Preface		xiii	
A	Acknowledgments		
	Part I FUNDAMENTALS		
1.	Radiomentry	3	
	1.1 The Nature of Light	4	
	1.2 Light from the Sun		
	Solar energy production	6 6 7	
	Solar energy arriving at earth	7	
	1.3 Measuring Radiant Energy	13	
	1.4 Directions and Solid Angles	16	
	Solid angle	19	
	Delta functions	20	
	1.5 Geometrical Radiometry	22	
	Radiance	22	
	Irradiance	24	
	Examples	27	
	Intensity	29	
	Terminology and notation	29	
	Radiance invariance law	33	
	Assigning surface radiances	35	
	1.6 Photosynthetically Available Radiation	36	
	1.7 Physical Foundations	37	
	1.8 Problems	38	
2.	Photometry	40	
	2.1 The Photopic Luminosity Function	40	
	2.2 The Lumen	42	
	2.3 Luminance	44	
	Examples	44	
	2.4 From Radiometry to Photometry	46	
	2.5 Colorimetry	47	
	The quantitative description of color	48	
	An example of experimentally determined		
	chromaticity coordinates	56	
	2.6 Problems	58	

3. Optical Properties of Water	60		
3.1 Inherent Optical Properties	61		
Modeling IOP's	66		
3.2 Apparent Optical Properties	67		
Average cosines	69		
Reflectances	70		
Diffuse attenuation coefficients	70		
Gordon's normalization of K_d	72		
3.3 Optically Significant Constituents of Natural Waters	73		
3.4 Particle Size Distributions	77		
3.5 Electromagnetic Properties of Water	80		
3.6 Real Index of Refraction	83		
3.7 Absorption	86		
Measurement of absorption	86		
Absorption by pure sea water	88		
Absorption by dissolved organic matter	91		
Absorption by phytoplankton	91		
Absorption by organic detritus	94		
Bio-optical models for absorption	95		
3.8 Scattering	100		
Measurement of scattering	100		
Scattering by pure water and by pure sea water	102		
Scattering by particles	105		
Scattering by turbulence	107		
Petzold's measurements of volume scattering functions	109		
Analytic approximations of phase functions	114		
Wavelength dependence of scattering; bio-optical models	117		
3.9 Beam Attenuation	125		
3.10 Diffuse Attenuation and Jerlov Water Types	128		
3.11 Single-particle Optics	135		
Mie theory	136		
Computing bulk IOP's	138		
3.12 Closure	141		
3.13 Summary	142		
3.14 Problems	142		
Part II			
RADIATIVE TRANSFER			
4. Across the Surface	147		
4.1 Interaction Principles	148		
Plane-parallel water bodies	149		
Interaction principle for the air-water surface	151		

	4.2 The Level Surface	154
	Fresnel reflectance	155
	The n^2 law for radiance	159
	Transfer functions for a level surface	162
	Conservation of energy	165
	4.3 Capillary Waves	166
	Wave slope-wind speed law	167
	Constructing a surface realization	168
	Fixing scales	171
	The probability distribution of wave slopes	171
	Symmetries of the air-water surface	172
	4.4 Ray Tracing	173
	4.5 Irradiance Transfer Functions	176
	Examples of ray paths	176
	The general recursive ray path	178
	Transfer functions as ensemble averages	180
	4.6 Numerical Examples of Irradiance Transfer	182
	Some observations on multiple scattering	182
	Reflectances for capillary waves and collimated sources	183
	Reflectances for capillary waves and distributed sources	190
	4.7 Radiance Transfer Functions	194
	Quad-averaged directional functions	195
	Mathematical formalism of quad averaging	197
	Partitioning the unit sphere	199
	Quad-averaged bidirectional functions	202
	Quad-averaged surface boundary conditions	204
	Radiance tranfer functions by Monte Carlo simulation	205
	Energy conservation at the surface	209
	4.8 Numerical Examples of Radiance Transfer	210
	A level surface	211
	Capillary wave surfaces: air-incident rays	214
	Capillary wave surfaces: water-incident rays	220
	4.9 Extensions to Arbitrary Wave Spectra	224
	A hybrid gravity-capillary wave model	225
	Generating a gravity-wave surface	226
	4.10 Limitations of the Air-Water-Surface Model	230
	Spatial and temporal resolution	230
	Whitecaps and foam	231
	4.11 Lambertian Bottom Surfaces	233
	4.12 Problems	235
5.	Within the Water	236
	5.1 Radiative Processes	237
	5.2 Elastic Scattering	238
	The path function for elastic scattering	238

Symmetries of the volume scattering function	241
The scattering coefficient for elastic scattering	243
5.3 Inelastic Scattering	244
5.4 True, Inelastic, and Total Absorption Coefficients	246
5.5 Total Attenuation	247
5.6 True Emission	247
5.7 Radiance Transfer Equations	248
The general RTE	250
The monochromatic RTE for plane-parallel waters	251
Standard form of the RTE	252
Limitations of the RTE	253
5.8 Integral Forms of the RTE	254
Beer's law	254
Integral form of the RTE	256
5.9 A Simple Model for Radiance	259
The asymptotic radiance distribution	261
5.10 The Divergence Law for Irradiance	262
5.11 Irradiance Transfer: The Two-flow Equations	265
Heuristic derivation	265
Rigorous derivation	267
Alternate forms of the two-flow equations	271
Significance of the diffuse absorption	
and scattering functions	274
5.12 Relations Among IOP's and AOP's	277
Approximate relations for R and K_d	281
5.13 Polarization	284
Stokes vectors and Mueller matrices	285
Polarized radiance transfer	290
5.14 Raman Scattering	292
5.15 Fluorescence	300
5.16 Bioluminescence	309
5.17 Historical Notes	312
5.18 Problems	315
Dowt III	
Part III SOLUTION METHODS	
6. Monte Carlo Methods	321
6.1 Forward Monte Carlo Methods	321
Sampling photon path lengths	321
Sampling photon interaction types	325
Sampling photon interaction types Sampling scattering directions	325
Solving the RTE	325
Strengths and weaknesses	320
6.2 Backward Monte Carlo Methods	329

	Reciprocity relations and adjoint problems	329
	Example	331
	Strengths and weakensses	334
	6.3 Variance Reduction Techniques	336
	Biased sampling	336
	Examples	337
	6.4 Summary	339
	6.5 Problems	340
7.	Invariant Imbedding Methods: Introduction	341
	7.1 The Two-flow Equations as a Mathematics Problem	343
	7.2 Solution Algorithm for a Two-flow Problem	344
	A global interaction principle	345
	Differential equations for $R(z,b)$ and $E_u^{t}(b,z)$	346
	Incorporation of the surface boundary conditions	348
	Recapitulation and interpretation	349
	7.3 Transport and Fundamental Operators	
	for the Air-water Surface	353
	7.4 The Fundamental Solution for Source-free Water Bodies	354
	The mapping and group properties	
	of the fundamental solution	357
	7.5 The Fundamental Solution Including Internal Sources	358
	The two-flow equations in matrix form	358
	Incorporation of internal sources	359
	Historical notes	360
	7.6 The Transport Solution for Bare Slabs	361
	Comments on notation	364
	7.7 The Transport Solution for Bounded Slabs	365
	Imbed rules (downward case)	365
	Union rules (downward case)	367
	Imbed and union rules (upward case)	367
	Imbed and union rules for the entire medium $S[a,b]$	369
	7.8 Differential Equations for the Standard Operators	370
	Summary of the transport solution	374
	7.9 Summary	375
	7.10 Problems	377
8.	Invariant Imbedding Methods: Solving the RTE	379
	8.1 The RTE as a Mathematics Problem	380
	8.2 Quad Averaging the RTE	382
	Numerical evaluation of the quad-averaged phase function	385
	Quad averaging the effective source function	387
	8.3 Fourier Polynomial Analysis	388
	Discrete orthogonality relations	389

		Fourier polynomial formulas	390
	8.4	Discrete Spectral Form of the RTE	393
		Spectral decomposition of the RTE	394
	8.5	Discrete Spectral Forms of the Boundary Conditions	403
		Implications of surface wave symmetries	404
		Spectral decomposition of the surface boundary conditions	406
		Spectral decomposition of the bottom boundary condition	408
	8.6	Fundamental and Transport Solutions	
		for the Radiance Amplitudes	409
		Local-transfer-matrix form of the	
		spectral amplitude equations	409
		Transport solution of the spectral amplitude equations	411
	8.7	Differential Equations for the Standard Operators	415
		Composit Forms of the <i>l</i> -mode Equations	418
		Completing the Solution	419
		Integrating the Riccati equations	420
		Incorporation of the air-water surface boundary conditions	421
		Interior radiance amplitudes	423
		Water-leaving radiance amplitudes	424
		Synthesis of the quad-averaged radiances	424
	8.10) Summary	425
		1 Problems	429
9.	Eigen	matrix Methods	430
	8		
	9.1	The Discrete-Ordinates Method	431
		Reduction of the RTE to matrix form	433
		Choosing the number of terms	
		in the phase function expansion	437
		Completing the solution	440
		Strengths and weaknesses	441
	9.2	A General Matrix Formulation of the	
		Local Interaction Principles	442
	9.3	Eigenstructures of the Local Transfer Matrix \underline{K}	444
		Natural basis functions for radiance amplitudes	444
		The eigenstructure equation	447
		Eigenrepresentation of the fundamental solution	448
	9.4	Properties of the Eigenstructures of \underline{K}	449
		Reversal property of the eigenstructures	450
		Uniqueness of the eigenstructures	451
		Reduction of the eigenmatrix order	452
	9.5	Radiance Reflectance of an Infinitely Deep Water Body	453
		Application to the quad-averaged	
		bottom boundary condition	455
	9.6	The Asymptotic Radiance Distribution	457
		Existence and computation of the	

		asymptotic radiance distribution	457
		Asymptotic behavior of apparent optical properties	460
		Dependence of asymptotic values on	
		inherent optical properties	461
		Rate of approach to asymptotic values	463
		An integral equation for the asymptotic radiance	468
	9.7	Problems	469
10.	Invers	se Methods	472
	10.1	Inverse Problems	472
		Classification of inverse problems	473
	10.2	Inversion of the RTE	474
		Uniqueness of the inversion	475
	10.2	The Wells compound radiometer	476
	10.3	Inversions Based on the Irradiance Quartet	478
		Information requirements for the inversion	478
		The algorithm of Priesendorfer and Mobley	479
		The algorithm of McCormick and Rinaldi	481
	10.4	Recovery of internal sources	482 483
	10.4	Inversions Based on the Plane Irradiances	485
		Gordon's inversion of K_d and R Detection of inelastic scattering	486
	10.5	Remote Sensing	487
	10.5	Ocean color	488
		Complications	492
		Remote-sensing reflectance	493
	10.6	Problems	496
		Part IV SOLUTIONS	
11	Undo		501
11.	Olidei	rwater Light Fields	301
	11.1	Model Validation	502
		Model-model comparison	502
		Standard radiance display	505
		Model-data comparison	509
		Depth Development of the Radiance Dsitribution	512
		Sky Effects	516
		Sea-surface Effects	521
		Bottom Effects	526
		Stratification Effects	529
		Phase Function Effects	531
	11.8	A Simulation of Case 1 Water	533
		Wavelength discretization	533

Inherent optical properties and boundary conditions	534
Radiances	543
Irradiances and <i>K</i> -functions	543
Reflectances	548
Average cosines	551
11.9 Problems	552
Epilogue	554
References	555
Index	579
Supplementary Notes	593