Optical Systems Engineering

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For anyone who finds this book useful

Preface

> I want to solve a problem.... I want to see how I can clarify the issue in order to reach the solution. I try to see how the area is determined, how it is built up in this figure.... Instead, someone comes and tells me to do this or that; viz., something like $1/a$ or $1/b$ or $(a - b)$ or $(a - b)^2$, things which clearly have no inner relation to the issue.... Why do just this? I am told "Just do it"; and then another step is added, again ununderstandable in its direction. The steps drop from the blue; their content, their direction, the whole process... appears arbitrary, blind to the issue of how the area is built up.... In the end, the steps do lead to a correct, or even proved answer. But the very result is seen in a way that gives no insight, no clarification.
>
> Max Wertheimer, *Productive Thinking*

> The result is that people who have understood even the simplest, most trivial-sounding economic models are often far more sophisticated than people who know thousands of facts and hundreds of anecdotes, who can use plenty of big words, but have no coherent framework to organize their thoughts.
>
> Paul Krugman, *The Accidental Theorist*

This book is for anyone developing optical hardware. With many optical engineering texts already on the market with a similar theme, what is there about this book that distinguishes it from the others?

On the simplest level, there are few books that approach optical systems engineering as a unique field of knowledge. For example, the range of system engineering skills useful in industry—system architecture trades, feasibility studies, performance modeling, requirements analysis and flow-down, allocation of error budgets, subsystem and component specifications, tying together the interfaces between subsystems, and evaluating vendor progress to ensure performance of critical hardware—are rarely addressed. These skills all build on a strong understanding of optical engineering fundamentals but are quite different from the traditional testing and lens design aspects of optical engineering found in other books.

At the same time, *no* book can provide the intuitive eye-hand-mind connections required for deep learning and the "aha!" moments that come from the first light of understanding. This intuition requires a kinesthetically enhanced, learning-by-doing-and-thinking (*mens et manus*) approach. However, the tone, language, and style of a book strongly affect the "mind" part of this balance, and the ability to imagine new designs is often limited not by a lack of inherent creative ability but rather by *how* the material was learned and the resulting associations formed.

As a result, and as implied by the opening quotations from Wertheimer and Krugman, the pedagogical goal is a book that encourages independent thinking—not memorization, anecdotes, or algebraic "flute music." This book is by no means perfect in that regard, but considerable effort has been made to emphasize physical understanding more so than algebra. Complex algebraic derivations are *not* a useful engineering skill, yet they seem to have become the norm for many university lectures. This development does not stem from any profundity in their content; instead, it has arisen because the academic system generally doesn't reward time put into teaching. Status and money are usually awarded to those professors who excel at winning research grants, with the result that students—and the faculty who enjoy working with them—are often left behind.

In contrast to these trends, the focus of this book is on the practical aspects of optical systems engineering that are useful in industry. The most important of these is the use of physical reasoning to understand design trends. For example, is a bigger or smaller engine needed to pull a heavy load up a steep mountain? It's not necessary to use Newton's laws to answer this question; with a few assumptions about what is meant by "heavy" and "steep," our experience with cars and mountains allows us to answer it immediately. Similar questions can be asked of optical systems: Is a bigger or smaller aperture needed for better image quality? Does the answer depend on pixel size? What about the amount of light the system collects—does it depend on the size of the aperture, the size of the pixels, or both? Unfortunately, much engineering instruction abounds with examples of what is *not* physical thinking. Geometrical optics, for example, is sometimes taught as if it were nothing more than a mathematical game of manipulating chief and marginal rays. Such an approach is sure to turn away students who are new to the field and would interest only those of an accounting mindset—who are not likely to be in an engineering classroom in the first place.

All this is not to say that mathematics has no value in hardware development. On the contrary, if a concept hasn't been quantified then it is equivalent to "viewgraph engineering," from which no useful hardware has ever been built. The correct strategy is not to ignore the mathematics but rather to ensure that comprehension and physical reasoning *precede* analysis, after which rules of thumb and back-of-the-envelope calculations—which are correct to an order of magnitude—can be applied. Such systems-level feasibility analysis can then be followed up with the use of specialized, "back-of-the-elephant" design software for lens design, optical filters, stray light modeling, STOP analysis, and so forth.

For additional background, the field of optical engineering has been blessed with a number of excellent books. These include Jenkins and White's *Fundamentals of Optics*, Hecht's *Optics*, Smith's *Modern Optical Engineering*, Fischer's *Optical System Design*, Friedman and Miller's *Photonics Rules of Thumb*, and Hobbs's *Building Electro-Optical Systems*. Although not strictly a text on optics, Frank Crawford's *Waves* is a work of teaching genius. The only prerequisites for this book are either Hecht or Jenkins and White along with familiarity with Snell's law, the lens equation for simple imaging, and the concepts of wavelength and wavefronts.

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CHAPTER 1

Introduction

The telescope was almost as big as a school bus, the largest ever launched into space. It was also one of the most sophisticated optical systems ever built, capable of imaging galaxies near the beginning of the universe with a quality and sensitivity designed to exceed the best cameras used by professional photographers.

The engineers, scientists, technicians, and managers who worked on its development waited anxiously as results from its collection of "first light" started to come in. In the month since its release from the Shuttle bay into an orbit around the Earth (Fig. 1.1), the Hubble Space Telescope (HST) had gone through a number of performance checks and was now ready to collect images.

Elation greeted those first images to come in, but it was soon followed by skepticism from one of the astronomers evaluating the results. Instead of crisp, high-quality images of far-away galaxies, the pictures were fuzzy—blurred to the point where it was soon clear to even the untrained eye that something had gone wrong. Rather than the vision of a young fighter pilot, NASA's new telescope was acting middle-aged and needed glasses.

As the root cause of the problem was slowly uncovered, it became clear that a simple error in measuring the shape of the largest mirror had turned a complex, $1.5 billion project into one of the most embarrassing mistakes in the history of optical systems development. At great cost, corrective "glasses" were eventually installed on the Hubble, which enabled images of the type shown in Fig. 1.2. Unfortunately, the company responsible for the error could not also repair its reputation and eventually sold off its once-profitable optics division, the price to be paid for engineering mistakes on this scale.

There were numerous opportunities to uncover the error before the telescope was launched. The reason it was not discovered evidently stems from an incorrect view of systems engineering that continues to this day—namely, that working hardware can be produced simply by "checking the boxes" for completed tasks. Unfortunately, this perspective misses some critical questions: Have the tasks been correctly defined, and have they been *successfully*

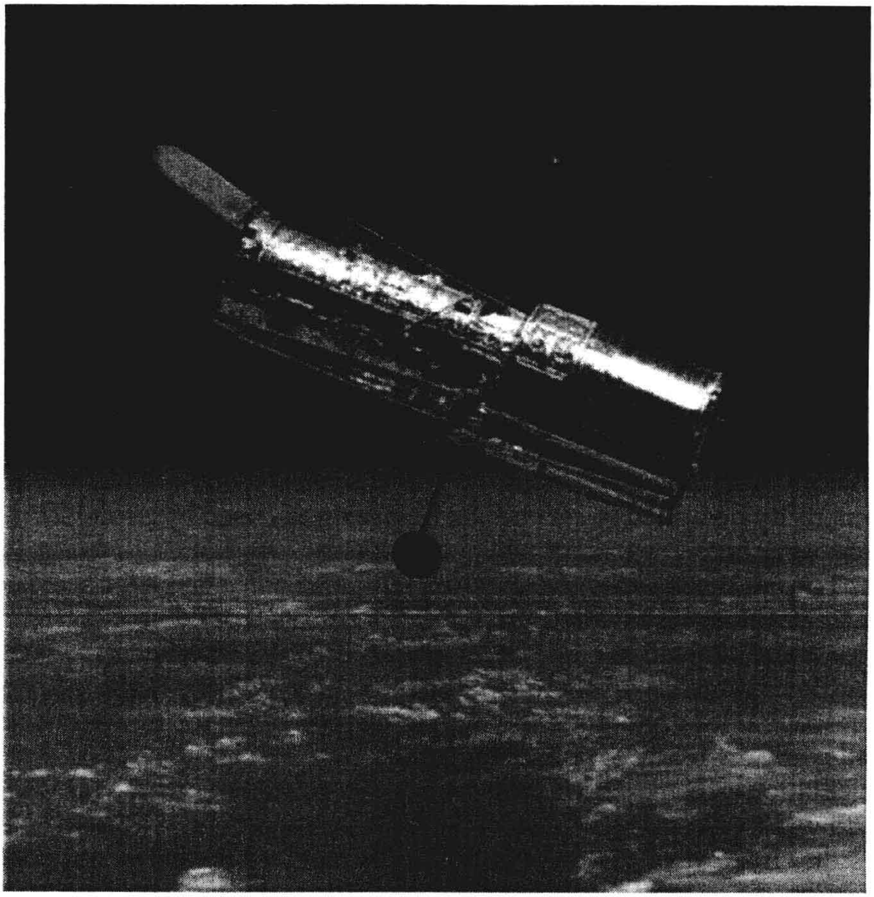

Figure 1.1 The Hubble Space Telescope in orbit around the Earth. This photo was taken from the Space Shuttle. (*Photo credit: NASA, www.nasa.gov.*)

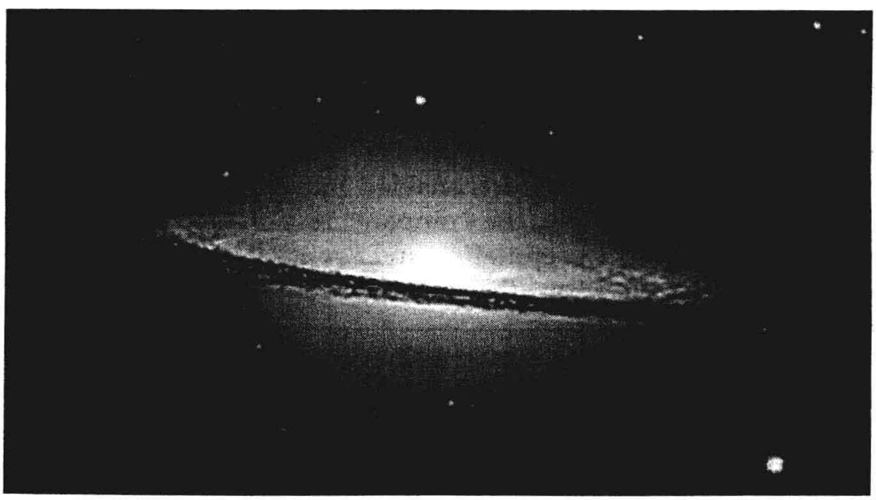

Figure 1.2 Hubble image of the M104 (Sombrero) Galaxy, located 30 million light years from Earth. The galaxy contains several hundred billion stars in a region 60,000 light years in diameter. (*Photo credit: NASA, www.nasa.gov.*)

completed? More importantly: Who is in a position to know? The NASA *Failure Report* described the cause in a similar manner:[9]

- "Although the telescope was recognized as a particular challenge, with a primary mirror requiring unprecedented performance, there was a surprising lack of optical experts with experience in the manufacture of large telescopes during the fabrication phase."
- "Fabrication of the HST mirror was the responsibility of the Optical Operations Division of Perkin-Elmer, which did not include optical design scientists and which did not use the skills external to the division which were available to Perkin-Elmer."
- "Perkin-Elmer line management did not review or supervise their Optical Operations Division adequately. In fact, the management structure provided a strong block against communication between the people actually doing the job and higher-level experts both within and outside Perkin-Elmer."
- "The Optical Operations Division at Perkin-Elmer operated in a 'closed door' environment which permitted discrepant data to be discounted without review."
- "The Perkin-Elmer Technical Advisory Group did not probe at all deeply into the optical manufacturing process . . . . This is particularly surprising since the members were aware of the history . . . where spherical aberration was known to be a common problem."
- "The quality assurance people at Perkin-Elmer . . . were not optical experts and, therefore, were not able to distinguish the presence of inconsistent data results from the optical tests."

While it's also easy to blame a "not invented here" (NIH) attitude for the lack of communication and cooperation, a more likely cause is short schedules and tight budgets. For example, the phrase "This is particularly surprising" that was used to describe the Perkin-Elmer Technical Advisory Group is a clue that project schedules took precedence over technical expertise. It's not difficult to imagine program managers, faced with a tight schedule and slowly realizing the complexity of the task, saying: "We don't have time for all this 'review' and 'oversight' stuff!"

The pressures of tight schedules can be overwhelming, but familiarity and experience with the tasks reduces the stress considerably. It seems that the "high-level experts" on the HST were so trained but that "the people actually doing the job" were not. Quality assurance people were singled out in the Hubble *Failure Report* as not being optical experts, but the same could probably be said of the technicians, assemblers, and machinists as well as a large fraction of the engineers.

Although not everyone can be an expert, the type of errors that occurred with the Hubble might have been avoided with appropriate education and training. Given such training, those who are doing the actual work form an effective backup system to counter weaknesses in the management structure. Such a system recognizes that mistakes can and will be made even by the most experienced and talented; this means that critical results should be verified and validated with a "second set of eyes."[10] When failures do occur, this backup system (the "second set of eyes") becomes the primary one. Although such bottom-up management has its own risks, at least there is a backup in place.

Looking beyond its initial failures, many other things on Hubble were done right. Thousands of images of the universe's incomprehensible complexity have been captured since corrective optics were installed during a dramatic in-orbit repair in 1993. With periodic hardware upgrades, Hubble is still operating more than 15 years later, serving as a platform for new instruments and collecting images more sophisticated than were ever thought possible at the beginning of its life.[8]

Despite the lessons learned from Hubble, decisions made during the development of new optical systems continue to be misguided. A more recent example was covered in depth by the *New York Times* ("Death of a Spy Satellite Program," 11 November 2007), where it was disclosed that a major spy satellite program was unable to deliver the performance promised by the aerospace contractor.[11] As shown in Chap. 7, one cause was—even more directly in this case—inadequate education, training, and experience in the development of optical systems.

1.1 Optical Systems

Optical systems can usually be classified as being one of five different types: imagers, radiometers, interferometers, spectrometers, and polarimeters. Without even knowing the meaning of these words, we can also combine them into "imaging radiometers," "imaging spectrometers," "spectropolarimeters," and so on, but the basic concepts remain the same. Complete mastery of optical systems engineering requires knowledge of all these types; however, the focus of this introductory book is on imagers and radiometers, which are prerequisites for understanding more advanced systems.

Imagers such as cameras capture light from a scene, as with the view provided by Google Earth from 500 km above the planet. The lenses in an imager focus light onto an array of detectors known as a focal plane array (FPA) to recreate the scene (or create an image). While conceptually simple, professional-level imaging lenses often have 15 to 20 individual lens elements to improve image quality far beyond that achievable with inexpensive cell-phone cameras. The concept of image quality reflects our intuitive sense of what makes for a good or bad photograph; for example, a good photo is "crisp" and "cheery" whereas a bad photo is fuzzy and dark. Cinematographers may turn these concepts upside down to communicate a message, but they still rely on a high level of performance from the optical system to make their statement.[12]

Radiometers are not designed for image quality; instead, they are used to accurately measure how *much* light is coming from a scene. Smokestack gases, for example, emit more light as they get hotter, possibly indicating an underlying problem with an industrial process that creates excess pollutants. Radiometers can be used to measure the difference in average gas temperature (and therefore light emitted) as a metric of process quality. Industrial monitoring of this sort does not typically require high-fidelity images of the scene, but the measuring equipment must be sensitive enough to detect small differences in temperature. Optical systems have also been designed to measure small differences in emitted or reflected light at every point in an image; such systems are known as *imaging radiometers* (or radiometric imagers).

What makes an imager or radiometer "optical" is the wavelength of light, or the distance between peaks of the waves carrying electromagnetic energy.[1,2] Wavelengths that, in a vacuum, range from about 0.1 to 30 micrometers (or microns, symbol μm) are usually classified as optical. The broad categories are ultraviolet (UV), visible (VIS), and infrared (IR); Table 1.1 shows that the associated range (or "band") of wavelengths are 0.1 to 0.4 μm, 0.4 to 0.7 μm, and 0.7 to 30 μm, respectively.

Wavelength Band	Abbreviation	Wavelength
Vacuum ultraviolet	VUV	0.10–0.18 μm
Deep ultraviolet	DUV	0.18–0.32 μm
Near ultraviolet	NUV	0.32–0.40 μm
Visible	VIS	0.4–0.7 μm
Near infrared	NIR	0.7–1 μm
Shortwave infrared	SWIR	1–3 μm
Midwave infrared	MWIR	3–5 μm
Longwave infrared	LWIR	8–12 μm
Very longwave infrared	VLWIR	12–30 μm

Table 1.1 Wavelengths corresponding to the associated bands used in optical systems. The wavelengths from 5 to 8 μm, which are strongly absorbed by the Earth's atmosphere, are sometimes included as part of the MWIR band.

The UV band is subdivided into vacuum UV (0.10–0.18 μm, wavelengths that are strongly absorbed by air and so require a vacuum), deep UV (0.18–0.32 μm), and near UV (0.32–0.40 μm). The IR band is subdivided into near IR (0.7–1.0 μm), shortwave IR (1–3 μm), midwave IR (3–5 μm, an atmospheric transmission band), longwave IR (8–12 μm, another atmospheric transmission band), and very longwave IR (12–30 μm). The basic unit of microns is very small compared with typical mechanical dimensions; this fact is a major contributor to the difficulty of building optical systems.

A wide range of optical systems have been built around these wavelengths. The components of a generic optical system are illustrated in Fig. 1.3. These components include: optical sources emitting energy; objects reflecting that energy; an atmosphere (or vacuum) through which the energy propagates on its way to the optics; lenses, mirrors, and other optical components used to collect this energy; detectors that capture an image of the source (an imager), measure its energy (a radiometer), or both (an imaging radiometer); electronics to convert the electrons from the detector into usable signals; and software and displays (such as high-definition TVs) to help interpret the results.

Figure 1.4 offers a schematic view of the Kepler Space Telescope, a not-so-typical optical system designed to search the skies for Earthlike planets that could support life. The source in this case is the universe of stars and extrasolar planets in the telescope's field of view (FOV) as well as some light from outside the FOV that makes its way onto the detector. This light-collecting telescope is relatively simple and consists of a primary mirror and corrector plate that brings the scene into slightly blurred focus on the detector. The detector comprises 42 rectangular arrays consisting of many individual detectors, called picture elements (or pixels), that create the instrument's focal plane array.

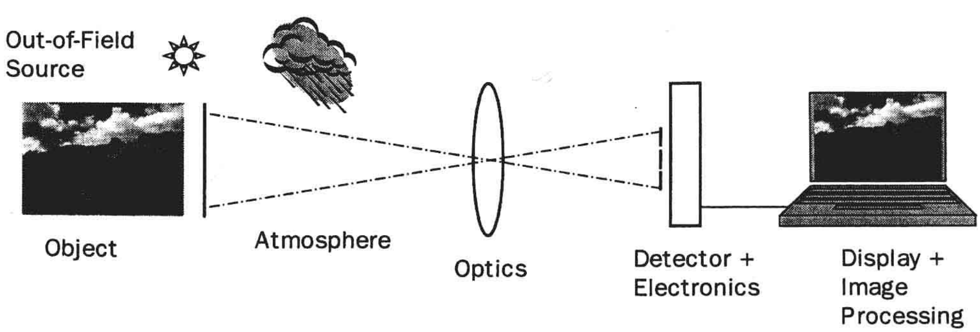

FIGURE 1.3 Conceptual diagram of the components of an optical system, which include an object illuminated by a source (such as the Sun), the atmosphere (for terrestrial systems), optics, detector, electronics, display, and image processing software. (*Photo credit: Mr. Brian Marotta, Louisville, Colorado.*)

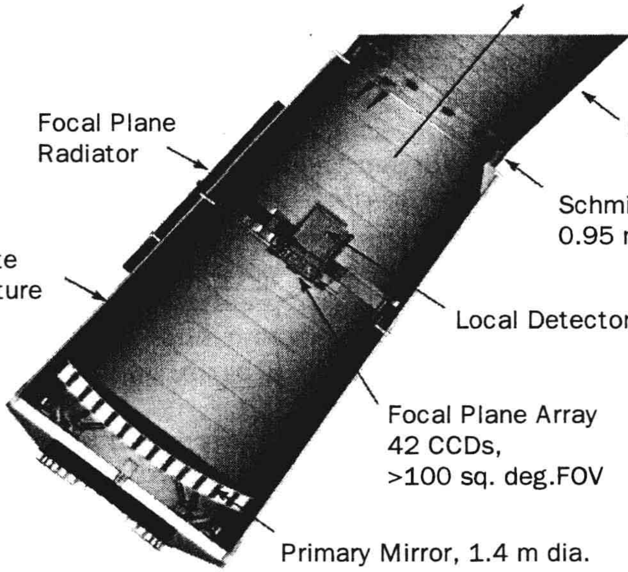

FIGURE 1.4 Schematic of the Kepler Space Telescope, a radiometer designed to search for Earthlike planets that could support life. (*Credit: NASA, www.kepler.nasa.gov.*)

Different types of space telescopes that point back toward Earth are used for remote sensing and environmental monitoring, revealing areas where pollution or degradation are prevalent. These source-plus-optics-plus-detector systems are the emphasis of this book and are found in a variety of applications, including cell-phone cameras, high-power microscopes, CD and DVD players, laser radar systems, fiber-optic communication networks that are the backbone of the Internet, and biomedical products such as confocal fluorescence microscopes for three-dimensional imaging of tumors.

Components such as high-efficiency solar cells and light-emitting diodes (LEDs), both of which play a key role in reducing greenhouse gases, also belong to the world of optical systems. Industrial applications such as fish-eye lenses for full-hemisphere imaging (Fig. 1.5), highly specialized lenses for the semiconductor lithography process used to manufacture integrated circuits, machine vision for automated inspection of food quality, and real-time inspection of heat loss (MWIR and LWIR radiation) from buildings are all common applications of optical systems within larger systems.

1.2 Optical Engineering

Designing and building optical systems requires a specific set of skills, typically classified as optical engineering, that also include aspects of mechanical, software, and electrical engineering.[1–7] The