# Basic Optics for the ASTRONOMICAL SCIENCES

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# Preface

Astronomical science advances use the following research cycle: measure parts of the universe, develop theories to explain the observations, use these new theories to forecast or predict observations, build new telescopes and instruments, measure again, refine the theories if needed, and repeat the process. Critical to the success of this cycle are new observations, which often require new, more sensitive, efficient astronomical telescopes and instruments.

Currently, the field of astronomy is undergoing a revolution. Several new important optical/infrared windows into the universe are opening as a result of advances in optics technology, including systems using high angular resolution, very high dynamic range, and highly precise velocity and position measurements. High-angular-resolution systems, which incorporate adaptive optics and interferometry, promise gains of more than $10^4$ in angular resolution on the sky above our current capabilities. Advanced coronagraphs enable very high-dynamic-range systems that enable astronomers to image an exoplanet in the presence of the blinding glare from its parent star that is more than $10^{12}$ times brighter.

Optical science is the study of the generation, propagation, control, and measurement of optical radiation. The optical region of the spectrum is considered to range across the wavelength region of ~0.3 to ~50 μm, or from the UV through the visual and into the far infrared. Different sensors or detectors are used for covering sections of this broad spectral region. However, the analysis tools required to design, build, align, test, and characterize these optical systems are common: geometrical raytracing, wavefront aberration theory, diffraction theory, polarization, partial coherence theory, radiometry, and digital image restoration. Advances in allied disciplines such as material science, thermal engineering, structures, dynamics, control theory, and modeling within the framework of the tolerances imposed by optics are essential for the next generation of telescopes.

This text provides the background in optics to give the reader insight into the way in which these new optical systems are designed, engineered, and built. The book is intended for astronomy and engineering students who want a basic understanding of optical system engineering as it is applied to telescopes and instruments for astronomical research in the areas of astrophysics, astrometry, exoplanet characterization, and planetary science. Giant ground-based optical telescopes such as the Giant Segmented Mirror Telescope, the Thirty Meter Telescope, and the Extremely Large Telescope are currently under development.

The James Webb Space Telescope is under construction, and the Space Interferometer Mission has successfully completed its technology program. The astronomical sciences are, indeed, at the threshold of many new discoveries.

Chapter 1 provides an historical perspective on the development of telescopes and their impact on our understanding of the universe. Chapter 2 reviews the optical measurements astronomers record and identifies the attributes for ground and space observatories. Chapter 3 provides the tools used for obtaining image location, size, and orientation and presents the geometrical constraints that need to be followed to maximize the amount of radiation passed by the system. Chapter 4 presents geometrical aberration theory and introduces the subject of image quality. Chapter 5 provides methods to maximize the amount of radiation passing through the optical system: transmittance, throughput, scattered light, and vignetting. Chapter 6 provides a basic introduction to radiative transfer through an optical system and identifies several factors needed to maximize the signal-to-noise ratio. Chapter 7 provides an introduction to the optics of the atmosphere necessary for ground-based astronomers. Chapter 8 introduces the scalar and vector wave theories of light and identifies sources of instrumental polarization that will affect the quality of astronomical data.

Using the Fourier transform, Chapter 9 provides an in-depth analysis of the propagation of scalar waves through an optical system as the basis of a discussion on the effects of astronomical telescopes and instruments on image quality. Chapter 10 provides a discussion of interferometry within the framework of partial coherence theory. The Fourier transform spectrometer, the Michelson stellar interferometer, and the rotational shear interferometer are used as examples and are analyzed in detail. Chapter 11, coauthored with Siddarayappa Bikkannavar, discusses the important new role that optical metrology and wavefront sensing and control play in the design and construction of very large ground- and space-based telescopes.

These 11 chapters have formed the basis of the Optical System Engineering class given by the author at CALTECH. Chapter 12 provides an analysis that is fundamental to the understanding of segmented-aperture telescopes and how they enable the next-generation, very large ground- and space-based telescopes. Chapter 13 presents an analysis of sparse-aperture telescopes, describes how they are used for extremely high angular resolution, and identifies their limitations. Chapter 14 discusses astrometric and imaging interferometry within the framework of basic optics. Chapter 15 develops basic concepts for extreme-contrast systems such as coronagraphs for the characterization of exoplanet systems.

**James B. Breckinridge**
Pasadena, California
May 2012

# Acknowledgments

This book would not have been written if Nick George (now of the Institute of Optics) had not invited me to teach a one-quarter class in optical engineering at CALTECH in 1979. Bill Bridges and Noel Corngold of CALTECH sustained interest in this class, allowing me to teach it for the following 25 years. Mustafa Chahine, then the chief scientist at JPL, and Lew Allen, the JPL director, encouraged my participation at the campus. Amnon Yariv suggested I write this book many years ago.

After a 40-year career in the optical sciences, there are too many colleagues to thank. Omissions are not intentional; unfortunately, I can only mention a few here. For Chapter 1 (Historical Perspective), I wish to acknowledge the Huntington Library in Pasadena, where, as a reader, I have spent many hours with old books on optics and optics technology from the Burndy History of Science and Technology collection. The contents of Chapters 3 (First-Order Optics), 4 (Aberration Theory: Image Quality), 5 (Transmittance, Throughput, and Vignetting), and 6 (Radiometry and Noise) were derived from the class notes of R. Shack, R. Shannon, and W. Wolfe at the College of Optical Sciences, University of Arizona and modified over the years to fit the needs of the author's CALTECH optics class. The contents of Chapter 7 (Optics of the Atmosphere) were derived from the author's 40 years of work to understand the propagation of optical wavefronts through the atmosphere. Chapter 9 (Scalar Diffraction and Image Formation) closely follows the excellent development by Prof. J. Goodman at Stanford University. Chapter 10 (Interferometry) originated with classes by R. Shack and A. Marathay that complemented the author's personal interest in the topic for the past 35 years. Chapter 11 (Optical Metrology and Wavefront Sensing and Control) was authored with Siddarayappa Bikkannavar. Chapter 12 (Segmented-Aperture Telescopes) was inspired by Meinel's work in large, next-generation telescopes. Chapter 13 (Sparse-Aperture Telescopes) was developed from an interest in the role of interferometry and partial coherence in the image-formation process and the work of my colleagues in this field, Jim Fienup of the Institute of Optics and Bob Fiete of Kodak. Chapter 14 (Astrometric and Imaging Interferometry) was inspired by the successful work of Mike Shao and Hal McAlister. Chapter 15 (Coronagraphy: Control of Unwanted Radiation) originated with my interest many years ago in solar coronagraphs and current challenges to building exoplanet-characterization coronagraphs.

I want to particularly thank my wife Ann and our two sons Doug and John, without whose help and patience over the past 45 years of my career this book would never have been written. I also acknowledge the help and support given by my mentors and colleagues over the years: J. J. Nassau, G. E. Kron, A. K. Pierce, C. B. Farmer, F. G. O'Callaghan, and A. B. Meinel. Finally, throughout my career, my students have been an invaluable aid.

# List of Acronyms

| | |
|---|---|
| BFD | back focal distance |
| BFP | back focal point |
| CAD | computer-aided design |
| CGH | computer-generated hologram |
| CHARA | Center for High Angular Resolution Astronomy |
| CTE | coefficient of thermal expansion |
| dp | detected photons |
| DM | deformable mirror |
| E-ELT | European Extremely Large Telescope |
| EFL | effective focal length |
| ESO | European Southern Observatory |
| FFL | front focal length |
| FOV | field of view |
| FP | Fabry–Pérot |
| FTS | Fourier transform spectrometer |
| GMT | Giant Magellan Telescope |
| GSMT | Giant Segmented Mirror Telescope |
| GTC | Gran Telescopio Canarias |
| HET | Hobby Eberly Telescope |
| H-R | Hertzsprung–Russel |
| HST | Hubble Space Telescope |
| ICESat | Ice, Cloud, and land Elevation Satellite |
| ISI | Infrared Spatial Interferometer |
| JWST | James Webb Space Telescope |
| LBT | Large Binocular Telescope |
| LDR | large deployable reflector |
| MACAO | multi-application curvature adaptive optics |
| marcsec | milli-arcseconds |
| MCF | mutual coherence function |
| MSI | Michelson stellar interferometer |
| MTF | modulation transfer function |
| MTT | multiple-telescope telescope |
| OPD | optical path difference |
| OTA | optical telescope assembly |
| OTF | optical transfer function |
| PSF | point spread function |

| | |
|---|---|
| rms | root-mean-square |
| rss | root of the sum of squares |
| SDSS | Sloan Digital Sky Survey |
| SIM | Space Interferometer Mission |
| SLR | single-lens reflex |
| SNR | signal-to-noise ratio |
| STIS | Space Telescope Imaging Spectrograph |
| TMT | Thirty Meter Telescope |
| TPF-C | Terrestrial Planet Finder Coronagraph |
| VCM | variable-curvature mirror |
| VLA | Very Large Array |
| VLTI | Very Large Telescope Interferometer |
| WFC | wavefront correction |
| WFE | wavefront error |
| WF/PC | Wide-Field/Planetary Camera |
| WFSC | wavefront sensing and control |
| WISE | Wide-field Infrared Survey Explorer |