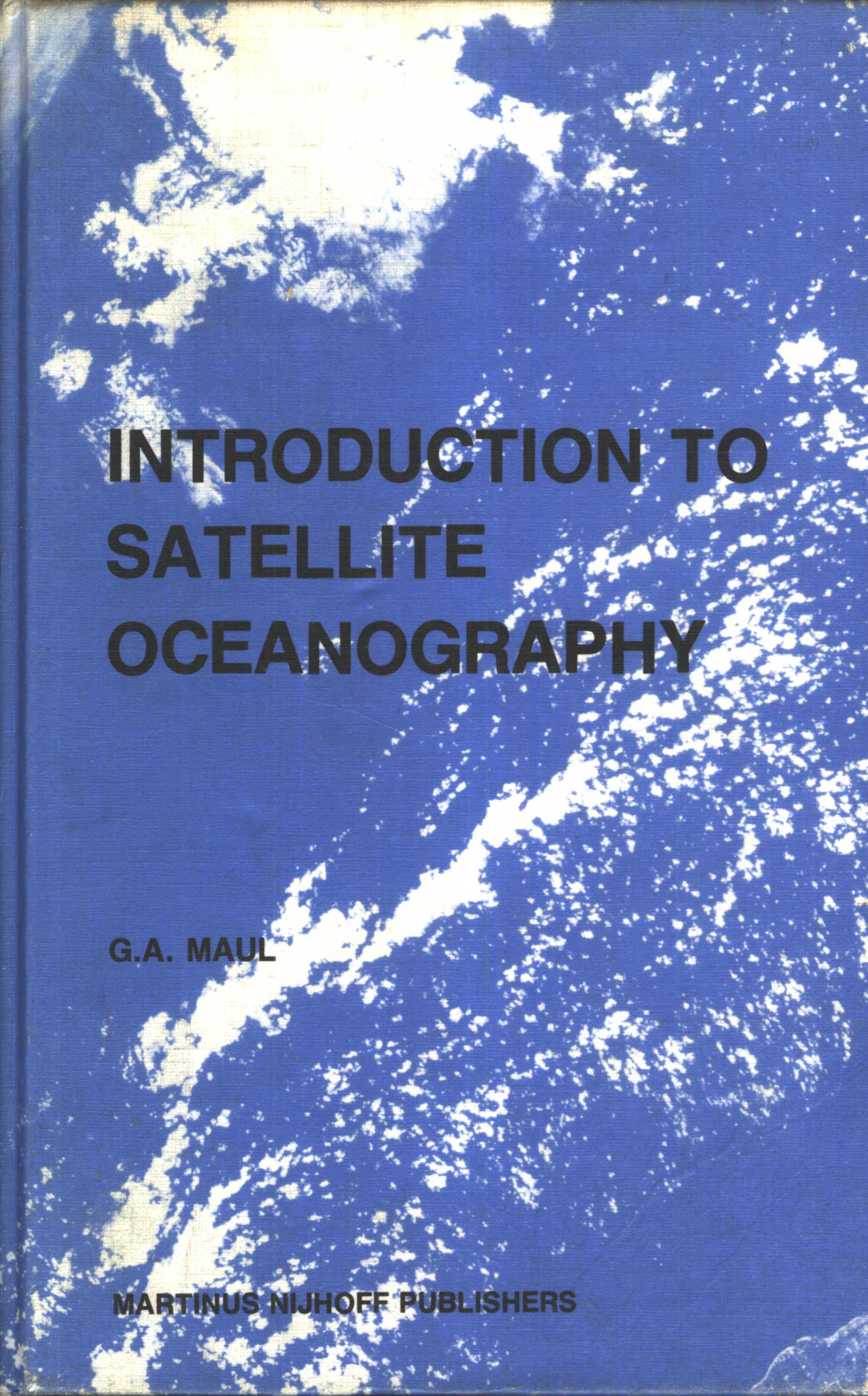


INTRODUCTION TO SATELLITE OCEANOGRAPHY

G.A. MAUL

MARTINUS NIJHOFF PUBLISHERS

Introduction to satellite oceanography

By

G.A. MAUL

Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida, USA

1985 **MARTINUS NIJHOFF PUBLISHERS**
a member of the KLUWER ACADEMIC PUBLISHERS GROUP
DORDRECHT / BOSTON / LANCASTER

Distributors

for the United States and Canada: Kluwer Academic Publishers, 190 Old Derby Street, Hingham, MA 02043, USA
for the UK and Ireland: Kluwer Academic Publishers, MTP Press Limited, Falcon House, Queen Square, Lancaster LA1 1RN, UK
for all other countries: Kluwer Academic Publishers Group, Distribution Center, P.O. Box 322, 3300 AH Dordrecht, The Netherlands

Library of Congress Catalog Card Number: 84-22693

ISBN 90-247-3096-1 (this volume)
ISBN 90-247-2851-7 (series)

PRINTED IN THE NETHERLANDS

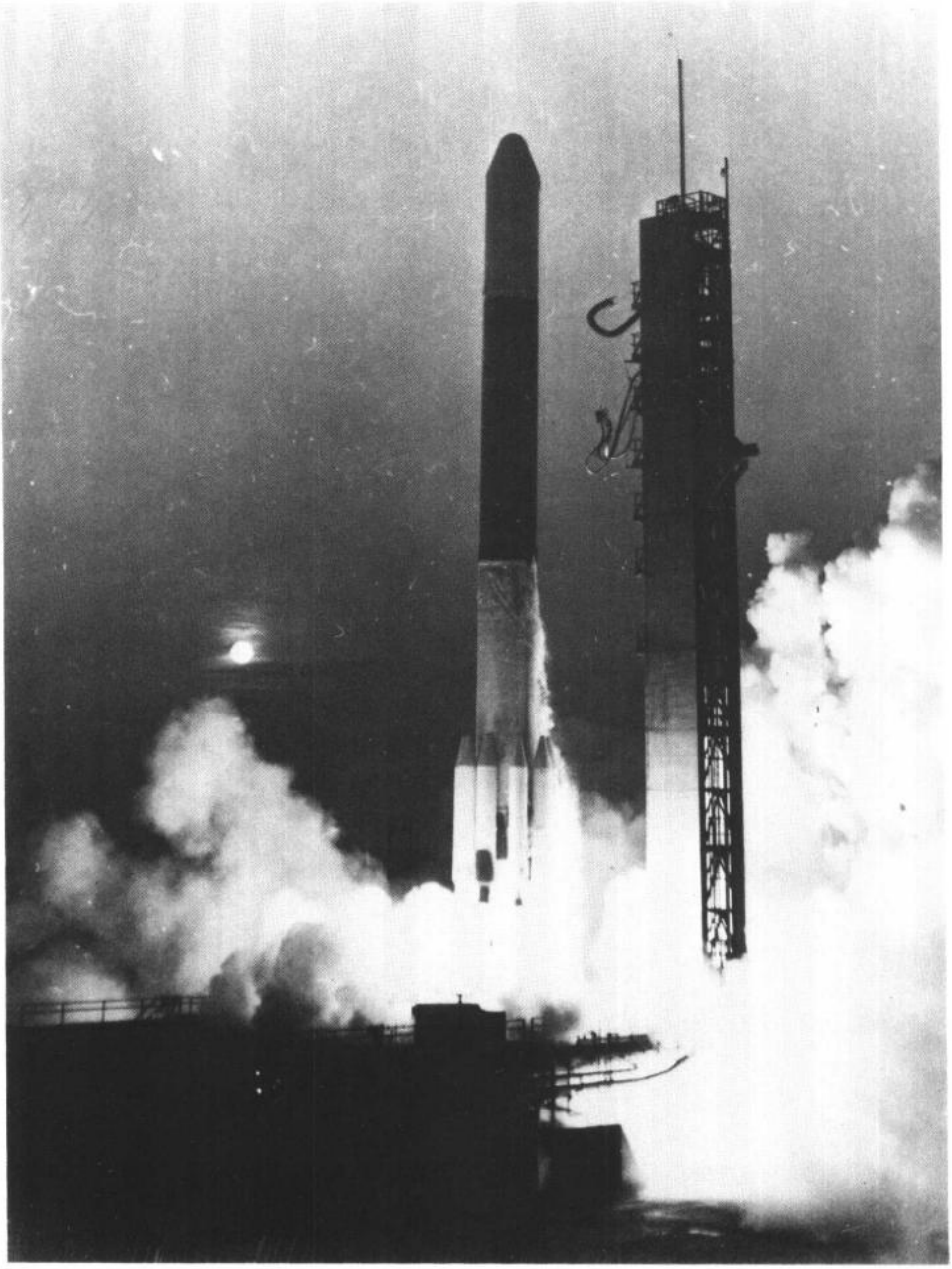
Introduction to satellite oceanography

REMOTE SENSING OF EARTH RESOURCES AND ENVIRONMENT

El-Baz, F.: Deserts and arid lands. 1984. ISBN 90-247-2850-9

Lindgren, D.T.: Land use planning and remote sensing. 1985.
ISBN 90-247-3083-X

Maul, G.A.: Introduction to satellite oceanography. 1985.
ISBN 90-247-3096-1



Launch of GOES-2 on 16 June 1977.

Preface

Satellite oceanography, as the term is used in this book, is a generic term that means application of the technology of aerospace electromagnetic remote sensing to the study of the oceans. The key words here are "application of technology...to the study of the oceans." The goal is to learn more about our planet's hydrosphere. As such, remote sensing technology is another tool in the oceanographer's sea bag, just like a bathythermograph or a plankton net.

But is a whole book necessary if remote sensing is just another tool? While it is true that no one has written a whole book on plankton nets, volumes have been written about what is found in those nets. Today's state-of-the-art measurements from spacecraft or aircraft first must be interpreted in terms of their physics; then the interpretations must be understood in terms of oceanic processes. This is not materially different from the analogy to a plankton net; marine biologists still argue about what didn't get caught in the net.

Introduction to Satellite Oceanography is written from the perspective of a physical oceanographer with training and experience in ocean optics, radiative transfer, and remote sensing. It is the result of developing, and then teaching, a course entitled "Satellite Oceanography" for a number of years at the University of Miami's Rosenstiel School of Marine and Atmospheric Science. Most of the students have been second-year graduate students in physical, biological, and geological oceanography and in several disciplines of engineering and physics. It is the author's intention to present a broad-based introduction to the subject for a wide range of oceanographers, engineers, and managers. Nevertheless, the subject is largely physical in nature and no apologies are made for it. While it is true that almost anyone can appreciate the beauty in a photograph, a quantitative understanding of the contents of that photograph requires knowledge that may be difficult to comprehend. A true understanding, however, offers new beauty well beyond the hues and tones seen only with the eye, but not with the mind.

Most of the material was gathered while a Fellow of the Cooperative Institute for Marine and Atmospheric Studies, which is a joint institute of the University of Miami and the National Oceanic and Atmospheric

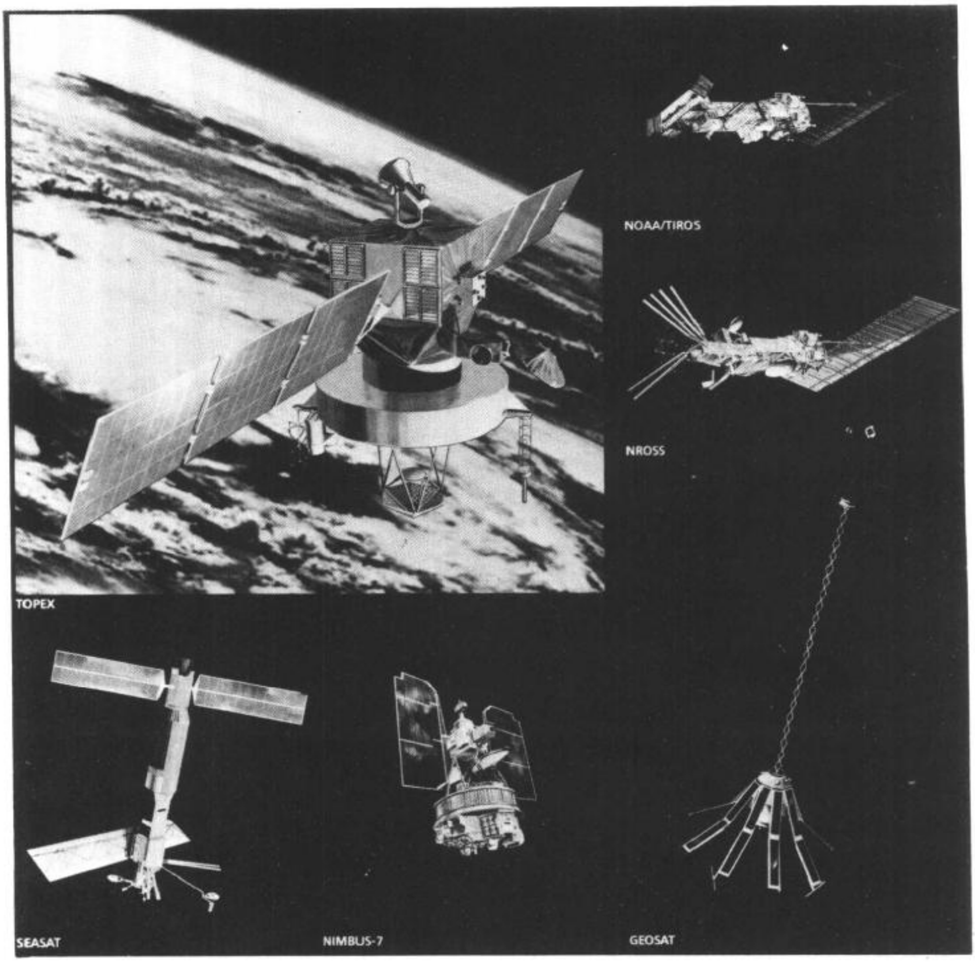
Administration. Drafting of the figures, photography, word processing, text editing, and page layout were all done by staff of the Atlantic Oceanographic and Meteorological Laboratory, and preliminary manuscript review was by staff of the University of Delaware and the Naval Research Laboratory. No royalties are paid to the author or the United States government in an effort to minimize the cost of publication; it is sincerely hoped that this will increase the book's affordability to professionals and students alike.

Many friends, colleagues, and family members have made this book possible and to mention some would be to forget so many others. Inspiration and courage and determination for a project such as this is the integral of a lifetime of inputs from God, man, and nature. Inverting that integral, or even attempting to, leads to ambiguous solutions; the issue is therefore avoided with a simple thank you.

Virginia Key GAM
August 1984

Contents

Chapter 1



Introduction to Ocean Remote Sensing.

Overleaf: Examples of satellites for oceanography. TOPEX, NASA's ocean topography experiment, is planned as a dedicated precise radar altimeter to measure sea surface topography. NOAA/TIROS is an operational meteorological satellite with sensors that can measure sea surface temperature, and locate Lagrangian drifters. NROSS, the Navy Remote Ocean Sensing System, is planned by the U.S. Navy with instruments for measuring surface winds, sea surface topography, ice concentrations, and location of oceanic fronts. GEOSAT, the U.S. Navy's Geopotential Satellite, has a SEASAT-type altimeter for improving the global geoid and for wind speed determination. NIMBUS-7, the last of the NASA series, has an ocean color scanner and a multichannel microwave scanner. SEASAT, the first satellite dedicated to oceanography, had five sensors for measuring surface winds, topography, temperature, ice concentration, and wave patterns. Figure courtesy of NASA JPL; original in color.

1.1 INTRODUCTION

Remote sensing has been a tool of oceanographers for many generations, if the literal definition of the term is used: **the acquisition of information about the sea through the use of sensing devices remote from the feature of interest.** Probably the most common remote sensing device of the classical oceanographer is the echo sounder, which has provided most of our information about sea floor topography. In the context of this book, remote sensing is limited to the "teledetection" and measurement of electromagnetic radiation by devices such as photographic cameras, television, spectroradiometers, radars, and radio receivers. The **goal** of remote sensing in oceanography, which is the use of aerospace technology to solve problems, involves the entire experiment plan, including the choice of sensors, the reception, recording and processing of signals, and analysis of the resultant data.

As part of an experiment plan, or in the design of an operational monitoring system, the variables that are to be measured must be defined. Remote sensing from satellites or aircraft has certain advantages and limitations, which must be considered at the outset. Table 1.1 is a summary of oceanic variables that are measurable by their electromagnetic properties. The depth (z) to which the property can be measured by an aircraft or satellite and the measurement techniques are also summarized. The accuracy and spatial resolution to which each variable can be determined depends upon the technique used and the altitude from which it is measured. As technology progresses, this list will surely change.

It is tempting to list accuracies and resolutions with the remotely sensible properties in Table 1.1, but such values are too ephemeral. For example, accuracy in infrared temperature detection of the ocean's surface has been claimed to be as good as ± 0.1K. Recent error analysis has shown theoretical uncertainty of ± 1.0K, and practical attempts from spacecraft usually report root mean square (r.m.s.) uncertainties of several times the theoretical limit. Continued research into the physics and technology associated with infrared measurements will undoubtedly improve these figures.

A number of the properties listed in Table 1.1 may surprise the uninitiated reader. Consider salinity, for example. If one thinks about remote sensing of the environment as an extension of human vision,

Table 1.1

Ocean Properties That Are Remotely Sensible

Property	Depth	Platform		Techniques
		Aircraft	Satellite	
Temperature	z = 0 m	X	X	Infrared Radiometry
	z = 0 m	X	X	Microwave Radiometry
	0 ≤ z ≤ 100 m	X	-	Laser
Water Depth	0 ≤ z ≤ 200 m	X	X	Photography
		X	X	Visible Radiometry
		X	-	Laser
Salinity	z = 0 m	X	-	Microwave Radiometry
	0 ≤ z ≤ 100 m	X	-	Laser Scatterometry
Visible Radiance (Color)	0 ≤ z ≤ 200 m	X	X	Photography
		X	X	Spectroscopy
Currents	z = 0	X	-	Photogrammetry
		X	X	Microwave Radar
		X	-	Doppler Laser
Geoid	z = 0	-	X	Microwave Radar
Tides	z = 0	-	X	Microwave Radar
Sea State	z = 0	X	-	Photography
		X	X	Microwave
		X	X	Visible Radiometry
		X	-	Laser
Surface Winds	z = 0	X	X	Microwave
Ice	z = 0	X	X	Photography
		X	X	Visible Radiometry
		X	X	Microwave
Oceanic Fronts	z = 0	X	X	Photography
		X	X	Visible Radiometry
		X	X	Infrared
		X	X	Microwave
Suspended Particulates	0 ≤ z ≤ 100 m	X	X	Photography
		X	X	Visible Spectroscopy
		X	-	Laser
Flotsam and Jetsam (*i.e.*, Petrochemicals)	0 ≤ z ≤ 20 m	X	X	Photography
		X	X	Visible Reflectance
		X	-	Laser
		X	X	Infrared Emittance
		X	X	Microwave (passive
		-	-	and active)

one will soon discover they have an eye disease called myopia, or a narrow field of vision. In the case of salinity, there is no obvious property of the ocean that you can "see" to tell you about its salt content. On the other hand, as the microwave properties of seawater are considered, and the dielectric properties at those wavelengths are investigated, certain new information is revealed: microwave emissivity of seawater is dependent upon salinity, among other things. Emissivity (discussed in chapter 2) is a parameter involved in the measurement of ocean radiation at all wavelengths, but is an especially large variable at microwave frequencies. Therefore, if a certain microwave instrument is sensitive to changes in the ocean's emissivity, it is also sensitive to changes in its salinity.

The point of this discussion is to encourage the reader to think beyond the bounds of conventional wisdom and to invent new and exciting approaches to the study of our planet's oceans. Before making that invention, it is necessary to have a common language. To facilitate that commonality, a glossary is included in appendix A, a list of symbols is given in appendix B, and the **electromagnetic spectrum** is shown in Figure 1.1.

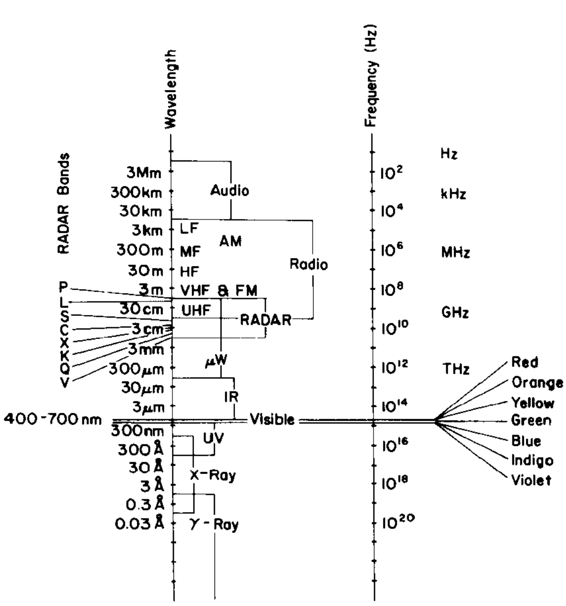


Figure 1.1: Spectrum of electromagnetic energy. Meanings of the abbreviations are given in the text and the glossary; detail of radar bands is given in Table 1.2.

Measurement units in remote sensing follow standard physical practice. The units of length, mass, and time are: meters (m), kilograms (kg) and seconds (s); the so-called MKS system. The prefixes, symbols, and their ratios, commonly used in remote sensing terminology are:

pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}
peta	P	10^{15}

Many derived units are used in this branch of physics as well; these units are introduced in the appropriate chapters. Units of temperature used here depend upon whether the value was derived by a contact method (*in-situ*) or by remote sensing; *in-situ* values are given in degrees Celsius (°C) and radiometric values are given in kelvins (K), where 0°C = 273.16K.

Twentieth-century scientists take for granted the broad nature of the electromagnetic spectrum, but its piece-wise discovery is rich in history. The wave-like nature of radiation, which forms the basis of the spectrum, is artificially segregated and named, based on that history. Radiation visible to the human eye ranges from violet, at about 0.4 μm (micrometers) to red, at about 0.7 μm. Wavelengths longer than 0.7 μm are called **infrared** (IR) and wavelengths shorter than 0.4 μm are called **ultraviolet** (UV). The central frequency of visible light is about 5.5×10^{15} hertz (abbreviated Hz; cycles per second), but common practice is to use wavelength units to identify radiation whose frequency is higher than a terahertz (10^{12} Hz) and to use frequency units at lower frequencies. It is also common practice to use **nanometers** (10^{-9} m) when referring to visible wavelengths, **micrometers** when referring to infrared radiation, and **Ångstroms** (10^{-10} m) when referring to ultraviolet, X-ray and gamma ray (abbreviated γ-ray in Figure 1.1).

Ocean remote sensing at wavelengths < 400 nm is not well developed at this time because of the low amounts of natural energy available for passive radiometry and the large amount of atmospheric signal caused by Rayleigh scattering. Passive remote sensing at infrared wavelengths has been an active area of research since the early 1950's, particularly in the 8-14 μm region of the spectrum where the earth's emitted heat produces the highest detectable levels of radiation. The **microwave** region (abbreviated μW in Figure 1.1) includes the radar wavelengths and is used for both active and passive radiometry of the oceans. For historical reasons, the radar wavelengths have been given alphabetical abbreviations, as shown in Figure 1.1 and explicated in Table 1.2.

Table 1.2

Radar Wavelengths or Bands

Designation	Frequency	Central Wavelength
P	220 - 300 MHz	115 cm
L	1 - 2 GHz	20 cm
S	2 - 4 GHz	10 cm
C	4 - 8 GHz	5 cm
X	8 - 12.5 GHz	3 cm
Ku	12.5 - 18 GHz	2 cm
K	18 - 26.5 Ghz	1.35 cm
Ka	26.5 - 40 GHz	1 cm

For completeness, the radio and audio frequencies are included in Figure 1.1. Low, Medium and High Frequency (LF, MF, HF) are the usual amplitude modulation (AM) bands used in communication. Very High Frequency (VHF) is the common frequency modulation (FM) band used in communications, and UHF stands for the Ultra High Frequency radio bands. Audio or sound waves (less than 30 kHz) are acoustic waves that are quite different in nature from electromagnetic waves, but can be transformed from one wave type to the other by a transducer, such as a microphone or a loudspeaker. While the human mind enjoys compartmentalizing the electromagnetic spectrum based on the limits of our own senses, the physical universe recognizes no such boundaries.