

**REMOTE SENSING
OPTICS AND
OPTICAL SYSTEMS**

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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.

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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
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
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 discriminator, 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
- NE ΔT 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_n meteorological 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
$\epsilon(\lambda)$	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
$\tau_{\text{ext}}(\lambda)$	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

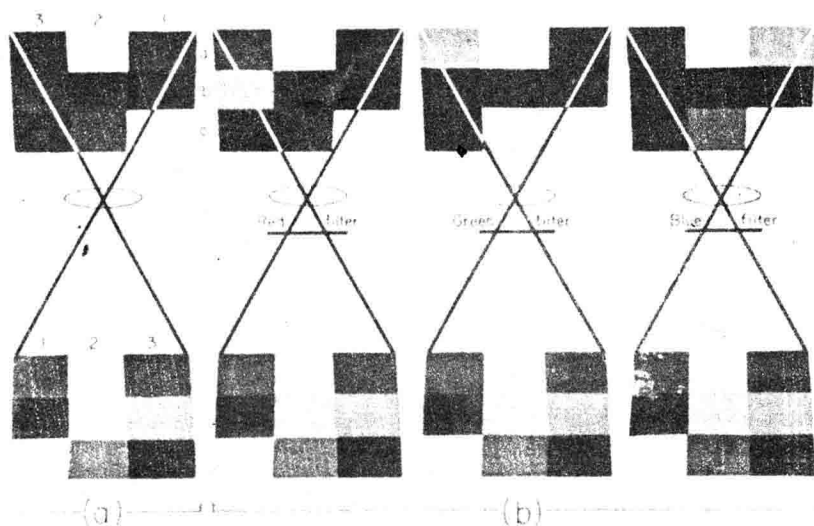


Fig. 2.2 Spatial resolution without (a) and with (b) spectral discrimination. The colored squares are blue, green, yellow, and red with a green-and-yellow square in the middle of the front row.

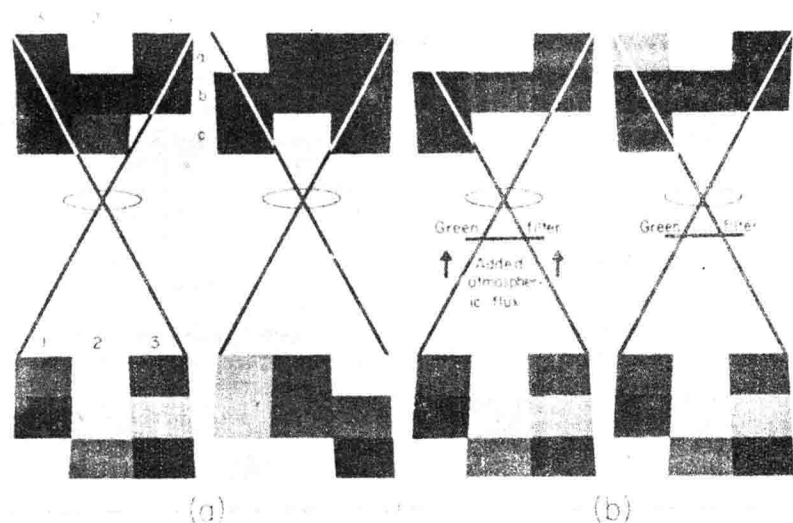


Fig. 2.5 (a) Spatial, spectral, and temporal resolution (see text); (b) the effect of atmospheric haze on multispectral imagery (see text).

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

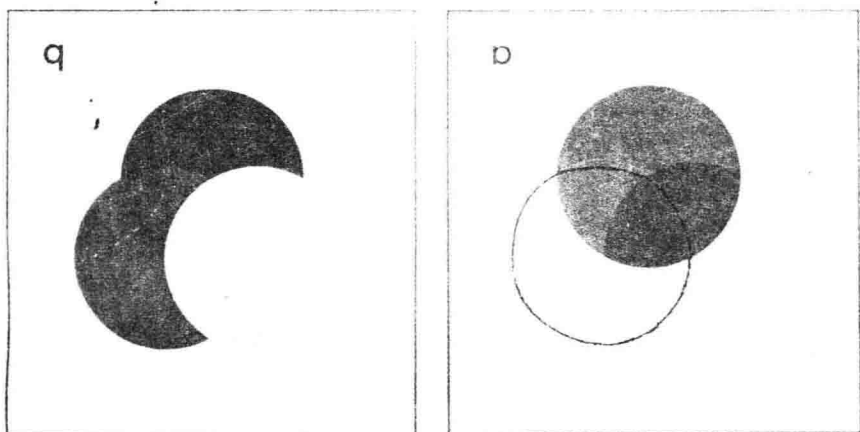
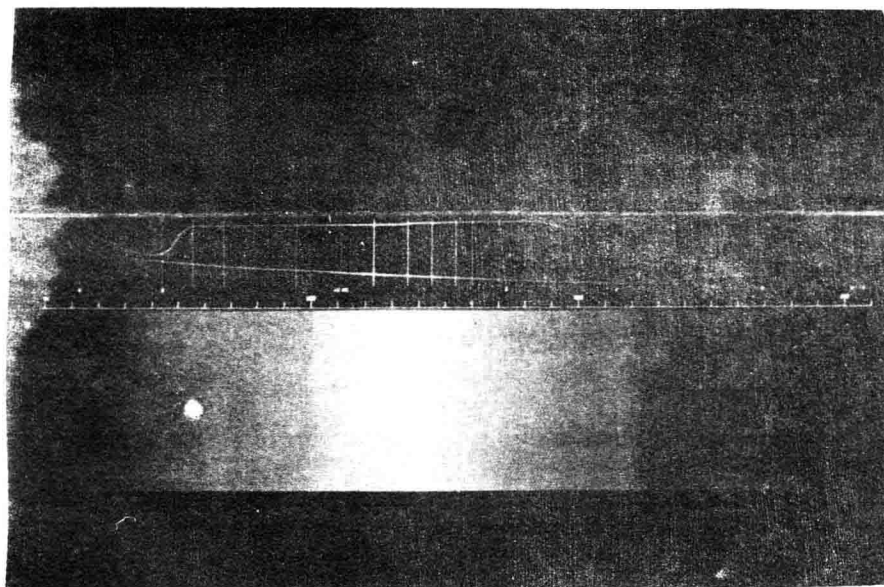


Fig. 3.2 The visible spectrum and other quantities important for remote sensing in the visible spectrum (see text for details).



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