BUILDING ELECTRO-OPTICAL SYSTEMS

Physical Constants and Rules of Thumb

Solar constant (at zenith, above atmosphere)	1.36 kW/m^2, 20 MW/m^2/sr, 136 klx
Transmittance of clear atmosphere	0.8
Minimum luminance for easy reading	5 lx
Bright room lights	400 lx
Bright desk lamp for close work	7000 lx
Peak luminous efficiency of light-adapted eye	683 lm/W @552 nm, -3 dB @510&610
Brightest stars (m_v = 0)	2.0 μlx at ground
Faintest naked-eye star (m_v = 6)	$8{\cdot}10^{-9}$ lx at ground
Black body radiation	56.7 kW/m^2 at 1000 K
Earth's magnetic field B	0.3 to 0.6 gauss
Circular cone of half-angle θ	NA = $n\sin\theta$, $\Omega' = \pi$(NA)^2
Airy disc radius of circular aperture of radius a	$0.61\lambda/a$ radians ($a \gg \lambda$)
Étendue of Gaussian beam	$(\pi\lambda/4)^2$
Waist radius of Gaussian beam	$w = \lambda/(\pi$NA)
Airy disc diameter in the visible	$a \approx f\#$ = 0.5/NA (a in microns)
Defocus Tolerance	$\lvert\Delta Z\rvert < 0.5\lambda$/(NA)^2
Peak efficiency of an optical system + photodiode	0.4 to 0.8 depending on coatings
Image flux density at f/8 (0.063 NA), distant object	1% of object flux density (Lambertian)
Strehl ratio with RMS wavefront error E waves	$S \approx \exp(-E^2/2)$
Diffraction limit	λ/4 RMS wavefront error $\rightarrow$ 0.8 Strehl
Hyperfocal distance of lens of diameter D	D^2/λ
Aberration scaling with NA and field angle	Spherical $\propto$ (NA)^3, Coma $\propto$ (NA)$^2\theta$, Astigmatism & Field Curvature $\propto$(NA)θ^2, Distortion (barrel or pincushion) $\propto \theta^3$
Things invariant under magnification:	radiance, $n^2A\Omega'$, # resolvable spots, phase shift, total power
Fibre Étendue: $n^2A\Omega'$ (cm^2·sr)	$\sim 3{\cdot}10^{-6}$ (SM), $3{\times}10^5$-10^{-3} (step MM)
Responsivity of photodiode (η = 1)	$\mathcal{R}_{\max} = \lambda/1.240\ \mu$m A/W
1 dB increase	26% power, 12% voltage
Additional noise producing 1 dB SNR reduction	5.87 dB below noise floor
Shot Noise limit	$i_{\text{photo}}R_L > 2kT/e$ (50 mV at 300 K)
Shot Noise Rule of One	1σ AC shift with 1 photon/s in 1 Hz coherently added
Shot Noise of 1 mA	17.90 pA/$\sqrt{\text{Hz}}$
Resistor with Johnson noise of 1 nV/$\sqrt{\text{Hz}}$ (300 K)	60.4 Ω
Resistor with Johnson noise of 1 pA/$\sqrt{\text{Hz}}$ (300 K)	16.56 kΩ
Noise power with matched source (NF = 0 dB for pure Johnson noise)	P_J(dBm) = -173.8 + NF + 10 log $\left(\frac{T}{300\text{K}}\right)$ + 10 log BW
Quantization noise	1/$\sqrt{12}$ ADU
Sine wave power (50 Ω)	P(dBm) = 4 + 20 log$_{10}V_{\text{pp}}$
Transconductance of bipolar transistor	$g_m = ei_C/(kT) = i_C$/25.7 mV (300 K)
Sheet resistance of 0.5-oz copper (0.017 mm)	1.0 m$\Omega/\square$ at 25°C
Inductance of 1 inch component lead	$L \approx$ 20 nH
Capacitance of 1mm^2 pad on 4-layer card	0.08 - 0.2 pF (1 & 3 layers from ground)
Low frequency capacitance of RG-58 cable	100 pF/m

BUILDING ELECTRO-OPTICAL SYSTEMS

MAKING IT ALL WORK
SECOND EDITION

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In memory of my father,
Gerald H. D. Hobbs
John 6:40

✝

We have a habit in writing articles published in scientific journals to make the work as finished as possible, to cover up all the tracks, to not worry about the blind alleys or describe how you had the wrong idea first, and so on. So there isn't any place to publish, in a dignified manner, what you actually *did* in order to get to do the work.

—Richard P. Feynman, Nobel lecture 1966.

CONTENTS

PREFACE

> You are fools, to say you learn from your mistakes. I learn from the mistakes of other men.
>
> —Otto von Bismarck

This is a book of lore. *Lore* is an old word for wisdom and knowledge. While it often refers to magic and epic poetry, what I mean by it is altogether more homely: a mixture of rules of thumb, experience, bits of theory, and an indefinable feeling for the right way to do things, a sort of technical taste. It is what makes the difference between analyzing a design once completed and coming up with a good design to fit a particular purpose. Course work and textbooks have lots of analysis but most contain no lore whatsoever.

One of the odd things about lore is that it lives in the fingers more than in the brain, like piano playing. In writing this book, I have often run up against the difference between how I do something and how I *think* I do it, or how I remember having done it. Since it's the actual lore of doing that is useful, I have where possible written or revised each section when I was actually doing that task or consulting with someone who was. I hope that this gives those sections a sense of immediacy and authenticity.

Apologia

Lore is acquired slowly through experience and apprenticeship. Beginners pester experts, who help fairly willingly, mostly because they're kept humble by stepping in potholes themselves. This mutual aid system works but is slow and unsystematic. As a beginner, I once spent nearly six months trying to get a fancy laser interferometer to work properly, a task that would now take about a week. The reason was a breakdown in the apprenticeship system—everyone consulted said 'Oh, that comes with practice'—perfectly true, and by no means unsympathetic, but not too helpful. Conversations with many others in the field indicate that this sort of thing is the rule and not the exception. Time, enthusiasm and confidence are far too precious to go wasting them like that.

This book is an attempt to provide a systematic and accessible presentation of the practical lore of electro-optical instrument design and construction—to be the book I needed as a graduate student. It is intended for graduate students at all levels, as well as practicing scientists and engineers: anyone who has electro-optical systems to build and could use some advice. Its applicability ranges from experimental apparatus to optical disc players.

The range of topics covered here is enormously broad, and I wish I were master of it all. Most of it was invented by others whose names I don't know; it's the lore of a whole field, as filtered through one designer's head. It's mostly been learned by watching and doing, or worked out with colleagues at a white board, rather than reading journal articles, so there aren't many references. For further reading, there is a list of 100 or so good books in the Appendix that should fill in the gaps.

I hope that a book like this can erect bridges between subdisciplines, prevent common mistakes and help all those working on an instrument project to see it as a whole. So much good stuff gets lost in the cracks between physics, electrical engineering, optical engineering, and computer science, that a salvage attempt seemed justified. I apologize to those whose work has been acknowledged inadequately or whose priority has been overlooked, and hope that they can remember once needing a book like this.

Mission

Designing and constructing electro-optical instruments is without a doubt one of the most interdisciplinary activities in engineering. It makes an absorbing and rewarding career, with little danger of growing stale. On the other hand, the same interdisciplinary quality means that instrument building is a bit scary and keeps us on our toes. The very broad range of technologies involved means that at least one vital subsystem lies outside the designer's expertise, presenting a very real danger of major schedule slippage or outright failure, which may not become apparent until very late in the project.

We in electro-optics rely on whatever subset of these technologies we are familiar with, together with a combination of outside advice, collaboration, and purchased parts. Often, there are many ways of reaching the goal of a robust, working system; then the problem is where to start among a range of unfamiliar alternatives. It's like the classic computer game `ADVENT`: `'You are in a maze of twisty little passages, all different.'` Some judicious advice (and perhaps a map left by a previous adventurer) is welcome at such times, and that's what this book is about, the lore of designing and building electro-optical instruments that work.

To have confidence in an instrument design, we really need to be able to calculate its performance ahead of time, without constructing an elaborate simulation. It is a nontrivial matter, given the current fragmented state of the literature, to calculate what the resolution and SNR of a measurement system will be before it is built. It's not that there isn't lots of information on how to calculate the performance of each lens, circuit, or computer program, but rather the complexity of the task and the very different ways in which the results are expressed in the different fields encountered. For example, what is the effect of fourth-order spherical aberration in the objective lens on the optimal band-setting filter in the analogue signal processor, and then on the signal-to-noise ratio of the ultimate digital data set? Somebody on the project had better know that, and my aim is to make you that somebody.

The book is intended in the first instance for use by oppressed graduate students in physics and electrical engineering, who have to get their apparatus working long enough to take some data before they can graduate. When they do, they'll find that real-world design work has much the same harassed and overextended flavour, so in the second instance, it's intended for working electro-optical designers. It can be used as a text in a combined lecture-laboratory course aimed at graduate students or fourth-year undergraduates, and as a self-teaching guide and professional reference by working designers.

The warm reception which the first edition received suggests that despite its faults it has filled a real need. In this edition, everything has been revised, some previously over-terse sections have been expanded, and more than 100 pages' worth of new material has been added. Component lists and electronic designs have been updated where needed. Only a very few things have been dropped, owing to space constraints or component obsolescence.

Organization

Textbooks usually aim at a linear presentation of concepts, in which the stuff on page n does not depend on your knowing pages $n + 1...N$. This is very valuable pedagogically, since the reader is initially unfamiliar with the material and usually will go through the book thoroughly, once, under the guidance of a teacher who is presenting information rapidly. Reference books are written for people who already have a grasp of the topic but need to find more detail or remind themselves of things dimly remembered. Thus they tend to treat topics in clumps, emphasizing completeness, and to be weak on overall explanations and on connections between topics.

Those two styles work pretty well in some subject areas, but design lore is not one of them. Its concepts aren't branched like a tree, or packed like eggs in a crate, but rather are interlinked like a fishnet or a sponge; thus a purely linear or clumped presentation of lore is all but impossible without doing violence to it. Nonetheless, to be any use, a lore book must be highly accessible, both easy to work through sequentially and attractive to leaf through many times.

Computer scientists use the concept of locality of reference—it's a good thing if an algorithm works mainly with data near each other in storage, since it saves cache misses and page faults, but all the data have to be there, regardless. That's the way I have tried to organize this book: most of the lore on a particular topic is kept close together in the book for conceptual unity and easy reference, but the topics are presented in a sufficiently linear order that later chapters build mainly on earlier ones, and important connections are noted in both forward and backward directions[1]. A certain amount of messiness results, which (it is to be hoped) has been kept close to a minimum. This approach gives rise to one minor oddity, which is that the same instruments are considered from different angles in different chapters, so some flipping of pages is required to get the whole picture.

The book is organized into three sections: Optics; Electronics and Signal Processing; and Special Topics In Depth (Front Ends and Bringing Up The System). There is also Supplementary Material, available from the web sites ftp://ftp.wiley.com/public/sci_tech_med/electro-optical and http://electrooptical.net, which comprises Chapter 20 on Thermal Control and chapter problems for the whole book.

The material is presented in varying levels of detail. The differences in the detail levels reflect the amount of published lore and the measured density of deep potholes that people

[1]Because electro-optical lore is so interconnected, useful connections which are tangential to the discussion are relegated to footnotes. An occasional polemic is found there too.

fall into. For example, there are lots of potholes in optomechanical design, but weighty books of relevant advice fill shelf after shelf. Anyway, mechanical problems aren't usually what cause instrument projects to fail—unexamined assumptions, inexperience, and plain discouragement are. To get the job done, we talk instead about how to avoid common mistakes while coming up with something simple that works reliably.

The one big exception to this general scheme is Chapter 1. It pulls in strands from everywhere, to present the process and the rhythm of conceptual design, and so contains things that many readers (especially beginners) may find unfamiliar. Don't worry too much about the technical aspects, because there's more on all those things later in the book, as well as pointers to other sources.

A complete instrument design course based on this book would probably have to wait for a first- or second-year graduate class. Undergraduate students with a good grasp of electromagnetism, physical optics, and Fourier transforms might benefit from a fourth-year course on optical instruments based selectively on the first ten chapters. To get the most out of such a course, the audience should be people with instruments of their own to build, either in a lab course, as a senior project, or as part of their graduate work. Because of the complicated, interdisciplinary nature of instrument building, the laboratory part of the course might best be done by teams working on an instrument project rather than individually, provided that each designer knows enough about everybody else's part to be able to explain it.

Chapter Problems

Chapter problems for the book are available on the websites listed above. Making complicated tasks intuitive is the true realm of lore—knowing the mathematical expression for the fringe pattern of a defocused beam is less useful than knowing which way to turn which knob to fix it. The most powerful method for gaining intuition is to use a combination of practical work and simple theoretical models that can be applied easily and stay close to the real physics. Accordingly, the emphasis in the problems is on extracting useful principles from theory and discussion.

Most of the problems have been taken from real design and scientific work, and so tend to be open-ended. Most students will have had a lot of theoretical training, but nowadays most will not have the skills of a Lightning Empiricist, a gimlet-eyed designer who's fast at mental rule-of-thumb calculations and who sanity checks everything by reflex. Perhaps this book can help fix that.

Errata

A certain number of errors and misconceptions—hopefully minor—are bound to creep into a book of this type, size and scope, unfortunately. I welcome your comments and corrections, large and small: errata and omissions will be made available at
ftp://ftp.wiley.com/public/sci_tech_med/electro-optical/errata2.txt
http://electrooptical.net/www/beos2e/errata2.txt,
and will be incorporated in future printings. Send email to hobbs@stanfordalumni.org.

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Michaelmas (September 29), 2008

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To acquire lore, one needs a big sandbox and long uninterrupted stretches of time to spend there, absorbed in the play. I am forever grateful to my parents for providing that sort of environment in my growing up, and for believing in me even when only the mess was visible.

I learned most of this material through participating in the stimulating and supportive technical cultures of the places where I've been fortunate enough to study and to work: the Edward L. Ginzton Laboratory at Stanford University, Stanford, California; the Department of Physics and the Department of Geophysics & Astronomy at the University of British Columbia and Microtel Pacific Research (both in Vancouver BC) and, for twenty-one years, the IBM Thomas J. Watson Research Center at Yorktown Heights, New York. I owe a special debt to IBM and to my managers there, Arthur Ciccolo, Frank Libsch, and John Mackay, for supporting this project and for generously allowing me time and resources to work on it.

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P. C. D. H.