Opto-Mechanical Systems Design

Third Edition

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Preface to the Third Edition

Building upon the success of the two prior editions, this third edition of *Opto-Mechanical Systems Design* updates the techniques used in opto-mechanics by emphasizing many important old and new technology developments. Most of these are discussed in depth while others are simply mentioned so readers interested in those particular topics can access the original documents for more details. Each of the 15 chapters treats its subject matter in sufficient detail for the reader to apply the technology to real-world problems. Numerical examples are employed to illustrate applications of theory and of the numerous equations provided herein. Many new references — some as recent as mid-2005 — make available key advances in opto-mechanical design of the past decade.

The field of opto-mechanics continues to grow, seemingly at an ever-increasing rate. Workers in the field are becoming much more willing to share their accomplishments with the community at large. To a large extent, this growth can be attributed to the continuing success of the International Society for Optical Engineering (SPIE), in attracting participation in its conferences and short courses and in publishing key technical papers in proceedings and journals as well as in books, CD-ROMs, videos, and other publications. By far, the SPIE's symposium proceedings represent today's most significant sources of information about new optical technology, about new tools and techniques for designing, building, and testing hardware, and about the performance of major systems such as astronomical telescopes and spaceborne scientific payloads. Since the publication date (1992) of this work's second edition, more than thirty-three SPIE conferences with papers contributing to opto-mechanical technology have been held. These papers describe, in significant detail, a large share of the new technology reported here.

The entire text of *Opto-Mechanical Systems Design* has been rewritten in an attempt to clarify certain technical details and to correct inadvertent errors that appeared in the earlier versions. In this new edition:

- In Chapter 1, coverage of the progress of the International Organization for Standards (ISO) and of the U.S. Optics and Electro-Optics Standards Council (OEOSC) relative to adoption of revised, broad-based standards in optics has been expanded and charts depicting the flow of activities during the conceptual, preliminary design, final design, manufacturing, and verification phases of optical instrument development have been added. The influences of computers and the Internet are noted.
- Information has been added to Chapter 2 on characteristics of the space environment, vibration criteria for sensitive equipment, ways to minimize contamination, and laser damage to optics.
- In Chapter 3 the list of optical glasses for which opto-mechanical characteristics are tabulated has been updated. This list reflects recent thinking by lens designers on "preferred" glass types. Several other tables of materials properties have also been updated and a table of coefficients of thermal defocus and thermo-optical coefficients for a variety of optical materials has been added.
- Sections have been added to Chapter 3 on special coatings for opto-mechanical materials and techniques for manufacturing opto-mechanical parts. These include discussions of protective finishes, optical black coatings, platings that improve surface smoothness of metal mirrors, and methods for making optical and mechanical components, including those made of composites.
- Details have been added to Chapter 4 on mounting lenses with retaining rings, flanges, and on flexures, effects of tightening tolerances on lens costs, calculating lens weights and center of gravity locations, and ways to align single lenses to their mounts.

- The discussion of catadioptric systems in Chapter 5 has been expanded and sections have been added on liquid coupling of lens elements and techniques for aligning multiple lenses in their mounts.
- New general considerations of windows and hardware design examples for domes and conformal windows have been added in Chapter 6.
- The discussions in Chapter 7 have been extended to include equations for designing 26 types of prisms and prism assemblies, and coverage on semikinematic mountings for prisms and techniques for bonding prisms to their mounts has been expanded.
- A new Chapter 8 on design and mounting of small mirrors, gratings, and pellicles has been added. Considerations of individual mirror designs and mirror system design, ghost image formation by second-surface mirrors, and numerous examples of typical component mounting designs are included.
- Chapter 9, which deals with lightweight, nonmetallic mirrors, has been expanded to include discussions of modeling built-up substrate structures, techniques for spin casting large (8 m class) mirror substrates, and estimating weight of contoured-back solid mirrors.
- The considerations of techniques for designing large mirrors and mountings for such mirrors in fixed horizontal axis, fixed vertical axis, and variable axis orientation applications have been expanded in Chapter 10 through Chapter 12. State-of-the-art design examples include the 2.49-m (98-in.)-diameter primary for the Hubble Space Telescope, the 2.7 m (106 in.) primary for the SOFIA Telescope, the 8.1 m (319 in.) primaries for the Gemini Telescopes, and the aspherical grazing incidence cylindrical mirrors that range in diameters from 0.68 m (27 in.) to 1.2 m (47 in.) for the Chandra X-ray Telescope.
- Prior chapters on design and mounting of metal mirrors have been consolidated into a single expanded Chapter 13. Considerations of such topics as metal matrix materials for mirrors, foam core construction, platings, single-point diamond turning (SPDT), and flexure mountings have been enhanced.
- Descriptions of several new optical instruments to illustrate favorable structural design principles have been added to Chapter 14. Considerations of modular design techniques have also been expanded. Athermalization techniques are discussed at length, and many new hardware examples are explained.
- In a new Chapter 15, discussions have been added about the effects of surface damage on the strength of optics, statistical methods for estimating optical component time to failure, and the basis for a rule-of-thumb tolerance for tensile stress in components made of common optical glasses, some optical crystals, and some nonmetallic mirror materials. The previously scattered discussions of techniques for analyzing stresses at optic-to-mount interfaces for lenses, prisms, and small mirrors have been consolidated in this chapter. Coverage of key effects such as temperature gradients and differential expansion/shrinkage effects from temperature changes in cemented and bonded joints have been significantly expanded. Prior investigations of the rate of change of axial preload with temperature (a parameter known as K_3) have been revisited and extended to allow preload at any temperature to be estimated much more confidently than previously possible. Discussions of axially and radially compliant mounts that can compensate for residual thermal expansion mismatches have been added, along with several representative hardware examples of such designs.
- An Appendix D has been added containing a glossary of terms and symbols used in this book.

Once again I acknowledge with thanks the support of many individuals, companies, and governmental agencies worldwide that provided much of the technical information included here. In particular, I acknowledge the superb assistance of Daniel Vukobratovich, Alson E. Hatheway, Roger A. Paquin, David Crompton, Victor L. Genberg, Keith B. Doyle, and William A. Goodman, who provided guidance, reviewed drafts of portions of the manuscript, identified sources of additional technical information, helped me understand some complex design issues, and checked some of the new theories and equations provided in this work. I trust that this information has been accurately conveyed and that credit has been given where appropriate. I take full responsibility for and deeply regret any misstatements, technical inaccuracies, or omissions. I hope that this book will enhance understanding of opto-mechanics by its readers, that it will prove useful in the workplace, and that future optical instruments and other hardware systems designed and developed as recommended here perform as intended.

Preface to the Second Edition

Since the first edition of this book appeared in 1986, the multifaceted discipline of opto-mechanical systems design has received increased attention, and a wealth of new literature on related subjects has been published. This is due, in part, to recent advancements in the degree of sophistication of analytical techniques for evaluating mechanical structures and the optic-to-mount interface, to the availability of new and improved materials, and to more complete information on the mechanical properties of existing materials.

Through this revised and expanded version of *Opto-Mechanical Systems Design*, I have attempted to bring as much of this new technology as is reasonably possible into the context of this work. Approximately 300 new literature references have been added, some as current as mid-1992. Many more hardware examples are examined for new and unique design approaches, the coverage of environmental influences on optical instruments is expanded, a summary of preferred techniques for evaluating optical hardware under adverse environmental conditions has been added, and our considerations of the effects of mounting forces on optical components have been broadened. Wherever feasible, both SI and U.S. customary units are employed in tables and quantified examples.

I acknowledge with thanks the assistance of the many individuals who so graciously contributed technical information to this new edition or allowed their published works to be described. I sincerely hope that this new edition will serve its readers well and that it will foster continued growth of this important discipline.

Preface to the First Edition

In the preface to his book on *Fundamentals of Optical Engineering* (McGraw Hill, 1943), Donald H. Jacobs wrote of his conviction that "in the design of any optical instrument, optical and mechanical considerations are not separate entities to be dealt with by different individuals but are merely two phases of a single problem." I have seen the truth of this statement many times during the design, development, and production of a variety of optical instruments — many of these being highly sophisticated systems intended for military and/or aerospace applications. The close interrelationship of the optical and mechanical disciplines cannot be ignored or left to chance encounters when the performance and reliability of the end item are vital to an important mission, such as photographing the farthest reaches of space with a spaceborne optical observatory. At the other extreme, the designers of even the simplest of optical instruments can benefit from a coordinated approach to the design problem.

This book is intended to be a compilation of opto-mechanical systems design guidelines and experiences. It tells how certain design tasks, such as the mounting of critical optical components in high-performance instruments, have been accomplished. The logic underlying those designs is outlined and, wherever possible, the success of the configuration used is evaluated. Included are considerations of analytical methods for predicting how a particular system or subsystem will react if exposed to specified environmental conditions. The mathematics of complete systems optimization is not stressed simply because the subject matter addressed here is so broad. A thorough analytical treatment of but a few of the design problems considered would fill a volume this size. Instead, this work concentrates on qualitative descriptions and references the optimization techniques explained elsewhere.

While many books on lens design and several on the design of mechanical structures and mechanisms have appeared in print since Jacobs first tried to tie together these topics, no author has given more that a fleeting consideration to them as an integrated topic. Indeed, Rudolph Kingslake specifically excluded considerations of the mechanical aspects of instrument design from the first five volumes of *Applied Optics and Optical Engineering* (Academic Press, 1965–1969), which he edited. It was not until 1980 when Robert E. Hopkins wrote on "Lens Mounting and Centering" in Volume VIII that an opto-mechanical topic was presented in any depth in that series.

The importance of the topic has been recognized, however, since many technical papers on opto-mechanical subjects have appeared in the *Journal of the Optical Society of America, Applied Optics, Journal of Scientific Instruments, Optical Engineering,* the *Soviet Journal of Optical Technology*, and similar publications. The subject has also been addressed by several professional society symposia, including OSA seminars, OSA workshops on optical fabrication and testing, and SPIE seminars on such topics as "Optics in Adverse Environments," "Opto-Mechanical Design," "Optical Specifications," and "Optical Systems Engineering." In assembling material for this book, I have unhesitatingly drawn on many available sources to provide pertinent information. The above-listed journals and symposia proceedings are heavily referenced. Lens design per se is intentionally not stressed here.

One of the most significant problems in developing a reference book such as this was the determination of how to organize the material to be covered. I chose to supply information that should be useful to individuals involved in developing optical instrument designs and carrying those designs to completion of operational hardware. Usually, such assignments include an optical design phase in which a collection of related optical elements is defined, and a mechanical design phase, which incorporates the optics into a suitable mechanical surround. The goal of the total effort is to create an instrument capable of doing a specific job within specific constraints of size, weight, cost, physical packaging, and environment.

The discussion begins with a summary of the total opto-mechanical systems design process from conceptualization to end item evaluation and documentation. This introduces us to the major steps that must be taken to achieve a successful design. Next, we examine environmental influences and the traditional, as well as some newer, materials from which we can fabricate the optics and the mechanical parts of the instrument. Techniques for mounting various typical optical elements and groupings thereof, ranging in aperture size from a few centimeters to several meters, are considered next. Included are design and mounting considerations for individual lenses, mirrors, and prisms; refracting and catadioptric subassemblies; lightweight mirror substrates; mountings for mirrors with axis horizontal, vertical, or in variable orientation; and design, fabrication, and mounting of metallic mirrors. We close with considerations of the structural design of optical instruments.

Familiarity on the part of reader with geometric optics, the functions of optical systems, and the fundamentals of mechanical engineering is assumed. Theory and analytical aspects of opto-mechanical engineering are minimized in favor of descriptions of past and current design approaches.

It is expected that this work will be of interest to a wide range of readers including optical instrument designers, developers, and users; optical and mechanical systems engineers; structural and materials engineers, and students of the optical sciences. It is hoped that the material presented here will serve as a useful guide in the conception, design, development, evaluation, and use of optical instrumentation in military, space, and commercial applications.

Many people have helped in the preparation of this book by providing information, photographs, comments and suggestions, and permissions to use previously published material. Hopefully, credits have been given properly in all cases; I express here my thanks to these individuals and to any whose contributions have inadvertently been omitted. Of great importance was the assistance of the following associates at Perkin-Elmer: Richard German and Ross Gelb, who prepared many of the illustrations, and Jessica Monda, Helen Ryan, Jo Anne Gresham, and Stephanie Shearer, who typed much of the manuscript. I am especially indebted to Richard Babish, Peter Mumola, and Julianne Grace of Perkin-Elmer, Brian Thompson of the University of Rochester, the staff of Marcel Dekker, Inc., and my wife, Elizabeth, for providing the encouragement that kept this project moving to completion.

The Author

Paul R. Yoder, Jr. serves the optical community as a consultant in optical engineering. For 55 years he has designed and analyzed optical instruments and managed optical technology development projects. He held various technical and engineering management positions with the U.S. Army's Frankford Arsenal, Perkin-Elmer Corporation, and Taunton Technologies, Inc. The author or coauthor of 65 technical papers on optical engineering topics and *BASIC-Programme fur die Optik* (Oldenbourg, 1986), he also wrote chapters for the OSA's *Handbook of Optics,* 2nd ed., Vol. I (McGraw-Hill, 1995) and for the *Handbook of Optomechanical Engineering* (CRC Press, 1997) as well as *Mounting Lenses in Optical Instruments* (SPIE Press, 1995); *Design and Mounting of Prisms and Small Mirrors in Optical Instruments* (SPIE Press, 1998); *Mounting Optics in Optical Instruments* (SPIE Press, 2002), and the two previous editions of the present work. He is listed as inventor or co-inventor on 15 U.S. and foreign patents.

Yoder received his B.S. and M.S. degrees in physics from Juniata College (1947) and Pennsylvania State University (1950), respectively. He is a Fellow of OSA, a Fellow of SPIE, a member of Sigma Xi and a founding member of the SPIE's Optomechanical/Instrument Working Group. He previously served as book reviews editor for *Optical Engineering*, as a topical editor for *Applied Optics*, as a member of the U.S. Advisory Group for the ISO's Technical Committee T172, *Optics and Optical Instruments*, and as a member of the U.S. Committee for the ICO. He also has taught numerous short courses on optical engineering and opto-mechanical design for SPIE, industry, and U.S. government agencies; graduate-level courses for the University of Connecticut; and two courses for the National Technological University Network.

Table of Contents

Chapter 4

Mounting Individual Lenses

Chapter 5

Mounting Multiple Lenses

Chapter 8

Design and Mounting Small, Nonmetallic Mirrors, Gratings, and Pellicles

Chapter 9

Lightweight Nonmetallic Mirror Design

Chapter 10

Mounting Large, Horizontal-Axis Mirrors

Chapter 11

Mounting Large Vertical-Axis Mirrors

Chapter 12

Mounting Large, Variable-Orientation Mirrors

Chapter 15

Analysis of the Opto-Mechanical Design