PHOTONICS RULES OF THUMB

Third Edition

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PHOTONICS RULES OF THUMB

Third Edition

John Lester Miller, Ed Friedman, Jack Sanders-Reed,
Katie Schwertz, and Brian McComas

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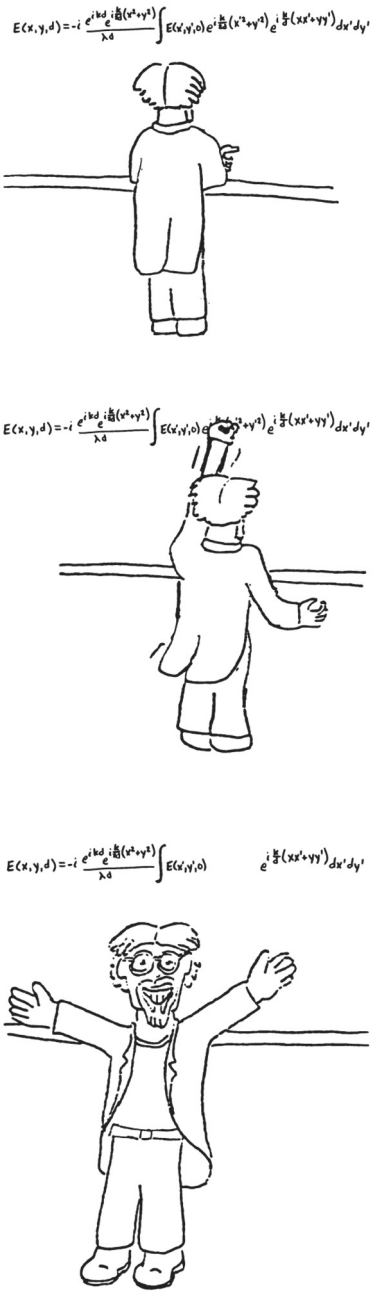


With the stroke of an eraser, Fraunhofer made diffraction calculations tractable (reprinted with permission from Brigham Young University).

Preface

The evolution of the photonic sciences parallels, and feeds from, developments in a number of somewhat unrelated fields, including astronomy, satellite and remote sensing technology, materials science, electronics, biomedical sciences, optical communications, military developments, and many others. The common thread of all of this effort, which was defined in the 1950s, is that scientists and engineers have been able to combine highly successful electronic technologies with the more ancient concepts and methods of optics and electromagnetic wave propagation. The merging of these fields has provided an unprecedented capability for instruments to "see" targets and communicate with them in a wide range of wavelengths for the benefit of security systems, science, defense, and (more recently) consumers. In the future, we see the rise of autonomous systems as a sea change that will drive a significant increase in the need for sensing systems to allow the autonomous system to sense and understand its environment.

Major departments at universities are now devoted to producing new graduates with specialties in this field. There is no end in sight for the advancement of these technologies, especially with the continued development of electronics and computing as increasingly integral parts of photonic instrumentation. One of the disturbing trends in this technology is the constant narrowing of the role of engineers. As the technology matures, it becomes more difficult for anyone working in an area of photonics to understand all that is being done in the related sciences and engineering. This book has been assembled to make a first, small step to expose anyone working in the optics and photonics community to a wide range of critical topics through simple calculations and explanations.

There is no intent to compete with classic texts or the many journals or conferences devoted to the photonics field, all of which provide considerable detail in every area. Rather, this book is intended to allow any engineer or scientist, regardless of specialty, to make rapid and accurate estimations on a wide range of topics that might be encountered in system design, modeling, or fabrication, as well as to provide a guide for choosing which details to consider more diligently. This book will help any electro-optics (EO) team to make quick assessments, generally requiring no more than a calculator, so that they quickly find the right solution for a design problem.

The book is also useful for managers, marketeers, and other semi-technical folks who are new to the optics industry (or are on its periphery) to develop a feel for the difference between the chimerical and the real. Students may find the same type of quick-calculation approach valuable, particularly in the case of oral exams in which the professor is pressuring the student to do a complex problem quickly. Using these assembled rules, you can keep your wits about you and provide an immediate and nearly correct answer,

which usually will save the day. But after the day is saved, you should go back to the question and perform a rigorous analysis. These rules are useful for quick sanity checks and basic relationships. Being familiar with the rules allows one to rapidly pinpoint trouble areas or ask probing questions in meetings. They aid in thinking on your feet and in developing a sense of what will work and what won't. Another potential application of the contents is to provide a checklist for reviewers asked to assess the completeness of a design or resolve trade studies early in the development of a system. But they are not, and never will be, the last word.

Dear reader, it is fully recognized that errors may still be present, and for that we apologize in advance to you and to those from whom the material was derived. We try to the best of our abilities to remove errors we inherit from the references we used and in new material we created. To assist us in this endeavor, we have solicited the cooperation of as many experts as would agree to help. Their input gives us a wide variety of experience from many different technical points of view. Alas, technology advances, and all of us wonder how we can possibly keep up. Hopefully, this book will not only provide some specific ideas related to photonics technology, it will also suggest some ways of thinking about things that will lead to a whole new generation of such rules and ideas.

As we discovered with the previous editions of this book, not everyone has the same thing in mind when considering "a rule of thumb." To qualify for our definition of a rule of thumb, a rule should be useful to a practitioner and possess at least most of the following attributes:

- It should be easy to implement.
- It should provide roughly the correct answer.
- The main points should be easy to remember.
- It should be simple to express.
- It should highlight the important variables and diminish the role of generally unimportant variables.
- It should provide useful insight to the workings of the subject matter.

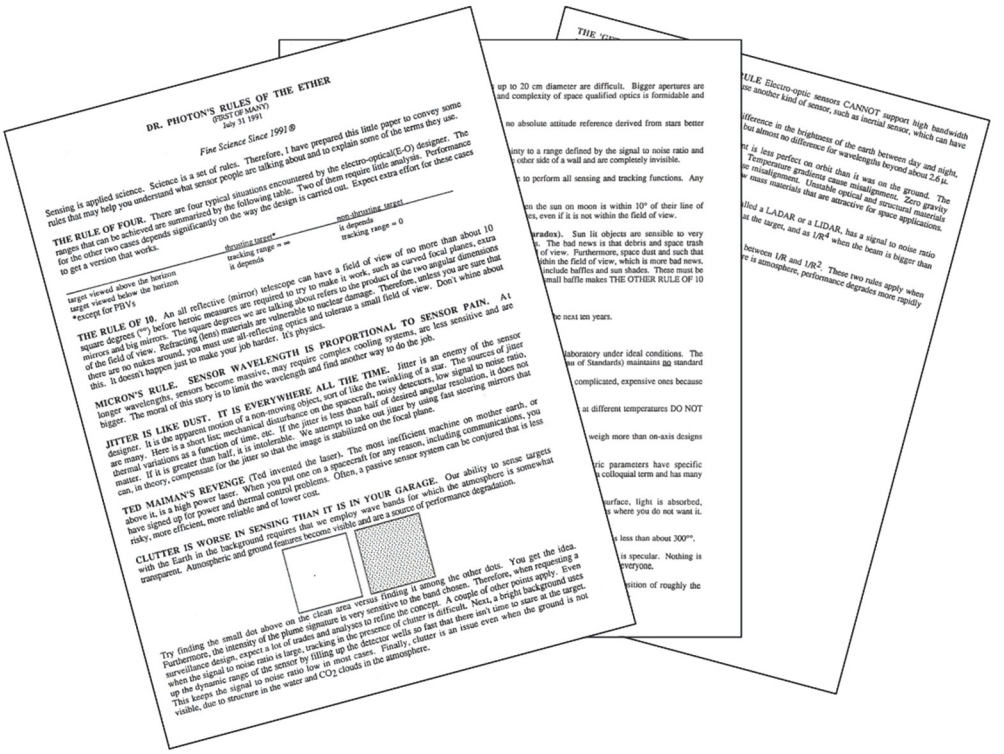
As in earlier editions of books in this series, we found it valuable to create a detailed standard form and stick to it as closely as possible. We did in this edition as well. References are provided whenever possible. In addition, reference material is mentioned that can be considered as recommended reading for the reader with a desire for more detail than could be presented in the "rule" and "discussion." The reader should note that each rule "stands on its own," so the abbreviations and terminology may not be entirely consistent throughout. This is intentional; we use the notation of the reference whenever we can so that if you read the original material you will recognize what that author defined. Some rules are derived from the laws of physics, and some represent existing technology trends. Many derive from observations made by researchers in the field, augmented by curve fitting that results in polynomial approximations.

The authors of the previous versions of this book arrived at the same place by very different paths. John (now retired, but busy consulting) spent some of his career in infrared astronomy before joining the aerospace industry to work on infrared sensors for space surveillance. He later worked on tactical sensors for search-and-rescue, self-driving cars, active imaging and enhanced vision systems. Ed (now retired, but very busy teaching) spent

most of his career working on remote sensing technologies applied to Earth, its atmosphere and oceans, and, more recently, astronomical instruments and advanced pointing systems. John and Ed met in Denver in 1985, both working for a major government contractor on exotic electro-optical systems.

Those were halcyon days, with money flowing like water, and contractors winning billions of dollars for some concepts that were overly optimistic or barely possible at best. In the center of the whole fray were bureaucrats, politicians, and managers who were demanding that we design systems that would be capable of the impossible. We saw many requirements and goals being levied on our systems that were far from realistic, often resulting from confusing (and poorly understood) interpretations of the capabilities of optical and electro-optical systems and the properties of targets or backgrounds.

We found a common ground when managers discovered that many co-workers, in an attempt to outdo the competition, were promising to perform sensor demonstrations that violated many rules of engineering, if not physics. On one multibillion-dollar program, after some consistent exposure to neophytes proposing all sorts of undoable things, we decided to try to educate everyone by creating a half-serious, half-humorous posting for the local bulletin board (this was before websites were ubiquitous) called "Dr. Photon's Rules of Thumb." It was a list of basic rules that apply when optics or electro-optics are used. Figure 1 shows the first version that we found all across the company, and even among competitors.



DR. PHOTON'S RULES OF THE ETHER

(FIRST OF MANY)

July 31 1991

Fine Science Since 1991 ®

Sensing is applied science. Science is a set of rules. Therefore, I have prepared this little paper to convey some rules that may help you understand what sensor people are talking about and to explain some of the terms they use.

THE RULE OF FOUR. There are four typical situations encountered by the electro-optical(E-O) designer. The ranges that can be achieved are summarized by the following table. Two of them require little analysis. Performance for the other two cases depends significantly on the way the design is carried out. Expect extra effort for these cases to get a version that works.

	throating target*	non-throating target
target viewed above the horizon	tracking range = ∞	it depends
target viewed below the horizon	it depends	tracking range = 0

*except for PBVs

THE RULE OF 10. An all reflective (mirror) telescope can have a field of view of no more than about 10 square degrees (~) before heroic measures are required to try to make it work, such as curved focal planes, extra mirrors and big mirrors. The square degrees we are talking about refers to the product of the two angular dimensions of the field of view. Refracting (lens) materials are vulnerable to nuclear damage. Therefore, unless you are sure that there are no nukes around, you must use all-reflecting optics and tolerate a small field of view. Don't whine about this. It doesn't happen just to make your job harder. It's physics.

MICRON'S RULE. SENSOR WAVELENGTH IS PROPORTIONAL TO SENSOR PAIN. At longer wavelengths, sensors become massive, may require complex cooling systems, are less sensitive and are bigger. The moral of this story is to limit the wavelength and find another way to do the job.

JITTER IS LIKE DUST. IT IS EVERYWHERE ALL THE TIME. Jitter is an enemy of the sensor designer. It is the apparent motion of a non-moving object, sort of like the twinkling of a star. The sources of jitter are many. Here is a short list; mechanical disturbance on the spacecraft, noisy detectors, low signal to noise ratio, thermal variations as a function of time, etc. If the jitter is less than half of desired angular resolution, it does not matter. If it is greater than half, it is intolerable. We attempts to take out jitter by using fast steering mirrors that can, in theory, compensate for the jitter so that the image is stabilized on the focal plane.

TED MAIMAN'S REVENGE (Ted invented the laser). The most inefficient machine on mother earth, or above it, is a high power laser. When you put one on a spacecraft for any reason, including communications, you have signed up for power and thermal control problems. Often, a passive sensor system can be conjured that is less risky, more efficient, more reliable and of lower cost.

CLUTTER IS WORSE IN SENSING THAN IT IS IN YOUR GARAGE. Our ability to sense targets with the Earth in the background requires that we employ wave bands for which the atmosphere is somewhat transparent. Atmospheric and ground features become visible and are a source of performance degradation.

Try finding the small dot above on the clean area versus finding it among the other dots. You get the idea. Furthermore, the intensity of the plume signature is very sensitive to the band chosen. Therefore, when requesting a surveillance design, expect a lot of trades and analyses to refine the concept. A couple of other points apply. Even when the signal to noise ratio is large, tracking in the presence of clutter is difficult. Next, a bright background uses up the dynamic range of the sensor by filling up the detector wells so fast that there isn't time to stare at the target. This keeps the signal to noise ratio low in most cases. Finally, clutter is an issue even when the ground is not visible, due to structure in the water and CO_2 clouds in the atmosphere.

Figure 1 The original Rules of Thumb that started this book.

For the current version, John and Ed invited (maybe some would say tricked) three other younger authors to modernize, enhance, and yield a new perspective. These luminaries are Jack Sanders-Reed, Brian McComas, and Katie Schwertz, whose bios appear in the back matter of this book.

Katie is a hybrid optical and optomechanical designer, drawing from her time at both the University of Rochester and University of Arizona optics programs. She primarily works on commercial and industrial optical subsystems. Her time spent under the tutelage of Jim Burge in Arizona taught her the value of a good estimation, which she didn't fully appreciate until her time spent in industry. Her Master's work involved optomechanics "rules of thumb." Jack has 40 years of experience ranging from medical imaging, to surface science, to pilot vision systems and atmospheric phenomenology, to target detection, tracking, and photogrammetry and covering the electromagnetic spectrum from hard x-ray through visible and infrared to millimeter-wave with both passive and active imaging. Brian has over 30 years of experience working on EO systems for military, astronomical, remote sensing, and industrial use. His Ph.D. was developed under the direction of Ed Friedman.

To summarize, this collection of rules and concepts represents an evolving, idiosyncratic, and eclectic toolbox. The rules, like tools, are neither good nor bad; they can be used to facilitate the transition of whimsical concepts to mature hardware or to immediately identify a technological path worth pursuing. Conversely, misused, they can obfuscate the truth and, if improperly applied, derive incorrect answers. Our job was to refine complex ideas to simplified concepts and present these rules to you with appropriate cautions. However, it is your responsibility to use them correctly. Remember, it is a poor worker who blames their tools and we hope you will find these tools useful.

John Lester Miller

Ed Friedman

Jack Sanders-Reed

Katie Schwertz

Brian McComas

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"Yes, applying short, approximation equations is a useful technique, but your analysis section was all thumbs."

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