STRAY LIGHT
Analysis and Control

Eric C. Fest
# Contents

Preface xi

Acknowledgments xv

## Chapter 1 Introduction and Terminology 1

1.1 Book Prerequisites 4
1.2 Book Organization 4
1.3 Stray Light Terminology 6
   1.3.1 Stray light paths 6
   1.3.2 Specular and scatter stray light mechanisms 7
   1.3.3 Critical and illuminated surfaces 8
   1.3.4 In-field and out-of-field stray light 8
   1.3.5 Internal and external stray light 9
   1.3.6 "Move it or Block it or Paint/coat it or Clean it" 9
1.4 Summary 10

## Chapter 2 Basic Radiometry for Stray Light Analysis 13

2.1 Radiometric Terms 13
   2.1.1 Flux, or power, and radiometric versus photometric units 14
   2.1.2 Reflectance, transmittance, and absorption 16
   2.1.3 Solid angle and projected solid angle 16
   2.1.4 Radiance 18
   2.1.5 Blackbody radiance 18
   2.1.6 Throughput 22
   2.1.7 Intensity 23
   2.1.8 Exitance 23
   2.1.9 Irradiance 24
   2.1.10 Bidirectional scattering distribution function 25
2.2 Radiative Transfer 29
   2.2.1 Point source transmittance 31
   2.2.2 Detector field of view 32
   2.2.3 Veiling glare index 32
Contents

2.2.4 Exclusion angle 32
2.2.5 Estimation of stray light using basic radiative transfer 33
2.2.6 Uncertainty of stray light estimates 36
2.3 Detector Responsivity 36
2.3.1 Noise equivalent irradiance 36
2.3.2 Noise equivalent delta temperature 37
2.4 Summary 38

Chapter 3 Basic Ray Tracing for Stray Light Analysis 41
3.1 Building the Stray Light Model 41
3.1.1 Defining optical and mechanical geometry 41
3.1.2 Defining optical properties 43
3.2 Ray Tracing 43
3.2.1 Using ray statistics to quantify speed of convergence 43
3.2.2 Aiming scattered rays to increase the speed of convergence 45
3.2.3 Backward ray tracing 48
3.2.4 Finding stray light paths using detector FOV 49
3.2.5 Determining critical and illuminated surfaces 50
3.2.6 Performing internal stray light calculations 51
3.2.7 Controlling ray ancestry to increase speed of convergence 55
3.2.8 Using Monte Carlo ray splitting to increase speed of convergence 55
3.2.9 Calculating the effect of stray light on modulation transfer function 56
3.3 Summary 58

Chapter 4 Scattering from Optical Surface Roughness and Coatings 61
4.1 Scattering from Uncoated Optical Surface Roughness 62
4.1.1 BSDF from RMS surface roughness 68
4.1.2 BSDF from PSD 70
4.1.3 BSDF from empirical fits to measured data 71
4.1.4 Artifacts from roughness scatter 72
4.2 Scattering from Coated Optical Surface Roughness 73
4.3 Scattering from Scratches and Digs 75
4.4 Summary 75

Chapter 5 Scattering from Particulate Contaminants 77
5.1 Scattering from Spherical Particles (Mie Scatter Theory) 78
5.2 Particle Density Function Models 80
5.2.1 The IEST CC1246D cleanliness standard 81
5.2.2 Measured (tabulated) distribution 87
### Chapter 5  Determining the Particle Density Function

5.2.3  Determining the particle density function using typical cleanliness levels, fallout rates, or direct measurement 87
   5.2.3.1  Use of typical cleanliness levels 89
   5.2.3.2  Use of fallout rates (uncleaned surfaces only) 89
   5.2.3.3  Use of a measured (tabulated) density function 90

5.3  BSDF Models 91
   5.3.1  BSDF from PAC 91
   5.3.2  BSDF from Mie scatter calculations 92
   5.3.3  BSDF from empirical fits to measured data 92
   5.3.4  Determining the uncertainty in BSDF from the uncertainty in particle density function 92
   5.3.5  Artifacts from contamination scatter 93

5.4  Comparison of Scatter from Contaminants and Scatter from Surface Roughness 95

5.5  Scattering from Inclusions in Bulk Media 95

5.6  Molecular Contamination 98

5.7  Summary 98

### Chapter 6  Scattering from Black Surface Treatments 101

6.1  Physics of Scattering from Black Surface Treatments 102
   6.1.1  BRDF from empirical fits to measured data 104
   6.1.2  Using published BRDF data 109
   6.1.3  Artifacts from black surface treatment scatter 111

6.2  Selection Criteria for Black Surface Treatments 112
   6.2.1  Absorption in the sensor waveband 113
   6.2.2  Specularity at high AOIs 113
   6.2.3  Particulate contamination 114
   6.2.4  Molecular contamination 114
   6.2.5  Conductivity 114

6.3  Types of Black Surface Treatments 114
   6.3.1  Appliqués 115
   6.3.2  Treatments that reduce surface thickness 115
   6.3.3  Treatments that increase surface thickness 116
      6.3.3.1  Painting 116
      6.3.3.2  Fused powders 116
      6.3.3.3  Black oxide coatings 119
      6.3.3.4  Anodize 119

6.4  Survey of Widely Used Black Surface Treatments 120

6.5  Summary 120

### Chapter 7  Ghost Reflections, Aperture Diffraction, and Diffraction from Diffractive Optical Elements 123

7.1  Ghost Reflections 123
   7.1.1  Reflectance of uncoated and coated surfaces 124
## Contents

7.1.1.1 Uncoated surfaces 124  
7.1.1.2 Coated surfaces 125  
7.1.2 Reflectance from typical values 126  
7.1.3 Reflectance from the stack definition or predicted performance data 128  
7.1.4 Reflectance from measured data 128  
7.1.5 Artifacts from ghost reflections 128  
7.1.6 “Reflective” ghosts 131  
7.2 Aperture Diffraction 132  
7.2.1 Aperture diffraction theory 132  
7.2.2 Calculation of aperture diffraction in stray light analysis programs 133  
7.2.3 Artifacts from aperture diffraction 134  
7.2.4 Expressions for wide-angle diffraction calculations 135  
7.3 Diffraction from Diffractive Optical Elements 137  
7.3.1 DOE diffraction theory 138  
7.3.2 Artifacts from DOE diffraction 140  
7.3.3 Scattering from DOE transition regions 140  
7.4 Summary 142  

### Chapter 8 Optical Design for Stray Light Control 145  
8.1 Use a Field Stop 145  
8.2 Use an Unobscured Optical Design 147  
8.3 Minimize the Number of Optical Elements between the Aperture Stop and the Focal Plane 148  
8.4 Use a Lyot Stop 150  
8.4.1 Calculating Lyot stop diameter from analytic expressions 151  
8.4.2 Calculating Lyot stop diameter from coherent beam analysis 152  
8.5 Use a Pupil Mask to Block Diffraction and Scattering from Struts and Other Obscurations 153  
8.6 Minimize Illumination of the Aperture Stop 154  
8.7 Minimize the Number of Optical Elements, Especially Refractive Elements 154  
8.8 Avoid Optical Elements at Intermediate Images 155  
8.9 Avoid Ghosts Focused at the Focal Plane 155  
8.10 Minimize Vignetting, Including the Projected Solid Angle of Struts 156  
8.11 Use Temporal, Spectral, or Polarization Filters 157  
8.12 Use Nonuniformity Compensation and Reflective Warm Shields in IR Systems 157  
8.13 Summary 160
Chapter 9  Baffle and Cold Shield Design  163
9.1 Design of the Main Baffles and Cold Shields  164
9.2 Design of Vanes for Main Baffles and Cold Shields  167
  9.2.1 Optimal aperture diameter, depth, and spacing for baffle vanes  168
  9.2.2 Edge radius, bevel angle, and angle for baffle vanes  172
  9.2.3 Groove-shaped baffle vanes  172
9.3 Design of Baffles for Cassegrain-Type Systems  174
9.4 Design of Reflective Baffle Vanes  178
9.5 Design of Masks  181
9.6 Summary  181

Chapter 10 Measurement of BSDF, TIS, and System Stray Light  183
10.1 Measurement of BSDF (Scatterometers)  183
10.2 Measurement of TIS  186
10.3 Measurement of System Stray Light  188
  10.3.1 Sensor radiometric calibration  188
  10.3.2 Collimated source test  189
  10.3.3 Extended source test  190
  10.3.4 Solar tests  191
      10.3.4.1 Using direct sunlight  191
      10.3.4.2 Using a heliostat  192
10.4 Internal Stray Light Testing  193
10.5 Summary  193

Chapter 11 Stray Light Engineering Process  195
11.1 Define Stray Light Requirements  195
  11.1.1 Maximum allowed image plane irradiance and exclusion angle  196
  11.1.2 Inheritance of stray light requirements from comparable systems  198
11.2 Design Optics, Pick Surface Roughness, Contamination Levels, and Coatings  198
11.3 Build Stray Light Model, Add Baffles and Black Surface Treatments  198
11.4 Compute Stray Light Performance  199
11.5 Build and Test  200
11.6 Process Completion  202
11.7 Summary  202
11.8 Guidelines and Rules of Thumb  202

Index  205