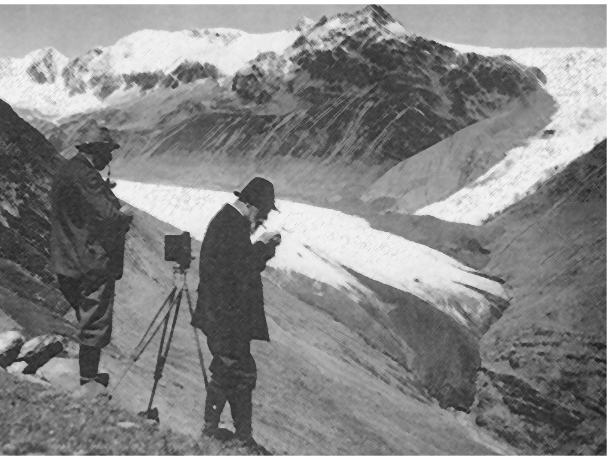
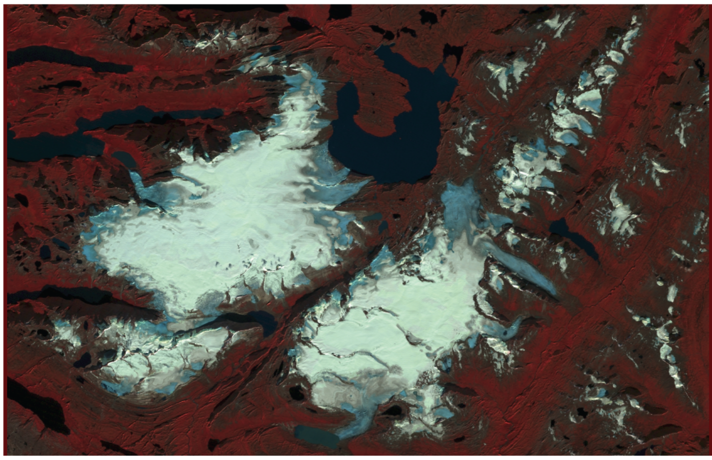
REMOTE SENSING of GLACIERS

TECHNIQUES FOR TOPOGRAPHIC, SPATIAL AND THEMATIC MAPPING OF GLACIERS

PETRI PELLIKKA AND W. GARETH REES (EDS.)





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Techniques for Topographic, Spatial and Thematic Mapping of Glaciers

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Heinrich Schatz and Hans Hess enjoying a smoke while surveying the confluence of Hintereisferner and Kesselwandferner in 1929.

Svartisen ice caps in Norway in Landsat ETM+ satellite image of September, 7, 1999. (Heiskanen, J., K. Kajuutti, M. Jackson, H. Elvehøy & P. Pellikka, 2003. Assessment of glaciological parameters using Landsat satellite data in Svartisen, Northern Norway. EARSeL eProceedings 2 1/2003, 34-42. Observing our Cryosphere from Space).

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Foreword

Glaciers are an important part of the global cryosphere. They account for less than 1% of the total volume of ice locked up on land as glaciers and ice sheets, but are at present the dominant cryospheric contributor to global sea-level rise. The question of whether glaciers are growing or decaying, and at what rate, is therefore not only an academic one but is also of direct interest to governments and policymakers. Glaciers, and the larger ice caps beyond the margins of the great ice sheets of Antarctica and Greenland, cover a total of several hundred thousand square kilometres. This very large spatial scale implies that remote sensing instruments, whether deployed from the air or from satellite platforms, are essential to the scientific investigation of glaciers and their mass balance or state of health.

In fact, most glaciers, whether in the Arctic or in the mountain regions of the World, are shrinking; that is to say, they are retreating and thinning. A clear task for remote sensing is to provide quantitative datasets that can be used to measure the rates at which such changes are taking place. These data need to be acquired over as long a time series as possible, and with wide geographical coverage, so that any acceleration in the rate of mass loss from glaciers in our warming World can be detected.

This book, edited by Petri Pellikka and Gareth Rees, brings together a number of experts in the field of remote sensing of glaciers, to provide a set of authoritative chapters that range from early terrestrial photogrammetry to the latest airborne laser and satellite radar methods for investigating glacier change. Chapters on the mass balance and flow of glaciers, and on the physical principles that underlie remote sensing at various wavelengths, provide important background to those on instruments and techniques of measurement. These chapters, taken together, provide a clearly focused view of glacier measurement and monitoring that is an important contribution to investigations of glacier mass balance, with its important implications for global sea-level change over the coming century and beyond.

Julian Dowdeswell
Director
Scott Polar Research Institute
University of Cambridge

Acknowledgments

This book is the final outcome of the OMEGA project, which was funded by the 5th Framework Programme of the European Commission under the research programme Energy, Environment and Sustainable Development, thematic priority Global Change, Climate and Biodiversity and research area Development of new long-term observation capacity. The OMEGA (Development of Operational Monitoring System for European Glacial Areas – synthesis of Earth observation data of the present, past and future) project was funded from 2001 to 2004. I am grateful to the co-proposers of the project, Prof. Henrik Haggrén, Mr. Kari Kajuutti and Ms. Kukka-Maaria Luukkonen, to our collaborators at the University of Turku, Helsinki University of Technology, Novosat Ltd., the University of Innsbruck, Joanneum Research, Norut Tromsø, the Norwegian Water and Energy Directorate (NVE), SITO Ltd. and the Bavarian Academy of Sciences and Humanities as well as to the European Commission for its support. Herewith, I also acknowledge the companies who carried out the airborne flight campaigns over the glaciers West Svartisen (Norway) and Hintereisferner (Austria), Topscan GmbH and DLR, the German Aerospace Centre.

It was a very interesting personal experience to coordinate OMEGA, in which partners from three different countries and more than 35 people of ten different nationalities were involved. I would like to thank all the partners and individuals of the OMEGA consortium for their participation in the project, which was a great pleasure for me to coordinate. I hope that the partnership and friendship created will last for the decades to come.

My personal work for this book was carried out at the Department of Geography of the University of Helsinki and at the Scott Polar Research Institute at the University of Cambridge, with a grant from the Academy of Finland. Herewith, I have the honour to express my gratitude to SPRI for the inspiring atmosphere which the staff, institute and Cambridge itself provided. Magnus Magnusson from the International Glaciological Society provided valuable help for finding authors for the last missing chapter.

This book would not have been possible without the specialists writing chapters and without the reviewers commenting on the manuscripts. Gratitude is expressed by presentation of a small biography of each author and by including the name of the reviewers at the end of the book. It can be observed from this list that specialists from many institutes were involved. In the end, one third of the book was written by colleagues outside the OMEGA consortium based on the collaborations OMEGA had during its operation. Some of the figures were provided by other scientists and journals, which are listed at the end of the book. I would also like to thank my co-editor, Dr. Gareth Rees from SPRI, for helping me with the book. Being experienced in producing books about remote sensing and physics and as a native English speaker, Gareth was both a great help and a friend.

Finally, I would like to thank my wife Kristiina for being patient, also with this work, and last but not least my three daughters, Reetta, Venla and Noora.

Petri Pellikka

Author biography

Petri Pellikka obtained his B.Sc. and M.Sc. degrees at the University of Helsinki, Finland, specializing in Physical geography and Development geography. He carried out his Ph.D. studies at the University of Munich, Germany and at the University of Oulu, Finland, on airborne video camera sensor calibration and its application in studies of forest phenology in the German Alps. He did his post-doctoral research at Carleton University, Canada (1998–1999) on the remote sensing of forest damage caused by freezing rain. Dr. Pellikka has been a professor of geoinformatics at the Faculty of Science of the University of Helsinki since 2002. He leads the GeoInformatics Research Group of 10 researchers and Ph.D. students at the Department of Geosciences and Geography. In 2007–2008 he spent a sabbatical year at the University of Ghent, Belgium and at the Scott Polar Research Institute of the University of Cambridge, England. Dr. Pellikka is a Member of the Commission for Glaciology of the Bavarian Academy of Sciences and Humanities and a lecturer of physical geography, especially its remote sensing applications, at the University of Turku. His current research activities are concentrated in remote sensing of forest, land cover and land use changes in East Africa, particularly in Kenya (http://www.helsinki.fi/science/taita). Dr. Pellikka was the coordinator of the OMEGA project (http://omega.utu.fi), and participated in the field work activities, both in the Hintereisferner and Svartisen glaciers. He has supervised various Ph.D. and M.Sc. students at the University of Turku and University of Helsinki who worked on subjects related to the OMEGA. He has published over 110 scientific papers and over 40 popular articles.

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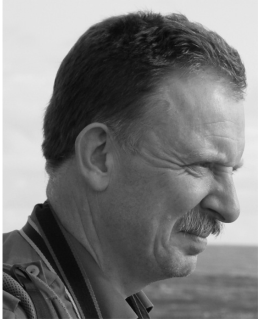

Gareth Rees studied Natural Sciences as an undergraduate, specialising in Physics, and Radio Astronomy for his Ph.D., at the University of Cambridge. Since 1985 he has been a member of the academic staff at the Scott Polar Research Institute (SPRI), specialising in the application of spaceborne and airborne remote sensing techniques to the investigation of polar environments. He directs the Polar Landscape and Remote Sensing Group at SPRI. The work of this group includes field-based investigation of glaciers and ice caps in Svalbard and Iceland and laboratory-based studies of snow and terrestrial ice in other parts of the world including Siberia and the Caucasus Mountains. The group also has a major research focus on the dynamics of high-latitude vegetation (tundra and the northern part of the boreal forest) and its response to global climate change. Dr. Rees is also the co-director of a core project of the International Polar Year in which the Arctic treeline region is investigated. Dr. Rees conducts frequent fieldwork in Svalbard and in northern Russia. He has published seven books and over 70 scientific papers.

W. Gareth Rees, Scott Polar Research Institute, University of Cambridge, Lensfield Road Cambridge CB2 1ER, England. wgr2@cam.ac.uk

Preface: Remote sensing of glaciers – glaciological research using remote sensing

The acronym OMEGA stands for Development of an Operational Monitoring System for European Glacial Areas – synthesis of Earth observation data of the present, past and future. The aim of the project was to develop methodologies using every potential remote sensing data source and method for constructing elevation models and areal delineations of glaciers. The data types used were terrestrial photography, aerial photography, digital airborne imagery, airborne laser scanner data, airborne radar data, optical high resolution satellite data (Landsat TM, ETM+), very high resolution optical satellite data (Ikonos, EROS), multiangular satellite data (MISR) and radar satellite data (ERS-1, Radarsat). In addition, old cartographic products dating back to late 1800s, were used. The time span of the remote sensing data ranged from 1907 (old terrestrial photography) to 2003.

A second aim was to develop an operational monitoring system for glacial areas. This system would compile the data developed in the project and could be updated periodically. In the first thoughts semi-automatic or automatic processing chains for satellite imagery were planned to be part of the system, but finally the system was modified to be a data management system rather than a monitoring system. In the system, the partners maintained their data among themselves, but shared the data using a common node set up at Norut in Tromsø, Norway. A few years after the project ended it became clear that the OMEGA system did not stand alone as planned as there was no sustainability and at the same time other glacier monitoring instruments, such as the World Glacier Monitoring System (WGMS) and Global Land Ice Measurements from Space (GLIMS), were functioning.

The glaciers Hintereisferner located in Öztal, Austria and Engabreen (part of the Svartisen ice cap, Norway) were chosen as study areas. The glaciers were different as Hintereisferner is a narrow retreating valley glacier and Engabreen is part of an ice cap and has advanced slightly during the 1990s. Common to both glaciers is the fact that they have been intensively studied: the University of Innsbruck has been studying Hintereisferner since the 1950s, and the Norwegian Water and Energy Directorate (NVE) has been studying the Engabreen outlet, which enabled us to use existing remote sensing data and glaciological measurements. In addition, there were old glacier maps of Hintereisferner and surrounding glaciers. The background knowledge was also very helpful when planning the field work activities.

During the project we faced some problems with the changing weather conditions, typical of mountainous areas, and also some technical and logistical problems related to airborne remote sensing. First of all, the time window for optical remote sensing data acquisition is narrow. The data should be acquired at the end of the glacier year, which means August-September in Europe and there should not be new snow on the glacier surface, since we also wanted to study the elevation of snow and firn lines at the end of the glacier's year. Sometimes this time window is too narrow to use airborne remote sensing, as well as for acquiring up-to-date satellite imagery.

However, we were able to acquire all the remote sensing data planned and also to analyse the data and produce the results. For example, laser scanner data were acquired ten times over Hintereisferner glacier in order to study the winter and summer balance changes. The D-day of the OMEGA project was August 12, 2003, when during one day, aerial photography, digital camera imagery, laser scanner data, Ikonos data and terrestrial photography were acquired. The field staff was also simultaneously in the field with their field measurement devices. In addition, two days later there was a MISR satellite overpass. These data allowed us to evaluate the accuracy of various elevation models over melting glacier surfaces, without temporal differences in various data types. More information about the OMEGA project can be found at http://omega.utu.fi.

This book presents the outcomes of the first aim of the OMEGA project, which was to develop methodologies using every potential remote sensing data and a method for constructing elevation models and areal delineations of glaciers. The target readers of this book are M.Sc. and Ph.D. students and professionals in natural sciences, especially in glaciology and remote sensing. It consists of chapters presenting principles of remote sensing, the background to glacier formation, and the main data types and their use in the remote sensing of glaciers.

In Chapter 1, remote sensing principles are introduced by Dr. Gareth Rees and by me, since basic knowledge of the physical background and data types of remote sensing is needed in the later chapters. In Chapter 2, Prof. Michael Kuhn presents the formation and dynamics of mountain valley glaciers, such as the Hintereisferner. In Chapter 3, the parameters that can be derived by remote sensing of glaciers are presented in order to highlight the connection between glaciology and remote sensing. In Chapter 4, Dr. Christoph Meyer presents the early history of remote sensing of glaciers, which is much older than aerial photography or satellite imagery. In Chapter 5, professors Matti Leppäranta and Hardy B. Granberg present the physics of the remote sensing of glaciers. In the following seven chapters, each data type and its applications are presented. In Chapter 6, Mr. Kari Kajuutti and his co-authors present the principles of terrestrial photogrammetry and in Chapter 7, Prof. Andreas Kääb presents aerial photogrammetry in glacier studies. The use of optical high resolution satellite imagery is presented in Chapters 8 and 12 by Dr. Frank Paul and Mr. Johan Hendriks. In Chapter 9, the principles of SAR imaging in glaciology are highlighted especially for Arctic glaciers by Dr. Kjell Arild Høgda and his co-authors. In Chapter 10, the most promising new data type, airborne laser scanner data, is presented by Dr. Thomas Geist and Prof. Hans Stötter. In Chapter 11, the use of a ground penetrating radar is presented for analyzing the internal characteristics and thickness of glaciers by Prof. Francisco Navarro and Dr. Olaf Eisen. In Chapter 13, the accuracies of the elevation models created from the data acquired on August 12, 2003, are presented by Dr. Olli Jokinen, and in Chapter 14, the accuracy aspects of topographical change detection are discussed by Jokinen and Geist. In the last Chapter 15, perspectives for world-wide glacier monitoring are provided by Prof. Andreas Kääb.

I hope that this book will be of interest to scientists specialized in glaciology, remote sensing and environmental issues in mountainous areas.

Petri Pellikka
Jalasjärvi, Finland
October 24, 2009

Abbreviations

3D	3 dimensional
AAR	accumulation area ratio
ADS-40	airborne digital sensor 40
AGC	automatic gain control
ALOS	Advanced Land Observing Satellite
ALS	airborne laser scanner
ALTM	Airborne Laser Terrain Mapper
ASAR	Advanced Synthetic Aperture Radar
ASIRAS	Airborne SAR/Interferometric Radar Altimeter System
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AWI	Alfred Wegener Institute
BEW	Bundesamt für Eich- und Vermessungswesen (Austrian Mapping Agency)
BIE	bounds for the interpolation error
BRDF	bidirectional reflectance distribution function
BV	brightness value
CCD	charge coupled device
CIAS	Correlation Image Analysis (software)
CMP	common-midpoint method
CRT	conventional radiative transfer
CSC	Finnish IT Centre for Science
CTS	cold-temperate transition surface
DEM	digital elevation model
DInSAR	differential interferometric synthetic aperture radar
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DMRT	dense medium radiative transfer
DN	digital number
DOS	dark object subtraction
DSM	digital surface model

DSS	drainage system side
DTM	digital terrain model
EL(A)	equilibrium line (altitude)
EROS	Earth Resources Observation and Science (of the United States Geological Survey)
ERS	European Remote Sensing Satellite
ESA	European Space Agency
E-SAR	Experimental Synthetic Aperture Radar
ETM+	Enhanced Thematic Mapper
FFT	fast Fourier transform
FM	frequency modulated
FMCW	frequency modulated continuous wave
FP5	Framework Programme 5 (of the European Commission)
GCM	global climate model
GCOS	Global Climate Observing System
GCP	ground control point
GeoTIFF	geographic tagged image file format
GHOST	Global Hierarchical Observing Strategy
GIFOV	ground-projected instantaneous field of view
GIS	Geographic Information System
GLIMS	Global Land Ice Measurements from Space
GPR	ground penetrating radar
GPS	Global Positioning System
GRACE	gravity recovery and climate experiment
GTOS	Global Terrestrial Observing System
HH	horizontal-horizontal (polarization)
HRSC-A	High Resolution Stereo Camera-Airborne
HRV	High Resolution Visible (SPOT)
HV	horizontal-vertical (polarization)
ICESat	Ice, Cloud and land Elevation Satellite
IGS	International Glaciological Society
IGY	International Geophysical Year
IMU	inertial measurement unit
INS	inertial navigation system
InSAR	interferometric SAR
IPY	International Polar Year
IR A	near infrared (NIR)
IR B	short wavelength infrared (SWIR)
IR C	mid wavelength infrared, long wavelength infrared (TIR)
IT	information technology
ITCZ	Inter Tropical Convergence Zone
LiDAR	Light Detection And Ranging
LISS (IRS)	Linear Imaging Self Scanning Sensor (Indian Remote Sensing)
LOS	line of sight
MIR	middle infrared
MISR	Multi-angle Imaging Spectroradiometer
MODIS	Moderate Resolution Imaging Spectroradiometer

NASA (JPL)	National Aeronautics and Space Administration (Jet Propulsion Laboratory)
NDSI	Normalised Difference Snow Index
NDVI	Normalised Difference Vegetation Index
NIR	near infrared
NSIDC	National Snow and Ice data Centre (of the United States)
NVE	Norwegian Water Resources and Energy Directorate
OMEGA	Operational Monitoring of European Glacial Areas
PALSAR	Phased Array type L-band Synthetic Aperture Radar
Pol-InSAR	Polarimetric SAR Interferometry
Radar	radio detection and ranging
RCM	regional climate model
RES	radio-echo sounding
RMS(E)	root mean square (error)
RWV	radio-wave velocity
SAR	synthetic aperture radar
SNR	signal to noise ratio
SPOT	Satellite Pour l’Observation de la Terre
SPRI	Scott Polar Research Institute
SRTM	shuttle radar topography mission
SWIR	short wavelength infrared
TIN	triangulated irregular network
TIR	thermal infrared
TM	Thematic Mapper
TOA	top of atmosphere
TUM	Technische Universität München (Technical University of Munich)
UHF	ultra high frequency
USD	United States dollar
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VHF	very high frequency
VNIR	visible and near infrared
VV	vertical-vertical (polarization)
VH	vertical-horizontal (polarization)
VHR	very high resolution
WGI	World Glacier Inventory
WGMS	World Glacier Monitoring Service
WGS	World Geodetic System
WiFS (IRS)	Wide Field Sensor (Indian Remote Sensing)
WMO	World Meteorology Organisation

Chapter 1

Principles of remote sensing

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1.1 BACKGROUND

Remote sensing is, in general, the collecting of information from an object without making direct physical contact with it. The term is usually used in a more restricted sense in which the observation is made from above the object of interest, from a sensor carried on an airborne or spaceborne platform, and the information is carried by electromagnetic radiation, i.e. visible light, infrared or ultraviolet radiation, or radio waves (Rees 2001, 2006). This radiation can occur naturally, in which case the type of remote sensing is said to be passive, or it can be transmitted from the sensor to the object under investigation, in which case the remote sensing is said to be active. Passive remote sensing developed originally from aerial photography, and can be thought of as an extension of the idea of aerial photography to include other parts of the electromagnetic spectrum, other technologies for detecting the radiation and storing the data, and other platforms to carry the sensor. Active remote sensing grew from the military development of radar during the Second World War.

One of the most significant factors in the increasing applicability of remote sensing to many investigations in the environmental sciences, amongst other disciplines, has been the use of spaceborne platforms. Although remote sensing instruments were carried into orbit around the Earth in the 1960s, the age of satellite remote sensing effectively began in 1972 with the launch of Landsat 1 satellite. Spaceborne remote sensing provides a number of advantages compared with airborne observations. Information can be obtained from huge areas in a short time, and from locations that could be difficult or dangerous to overfly. As important as these, however, is the scope for continuity of data collection. While an individual satellite mission does not normally have a planned lifetime exceeding three to five years, even this is enormously longer than the period of continuous data collection achievable from an airborne platform. However, missions are often designed to provide continuity of consistent data coverage with previous missions, in some cases for several decades. These are all advantages that make spaceborne remote sensing particularly valuable for the study of glaciers, and the glaciological research community was and remains quick to identify and exploit the possibilities offered by satellite data.

1.2 ELECTROMAGNETIC RADIATION

The electromagnetic spectrum differentiates EMR (electromagnetic radiation) according to its wavelength, or equivalently its frequency. Different regions of the spectrum are given conventional names, more or less precisely defined, and while the entire spectrum includes many types of named EMR, only a few of these are important in remote sensing (Figure 1.1). We shall essentially be concerned only with that part of the spectrum having wavelengths between a few tenths of a micrometre (1 μm, a millionth of a metre, often informally called a *micron*) and a few centimetres, i.e. embracing the visible (possibly also the ultraviolet), infrared and microwave regions. Microwaves are a particular kind of radio wave, having wavelengths between 1 mm and 1 m. There are two main reasons for this restriction: firstly, it is in this part of the spectrum that virtually all naturally occurring radiation is found, and secondly, the Earth's atmosphere is more or less opaque to other forms of EMR, severely limiting the possibility of acquiring useful data about the Earth's surface, especially from a spaceborne platform. Within the optical part of EMR, several atmospheric gases, such as N_2O, O_2, O_3, CO_2 and H_2O, absorb or scatter the solar radiation, so that very little radiation reaches the earth's surface. In some parts of the spectrum radiation travels freely to the surface, where it is absorbed, reflected or transmitted. These wavelength regions are called atmospheric windows (Figure 1.1), and remote sensing sensors are designed to operate within these windows.

There are two important natural sources of EMR. The first of these is the Sun. Solar radiation (sunlight) is composed principally of ultraviolet, visible and infrared radiation, although much of the ultraviolet and infrared components are filtered out by the Earth's atmosphere. Passive remote sensing instruments that operate in this range of wavelengths are usually measuring reflected solar radiation. The other major

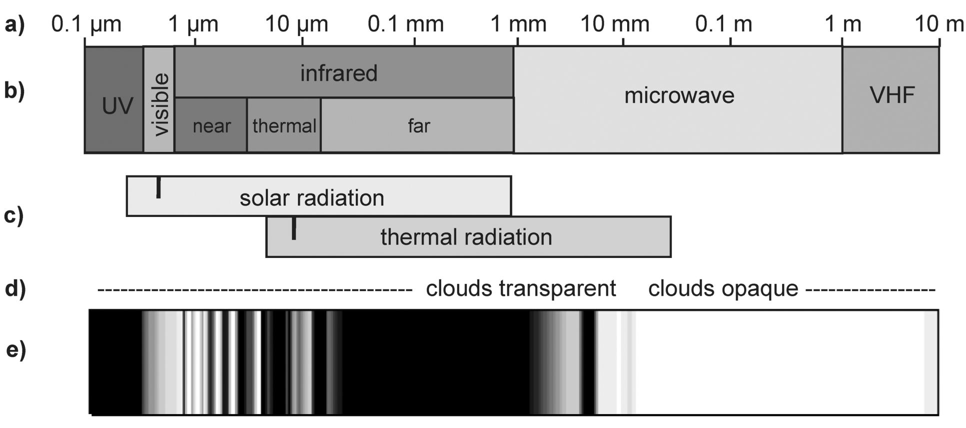

Figure 1.1 Region of the electromagnetic spectrum important in remote sensing. a) wavelength; b) spectral regions; c) approximate ranges of radiation emitted by the Sun and by objects at typical terrestrial temperatures (peak emissions are shown by heavier lines); d) transparency of clouds to EMR; e) typical transparency of the clear atmosphere to EMR. Lighter shades denote increasing transparency (atmospheric windows).

natural source of EMR is variously termed thermal radiation, black-body radiation or Planck radiation. This is radiation emitted by all bodies having a temperature above absolute zero (i.e. by all bodies), and the distribution of the radiation with wavelength depends on the temperature of the body. For example, for an object at 0°C (273 K) the dominant wavelength is around 11 μm and most normal terrestrial temperatures generate radiation in this region of the spectrum. For this reason, the part of the infrared spectrum between about 3 μm and 15 μm is often referred to as the *thermal infrared* region (also as mid-wavelength or long wavelength infrared, see Chapter 5). In fact, the distribution of the radiation is such that, while almost none is emitted at wavelengths significantly shorter than the dominant wavelength, there is a long 'tail' of emission at longer wavelengths. The Earth's atmosphere is highly opaque to wavelengths between about 20 μm and a few millimetres, but measurable amounts of thermal radiation can be detected at longer wavelengths, in the microwave region. This forms the basis of *passive microwave* remote sensing.

1.3 WHAT PROPERTIES OF EMR CAN BE MEASURED?

As we noted above, the fundamental idea of remote sensing is that information about the object being investigated is carried by EMR. This involves measuring some physical property of the EMR. In the case of passive systems that detect reflected solar radiation, the basic property is the *radiance* of the radiation reaching the sensor. Radiance is a measure of the intensity of the radiation in a particular direction, often specified as a function of wavelength, and in a typical remote sensing instrument the radiance is measured for a number of different wavebands across the visible and near-infrared spectrum. The radiance is often used to calculate a derived quantity, the *reflectance* of the surface from which the radiation was reflected. This depends on knowing how much radiation was incident on the Earth's surface in the same waveband and the geometry of the observation. However, a complication is introduced by the presence of the Earth's atmosphere, which both attenuates the radiance of EMR passing through it and also adds to the radiance, as a result of absorption and scattering processes. The reflectance should be calculated from the at-surface radiances, but the remote sensing instrument measures radiances above the atmosphere (or above some of the atmosphere in the case of an airborne observation). It is thus necessary to convert the at-satellite radiance to an at-surface radiance through atmospheric correction algorithms like MODTRAN (Berk et al. 1999) or 6S (Vermote et al. 1997).

The concept of radiance also applies to thermal radiation. However, another useful way of specifying the radiance in this case is as a *brightness temperature*. This is the temperature of a theoretical perfect emitter (a *black body*) that would produce the same radiance. As with measurements of reflected solar radiation, it is necessary to distinguish between at-surface and at-satellite brightness temperatures. A related concept is the *emissivity*. This is the ratio of the actual (at-surface) radiance to the radiance of a perfect emitter at the same physical temperature. Since no real object can emit more radiation than a perfect emitter at the same temperature, the emissivity has a maximum value of 1. Knowing the at-surface brightness temperature of a body whose emissivity is also known allows its physical temperature to be determined.

Table 1.1 The radar wavelengths and frequencies used in active microwave remote sensing.

Band	*Wavelength (cm)*	*Frequency (GHz)*	*Sensor*
K	0.75–2.4	40.0–12.5	
X	2.4–3.75	12.5–8.0	SIR-C/X-SAR
C	3.75–7.5	8.0–4.0	Radarsat, ERS-1/2, Envisat ASAR
S	7.5–15.0	4.0–2.0	
L	15.0–30.0	2.0–1.0	JERS-1, SEASAT
P	30.0–100.0	1.0–0.3	

Active remote sensing systems can provide more flexibility in the choice of measurable quantities, since the characteristics of the illuminating radiation can be controlled. There are two principal types of active instrument: *ranging* instruments, which measure the distance from the instrument to some reflecting interface which may be the surface of the Earth (for example, a glacier surface) but may instead be some sub-surface interface such as that between a glacier and the underlying bedrock, and instruments that measure the surface reflectance. The distinction is not a rigid one, and instruments may combine both aspects. There are ranging instruments using both the visible (in fact more usually the near-infrared) and the radio parts of the spectrum, but in all cases the primary variable to be measured is simply the two-way travel time for a short pulse of EMR transmitted from, and subsequently received back at, the instrument. Active instruments that measure the surface reflectance operate almost entirely in the microwave part of the spectrum, and are hence all broadly speaking *radars* (RAdio Detection And Ranging) of one kind or another. Although the concept is very similar to that of surface reflectance, the variable that is usually measured by these instruments is the *backscattering coefficient* ($\sigma°$) measured as decibels (dB). The backscattering coefficient often depends on the geometry of the observation, as well as on the wavelength of the radiation. The *polarization* of the transmitted and received radiation can also be significant in determining the backscattering coefficient. Here the polarization refers to radiation transmitted by the sensor and received by it. The signal can be transmitted and received in horizontal (H) or vertical (V) polarization. In the other words, there are four possible polarization combinations: HH, VV, HV, VH (Table 9.1). The *phase* of the returned signal can also be important, in the case of radar interferometry. The wavelengths of the EMR used in radar are much longer than in the visible and infrared parts of the spectrum, typically centimetres (Figure 1.1), and they are sometimes named using various letters of the alphabet (K, X, C, S, L, P). Alternatively, the region of the electromagnetic spectrum occupied by radar radiation can be specified by its frequency, and this can be particularly useful since frequency remains constant while wavelength changes when radiation passes through material of different refractive indices (Jensen 2000). The wavelengths and frequencies of the radar bands are described in Table 1.1. Similarly to optical measurements the radar wavelength is an important variable in the detection of various phenomena on the ground.

1.4 RESOLUTION

After the wavelength and type of measurement, one of the most important systems concepts that can be used to assess the suitability of a particular instrument for its intended application is its resolution, or resolving power. In very general terms, this relates to the ability of the instrument to distinguish between two similar things. It is convenient to identify four aspects to resolution: spatial, spectral, radiometric and temporal, which are described in Table 1.2 for some representative spaceborne optical remote sensing data applied to remote sensing of glaciers.

1.4.1 Spatial resolution

Most remote sensing instruments form two-dimensional images of the Earth's surface. In this context, spatial resolution can be thought of as the ability to distinguish between a point object and a horizontally extended object, or to recognise spatially distributed detail in an object. It is often assumed to be more or less coincident with the *pixel size*, or more precisely the size of the element on the surface that is imaged in a single pixel (picture element). This is something of an oversimplification, but it is often a useful approximation unless the imagery has been significantly oversampled (in which case the resolution will be coarser than the pixel size). In the case of analogue (film) photography, the image is not represented by pixels and it is more usual to specify the resolution by stating the scale of the photograph. However, as aerial photographs are increasingly being digitised using scanners, the pixel size or *ground resolution* is a practical characterisation of its spatial resolution. The effect of ground resolution on our ability to distinguish various features in a digital camera image over Svartisen glacier in Norway is shown in Figure 1.2. The finest resolutions in this figure (0.6 and 2.4 m) are similar to very high resolution (VHR) satellite data, the 12 and 24 m resolution to high resolution data (ASTER and Landsat TM/ETM+), and the coarsest (60 and 120 m) similar to Landsat MSS data. The ability to detect different surface features increases with finer spatial resolution.

Table 1.2 The resolutions of typical optical satellite sensors applied in glaciological research. VNIR = visible – near infrared, SWIR, short wavelength infrared, TIR = thermal infrared.

Resolution	*Landsat MSS*	*Landsat TM*	*Landsat ETM+*	*SPOT HRV*	*SPOT 4*	*ASTER*	*MODIS*	*NOAA AVHRR*	*Ikonos*
Spatial (m)	80 (VNIR) 240 TIR	30 (VNIR, SWIR) 120 TIR	30 (VNIR, SWIR) 60 TIR	20 (VNIR) 10 PAN	20 (VNIR, SWIR) 10 PAN	15 (VNIR) 30 (SWIR) 90 (TIR)	250 (1–2) 500 (3–7) 1000 (8–36)	1100	1 (PAN) 4 (VNIR)
Spectral	5 bands	7 bands	7 bands	3 bands	4 bands	14 bands	36 bands	6 bands	4 bands
Radiometric	6-bits 64 DN	8-bits 256 DN	8-bits 256 DN	8-bits 256 DN	8-bits 256 DN	8-bits 256 DN	12-bits 4096 DN	10-bits 1024 DN	11-bits 2048 DN
Temporal	18 days	16 days	16 days	26 days	26 days	16 days	1–2 days	<1 day	<3 days
Swath width (km)	185	185	185	60	60	60	2330	2700	11

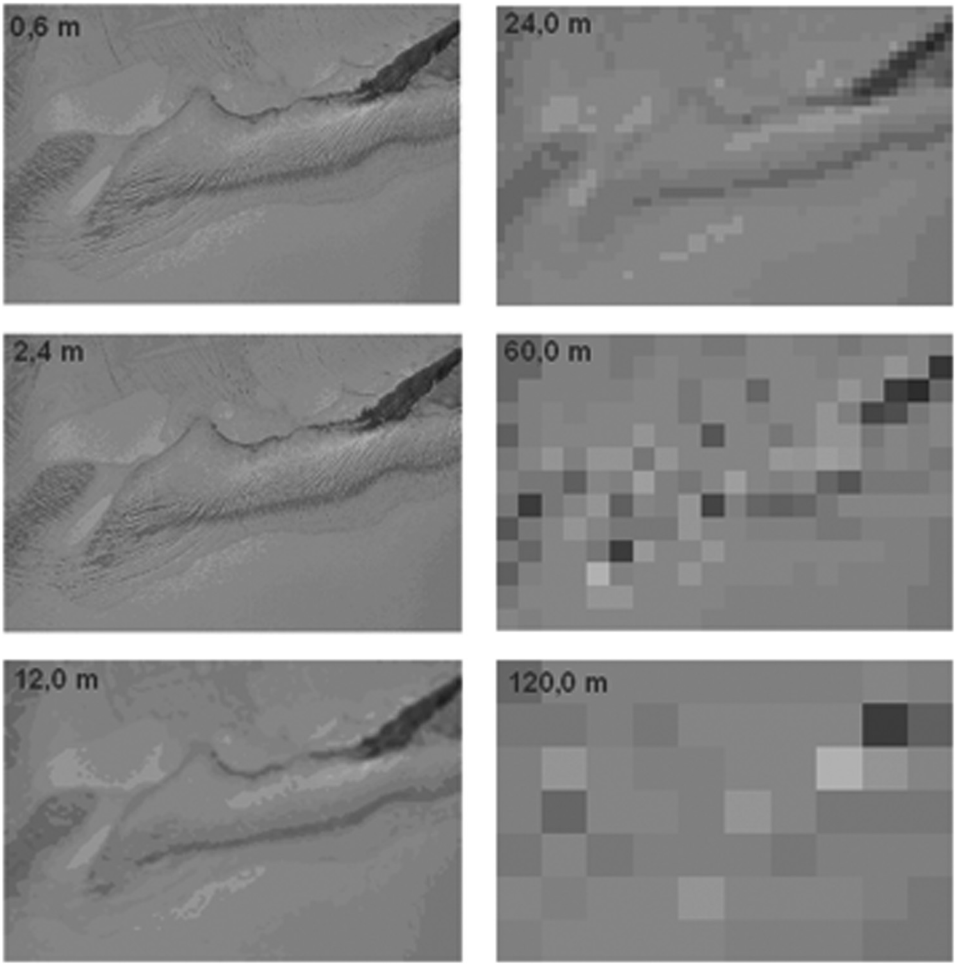

Figure 1.2 The effect of spatial resolution on the detection of features on a glacier surface, Svartisen, September 24, 2001. In the original NIKON D1H digital camera imagery of 0.6 m resolution several features can be detected (rock, ice, snow, crevasses, various firn lines), but at 60 and 120 m resolution only glacier and rock can be distinguished.

The spatial resolution of imaging systems other than synthetic aperture radars can be described as the product of the *angular resolution* with the range (i.e. the height above the surface for a downward-looking instrument). The angular resolution is more or less determined by the wavelength of the radiation and by the diameter of the objective lens (or, in the case of microwave systems, the antenna), short wavelengths and large lenses being needed for the finest angular resolutions. Thus the same instrument, deployed at different heights above the Earth's surface, will yield a spatial resolution proportional to the height. This has profound significance for the choice of an airborne as opposed to a spaceborne system. Aircraft used to acquire remote sensing data generally fly one or a few kilometres above the surface, while satellites used for the same purpose usually orbit at least 700 km above the surface. Airborne systems thus generally offer maximum spatial resolutions that are finer, by a factor of a hundred, than those achievable from spaceborne systems. For example, spaceborne imaging systems that operate in the visible/near infrared part of the spectrum typically give resolutions of 10s or 100s of metres (finer resolutions are possible), while airborne systems can give resolutions of 10s of centimetres. This difference, however, has diminished recently with the advent of very high resolution satellite imagery, such as from Ikonos, QuickBird or EROS, which provides spatial resolutions of the order of one metre or finer (Table 1.2). Not all imaging systems are designed to maximise the spatial resolution, since that may cause limitations elsewhere. This point is discussed under *temporal resolution* in Section 1.4.4. In the case of ranging instruments such as laser scanner (also known as LiDAR, Light Detection And Ranging) and ground-penetrating radar (GPR), the concept of spatial resolution also includes the *range resolution*. This is mainly determined by the duration of the transmitted pulse and hence largely independent of the height.

1.4.2 Spectral resolution

Spectral resolution refers to the ability to distinguish between radiation of different wavelengths. Typically spectral resolution is defined through the number and width of the instrument's wavebands, i.e. spectral ranges of sensitivity (Table 1.2). Narrower bands correspond to higher spectral resolutions. Imaging systems that operate in the visible/near infrared part of the spectrum are usually designed to capture the variation in radiance, and hence reflectance, with wavelength, since this can be characteristic of the surface type or condition. Colour photography achieves this aim to some extent, responding to the intensity of light reaching the film in the red, green and blue regions of the spectrum. These three spectral ranges are defined by filters, within the film in the case of analogue photography or in the camera in the case of digital camera imagery. The spectral resolution is comparatively coarse, each range being roughly 100 nm wide. Most visible/near infrared imagers provide a number of wavebands, typically 50 to 100 nm wide and defined by filters, to achieve what is usually termed *multispectral imaging*. Some instruments give significantly finer spectral resolution, usually to resolve particular features such as absorption lines, and *hyperspectral imagers*, such as AISA (www.specim.fi), provide hundreds or even thousands of narrow contiguous wavebands. Hyperspectral instruments have not yet found significant application to the study of glaciers, but some some research has been done on snow surfaces (e.g. Painter et al. 2003).

1.4.3 Radiometric resolution

Radiometric resolution is the ability to distinguish between two similar but not identical radiances. It can be thought of as having two components: the range of values of radiance to which the instrument can respond without the response being saturated, and the number of levels into which this range is divided. In the case of digital data, the latter is controlled by the number of bits (binary digits) used to represent the value of the radiance. Commonly, digital imaging systems use 8-bit data since this is simply compatible with many computer-based processing systems. This means that the value of the radiance (or whatever other parameter describing the radiometric response, such as the brightness temperature or the backscattering coefficient) is represented by an integer between 0 and 255, and that the range between the minimum and maximum values that can be represented is divided into 255 steps (digital numbers, DN). However, sometimes the number is less than 255, since some numbers may be reserved to indicate particular conditions such as that the data are not reliable for some reason. For example, data from band 1 of the ETM+ sensor carried on Landsat 7 are recorded as 8-bit numbers, which can be used as an approximation of radiometric resolution (Table 1.2). The lowest representable value of the radiance in this band is $-6.2\ \mathrm{W\ m^{-2}\ sr^{-1}\mu m^{-1}}$ and the highest value is either 293.7 or 191.6 in the same units, depending on whether the band is set to its low or high gain setting respectively. The radiometric resolution of this band is thus either 1.18 or $0.78\ \mathrm{W\ m^{-2}\ sr^{-1}\mu m^{-1}}$, corresponding to a resolution of around 0.2 or 0.1% in the reflectance. Similar considerations apply to thermal infrared channels. Again taking the ETM+ instrument as an example, the band 6 (thermal infrared) data are represented as 8-bit numbers with the minimum possible value corresponding to a radiance of 0 and the maximum value to $17.04\ \mathrm{W\ m^{-2}\ sr^{-1}\mu m^{-1}}$ (in low-gain mode). This gives a radiometric resolution of $0.067\ \mathrm{W\ m^{-2}\ sr^{-1}\mu m^{-1}}$, and a corresponding resolution in the at-satellite brightness temperature of about 0.6 K (°C) for brightness temperatures around 273 K (0°C).

1.4.4 Temporal resolution

The concept of temporal resolution is normally applied to situations in which data are acquired repeatedly from the same location, in which case it is essentially the frequency of data collection. It is possible to identify some general principles governing temporal resolution in the case of spaceborne sensors.

Many remote sensing satellites are placed in *exactly-repeating orbits*, in which the sub-satellite track forms a closed curve on the Earth's surface, revisiting precisely the same location after n_1 days and n_2 orbits, n_1 and n_2 being integers. For satellites in low-Earth orbits, the ratio n_2/n_1 is close to 14.3. For example, Landsat 7 is in an exactly-repeating orbit with $n_1 = 16$ and $n_2 = 233$. There is thus one sense in which the temporal resolution of the ETM+ sensor carried by Landsat 7 is 16 days: a given point on the Earth's surface can potentially be imaged with the same geometry once every 16 days. Whether the potential is realised or not depends on the decision by the operating agency whether to collect data during a particular orbit of the satellite, and whether the location is free of cloud.

However, in another sense the temporal resolution of the ETM+ sensor is shorter than 16 days. The spacing between spatially adjacent sub-satellite tracks of the Landsat 7 satellite is $360°/233 = 1.55°$ in longitude, or about 120 km at a latitude of 45° North or South. Since the swath width of the ETM+ instrument is 185 km, a given point on the Earth's surface can potentially be imaged more than once in every 16 days, albeit not with the same geometry (Rees 1992). In fact, we would expect an average interval of roughly $16 \times 120/185 \approx 10$ days between these opportunities. Because of the convergence of lines of longitude, the temporal resolution increases towards the poles. The most important factor controlling the temporal resolution is the swath width of the sensor: wider swaths give more frequent viewing opportunities (Rees et al. 2002). Swath width and spatial resolution cannot be chosen completely independently of one another, and the maximum swath width usually corresponds to not more than about 10000 pixels. This implies that spatial and temporal resolution can also not be chosen independently, and is an important reason why coarser resolution sensors continue to be operated in parallel with finer-resolution sensors. For example, as we have noted, the ETM+ on Landsat 7 has approximately one viewing opportunity every 10 days at a latitude of 45°. On the other hand the MODIS instrument, with a swath width of around 2300 km (and a correspondingly coarser spatial resolution of 250–1000 m), gives more than one viewing opportunity per day (Table 1.2).

1.5 HOW ARE ELECTROMAGNETIC MEASUREMENTS CONVERTED INTO INFORMATION ABOUT GLACIERS?

We noted in Section 1.3 that what is measured in remote sensing is some property or combination of properties of electromagnetic radiation, detected at the sensor. From this, some property of the glacier has to be deduced. This is the purpose of a retrieval algorithm (Campbell 2007), and these are described in later chapters. In some cases there is an obvious link between the sensed property of the radiation and the geophysical parameter of interest. Examples of this situation include converting the range in a sounding or ranging measurement to the position of the reflecting point or surface, or calculating the physical surface of the temperature from the brightness temperature of the detected radiation. Less obvious retrievals have no direct link of this kind. For example, one might wish to delineate the boundary of a snow-covered area from an aerial photograph or a digital image acquired in the visible/near infrared. This delineation might be based on the fact that the reflectance of snow is higher than that of any other materials represented in the image, so that the image can be classified into snow/non-snow areas on this basis. Such classification could be performed manually or automatically, and might require training, in which case areas known (e.g. by field work) to represent snow and non-snow types are used to calibrate the process. More sophisticated forms of classification make use of multi-dimensional datasets, for example multispectral data from a sensor such as the ETM+, SAR backscattering data from different dates, and so on. Many commercial and public-domain computer packages, such as ENVI, Erdas Imagine, ER Mapper, Idrisi, Grass, etc. are available for performing image processing steps and classification.

1.6 PASSIVE REMOTE SENSING SYSTEMS

In Sections 1.6 and 1.7 we classify the principal types of remote sensing system considered in this book, and briefly outline their characteristics. The topics treated in the remainder of this chapter are covered in greater detail by, for example, Rees (2001, 2006).