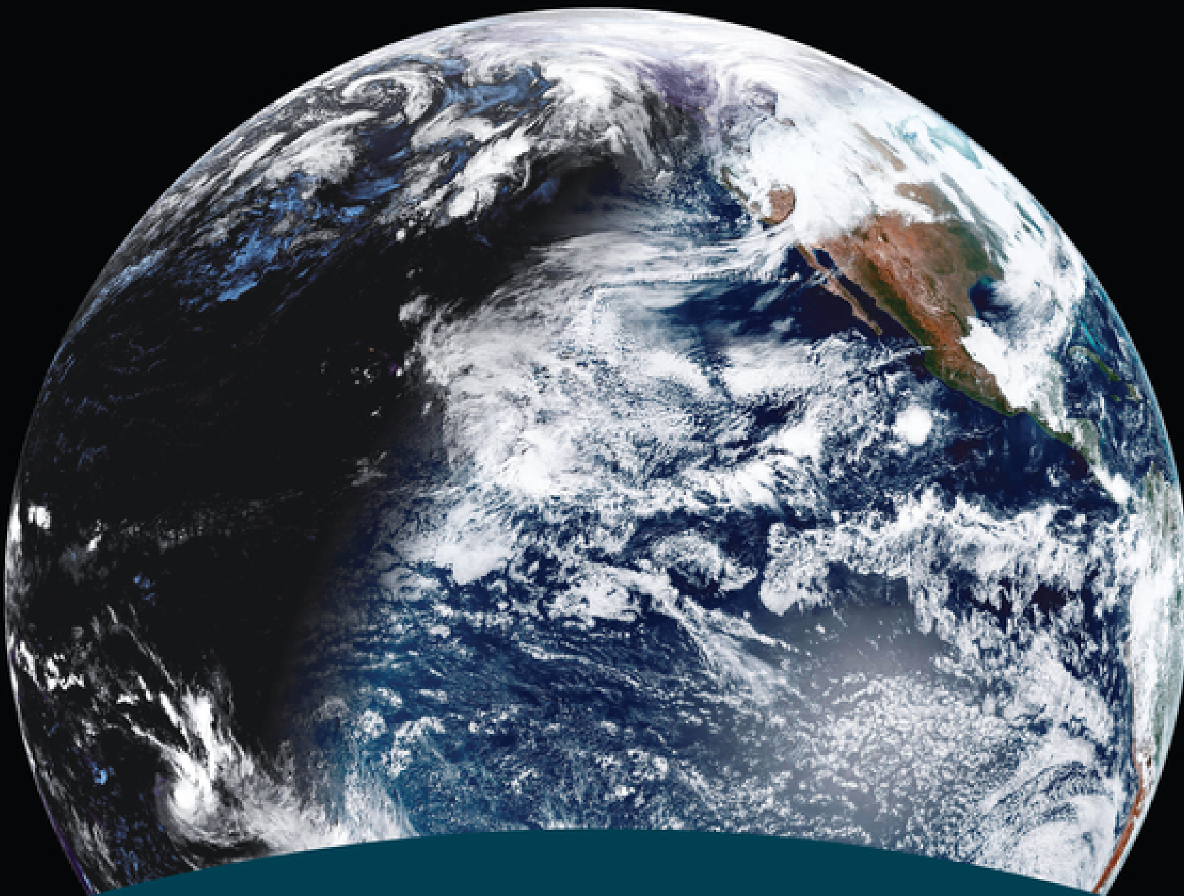

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Remote Sensing Physics

An Introduction to Observing Earth from Space

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The Johns Hopkins University Applied Physics Laboratory, USA

Richard Gasparovic
The Johns Hopkins University Applied Physics Laboratory (Ret.), USA

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Preface

At no time in history has it been more imperative to understand the present condition of our Earth's environment, especially the impacts of myriad human-induced activities and their portents for the future of our planet. The information provided by Earth observations from space-based remote sensors has become a critical element for this crucial endeavor.

The development of technology for Earth remote sensing has been a true multidisciplinary effort involving a variety of scientific disciplines, sensor and satellite engineering technologies, as well as advances in computer technology. Beginning in the 1960s with early images of cloud patterns observed with various electro-optical sensors, scientists and engineers soon recognized the potential for new information obtainable with instruments operating throughout the electromagnetic spectrum. This quickly led to the launch of infrared sensors for measuring ocean, land, and atmospheric temperatures; optical sensors for ocean color data, vegetation coverage, and atmospheric gases and aerosols; along with microwave instruments for monitoring polar regions, ocean winds and waves, sea level rise, and land surface deformations.

Exploitation of these advances in remote sensing technology would not have been possible without the parallel explosion in computer processing capabilities needed to acquire, store, display and synthesize the massive global data sets transmitted daily from Earth-observing satellites. Now, nearly half a century later, weather and severe storm forecasts based on satellite observations have become part of daily life, along with rainfall and drought monitoring, and forest fire detection. Moreover, space-based remote sensing technology now affords the only practical means for long-term global monitoring and prediction of such climate variables as sea level rise, ocean temperatures and biological productivity, and atmospheric conditions.

The purpose of this text is to provide an introduction to the physical principles underlying the techniques being used for remote sensing of the Earth. Our focus is on providing the reader with coherent treatments of the basic physics needed to understand exactly what the various instruments are measuring, including how and why the raw signals must be calibrated and corrected for interference or contamination by various environmental factors in order to extract the physical parameters of interest.

We have endeavored also to describe the relevant sensor technologies in sufficient detail for the reader to appreciate the engineering approaches to the acquisition of remotely sensed data. The references cited in each chapter can provide the interested reader with significantly more in-depth information on these engineering aspects. Software systems currently available for processing, display, and extraction of information from remote sensor data is an area we have intentionally omitted. References to some useful starting points on this topic can be found in one of the Appendixes.

An attempt has been made throughout to present the material at a level that should be understandable to upper-class undergraduate science and engineering students, as well as to early-year graduate students in these disciplines.

The book is conceptually divided into three main parts. The first part consists of a brief overview of Earth remote sensing (Chapter 1) and a description of satellite orbits relevant to instruments deployed for Earth observations (Chapter 2). The second major part, comprising Chapters 3 through 6, discusses observations made with passive sensors, i.e., those which make use of natural illumination from the sun and/or thermal radiation from the ocean, land surfaces, and Earth's atmosphere. Observations with active sensors which provide their own illumination, such as radars of various types and lidars, are treated in Chapters 7 through 11 of the final part. The book concludes with a brief overview of two sensing techniques not discussed previously, along with a short summary of future Earth observation missions being planned by NASA and the European Space Agency (Chapter 12).

A compendium of links to a wide variety of remote sensing resources available on the Internet can be found in Appendix F. An extensive bibliography with references to other books, journal publications, and technical reports is included to supplement the material presented in the individual chapters of the book. Our expectation is that these items will prove valuable to students and researchers alike.

A substantial fraction of the material in this book was originally developed for remote sensing courses taught by the authors over many years to Masters Degree students in the Applied Physics curriculum within the Engineering for Professionals Program at the Johns Hopkins Whiting School of Engineering. The authors hereby gratefully acknowledge the numerous and invaluable contributions from these student interactions.

The authors also want to thank the numerous colleagues who reviewed chapters of the book: Dr. Steve Borchardt, Dr. Joshua Broadwater, Dr. Eric Ericson, Dr. David Jansing, Dr. Kevin Kwon, Dr. Carl Lueschen, Mr. Frank Monaldo, Dr. David Porter, Dr. Keith Raney, and Dr. Scott Wunsch. We especially want to thank Dr. Adrienne Criss and Captain James Miller (USN, Ret.) for reviewing the book in its entirety, which was not a small undertaking. We acknowledge the efforts of Mr. Chris Jackson (NOAA) who reprocessed SAR wind data for Figures 10.48-10.52 and Dr. James Churnside (NOAA) who provided lidar data for Figure 11.10. We also appreciate the efforts of numerous editors and reviewers at the AGU and Wiley for their contributions to this book.

Acronyms

ACE	Advanced Composition Explorer
ADCP	Acoustic Doppler Current Profiler
ADEOS	Advanced Earth Observing Satellite
ADM	Atmospheric Dynamics Mission
AIS	Automatic Identification System
ALADIN	Atmospheric LAser Doppler INstrument
ALI	Advanced Land Imager
ALOS	Advanced Land Observing Satellite
ALtiKa	Altimeter Ka-band
AMI	Active Microwave Instrument
AMSR	Advanced Microwave Scanning Radiometer
AMSR-E	Advanced Microwave Scanning Radiometer-EOS
AMSU	Advanced Microwave Sounding Unit
ARM	Atmospheric Radiation Measurement
ASAR	Advanced Synthetic Aperture Radar
ASCAT	Advanced Scatterometer
ASCII	American Standard Code for Information Interchange
ASF	Alaska SAR Facility
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AT	Along Track
ATI	Along-Track Interferometry
ATISAR	Along-Track Interferometric SAR
ATLAS	Advanced Topographic Laser Altimeter System
ATM	NASA Airborne Topographic Mapper
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
B81	Brown 1981 model
BB	Blackbody
BRDF	Bidirectional Reflectance Distribution Function
BSF	Beam Spread Function
BW	Bandwidth
CAD	Computer Aided Drafting

CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CAVIS	Clouds, Aerosols, Water Vapor, Ice and Snow instrument
CCD	Charge-Coupled Device, Coherent Change Detection
CCI	Climate Change Initiative
CDOM	Colored Dissolved Organic Material
CFOSAT	China-France Oceanography Satellite
CIE	International Commission on Illumination
CLW	Cloud Liquid Water
CMOD	C-band Geophysical Model Function
CMODIS	Chinese Moderate Resolution Imaging Spectrometer
CMOS	Complementary Metal-Oxide Semiconductor
CNES	French National Centre for Space Studies
CNSA	China National Space Administration
COCTS	Chinese Ocean Color and Temperature Scanner
COSMO-SkyMed	Constellation of Small Satellites for Mediterranean basin Observation
CPI	Coherent Processing Interval
CSA	Canadian Space Agency
CSV	Comma Separated Values format
CYGNSS	Cyclone Global Navigation Satellite System
CZCS	Coastal Zone Color Scanner
CZI	Coastal Zone Imager
D2P	Delay-Doppler Altimeter
DAAC	NASA Distributed Active Archive Center
DC	Direct Current (0 frequency)
DEM	Digital Elevation Model
DIAL	Differential Absorption Lidar
DLR	German Aerospace Center
DMSP	Defense Meterological Satellite Program
DOD	U.S. Department of Defense
DP	Differential Phase Shift
DR	Differential Reflectivity
DSCOVR	Deep Space Climate Observatory
E&M	Electricity and Magnetism
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
EGM2008	Earth Gravitational Model 2008
EHF	Extremely High Frequency
ELF	Extremely Low Frequency
EM	Electromagnetic
EnMAP	Environmental Mapping and Analysis Program
ENVISAT	Environmental Satellite
EO	Electro-optic
EOF	Empirical Orthogonal Functions
EOS	Earth Observing System
EOSDIS	Earth Observing System Data and Information System

ERS	European Remote-Sensing Satellite
ESA	European Space Agency
ET	Evapotranspiration
ETM	Enhanced Thematic Mapper
ETM+	Enhanced Thematic Mapper Plus
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EVI	Enhanced Vegetation Index
FAA	U.S. Federal Aviation Administration
FLH	Fluorescence Line Height
FM	Frequency Modulated
FOR	Field of Regard
FOV	Field of View
GAC	Global Area Coverage
GCOM-C	Global Change Observation Mission - Climate
GEDI	Global Ecosystem Dynamics Investigation
GEO-CAPE	GEOstationary Coastal and Air Pollution Events
GEO	Geostationary Earth Orbit
GeoCarb	Geostationary Carbon Observatory
GG	Glazman and Greysukh 1993 model
GISAT	Geo Imaging Satellite
GLAS	Geoscience Laser Altimeter System
GLI	Japanese Global Imager
GLONASS	Global Navigation Satellite System
GmAPD	Geiger-mode Avalanche Photo Diodes
GML	Geiger Mode Lidar
GNSS	Global Navigation Satellite System
GOCI	Geostationary Ocean Color Imager
GOES-3	Geodynamics Experimental Ocean Satellite 3
GOES	Geostationary Operational Environmental Satellites
GOSAT	Greenhouse gases Observing SATellite
GPM	Global Precipitation Measurement
GPO	U.S. Government Publishing Office
GPS	Global Position System
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment-Follow On
GSD	Ground Sample Distance
GSFC	Goddard Space Flight Center
HDF	Hierarchical Data Format
HEO	High Earth Orbit
HERA	Hybrid Extinction Retrieval Algorithm
HF	High Frequency
HFSWR	High-Frequency Surface Wave Radar
HH	Horizontal Transmit – Horizontal Receive
HICO	Hyperspectral Imager for the Coastal Ocean
HITRAN	High-resolution Transmission Molecular Absorption Database

HRPT	High-Resolution Picture Transmission
HSI	Hyperspectral Imaging
HV	Horizontal Transmit – Vertical Receive
HV SC	HeaVy-Snow Covered ice
HySI	Hyperspectral Imager
HyspIRI	Hyperspectral Infrared Imager
IF	Intermediate Frequency
IFOV	Instantaneous Field of View
IGS	Information Gathering Satellites
InGaAs	Indium Gallium Arsenide
INSAR	Interferometric SAR
IR	Infrared
ISRO	Indian Space Research Organisation
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JB	Jianbing
JERS	Japanese Earth Resources Satellite
JHU/APL	The Johns Hopkins University Applied Physics Laboratory
JPL	NASA Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
KARI	Korea Aerospace Research Institute
LAC	Local Area Coverage, LEISA Atmospheric Corrector
LCM	Linear Composite Model
LED	Light Emitting Diode
LEISA	Linear Etalon Imaging Spectrometer Array
LEO	Low Earth Orbit
LF	Low Frequency
LFM	Linear Frequency Modulated
LIS	Lightning Imaging Sensor
LO	Local Oscillator
LOS	Line of Sight
LS	Landsat
LST	Land Surface Temperature, Local Solar Time
LWIR	Long-wave Infrared
MABL	Marine Atmospheric Boundary Layer
MAIA	Multi-Angle Imager for Aerosols
MB	Megabyte, Main Beam
MCW	Modified Chelton and Wentz model
MEO	Mid-Earth Orbit
MERIS	Medium-spectral Resolution, Imaging Spectrometer
MF	Medium Frequency
MFY	Medium First-Year ice
MHS	Microwave Humidity Sounder
MOBY	Marine Optical Buoy
MODIS	Moderate-resolution Imaging Spectrometer

MODTRAN	Moderate Resolution Atmospheric Transmission
MOS	Modular Opto-electric Sensor
MP	Melt Ponds
MSS	Multispectral Scanner
MWIR	Medium-wave Infrared
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
Nd:YAG	Neodymium-Doped Yttrium Aluminum Garnet
NDBC	U.S. National Data Buoy Center
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NEδL	Noise Equivalent Delta Radiance
NEδT	Noise Equivalent Delta Temperature
NEXRAD	Next-Generation Radar
NF	Noise Figure
NIR	Near-Infrared
NISAR	NASA-ISRO Synthetic Aperture Radar
NISTAR	National Institute of Standards and Technology Advanced Radiometer
NOAA	National Oceanographic and Atmospheric Administration
NOMAD	NASA bio-Optical Marine Algorithm Dataset
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	National Polar-Orbiting Partnership
NRC	U.S. National Research Council
NRCS	Normalized Radar Cross-Section
NRL	U.S. Naval Research Laboratory
NSCAT	NASA Scatterometer
NWP3	Freilich and Dunbar 1993 model
OC3V	Ocean Chlorophyll 3-band VIIRS Algorithm
OC4	Ocean Chlorophyll 4-band Algorithm
OCI	Ocean Color Imager
OCM	Ocean Colour Monitor
OCO	Orbiting Carbon Observatory
OCTS	Ocean Color and Temperature Scanner
OES	Ocean Ecosystem Radiometer
OLCI	Ocean Land Color Imager
OMPS	Ozone Mapping and Profiler Suite
OSC	Orbital Sciences Corporation
OSCAT	OceanSat-2 Scanning Scatterometer
OSMI	Ocean Scanning Multispectral Imager
OSTM	Ocean Surface Topography Mission
PACE	Plankton, Aerosol, Cloud and ocean Ecosystem
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PAR	Photosynthetically Available Radiation
PCR	Pulse Compression Ratio
PD	Power Density

PDF	Probability Density Function
PHyTIR	Prototype HyspIRI Thermal Infrared Radiometer
PNG	Portable Network Graphics format
POES	Polar Operational Environmental Satellites
POLDER	POLarization and Directionality of the Earth's Reflectances
PR	Pressure Ridges
PREFIRE	Polar Radiant Energy in the Far-InfraRed Experiment
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
PT-JPL	Priestley–Taylor Jet Propulsion Laboratory
QE	Quantum Efficiency
RAM	Random Access Memory
RCM	Radarsat Constellation Mission
RCS	Radar Cross-Section
RF	Radio Frequency
RFSCAT	Rotating Fan Beam SCATterometer
RISAT	Radar Imaging Satellite
RMS	Root Mean Square
ROCSAT	Republic of China Satellite
ROIC	Readout Integrated Circuits
RVI	Radar Vegetation Index
S-NPP	Suomi National Polar-Orbiting Partnership
SABIA-Mar	Satélites Argentino-Brasileño para Información Ambiental del Mar
SAGE-III	Stratospheric Aerosol and Gas Experiment III
SAOCOM	Argentine Microwaves Observation Satellite
SAR	Synthetic Aperture Radar
SARAL	Satellite with ARgos and ALtiKa
SASS	Seasat Scatterometer
SB	Smoothed Brown model
SDP	Simplified Deep Space Perturbations
SDPS	SeaWiFS Data Processing System
SeaBASS	SeaWiFS Bio-optical Archive and Storage System
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SGLI	Second generation GLobal Imager
SGP	Simplified General Perturbations
SHF	Super High Frequency
SIR-C	Spaceborne Imaging Radar-C band
SLC	Scan Line Corrector
SLF	Super Low Frequency
SMAP	Soil Moisture Active Passive
SMI	Standard Mapped Image
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SNR	Signal-to-Noise Ratio
SOA	Chinese State Ocean Administration

SORCE	Solar Radiation and Climate Experiment
SPL	Single Photon Lidar
SRAL	Sentinel Radar Altimeter
SS MP	SubSurface Melt Ponds
SSA	Small-Slope Approximation
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager/Sounder
SST	Sea Surface Temperature
SVD	Singular Value Decomposition
SW	Surface Wave
SWH	Significant Wave Height
SWIR	Short-wave Infrared
SWOT	Surface Water & Ocean Topography
TCI	Temperature Condition Index
TCTE	Total Solar Irradiance Calibration Transfer Experiment
TDI	Time-Delay and Integration
TDRSS	Tracking and Data Relay Satellite System
TDWR	Terminal Doppler Weather Radar
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TES	Temperature Emissivity Separation
TFY	Thick First-Year ice
THF	Tremendously High Frequency
ThFY	Thin First-Year ice
TIRS	Thermal Infrared Sensor
TLE	Two-Line Elements
TM	Thematic Mapper
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
TROPICS	Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats
TSIS-1	Total and Spectral Solar Irradiance Sensor
TV	Television
UHF	Ultra High Frequency
ULF	Ultra Low Frequency
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
UV	Ultraviolet
VCI	Vegetation Condition Index
VH	Vertical Transmit – Horizontal Receive
VHF	Very High Frequency
VIIRS	Visible Infrared Imaging Radiometer Suite
VLF	Very Low Frequency
VNIR	Visible and Near-Infrared
VSWIR	Visible to Short Wavelength Infrared
VV	Vertical Transmit – Vertical Receive

WFF	Wallops Flight Facility
WGS	World Geodetic System
WiFS	Wide Field Sensor
WMO	World Meteorological Organization
WS	Wind Speed
WSR	Weather Surveillance Radar
WV	Water Vapor

About the Companion Website

This book is accompanied by a companion website.

www.wiley.com/go/chapman/physicsofearthremotesensing

The website includes:

- Example homework problems
- PDF and Powerpoint files of all figures from the book for downloading
- Latex and Powerpoint files containing all equations used in the text
- Multiple animations for use in the classroom

1

Introduction to Remote Sensing

Remote sensing is commonly defined as the process by which electromagnetic energy is exploited to interrogate some property of the Earth's environment – either its surface or its surrounding atmosphere – by using a sensor system located at some distance from the region of interest.

Yet remote sensing is a bit more general than this. For example, the interior structures of the Earth have been remotely sensed using neutrino detectors. And spacecraft have been deployed to remotely sense the characteristics of other planets, asteroids and comets. Still this definition characterizes most of the remote sensing described in this book, which concentrates on Earth remote sensing using electromagnetic energy.

This image of the Gulf Stream shown in Figure 1.1 is a classic example. The image was created from data obtained by a multiple-wavelength imaging system flown on the NOAA-12 satellite. The data from this camera were transmitted to a ground station located at The Johns Hopkins University Applied Physics Laboratory (JHU/APL), where they were processed using sophisticated algorithms to estimate sea surface temperature. The image you see is a computer-generated false-color map of sea surface temperature.

This book describes the physical basis for such measurements and examines the algorithms used to derive geophysical information from such data.

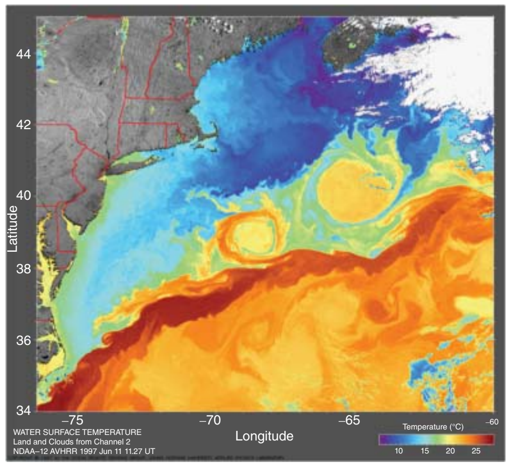

Figure 1.1 Sea surface temperature in Western Atlantic. Source: Courtesy of R. E. Sterner, JHU/APL.

Such calibrated satellite imagery provides a unique source of information on scales that would be otherwise inaccessible to terrestrial sensors. But it is hard today to recall how revolutionary such data really are. For example, in Figure 1.1, the blobs of warm water located just north of the Gulf Stream wall are massive warm core eddies. These eddies are rotating lenses of fluid that are occasionally spun off of the Gulf Stream. The amazing thing is that oceanographers were unaware of the existence of such warm core eddies until the first large-scale black and white images of the ocean were returned from early satellites.

Remote Sensing Physics: An Introduction to Observing Earth from Space, Advanced Textbook 3, First Edition.
Rick Chapman and Richard Gasparovic.

Companion website: www.wiley.com/go/chapman/physicsofearthremotesensing

Figure 1.2 Flows near Grand Geyser, Yellowstone National Park.

Remote sensing does not have to occur from so far away. The photographs shown in Figure 1.2 were taken in Yellowstone National Park while awaiting the eruption of Grand Geyser. Water leaking from the geyser flowed down the slight incline towards the raised walkway (top). The middle photograph shows the ripples in the water created by flow past obstacles. The bottom photograph shows a blowup of one set of these ripples.

Surface waves can be created by flow past obstacles, just like a moving boat in still water creates waves. The ripples shown here are capillary waves that propagate slightly upstream of the disturbance. Those waves whose speed is arrested by the flow are stationary and hence can grow. The dispersion relation for surface waves is well known. So wavelength measurements from this single photograph could be used to determine the flow speed!

Without the measurement and a physical model, this is no more than a pretty picture. When combined with quantitative measurements and a physical model this photograph becomes remote sensing data.

This text discusses all aspects of the acquisition, measurement, and physical interpretation of the most common types of remote sensing. While the text primarily concentrates on satellite-based remote sensing of the environment, remote sensors deployed from aircraft and other platforms are also described.

As shown in Figure 1.3, satellites are used for a wide range of applications. They are used for communications, navigation and timing (GPS), as well as military applications such as intelligence collection. Satellites are also used to perform scientific measurements involving space environment, Earth environment, and astronomy (Davis, 2007).

This text concentrates on the Earth environment applications, such as measurements of the atmosphere, land, and oceans. Despite this concentration, the physics of remote sensing are also relevant for other applications.

There are a wide variety of applications for remote sensing data, as shown by the partial list in Box 1.1. These applications span the range from oceans to land to the atmosphere. Many of these applications are discussed in some detail throughout this book.

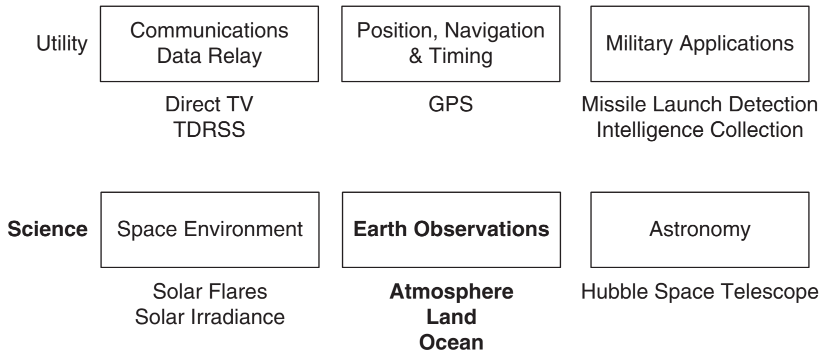

Figure 1.3 Satellite applications.

Box 1.1 Applications for remote sensing data.

- Ocean Observations
  - Sea surface temperature
  - Ocean color
  - Biological productivity
  - Coral bleaching
  - Sea ice concentration and extent
  - Sea level rise and tides
  - Currents, eddies, bathymetry
  - Surface winds
- Atmospheric Observations
  - Weather systems - clouds, storms
  - Temperature and moisture profiles
  - Pollution - dust, volcano plumes
  - CO_2 concentration
- Land Observations
  - Surface temperature
  - Vegetation coverage
  - Snow cover
  - Soil moisture
  - Continental ice sheets
  - Elevation changes
  - Floods
  - Forest fires
  - Urbanization changes
  - Maps
- Earth Radiation Budget
  - Solar insolation
  - Reflected sunlight
  - Emitted thermal radiation

Maybe more important than the specific applications is the ability to regularly make measurements over most or all of the globe and to make those measurements over years or even decades. This makes satellite data particularly useful for radiation budget and climate studies.

Satellites are not ideal – they have a variety of limitations as remote sensing platforms. Most satellites can provide only intermittent observations at any location on the globe. Time intervals between revisits are determined by orbital parameters, sensor swath width and environmental limitations, such as the need for daylight or cloud-free line of sight to the surface. High-resolution sensors typically provide only limited area coverage per orbit. Dwell time per sensed area is typically short, so short duration transient events are seen only by chance. While individual satellites can provide continuous data records of a decade or more, these records are short relative to climate time scales. Time series exceeding the lifetime of an individual sensor require difficult multisensor intercomparisons and intercalibrations.

In addition, interpretation of remote sensing data is not easy. Remote sensors detect properties of electromagnetic radiation emitted,

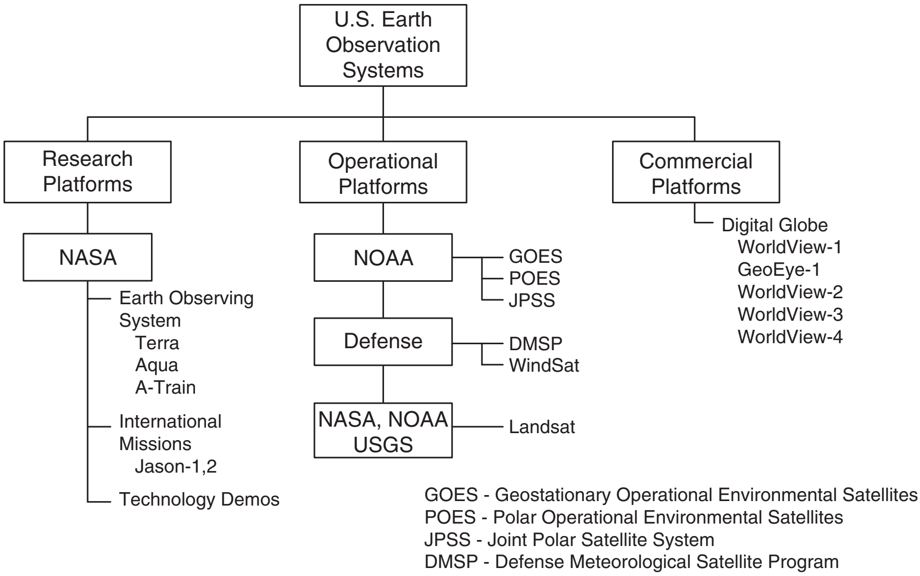

Figure 1.4 Overview of U.S. Earth observation systems.

scattered, or reflected from scenes of interest, but these properties are often affected by multiple geophysical parameters. Models are developed to describe the sensor output as a function of the geophysical parameters. "Inversion" is the process of inferring the geophysical parameters from the sensor output. Inversions are not always unique and validation of geophysical retrieval algorithms is frequently difficult. These are challenges that are discussed throughout this text.

Because this text concentrates on satellite-based environmental remote sensing, it is worth mentioning the organizations responsible for current U.S. Earth observation systems (Figure 1.4). NASA is responsible for research platforms, such as the Terra (Kaufman et al., 1998; Ungar et al., 2003) and Aqua (Parkinson, 2003) Earth observing satellites. They also coordinate with international partners and develop technology demonstrators.

U.S. government satellites that are needed for operational requirements, such as weather prediction, are either run by NOAA or by the military and intelligence communities.

Historically, the earliest Earth observation satellites were developed and launched by U.S. government agencies in the late 1950s and early 1960s to acquire meteorological data (Davis, 2007). The Soviet Union followed in the late 1960s with a similar focus on meteorology. Interest in ocean and land observations came into prominence in the 1970s following major technology developments in optical and microwave sensors. Today, Earth remote sensing has become a truly international endeavor involving tens of countries building and operating scores of both government and commercially funded satellites. In addition, the ready availability of large volumes of digital data from these systems has been the impetus for innovations in processing, display, and dissemination of products for an ever expanding range of applications.

1.1 How Remote Sensing Works

The general process of how remote sensing works is illustrated in Figure 1.5.

A sensor attached to a platform such as a satellite looks down to make measurements. The sensor can typically make measurements of one or more resolution cells within its field