Index

Symbols

\( \alpha \), see absorptance
\( \alpha \), see absorption attenuation coefficient
\( \beta \), see optical thickness
\( \gamma \), see attenuation coefficient
\( \Delta f \), see noise equivalent bandwidth
\( \epsilon \), see emissivity
\( \eta \), see quantum efficiency
\( \eta_a, \eta_b \), see image fill efficiency
\( \eta_s \), see scanning efficiency
\( \lambda \), see wavelength
\( \lambda_c \), see cutoff wavelength
\( \nu \), see frequency, optical
\( \bar{\nu} \), see wavenumber
\( \rho \), see reflectance
\( \sigma \), see scattering attenuation coefficient
\( \sigma_r \), see surface roughness
\( \sigma_\lambda \), see Stefan–Boltzmann constant
\( \sigma_\nu \), see Stefan–Boltzmann constant
\( \tau \), see transmittance
\( \Phi \), see flux
\( \psi \), see sun geometry factor
\( \omega \), see solid angle, geometric
\( \Omega \), see solid angle, projected
\( \Omega_r \), see field of regard
\( C_v \), see contrast threshold
\( D \), see pupil diameter
\( D^* \), see specific detectivity
\( dA \), see elemental area
\( E \), see irradiance
\( E_\lambda \), see bandgap
\( f \), see electrical frequency
\( f \), see focal length
\( F \), see spatial view factor
\( f_n \), see f-number
\( f_r \), see bidirectional reflection distribution function
\( f_{-3\,dB} \), see bandwidth, \( -3\,dB \)

\( h \), see Planck constant
\( h\nu \), see photon energy
\( I \), see intensity
\( I_{ph} \), see photocurrent
\( I_{sat} \), see reverse-bias-saturation current
\( K_\lambda \), see photopic efficacy
\( k_f \), see time-bandwidth product
\( k_n \), see noise equivalent bandwidth
\( L \), see radiance
\( M \), see exitance
\( n \), see index of refraction
\( P_d \), see probability of detection
\( P_n \), see probability of false detection
\( q \), see absolute humidity
\( q \), see quanta
\( R \), see responsivity
\( R_v \), see meteorological range
\( S \), see sensor response
\( V_\lambda \), see photopic vision
\( V'_\lambda \), see scotopic vision
\( Z_t \), see detector preamplifier gain

A
aberrations, 232–235
  astigmatism, 232
  chromatic, 232
  comatic/coma, 232
  distortion, 235
  field curvature, 235
  spherical, 232
absolute humidity, 123
absorptance
  attenuation coefficient, 99, 110
detector, 242
Kirchhoff’s law, 69
material property, 27
absorption coefficient
direct transition materials, 177
extrinsic semiconductor, 178, 183

477
free-carrier, 177
indirect transition materials, 177
intrinsic semiconductor, 178, 183
refractive index, 176
spectral, 177
typical curves, 178
Urbach tail, 177
advanced model, see lifecycle phases
aerosols, 112–116
atmospheric transmittance, 113
land, 112
manmade, 112
maritime, 112
meteorological range, 127
Mie scattering, 116
Rayleigh scattering, 115
scattering attenuation coefficient, 128
afocal optics, 236, 237
aliasing, 146, 391, 396–398
angle
factor, see spatial view factor
linear, 27
solid, 28–35
aperture stop, 222, 232
approximation
bandgap, 139
BRDF, 81
grey body, 285
layered atmosphere, 104
Planck law, 64
responsivity, 415
scattering, 114
scotopic efficiency spectral shape, 46
Seebeck coefficient, 160
solid angle, 33, 437, 441
thin lens, 221, 225–227
time bandwidth, 150
transmittance, 108
area
clear aperture, 242
dimensional analysis, 367
elemental, 19
estimation of a flame, 288–290, 352
example calculations, 316, 441–447
pixel footprint, 269
projected, 28–35
solid angle, 28–35, 366
spatial integral, 407–409
sun, 316
areance, see irradiance and exitance
aspheric lens, 237
assumption management, 11
atmosphere, 108–128
absolute humidity, 123
aerosols, 112
attenuation, 108, 110
composition, 108
contrast transmittance, 124–127
definitions, 109
effect on image, 268–272
effective transmittance, 107
looking up/down, 121
meteorological range, 127
Mie scattering, 116
molecular
absorption, 111–112
constituents, 111
transmittance, 113
overview, 110
path radiance, 118–121, 283
LWIR band, 120
MWIR band, 119
NIR band, 118
visual band, 118
radiative transfer codes, 129
Rayleigh scattering, 115
relative humidity, 123
scattering, 112, 127
scattering modes, 114
sky radiance, 283, 398–401
standard profiles, 109
transmittance, 113, 382
water vapor content, 121
windows, 116
LWIR band, 117
MWIR band, 117
NIR band, 117
visual band, 116
attenuation
atmosphere, 108
coefficient, 98–99
avalanche detector, 198
B
background, 256
background-limited operation, 147, 183, 192, 205, 211
baffle, 223
band-limited noise, 142
bandgap, 138–139
  Varshni approximation, 139
bandwidth
  −3 dB, 262
  Butterworth filter, 263
  noise equivalent, 262
best practices, 365–373
bidirectional reflection distribution function (BRDF), 80–83
  Cook–Torrance model, 82
  diffuse reflection, 81
  measurements, 83
  mirror reflection, 81
  modeling approach, 82
  Phong model, 82
  reflection signatures, 284
  specular reflective surface, 327
  surface roughness, 76
blackbody
  aperture, 75
  curves, 68, 69, 72
  definition, 59
  emissivity, 65
  Kirchhoff’s law, 70
  laboratory instrument, 59
  Lambertian source, 41
  Planck’s law, 60–62
  Stefan–Boltzmann law, 63
  Wien’s displacement law, 62
Bloch functions, 170
bolometer, 155–157
  construction, 155
  noise, 157
  responsivity, 156
Boltzmann probability distribution, 58
book website, xxv, 411
Bouguer’s law, 98
  optical thickness, 103
  transmittance approximation, 108
  transmittance scaling, 108
Bravais lattice, 164
Bunsen burner flame case study
  data analysis, 350–355
  instrument calibration, 346–348
  measurements, 348–350
  workflow, 345–346
Butterworth filter, 262
C
carrier lifetime, 179
case study
  Bunsen burner flame, 344–355
  cloud model, 297–300
  flame sensor, 309–311
  flame-area estimation, 288
  high-temperature flame measurement, 295
  infrared scene simulation, 385–401
  infrared sensor radiometry, 337–344
  laser rangefinder range equation, 321–330
  low-emissivity surface measurement, 295
  object appearance in an image, 311–314
  solar cell, 315–321
  sun-glint, 302
  temperature cross-over, 300
  thermal camera sensitivity, 334–337
  thermal imaging sensor model, 330–334
  thermally transparent paints, 301
  Cassegrain telescope, 236, 237
  solid angle worked example, 448
  cavity, 57, 74
  emissivity, 74
  reflectance, 74
  chief ray, 224, 230
cloud model case study
  measurement, 297
  model, 298–300
  relative signature contributions, 300
  silver-lining factor, 298
  worked example in Matlab®, 451
clutter, 256
CODATA constants, see constants
cold finger, 337
cold shield, 338
design, 342
efficiency, 341, 342
collimator, 238–239
color
  coordinates, 48–51
    worked example Python™, 430
  normalization, 48
  Planckian locus, 49
  ratio, 291, 398–401
  sensitivity to source spectrum, 49
  space, CIE 1931, 48
  xy chart, CIE, 381
coma, 234
  complex lens, see thick lens
concept study, see lifecycle phases
conduction band, 168
conductors, 170
  energy bands, 171
configuration factor, see spatial view factor
conservation of radiance, 35–37
constants
  CODATA, 65
  mathematical, 376
  physical, 376
  Planck law, 66, 377
contrast
  difference, 271
  inversion, 300
  radiometric, 272
  reduction, 102
  signature, 398–401
  threshold
    Koschmieder, 127
    World Meteorological Organization, 127
transmittance, 103
  atmosphere, 124–127
conversion
  radiometric to photometric, 47
  spectral quantities, 26
convolution, 265–267
  Cook–Torrance BRDF model, 82
  \( \cos^3 \), 32, 449
  \( \cos^4 \), 33
cryogenic coolers, 185
Joule–Thomson, 185–186
  Stirling, 186
crystalline materials, 163–179
  acceptor doping, 172
  basis, 164
  conductors, 170
  donor doping, 172
  energy bands, 165–170
  insulators, 170
  lattice, 164
  n-type material, 171
  p-type material, 172
  pentavalent, 171
  photon-electron interactions, 174–176
  physical parameters, 379–380
  semiconductors, 170
  169–170
    band structure, 169–170
    intrinsic and extrinsic materials, 171–174
    light absorption, 176–178
    structure, 164
    tetravalent, 170, 171
cutoff wavelength, 138
data analysis, 292–295
  imaging-camera example, 350–355
  workflow example, 345–346
definition study, see lifecycle phases
design, 2, 3
  prerequisites, 3
  process, 12
  review, 6
  trade off, 1
detection
  probability, 259, 272
  probability of false, 260
  pulse, 272–275
  pulse example calculation, 436
  range, 267–268, 326
  range example calculation, 326–327
detectivity, 147–149, 258
  specific, 148, 183, 184, 205, 258
detector
  avalanche, 198
  conductivity, 188
configurations, 140
cooling, 183–187
gas/liquid cryogen, 185
radiative, 185
thermo-electric, 185
cutoff wavelength, 138
detection process, 136–140
detectivity, see detectivity
dewar, 185
effective responsivity, 148
filter, 338
history, 135–136
intrinsic material, 173
material parameters, 379–380
noise, 140–150, 183
normalized spectral responsivity, 140, 243
peak responsivity, 140, 243
performance modeling, 207–210
photoconductive, 179, 187–193
photon, 138–140
detection process, 179–183
quantum efficiency, 181–183
photovoltaic, 179, 193–207
preamplifier gain, 243
signal voltage, 243
spectral responsivity, 182, 243
technology impact, 210–212
thermal, 136–138, 151–163
wideband responsivity, 261
detector-limited operation, 205, 206
development
optronic sensor systems, 385–386
parallel activities, 7
phase, see lifecycle phases
product, 4
development model, see also lifecycle phases
dewar, 185
difference
contrast, 271–272
noise equivalent temperature (NETD), 247, 259, 332–333
operator, 19
diffuse
reflectance, 76, 81
example visual spectra, 50
Phong BRDF model, 82
signature components, 279–283
reflectance, Phong BRDF, 82
shape factor, see spatial view factor
dimensional analysis, 367–368
example, 454, 461, 462
discrete ordinates, 104
distortion, 234
domain
space, 256
time, 256
doped materials
acceptor doping, 172
concentrations, 174
donor doping, 172
Duntley equations, 101
E
effective, see also normalization
detector responsivity, 148
mass
electron, 379
hole, 379
transmittance, 105–108
example humid atmosphere, 124
example various sources, 107
scaling with range, 108
simulation application, 393
value normalization, 261–262
efficacy
photopic, 47
scotopic, 47
total luminous, 47
efficiency
cold shield, 341
image fill, 331
photopic, 47
quantum, 139
relative luminous, 46
human eye, 47, 378
scanning, 330
scotopic, 47
spectral shape approximation, 46
solar cell, 318
Einstein equation, 180
electrical frequency, 141
electro-optical system
Index

analysis
  example, 309–364
  pyradi toolkit, 411
definition, 14
elements, 15
  functions, 221
  high-level design, 15
  major components, 14
  modeling and simulation, 16
  multispectral, 40
  simulation application, 385–401
emotagnetic
  radiation, 20–22
  particle model, 20
  wave model, 20
  spectrum, 21
electron-hole pair, 179
  elemental area, 19
emissivity, 65–74
  absorptivity, 69
  atmosphere, 120, 121
  blackbody, 59
cavity, 74
definitions, 70
directional, 83–86
  example curves, 85
  in nature, 85
gas radiator source, 103, 310
grey body, 71
Kirchhoff’s law, 69
low, 73
  measurement, 295–296
  path radiance, 101–103
  practical estimation, 287–288, 344–355
  spectral, 71
  hemispherical, 84
temporal variation, 390
  thermally transparent paint, 301, 302
energy bands, 165–170
  bandgap, 165
  thermal carrier excitation, 183
  conduction band, 168
Fermi level, 166, 168
  Fermi–Dirac distribution, 166
  interband transitions, 174–176
  intraband transitions, 174, 175
orbitals, 165
  photon-electron interactions, 174–176
  semiconductor, 169–170
  valence band, 168
wave model, 166–169
  Bloch functions, 170
density of states, 166
  wave function, 167
equivalent path length, 99
étdendue, see throughput
exitance, 24
  Lambertian source, 41–42
  luminous, 23
  noise equivalent (NEM), 247, 259
  photon, 23, 60
Planck’s law, 59–62
  temperature derivative, 60–62
  radiant, 23, 38
  relation to radiance, 41
  source shape, 44–45
Stefan–Boltzmann law, 63
  Wien’s displacement law, 62
  experimental model, see lifecycle phases
extended target, 232, 311–314
  extinction coefficient, see attenuation coefficient
extrinsic
detector, see photon detector
detector material, 173
eye spectral response, 46
F
  1/f noise, 142, 145
  photoconductive detectors, 191
  power spectral density, 145
false alarm rate (FAR), 260
  pulse detection, 272–275
calculation in Matlab®, 436
calculation in Python™, 436
  example calculation, 273–275
Fermi level, 166, 168
  Fermi–Dirac distribution, 166, 167, 173
  ferroelectric effect, 157–158
field
  angle, 224, 240
curvature, 234, 235
  of regard, 330
of view (FOV), 227–232, 240
small angle, 241
stop, 223, 226–232
figures of merit, see performance measures
fill factor, 317
filter
absorption, 240
antisolar, 297
Butterworth, 262
interference, 240
multi-spectral, 39–41
optical, 240
passband, 240
spectral, 240
function, 413–415
spectral response, 223, 240
stopband, 240
transmittance, 240
flame
area calculation in Matlab®, 434
Bunsen burner, 344–355
sensor, 309–311
worked example Matlab®, 417
worked example Python™, 421
temperature measurement, 295
fluctuation noise, 146–147
background flux, 147
signal flux, 146
flux, 24
collecting solid angle, 230, 231
Lambertian source, 41
luminous, 23
photon, 23
radiant, 23
system throughput, 249
transfer, 35–41, 70
generational construction, 36
lossless medium, 37–38
lossy medium, 38
multi-spectral, 39–41
radiative transfer equation, 101
worked example, 448–451
f-number (f/#), 229–230
clear aperture area, 242
optics diameter, 242
focal
length, 224
plane, 223, 224
folded optics, 236, 237
foreground, 256
frequency
electrical, 141
optical, 20
relation to wavelength, 20
response
photoconductive detector, 190–191
photovoltaic detector, 202–203
Fresnel reflectance, 77–79
gold surface, 85
full-width-half-maximum (FWHM) bandwidth, 150
G
gaseous radiator, 70–73, 103–104, see also flame
simulation, 389
generation–recombination (g-r) noise, 144–145
photoconductive detectors, 191–192
power spectral density, 145
rms noise current, 144
golden rules, 365–373
Gregorian telescope, 236, 237
grey body, 71–73
I
I-V curve, 196
image, 221, 268
collimated, see collimator
contrast, 102–103, 271
flux-collecting solid angle, 230
focal plane, 223
modulation transfer function, see modulation transfer function (MTF)
object appearance, 311–314
object relationship, 225
optical aberrations, see aberrations
pixel irradiance, 268–271
pixels, 268
plane, 223, 227, 246
field stop, 227
pupil, 227
vignetting, 227
point spread function, see point spread function (PSF)
probability of detection, 274
ray tracing, 225
rendering, 391–398
resolved object, 268–271
simulation, see infrared scene simulation
spatial sampling, see aliasing
unresolved object, 268–271
image fill efficiency, 331
index of refraction, 20
atmosphere, 97
chromatic aberration, 232
complex, 78, 176
Fresnel reflectance, 78
imaginary component, 176
metal, 78
numerical aperture (NA), 229
real component, 176
Snell’s law, 176
wave equation, 176
industrialization, see lifecycle phases
infinite conjugates, 224, 229
clear aperture, 242
collimator, see collimator
f-number, 229
optics diameter, 242
infrared scene simulation, 385–401
application, 387
benefits, 385
image rendering, see rendering OSSIM, 393
radiometric accuracy, 392
rendering equation, 393–396
effective transmittance, 394
signature model, 393
spectral calculation, 394
spectral discretization, 393
wideband calculation, 395
scene model
atmospheric attenuation, 390
geometry, 388
optical signature, 388
temperature, 390
temporal variation, 390
texture, 390
inhomogeneous medium, 104
insulators, 170
intensity, 24
Lambertian source, 42
luminous, 23, 46
photon, 23
radiant, 23, 38
interface electronics noise, 146
intrinsic carrier concentration, 174
intrinsic detector, see photon detector
irradiance, 24
apparent, 244, 265
in an image, 268–271, see also object appearance in an image
luminous, 23
noise equivalent (NEE), 246, 258,
see also laser rangefinder example
photon, 23
pixel, 268
radiant, 23, 37
isolators
energy bands, 171
J
Johnson noise, 142–143
frequency spectrum, 143
interface electronics, 146
photoconductive detectors, 191–193
photovoltaic detectors, 204
power spectral density (PSD), 143
K
Kirchhoff’s law, 69
knowledge management, 386
Koschmieder, 127
Kubelka–Munk theory, 100
L
laboratory
blackbody, 59, 75
collimator, 238–239
Lagrange invariant, 249
Lambertian source, 41–42
flux, exitance, radiance, 41
blackbody, 41
definition, 41
intensity, 42
projected solid angle, 42
reflectance, 76, 81
reflected sun radiance, 87
shape, 44–45
signature model, 279–283
spatial view factor, 43
view angle, 42
laser rangefinder
detection range, 326
example calculation
range equation, 326–327
signal-to-noise ratio (SNR), 274
threshold-to-noise ratio (TNR), 274
Lambertian reflective surface, 323–325
noise equivalent irradiance (NEE), 321
range equation case study, 321–330
signal irradiance, 322
specular reflective surface, 327–330
target optical cross section, 324
lifecycle phases, 4–7
light models, 22
light traps, 76
linear angle, 27, 28
long-wave infrared (LWIR), 65
atmospheric aerosol scattering, 127–128
atmospheric window, 117
contrast transmittance, 125
path radiance, 120
luminance, 25, 46–48
photopic, 47
scotopic, 47

M
marginal ray, 224, 229, 230
material properties, 27
Matlab®, 409
measurement
bidirectional reflection distribution function (BRDF), 76, 83
cloud, 297
data analysis, 292–295
flame example, 348–350
instrument calibration, 346–348
linear angle, 27
spectroradiometer, 287
technical performance, 255
temperature, 73, 290–292, 295, 354
medium, 14
absorption attenuation coefficient, 99
atmosphere, 108–128
attenuation coefficient, 99
contending, 78
discrete ordinates, 104
equivalent path length, 99
homogeneous, 98
index of refraction, 20
inhomogeneous, 99, 104–105
lossless, 37–38
lossy, 38
optical, 98–104
optical thickness, 103
path radiance, 99–103
scattering attenuation coefficient, 99
transmittance, 38, 98, 108
medium-wave infrared (MWIR), 65
atmospheric aerosol scattering, 127–128
atmospheric window, 117
contrast transmittance, 125
path radiance, 119
mesopic vision, 46
meteorological range, 127
microbolometer, 156–157
Mie scattering, 116
minimum detectable temperature (MDT), 259
minimum resolvable temperature (MRT), 259
model, 12
atmospheric, 129
BRDF, see bidirectional reflection distribution function (BRDF)
cloud, 297–300
detector, 207–210
equivalent, 208
discrete ordinates, 104
electromagnetic wave, 20
imaging sensor, 240–245, 337–344
light, 22
photon particle, 22
photovoltaic detectors circuit, 200
signature, 279–283
solar cell, 319–321
solar irradiance, 86
source–medium–sensor, 14
validation, 275
modeling and simulation (M&S), 7, 16, 385–401
Modtran™
description, 129
meteorological range, 127
visibility, 127
modulation transfer function (MTF), 236, 260
multi-spectral, 39–41
N
near-infrared (NIR), 65
atmospheric window, 117
path radiance, 118
Phong BRDF parameters, 285
noise, 245–247, 256
bolometer, 157
considerations in imaging systems, 146
equivalent bandwidth, 149–150, 262
exitance (NEM), 247, 259
irradiance (NEE), 246, 258
power (NEP), 147–149, 246, 258
radiance (NEL), 247, 258
reflectance (NER), 259
target contrast (NETC), 335–337
temperature difference (NETD), 247, 259, 332–333
1/f, 145
fluctuation, 146–147
generation–recombination (g-r), 144–145
interface electronics, 146
Johnson, 142–143
Nyquist, see Johnson noise
photoconductive detectors, 191–193
photovoltaic detectors, 203–207
physical processes, 140
power spectral density, 141–142
pyroelectric detector, 159
shot, 143–144
system, 141
temperature-fluctuation, 145–146
thermal, see Johnson noise
thermoelectric detector, 161
time-bandwidth product, 150
normalization, 261–263
color coordinates, 48
effective value, 261–262
peak, 262
spatial, 29, 261
weighted mapping, 263
normalized spectral responsivity, 243
n-type material, 171
electron concentration, 174
numerical aperture (NA), 229, 230
O
object
appearance in an image, 311–314
worked example Python™, 424
resolved, 268
unresolved, 268
open-circuit operation, 198, 200
optics, 223–236
aberrations, 232–235
aperture, 226
aspheric lens, 237
axis, 224
chief ray, 224, 230
collimator, 238
conjugates, 224
elements, 222–224
field angle, 224
stop, 226, 230
flux collecting, 230
f-number, 229, 230
focal length, 224
plane, 223, 224
frequency, 20
infinite conjugates, 224, 229
marginal ray, 224, 229, 230
medium, 97–104
modulation transfer function (MTF), 236
numerical aperture (NA), 229, 230
point spread function (PSF), 235
power, 223
principal plane, 224
pupil, 226–230
ray tracing, 225
signature, 279–292
model, 279–283
rendering, 387
spectral filter, 240
stray light, 227
system, 236
afocal, 236
Cassegrain, 236
Gregorian, 236
refractive, 236
thick lens, 225
thickness, 103
thin-lens approximation, 224, 225
transfer function (OTF), 236, 260
vignetting, 227, 238
Optronics System Simulation (OSSIM), 393
orbital, 165
P
paraxial approximation, see thin-lens approximation
particle model, 20
passband, 240
path radiance, 99–103, 118–121
Duntley equations, 100
emissivity, 101–103
Kubelka–Munk theory, 100
LWIR band, 120
MWIR band, 119
NIR band, 118
visual band, 118
Pauli’s exclusion principle, 165, 166, 176
peak responsivity, 243
Peltier effect, 151, 186
performance measures, 10, 255–261
definition, 256
detectivity, 258
false alarm rate (FAR), 260
minimum
detectable temperature (MDT), 259
resolvable temperature (MRT), 259
modulation transfer function (MTF), 260
noise equivalent
exitance (NEM), 259
irradiance (NEE), 258
power (NEP), 258
radiance (NEL), 258
reflectance (NER), 259
temperature difference (NETD), 259
optical transfer function (OTF), 260
point spread function (PSF), 260
probability of detection, 259
probability of false detection, 260
role, 255
signal-to-clutter ratio (SCR), 257
signal-to-noise ratio (SNR), 257
specific detectivity, 258
Phong BRDF model, 82
phonon, 175–177
photoconductive detector, 179, 187
bias circuitry, 189–190
conductivity, 188
frequency response, 190–191
geometry, 189
noise, 191–193
generation–recombination (g–r), 192
Johnson, 192–193
photoconductive gain, 190
quantum efficiency, 187
responsivity, 189
signal, 187–189
photocurrent, 179, 197, 200, 202, 204, 209
photodiode, see photovoltaic detector
photoemissive detector, see photon detector
photometry, 23, 45–51
units, 45
photon, 22
absorption, 176–178
Index

absorption coefficient, 177–178
detector, 138–140
noise, see noise
operation, 179
quantum efficiency, 139
responsivity, 139
electron interactions, 174
energy, 22
wave packet, 22
photonic
efficiency, 47
luminance, 47
relative spectral efficiency, 378
vision, 46
photovoltaic detector, 179, 193
background flux, 204
background-limited operation, 205
bias configurations, 197–202
circuit model, 200
open-circuit, 200–202
reverse, 198–200
short-circuit, 202
construction, 194
depletion region, 194
detector-limited operation
open-circuit mode, 206–207
short-circuit mode, 205–206
diffusion current, 197, 204
energy diagrams, 195
frequency response, 202–203
I-V curve, 196–197
noise, 203–207
Johnson, 204
shot, 204
noise equivalent power (NEP), 204
optimal power transfer, 202
photocurrent, 204
p-n junction, 194
quantum efficiency, 196
resistance, 204
responsivity, 196
reverse-bias-saturation current, 197
specific detectivity, 205
thermally generated current, 204
vs photoconductive detector, 194
photovoltaic detectors
energy bands, 198
physical and mathematical constants, 376
pixel, 268
irradiance in an image, 268–271
signal magnitude, 268
Planck
constant, 22
exitance function Matlab®, 412
exitance function Python™, 412
law, 57–65
constants, 377
derivative exitance, 60–62
exitance, 60–62
integrated, 63
maximum, 62
summary, 65
summation approximation, 64
radiator, 59, 65
Planckian locus, 49
plume, 103
effective transmittance, 106
surface radiator, 104
volume radiator, 104
p-n diode, see photovoltaic detector
p-n junction, 194
point spread function (PSF), 235, 260
point target, 232
Poisson statistics, 144
power spectral density (PSD), 141–142
1/f noise, 142, 145
band-limited noise, 142
combining spectra, 149
generation–recombination (g-r) noise, 145
Johnson noise, 143
shot noise, 143
temperature-fluctuation noise, 145
white noise, 142
principal plane, 224
probability of detection, 259
probability of false detection, 260
prototype, see lifecycle phases
p-type material, 172
hole concentration, 174
pulse detection, 272–275
calculation in Matlab®, 436
calculation in Python™, 436
false alarm rate, 272–275
pupil, 226–230
diameter, 229, 230
pyradi toolkit, 411
pyroelectric detector, 157–159
noise, 159
responsivity, 159
structure, 158
Python™, 409

Q
quanta, 20
quantum efficiency, 139, 181, 182
external, 181
anti-reflection coatings, 182
reflection, 181
internal, 181
photoconductive detector, 187
quantum well detector (QWIP), see photon detector

R
1/R^2 losses, 311–314
radiance, 24
atmospheric path, 283
basic, 37
conservation, 35–37
Lambertian source, 41
luminous (luminance), 25
photon, 25
radiant, 25
reflected
ambient, 283
sky, 283
solar, 283
self-emitted, 281
signature model, 279–283
spatial invariance, 36
transfer, 35–41
transmitted background, 283
radiative transfer equation (RTE), 97, 101
radiator
gaseous, 70, 103
grey body, 71
Planck, 59, 65
selective, 71
surface, 104
thermal, 285–292
volume, 104
radiometer measurements
atmospheric correction, 267
spectral radiance, 287
radiometric quantities, 375
radiometry, 22
definition, xxv
nomenclature, 23
quantities, 24
techniques, 255–276
range equation, 267
solved in Python™, 435
ray
chief, 224
marginal, 224
tracing, 225
Rayleigh scattering, 115
reductionism, xxiii
reflectance
bidirectional, 76, 80–83
cavity, 74
diffuse, 76, 81, 82
directional, 75–83
in nature, 85
Fresnel, 77–79
geometry, 77
high, 73
Lambertian, 76, 81
material property, 27
mirror, 81
Snell’s law, 77, 79, 405
specular, 76, 82
refractive index, see index of refraction
relative humidity (RH), 123
relative luminous efficiency, 46
photopic, 46
scotopic, 46
rendering, 387–398
aliasing, 391, 396–398
rasterization, 391
priority fill algorithm, 391
side-effects, 393
z-buffering, 391
super-sampling, 392, 396–398
requirement allocation, 8
response
eye, 46
Index

filter, 223, 240
  frequency, 150
  complex valued optical, 236
  photoconductive detector, 190–191
  photovoltaic detector, 202–203
  impulse, 235, 260
  normalizing, 140
  spatial frequency, 260
  spectral weighting, 106, 244, 263–264
  system, 246
  thermal detector, 136
  unlimited, 161
responsivity
  bolometer, 156
  normalized, 140, 243
  peak, 140, 243
  photoconductive detector, 189
  photon detector, 139
  pyroelectric detector, 159
  spectral, 140, 243
  thermal detector, 136, 152–154
  thermoelectric detector, 161
reverse-bias operation, 198
reverse-bias-saturation current, 197, 319
review, see design
root-mean-square (rms), 257
S
  scanning efficiency, 330
scattering
  atmosphere, 112
  aerosols, 112
  attenuation coefficient, 99, 110
  Mie, 116, 134
  Rayleigh, 115, 134
scattering modes, 114
Schrödinger equation, 169
scotopic
  efficacy, 47
  efficiency, 47
  luminance, 47
  relative spectral efficiency, 378
  vision, 46
Seebeck coefficient, 160
selective radiator, see gaseous radiator
semiconductors
  current flow, 179
  carrier diffusion, 179
  carrier drift, 180
  charge mobility, 180
  diffusion constant, 180
  diffusion current, 180
  diffusion current density, 180
  drift current, 180
  drift current density, 180
  energy bands, 171
  structure, 169–170
  extrinsic materials, 171
  concentrations, 173
  examples, 174
  Fermi energy level, 173
  Fermi–Dirac distributions, 173
  intrinsic materials, 171
  concentrations, 173
  examples, 173
  Fermi energy level, 173
  intrinsic carrier concentration, 174
  light absorption, 176–178
  material parameters, 379–380
  Schrödinger equation, 169
  silicon lattice, 172
  wave equation, 176
sensor, 14
  aperture stop, 222
  field stop, 223
  noise model, 330–334
optical
  elements, 222
  model, 240
  throughput, 248–250
optimization worked example Matlab®, 459
radiometric model, 242–245, 337–344
  complex source, 245
  detector signal, 242
  source area variations, 244
  signal calculations, 242–245
  complex source, 245
detector, 242
### Index

source area variations, 244
silicon detector, 139
solid angle
field of view, 230
flux-collecting, 230
spatial angles, 230
spectral
filter, 223
response, 223, 243
stops/baffle, 223
terminology, 221–223
window, 222
worked example, 450
sharing, xxiii
short-circuit operation, 198, 202
short-wave infrared (SWIR), 65
shot noise, 143–144
interface electronics, 146
photovoltaic detectors, 203, 204
power spectral density, 143
signal, 256
reference planes, 245
electronics plane, 246
image plane, 246
object plane, 246
optics plane, 246
voltage, 243
signal-to-clutter ratio (SCR), 257
signal-to-noise ratio (SNR), 257
signature
model, 279–283
atmospheric path radiance, 283
BRDF, 284
equation, 281
main contributors, 280
reflected ambient radiance, 283
reflected sky radiance, 283
reflected solar radiance, 283
self-emitted radiance, 281
spatial properties, 279
terminology, 282
thermal radiator, 285–292
transmitted background radiance, 283
reflected vs emitted contribution, 283
rendering, 387
thermal radiation from common objects, 65
sky radiance, 283, 398–401
Snell’s law, 79, 176, 403–405
solar cell analysis, 315–321
configuration, 318
experimental measurement, 315
model, 319–321
radiometry, 317
solid angles, 316
source areas, 316
solid angle, 28–35
approximation, 33
worked example Matlab®, 441
Cassegrain telescope example, 448
field of view, 230
flux collecting, 230
geometric, 28
cone, 29
flat rectangular surface, 32
projected, 29, 41
cone, 31
flat rectangular surface, 32
sphere, 34
temperature, 230
source area, 366
source, 14
gaseous, 103
Lambertian, 41–42
shape, see Lambertian source, shape
space domain, 256
spatial
integral, 38, 407
calculation in Matlab®, 437
view factor, 43
specific detectivity, 148, 183, 184, 205, 258
photon-noise-limited thermal detector, 161
specification hierarchy, 8
specifications, 8–10
spectral
band (NIR, MWIR, SWIR, LWIR), 65
calculations, 264–267
convolution, 265–267
knowledge management, 386
validation, 386
detector function, 415–417
  in Matlab®, 415
  in Python™, 416
domains, 25
emissivity, 71
  measurement, 288
filter, 223, 240
filter function, 413–415
  in Matlab®, 413
  in Python™, 414
filtering, 39
integral, 407
integration, summation, 26
mismatch, 264
quantities, 25
  conversion, 26
  density, 25
response
  eye, 46
  filter, 240
  photon and thermal detectors, 138
  sensor, 223, 246
responsivity, 243
weighting, 106, 244, 263–264
spectroradiometer, 287
specular reflectance, 76, 82
Stefan–Boltzmann law, 63
stopband, 240
subsystem, 2
sun, 86
  area, 316
  geometry factor, 87
  glint, 302
  reflected radiance, 283, 398–401
surface radiator, 104
surface roughness, 75
scale, 76
system, 2
  acceptance, see lifecycle phases
  context, 1
  engineering, 2
  noise, 245–247
performance measures, 255–261
segment, see subsystem
source–medium–sensor model, 242–245
V-chart, 8

T
target
  extended, 268
  point, 268
technical performance measure (TPM), 10

telescope
  Cassegrain, 236
  Gregorian, 236
temperature
  apparent, 73
  cross-over, 300
  estimation of a flame, 290–292
  minimum detectable, 259
  minimum resolvable, 259
  noncontact measurement, 73
  radiation, 73
temperature-fluctuation noise, 145–146
  flux, 146
  power spectral density, 145
thermal detector, 136–138, 151–163
  bolometer, 155–157
  conceptual model, 152
  noise, see noise
  overview, 151–152
  photon-noise-limited, 161–163
    noise equivalent temperature difference (NETD), 163
    specific detectivity, 161–163
  pyroelectric, 157–159
  responsivity, 136, 152–154
  temperature-fluctuation-noise-limited, 163
  noise equivalent temperature difference (NETD), 163
  specific detectivity, 163
  thermoelectric, 159–161
thermal imager
  sensitivity, 334–337
  sensor model, 330–334
    assumptions, 330
    electronic parameters, 330
    example calculation, 333
    flux on the detector, 337–339
    focused optics, 339–342
    noise, 331–333
    out-of-focus optics, 342–344
thermal radiator, see grey body, see
Index

Planck radiator
  white point, 49, 92
thermal radiator model, 285–292
  area estimation, 288
  emissivity estimation, 287
  process, 287
  temperature estimation, 290
thermally transparent paint, 301
thermocouple
  equation, 161
gas measurement, 354
thermodynamic equilibrium, 57
thermoelectric coolers, 186–187
thermoelectric detector, 159–161
  layout, 160
  noise, 161
  responsivity, 161
thick lens, 225–227
thin-lens approximation, 221, 224–227
throughput, 248–250
time domain, 256
time-bandwidth product, 150
transfer function
  modulation (MTF), 236, 260
  optical (OTF), 236, 260
transmittance
  atmospheric windows, 116
    LWIR band, 117
    MWIR band, 117
    NIR band, 117
    visual band, 116
  background, 283
  Bouguer’s law, 98
  contrast, 103
  effective, 105
  filter, 240
  homogeneous medium, 98
  inhomogeneous medium, 99
  material property, 27
  medium, 38, 98
  range, 108
two-flux Kubelka–Munk, 100

U
  up/down atmospheric radiance, 121
  Urbach tail, 177

V
  valence band, 168

validation, 275, 386
value system, 11
Varshni approximation, 139
V-chart, see system
vignetting, 222, 227
  collimator beam, 238, 239
  control of, 228
  in practical design, 341–342
visibility, see meteorological range
  vision
    mesopic, 46
    photopic, 46
    scotopic, 46
visual spectral band
  atmospheric window, 116
  contrast transmittance, 125
  path radiance, 118
volume radiator, 104

W
  wave model
    electronic, 166
      Bloch functions, 170
      field strength, 176
      velocity, 176
      wave equation, 176
    light, 20
    wave packet, 22
    wavefront, 20
    wavelength, 20
    cutoff, 138
    relation to frequency, 20
    relation to wavenumber, 26
    spectral density conversion, 26
    wavenumber, 25
    website, xxv, 411
  white noise, 142
  white point, 49, 92
  Wien’s displacement law, 62–63, 67
Z
  zero field angle, see optical axis
Cornelius J. (Nelis) Willers completed a B.Eng (Honns) Electronics Engineering degree at the University of Pretoria in 1976 and an MS (Optical Engineering) degree at the University of Arizona in 1983. He is registered as a professional engineer. His 36 years of work experience includes electro-optical system development, system architecture and systems engineering, software development, and infrared scene simulation. His most notable achievements include being the chief architect and technical lead in establishing an imaging missile seeker technology base, and in the process, spearheading advanced physics-based infrared image simulation. The simulation system is currently used for a number of different applications in laboratories across the globe. His current interests include infrared signature measurement and data analysis, infrared system modeling and simulation, and the development of aircraft self-protection systems. He is leading the open-source, Python-based pyradi radiometry toolkit project. He has published a large number of technical and research reports. His conference paper topics include infrared system modeling and simulation, and the modeling of military conflict using agent-based techniques. He teaches radiometry and infrared system design in short courses and at a masters-degree level at the University of Pretoria.