolution astronomy
CS	Curvature sensor
DM	Deformable mirror
EMCCD	Electron multiplying CCD
ESA	European space agency
ESO	European Southern Observatory
ESPI	Electronic speckle pattern interferometry
FOV	Field-of-view
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
FT	Fourier Transform
FWHM	Full width at half maximum
Hz	Hertz

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HF	High frequency
HR	Hertzsprung-Russell
HST	Hubble space telescope
ICCD	Intensified CCD
IDL	Interactive Data Language
IMF	Initial mass function
IR	Infrared
I2T	Interféromètre à deux Télescopes
KT	Knox-Thomson
kV	Kilovolt
laser	Light Amplification by Stimulated Emission of Radiation
LBOI	Long baseline optical interferometers
LBT	Large Binocular Telescope
LC	Liquid crystal
LF	Low frequency
LGS	Laser guide star
LHS	Left Hand Side
LSI	Lateral shear interferometer
L3CCD	Low light level CCD
maser	Microwave Amplification by Stimulated Emission of Radiation
MCAO	Multi-conjugate adaptive optics
MCP	Micro-channel plate
MEM	Maximum entropy method
MHz	Megahertz
MISTRAL	Myopic iterative step preserving algorithm
MMDM	Micro-machined deformable mirror
MMT	Multi mirror telescope
MOS	Metal-oxide semiconductor
MTF	Modulus Transfer Function
NGS	Natural guide star
NICMOS	Near Infrared Camera and Multi-Object Spectrograph
NLC	Nematic liquid crystal
NLR	Narrow-line region
NRM	Non-redundant aperture masking
NTT	New Technology Telescope
OPD	Optical Path Difference
OTF	Optical Transfer Function
PAPA	Precision analog photon address

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PHD	Pulse height distribution
PMT	Photo-multiplier tube
PN	Planetary nebula
PSF	Point Spread Function
PTF	Pupil Transmission Function
PZT	Lead-zirconate-titanate
QE	Quantum efficiency
QSO	Quasi-stellar object
RA	Right Ascension
RHS	Right Hand Side
RMS	Root Mean Square
SAA	Shift-and-add
SDC	Static dielectric cell
SLC	Smectic liquid crystal
SH	Shack-Hartmann
SL	Shoemaker-Levy
SN	Supernova
S/N	Signal-to-noise
SOHO	Solar and heliospheric observatory
SUSI	Sydney University Stellar Interferometer
TC	Triple-correlation
TTF	Telescope Transfer Function
UV	Ultraviolet
VBO	Vainu Bappu Observatory
VBT	Vainu Bappu Telescope
VTT	Vacuum Tower Telescope
WFP	Wiener filter parameter
WFS	Wavefront sensor
YSO	Young stellar objects

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