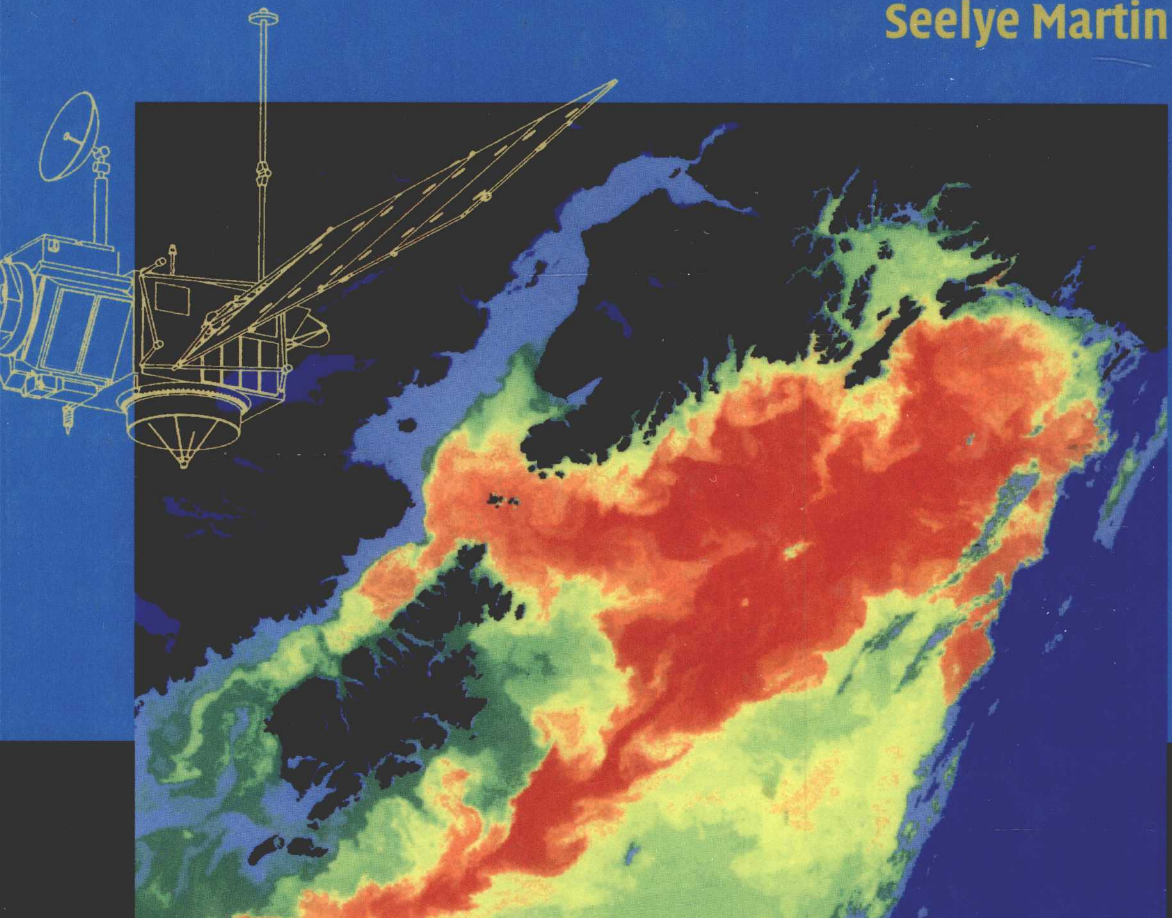
An Introduction to
Ocean Remote Sensing

Seelye Martin



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AN INTRODUCTION TO OCEAN REMOTE SENSING

An Introduction to Ocean Remote Sensing describes the use of satellite data in the retrieval of oceanic physical and biological properties. It gives many examples of the kinds of data that can be acquired and describes their oceanographic application. It also describes the numerous national and international programs in satellite oceanography that have been initiated during the past two decades, and reviews current and future programs up to 2019. The book covers radiative transfer, ocean surface properties, satellite orbits, instruments and methods, visible remote sensing of biological properties, infrared sea surface temperature retrieval, passive microwave measurements, scatterometer wind retrieval, altimetry and SAR. New and proposed techniques, such as polarimetric passive microwave radiometers and SARs, interferometric radar altimetry and sea surface salinity retrieval are also discussed.

This textbook is designed for use in graduate and senior undergraduate courses in satellite oceanography, and will prepare the student and interested scientist to use satellite data in oceanographic research.

SEELYE MARTIN received his Ph.D. in engineering mechanics from Johns Hopkins University in 1967 then spent two years as a research associate in the Department of Meteorology at the Massachusetts Institute of Technology. In 1969 he took up a position in the School of Oceanography at the University of Washington where he is now a Professor of physical oceanography. He has taught courses on remote sensing of the oceans since 1987. Professor Martin has been involved with passive microwave, visible/infrared, and radar ice research since 1979 and was a member of the NASA Earth Observing System (EOS) committee from 1984 to 1989. Since this time, he has served on additional NASA committees and panels involving SAR and high latitude processes. He has made many trips to the Arctic for research on sea ice properties and oceanography and was a Visiting Scientist at the National Institute of Polar Research in Tokyo from 1993 to 1994.

To the memory of my mother
Lucy Gray Martin

April 19, 1915–June 13, 2002

Preface

During the past two decades, there has been a dramatic growth in the number and variety of ocean observing satellites. This growth, combined with a similar growth in computational resources and surface receiving and distribution networks, has greatly increased our knowledge of the properties of the upper ocean, its surface, and the overlying atmosphere. During the same period, an increasing number of countries have either launched or contributed instruments to ocean satellites. In the early 1980s, only the United States and the Soviet Union had ocean observing programs. In 2000, the countries or groups of countries with ocean observing programs included Brazil, Canada, China, Europe, India, Japan, Republic of Korea, Republic of China, Russia, Ukraine, the United States and at least one private corporation.

The developments in the application of the electromagnetic spectrum to ocean observing combined with our understanding of the ocean surface and atmospheric properties have served as the basis for a large variety of innovative instrumentation. Many of the sensors that were experimental in the 1980s are now essential tools of oceanography. These include the use of narrow band optical sensors to estimate biological productivity and observe plankton-associated fluorescence; infrared measurements of sea surface temperature that approach the accuracy necessary to observe climate change; passive microwave sensors that provide global cloud-independent observations of sea surface temperature; and altimeters capable of measuring sea surface height to a 2-cm precision. Because of the increase in computational resources, these data sets are rapidly made available and are often posted on public websites.

Remote sensing involves primarily the use of the electromagnetic spectrum to observe the ocean, and secondarily the use of gravity observations to observe ocean currents and tides. Because remote sensing involves many disciplines, the book provides under one cover the necessary background in electromagnetic theory, atmospheric and seawater properties, physical and biological oceanography, physical properties of the sea surface and satellite orbital mechanics. The material discussed ranges from the reflective and emissive properties of clouds and foam to radar scattering properties of ocean waves, to the optical properties of plankton-associated pigments. It also includes many examples. The book describes the development of satellite oceanography from 1975 to 2004, and summarizes future activities through 2019. As prerequisites, the book requires only an introductory knowledge of electromagnetic theory and differential equations.

The text divides into five parts. Chapters 1, 2 and 3 provide an introduction to satellite systems, ocean surface properties and electromagnetic theory. Chapters 4–7 discuss remote sensing in the visible and infrared spectrum, including atmospheric properties, the ocean/atmosphere interface, the visible retrieval of ocean color and the infrared retrieval of sea surface temperature. Chapters 8 and 9 discuss the passive microwave, including antennas, instruments, atmospheric properties and the retrieval of ocean surface and atmospheric variables. Chapters 9–13 discuss the active microwave, including the use of a large variety of radars to retrieve wind speed and direction, sea surface height, and images of the ocean surface. Finally, for 2004 through 2019, Chapter 14 describes the approved and proposed satellite missions.

I wrote the first draft of this book during 1993–94, when I was a visiting scientist at the National Institute of Polar Research in Tokyo. I greatly appreciate the opportunities and hospitality offered to me by the Institute and thank Takao Hoshiai and Nobuo Ono for inviting me. I also thank the Japanese Ministry of Education, Science, Sports and Culture (Monbusho) and Dean Ross Heath of the College of Ocean and Fisheries Sciences, University of Washington for financial support.

The book benefited from my work with the National Aeronautics and Space Administration (NASA); I am particularly grateful to Dixon Butler and the other members of the EOS steering committee during my three years of service, and to the research support of Robert Thomas, Kim Partington and Waleed Abdalati at the Oceans and Ice Division at NASA Headquarters. I taught the subject matter of this book both by myself and jointly with Miles Logsdon. I thank Miles and all of the students, who always managed to focus on those points that I did not understand. In my teaching, I also benefited from the class notes of Dudley Chelton and those of James Mueller and Carlyle Wash, and the textbooks of Charles Elachi, George Maul, Ian Robinson and Robert Stewart.

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I also thank Lin Robinovitch for her skill and assistance with figure preparation and thank NASA for allowing the use of carryover funds from NAGW-6894 for partial support of her work. I thank the School of Oceanography for additional support of figure preparation. I thank my cousin Ann Warren Turner for her perspective on large writing projects, and for recommending the book *Bird by Bird* by Anne Lamott, as a primer on organization and writing. I thank Mary Jane Perry for help with the biology and for her critical reading of an draft of the biology chapter, Ted Straub for his reading of several chapters, and Mike Alfultis for his early and detailed critique of the entire book. I also thank Gary Mineart for a post-publication critical reading of the entire book, and Chaumin Hu for correcting several equations. Any errors are my own.

Many of the papers, reports and presentations cited in this book are taken from websites that are maintained by agencies such as NASA, ESA and the Japan Aerospace Exploration Agency (JAXA). Because their web addresses tend to change, the material can generally be found using search engines such as Google. At Cambridge University Press I thank Jayne Aldhouse, Susan Francis, Matt Lloyd, Margaret Patterson and Sally Thomas.

The generosity of my parents, William Ted Martin and Lucy Gray Martin, made it possible for me to finish the book. I thank my son and daughter, Carl William Coryell-Martin and Maria Elizabeth Coryell-Martin for putting up with all this, and my wife Julie Esther Coryell for her optimism that I might finish the book, for reading all of the chapters in draft, and for her support. Finally, I ask the reader to remember that each of the satellites, instruments and algorithms described in this book began as an idea generated by a single individual or a small committee.

Chemical symbols

Ar	Argon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
Fe	Iron
H_2O	Water
N_2	Nitrogen
N_2O	Nitrous oxide
O_2	Oxygen
O_3	Ozone
$H\alpha$, $H\beta$, $H\gamma$	Hydrogen lines in the Fraunhofer spectrum
Mg-I	Magnesium-Iodine line
O_2-A	Oxygen-A line

Mathematical symbols

Symbol	Unit	Definition
A	m^2	Area, or instrument aperture area
A_e	m^2	Effective antenna aperture area
A_{FOV}	area	Antenna half-power field-of-view
$A_i(400)$	m^{-1}	Reference absorption at 400 nm; i refers to particulates or CDOM
$a(\lambda)$	m^{-1}	Volume absorption coefficient
$\hat{a}(\lambda;\theta,\phi)$	—	Ratio of gray body to blackbody absorption; in VIR, the absorptance, in microwave, the absorptivity
a_{CDOM}	m^{-1}	CDOM absorption coefficient
a_w	m	Amplitude of ocean surface waves
$a_w(\lambda)$, a_p, a_ϕ, a_T	m^{-1}	Absorption coefficients for seawater, particulate, phytoplankton and total absorption
B	$W\ m^{-2}\ sr^{-1}$	Brightness, used for radiance in the passive microwave
$\mathbf{B}$	$tesla\ m^{-1}$	Magnetic field vector
B_f	$J\ m^{-2}\ sr^{-1}$	Frequency form of spectral brightness
$b(\lambda)$	m^{-1}	Volume scattering coefficient of seawater
$b_b(\lambda)$, $b_{bw}(\lambda)$	m^{-1}	Backscatter coefficient of pure seawater
$b_{bT}(\lambda)$	m^{-1}	Total backscatter coefficient of seawater
°C		Degrees Celsius
C_a	mg Chl-a m^{-3}	Chlorophyll concentration
C_W, C_I	—	Concentrations of open water and sea ice
c	$m\ s^{-1}$	Speed of light in vacuum
$c(\lambda)$	m^{-1}	Volume attenuation coefficient of seawater
D	cm, m	Aperture diameter of a lens or length of an antenna
$\hat{d}(\lambda)$	—	Normalized absorption depth
$d_a(\lambda)$	m	Absorption depth of radiation in seawater

Symbol	Unit	Definition
E	W m^{-2}	Irradiance, the incident flux density per unit area
$\boldsymbol{E}$	V m^{-1}	Electric field vector
$\hat{E}$	J	Energy of a photon
$\boldsymbol{E}_0$	V m^{-1}	Reference amplitude of an electric field vector
$E_{\mathrm{d}}(\lambda, 0_+)$	W m^{-2}	Downwelled solar irradiance measured just above the ocean surface
$E_{\mathrm{R}}(\chi, \psi)$	km	Height of reference ellipsoid above Earth's center of mass
$E_{\mathrm{u}}(0_-)$	W m^{-2}	Upwelled solar irradiance just below the water surface
E_{V}, E_{H}	V m^{-1}	Vertically and horizontally polarized components of the electric field vector
$e(\lambda; \theta, \phi)$	—	Emissivity, which is the ratio of a gray body to blackbody radiance
e_0	—	Temperature- and salinity-dependent emissivity of a specular ocean surface
$F(\lambda, z)$	W m^{-2} nm^{-1}	Solar irradiance at a height z in the atmosphere
F_{n}	—	Normalized power or radiation pattern
$F_{\mathrm{S}}(\lambda)$	W m^{-2} nm^{-1}	Solar irradiance at the top of the atmosphere
$F'_{\mathrm{S}}(\lambda)$	W m^{-2} nm^{-1}	$F_{\mathrm{S}}(\lambda)$ attenuated by two passes through the ozone layer
f	s^{-1}	Coriolis parameter
f	Hz	Frequency
$f(x)$	V m^{-1}	Antenna illumination pattern
f_{L}	m	Focal length
f_{N}	s^{-1}	Nyquist sampling frequency
$f_{\mathrm{P}}(T, \lambda)$	W m^{-3} sr^{-1}	Planck blackbody radiance
G	—	Antenna gain
G_0	—	Maximum antenna gain
G_{R}	—	Gradient ratio used in the derivation of sea ice concentration
g	m s^{-2}	Acceleration of gravity
H	km	Radial distance of a satellite from Earth's center of mass
$H_{1/3}$	m	Significant wave height
Hz	s^{-1}	Cycles-per-second
h	length	Height of satellite above ocean surface
h_{S}	length	Height of sea surface above Earth's center of mass
$\overline{h}_{\mathrm{S}}$	length	Temporal mean of sea surface height

Symbol	Unit	Definition
$\hbar$	J s	Planck constant, 6.625×10^{-34} J s
I	deg	Inclination, the angle between the Earth's rotation axis and the normal to the orbit plane
$I(r, \theta, \phi)$	W sr^{-1}	Radiant intensity
I_0	W sr^{-1}	Maximum radiant intensity
i		Imaginary part of complex number
J		Joules
K		Degrees Kelvin
k, k_{im}	m^{-1}	Real and imaginary part of the wavenumber
$\boldsymbol{k}$	m^{-1}	Vector wavenumber
k_B	J K^{-1}	Boltzmann constant, 1.38×10^{-23} J K^{-1}
k_w	m^{-1}	Wave number of ocean waves
L	mm	Columnar equivalent of non-raining cloud liquid water
$L(\lambda)$	μW cm^{-2} nm^{-1} sr^{-1}	Radiance
	W m^{-3} sr^{-1}	(Alternative units of L)
$L_A(\lambda)$	μW cm^{-2} nm^{-1} sr^{-1}	Path radiance generated by aerosol atmospheric scattering
L_E	km	Equatorial separation between successive orbits
$L_f(\lambda)$	J m^{-2} sr^{-1}	Frequency form of spectral radiance
$L_R(\lambda)$	μW cm^{-2} nm^{-1} sr^{-1}	Path radiance generated by Rayleigh scattering
$L_S(\lambda)$	μW cm^{-2} nm^{-1} sr^{-1}	Solar radiance at the top of the atmosphere
$L_T(\lambda)$	μW cm^{-2} nm^{-1} sr^{-1}	Total radiance received at the satellite
$L_w(\lambda)$	μW cm^{-2} nm^{-1} sr^{-1}	Water-leaving radiance
$[L_w(\lambda)]_N$	μW cm^{-2} nm^{-1} sr^{-1}	Normalized water-leaving radiance
$L_\lambda(\lambda)$	μW cm^{-2} nm^{-1} sr^{-1}	Wavelength form of spectral radiance
l	m	Length of an imaging radar
M	W m^{-2}	Exitance, or emitted flux or power density
$N(\chi, \psi)$	m	Geoid undulation, or height of geoid relative to the reference ellipsoid E_R
Np, nepers	—	Units of atmospheric absorption used in microwave
$NE\Delta T$	K	Noise-equivalent-delta-temperature
$NE\Delta L$	μW cm^{-2} nm^{-1} sr^{-1}	Noise-equivalent-delta-radiance
$NE\Delta\sigma_0$	—	Noise-equivalent-delta-sigma-zero
n	—	Real part of the index of refraction
P	—	For radiometers, subscript indicates V or H polarization. For radars, subscript indicates VV or HH polarization

Symbol	Unit	Definition
$P(\theta)$	sr^{-1}	Atmospheric scattering phase function
P_R	—	Polarization ratio used in the derivation of sea ice concentration
$P_R(\theta)$	sr^{-1}	Rayleigh atmospheric scattering phase function
p	$kg\ m^{-1}\ s^{-2}$	Atmospheric pressure
Q	—	Coefficient used in description of the water-leaving radiance
$R(\lambda)$	—	Plane irradiance reflectance
$R(\lambda, 0_-)$	—	Irradiance reflectance evaluated just below the surface
R_0	km	Distance from radar to target
R_c	mm, μm	Radius of curvature of the sea surface
$R_F(\lambda)$	—	Irradiance reflectance of foam
R_R	$mm\ h^{-1}$	Rain rate
$R_{rs}(\lambda)$	—	Remote sensing reflectance
r	length	Radius
$\boldsymbol{r}$	length	Vector radius (r, θ, ϕ)
$r(\theta)$	—	Unpolarized radiance reflectance
S	psu	Salinity
S_N	—	Signal-to-noise ratio
S_S	psu	Surface salinity
T	°C, K	Temperature
$\overline{T}$	°C, K	Mean temperature of the lower troposphere
$T(\theta)$	—	Interface transmittance
T_3, T_4, T_5	K	AVHRR brightness temperatures for bands 3, 4, 5
$T_{22}, T_{23}, T_{31}, T_{32}$	K	MODIS brightness temperatures for bands 22, 23, 31, 32
T_A	K	Antenna temperature
T_a	K	Air temperature
T_B	K	Brightness temperature
T_b	°C	Buoy or bulk temperature
T_{BV}, T_{BH}	K	Vertically and horizontally polarized components of brightness temperatures
T_{ext}	K	Extraterrestrial brightness temperature exclusive of the sun
T_{gal}	K	Brightness temperature of the Milky Way galaxy
T_S	°C, K	Ocean surface skin temperature
T_{sfc}	°C, K	Externally supplied surface temperature to algorithms

Symbol	Unit	Definition
T_{sol}	K	Solar contribution to the antenna brightness temperature
T_{sun}	K	Solar brightness temperature
T_{univ}	K	The 2.7 K universe background temperature
T_w	s	Period of ocean surface waves
t		Time
t	—	In the visible/infrared, the atmospheric transmittance; in the microwave, the atmospheric transmissivity
$t_D(\lambda)$	—	Diffuse transmittance
U	$m\ s^{-1}$	The scalar wind speed at a 10-m height
U_0	$m\ s^{-1}$	Spacecraft velocity
U_{LOS}	$m\ s^{-1}$	Line-of-sight wind speed, the wind speed in the azimuthal look direction of a passive microwave radiometer
u, v	$m\ s^{-1}$	x- and y-components of an ocean current
V	mm	Equivalent height in liquid water of the columnar water vapor
v	$m\ s^{-1}$	Local phase speed of light
w	m	Width of an imaging radar
$\boldsymbol{x}$	length	Vector position (x, y, z)
X, Y	—	Coefficients used in discussion of particulate scattering properties
X_S	length	Imaging radar cross-track swathwidth
Y_S	length	Imaging radar along-track swathwidth
z_H	km	Reference height for the top of the atmosphere
α	deg	Scattering angle relative to the forward direction
α	—	Ångström exponent used to describe aerosols
α_S	sr	Solid angle resolution of an ideal optical instrument
$\beta(\alpha, \lambda)$	$km^{-1}\ sr^{-1}$, $m^{-1}\ sr^{-1}$	Atmospheric and oceanic volume scattering function
$\tilde{\beta}(\alpha, \lambda)$	sr^{-1}	Oceanic scattering phase function
β_0	$km^{-1}\ sr^{-1}$, $m^{-1}\ sr^{-1}$	Isotropic scattering phase function
$\beta_T, \beta_w, \beta_p, \beta_\phi$	$m^{-1}\ sr^{-1}$	Total, pure seawater, particulate, and phytoplankton volume scattering function
$\Delta\hat{E}$	J	Energy difference associated with a change in the internal state of a molecule or atom
Δf	Hz, MHz	Instrument bandwidth, also used to describe Doppler shift

Symbol	Unit	Definition
Δh_{ion}	m	Range delay caused by atmospheric free electrons
ΔT_{45}	K	Temperature difference between AVHRR channels 4 and 5, $\Delta T_{45} = T_4 - T_5$
ΔT_{53}	K	Temperature difference between AVHRR channels 5 and 3, $\Delta T_{53} = T_5 - T_3$
Δx, Δy	m	Radar resolution in the cross-track and along-track direction
$\Delta\theta_{1/2}$	deg	Half-power beamwidth; for imaging radars, the half-power beamwidth in the cross-track direction
$\Delta\phi_{1/2}$	deg	Half-power beamwidth in the along-track direction
ε	farad m^{-1}	Electrical permittivity
$\varepsilon(\lambda, \lambda_0)$	—	Single scattering color ratio for aerosols
ε_0	farad m^{-1}	Permittivity in vacuum
ε_{r}	—	Complex dielectric constant, $\varepsilon_{\text{r}} = \varepsilon' + \text{i}\varepsilon''$
ζ	m	Sea surface height relative to the geoid
ζ_{D}	m	Dynamic height, or the oceanographic height calculated from the vertical density structure
η	—	Complex index of refraction, $\eta = n + \text{i}\chi$
η	m	Vertical displacement of ocean surface waves
η_{M}	—	Main beam efficiency of a microwave antenna
θ	deg	Incidence, look or zenith angle
θ_{S}	deg	Solar zenith angle
$\theta_{\hat{\text{v}}}$	deg	View or scan
κ_{A}, κ_{E}, κ_{S}	km^{-1}	Atmospheric absorption, extinction and scattering coefficients
κ_{R}	km^{-1}	Rayleigh scattering attenuation coefficient
κ_{oxy}	km^{-1}	Oxygen absorption coefficient
κ_{vap}	km^{-1}	Water vapor absorption coefficient
λ	nm, μm	Radiation wavelength
λ_{w}	mm, m	Wavelength of ocean surface waves
μ	henry m^{-1}	Magnetic permeability
μ_0	henry m^{-1}	Vacuum permeability
Π	W m^{-4} sr^{-1}	The atmospheric radiative source term
ρ	kg m^{-3}	Density of seawater
ρ_{a}	kg m^{-3}	Density of air
ρ_{H}, ρ_{V}	—	Horizontal, vertical reflection coefficients
ρ_{ion}	TECU	Free-electron columnar density

Symbol	Unit	Definition
$\rho_w(\lambda)$	—	Extraterrestrial reflectance generated by the water-leaving radiance
$[\rho_w(\lambda)]_N$	—	Normalized extraterrestrial reflectance
σ	siemens m^{-1}	Electrical conductivity
σ	m^2	Radar scattering cross section
σ^2	—	Mean-square sea surface slope
σ_0	—	Normalized radar scattering cross section (pronounced sigma-zero)
σ_N	—	Standard deviation of noise
$\sigma_{VV}, \sigma_{HH}, \sigma_{HV}, \sigma_{VH}$	—	Normalized radar scattering cross section for VV, HH, HV, and VH transmitting and receiving
σ_η	m	Root-mean-square sea surface height
τ	s	Pulse duration or length
$\tau(\lambda)$	—	Optical depth
τ_A	—	Optical depth associated with aerosol scattering
τ_{OZ}	—	Optical thickness of the ozone layer
$\tau_R(\lambda)$	km	Rayleigh optical thickness
Φ	W	Radiant flux or power
Φ_N	W	Noise generated internally to an instrument
Φ_T	W	Total radiant flux or power transmitted by an antenna
$\Phi_{(V, H)}$	W	V-pol or H-pol radiant flux received by an antenna
Φ_λ	W μm^{-1}	Spectral form of the radiant flux
Φ_σ	W	Received power corrected for atmospheric attenuation
ϕ	deg	Azimuth angle
ϕ_R	deg	Azimuthal angle relative to the wind direction
ϕ_W	deg	Azimuthal wind direction
χ	—	Imaginary part of the index of refraction
χ, ψ	deg	Latitude, longitude
Ω	sr	Solid angle
Ω_E	s^{-1}	Angular rotation of the Earth
Ω_M	sr	Main beam solid angle of a microwave antenna
Ω_p	sr	Pattern solid angle of a microwave antenna
ω	s^{-1}	Radian frequency of an electromagnetic wave
$\omega_0(\lambda)$	—	Single scattering atmospheric albedo
$\omega_A(\lambda)$	—	Aerosol single scattering albedo
$\omega_R(\lambda)$	—	Rayleigh single scattering albedo

Abbreviations and acronyms

AATSR	Advanced ATSR (ESA)
ADEOS-1, -2	Advanced Earth Observing Satellite (Japan)
AGC	Automatic Gain Control (Altimeter function)
AHRPT	Advanced High Resolution Picture Transmission (METOP)
ALOS	Advanced Land Observing Satellite (Japan)
ALT	Altimeter on TOPEX/POSEIDON
AMSR	Advanced Microwave Scanning Radiometer (Japan) on ADEOS-2
AMSR-E	AMSR-EOS (Japan) on AQUA
AOML	Atlantic Oceanographic and Meteorological Laboratory (NOAA)
AOP	Apparent Optical Properties
APC	Antenna Pattern Correction
APT	Automatic Picture Transmission (data transfer mode for AVHRR)
AQUA	Second major EOS satellite (Not an abbreviation)
ASAR	Advanced SAR (ENVISAT)
ASCAT	Advanced Scatterometer (METOP)
ATSR	Along-Track Scanning Radiometer (ESA)
AVHRR	Advanced Very High Resolution Radiometer (US)
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data (France)
CalTech	California Institute of Technology
C-band	Frequencies of about 5 Ghz
CDOM	Colored Dissolved Organic Material
CHAMP	CHAllenging Minisatellite Payload (German gravity mission)
Chl-*a*	Chlorophyll-a
CMIS	Conical-scanning Microwave Imager/Sounder (US microwave imager on NPOESS)
CNES	Centre National d'Études Spatiales (National Center for Space Studies, France)
CryoSat	ESA satellite for ice sheet investigation
CSA	Canadian Space Agency
CZCS	Coastal Zone Color Scanner