Mounting Optics
in Optical Instruments
Second Edition

Paul R. Yoder, Jr.
Dedication

I gratefully and lovingly dedicate the second edition of this book to Betty, my late best friend and wife for over 58 years, and to our children: David, Marty, Carol, and Alan. Over the years, they have all encouraged me to continue writing technical books and teaching short courses because I really enjoy such efforts. Further, I cannot as yet see my way clear to abandon my adopted field of optomechanics to just sit on the sun porch or in a rocking chair by the fireplace and let the rest of the world have all the fun.
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CD-ROM (2nd edition) Inside back cover
Preface to the Second Edition

This second edition of *Mounting Optics in Optical Instruments* updates and expands the prior discussions of pertinent technologies for interfacing optics with their mechanical surroundings in optical instruments. The general format of the first edition is maintained, but some topics are repositioned to fit better into the contexts of the various chapters. Two new chapters—one with expanded coverage of the design, fabrication, and mounting of metallic mirrors, and another dealing with aligning single and multiple lenses and reflecting optical systems—have been added.

The entire text of the book has been rewritten to help clarify many technical details, to correct some misleading statements in the earlier version, and to add new material. All equations that carry over from the first edition have been checked and a few corrections made. New equations have been added as appropriate to enhance the technical content of the new edition. As Jacobs' once said: "it is not possible to make drawings that clearly show the functioning of optical instruments without exaggeration of some details. In some cases, these exaggerations lead to technical absurdities." I also believe that, in a work of this sort, the primary purpose of a drawing can be to instruct rather than to be an exact representation of an original. For this reason, I have not hesitated to exaggerate drawing details whenever appropriate for the sake of clarity.

Specific major improvements in this edition are as follows:

- **In Chapter 1 (Introduction),** useful information regarding stress-induced birefringence and radiation effects in glasses has been added. Discussions of environmental effects on optics and on optical instruments are expanded. A basic procedure for tolerancing optics is outlined, and the possible effects of tightening tolerances for typical component parameters on costs of those components are indicated. Key techniques for making mechanical parts for optical instruments are summarized. The number of figures has grown ~400%.

- **In Chapter 2 (Optic/Mount Interface),** the important topic of centering optics in their mounts is significantly expanded. Various techniques that can be used to measure lens centration errors are explained. Basic techniques for sealing instruments statically and dynamically are illustrated. The number of pages has grown by 67%, and the number of figures has increased by ~33%.

- **In Chapter 3 (Mounting Single Lenses),** a new method is suggested for estimating the appropriate axial preload on lenses when those lenses are not otherwise constrained radially and are exposed to transverse accelerations. Techniques for estimating the weights and the locations of centers of gravity for lenses of different configurations are outlined and illustrated with examples. Methods for determining the annular thicknesses required in athermal elastomeric ring mountings for circular optics are outlined and the significance of the elastomer's Poisson's ratio in these calculations is explained. The size of the chapter and the number of figures have remained constant, but the number of equations has increased by ~33%.

- **Chapter 4 (Mounting Multiple Lenses) now includes descriptions of hardware designs for a large astrographic objective, assemblies featuring lenses mounted in**
poker-chip fashion, and optomechanical designs for high acceleration applications. Details are added regarding various photographic lenses, all-plastic lens assemblies, and mechanisms used to focus lenses and to change (i.e., zoom) their focal lengths. Page and figure counts have increased by ~22% and ~49% respectively.

- In Chapter 5 (Mounting Windows, Filters, Shells and Domes) we now include examples of designs in which the optic contours conform more or less to the skin configurations of the structure. A design for a fail-safe dual-pane window suitable for photographic use in a commercial aircraft also is referenced. The size of this chapter has increased 20%, and the figure count grew 53%.

- Chapter 6 (Prism Design) once again shows designs for various prisms and includes several types not previously included. The page count and the number of figures have increased more than 20%.

- Chapter 7 (Mounting Prisms) is basically unchanged from the corresponding chapter in the first edition.

- Chapter 8 (Mirror Design) now includes additional information on image orientation control, the layout of simple two-mirror periscopes, silicon and metallic foam-core mirrors, the adaptive secondary mirrors for the Large Binocular Telescopes, the beryllium secondary for the Very Large Telescope, and the James Webb Space Telescope segmented primary. Page count is increased by ~45%, the number of figures by ~62%, and the number of equations by ~44%.

- In Chapter 9 (Mounting Smaller Mirrors), we have added descriptions of mountings for small circular mirrors with multiple discrete bond joints to structure on the mirror's back surface and on its rim. Equations given previously for design of a 9-point Hindle mount for axial support of circular solid mirrors have been augmented to allow the nominal design of an 18-point mount. Page and figure counts have increased slightly.

- Chapter 10 (Mounting Metallic Mirrors) is expanded significantly as compared to the treatment of this subject as a section of Chapter 9 in the first edition. A much more detailed treatment of the use of single point diamond turning (SPDT) fabrication techniques is now included. Several additional examples of hardware designs are described. Many of these designs feature flexures that isolate the optical surface from forces delivered by the mounting. Published developments of platings for metallic mirror surfaces are summarized briefly and some effects of key types on mirror performance under temperature changes are indicated. Subject matter coverage, as measured by either page count or the number of figures, has increased manyfold.

- Chapter 11 (Mounting Larger Mirrors) has been reformatted to group designs into axis horizontal, axis vertical, axis variable, and space borne applications. Many of the included designs depict key developments that have allowed significant performance enhancement and size growth in astronomical telescope systems. The page count and number of figures for this important topic are both increased by ~30%.

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Chapter 12 (Aligning Lens and Mirror Systems) is a new chapter amplifying the material previously in sections of Chapters 3 and 4. New topics include the use of a modified alignment telescope and of a Point Source Microscope\textsuperscript{*} to align individual and multiple lenses. Also added are descriptions of an extremely precise method for aligning very high performance microscope objectives and of a method for determining which components to adjust during final assembly to optimize performance of complex systems. Page count and the number of figures are increased by \(-300\%\) and \(-400\%\) respectively.

In Chapter 13 (Estimating Mounting Stresses), previously published research leading to the now generally accepted rule-of-thumb limit, or tolerance, of 1000 lb/in.\textsuperscript{2} (6.89 MPa) for tensile stress created in a typical glass optic by applied mounting force is summarized. The effects of surface flaws, such as scratches or subsurface cracks, on this tolerance also are indicated. If the worst-case condition of the surfaces on the optic is known or can be estimated, the useful lifetime of the optic can be predicted statistically. As in the prior edition, computational methods, many utilizing equations developed by Roark\textsuperscript{2} for peak compressive stresses generated in the contacting optical and mechanical members, are applied to various types of mechanical interfaces with optical components. These computations are extended in this edition by utilizing theory from Timoshenko and Goodier\textsuperscript{3} to quantify the corresponding tensile stresses in the optic. We then show how the suitability of a given optomechanical mounting design can be determined by comparison of these stress levels with the rule-of-thumb tolerance. The scope of the subject matter treatment in this edition (measured by page count and numbers of figures and equations) has slightly changed from that in the prior edition.

In Chapter 14 (Temperature Effects), we have extended the previously published discussion of how temperature changes affect axial and transverse mounting forces. Several pertinent factors not considered in the first edition are defined. Some, but not all, of these can be quantified using available theory. In the absence of complete methodology for quantifying temperature effects on any given hardware design, we now advocate the provision of a controlled amount of compliance in the mechanical design of that hardware so as to minimize these temperature effects. Several typical practical design examples are considered. The page count of this chapter is expanded by \(>36\%\) while the number of figures is increased by \(>46\%\).

Chapter 15 (Hardware Examples) continues the practice established in the first edition of discussing the optomechanical designs of selected hardware items to illustrate many of the topics considered in the text. In this edition, twenty such examples are given while, in the prior edition, there were thirty. This, however, does not represent a reduction in the book's total technical scope because some new examples have been added to this chapter, and many of the previous examples are now discussed in the context of the pertinent technology in earlier chapters.

Appendices A and B to the new edition provide unit conversion factors and some updated values for properties and other characteristics of the materials used in optomechanical design. As before, Appendix C derives the torque-preload

\textsuperscript{*} A new device offered by Optical Perspectives Group, LLC of Tucson, AZ.
relationship for a threaded retaining ring. It is often helpful to know early in the
design phase how an optical component, subassembly, or complete instrument will
eventually be tested to prove its suitability to withstand adverse environmental
conditions. Appendix D, paraphrased from ISO Standard 9022, summarizes test
methods that might be applied to simulate various environments.

- Once again, a CD-ROM is provided with this book so the reader can access
Microsoft Excel worksheets that use the ~250 equations given in the text to solve the
numerical examples intermingled with the technical discussions as well as to design
prisms and prism assemblies that are described here. The worksheets are configured
so new input data can be inserted to create new designs or to conduct parametric
analyses.

I acknowledge the contributions of the many friends and associates who provided
new information to this book or helped me clarify confusing matters previously
presented. In particular, thanks are offered to Daniel Vukobratovich and Alson E.
Hatheway who have helped me understand many pertinent intricacies of optomechanical
design. On the editorial side, I sincerely thank Merry Schnell and Scott Schrum, who
helped me straighten out editorial details and kept the production schedule moving at
SPIE Press. While all contributors tried valiantly to help me present the technical material
clearly and correctly, total responsibility for any errors that remain rests on my shoulders.
Finally, I sincerely hope this book proves useful to all its readers.

   York, 1970.
   Standardization, Geneva.

Paul R. Yoder, Jr.
Norwalk, Connecticut
June 2008
Preface to the First Edition

This work is intended to provide practitioners in the fields of optical engineering and optomechanical design with a comprehensive understanding of the principal ways in which optical components such as lenses, windows, filters, shells, domes, prisms, and mirrors of all sizes typically are mounted in optical instruments. It also addresses the advantages and disadvantages of various mounting arrangements and provides some analytical tools that can be used to evaluate and compare different optomechanical designs. The presentation includes the theoretical background for some of these tools and cites the sources for the most of the equations listed. Each section contains an illustrated discussion of the technology involved and, wherever feasible, one or more worked-out practical examples.

Two chapters deal with the fundamentals of design for optical components. These are Chapter 6 on prism design and Chapter 8 on mirror design. These topics are considered appropriate, and indeed necessary, as background for considering how best to mount these very important types of optics.

The book is based, in part, on short courses entitled Precision Optical Component Mounting Techniques and Principles for Mounting Optical Components offered by SPIE—The International Society for Optical Engineering—that I have had the privilege of teaching over a period of several years. Many, but not all, of the techniques for mounting optics covered here have been presented previously in the tutorial texts Mounting Lenses in Optical Instruments1 and Design and Mounting of Prisms and Small Mirrors in Optical Instruments2 as well as in my earlier reference book Opto-Mechanical Systems Design.3 Several recent designs for mounting optics are included here to broaden the coverage and to bring the material more nearly up to date. Coverage of window-type optics and of large mirrors has been expanded over the previous works.

Wherever possible, numerical values given in this book are expressed in both the metric or Système International (SI) units and the units in customary use in the United States and Canada. The latter are abbreviated in this book as "USC" as in some recent textbooks. Examples taken directly from the literature may be expressed only in the system used by the original author. Units can be easily changed from one system to the other through use of the conversion factors given in Appendix A.

All the designs discussed here are drawn from the literature, my own experiences in optical instrument design and development, and the work of colleagues. I acknowledge with my deepest thanks the contributions of others, including the many participants in the above-mentioned SPIE short courses and the readers of my previous books, and sincerely hope that I have accurately recorded and explained the information they have given to me. I acknowledge and thank Donald O'Shea and Daniel Vukobratovich, who reviewed the manuscript for this book and suggested many improvements. I also thank Mary Haas, Rick Hermann, and Sharon Streams for their outstanding copy editing and editorial suggestions. While these people helped me to present the material clearly and correctly, I am solely responsible for and deeply regret any errors that remain. One particularly annoying error is that the headings on even numbered pages differ from the actual title of the book!
The mounting stress theories discussed in Chapter 11 are considered to be conservative approximations. They are intended to indicate whether a given design can be judged to be adequate from a stress viewpoint or if it should be analyzed by more elaborate finite-element and/or statistical techniques. The same is true of the treatment of temperature effects on axial preload in Chapter 12. These topics would benefit greatly from further investigation, refinement, and (it is hoped) verification by other workers based on more precise computational methods, such as finite-element analysis. I would welcome comments, corrections, and suggestions for improvements in the presentations of these topics and/or in any other portion of this book.

A feature included with this book is a CD-ROM containing two Microsoft Excel worksheets that allow convenient use of the many equations given in this text to solve typical optomechanical interface design and analysis problems. Some of these equations are relatively complex, so the worksheets have been developed to facilitate equation use and to reduce the chance of improper parameter application. The 102 files included in each worksheet correspond to designs and/or numerical examples worked out in the text. Input values pertaining specifically to those examples are listed. The two worksheets on the disk are different versions of the same program. In Version 1, data inputs are in U.S. Customary units while in Version 2 inputs are in metric units. In both cases, all data are presented in both sets of units. A table of files (with hyperlinks) is provided in each worksheet to assist in finding the proper file for a specific computation. The examples in the text are cross-referenced to the applicable worksheet files. Custom solutions to problems similar to the examples in the text can be obtained by revising the input data in the file as appropriate for the case to be evaluated. The program will then automatically solve the problem using those inputs and the appropriate equations from the text. This tool should be especially useful when parametric analysis of variations of key parameters is needed to obtain an optimum design.

I sincerely wish for the users of this book and of the CD-ROM a deepening understanding of the technologies discussed and success in the application of the concepts, designs, and analysis techniques presented here.


Paul R. Yoder, Jr.
Norwalk, Connecticut
Terms and Symbols

This list of the terms and symbols used in this book is intended to help the reader sort through the shorthand language of the various technical topics and the equations used to express the relationships so useful in the design process and the analysis of designs. The author has attempted to be consistent in the use of symbols for variables throughout the text, but there are occasions where the same symbol has more than one meaning. To some extent, customary usage in the field of optomechanics has dictated the use of a specific term or terms. The symbol \( \alpha \) is a good example since it is used to represent the coefficient of thermal expansion for a material when the common abbreviation CTE is not appropriate, as in equations. Subscripts are frequently used to identify the specific application of a symbol to a specific material (as in the use of \( \alpha_M \) to designate the CTE for a metal as distinguished from \( \alpha_G \) for a glass). We list here fundamental parameters and their units, frequently used prefixes, Greek symbol applications, acronyms, abbreviations, and other terms found in the text. Symbols representing variables are italicized in the equations.

Units of Measure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SI or metric</th>
<th>U.S. and Canadian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle</td>
<td>rad, radian</td>
<td>( ^\circ ), degree</td>
</tr>
<tr>
<td>Area</td>
<td>m², square meter</td>
<td>in.², square inch</td>
</tr>
<tr>
<td>Conductivity, thermal</td>
<td>W/mK, watt/meter-kelvin</td>
<td>Btu/hr-ft.(^{\circ})F, British</td>
</tr>
<tr>
<td></td>
<td></td>
<td>thermal unit per hour-foot-degree Fahrenheit</td>
</tr>
<tr>
<td>Density</td>
<td>g/m³, gram per cubic meter</td>
<td>lb/in.³, pound per cubic inch</td>
</tr>
<tr>
<td>Diffusivity, thermal</td>
<td>m²/s, meter squared per second</td>
<td>in.²/s, inch squared per second</td>
</tr>
<tr>
<td>Force</td>
<td>N, newton</td>
<td>lb, pound</td>
</tr>
<tr>
<td>Frequency</td>
<td>Hz, hertz</td>
<td>Hz, hertz</td>
</tr>
<tr>
<td>Heat</td>
<td>Btu, British thermal unit</td>
<td>joule (J)</td>
</tr>
<tr>
<td>Length</td>
<td>m, meter</td>
<td>in., inch</td>
</tr>
<tr>
<td>Mass</td>
<td>kg, kilogram</td>
<td>lb, pound</td>
</tr>
<tr>
<td>Moment of force (torque)</td>
<td>N/m, newton-meter</td>
<td>lb-ft, pound-foot</td>
</tr>
<tr>
<td>Pressure</td>
<td>Pa, pascal</td>
<td>lb/in.², pound per square inch</td>
</tr>
<tr>
<td>Specific heat</td>
<td>J/kg-K, joule/kilogram-Kelvin</td>
<td>Btu/lb.(^{\circ})F, British thermal unit per pound-degree Fahrenheit</td>
</tr>
<tr>
<td>Strain</td>
<td>( \mu )m/m, micrometer/meter</td>
<td>( \mu )in. per in., microinch per inch</td>
</tr>
<tr>
<td>Stress</td>
<td>Pa, pascal</td>
<td>lb/in.², pound per square inch</td>
</tr>
<tr>
<td>Temperature</td>
<td>K, kelvin; ( ^\circ )C, degree Celsius</td>
<td>( ^\circ )F, degree Fahrenheit</td>
</tr>
<tr>
<td>Time</td>
<td>s or sec, second</td>
<td>s or sec, hr, second, hour</td>
</tr>
<tr>
<td>Velocity</td>
<td>m/s or m/sec, meter/second</td>
<td>mph, mile per hour</td>
</tr>
<tr>
<td>Viscosity</td>
<td>P, poise; cP, centipoise</td>
<td>lb-s/ft², pound-sec per square foot</td>
</tr>
<tr>
<td>Volume (solid)</td>
<td>m³, cubic meter</td>
<td>in.³, cubic inch</td>
</tr>
</tbody>
</table>
Prefixes

mega M million
kilo k thousand
centi c hundredth
milli m thousandth
micro µ millionth
nano n billionth

Greek Symbol Applications

α CTE; angle
β angle; term used in equation for shear stress in a bonded optic
βO rate of change in refractive index with change in temperature (dn/dT)
γ shape factor for a resilient pad in a prism mounting
γG thermo-optical coefficient for a glass
δ decentration of an elastomeric-supported optic; ray angular deviation
δG glass coefficient of thermal defocus
Δ spring deflection; finite difference (change)
ΔE eyepiece focus motion per diopter
η damping factor
θ angle
λ wavelength; thermal conductivity in Schott catalog
μ Poisson's ratio in Schott catalog
µM, µG coefficient of friction for metal, glass
ξ ratio of shortest to longest dimensions of a rectangular mirror; rms acceleration response
π 3.14159
ρ density
σ standard deviation
Σ summation
σ tensile yield strength of components in a bonded joint
υ Poisson's ratio; with subscript representing wavelength, Abbe number
φ angle, cone half-angle

Acronyms and Abbreviations

A aperture of an optic, face width of a prism; area
a, b, c, etc. dimensions
-A-, -B-, etc. reference feature designation on a drawing
A/R antireflection
AC area of elastically deformed region at an interface
α0 acceleration factor (interpreted as "times ambient gravity")
ANSI American National Standards Institute
ASME American Society for Mechanical Engineering
AT annular area of a thread
AVG as subscript, indicates average value
AW unsupported area of a window
AWJ abrasive water jet (Corning designation)
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AXAF</td>
<td>Advanced X-ray Astrophysical Facility (now Spitzer Space Telescope)</td>
</tr>
<tr>
<td>b</td>
<td>flat spring width, length of cylindrical pad</td>
</tr>
<tr>
<td>C</td>
<td>Celsius; as subscript, indicates circular shape for a bond; center of curvature</td>
</tr>
<tr>
<td>C, d, D, e, F, g, s</td>
<td>as subscripts, refer to wavelengths of Fraunhofer absorption lines</td>
</tr>
<tr>
<td>CA</td>
<td>clear aperture</td>
</tr>
<tr>
<td>CAD, CAM</td>
<td>computer aided design, manufacturing</td>
</tr>
<tr>
<td>CCD</td>
<td>charge coupled detector device</td>
</tr>
<tr>
<td>CG</td>
<td>center of gravity</td>
</tr>
<tr>
<td>C_K</td>
<td>mirror mount type factor used to determine gravitational effect</td>
</tr>
<tr>
<td>CLAES</td>
<td>Cryogenic Limb Array Etalon Spectrometer</td>
</tr>
<tr>
<td>CMC</td>
<td>carbon matrix composite</td>
</tr>
<tr>
<td>CNC</td>
<td>computer numerically controlled</td>
</tr>
<tr>
<td>C_p</td>
<td>specific heat</td>
</tr>
<tr>
<td>c_p</td>
<td>centipoise (unit for viscosity)</td>
</tr>
<tr>
<td>C_R, C_T</td>
<td>spring constants in radial, tangential directions</td>
</tr>
<tr>
<td>CRES</td>
<td>corrosion-resistant (stainless) steel</td>
</tr>
<tr>
<td>C_S</td>
<td>compressive stress in a mechanical pad</td>
</tr>
<tr>
<td>C_T</td>
<td>center of curvature of a toroidal surface</td>
</tr>
<tr>
<td>CTE</td>
<td>coefficient of thermal expansion</td>
</tr>
<tr>
<td>CVD</td>
<td>chemical vapor deposited</td>
</tr>
<tr>
<td>CYL</td>
<td>as subscript, indicates cylindrical shape</td>
</tr>
<tr>
<td>d</td>
<td>major diameter of an internal thread</td>
</tr>
<tr>
<td>D</td>
<td>thermal diffusivity, diopter, major diameter of an external thread</td>
</tr>
<tr>
<td>D_B</td>
<td>diameter of a bolt circle</td>
</tr>
<tr>
<td>D_D</td>
<td>outside diameter of a circular optic</td>
</tr>
<tr>
<td>DIEMOS</td>
<td>Deep Imaging Multi-Object Spectrograph</td>
</tr>
<tr>
<td>D_M</td>
<td>inside diameter of a mechanical part, such as a cell</td>
</tr>
<tr>
<td>dn/dT</td>
<td>rate of change in refractive index with change in temperature</td>
</tr>
<tr>
<td>DOF</td>
<td>degrees of freedom</td>
</tr>
<tr>
<td>D_E</td>
<td>diameter of a resilient pad</td>
</tr>
<tr>
<td>D_R</td>
<td>OD of a compressed snap ring</td>
</tr>
<tr>
<td>D_T</td>
<td>pitch diameter of a thread</td>
</tr>
<tr>
<td>E, E_G, E_M, E_e</td>
<td>Young's modulus, for glass, for metal, for elastomer</td>
</tr>
<tr>
<td>E/p</td>
<td>specific stiffness</td>
</tr>
<tr>
<td>ECM</td>
<td>electro-chemical machining (process for contouring metal)</td>
</tr>
<tr>
<td>EDM</td>
<td>electric discharge machining (process for contouring metal)</td>
</tr>
<tr>
<td>EFL</td>
<td>effective focal length (as of a lens or mirror)</td>
</tr>
<tr>
<td>ELN</td>
<td>electroless nickel plating</td>
</tr>
<tr>
<td>EN</td>
<td>electrolytic nickel plating</td>
</tr>
<tr>
<td>EPROM</td>
<td>erasable programmable read only memory</td>
</tr>
<tr>
<td>ERO</td>
<td>edge run out</td>
</tr>
<tr>
<td>ES0</td>
<td>European Southern Observatory</td>
</tr>
<tr>
<td>EUV</td>
<td>extreme ultraviolet radiation</td>
</tr>
<tr>
<td>f</td>
<td>focal length</td>
</tr>
<tr>
<td>F</td>
<td>force, Fahrenheit temperature</td>
</tr>
<tr>
<td>f_f0</td>
<td>focal length (see EFL), of an eyepiece, of an objective</td>
</tr>
<tr>
<td>FEA</td>
<td>finite element analysis</td>
</tr>
<tr>
<td>FIM</td>
<td>full indicator movement (replaces TIR)</td>
</tr>
</tbody>
</table>
FLIR
forward looking infrared sensor

f
natural frequency of vibration

fs
factor of safety

FUSE
Far Ultraviolet Spectroscopic Explorer

G
acceleration due to ambient gravity (see \(a_0\))

GAP_a, GAP_r
axial and radial gaps between surfaces of an optic and its mount

GEO
Geosynchronous Earth orbit

GOES
Geostationary Operational Environmental Satellite

Gy
abbreviation for unit of radiation dose (gray)

H
thread crest-to-crest height, Vickers hardness of a material

HeNe
helium-neon laser

HIP
hot isostatic pressing

HK
Knoop hardness of a material

HRMA
high resolution mirror assembly (in the Chandra Space Telescope)

HST
Hubble Space Telescope

i
paraxial tilt angle of a plane parallel plate; as subscript, \(i^*\) component

I, I'
angle of incidence, refraction

I', I_o
beam intensity after, before an interface

ID
inside diameter

IPD
interpupillary distance

IR
infrared

IRAS
Infrared Astronomical Satellite

ISO
International Organization for Standards

J
strength of an adhesive bond

JWST
James Webb Space Telescope

K
stress optic coefficient

K
thermal conductivity

K_a, K_g
Kelvin temperature; stress optic coefficient

K_1, K_A, etc.
constant term in an equation

KAO
Kuiper Airborne Observatory

K_C
fracture toughness (strength) of a brittle material

L
length of a spring that is free to bend; width or diameter of a bond

L_1, L_2
Lagrange points 1 and 2 (Sun/Earth/Moon orbit)

LAGEOS
Laser Geodynamic Satellite

LEO
Low Earth orbit

L_{3k}
axial length of a lens spacer between surfaces i and j

LLTV
low light-level television

ln (x)
natural logarithm of x

LOS
line of sight

lp
line pair (element for resolution measurement, as in lp/mm)

LRR
lower rim ray at maximum semifield angle

m
mass, reciprocal of Poisson’s ratio

MEO
middle Earth orbit

MIL-STD
U.S. Military Standard

MISR
Multispectral Imaging Spectroradiometer

MLI
multilayer insulation

MMC
metal matrix composite

MMT
Multiple Mirror Telescope

MTF
modulation transfer function

N
newton; number of springs
n, n_{ABS}, n_{REL} \quad \text{refractive index, refractive index in vacuum, refractive index in air}
n_{1}, n_{2} \quad \text{refractive index for parallel or perpendicular polarized light component}
N \quad \text{number of springs; as prefix in Schott glass name, indicates "new"}
NASA \quad \text{National Aeronautics and Space Administration}
n_{d} \quad \text{refractive index for } \lambda = 546.074 \text{ nm}
N_{E}, N_{1}, N_{2} \quad \text{number of threads per unit length of differential thread}
n_{x} \quad \text{refractive index for a specific wavelength}
OAO-C \quad \text{Orbiting Astronomical Observatory-Copernicus}
OD \quad \text{outside diameter}
OFHC \quad \text{oxygen-free high-conductivity (designation of a variety of copper)}
OPD \quad \text{optical path difference}
OTF \quad \text{optical transfer function}
P \quad \text{preload force; optical power}
p \quad \text{thread crest-to-crest pitch; linear preload}
P_{F}, P_{S} \quad \text{statistical probability of failure, of survival (or of success)}
P_{f} \quad \text{preload force per spring}
ppm \quad \text{parts per million}
PSD \quad \text{power spectral density}
PTFE \quad \text{polytetrafluoroethylene (Teflon)}
p-v \quad \text{peak to valley}
q \quad \text{heat flux per unit of area}
Q \quad \text{torque; bond area}
Q_{\text{MAX}} \quad \text{maximum bond area within prism or mirror face dimension}
Q_{\text{MIN}} \quad \text{minimum bond area to provide needed joint strength}
r \quad \text{snap ring cross sectional radius}
R \quad \text{surface radius}
r_{c} \quad \text{radius of elastically deformed region at an interface}
RH \quad \text{relative humidity}
rms \quad \text{root mean square}
roll \quad \text{component tilt about transverse axis}
r_{s} \quad \text{radius to center of a spacer}
R_{S} \quad \text{reflectance}
R_{T} \quad \text{cross-section radius of toroidal surface}
RT \quad \text{as subscript, indicates racetrack shape for bond area}
R_{T} \quad \text{radius of a toroid}
RTV \quad \text{room temperature vulcanizing sealant}
R_{A} \quad \text{reflectance of a surface at wavelength } \lambda\nS_{\text{AVG}} \quad \text{average contact stress in an interface}
S_{b} \quad \text{stress in a bent mechanical part, such as a spring}
S_{C, \text{CYL}}, S_{C, \text{SPH}} \quad \text{compressive stress from contact with a cylindrical or spherical pad}
S_{C, \text{SC}}, S_{C, \text{TAN}}, S_{C, \text{TOR}} \quad \text{compressive stress from contact with a sharp, conical, or toroidal mount corner}
SC \quad \text{as subscript, indicates sharp corner interface}
S_{C}, S_{T} \quad \text{compressive stress, tensile stress at an optic-to-mount interface}
S_{e} \quad \text{shear modulus of an elastomer}
S_{f} \quad \text{fracture strength of a window material}
SIRTFT \quad \text{Space Infrared Telescope Facility (now Spitzer Space Telescope)}
S_{i}, S_{k} \quad \text{sagittal depth of the "ith" or "jth" surface}
S_{M} \quad \text{tangential tensile (hoop) stress in a mount's wall}
SMY  microyield strength
SOFIA  Stratospheric Observatory for Infrared Astronomy
SPAD  average stress in a pad-to-optic interface
SPDT  single-point diamond turning
SPH  as subscript, indicates spherical interface
SR  radial stress at an optic-to-mount interface
SS  shear stress developed in a bonded joint
ST  tensile stress
SW  yield strength for window material
SXÁ  a proprietary aluminum metal matrix composite
SV, SMY  yield strength; microyield strength of a material
T  temperature
t  thickness, as that of a flat spring
TA  axial path length in a refracting material
TA, TMAX, TMIN  assembly, maximum, minimum temperature
TAN  as subscript, indicates a tangential interface
tanh  hyperbolic tangent function
tc  cell wall thickness
TC  temperature at which assembly preload reduces to zero
tE  edge thickness of a lens or mirror
tc  thickness of an adhesive bond; of an elastomeric ring
TIR  total internal reflection; total indicator runout (see FIM)
TOR  as subscript, indicates a toroidal interface
tpi  threads per inch
Tλ  transmittance of a surface at wavelength λ
U, U'  angle with respect to the axis of a marginal ray in object, image space
ULE  Corning's ultra-low expansion glass-ceramic material
UNC, UNF  unified coarse or fine thread
URR  upper rim ray at maximum semifield angle
USC  U.S. customary system of units (the "inch" system)
UV  ultraviolet
V  volume, lens vertex
VA  Abbe number for \( \lambda = 546.074 \text{ nm} \)
VLT  Very Large Telescope
w  unit applied load
W  weight
ws  wall thickness of a spacer
X, Y, Z  coordinate axes
yc  mechanical contact height on an optic (measured from the axis)
ys  ID/2 for a lens mounting
Mounting Optics
in Optical Instruments
Second Edition