REMOTE SENSING
OPTICS AND OPTICAL SYSTEMS

Philip N. Slater

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Preface

The rapid growth of remote sensing science, technology, and applications since the 1960s has been paralleled by a substantial increase in the number of books and manuals on the subject. Some of these attempt to cover the whole subject and represent, perforce, the combined work of many authors who are specialists in the many disciplines that remote sensing embraces. Others deal with a single application, describing in an introductory manner the physics and sensor systems pertinent to that application. The present book takes a third approach by emphasizing the optics and the optical sensor systems used in remote sensing. It does not describe remote sensing outside the spectral range 0.4 to 16 μm, nor does it discuss image processing and scene classification procedures or specific applications.

This book provides the foundation for those wishing to pursue applications in remote sensing in which optical techniques and sensors are employed. It is appropriate to the student, at or beyond the first year graduate level, who needs information on the basic optical considerations of remote sensing. It also provides detailed information for the researcher and engineer involved in spectroradiometric measurement and calibration procedures, instrumentation theory, modeling of the interactions of radiant flux with the earth's atmosphere and surface, characteristics of film and electro-optical detectors, and design and performance of optical remote sensing systems.

The text includes several calculations to provide the reader examples of how various concepts are reduced to practice. There are examples involving the radiative transfer from a point or a surface to a surface; radiometric-to-photometric conversions; and the radiometry of the mirror beacon experiment. Calculations are made to compare the performances of prism, grating, Fabry-Perot, and Fourier transform spectrometers and to compare the information capacities of photographic film and magnetic tape. Signal-to-noise ratio analyses are carried out for systems using different types of electro-optical detectors. The feasibility of an orbital Fraunhofer line discriminator is considered from the standpoint of system signal-to-noise ratio. A comparison is described between the signal-to-noise ratios of imagery produced by linear array and film systems having the same image-forming optics. An appendix deals with the calculation of the number of pixels and the telemetry requirements for a Landsat scene.

Wherever possible the practical aspects of instrument performance and measurement procedures are described. For example, there is a discussion of the limitations of F number as a measure of system speed; reference is made to the problems of stray light, order overlap, system-induced polarization effects, inadequate off-band rejection for spectral filters, and other sources of noise and uncertainty in remote sensing measurements. These problems are discussed in terms of instrument type rather than for specific commercially available instruments; the comments should thus be generally useful to both the system designer and the system engineer. Methods for correcting spectral signatures for atmospheric and system-dependent effects are described in detail.

Several aerial systems and all the space remote sensing systems flown to date are described. Emphasis is placed on the Landsat Multispectral Scanner System and

Thematic Mapper. Details are given on the data products and processing pertaining to Landsat imagery. There is a discussion of multispectral linear array systems and their advantages and disadvantages with respect to mechanical scanners. Several space multispectral array systems in the planning or fabrication stage are described.

Having for several years taught a first-year graduate level course in remote sensing optics and optical systems to applications students who have not usually been proficient in mathematics, I realize the importance of avoiding unnecessarily complicated mathematical treatments. Unfortunately, some nonmathematical remote sensing students do not know what a radian is, not to mention a steradian, so an appendix is devoted to angular measures. On the other hand, the derivation of the equations that model the interaction of radiant flux with vegetative canopies involves fairly complicated mathematics. Inevitably then, the mathematical level varies from chapter to chapter, but it is unlikely that the reader will find that unnecessarily advanced mathematics has been used to describe the various topics.

It gives me great pleasure to acknowledge the encouragement and financial support provided me for writing this book by Drs. Herbert E. Carter and A. Richard Kassander, Jr., and the Committee on Remote Sensing at the University of Arizona. I also wish to thank Dr. Peter A. Franken for relieving me of administrative responsibilities so I could find the necessary time to write, and Dr. David S. Simonett for his involvement as series editor.

Very many colleagues and friends have kindly and patiently answered numerous questions related to the material in this book. In particular I wish to thank the following: L. R. Baker, J. J. Burke, K. R. Castle, A. E. Craig, E. L. Dereniak, B. M. Herman, S. J. Martinek, J. M. Palmer, R. A. Schowengerdt, and R. D. Wooden of the University of Arizona; R. W. Cline and J. C. Lansing, Jr., of the Santa Barbara Research Center, a subsidiary of Hughes Aircraft Company; A. P. Colvocoresses, F. J. Doyle, J. S. Fletcher, G. Harris, Jr., J. R. McCord, R. B. McEwen, D. E. Ulmer, K. Watson, and R. D. Watson of the U.S. Geological Survey; K. R. Crouse of Technicolor Graphic Services, Inc.; A. F. H. Goetz of the Jet Propulsion Laboratory; G. J. Grebowski, H. Ostrow, C. C. Schnetzler, and L. L. Thompson of the Goddard Space Flight Center; J. Horton of the Perkin-Elmer Corporation; G. T. Keene of the Eastman Kodak Corporation; V. T. Norwood of the Hughes Aircraft Company; R. J. Ondrejka of the Itek Corporation; J. A. Smith of Colorado State University; G. H. Suits of the Environmental Research Institute of Michigan; and A. Weigandt of Chicago Aerial Industries. It is a pleasure for me to thank in particular A. P. Colvocoresses, R. A. Schowengerdt, and L. L. Thompson for the benefit of many useful discussions of different aspects of remote sensing. In spite of all the expert advice and assistance I have received, inevitably errors will be found and these are solely my responsibility.

I also wish to thank several secretaries of the Optical Sciences Center who typed different parts of the manuscript, D. R. Cowen for the artwork, and Martha Stockton who has helped in editing some of the more difficult portions. Lastly, I wish to thank the publisher for efficient handling of the production of the book.

PHILIP N. SLATER

LIST OF ABBREVIATIONS AND SYMBOLS*

A ratio of diameter of central obscuration to that of primary mirror, 118
A_o, A_i area of object and image, 112
AFS aerial film speed, 362
ANSI American National Standard Institute, 89
ASOS antimony oxide oxysulfide, 403
AU astronomical unit, 38
AWAR area weighted average resolution, 329
B/H base to height ratio, 341
BIL band interleaved by line, 490
BRDF bidirectional reflectance distribution function, 231
BSQ band sequential format, 490
CCD charge coupled device, 280
CCT computer compatible tape, 6
CIE Commission Internationale de l'Éclairage, 89
C_R contrast ratio, 206
c velocity of light, 34
cd candela, 91
cm centimetre, 92
c_m velocity of light in medium, 34
D photographic density, 355
$\mathbf{D}$ electric displacement, 55
$D(\lambda)$ spectral detectivity, 405
D^* D-star, 406
D^{**} D-double-star, 406
D^*_{blip} D-star blip, 406
DDL distinguishable density level, 368
DQE detective quantum efficiency, 375
E irradiance, 75
$\mathbf{E}$ electric field strength, 55
EDC EROS Data Center, 367
EDIPS EROS Digital Image Processing System, 492
EIFOV effective instantaneous field of view, 27
EROS Earth Resources Observation System, 11
ERTS Earth Resources Technology Satellite, 4
E_f irradiance due to flare, 120
E_i image irradiance, 114
E_λ spectral irradiance, 180
$E_{\lambda 0}$ solar spectral irradiance at top of atmosphere, 180
eV electron volt, 36
FAO United Nations Food and Agriculture Organization, 2
FLD Fraunhofer line descriminator, 272
FMC forward motion compensation, 346
FOV field of view, 302
FTS Fourier transform spectrometer, 167
f chopping frequency, 405

*Limited to the more important and frequently used abbreviations and symbols. The page number on which the abbreviation or symbol first appears is indicated.

f'	focal length, 114
G	giga, 34
GSFC	Goddard Space Flight Center, 369
H	exposure, 356
H	magnetic field strength, 55
HDT	high density tape, 25
HgCdTe	mercury cadmium telluride, 403
Hz	hertz, 34
h	Planck's constant, 36
h'	image height, 141
I	radiant intensity, 75
IFOV	instantaneous field of view, 27
InSb	indium antimonide, 403
IPF	Image Processing Facility, 488
IR	infrared, 9
J	joule, 92
JPL	Jet Propulsion Laboratory, 509
$J_1(z)$	Bessel function, order 1, 323
K	absolute temperature, kelvins, 31
K_m	maximum value of luminous efficiency function (683 lumens/watt), 93
k	Boltzmann's constant, 37
keV	thousand electron volts, 36
km	kilometres, 25
L	radiance, 90
LACIE	Large Area Crop Inventory Experiment, 24
LAI	leaf area index, 260
LBR	Laser Beam Recorder, 368
L_{eq}	equilibrium radiance, 281
L_o, L_i	radiance of object and image, 112, 113
L_u	upwelling path radiance, 120
$L_{\lambda d}$	downwelling spectral radiance, 238
$L_{\lambda T}$	thermal radiance, 237
$L_{\lambda u}$	upwelling path spectral radiance, 237
$L_{\lambda s}$	spectral radiance at entrance pupil of sensor, 311
l	object distance, 120
l'	image distance, 119
lm	lumen, 91
lx	lux, 93
M	radiant exitance, 90
M	magnification, 114
M	modulation, 206
MeV	million electron volts, 36
MLA	multispectral linear array, 281
MRS	Multispectral Resource Sampler, 206
MSS	Multispectral Scanner System, 6
MTF	modulation transfer function, 282
M_{bb}	radiant exitance of blackbody, 102
M_λ	spectral radiant exitance, 37
m	metre, 13

m	airmass, 302
mm	millimetre, 47
mrad	milliradian, 38
N	f number, 115
NA	numerical aperture, 114
NASA	National Aeronautics and Space Administration, 5
NEP(λ)	spectral noise equivalent power, 405
NES	noise equivalent signal, 282
NE$\Delta\rho$	noise equivalent reflectance difference, 461
NEΔT	noise equivalent temperature difference, 431
NOAA	National Oceanographic and Atmospheric Administration, 24
n	refractive index, 35
$\hat{n}$	complex index of refraction, 78
nm	nanometre (10^{-9} metre), 15
P	degree of polarization, 72
PMT	photomultiplier tube, 401
p	diffracted order number, 147
ppb	parts per billion, 279
Q	energy of quantum, 36
R	resolving power, 281
$R(\lambda)$	spectral responsivity, 405
RBV	return beam vidicon, 338
RQE	responsive quantum efficiency, 376
rad	radian, 143
rms	root mean square, 366
SI	Système International d'Unités, 44
Si	silicon, 403
SNR	signal to noise ratio, 277
SPOT	Système Probatoire d'Observation de la Terre, 510
s	second, 34
sr	steradian, 37
T	absolute temperature, 37
TDRSS	Tracking and Data Relay Satellite System, 508
TIR	thermal infrared, 31
TM	Thematic Mapper, 220
t	time, 51
u'	marginal ray angle in image space, 141
UV	ultraviolet, 32
USAF	U.S. Air Force, 327
USDA	U.S. Department of Agriculture, 24
USDI	U.S. Department of Interior, 11
USGS	U.S. Geological Survey, 337
V	volume, 61
V_η	meterological range in kilometres, 215
V/H	velocity to height ratio, 344
W	watt, 37
w	radiant density, 92
α	absorptance, 92
$\alpha(\lambda)$	spectral absorptance, 103

β integrated scattering coefficient, 76
$\beta(\theta)$ volume scattering coefficient, 75
β_{ext} scattering extinction coefficient, 76
γ slope of characteristic curve, 356
$\Delta x \cdot \Delta y$ area of interest, 237
ε dielectric constant (Chapter 4 only), 55
ϵ emissivity, 86
$\varepsilon(\lambda)$ spectral emissivity, 101
η coefficient of luminescence, 271
η responsive quantum efficiency, 406
θ angle of incidence, 35
θ' angle of reflection or detection, 231
θ_c critical angle, 72
θ_m, θ'_m marginal ray angle to axis, 113
θ_h angle off nadir, 310
θ_p polarizing angle, 70
θ_z solar zenith angle, 230
κ extinction coefficient, 77
λ wavelength, 34
λ_m wavelength in medium, 77
λ_{max} wavelength of maximum blackbody output, 100
μ coefficient of absorption, 76
μ, μ_0 permeability, 55
μJ microjoule, 419
μm micrometre (10^{-6} metre), 26
ν frequency, 34
Π Poynting vector, 61
ρ reflectance, 92
$\rho(\lambda)$ spectral reflectance, 97
σ Stefan-Boltzmann constant, 100
$\sigma(D)$ rms deviation in density, 366
τ transmittance, 93
$\tau(\lambda)$ spectral transmittance, 120
$\tau'_{ext}(\lambda)$ spectral extinction optical thickness, 180
τ'_{ext} extinction optical thickness, 195
τ_o transmittance of optical system, 118
Φ radiant flux, 90
Φ_λ spectral radiant flux, 90
ϕ azimuthal angle of incidence, 231
ϕ' azimuthal angle of detection, 231
ϕ_z azimuth angle, 203
Ψ transverse displacement, 51
Ω solid angle, 89
ω frequency, 52

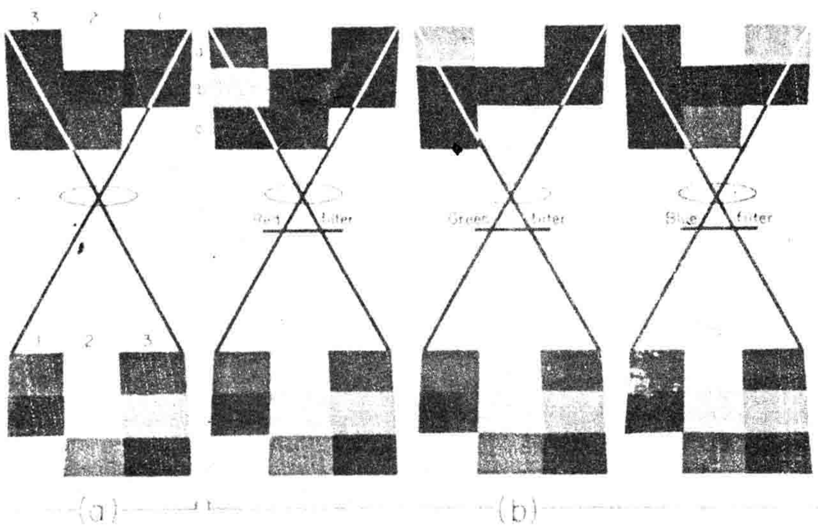

Fig. 2.2 Spatial resolution without (a) and with (b) spectral discrimination. The colored squares are blue, green, yellow, and red with a green-and-yellow square in the middle of the front row.

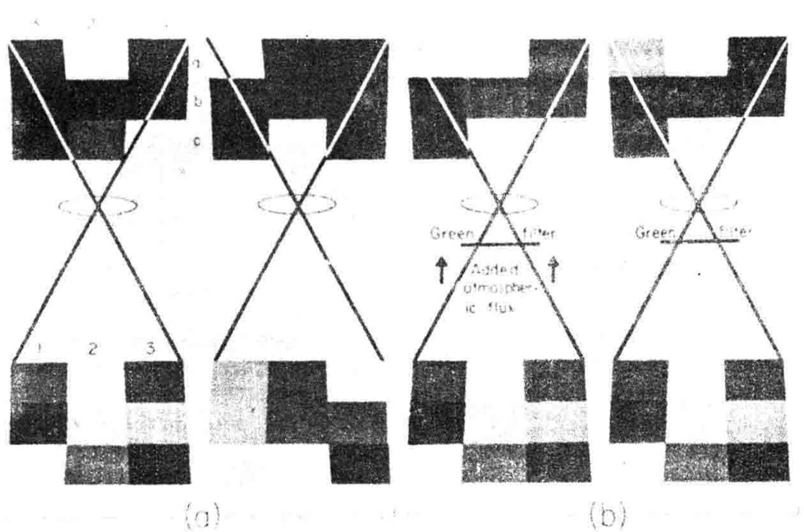

Fig. 2.5 (a) Spatial, spectral, and temporal resolution (see text); (b) the effect of atmospheric haze on multispectral imagery (see text).

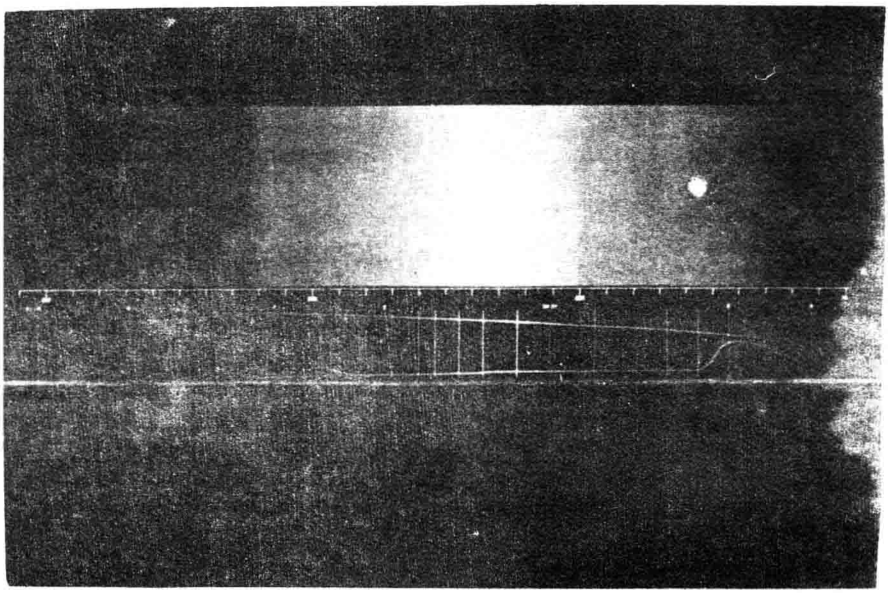

Fig. 3.2 The visible spectrum and other quantities important for remote sensing in the visible spectrum (see text for details).

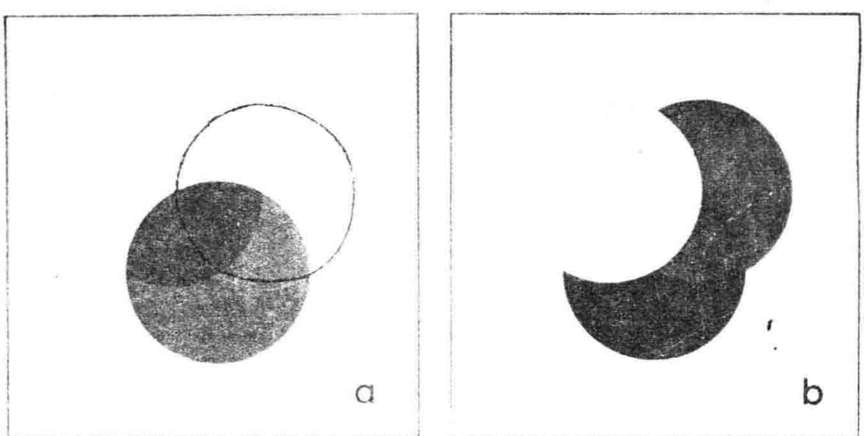

Fig. 7.27 The production of color. (a) The subtractive process. The circles represent colored filters viewed in transmission. (b) The additive process. In this case the color circles are as seen when projected onto a colorless screen.

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