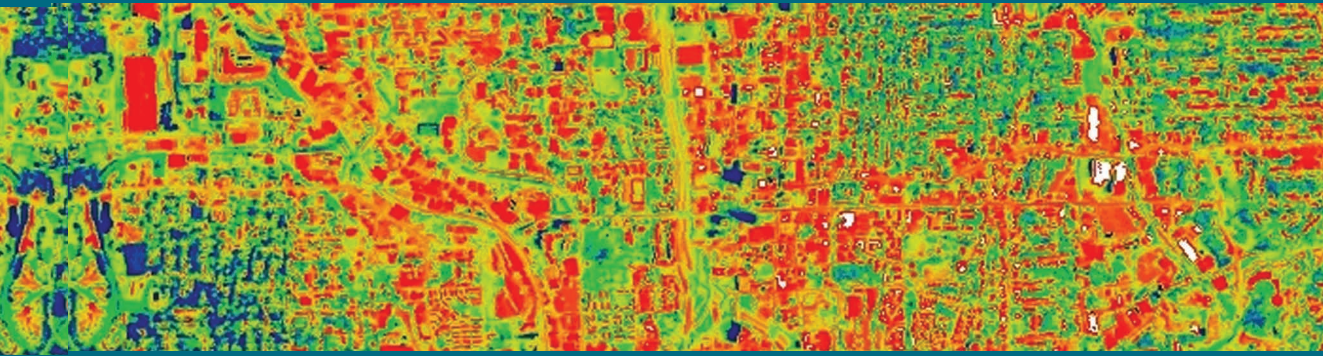
The SAGE Handbook of Remote Sensing



Edited by

Timothy A. Warner

M. Duane Nellis

and Giles M. Foody

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Dedication

This book is dedicated to the many pioneers in remote sensing, including:

Mike Barnsley

Jack Estes

Don Levandowski

Contents

Preface

Although the term remote sensing is about 50 years old, having been coined in 1958 by Evelyn Pruitt, a geographer at the US Office of Naval Research (Estes and Jensen, 1998), the subject matter covered by the field of remote sensing is vast. As a methodological approach, remote sensing has underpinnings in physics, mathematics, engineering, and computer science. Remote sensing plays an important role in the scientific, commercial, and national security arenas, and the applications of remote sensing extend from the Earth's atmosphere to the hydrosphere, cryosphere, biosphere, and lithosphere, as well as to the moon, planets, and asteroids.

The challenge in compiling a relatively comprehensive survey of such a vast field is evident in the fact that, to our knowledge, this book is the first comprehensive text in a quarter of a century. Our work follows in the tradition of the major series, *The Manual of Remote Sensing*, first published in two volumes by the American Society of Photogrammetry and Remote Sensing (ASPRS) in 1975, with a second edition in 1983. Notably, for the third edition, the idea of a single publication was abandoned and an apparently open-ended series was decided upon. As a result, six volumes in this series have already been published in the decade since 1997, with additional volumes planned.

For our book, we desired a single volume that provided as broad a view of the field as possible. Our aim was to give the reader a forward-looking perspective that also explained the developments that led to the current context. The chapters assume a basic background in remote sensing, but not necessarily in the specific topics covered. This book should therefore be particularly useful to professionals and advanced students who desire a systematic overview of the state of the art, as well as potential future challenges.

In addressing such a huge field we have by necessity had to be selective in our approach. Therefore, from the outset we limited our scope to the terrestrial Earth. By keeping this focus, we have been able to cover not only the traditional remote sensing applications, such as in soils, geology, and vegetation, but also the relatively new applications such as in the social sciences, biogeochemical modeling, and disaster monitoring.

The initial concept for this volume was developed in a 10-page outline, which was reviewed by 13 anonymous external reviewers. With advice and feedback from those reviewers, we recruited 33 authors to lead the individual chapters. Those lead authors recruited an additional 42 co-authors, resulting in a total of 75 authors. The chapters were reviewed by the editors as well as over 90 reviewers.

The book is organized in six major sections. Section I, an introduction, covers broad overarching issues, including remote sensing policy. Section II is a systematic treatment of the interaction of electromagnetic radiation with the terrestrial environment. This section provides a key background for the later section on remote sensing applications. The chapters are organized from short to long wavelength, specifically from the visible to microwave regions. Section III, on digital sensors and platforms, provides an overview of how the engineering of image acquisition influences image properties. The section includes chapters on sensor technology, as well as a series on satellite sensors, organized by relative spatial resolution. Separate chapters cover hyperspectral sensors, microwave sensors, airborne imaging, and airborne laser scanning (also known as lidar). Section IV covers remote sensing analysis, from design to implementation. This section covers both field work and image analysis issues, ending with a discussion on accuracy assessment. Section V, on remote sensing applications, comprises approximately one third of the book, and is organized in four subsections: (a) lithospheric sciences, (b) plant sciences, (c) hydrospheric and crysopheric sciences, and (d) global change and human environments. Section VI provides a short forward-looking summary of the book.

ACKNOWLEDGEMENTS

This book was only possible through the enthusiasm, cooperation, and support from a wide range of people. The role of the authors of course was central. In addition, the contribution of the external reviewers was particularly important in ensuring the highest quality for the chapters, and their role is gratefully acknowledged. We would also like to thank SAGE for unfailing encouragement and patience throughout this long process, especially Commissioning Editor Robert Rojek and Editorial Assistant Sarah-Jayne Boyd.

The external reviewers include:

Michael Abrams, NASA/Jet Propulsion Laboratory, USA

John Althausen, Lockheed Martin Corporation, USA

Hans-Erik Andersen, USDA Forest Service, USA

Paul Aplin, University of Nottingham, UK

Richard L. Armstrong, University of Colorado at Boulder, USA

Manoj Arora, IIT Roorkee, India

Gregory P. Asner, Carnegie Institution, USA

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Paul Curran, Bournemouth University, UK

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Yongxin Deng, Western Illinois University, USA

Mark R. Drinkwater, European Space Agency, ESTEC, The Netherlands

Gregory Elmes, West Virginia University, USA

Robert Erskine, US Department of Agriculture, Agricultural Research Service, USA

Ian S. Evans, Durham University, UK

Steven Fassnacht, Colorado State University, USA

Pete Fisher, University of Leicester, UK

Igor Florinsky, Russian Academy of Sciences, Russia

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Mark Friedl, Boston University, USA

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Kathleen Galvin, Colorado State University, USA

Jerry Griffith, University of Southern Mississippi, USA

Randy M. Hamilton, RedCastle Resources, Inc., USA

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Greg McDermid, University of Calgary, Canada

Kyle McDonald, Jet Propulsion Laboratory, California Institute of Technology, USA

Assefa M. Melesse, Florida International University, USA

Gay Mitchelson-Jacob, Bangor University, UK

Mahta Moghaddam, The University of Michigan, USA

Keith Morris, Louisiana State University, USA

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Janet Nichol, The Hong Kong Polytechnic University, Hong Kong

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Robert Gilmore Pontius Jr., Clark University, USA

Sorin Popescu, Texas A&M University, USA

Dale A. Quattrochi, NASA Marshall Space Flight Center, USA

R. Douglas Ramsey, Utah State University, USA

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Ronald G. Resmini, George Mason University, USA

John Rogan, Clark University, USA

Kenton Ross, Science Systems and Applications, Inc., USA

Vincent V. Salomonson, University of Utah, USA

Michael E. Schaepman, Wageningen University, The Netherlands

James Schepers, US Department of Agriculture, Agricultural Research Service, USA

Edwin Sheffner, NASA – Ames Research Center, USA

Steve Stehman, SUNY College of Environmental Science and Forestry, USA

Douglas Stow, San Diego State University, USA

Gregg Swayze, US Geological Survey, USA

Richard M. Teeuw, University of Portsmouth, UK

Gerd Ulbrich, European Space Agency ESA/ESTEC, The Netherlands

Freek van der Meer, International Institute for Geo-Information Science and Earth Observation (ITC), and Utrecht University, The Netherlands

Jakob van Zyl, Jet Propulsion Laboratory, California Institute of Technology, USA

Wouter Verhoef, National Aerospace Laboratory NLR, The Netherlands

Eric Vermote, University of Maryland, and NASA Goddard Space Flight Center, USA

Chenghai Yang, US Department of Agriculture, Agricultural Research Service, USA

Stephen Yool, The University of Arizona, USA

Kenneth Young, University of Texas at Austin, USA

Howard A. Zebker, Stanford University, USA

Plus, an additional five reviewers who wished to remain anonymous.

REFERENCES

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The Editors

Timothy A. Warner, West Virginia University

M. Duane Nellis, Kansas State University

Giles M. Foody, University of Nottingham

Notes on Contributors

EDITORS

Timothy A. Warner is Professor of both Geology and Geography at West Virginia University, in Morgantown, West Virginia, USA. He matriculated at the South African College Schools (SACS), has a B.Sc. (Hons.) in Geology from the University of Cape Town, and a Ph.D. from Purdue University in geological remote sensing. His research specialties include the spatial properties of images, high resolution remote sensing, and lidar. He has served as a founding board member and Secretary of AmericaView, and as Chair of the Remote Sensing Specialty Group (RSSG) of the Association of American Geographers (AAG). He received the 2006 *RSSG Outstanding Contributions Award*, and the 2006 *Boeing Award for Best Paper in Image Analysis and Interpretation* from the American Society of Photogrammetry and Remote Sensing. In 2007, he was a Fulbright Fellow at the University of Louis Pasteur, in Strasbourg, France. He serves on the editorial board of *Geographical Compass.*

M. Duane Nellis is Provost and Senior Vice President, as well as Professor of Geography, at Kansas State University. He has published over 100 articles and more than a dozen books and book chapters on various aspects of remote sensing and GIS applications to natural resources assessment, and other dimensions of rural geography. He is past president of both the Association of American Geographers (AAG), and the National Council for Geographic Education (NCGE). Nellis has also served as co-editor of the GIS/remote sensing journal *Geocarto International.* He has received numerous honors and awards including National Honors from the AAG, election as a fellow of the American Association for the Advancement of Science (AAAS), the Royal Geographical Society, and the Explorers Club. In addition, he is past Chair of the AAG Remote Sensing Specialty Group and received that groups, Outstanding Contributions Award. At Kansas State he received the University Outstanding Teaching Award, the Phi Kappa Phi Research Scholars Award, and the University Outstanding Advisor Award. Nellis completed his undergraduate degree at Montana State University and his masters and Ph.D. at Oregon State University. He started his academic career at Kansas State University, where he moved from Assistant to Full Professor, and where he served as the head of Geography Department and Associate Dean of Arts and Sciences. In 1997, he was named Dean of the Eberly College of Arts and Sciences at West Virginia University. He then returned to Kansas State University in 2004 as Provost.

Giles M. Foody completed B.Sc. and Ph.D. at the University of Sheffield in 1983 and 1986 respectively and is currently Professor of Geographical Information Science at the University of Nottingham. His main research interests lie at the interface between remote sensing, biogeography, and informatics. Topics of particular interest relate to image classification for land cover mapping and monitoring applications, addressing issues at scales ranging from the sub-pixel to global. His publication list includes seven books and more than 135 refereed journal articles as well as many conference papers. He currently serves as editor-in-chief of the *International Journal of Remote Sensing* and holds editorial roles with *Ecological Informatics* and *Landscape Ecology* as well as serving on the editorial boards of journals including *Remote Sensing of Environment*, *Geocarto International*, and *International Journal of Applied Earth Observation and Geoinformation*.

CHAPTER 1

Timothy A. Warner, M. Duane Nellis, and **Giles M. Foody** (see editors' biographical descriptions).

CHAPTER 2

Ray Harris is Emeritus Professor of Geography and a former Executive Dean of the Faculty of Social and Historical Sciences at University College London. In addition to UCL, his career has included periods at Logica UK plc, Software Sciences and the University of Durham. His research and teaching interests are in satellite Earth observation, science policy and in the Middle East. He has worked extensively with the European Space Agency, the European Commission, NASA, NOAA, JAXA and other space organizations on the applications of Earth observation data and on the development of data policy. He was a member of two International Council for Science (ICSU) panels on scientific data and information policy, and has worked on both GMES and GEOSS. For nearly 30 years he has worked on remote sensing applications in the UK, Kuwait, Oman, Jordan, Tunisia and Iran, focusing on agriculture, land degradation and land cover change. He is the author of four books on remote sensing and many journal articles, book chapters and reports.

CHAPTER 3

Willem J. D. van Leeuwen received the B.Sc. and M.Sc. degrees in soil science from the Wageningen University for Life Sciences, the Netherlands in 1985 and 1987 respectively, and the Ph.D. degree in soil and remote sensing science from the Department of Soil, Water, and Environmental Science, University of Arizona, Tucson, in 1995. He has been a research scientist and a member of the MODIS land science team, worked on global spectral vegetation index and albedo product and algorithm development, and is currently working on post wildfire vegetation recovery, land degradation, and vegetation community phenology research, employing remote sensing and geospatial tools. He also works on web-based decision support tools for natural resource managers. Since 2005, Dr. van Leeuwen is an Assistant Professor and has a joint appointment with the Department of Geography and Regional Development and the Office of Arid Lands Studies at the University of Arizona, Tucson, where he teaches classes in geographical field methods, biogeography, and remote sensing. He is a member of American Geophysical Union (AGU), American Society of Photogrammetry and Remote Sensing (ASPRS), Association of American Geographers (AAG), IEEE Geoscience and Remote Sensing Society (IGARSS), and the International Association for Landscape Ecology (IALE).

CHAPTER 4

Arthur P. Cracknell graduated in physics from Cambridge University, in 1961 and then did his D.Phil. at Oxford University on theoretical solid state physics. He has worked at Singapore University (now the National University of Singapore), Essex University, and Dundee University, where he became a professor in 1978. He retired from Dundee University in 2002 and now holds the title of emeritus professor there. He is currently working on various short-term contracts in several universities and research institutes in China and Malaysia.

After several years of research work in solid state physics, he turned his interests in the late 1970s to remote sensing and he has been the editor of the *International Journal of Remote Sensing* for over 20 years. His particular research interests in remote sensing include the extraction of the values of various geophysical parameters from satellite data and the correction of remotely-sensed images for atmospheric effects. He and his colleagues and research students have published around 300 research papers and he is the author or co-author of several books, both on theoretical solid state physics and on remote sensing. He also pioneered the teaching of remote sensing at postgraduate level at Dundee University.

Doreen S. Boyd received the B.Sc. degree in geography from the University of Wales, UK, in 1992 and the Ph.D. degree from the University of Southampton, UK, in 1996. She is currently an Associate Professor with the School of Geography, University of Nottingham, UK, having held Lectureships at Manchester, Kingston, and Bournemouth Universities. Between 2004 and 2006, she held the position of senior research leader in Research and Innovation at Ordnance Survey, Great Britain. Her main research interests are in the remote sensing of terrestrial ecosystems and the monitoring of environmental change. She serves on the editorial board of *Visual Geosciences* and the advisory board of the *Journal of Maps*. She is the co-founder and co-chair of the laser scanning and LiDAR special interest group of the Remote Sensing and Photogrammetry Society.

CHAPTER 5

Dale A. Quattrochi is currently employed by NASA as a Geographer and Senior Research Scientist at the George C. Marshall Space Flight Center in Huntsville, Alabama. He holds a B.S. (1973, Geography) from Ohio University, an M.S. (1978, Geography/Remote Sensing) from the University of Tennessee, and a Ph.D. (1990, Geography/Remote Sensing) from the University of Utah. Dr. Quattrochi's research interests focus on the application of thermal remote sensing data for analysis of heating and cooling patterns across the landscape as they impact local and regional environments. Much of his work has been on applying thermal infrared data to analysis of the urban heat island effect. He is also working on the application of remote sensing data to public health effects, such as asthma and respiratory distress. Additionally, he is also conducting research on the use of geospatial statistical techniques, such as fractal analysis, to multiscaled remote sensing data. Dr. Quattrochi is the recipient of numerous awards, including the NASA Exceptional Scientific Achievement Medal, NASA's highest science award, which he received for his research on urban heat islands and remote sensing. He is also a recipient of the Ohio University College of Arts and Sciences distinguished Alumni Award.

Jeffrey C. Luvall is a NASA Senior Research Scientist at Marshall Space Flight Center. He holds a B.S. (1974, Forestry) an M.S. (1976, Forest Ecology) from Southern Illinois University, Carbondale, IL, and a Ph.D. (1984, Tropical Forest Ecology) from the University of Georgia, Athens, GA. His current research involves the modeling of forest canopy energy budgets using airborne thermal scanners. These investigations have resulted in the development of a Thermal Response Number (TRN), which quantifies the land surface's energy response in terms of $\mathrm{kJ\,m^{-2}\,{}^{\circ}C^{-1}}$ and can be used to classify land surfaces in regional surface budget modeling by their energy use. A logical outgrowth of characterizing surface energy budgets of forests is the application of thermal remote sensing to quantify the urban heat island effect. One important breakthrough is the ability to quantify the importance of trees in keeping the city cool. His current research involves alternate mitigation strategies to reduce ozone production through the use of high albedo surfaces for roofs and pavements and increasing tree cover in urban areas to cool cities.

CHAPTER 6

Mahta Moghaddam received a B.S. degree (with highest distinction) from the University of Kansas, Lawrence, in 1986 and M.S. and Ph.D. degrees from the University of Illinois, Urbana-Champaign, in 1989 and 1991, respectively, all in electrical and computer engineering. She is an Associate Professor of Electrical Engineering and Computer Science at the University of Michigan, where she has been since 2003. From 1991 to 2003, she was with the Radar Science and Engineering Section, NASA Jet Propulsion Laboratory (JPL) in Pasadena, CA. She has introduced innovative approaches and algorithms for quantitative interpretation of multichannel SAR imagery based on analytical inverse scattering techniques applied to complex and random media. She has also introduced a quantitative approach for data fusion by combining SAR and optical remote sensing data for nonlinear estimation of vegetation and surface parameters. She has led the development of new radar instrument and measurement technologies for subsurface and subcanopy characterization. Dr. Moghaddam's research group is engaged in a variety of research topics related to applied electromagnetics, including the development of advanced radar systems for subsurface characterization, continental scale wetlands mapping with SAR, mixed-mode high resolution medical imaging techniques, and smart sensor webs for remote sensing data collection and validation.

CHAPTER 7

John P. Kerekes received his B.S., M.S., and Ph.D. degrees in electrical engineering from Purdue University, West Lafayette, Indiana, USA, in 1983, 1986, and 1989, respectively. From 1983 to 1984, he was a member of the technical staff with the Space and Communications Group, Hughes Aircraft Co., El Segundo, California, USA. From 1989 to 2004, he was a technical staff member with Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts, USA. In 2004, he became an Associate Professor in the Center for Imaging Science, Rochester Institute of Technology, Rochester, New York, USA. He is a senior member of the Institute of Electrical and Electronics Engineers (IEEE) and a member of Tau Beta Phi, Eta Kappa Nu, American Geophysical Union, American Meteorological Society, American Society for Photogrammetry and Remote Sensing, and SPIE. Since 2000 he has served as an Associate Editor of the *IEEE Transactions on Geoscience and Remote Sensing*. He was the General co-chair of the 2008 International Geoscience and Remote Sensing Symposium (IGARSS'08) held in Boston, Massachusetts, USA. His research interests include the modeling and analysis of remote sensing system performance in pattern recognition and geophysical parameter retrieval applications.

CHAPTER 8

Thierry Toutin, educated both in France and Canada, received his final diploma, the Dr.-Ing. degree, in geodetic sciences and remote sensing from the Ecole Nationale des Sciences Géographiques of the Institut Géographique National, Paris, France, in 1985. After a few years in the Canadian private industry, he has worked since 1988 as senior research scientist at the Canada Center for Remote Sensing, Natural Resources Canada. He currently develops mathematical tools and prototype systems for stereoscopy, radargrammetry, interferometry, and the chromostereoscopy, using a broad range of Earth observation data (airborne and spaceborne; VIR and SAR; fine to coarse resolution). In recent years, he has focused mainly on 3D physical models and their generalization to fine spatial resolution optical imagery (SPOT5, EROS, IKONOS, Quickbird, Formosat, etc.). His main fields of interest are 3D modeling and reconstruction, interactive feature extraction, cartographic applications of Earth observation data, and the integration of multisource data.

CHAPTER 9

Samuel N. Goward is Professor of Geography at the University of Maryland. He has been involved in land remote sensing since the early 1970s. One primary research focus area has been automated processing and analysis of regional and global data sets from AVHRR and Landsat. From 1997 to 2002 he served as the Landsat Science Team leader and was recently selected to serve as a member of the new USGS/NASA Landsat Science Team. He also continues to work with the NASA Landsat Project Science Office to develop operational concepts including the long-term acquisition plan. Currently his research is carried out under the North American Carbon Program, in association with NASA and US. Forest Service colleagues, seeking to improve forest dynamics analysis with Landsat time-series data. Earlier he also worked with the NASA Stennis Space Center, to evaluate commercial sources of land remote sensing data, including the IKONOS and QuickBird. Over the last decade he served as co-chair of the advisory committee for the USGS National Satellite Land Remote Sensing Data Archive (NSLRSDA) at USGS EROS and continues on the editorial board of *Remote Sensing of Environment*. Among several honors, he has recently been awarded the USGS *John Wesley Powell Award* (2006) and the USGS/NASA *William T. Pecora Award* (2008) for contributions to the Landsat Mission.

Terry Arvidson has been part of the Landsat program since 1979, from pre-proposal phases through on-orbit operations, from developer and tester to operations engineer and project manager. Currently, she is a manager of sustaining engineering for Landsat 7, and supports both the USGS and NASA/GSFC. Ms. Arvidson serves as the liaison between the satellite operations team and the Landsat Science Project Office. She has been an active member of the international Landsat Ground Station Operators Working Group since the 1980s. Ms. Arvidson managed the development of the Landsat-7 Long-Term Acquisition Plan (LTAP), working with the science community on specialized requirements for land covers such as glaciers and reefs, and maintaining the LTAP databases. She continues to interface with the science community on scheduling and operations issues and in support of Drs. Goward and Williams on the Landsat Science Team. Ms. Arvidson has researched the

Landsat historical archive for the Landsat Legacy project, including internationally-held archives, and participated in oral history interviews and document preservation. She has published numerous articles on the LTAP and the Landsat archive history, and co-edited, with Drs. Goward and Williams, a PE&RS special issue on Landsat 7. Ms. Arvidson has a B.Sc. degree from the University of Maryland.

Darrel L. Williams serves as Associate Chief of the Hydrospheric and Biospheric Sciences Laboratory within the Earth Sciences Division at NASA's Goddard Space Flight Center. He also serves as the Project Scientist for the Landsat 5 and 7 missions currently in orbit, and is entrusted with ensuring the scientific integrity of these missions. Prior to his more recent roles in science management, his remote sensing research involved the development of enhanced techniques for assessing forest ecosystems worldwide. He has authored ∼100 publications in the field of quantitative remote sensing and served on the editorial board of the *International Journal of Remote Sensing* throughout the 1990s. Dr. Williams has received numerous prestigious awards such as the NASA Medal for Outstanding Leadership (1997), NASA's Exceptional Service Medal (2000), and the 'Aviation Week and Space Technology 1999 Laurels Award' for outstanding achievement in the field of *Space* in recognition of his science leadership of the Landsat 7 mission. Recently Dr. Williams received an 'Outstanding Alumni Award' from the School of Forest Resources at the Pennsylvania State University. Additional awards have been bestowed by the US Department of Agriculture, the US Department of the Interior, and the American Society of Photogrammetry and Remote Sensing.

Richard Irish accepted a position, in 1993, with Science Systems Applications, Inc., to work on NASA's Landsat-7 program at the Goddard Space Flight Center. There, he developed the cloud cover recognition algorithm used for Landsat-7, created the Calibration Parameter File used for radiometric and geometric processing and updates, and defined the standard Landsat-7 distribution product, now an international exchange standard that is used world wide. Mr. Irish continues his work within NASA's Biospheric Sciences Branch on the Landsat program. His research endeavors include developing cloud shadow discrimination and multiscene merging algorithms for the TM, ETM+, and LDCM missions. He is also the Landsat-7 science liaison to the user community. He wrote and maintains the frequently visited Landsat-7 Science Data Users Handbook web site.

James R. Irons is the Associate Chief of the Laboratory for Atmospheres, NASA Goddard Space Flight Center (GSFC). He is also the NASA Landsat Data Continuity Mission (LDCM) Project Scientist. Prior to 2007, Dr. Irons worked for 28 years as a physical scientist in the Biospheric Sciences Branch, NASA GSFC where he served as the Landsat-7 Deputy Project Scientist beginning in 1992. Dr. Irons' career has been devoted to advancing the science and practice of land remote sensing. His research has focused on applying Landsat data to land cover mapping. His research has also encompassed the characterization and understanding bi-directional reflectance distribution functions (BRDFs) for land surfaces, particularly plant canopies and soil. He is the principal or co-author of 35 peer reviewed journal articles and two book chapters. Dr. Irons received his B.Sc. degree in environmental resources management in 1976 and the M.Sc. degree in agronomy in 1979 from the Pennsylvania State University. He received his Ph.D. degree in agronomy in 1993 from the University of Maryland.

CHAPTER 10

Christopher Owen Justice received his Ph.D. in geography from the University of Reading, UK. In 1978 he came to NASA's Goddard Space Flight Center as a National Academy of Sciences post-doctoral fellow. In 1981 he took a fellowship position at ESA ESRIN and in 1983 he returned to the Goddard Space Flight Center to work with AVHRR data on land studies and helped form the GIMMS Group with Compton Tucker and Brent Holben. Since 2001 he has been a professor and research director in the Geography Department of the University of Maryland. He is a team member and land discipline chair of the NASA Moderate Imaging Spectroradiometer (MODIS) Science Team and is responsible for the MODIS Fire Product and helped develop the MODIS Rapid Response System. He is a member of the NASA NPOESS Preparatory Project (NPP) Science Team. He is co-chair of the GOFC/GOLD-Fire Implementation Team, a project of the Global Terrestrial Observing System (GTOS), and a member of the Integrated Global Observation of Land (IGOL) Steering Committee and leader of the GEOSS Agricultural Monitoring Task. He is on the Strategic Objective Team for USAID's Central Africa Regional Project for the Environment. He is a Co.I.

on the USGS Landsat Science Team. He is Program Scientist for the NASA Land Cover Land Use Change Program. His current research is on land cover and land use change, the extent and impacts of global fire, global agricultural monitoring (with the US Department of Agriculture, Foreign Agricultural Service, and the GIMMS group at Goddard Space Flight Center), and their associated information technology and decision support systems.

Compton James Tucker III received his B.S. degree in biology in 1969 from Colorado State University. After working in two banks and realizing banking was not his calling, he returned to Colorado State University and received his M.S. degree in forestry in 1973 and his Ph.D. degree, also in forestry, in 1975. He came to NASA's Goddard Space Flight Center as a National Academy of Sciences post-doctoral fellow in late 1975. Since 1977 he has been a physical scientist and leader of the GIMMS group at NASA's Goddard Space Flight Center. In the mid 1970s he contributed to the sensor configuration of Landsat's thematic mapper instrument. He has been a pioneer in demonstrating the utility of coarse-resolution remote sensing using AVHRR and similar data for large-scale vegetation studies exploiting temporal information. Currently he is using satellite data to study climatically-coupled hemorrhagic fevers, global primary production including agricultural monitoring, tropical deforestation and habitat fragmentation, and glacier variations from the 1970s to the present. Since 2005 he has worked for NASA at the Climate Change Science Program Office in the areas of land use and land cover change and climate and worked to prioritize satellite and *in situ* observations for climate research.

CHAPTER 11

Douglas A. Stow is a Professor of Geography at San Diego State University (SDSU) and specializes in remote sensing. He received B.A., M.A., and Ph.D degrees in Geography from the University of California, Santa Barbara. His remote sensing studies focus on land cover change analyses with emphases on Mediterranean-type and Arctic tundra ecosystems, and urban areas. He is the co-director of the Center for Earth Systems Analysis Research and doctoral program coordinator. Stow is currently the P.I. for a NASA REASoN project on integration of remote sensing and decision support systems for international border security. He has also served as P.I. for several state and local agency contracts, and as a co-investigator on numerous NASA, NSF, and NIH grants. He is the author or co-author of over 100 refereed publications and 35 conference proceedings papers, mostly on remote sensing topics.

Lloyd L. Coulter has worked as a staff researcher in the Department of Geography at San Diego State University, since November 1998. He specializes in remote sensing and image processing. Mr. Coulter has served as technical lead on several projects using fine spatial resolution imagery for detecting changes in southern California native habitat and for mapping such things as invasive plants, urban irrigated vegetation, urban canyon fire hazards, and land use. Mr. Coulter is also the operator of an ADAR 5500 airborne digital multispectral camera system owned and operated by the Department of Geography. He has several years of experience in airborne digital image acquisition and post-processing.

Cody A. Benkelman is the lead engineer at Mission Mountain Technology Associates, which provides remote sensing, image processing, and geographic information systems services. He served as lead engineer and co-founder of Positive Systems, Inc., developing multispectral airborne imaging systems and image processing software. Mr. Benkelman also served as principal investigator and project manager on numerous NASA R&D projects, focused on development of image co-registration software (SBIR Phase I and Phase II, 2004–2006), multispectral data acquisition for the EOS Science Data Buy Program (1997–2001) and imaging system design and development (Earth Observation Commercialization and Applications Program, 1993). Mr. Benkelman was awarded peer-reviewed certification as a 'Mapping Scientist in Remote Sensing' by the American Society for Photogrammetry and Remote Sensing (ASPRS), certification number RS144, effective 10/6/03. He received his M.S. degree in electrical engineering from the University of Colorado in 1987 and a B.S. in physics from Montana State University in 1981.

CHAPTER 12

Michael E. Schaepman is full Professor in remote sensing at the University of Zurich in Switzerland and adjoint Professor in Geo-Information science with special emphasis on remote sensing at Wageningen

University (WU) in The Netherlands. His specialization is in quantitative, physical based remote sensing using imaging spectrometers and multiangular instruments. He pays particular attention on the retrieval of land surface variables in vegetated areas. After obtaining M.Sc. (1994) and Ph.D. (1998) degrees from the University of Zurich (CH) in geography and remote sensing, he spent part of his post doctorate at the University of Arizona (College of Optical Sciences, Tucson, AZ) before being appointed full chair in Wageningen in 2003 and scientific manager in 2005, and full chair in Zurich in 2008 respectively. He serves as Chairman of the ISPRS WG VII/1 on Physical Modeling and has significantly contributed to the further development of imaging spectroscopy over recent years, namely to ESA missions such as LSPIM, SPECTRA, FLEX and APEX. Michael E. Schaepman has co-authored more than 300 scientific publications ($>$60 peer reviewed papers).

CHAPTER 13

Josef Martin Kellndorfer's research focuses on the monitoring and assessment of terrestrial and aquatic ecosystems using geographic information systems (GIS) and remote sensing technology. He studies land-use, land cover change and their links to the carbon cycle with a focus on climate change at a regional and global scale. With his scientific findings he strives to support environmental policy decisions at the global scale, and is involved in supporting the UNFCCC negotiations on 'Reducing Emissions from Deforestation and Degradation' (REDD). Dr. Kellndorfer has been principal and co-investigator on numerous projects involving imaging radar technology. His current research activities include a NASA-funded project to generate the first high-resolution above-ground biomass and carbon dataset of the United States based on the integration of space shuttle radar and optical satellite imagery, as well as research on forest monitoring using the new class of space-borne imaging radar satellites like ALOS//PALSAR, EnviSat, Radarsat, and TerraSAR-X. Before joining the Woods Hole Research Center, Dr. Kellndorfer was a research scientist with the Radiation Laboratory in the Department of Electrical Engineering and Computer Science at the University of Michigan. Dr. Kellndorfer holds a diploma degree in physical geography, computer science, and remote sensing, and a doctorate in geosciences from the Ludwig-Maximilians-University in Munich, Germany. Dr. Kellndorfer is a senior member of the IEEE Geoscience and Remote Sensing Society.

Kyle C. McDonald is a Research Scientist in the Water and Carbon Cycles Group of JPL's Science Division. He received the Bachelor of Electrical Engineering degree (co-operative plan with highest honors) from the Georgia Institute of Technology, Atlanta, Georgia in 1983, the M.S. degree in numerical science from Johns Hopkins University, Baltimore, Maryland, in 1985, and the M.S. and Ph.D. degrees in electrical engineering from the University of Michigan, Ann Arbor, Michigan, in 1986 and 1991, respectively.

Dr. McDonald has been employed in the Science Division, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, since 1991, and is currently a Research Scientist in the Water and Carbon Cycles Group. He specializes in electromagnetic scattering and propagation, with emphasis on microwave remote sensing of terrestrial ecosystems. His research interests have primarily involved the application of microwave remote sensing techniques for monitoring seasonal dynamics in boreal ecosystems, as related to ecological and hydrological processes and the global carbon and water cycles. Recent activities have included development of radar instrumentation for measuring sea ice thickness from airborne platforms. Dr. McDonald has been a Principal and co-investigator on numerous NASA Earth Science investigations. He is a member of NASA's North American Carbon Program (NACP) science team, NSF's Pan-Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP) Science Steering Committee, and the ALOS PALSAR Kyoto and Carbon Initiative science panel.

CHAPTER 14

Juha Hyyppä received his Master of Science, the Licentiate in Technology, and the Doctor of Technology degrees from the Helsinki University of Technology (HUT), Faculty of E.Eng., all with honors, in 1987, 1990, and 1994, respectively. He has been Professor and Head of the Department at the Finnish Geodetic Institute since 2000. He has docentship in space technology especially in remote sensing (HUT, E.E., 1997–), in laser scanning (HUT, Surveying, 2004–), and in remote sensing of forests (Helsinki University, 2005–).

He has been Earth Observation Programme Manager at National Funding Agency Tekes, responsible for the coordination of national and international (ESA and EU) remote sensing activities of Finland, Finnish adviser to ESA Earth Observation Programme Board, and to ESA Potential Participant Meetings (1994–1995), coordinator of the Design Phase of the National Remote Sensing Programme (1995), President of EuroSDR Com II (information extraction) 2004–2010, co-chair to ISPRS WG III/3 2004–2008, Vice-President of ISPRS Com VII 2008–2012, and Principal Investigator in ESA/NASA Announcement of Opportunity studies and coordinator for more than 10 international research projects. His references are represented by over 200 scientific/technical papers (more than 100 refereed papers). His personal hobby is the development of retrieval methods for laser-assisted individual tree based forest inventory together with Finnish industry.

Wolfgang Wagner received the Dipl.-Ing. degree in physics and the Dr.techn. degree in remote sensing, both with excellence, from the Vienna University of Technology (TU Wien), Austria, in 1995 and 1999 respectively. He received fellowships to carry out research at the University of Bern, Atmospheric Environment Service Canada, NASA Goddard Space Flight Center, European Space Agency, and the Joint Research Centre of the European Commission. From 1999 to 2001 he was with the German Aerospace Agency. In 2001 he was appointed Professor for Remote Sensing at the Institute of Photogrammetry and Remote Sensing of TU Wien. Since 2006 he has been the head of the institute. In the period 2008–2012 he is the president of ISPRS Commission VII (Thematic Processing, Modeling and Analysis of Remotely Sensed Data). His main research interests lies in geophysical parameter retrieval techniques from remote sensing data and application development. He focuses on active remote sensing techniques, in particular scatterometry, SAR and airborne laser scanning. He is a member of the Science Advisory Groups for SMOS and ASCAT and committee Chair of the EGU Hydrologic Sciences Sub-Division on Remote Sensing and Data Assimilation. Since December 2003 he has been the coordinator of the Christian Doppler Laboratory for ‘Spatial Data from Laser Scanning and Remote Sensing’.

Markus Hollaus, born in 1973, finished his studies of land and water management and engineering at the University of Natural Resources and Applied Life Sciences (BOKU), Vienna, in March 2000. During his studies he received a fellowship to study at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. From 2001 to 2003 he was a research scientist at the Institute of Surveying, Remote Sensing and Land Information at the BOKU. He was involved in several remote sensing and GIS projects with the focus on land use/cover classification and change. From 2004 to 2008 he was research scientist at the Institute of Photogrammetry and Remote Sensing (TU – Vienna) and also worked for the Christian Doppler Laboratory on ‘Spatial Data from Laser Scanning and Remote Sensing’. He received the Dr.techn. (Ph.D.) degree in November 2006 with the thesis ‘Large scale applications of airborne laser scanning for a complex mountainous environment’. Since 2009 he is university assistant at the Institute of Photogrammetry and Remote Sensing at the TU Vienna. The focus of his work is the derivation and modeling of vegetation parameters from airborne laser scanner data and aerial photographs and the classification of 3D point clouds using full-waveform airborne laser scanner data.

Hannu Hyyppä received his Master of Science, the Licentiate in Technology, and the Doctor of Technology degrees from the Helsinki University of Technology (HUT), Faculty of Civil Engineering, in 1986, 1989, and 2000, respectively. He has a docentship at HUT. Currently, he is post-doctoral fellow of the Academy of Finland in the Department of Surveying, at the Institute of Photogrammetry and Remote Sensing, Helsinki University of Technology. Previous employment include Research Fellow, Research Scientist and Assistant Coordinator, part-time R&D director of DI_Ware Oy, part-time president of UbiMap Oy, Project Manager, Development and Planning Engineer at Consulting Company Plancenter Ltd, Assistant, Senior Assistant, and Junior Fellow of the Academy of Finland and Research Scientist at the Laboratory of Road and Railway Engineering of the Department of Civil Engineering and Surveying at the HUT. He has 18 years of work experience in the research of civil and environmental engineering and geoinformatics. His references are represented by over 100 publications in the fields of civil and environmental engineering and geoinformatics, including more than 20 scientific refereed publications. His interests include the use of laser scanning and geoinformatics in new applications in built environment.

CHAPTER 15

Gabriela Schaepman-Strub obtained her Ph.D. degree in natural sciences from the University of Zurich, Switzerland, in 2004. In 2001, she was a guest researcher at the Department of Geography, Boston University. She obtained a post-doctoral fellowship for prospective researchers from the Swiss National

Science Foundation in 2005 and was an external post-doctoral fellow of the European Space Agency (2005–2007) at Wageningen University, the Netherlands. She is currently affiliated with the Nature Conservation and Plant Ecology Group and the Centre for Geo-information at Wageningen University. Her experience include performing and analyzing field spectrometer and goniometer measurements of vegetation canopies, reflectance product terminology, albedo analysis of tundra areas in Northern high latitudes, and plant functional type related analysis in highly dynamic (e.g., floodplain) and vulnerable (e.g., peatland) ecosystems. Her main interests lie in linking advanced vegetation products with dynamic vegetation models, and investigating remote sensing based land surface albedo products for climate modeling applications.

Michael E. Schaepman (see Chapter 12).

John Martonchik obtained the Ph.D. degree in astronomy from the University of Texas at Austin, in 1974. He joined NASA's Jet Propulsion Laboratory in 1972 and is currently in the Multi-angle Imaging element of the Earth and Space Sciences Division with the title of Research Scientist. His experience include analyzing telescopic and spacecraft observations of planetary atmospheres, laboratory and theoretical studies of the optical properties of gaseous, liquid, and solid materials, and development and implementation of 1- and 3-dimensional radiative transfer and line-by-line spectroscopy algorithms for studies of planetary atmospheres and Earth tropospheric remote sensing. He has been involved in several NASA Land Processes programs including Remote Sensing Science, FIFE, and BOREAS and is presently the Aerosol/Surface product algorithm scientist for the EOS MISR experiment.

Thomas Painter is Assistant Professor of Geography and Director of the Snow Optics Laboratory at the University of Utah, Salt Lake City. He is also Affiliate Research Scientist with the National Snow and Ice Data Center and Western Water Assessment of the University of Colorado, Boulder. His research focuses on radiative, hydrologic, and climatic forcings of dust and soot in snow and ice, alpine surface radiation, multispectral and hyperspectral remote sensing of snow physical properties, snowmelt hydrology, snow radiative properties, integration of remote sensing and distributed snow models, dust source mapping, and robotic goniometry. He is currently a member of the GOES-R cryosphere team, developing the fractional snow cover algorithm for the next generation geostationary satellite. His research on radiative and climate effects of dust in snow has been the subject of stories on National Public Radio, Reuters, The Weather Channel, and myriad articles in the domestic and international media. He is a member of the AGU Cryospheric Executive Committee and the AGU Hydrology Remote Sensing Technical Committee. His memberships in professional organizations include the American Geophysical Union, the European Geophysical Union, International Glaciological Society, and the Western Snow Conference.

Stefan Dangel obtained his Ph.D. degree in physics from the University of Zurich in 1997, specializing in quantum optics and nonlinear dynamics of pattern formation. His research interests include nonlinear wave propagation in low frequency seismology with applications for the oil and gas industry as well as spectro-directional effects, BRDF retrieval for field and laboratory goniometer measurements and goniometer measurement intercomparison in the field of remote sensing. He has contributed to ESA's SPECTRA mission as principal investigator for the development of a SPECTRA, end-to-end simulator. He also obtained a Master's degree in music. His current focus is on teaching mathematics, physics and bassoon.

CHAPTER 16

Freek van der Meer has an M.Sc. in structural geology and tectonics of the Free University of Amsterdam (1989) and a Ph.D. in remote sensing from Wageningen Agricultural University (1995) both in the Netherlands. He started his career at Delft Geotechnics (now Geodelft) working on geophysical processing of ground penetrating radar data. In 1989 he was appointed lecturer in geology at the International Institute for Aerospace Surveys and Earth Sciences (ITC in Enschede, the Netherlands) where he has worked to date in various positions (presently Professor and Chairman of the Earth Science Department). His research is directed toward the use of hyperspectral remote sensing for geological applications. In 1999, Dr. van der Meer was appointed full professor at the Delft University of Technology. In 2004, Dr. van der Meer was appointed adjunct professor at the Asian Institute of Technology in Bangkok (Thailand). In 2005 he was appointed Professor in Geological Remote Sensing at the University Utrecht. Professor van der Meer published over 100 papers in international journals, authored more than 150 conference papers and reports, has supervised over 50 M.Sc. projects and graduated eight Ph.D. candidates. He is the past chairman of the Netherlands Society for Earth Observation and Geoinformatics, chairman of the special interest group geological remote sensing of EARSeL, member of the Royal Netherlands Academy of Sciences, Associate Editor for *Terra Nova*, editor for the *International Journal of Applied Geoinformation Science and Earth Observation*, editor for the *Netherlands Journal of Geosciences*, and editor of the *Remote Sensing and Digital Image Processing Series* of Springer.

Harald van der Werff received his M.Sc. degree in geology from Utrecht University. Thereafter he worked as a researcher at the German Space Organization DLR in Oberpfaffenhofen in the spectroscopy group led by Andreas Mueller. In 2001 he joined ITC as a Ph.D. candidate working on the development of spectral-spatial contextual image analysis techniques. He received his Ph.D. in 2006 from the University of Utrecht on a thesis entitled 'Knowledge based remote sensing of complex objects'. To date Dr. van der Werff works as an Assistant Professor at ITC. His research interests are on (geological) hyperspectral remote sensing and on the integration of spectral and spatial information of remotely sensed images. Current research is on airborne detection of hydrocarbon spills from pipelines and geological interpretation of hyperspectral data (OMEGA, CRISM) from Mars by segmentation and landform analysis.

Steven M. de Jong is Professor in Physical Geography with emphasis on land degradation and remote sensing at the Faculty of Geosciences of Utrecht University since 2001. From 1998 to 2001 he was head of the Centre for Geo-information and Remote Sensing of Wageningen University. De Jong is chairman of the research school Centre for Geo-ecological Research (ICG) and research director of Physical Geography, Utrecht. From 1995 to 1996 he worked as a visiting scientist at NASA's Jet Propulsion Laboratory in Pasadena and conducted research to applications of NASA's Airborne Visible Infrared Imaging Spectrometer (AVIRIS). In 1997, 1998, and 2001 de Jong was Principle Investigator of several experimental campaigns investigating the usefulness of imaging spectrometers (DAIS7915, HyMap) for environmental applications in France and Spain. From 1998, to 2001 he was leader of a project investigating the use of SPOT-XS and IKONOS imagery for urban mapping in Burkina Faso. In 1994 he completed his Ph.D. thesis 'Soil Erosion Modelling using Hyperspectral Images in Mediterranean Areas'. De Jong is a member of the editioral board of *Remote Sensing and Digital Image Processing* book series (Kluwer) and of the *International Journal of Applied Earth Observation and Geo-information* (Elsevier).

CHAPTER 17

Chris J. Johannsen is a Professor Emeritus of Agronomy and Director Emeritus of the Laboratory for Applications of Remote Sensing (LARS) at Purdue University. His research has related to remote sensing and GIS applications for precision farming, soil pattern influences on reflectance, spatial-spectral-temporal resolution impacts and land degradation. He is co-editor of a book titled *Remote Sensing for Resource Management*, contributor to 16 book chapters and author or co-author of over 260 papers and articles. He served as International President of the Soil and Water Conservation Society in 1982–1983. Dr. Johannsen was responsible for the collection of ground reference information at LARS (1966–1972), continued research involving uses of reference information at the University of Missouri – Columbia (1972–1984) and resumed research, education, and outreach responsibilities for LARS as Director (1985–2003). He has received much recognition for his work including Fellow of five professional societies. Recently, he received the prestigious Hugh Hammond Bennett Award from the SWCS for his work on spatial technologies relating to studying land degradation.

Craig S. T. Daughtry is a Research Agronomist in the USDA-ARS Hydrology and Remote Sensing Laboratory in Beltsville, Maryland, USA. His research has focused on measuring and modeling the spectral reflectance of crops and soils. Daughtry joined the Laboratory of Applications of Remote Sensing (LARS) at Purdue University in 1976 and made significant advancements in integrating remotely sensed data into crop growth and yield models. After joining ARS in 1987, he has developed innovative techniques for measuring optical properties of leaves, increasing sampling efficiency, and managing the spatial variability of crops and soils. He also pioneered the use of fluorescence and shortwave infrared technologies to estimate crop residue cover for quantitatively assessing conservation tillage practices and tracking carbon sequestration. He is author or co-author of over 180 papers and articles. He has served on various committees of American

Society of Agronomy and editorial boards of *Photogrammetric Engineering and Remote Sensing and Agronomy Journal*.

CHAPTER 18

James W. Merchant is Professor in the School of Natural Resources, University of Nebraska-Lincoln (UNL) and is Director of UNL's Center for Advanced Land Management Information Technologies (CALMIT). Dr. Merchant received a B.A. in geography from Towson University, Baltimore, Maryland, and both the M.A. and Ph.D. in geography from the University of Kansas. His research has focused upon (1) development of strategies for large-area land cover characterization using digital multispectral satellite data, (2) spatial and contextual analysis of digital images, and (3) applications of geographic information systems in management of natural resources. Dr. Merchant was recipient of the 1999 Outstanding Contributions Award presented by the Nebraska GIS/LIS Association and the 1998 Outstanding Achievements Award conferred by the Remote Sensing Specialty Group of the Association of American Geographers. In 1997 he was honored with the John Wesley Powell Award that recognizes significant achievements in contributing to the research of the US Geological Survey. From 2000–2007 Dr. Merchant served as Editor of *Photogrammetric Engineering and Remote Sensing*, the journal of the American Society for Photogrammetry and Remote Sensing (ASPRS).

Sunil Narumalani is a Professor in the School of Natural Resources, and Associate Director of the Center for Advanced Land Management Information Technologies (CALMIT), University of Nebraska, Lincoln (UNL). He received his Ph.D. in geography from the University of South Carolina in 1993. Dr. Narumalani teaches courses in remote sensing (digital image analysis), introductory and advanced geographic information systems. His research focuses on the use of remote sensing for the extraction of biophysical information from satellite data and aircraft multispectral scanner systems, integration of geospatial data sets for ecological and natural resources mapping and monitoring, and the development of new image analyses techniques. Some of Dr. Narumalani's recent research has been on using remote sensing and GIS for the assessment of coral reefs and seagrasses off the coast of Florida and in the Caribbean. Over the past several years he has also been involved with projects pertaining to homeland security and military applications of geospatial technologies including the development of workshops for military intelligence units, integration of geospatial technologies for the National Guard, and initiating operational geographic databases for the Nebraska Emergency Management Agency (NEMA). Dr. Narumalani is also the Geography Program Coordinator at UNL.

CHAPTER 19

John R. Jensen is a Carolina Distinguished Professor in the Department of Geography at the University of South Carolina (USC). He majored in physical geography, cartography, and remote sensing at California State University, Fullerton, 1971 (B.A.); Breghan Young University, 1972 (M.A.); and UCLA, 1976 (Ph.D.). While at UCLA, he was trained in photogrammetry at Aero Service, Inc. In 1977, he accepted a professorship at the University of Georgia. In 1981, he went to USC and helped in developing the Ph.D. in GIScience. Dr. Jensen has mentored 60 M.S. and 28 Ph.Ds. His research focuses on: (a) remote sensing of wetland resources and water quality, (b) development of algorithms to classify land cover and detect change, and (c) the development of remote sensing-assisted decision support systems. Dr. Jensen was President of ASPRS in 1996. He has published >120 remote sensing articles. He was a co-author of ASPRS' *Manual of Remote Sensing* (1st and 2nd editions) and *Manual of Photographic Interpretation* (1997). He co-authored *Geographic Information for Sustainable Development in Africa* (2002) published by the National Academy Press. His textbooks *Remote Sensing of the Environment* (2007) and *Introductory Digital Image Processing* (2005) are used throughout the world. He received the ASPRS *SAIC John E. Estes Teaching Award* in 2004.

Jungho Im received his B.S. in 1998 in oceanography from Seoul National University, an M.C.P. in 2000 in environmental management from Seoul National University, and his Ph.D. in 2006 in geography with Dr. Jensen at the University of South Carolina. From 2006 to 2007, he worked as a post-doctoral research scientist in the Center for GIS and Remote Sensing, Department of Geography, University of South Carolina. In 2007, he became an Assistant Professor in the Environmental Resources and Forest

Engineering, State University of New York College of Environmental Science and Forestry, Syracuse, New York, USA. He is a member of the Association of American Geographers (AAG) and American Society for Photogrammetry and Remote Sensing (ASPRS). His research interests include Geographic Information Systems (GIS), GIS-based modeling, digital image processing, and environmental remote sensing.

Perry Hardin is currently an Associate Professor of Geography at Brigham Young University. He received his Ph.D. in geography from the University of Utah in 1989 where his dissertation focused on statistical classification of Landsat imagery. He has authored several journal papers related to nonparametric classification methods, confusion matrix analysis, and the use of neural networks in remote sensing. His current research interest is the use of neural networks to estimate biophysical and socioeconomic parameters (e.g., leaf area index, population data) in urban areas where calibration ground data is unavailable. Dr. Hardin served for two years on the editorial board of *Photogrammetric Engineering and Remote Sensing* and as chair of the Publications Committee for the American Society of Photogrammetry and Remote Sensing.

Ryan R. Jensen is an Associate Professor in the Department of Geography at Brigham Young University. Before this, he was an Assistant and then Associate Professor in the Department of Geography, Geology, and Anthropology where he served as the Director of the Center for Remote Sensing and Geographic Information Systems and as the Associate Director for Forest Research in the Center for State Park Research.

Dr. Jensen received his B.S. (cartography and geographic information systems) and M.S. (geography) from Brigham Young University. He received his Ph.D. from the University of Florida in geography with a minor in botany and a concentration in interdisciplinary geographic information systems. His research interests include using remote sensing and GIS to study biogeography and landscape patterns. He currently has active research programs in urban forestry, fire ecology in the southeastern (United States) coastal plain, and hyperspectral remote sensing.

CHAPTER 20

Shunlin Liang received his Ph.D. degree from Boston University. He was a post-doctoral research associate in Boston University from 1992 to 1993, and Validation Scientist of the NOAA/NASA Pathfinder AVHRR Land Project from 1993 to 1994. He joined the University of Maryland in 1993 and currently is a professor.

His present research interests focus on radiative transfer modeling, inversion of environmental information from satellite observations, spatio-temporal analysis of remotely sensed data, integration of numerical models with different data from various sources (i.e., data assimilation), and remote sensing applications to agriculture, weather and climate, and carbon and water cycles.

He is a principal investigator of numerous grants and contracts from NASA, NOAA, and other funding agencies. He is an Associate Editor of the *IEEE Transactions on Geoscience and Remote Sensing*, a member of several satellite science teams (e.g., MODIS, MISR, ASTER, EO1) of NASA and other space agencies, and co-chairman of the International Society for Photogrammetry and Remote Sensing Commission VII/I on Fundamental Physics and Modeling. He is an author of about 100 peer-reviewed journal papers and the book entitled *Quantitative Remote Sensing of Land Surfaces* (2004).

CHAPTER 21

Stephen V. Stehman has been a Biometrician in the Department of Forest and Natural Resources Management at the State University of New York College of Environmental Science and Forestry since 1989. He received his Ph.D. in biometry from Cornell University, an M.S. in statistics from Oregon State University, and a B.S. in biology from Penn. State University. His research activity has focused on the theory and practical application of rigorous sampling strategies for assessing map accuracy.

Giles M. Foody (see editors' biographical descriptions).

CHAPTER 22

Yongxin Deng is an Assistant Professor in the Department of Geography, Western Illinois University, teaching GIS and physical geography courses. He earned his Ph.D. in the Department of Geography, University of Southern California in 2005, focusing on geographical information science. His earlier experience in China includes a Bachelor's degree in physical geography in 1986 from Xinjiang University, a Master's degree in soil science in 1991 from the Chinese Academy of Sciences, and six ensuing years' (1991–1997) research at the Chinese Academy of Sciences, mostly conducting environmental impact assessment and natural resource evaluations in arid northwestern China. His current research interests include quantitative and classification methods in GIS, digital terrain analysis, mountain landscapes, urban landscape modeling, fuzzy logic, and spatial scale.

CHAPTER 23

Xianfeng Chen was born in Kurla, China, in 1963. He studied physical geography in the Department of Geography, Xinjiang University, China, from 1982 to 1986, and graduated with a B.S. degree in 1986. For the next three years he studied geomorphology at the graduate school of the Chinese Academy of Sciences, receiving an M.S. degree in 1989. He was recruited as a research scientist by Xinjiang Institute of Geography, Chinese Academy of Sciences, in 1989. Beginning in the summer of 1997, he spent a year at West Virginia University as a visiting scholar, working with Dr. Tim Warner. After his return to China, he was involved in several research projects in remote sensing and GIS. In 2000, he began the Ph.D. program in geology at West Virginia University. His dissertation, 'Integrating Hyperspectral and Thermal Remote Sensing for Geological Mapping,' was supervised by Dr. Tim Warner. After graduation in 2005, he joined the faculty of Slippery Rock University of Pennsylvania. His research interests include geological applications of hyperspectral and thermal remote sensing, land use and land cover studies, and environmental modeling with GIS and remote sensing.

David J. Campagna is a Remote Sensing Geologist with over 20 years of industry and academic experience. He is currently the Chief Science Officer of SkyTruth, Inc., a non-profit remote sensing group and serves as Adjunct Faculty in the Department of Geology and Geography at West Virginia University. He also consults for worldwide investigations of unconventional reservoirs, naturally fractured reservoirs, and structurally complex terrains. Dr. Campagna has previously worked with Advanced Resources International, Unocal Exploration, and Petro-Hunt in both domestic and international operations. He holds a Ph.D. in structural geology from Purdue University.

CHAPTER 24

James B. Campbell, PhD, has devoted his career to applications of aerial survey and remote sensing to studies of land use, geomorphology, and soils. Since 1997 he has served as co-director of Virginia Tech's Center for Environmental Analysis of Remote Sensing (CEARS). He is author of numerous technical articles and several books; his recent research addresses human impact upon coastal geomorphology and the history of aerial survey. Employment: Professor, Department of Geography, Virginia Tech, Blacksburg, VA.

CHAPTER 25

Michael A. Wulder received his B.Sc. (1995) degree from the University of Calgary and his M.E.S. (1996) and Ph.D. (1998) degrees from the Faculty of Environmental Studies at the University of Waterloo. On graduation, he joined the Canadian Forest Service of Natural Resources Canada at the Pacific Forestry Centre, in Victoria, British Columbia, as a Research Scientist. Dr. Wulder's research interests focus on the application of and integration of remote sensing and GIS to address issues of forest structure and function. He is an Adjunct Professor in the Department of Geography at the University of Victoria and the Department of Forest Resources Management of the University of British Columbia. Dr. Wulder is also a member of the GOFC-GOLD Land Cover Implementation Team and the USGS/NASA Landsat Science Team.

Joanne C. White received her B.Sc. (1994) and M.Sc. (1998) degrees in geography from the University of Victoria. She has worked in the fields of remote sensing and GIS, in a forestry context, for over 13 years. Joanne has been employed by federal, provincial, and private forest agencies, and has experience in operational, strategic, and research-oriented environments. She joined the Canadian Forest Service of Natural Resources Canada at the Pacific Forestry Centre, in Victoria, British Columbia, in 2003 as a Spatial Analyst.

Nicholas C. Coops received his B.App.Sc. (1991) and Ph.D. (1996) degrees from the Royal Melbourne Institute of Technology in Melbourne, Australia. He then worked as a research scientist at the CSIRO Australia Research Institution in the Forestry and Wildlife Divisions, in Canberra and Melbourne, from 1994 to 2004. In 2004, Dr. Coops accepted a faculty position at the University of British Columbia in Vancouver, British Columbia. He is the Canadian Research Chair in remote sensing and the editor of the *Canadian Journal of Remote Sensing*. His research interests focus on the theoretical development and application of remote sensing technologies to vegetation studies.

Stephanie Ortlepp received her B.Sc.F. (1999) and her M.Sc. (2003) degrees from the Faculty of Forestry at the University of British Columbia. After graduation, she worked for Pacific Geomatics Ltd. as an image processing specialist for over two years, before joining the Canadian Forest Service of Natural Resources Canada at the Pacific Forestry Centre, in Victoria, British Columbia in 2007 as a Monitoring Analyst.

CHAPTER 26

M. Duane Nellis (see editors' biographical descriptions).

Kevin P. Price is a Professor of Geography and served as the Associate Director of the Kansas Applied Remote Sensing (KARS) Program for 15 years at the University of Kansas (KU). While at KU, he has also retained a courtesy appointment in the Environmental Studies Program. He recently accepted a new position at Kansas State University (KSU), and will have a joint appointment in Agronomy and Geography from August of 2008. Given his agricultural academic training and interests, he looks forward to working at KSU, which is a well-respected agricultural school. He has been the recipient of national awards for service within the remote sensing community and served as the Associate Chair and Chair of the Remote Sensing Specialty Group of the Association of American Geographers. He also served on two National Research Council (NRC) committees that addressed issues of sustainable development in Africa and environmental satellite data utilization. His academic training includes a Ph.D. in geography (specialty in biogeography, remote sensing, and GIS) at the University of Utah, and B.S. and M.S. degrees in range science at Brigham Young University. Before coming to KU, he was an Assistant Professor in Geography at Utah State University where he also served as an Adjunct Professor in the Departments of Forestry, Range Science, Fisheries and Wildlife, and Landscape Architecture. Dr. Price's research has focused on the use of tools in the GISciences to study 'natural' and anthropogenically driven forcings that influences ecosystem (including agro-ecosystem) dynamics. He has conducted research throughout most regions of the world, and is the author or co-author of over 230 publications and an investigator on 75 research grants and contracts.

Donald Rundquist is a Professor with the School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln (UNL). He also serves as Director of the Center for Advanced Land Management Information Technologies (CALMIT). Rundquist holds a Ph.D. in geography from UNL (1977). He has been conducting research in and teaching courses on the subject of remote sensing since the early 1970s. His research involves high spectral and spatial resolution remote sensing of both cropland-vegetation canopies and surface waters, field techniques in support of remote-sensing campaigns, and airborne imaging spectrometry.

CHAPTER 27

Samantha Lavender has over 15 years research experience, and is Reader in Geomatics at the University of Plymouth (UoP), England, and Managing Director of ARGANS Limited. Her research interests have focused primarily on the quantitative remote sensing of water bodies using their color signature. Often called ocean color, it is used to quantify concentrations and behavior of what is dissolved or suspended by modeling the optical properties. Research extends from the movement of sediments in the coastal zone to phytoplankton in the open ocean. Both topics link to wider issues, such as climate change, as remote sensing is an important monitoring tool. Through the UoP Geomatics research group this links into Geographical Information Systems and coastal zone management. Recent community activities have also included the NERC Centre for observation of Air–Sea Interactions and fluXes (CASIX) Centre of Excellence and ESA GlobColour project; demonstrating an Earth Observation based service. She is also a council member for the Remote Sensing and Photogrammetric Society and, at an international level, Chair of the International Society for Photogrammetry and Remote Sensing Working Group VIII.6 (Coastal Zones Management, Ocean Colour and Ocean State Forecasting) and a committee member on the International Ocean Colour Coordinating Group.

CHAPTER 28

Jeff Dozier, Professor of Environmental Science and Management at the University of California, Santa Barbara, teaches and does research in the fields of snow hydrology, Earth system science, remote sensing, and information systems. He has pioneered interdisciplinary studies in two areas: one involves the hydrology, hydrochemistry, and remote sensing of mountainous drainage basins; the other is in the integration of environmental science with computer science and technology. In addition, he has played a role in development of the educational and scientific infrastructure. He founded UCSB's Donald Bren School of Environmental Science and Management and served as its first Dean for six years. He was the Senior Project Scientist for NASA's Earth Observing System in its formative stages when the configuration for the system was established. Professor Dozier received his B.A. from California State University, Hayward in 1968 and his Ph.D. from the University of Michigan in 1973. He is a Fellow of the American Geophysical Union, the American Association for the Advancement of Science, and the UK's National Institute for Environmental eScience. He is also an Honorary Professor of the Chinese Academy of Sciences, a recipient of the NASA Public Service Medal, and one of two winners of the 2005 Pecora Award from the Department of Interior and NASA.

CHAPTER 29

Gregory P. Asner's is a Staff Scientist in the Department of Global Ecology at the Carnegie Institution for Science. He is also a professor in the Department of Environmental Earth Systems Science at Stanford University. His scientific research centers on how human activities alter the composition and functioning of ecosystems at regional scales. Asner combines field work, airborne and satellite mapping, and computer simulation modeling to understand the response of ecosystems to land use and climate change. His most recent work includes satellite monitoring of deforestation, selective logging and forest disturbance throughout the Amazon Basin, invasive species and biodiversity in tropical rainforests, and climate effects on tropical forest carbon dynamics. His remote sensing efforts focus on the use of new technologies for studies of ecosystem structure, chemistry and biodiversity in the context of conservation, management, and policy development. He directs the Carnegie Airborne Observatory, a new airborne laser and hyperspectral remote sensing platform designed for regional assessments of the carbon, water, and biodiversity services provided by ecosystems to society.

Scott V. Ollinger is an Associate Professor at the University of New Hampshire with appointments in the Institute for the Study of Earth Oceans and Space and the Department of Natural Resources. His specialties are in ecosystem ecology and biogeochemistry with emphasis on basic ecological processes and interactions with human-induced environmental stressors. His research interests include: carbon and nitrogen cycling in forests; factors affecting carbon assimilation and storage by ecosystems; ecological effects of climate change, rising CO_2 and air pollution; and regional patterns of climate and atmospheric pollutant deposition in the Northeastern US. His work typically involves equal measures of field studies, remote sensing, and ecosystem modeling. At present, he is a principal investigator with the North American Carbon Program, an Associate Editor for Biogeochemistry and he serves or has served on numerous science advisory boards and steering committees. He also teaches courses in forest ecology and biogeochemistry. Dr. Ollinger received his Ph.D. from the University of New Hampshire in 2000.

CHAPTER 30

Janet Nichol is a Physical Geographer, specializing in biogeography and remote sensing. She obtained her B.Sc. from Queen Mary College London University, M.A. from the Institute of Arctic and Alpine Research at the University of Colorado, and Ph.D. from the University of Aston in Birmingham, England. She has lectured and conducted research in the United Kingdom, Nigeria, Singapore, Ireland, and Hong Kong and is currently a Professor in the Department of Land Surveying and GeoInformatics at the Hong Kong Polytechnic University. Her main research interests are in the application of remote sensing techniques to environmental assessment and monitoring, including the urban heat island, air quality, urban environmental quality, ecological mapping and evaluation, and the assessment of climate change impacts. She has published widely on these topics and is a reviewer for journals specializing in remote sensing, planning, and environmental issues.

CHAPTER 31

Kelley A. Crews is at the University of Texas at Austin where she is an Associate Professor of Geography and the Environment and Director of the GIScience Center, and is a faculty research associate of the Population Research Center, Center for Space Research, Environmental Science Institute, and Lozano Long Institute of Latin American Studies. She is currently both Chair of the Remote Sensing Specialty Group and member of Honors B Committee of the AAG, and Deputy Director of the Awards Committee for the ASPRS. She serves on the advisory committee for NASA's only *socioeconomic* data and applications center housed at CIESIN of the Earth Institute at Columbia University. She is currently a member of the editorial boards of *Geocarto International*, *Geography Compass*, and *Southwestern Geographer*, and has served on review panels for NSF and SSRC. She recently co-edited a "Focus" section of *Professional Geographer* and also has a co-edited book with Kluwer Academic Publishers on expanding the socio-spatial frontiers of GIScience. Her publications span outlets focusing on remote sensing (*Photogrammetric Engineering and Remote Sensing*; *International Journal of Remote Sensing*), environment and policy (*Agriculture, Ecosystems, and Environment*; *Environmental Management*), and population–system interactions (*Population Research and Policy Review*; *Urban Ecosystems*). Her research focuses on the global tropics, with current projects in the Andes–Amazon Corridor and the Okavango Delta, Botswana, and funded by grants from NASA and NSF.

Stephen J. Walsh is at the University of North Carolina at Chapel Hill and is Professor of Geography, member of the Ecology Curriculum, and Research Fellow of the Carolina Population Center where he is faculty advisor to the Spatial Analysis Unit. He has served as Chair of the Geographic Information Systems and the Remote Sensing Specialty Groups of the AAG. He was awarded the Outstanding Contributions Award and Medal from the Remote Sensing Specialty Group of the AAG and National Research Honors for Distinguished Scholarship from the AAG, and was elected into the American Association for the Advancement of Science. He is currently a member of the editorial boards of *Annals of the Association of American Geographers*, *Plant Ecology*, and *Geocarto International*, and has served on review panels for the NSF and NIH. He has co-edited special remote sensing and GIS issues in the *Journal of Vegetation Science*, *Geomorphology*, *GeoForum*, and *Photogrammetric Engineering and Remote Sensing*. He has co-edited a series of three books for Kluwer Academic Publishers and has published over 170 articles and book chapters on the research and practice of digitally integrated spatial science. His current research is conducted in Thailand, the Ecuadorian Amazon, the Galapagos Islands, and the Mountains of the American West and is funded by grants from NASA, NIH, NSF, and the USGS.

CHAPTER 32

Richard Teeuw is Senior Lecturer in applied geomorphology and remote sensing in the School of Earth and Environmental Sciences at the University of Portsmouth, England. Richard has extensive experience of mapping natural resources and geohazards in Africa, working as a consultant for the overseas development agencies of Canada (CIDA), Germany (GTZ), and Japan (JICA), as well as various mineral exploration organizations. Current interests focus on using low-cost satellite imagery for mapping geohazards and vulnerability, leading to disaster risk reduction, with research projects in SE Spain, Turkey, Costa Rica, and the Caribbean. Currently Chair of the Geological Remote Sensing Group (http://www.grsg.org), Richard has also edited books on the remote sensing of geohazards and the uses of geoinformatics for fieldwork.

Paul Aplin is an Associate Professor in Geographical Information Science at the University of Nottingham, UK. He specializes in environmental remote sensing, with principal research interests in the development of innovative approaches for land cover classification, the influence of scale of observation on image analysis and the application of spatial approaches for ecological investigation. He is currently engaged as Chairman of the Remote Sensing and Photogrammetry Society and Book Series Editor of the International Society for Photogrammetry and Remote Sensing.

Nicholas McWilliam has been developing information management and mapping applications in humanitarian disaster response with the UK-bsaed NGO MapAction since 2003, through research and training projects and emergency-response missions. Most recently he worked for the UN Joint Logistics Centre in South Sudan. Before that he was a lecturer in GIS for geography and life sciences, and worked for British Antarctic Survey's mapping centre. His first GIS use was modeling large mammal populations in Tanzania, and he has remained involved in National Parks mapping in East Africa. He co-edited the Royal Geographical Society's fieldwork manual *GIS, GPS and Remote Sensing* and regularly runs GIS workshops with the RGS for student research projects.

Toby Wicks is the European Engagement Manager at EuroGeographics, the association representing Europe's National Mapping and Cadastral Agencies. He is motivated by the use of geographic information to better coordinate response to sudden-onset disasters. Previously Toby has held positions at Ordnance Survey Great Britain, the World Health Organisation, and Spot Image. Toby has a Ph.D. in remote sensing, is a trustee and council member of the UK's Remote Sensing and Photogrammetry Society, a Fellow of the Royal Geographical Society and has been a volunteer for the UK-based NGO MapAction since 2004.

Matthieu Kervyn is a young Belgian Geoscientist. He holds a Master's degree in Geography from the Université Catholique de Louvain. Since 2004, he developed a Ph.D. in volcanology within the Mercator and Ortelius Research Centre for Eruption Dynamics at Ghent University, under the supervision of Dr. Gerald G.J. Ernst, and Prof. P. Jacobs. His research interests focus on the use of low cost remote sensing, analogue and numerical modeling to gain insights on the relationships between eruption dynamics, volcano growth, and associated hazards. Matthieu has been involved in assessing hazards and developing low cost remote sensing monitoring at several African volcanoes, including Oldoinyo Lengai, Tanzania, and Mt. Cameroon.

Gerald G. J. Ernst is a Geohazard Researcher interested in understanding how eruptions and volcanoes work and in applications to poverty alleviation and to hazard assessment at volcanoes in the developing world, especially across Central Africa. Exploring new applications of remote sensing including low cost approaches and combining this with analogue modeling is a key focus of interest. After 12 years of training, researching, and lecturing in volcanology and geological fluid dynamics at the Department of Earth Sciences, University of Bristol, UK, Dr. Ernst has joined the Belgian NSF (Flanders) in 2003 and is now working toward establishing the Mercator and Ortelius Research Centre for Eruption Dynamics – a school for volcanology research and an analogue modeling laboratory at the University of Ghent, Belgium. Dr. Ernst has published approximately 30 peer-reviewed articles related to volcanology, analogue modeling, or volcano remote sensing and co-edited the first textbook on *Volcanoes and the Environment* (CUP, 2005). In recent years, he has been developing initiatives working with African colleagues to develop the capacity for volcano research and monitoring in sub-tropical developing countries. He has received four prizes in recognition of his efforts so far including the 2002 Golden Clover Prize from the *Fondation Belge de la Vocation*, a foundation patronized by HM Queen Fabiola of Belgium. He trained over 50 students through supervision of research projects. Two former students he helped train are now award-winning volcano scientists.

CHAPTER 33

Timothy A. Warner (see editors' biographical descriptions).

Abdullah Almutairi is an Assistant Professor of Geography at Emam Muhammad Bin Saud University, in Riyadh, Kingdom of Saudi Arabia (KSA). He has a Bachelor's degree in Geography from the Emam

Muhammad Bin Saud University. His received his graduate education in geography with a specialization in remote sensing at West Virginia University, where he earned a Master's degree in 2000 and a Ph.D. in 2004. He has served as Chair of the Geography Department at Emam Muhammad Bin Saud University. He is a member of the Social Geographical Society and GIS Club, and has served as a consultant to the KSA Ministry of High Education. His research specialties include the spatial properties of images, high resolution remote sensing, and the use of remote sensing and GIS in planning.

Jong Yeol Lee is Research Fellow of the Geospatial Science Research Centre at the Korea Research Institute for Human Settlements (KRIHS), an affiliated research institute of the Office of the Prime Minster of the Republic of Korea. He graduated with a B.S. in geography from the College of Education at Seoul National University. He has a Ph.D. from West Virginia University in geography with specialization in remote sensing. He has served as the director of the Geospatial Science Research Centre at KRIHS, and is an Adjunct Professor at the University of Seoul. He serves on the board of directors of the Korean Geography Society, and is also a member of the executive board of the Korean Society of Remote Sensing. His specialty is high spatial resolution image analysis, integration of remote sensing and GIS, and regional analysis in regional studies.

CHAPTER 34

Giles M. Foody, Timothy A. Warner, and **M. Duane Nellis** (see editors' biographical descriptions).

SECTION I

Introduction

1

Remote Sensing Scale and Data Selection Issues

Timothy A. Warner, M. Duane Nellis, and Giles M. Foody

Keywords: remote sensing data, scale, spectral scale, spatial scale, temporal scale, radiometric scale.

INTRODUCTION

Remote sensing can be termed a mature discipline, in the sense that the underlying physical principles are well understood, and applications are beginning to appear in operational contexts spanning a diverse array of applications. In addition, the supporting technology has evolved to the extent that image acquisition, field work, and digital analysis are today much more sophisticated than in the early days of analog imaging, computer mainframe-based processing, and qualitative analysis. However, with the wide range of remotely sensed data that is now available, the rapid and continued advances in the power and storage capacity of modern desktop computers, and the sophistication of the many software packages available, remote sensing is far from a static field. Indeed, the last decade has seen the development of commercial fine resolution remote sensing from space (Toutin, in this volume), the exponential growth of lidar (also known as airborne laser scanning) (Hyyppä et al., in this volume), and the increasing sophistication and automation of image processing, to name just a few examples. This rapid evolution of remote sensing technology suggests that there is a need for a periodic and relatively comprehensive review of the field of remote sensing. This book is an attempt to address that need.

In this introductory chapter we lay the groundwork for a theme that is common throughout many of the chapters in this book, namely, the trade-offs and issues that should be considered in selecting data for a specific problem. For example, in Chapter 25 Wulder et al. consider data selection within the context of vegetation characterization, and in Chapter 31, Crews and Walsh review data selection from the perspective of social scientists. This introductory chapter provides a broad perspective on this important topic.

Ironically, selecting data is today more challenging than in the past, a consequence of the wide range of data currently available. In the past, few remotely sensed data sets were available, and consequently the properties of the available data tended to determine the nature of the problems that could be addressed. Thus, an important part of early remote sensing research using the Earth Resources Technology Satellite (ERTS, later renamed Landsat) was simply to ask the question, ‘What can we do with these new data?’ Today, we have a vast array of data to select from in remote sensing, and so a new problem has emerged – how do we optimize the data characteristics that we use, so that the data will most effectively address a particular application or research problem? It should thus be clear that the definition of an optimal data set is entirely dependent on the aims of the project for which the data are intended.

Adding to the complexity of choosing data attributes are three related issues. Firstly, there are fundamental physical and engineering trade-offs that limit the nature and detail of the data that can be collected using an imaging system (Kerekes, in this volume; Figure 1.1). These constraints help explain the design choices made in satellite-borne sensors, and likewise need to be considered by those planning their own custom acquisitions of aerial imagery (Stow, in this volume).

A second issue that makes selecting the appropriate data for a project complex is that, just as too little data will likely reduce quality of the analysis, data with too much detail may also have a negative effect (Latty et al. 1985). It is intuitive that too much spatial detail can be burdensome for a computer-based analysis, and the same principle applies to other components of imagine information, including the spectral, radiometric, and temporal scales of the data. For example, Hughes (1968) showed that an excessive number of spectral bands can lead to lower classification accuracy, an observation that is known as the *Hughes phenomenon* (Swain and Davis 1978).

The last issue, perhaps the most important of the three, is the need to match the scale of the analysis to the scale of the phenomena under investigation (Wiens 1989). Inferences drawn from an analysis at one spatial scale are not necessarily valid at another scale, an issue known in ecology as *cross-level ecological fallacy* (Robinson 1950, Alker 1969). In geography, the dependence of observed patterns on how data are aggregated is known as *the modifiable areal unit problem* (MAUP, Openshaw and

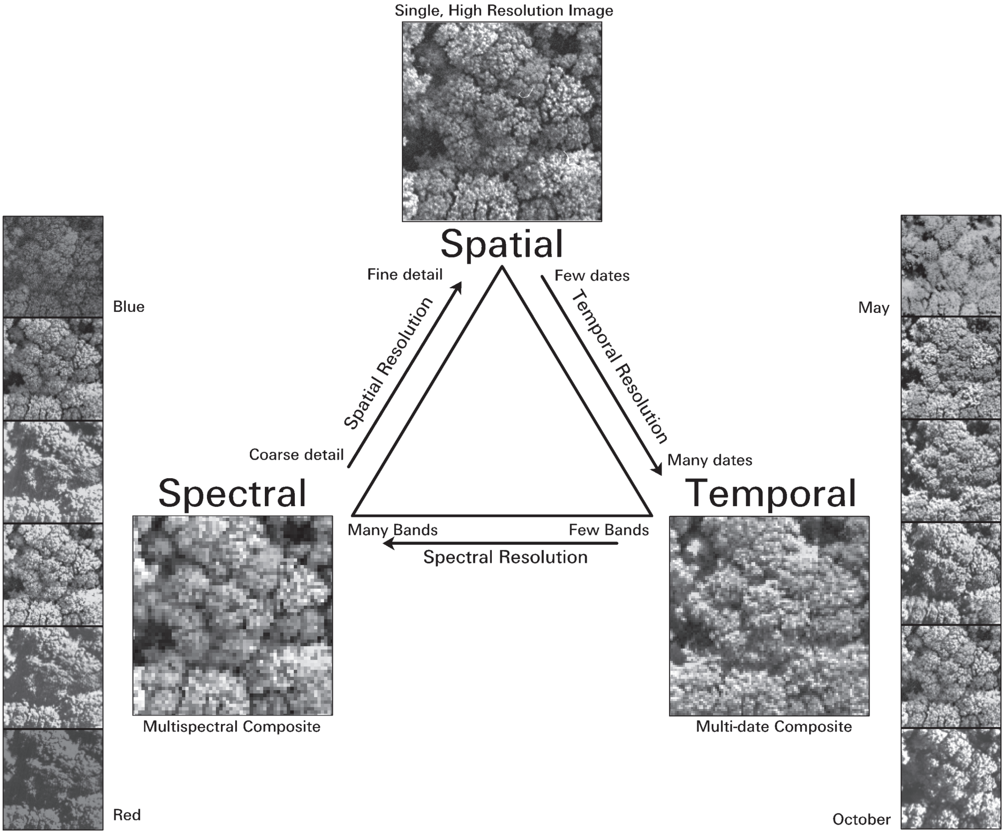

Figure 1.1 Given a limited bandwidth for image acquisition, storage, and communication, trade-offs have to be made regarding the spatial, spectral, and temporal scale of the imagery that can be acquired. Radiometric scale (not shown) is also important. (See the color plate section of this volume for a color version of this figure).
***Source*: Figure reproduced from T. Key, T. Warner, J. McGraw, and M. A. Fajvan, 2001. A comparison of multispectral and multitemporal imagery for tree species classification. *Remote Sensing of Environment* 75: 100–112.**

Taylor 1979, Openshaw 1983, 1984). The MAUP has two components (Jelinsky and Wu 1996):

- The scale problem, which focuses on how results may vary as the size of the aggregation units (pixels, in the typical remote sensing analysis) varies.
- The zoning (or aggregation) problem, which focuses on how the results may vary as the shape, orientation and position of the units vary, even as the number of aggregation units is held constant.

In remote sensing, attention has usually focused on the MAUP scale problem, and less attention has been applied to the zoning problem (for an exception, see Jelinsky and Wu 1996), because most pixels are assumed to represent a similar, approximately square shape. However, NOAA Advanced Very High Resolution Radiometer (AVHRR) Global Area Coverage (GAC) data is produced by aggregating a linear-oriented subset of finer scale Local Area Coverage pixels (Justice and Tucker, in this volume), thus potentially opening the GAC data to zoning problems. Clearly, both scale and zoning MAUP problems are potentially present when ancillary vector-derived data are used in a remote sensing analysis (Merchant and Narumalani, in this volume).

Woodcock and Strahler (1987) provide a useful remote sensing conceptual framework that categorizes images based on the size of the pixels relative to objects in the scene. Thus an H-resolution image has pixels small enough to resolve objects or phenomena of interest in the scene. In contrast, in an L-resolution image, the pixels are too large to resolve the individual objects. However, most scenes have objects at a variety of scales, and therefore it may be more useful to refer to H- and L-resolution image elements, both of which are likely to be present in any one image (Ferro and Warner 2002).

Central to the ideas presented so far is the concept of scale (Quattrochi and Goodchild 1997, Walsh et al. 1997, 2003, Marceau and Hay 1999, Spiker and Warner 2007). Landscape ecology recognizes scale as having two attributes: grain and extent (Turner et al. 2001). Although there are numerous definitions of these terms, for our purposes we will define *grain* as the finest level of measurement, the degree of detail, or the sampling unit. An example of grain is the instantaneous field of view (IFOV) of the sensor, which in turn is related to the ground sampling distance or ground resolution element, depending on the context. (Although pixel size is not as precise a term, for simplicity we will use it to represent the concept of ground sampling distance in this chapter.) *Extent* can be defined as the range over which measurements are made, for example, the area represented in an imaged scene. Grain and extent tend to be inversely related, simply because the total amount of data that can be collected is usually constrained.

Even though the examples given here draw on image spatial properties, the term scale is often also applied to the three other attributes of image data already referred to, namely the spectral, radiometric, and temporal properties. Although scale is a common thread in this chapter, it is important to note that it is not the only attribute that is important in selecting data to address a particular problem.

The remainder of this chapter is organized in seven major sections. Following this general introduction, we discuss factors that influence the optimal characteristics of each of the four major types of image properties: spatial, spectral, radiometric, and temporal. We then present some examples of the interactions and trade-offs between the individual types of major image properties, before considering some broader, more general issues. In the concluding sections, we look to the future to discuss challenges and opportunities on the horizon.

SELECTING IMAGES WITH OPTIMAL SPATIAL PROPERTIES

Scale and image spatial properties

The concept of scale is particularly useful for discussing image spatial properties (Cao and Lam 1997, Marceau and Hay 1999). For example, the section in this book on satellite-borne sensors is partly organized along the lines of pixel size. Thus, we have chapters on fine (Toutin, in this volume), moderate (Goward et al., in this volume), and coarse spatial resolution (Justice and Tucker, in this volume) sensors. However, the challenges that the authors of these chapters faced, both in arriving at these terms, and in using them consistently, suggests that meaning of scale varies greatly depending on the focus of the analysis, and perhaps also the historical context of the time. Thus, despite its name, the Advanced Very High Resolution Radiometer (AVHRR), with 1.1 km pixels, is grouped in this book with coarse resolution sensors. The Landsat Enhanced Thematic Mapper Plus (ETM+), which we treat as a moderate resolution sensor, has also been termed a fine spatial resolution sensor by some. Adding complexity is the fact that many satellite-borne sensors have bands of differing spatial resolution. For example ASTER acquires data in three bands with 15 m pixels, six bands with 30 m pixels, and five bands with 90 m pixels. It is apparent that spatial resolution of modern satellite sensors fall

Table 1.1 Image spatial resolution categories

Pixel size (m)	*Spatial resolution*	*Example satellite-borne sensors*
<1	very fine	WorldView
1–10	Fine	IKONOS
10–100	Moderate	ASTER, AWIFS, ETM+, MSS, SPOT
100–1000	Coarse	MODIS, MERIS
>1000	Very coarse	AVHRR, GOES, METEOSAT

along a continuum, and therefore attempts to label sensors by simple spatial resolution descriptors is inherently arbitrary. Nevertheless, to minimize confusion, we have attempted throughout this book to standardize as far as possible on the terms summarized in Table 1.1.

Although often used interchangeably, *spatial resolution* and *pixel size* are not strictly speaking equivalent. This is because pixel size refers to the sampling frequency, and not the ground resolution element or sampling area. Thus, for example, the Landsat MultiSpectral Scanner (MSS) oversampled data along the scan line, producing pixels that are smaller than the ground resolution element. In addition, spatial resolution is dependent on the spectral radiometric properties of both the object being resolved, and the background against which it is being resolved. Generally, a higher spectral radiometric contrast between an object and its background will result in a higher apparent spatial resolution. At the one extreme, an object with no contrast against the background is not resolvable, irrespective of its size. At the other extreme, it is potentially possible to detect the presence of a single, bright object that is much smaller than a pixel, as long as the object is surrounded by a much darker background. However, for this latter example, it is not normally possible to predict where in the pixel that object occurs, so in that sense, the resolution is ultimately limited by the pixel size. Nevertheless, because of mixed pixels, and the low contrast of most Earth scenes, objects generally need to be multiple times the size of a single pixel before they are large enough to be discerned as distinct spatial features.

A more precise way of specifying resolution is the modulation transfer function (MTF). This is a specification of how contrast in the scene is represented in ('transferred to') the image. To measure MTF, a test signal of multiple bars of defined contrast, and varying spatial frequency (width of the bars), is imaged, normally in a laboratory setting. The contrast in the resulting image, at each of the various spatial frequencies, is then measured as a proportion of the original contrast. A similar measure is the point spread function (PSF), which characterizes how a point signal is blurred when it is measured by the sensor (Huang et al. 2002). Blurring results from the effects of the atmosphere, the sensor optics and electronics, and image resampling. Because of blurring, the information in a pixel usually includes a component from neighboring pixels (Zhang et al. 2006). Huang et al. (2002) have shown how modeling of the PSF can be used to reduce this adjacency effect, and thus improve the overall fidelity of the image.

In real images, quantifying spatial resolution requires identification and exploitation of natural boundaries between features in the image. Tarnavsky et al. (2004) used the full-width-half-maximum (FWHM) of the line spread function (LSF), derived from the study of the edges of objects in the image, to compare the spatial fidelity of scanned aerial film, and digital aerial images.

Image spatial extent and pixel size are generally inversely related. Thus, spatial resolution generally limits the potential extent of the scene. For example, it is possible to collect a global set of near cloud-free Landsat 7 ETM+ imagery, with 30 m pixel size, on a seasonal basis (Goward et al., in this volume). However, MODIS with 250 m visible and near infrared (NIR) pixels, can provide weekly global composites of nearly cloud-free imagery (Justice et al. 2002). In contrast, despite almost a decade of data collection by multiple commercial companies, there is as yet no fine spatial resolution global data set.

Choosing an optimal spatial scale

What is the optimal spatial resolution for a particular project? As already mentioned, it is important to clarify the interpretation objective of a project, before this question can be addressed. If the aim is to map the location of discrete objects, or the overall spatial patterns in an image data set, then methods that estimate optimal resolution based on finding the pixel size with the maximum local variation have been shown to be very effective. For example, Woodcock and Strahler (1987) related the graph of local variation plotted against pixel size to the average size of objects in an image. Variograms, which characterize the variability between measurements as a function of distance between those measurements (Jupp et al. 1989), have a particularly rich theoretical underpinning (Matheron 1971, Journel and Huijbregts 1978, Jupp et al. 1988). Variograms have been used to identify optimal distances between field measurements and the optimal pixel size (Hyppänen 1996, Atkinson and Curran 1997). An alternative measure, lacunarity, which is based on fractal theory, is useful for identifying multiple scales in an image (Butson and King 2006).

If the aim is to map the size and spatial extent of individual objects or regions, then it is important to have a pixel size much smaller than the distance calculated for optimal sampling, as described above. However, if the resolution becomes too fine, unwanted spatial detail will likely be resolved in the image, and, at least using conventional image analysis techniques, classification accuracy may be lower (Latty et al. 1985). On this basis, the optimal resolution has been defined as the scale that minimizes variance within the classes to be mapped (Marceau et al. 1994). An important consequence of this definition is that the optimal scale is therefore likely to be class-dependent (Marceau et al. 1994).

Hengl (2006) provides a thorough overview of the issues associated with choosing an optimal scale. He recommends a scale that is a compromise between *the coarsest legible scale*, which respects the scale and properties of the dataset; and *the finest legible scale*, which preserves at least 95% of the object or scene variability (Hengl 2006). McCloy and Bøcher (2007) extend Woodcock and Strahler's (1987) local variance concept to show how a graph of average local variance (AVL) can help predict a scale that minimizes within class variance, and thus optimizes the accuracy of subsequent classifications.

Image geometric properties

Another issue that should be considered in selecting data is the quality of the georeferencing to a cartographic projection. High quality georeferencing is generally expensive. For an image acquired from a nadir-viewing sensor, a simple polynomial warp that does not include terrain correction may be sufficient, and if local map control at a sufficient scale is available, can be applied routinely. Topographically induced image distortion increases with increasing angle away from nadir, as does the distortion of the shape and size of the pixel. Thus, with sensors that have a pointing capability, the view angle is an important variable to consider in selecting data. However, the increasing sophistication and availability of automated photogrammetric software makes it potentially possible for non-specialists to generate high quality orthorectifications, although the procedure remains relatively complex.

The quality of the image geometric properties is particularly important for multi-temporal analysis. Even a 0.2 pixel misregistration can cause as much as 10% error in the estimate of the change in spectral values, depending on the heterogeneity of the scene (Townshend et al. 1992). The quality of georeferencing is also important for change detection derived from object-based classification. In object-based classification, pixels are first grouped into so-called image objects, which are then classified as a single unit (Jensen et al., in this volume). In a series of experiments on the effects of misregistration on object-based change detection, Wang and Ellis (2005) found change detection error increased with increased positional error, increased landscape heterogeneity, and finer change detection resolution (the local region over which change is identified). The relationships between these variables were summarized using regression, and then used to calculate an optimal change detection resolution, based on a desired degree of accuracy (Wang and Ellis 2005).

SELECTING IMAGES WITH OPTIMAL SPECTRAL PROPERTIES

Scale and image spectral properties

When the concept of scale is applied to spectral properties, *spectral grain* can be used to refer to the wavelength interval, or width, of the spectral bands. Multispectral sensors, with a coarse spectral grain, have bands that span hundreds to thousands of nm. The *spectral extent* can be used to describe the spectral wavelength region encompassed by the bands (e.g., many optical sensors operate in the visible and near-infrared spectral region), and the total number of bands. The definition of hyperspectral data, which usually emphasizes the number, width and contiguity of the spectral bands (Schaepman, in this volume), thus encompasses the concepts of both spectral grain and extent.

The specific location and width of spectral bands can be very important for subsequent analysis. For example, Teillet et al. (1997) show that normalized difference vegetation index (NDVI) values are not necessarily comparable between satellites with different spectral properties, even if the data are atmospherically corrected and radiometrically calibrated. The width and location of the red band used in the NDVI calculation is particularly important, and should ideally be less than 50 nm wide (Teillet et al. 1997). Thus the spectral grain of Envisat Medium Resolution Imaging Spectrometer (MERIS) appears to be more appropriate for NDVI work than either the Landsat TM or SPOT HRV sensors (Teillet et al. 1997).

The choice between using multispectral and hyperspectral data has important ramifications for the range of information extraction routines that are appropriate for subsequent analysis. Multispectral analysis techniques tend to use data from within the scene to develop empirical models and classifications. Obtaining sufficient reliable within-scene training data can be a major challenge with multispectral analyses. In addition, the spectral separability of the classes of interest may be limited with multispectral data.

Hyperspectral analysis techniques often employ methods that are not premised on requiring in-scene knowledge. For example, hyperspectral methods may employ theoretical biophysical models, or draw on spectral libraries for classification (Chen and Campagna, in this volume). Spectral libraries consist of high quality spectra, usually acquired under laboratory conditions, which are assumed to represent material classes over wide areas. A number of extensive mineralogical spectral libraries are available in the public domain (for example, Clark et al. 2003); more recently an urban land cover library has been developed (Herold et al. 2003). The availability of spectral libraries for vegetation tends to be more limited, because of the phenological and environmental variation in vegetation properties limit the generalization that can be achieved. One of the difficulties in exploiting library spectra is that scaling from small laboratory samples and field spectrometer measurements to pixels, is complex (Baccini et al. 2007).

Choosing the optimal spectral bands

In the early days of digital image processing of remotely sensed data, limited computing power made it attractive to select only the most useful bands for classification. This constraint has largely fallen away with the steady improvement in computing power. Nevertheless band reduction is still often desirable, especially as advances in sensor technology enable data acquisition in more bands. The Hughes phenomenon (Hughes 1968, Warner and Nerry 2008), which has already been referred to above, is assumed to result from the increased number of parameters needed to characterize the distributions of training samples as the number of bands increases. The effect of the Hughes phenomenon is most likely classifier-dependent, and indeed, support vector machines are thought to be less susceptible to this problem (Melgani and Bruzzone 2004).

The simplest way of selecting bands is to use knowledge of the spectral properties of interest. For example, in a vegetation application one might select bands from the visible, NIR, and short wave infrared (SWIR) to sample spectral regions influenced by vegetation pigments, leaf structure, and moisture status, respectively (van Leeuwen, in this volume). In geological applications, one might use spectral libraries to identify the wavelengths associated with important diagnostic absorption features of the minerals and rocks of interest (Chen and Campagna, in this volume).

A variety of automated and statistical approaches have been proposed for selecting optimal subsets of image bands that carry the most information (Serpico and Moser 2007). One assumption common to many band selection methods is that highly correlated bands are redundant (Wiersma and Landgrebe 1980, Miao et al. 2007). Using the statistical method of principle component analysis (PCA) (Jensen 2005), the axes of multidimensional data can be rotated so that an n-band original data set is transformed to n new orthogonal and uncorrelated bands. The new bands are normally ordered according to the proportion of the original variance each new band explains. This strategy generally works very well, with the first few principle components carrying most of the information, and the remaining, low variance components generally dominated by noise. PCA is one of the most widely-used general image analysis techniques, having applications that go well beyond data compression and band selection. The minimum noise fraction (MNF) transformation (Green et al. 1988), typically applied to hyperspectral data, is a cascaded sequence of PCA transformations in which the noise is isolated and removed.

Despite the robustness of PCA, it is important to be aware that this method uses correlated variance as a surrogate measure for information. In situations where the signal of interest is not correlated across bands, but is instead isolated in a narrow spectral absorption feature, PCA will not be so useful. In addition, although highly correlated bands are likely somewhat redundant, they may nevertheless contain non-redundant information that can be very useful for separating subtle spectral differences (Warner and Shank 1997).

An alternative to this focus on covariance is data transformations and band selections that specifically enhance the spatial patterns in the resulting images. The spatial analog to PCA is multivariate spatial correlation (MSC) (Wartenberg 1985), which can be used to transform and compress image data (Warner 1999). Comparisons of the autocorrelation of ratios of image bands have also been used to select individual bands, and combinations of bands (Warner and Shank 1997). This autocorrelation-based method of selecting bands has been found not only to increase classification accuracy, but also to result in classifications that have higher autocorrelation, and thus potentially more clearly defined spatial patterns (Warner et al. 1999).

Data fusion

Data fusion has been defined as:

> a formal framework in which [there] are expressed means and tools for the alliance of data originating from different sources. It aims at obtaining information of greater quality; the exact definition of 'greater quality' will depend upon the application. (Wald 1999: 1191)

Pohl and Van Genderen (1998) note that data fusion can take place at three different levels in the image processing chain of analysis:

1 At the *pixel level*, by combining raw image bands of different sources.
2 At the *feature level*, by segmenting the images to identify image objects, and combining the different images in the context of each image object.
3 At the *decision level*, where each image is first analyzed separately, and then the derived information is combined.

The attributes of the data that are combined through data fusion could potentially cover any individual or combinations of the four attributes of scale: spatial, spectral, radiometric, and temporal, as well as a combination of imagery with ancillary data (Pohl and Van Genderen 1998). In this section, which focuses on image spectral properties, the discussion will be limited to attempts to increase the information content of a data set by combining images of disparate wavelengths at the pixel level (Briem et al. 2002). Subsequently, in the section on interactions between the different scale components, pan-sharpening using multi-spatial resolution data fusion will also be discussed.

The underlying rational for multi-wavelength data fusion is that different wavelength regions may respond to different physical phenomena. Thus, for example, a combined analysis of optical and synthetic aperture radar imagery potentially can provide information about vegetation type, biomass, structure, and water content (Hill et al. 2005).

Similarly, combining hyperspectral VNIR and SWIR with multispectral thermal infrared (TIR) data may allow the incorporation of temperature or emittance variations in discrimination between land cover units. For mineral mapping, SWIR bands often provide an ability to discriminate clays, whereas multispectral thermal bands are valuable for separating silicate minerals (Chen and Campagna, in this volume; Chen et al. 2007a). However, the benefits of combining these disparate wavelength regions varies greatly with classification method used (Chen et al. 2007b), and for some classifiers, the accuracy may actually decline when disparate data are combined. This suggests that a suitable approach for mineral discrimination may sometimes be an expert system that adapts to the spectral pattern of each pixel to draw on different classifiers, using different wavelength intervals, to classify each pixel independently.

The fusion of VNIR and SWIR data with multispectral thermal data also holds promise for classification in the urban environment, especially for the discrimination of different roof and road materials. In a study of Strasbourg, France, it was found that various combinations of four to six broad bands from the visible, NIR and SWIR, together with six multispectral TIR bands, resulted in higher classification accuracy than with using 71 hyperspectral visible, NIR, and SWIR bands (Warner and Nerry 2008). Unfortunately, there are currently no planned medium or high spatial resolution thermal satellite-based sensors, and therefore opportunities to exploit data fusion with TIR may remain limited.

SELECTING IMAGES WITH OPTIMAL RADIOMETRIC PROPERTIES

Scale and image radiometric properties

Radiometric resolution is arguably as important as spatial, spectral, and temporal resolution, yet does not seem to receive as much attention as the other image attributes. When scale is applied to radiometric properties, *grain* refers to the fineness of the division between successive brightness levels the sensor measures. *Extent* refers to the range of brightness levels over which the sensor can differentiate changes in radiance. A sensor with a rather unusual radiometric extent is the Operational Linescan System (OLS), which is flown aboard the Defense Meteorological Satellite Program (DSPM). The OLS is particularly sensitive to a range of low light levels, which makes it possible to detect illumination at night from street lights (Henderson et al. 2003) and other sources of illumination, such as fires and flares.

The number of bits over which the signal is quantized can serve as an indicator of the radiometric grain. An eight-bit resolution (2^8, or 0–255 DN values) has been until recently a common choice, partly because this data range corresponds to the underlying structure of computer data storage. Nevertheless, it is important to consider the range of radiometric values actually filled (Malila 1985), as well as the noise in the data. Thus, radiometric grain is perhaps more usefully characterized as the minimum radiance change that can be detected reliably. This change can be measured in radiance units, or as the signal-to-noise ratio. The latter measure is normally defined as the mean signal divided by the standard deviation of the noise. Atkinson et al. (2007) have demonstrated the utility of using land-cover-specific variograms to estimate the signal-to-noise ratio based on the relative variance of both the signal and noise. This land-cover-specific measure of radiometric grain emphasizes the importance of the scene context in interpreting measures of noise.

Over time the radiometric range of data quantization from available sensors has increased notably. Tarnavsky et al. (2004) have shown that scanned color infrared aerial photographs have more noise than Airborne Data Acquisition and Registration (ADAR) 5500 multispectral images, which are acquired using digital cameras. The original Landsat MSS sensor recorded just six bits of data, although the data for the first three bands were scaled non-linearly to provide an effective seven-bit range (Goward et al., in this volume). In contrast, Landsat TM data is quantized over eight bits. Malila (1985) used an analysis of entropy to show the importance of this radiometric improvement in increasing the information content compared to the improvement in the number, width and location of the spectral bands. On the other hand, Narayanan et al. (2000) suggest that TM imagery can potentially be compressed to as few as only four bits per pixel, and still produce classifications that are similar in accuracy to the original eight-bit data.

The commercial high resolution sensors of IKONOS, Quickbird and OrbView are all quantized with 11-bit data (Toutin, in this volume). Nevertheless, purchasers of these data sets are offered degraded 8-bit versions of the data, perhaps reflecting legacy software or limited hardware and software available to some purchasers. Based on the personal experience of the authors, one of the advantages of the higher radiometric resolution of the commercial sensors appears to be the increased information content in dark areas of the images, especially shadows.

Radiometric normalization and calibration

Many image analysis procedures can be undertaken with images in DN format. However, some change detection techniques and most biophysical transformations (e.g. vegetation indices) require normalization or calibration to radiance units or equivalent reflectance (Teillet et al. 1997, Song et al. 2001). For example, conversion to reflectance is particularly important for hyperspectral data, especially if the imagery is to be classified using spectral libraries (Chen and Campagna, in this volume). In comparing radiance and reflectance measurements between sensors, and between field spectrometers and remote imaging devices, it is particularly important to define and consider the geometric arrangement of the illuminating energy and the observing sensor. Schaepman-Strub et al. (in this volume) provide a comprehensive review of the terminology and the relationships between different types of spectral measurements.

Conversion to reflectance requires information about the spectral sensitivity of the sensor, as well as both solar illumination and atmospheric transmission and scattering. The effect of topography on illumination may be calculated if a sufficiently detailed digital elevation model is available (Warner and Chen 2001). However, the bidirectional reflectance distribution function (BRDF), or dependence of reflectance on the geometry on the illumination and observation (Schaepman-Strub et al., in this volume), varies between different materials, and thus if a single BRDF model is used to normalize topographic variations in an area of varying land cover properties, the calculated reflectances may have cover-dependent errors.

SELECTING IMAGES WITH OPTIMAL TEMPORAL PROPERTIES

Scale and image temporal properties

The application of the concept of scale to image temporal properties is somewhat more complex than in the spatial and spectral domains. Normally, an image is acquired in a single, very short period of time, which might be referred to as the temporal scale extent. If only one image is considered, the grain and extent are identical. On the other hand, the concept of temporal scale is very useful for discussing multitemporal image archives, as well as for characterizing change detection and time series analyses. The temporal *extent* of an archive is quite straightforward, and is the overall period of time covered. However, the temporal *grain* can potentially refer to two different attributes. In the case of a series of individual images, the grain might be the period *between* the image acquisition dates. However, for coarse resolution data, single bands are often generated on a pixel by pixel basis from multiple sequential images, using algorithms that minimize the effects of cloud. For such data, the final image represents a multitemporal composite, where each pixel has been individually selected from the images acquired during the compositing period (Holben 1986). Thus, at least for multitemporal composited data, grain could also refer to *the period of time over which the image data have been integrated.* For example, a compositing period of a week or a month is often used to generate some image data products (Justice et al. 2002).

Cloud-free multitemporal composites have been found to be particularly useful for characterizing the annual pattern of ecosystem response to annual weather patterns (Loveland et al. 1995). For example, the date of onset of greenness, total integrated greenness over time, and maximum greenness, have been used to classify different land cover classes. By extending such studies over multiple years, apparent changes in climate have been observed, including an earlier spring greenup at high latitudes (Myneni et al. 1997, Delbart et al. 2006). However, Schwartz et al. (2002) have cautioned that the integration of data over a week or longer periods can result in uncertainty and bias in the phenological trends identified.

For change detection studies, the temporal extent of the available image archive constrains the period over which change can be observed. Thus, the Landsat TM and ETM+ sensors provide a particularly important long term data set, with a temporal extent of over 25 years (Goward et al., in this volume). The temporal extent of change detection studies can be extended back to 1972 by using Landsat MSS imagery, and for some areas, to as early as 1960, by using declassified CORONA imagery, although the latter are mostly digitized black and white film. However, for change detection studies, images from different sensors should be used with caution, because it can be challenging to differentiate between real changes in the scene, and changes in the sensors.

The grain, or revisit period of the sensor, also constrains the potential differentiation of events within the period studied. However, the actual availability of cloud free imagery is usually some small fraction of what might be assumed based on only the sensor revisit time.

Image acquisition frequency

Finding recent imagery tends to be an important consideration for some applications. Procedures for satellite data collection vary greatly between the nadir viewing sensors, such as Landsat ETM+, and pointable satellites, a category which includes all fine resolution sensors, such as IKONOS and WorldView. For nadir-viewing sensors, the operators usually attempt to acquire and archive all images on a systematic basis, at least when the satellite is within sight of a receiving station. Landsat ETM+ is unique in that the operators have a policy of acquiring multiple global data sets on a regular basis (Goward et al., in this volume). For pointable satellites, image acquisition is prioritized based on requests from customers, who pay a premium for tasking the satellite. Thus, archive imagery is only available over limited areas, and new acquisitions may be delayed depending on the priorities of the operator. These same issues tend to apply to other sensors that have only a limited acquisition capability, such as ASTER and HYPERION.

Obtaining images of the appropriate season is also important. This is particularly true of vegetation studies, where the timing of phenological events such as leaf out and senescence may be as valuable as spectral information (Key et al. 2001).

Geostationary satellites, such as European EuMetSat's Meteosat Second Generation (MSG) satellites and the planned US National Polar-orbiting Operational Environmental Satellite System (NPOESS) satellites, offer the greatest potential for high frequency of coverage. For example METOSAT-9 acquires full disk images of Earth every 15 minutes, and in rapid scanning mode, where only part of the Earth disk is imaged, images can be acquired even more frequently. The trade-off with geostationary sensors is the comparatively low spatial resolution, for example 1–3 km pixels at the sub-satellite point for the METEOSAT Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument. Nevertheless, this high temporal frequency of acquisition opens the possibility for completely new remote sensing applications associated with highly dynamic phenomena, such as modeling the growth and development of individual fires (Umamaheshwaran et al. 2007).

Airborne sensors (Stow et al., in this volume) can provide high spatial resolution as well as complete user-control of acquisition timing, including not just the date, but even time of day. In practice, however, mobilization and operational costs may limit the degree to which the user can achieve this flexibility.

Acquisitions for time-critical events

Time-critical applications of remote sensing include disaster response (Teeuw et al., in this volume) and precision agriculture (Nellis et al., in this volume) support. When timing is critical, pointable sensors clearly have advantage over nadir viewing sensors in that they have a shorter potential revisit period.

For disaster response, a rapid delivery of analyzed imagery requires a series of expedited responses, starting with emergency tasking of the satellite, pre-preprocessing by the satellite operator, and internet-based data delivery. Following receipt of the data, the analyst may need to perform additional georeferencing work before interpretation can be done. Because time is normally very limited, relatively routine or simple methods are necessary.

The fact that rapid response requires some advance planning and organization is demonstrated by the establishment of the International Charter on Space and Major Disasters (International Charter 2007, Harris, in this volume, Teeuw et al., in this volume). This agreement, initiated by the French, European, and Canadian space agencies in 2000, now includes the space agencies of six other countries, and additional agreements with commercial satellite operators. The charter provides for 24-hour availability of a single point of contact for requesting emergency remote sensing support. In France, the organization Service Régional de Traitement d'Image et de Télédétection (SERTIT) has been contracted by the French space agency, CNES, to provide 24-hour availability of image analysts (SERTIT 2005). SERTIT places its image map products on a website, for free download (http://sertit.u-strasbg.fr/documents/RMS_page_garde/RMS_page_garde.htm).

Of course, data currency is a concern not just in disaster response, but in all applications studying dynamic phenomena. Satellite images typically require preprocessing by the data provider prior to being made available to the user. Additional bottlenecks may occur in the distribution, although internet access to the data can overcome this problem.

INTERACTIONS BETWEEN DIFFERENT COMPONENTS OF SCALE

So far, the discussion has been limited to each of the different components of scale: spatial, spectral, temporal, and radiometric. However, clearly, these components are linked. For example, if image acquisition is constrained by the rate at which data are stored and transmitted, then increasing one type of resolution (such as spectral resolution), will necessarily require changes to other types of resolution (such as spatial resolution) (Figure 1.1). The Compact Airborne Spectral Imager (CASI), manufactured by ITRES of Canada, is a good example of an instrument that is designed to have maximum flexibility within the constraints of data acquisition trade-offs. CASI is a programmable sensor, in which the operator chooses the number, width, and location of spectral bands prior to image acquisition. Because longer integration times are needed as the number of bands imaged increases, there is an inverse relationship between the number of bands and the spatial resolution for this sensor (ITRES 2007).

Alternatively, it is possible in some instances to overcome the spatial-spectral constraint described above by employing pan sharpening, in which data fusion is used to combine high spatial resolution, panchromatic (i.e., single band) images with comparatively low spatial resolution, multispectral images (Alparone et al. 2007). Pan sharpening has become increasingly important since the SPOT sensors popularized the concept of acquiring simultaneous high spatial resolution panchromatic data to complement a lower spatial resolution multispectral data set, and this design approach has been followed for a number of subsequent sensors, including ETM+ (Goward et al., in this volume), IKONOS, and QuickBird (Toutin, in this volume). The aim of pan sharpening is quite simple: to incorporate the spatial detail from the panchromatic image, and the spectral information from the multispectral images. The challenge, however, is to ensure that the combined data set maintains a spectral balance such that when the images are displayed as a color composite, the colors of the sharpened images are similar to the original, low spatial resolution multispectral data set (Alparone et al. 2007). This challenge is particularly great if the panchromatic band is poorly correlated with the individual multispectral bands (Gross and Schott 1998, Price 1999).

Pohl and Van Genderen (1998) provide a comprehensive review of pan sharpening methods. Alparone et al. (2007) empirically compared eight different methods, and found that multiresolution analysis, incorporating for example wavelets or Laplacian pyramids to characterize the spatial dependence of DN values on scale, generally outperformed component substitution, in which some transformed component of the multispectral data set, such as the first principal component, is replaced by the panchromatic data. In particular, the two methods found to have the best results both take into account physical models of the image formation, namely the modulation transfer function (Alparone et al. 2007). Wang et al. (2005) use a theoretical framework, which they term general image fusion, to compare the different methods, and conclude that the optimal method is multiresolution analysis-based intensity modulation. Pan sharpening using spectral mixture analysis also shows promise, especially for hyperspectral imagery (Gross and Schott 1998).

There are other complex interactions between the different types of resolution. Malila (1985) has found that, although the increased number and range of spectral bands of TM compared to MSS provide a great deal more information as indicated by studies of entropy, if both TM and MSS had been quantized at just five bits, the information content of the two sensors would have been approximately equal.

Key et al. (2001) compared the value of multiple spectral bands with multiple image dates for classifying individual deciduous trees species. Their study showed that a single, optimally chosen, multispectral image acquired during peak autumn colors resulted in relatively high classification accuracy. However, multiple dates of single band imagery could provide a similar high accuracy. This finding suggests that if the spatial resolution of multispectral imagery is too coarse, panchromatic imagery, which typically has a higher spatial resolution, may be substituted, if multiple dates can be obtained (Key et al. 2001). For example, the current highest spatial resolution from commercial satellites is provided by the WorldView-1 sensor, launched in 2007. WorldView-1 provides imagery with 0.5 m pixels, but only panchromatic data, with no multispectral bands (DigitalGlobe 2007).

OTHER ISSUES

Additional, broader issues should be considered in selecting image data sets. Data cost, particularly for the new commercial sensors, can be high. However, the commercial providers generally make a distinction between new acquisitions, which require tasking the satellite, and existing images in the companies' archives, charging a premium for the former. Commercial image licensing agreements may constrain sharing the data with others, even in the same organization. Thus purchasers should consider the long-term use of imagery, and consider paying extra to have more flexible use of the data. One of the major advantages of US government data, including Landsat TM, ETM+, and Terra and Aqua MODIS data, is not only the very economical price, but the absence of constraints on data sharing (Harris, in this volume). Indeed, large internet archives of US satellite imagery are available for free downloading (Table 1.2).

A second major issue relates to data volume. Large volumes of data can strain computer storage and processing capacity. Although this issue is far less significant today compared to when early sensing systems such as the Landsat MSS were launched, it is still important for projects that cover relatively large geographic areas, or use multiple dates of images.

In addition to improvements in computer hardware, software has also advanced considerably since the early 1970s. Early programs, typically running on main-frame computers, often were based on command-line program initiation. Today, remote sensing packages typically have graphical user-interfaces, and even semi-automated 'wizards' that help guide the less sophisticated users. Furthermore, there are now specific programs for advanced analysis such as for photogrammetry and hyperspectral classification. On the other hand, the development of software that integrates remote sensing analysis and GIS analysis has been more mixed (Merchant and Narumalani, in this volume).

FUTURE CHALLENGES AND OPPORTUNITIES

It is evident that the number and diversity of satellite-borne sensors will only grow in future years, especially as the commercial satellite sector grows, and additional nations launch and operate their own satellite programs. Thus, the challenges, and opportunities, in selecting data to address specific problems, will also likely grow. Some specific trends can be observed with regards to image spatial and spectral properties, as well as the availability of relatively new types of image data.

With regards to spatial resolution, it appears for the moment that ~0.5 m is the smallest pixel size of space-borne imagery that will be available to non-government users, due to security issues. Thus, the operating licenses for both Worldview-1 (DigitalGlobe 2007) and the planned GEOEYE-1 (GeoEye 2007) limit the spatial resolution of imagery that is sold to the general public to 0.5 m.

In terms of spectral properties, one likely future development is finally to achieve operational hyperspectral imaging from space. For the user, space-based hyperspectral imagery should be more economical than contracting for airborne hyperspectral data. An operational satellite-borne hyperspectral system will also remove the geographical constraints of the narrow swath of the experimental satellite-based Hyperion hyperspectral sensor. Once these financial and geographical barriers are removed, hyperspectral analysis may enter the mainstream, especially if there is continued improvement in the ease of use of hyperspectral software analysis tools. Nevertheless, limits on the signal-to-noise and spatial resolution for space-based hyperspectral sensors may ensure that aerial hyperspectral imaging will continue to play an important role for some time to come.

Another area of likely future importance, and challenge to users, will be greater integration of diverse wavelength regions and characteristics, including hyperspectral VNIR and SWIR,

Table 1.2 ***Sources of free imagery***

Facility	*Example data*	*URL*[1]
Global Land Cover Facility, University of Maryland	TM, MSS, MODIS, ASTER	http://glcf.umiacs.umd.edu
AmericaView	Landsat	http://glovis.texasview.org
USGS EROS	Landsat	http://edc.usgs.gov/products/satellite/landsat_ortho.html
USGS-NASA DataPool	ASTER, MODIS	http://lpdaac.usgs.gov/datapool/datapool.asp
Boston University Climate and Vegetation Group	AVHRR, MODIS	http://cliveg.bu.edu/modismisr/products/products.html
Boston University Land Cover and Land Cover Dynamics	MODIS	http://duckwater.bu.edu/lc/datasets.html

[1] URLs current as of January 2008.

hyperspectral thermal, and multi-wavelength, fully polarimetric radar. The integration of lidar with multispectral and hyperspectral imagery seems a particularly promising area (Bork and Su 2007).

Relatively new types of data will also likely become more available, although once again the general exploitation of these data may be dependent on the development of easy to use software. Polarization information, currently used mainly with microwave wavelengths, holds promise for improved image analysis of optical wavelengths (Zallat et al. 2004). Multi-angular imaging, already available from the Multiangle Imaging SpectroRadiometer (MISR) experimental satellite, allows characterization and exploitation of BRDF information (Armston et al. 2007, Jovanovic et al. 2007). One particularly interesting application of BRDF information is for mapping wetlands by exploiting the distinctive and strong angular reflection signature of water compared to other surface types. This approach has been shown to be effective for discriminating inundated areas with emergent vegetation, open water, and non-inundated areas (Vanderbilt et al. 2002). One strength of this approach is that as the pixel size increases, the accuracy of unmixing the proportions of these cover types tends to increase (Vanderbilt et al. 2007), making the method particularly effective for global-scale hydrological modeling.

In conclusion, remote sensing has advanced greatly since the early 1970s and since the beginnings of regular satellite Earth observations with the ERTS/Landsat MSS sensor. The many advances in remote sensing technology have themselves brought new challenges, as exemplified by issues such as the Hughes Phenomenon (Hughes 1968). Although many of these challenges can be addressed through innovative research, one area outside the control of most individual scientists is the general area of remote sensing policy (Harris, in this volume). For example, despite the importance of data continuity in global change studies, there unfortunately seems to be a lack of political will, at least in the United States, to support an aggressive, long term strategy to ensure data continuity for moderate resolution imaging. This problem has recently been highlighted by the difficulties associated with the Landsat Data Continuity Mission (Goward et al., in this volume). Despite these difficulties, remote sensing offers a powerful, objective, and consistent tool for studying the earth, from local to global scales. The value of remote sensing is demonstrated by the growing number of research studies, and the increasing use of remote sensing in operational environments. The chapters that follow give insight into the many facets and key issues of this rapidly developing subject.

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2

Remote Sensing Policy

Ray Harris

Keywords: global policies, access, government, pricing, geospatial data, United States, Europe, India, Japan.

INTRODUCTION

> Policy: (1) a course or principle of action adopted or proposed by an organization or an individual; (2) prudent or expedient conduct or action. Origin: from the French *police*–bill of lading, contract of insurance. *Oxford English Dictionary*

> Act so as to produce the greatest good for the greatest number. *The Principle of Utility*, Jeremy Bentham (1748–1832)

The history of satellite remote sensing has so far shown a commendable although unconscious example of Bentham's *Principle of Utility*, or *Utilitarianism* (Harte and North 2004). Satellite remote sensing missions have mainly been general purpose satellite missions, such as Landsat, designed to capture environmental data that can be used by anyone with the knowledge and technical capability to do so. Sometimes policy development has preceded this technical capability and sometimes followed it, but remote sensing policy has in general been characterized by utilitarianism, that is the greatest good for the greatest number.

Remote sensing policy is mainly written by governments in some form, be it through national legislation as in the USA or through national representation in international organizations, such as the European Space Agency (ESA) or Eumetsat. In that sense remote sensing is often an extension of national policy. The USA is a good case in point. Each fiscal year a report is sent to the US Congress entitled *Our Changing Planet* (CCSP 2006). The report, which summarizes a great deal of US remote sensing research and applications, describes the activities and the plans of the Climate Change Science Program that was established under the US Global Change Research Act of 1990 and the US Climate Change Research Initiative established by the US President in 2001. While the report has the appearance of a science progress report it has a foundation in national government policy that is part of a wider US policy landscape, for example on science, national security and industry privatization. The report *Our Changing Planet* is transmitted each year to the US Congress by the Secretaries of State for Commerce and for Energy, both political appointments, together with the Director of the Office for Science and Technology Policy of the Executive Office of the President. Where governments appear not to be directly involved in remote sensing policy they still have a responsibility for regulation or licencing. Fine spatial resolution missions such as DigitalGlobe or IKONOS operate with a licence issued by the US government which in turn relays the national commitments it has entered into as well as reflecting national government priorities.

Government influence is therefore important in understanding remote sensing policy. As different national governments around the world have different political complexions, and indeed political complexions that change over time, so remote sensing policies are different. The remote sensing policy debate is especially contentious within the Group on Earth Observation (GEO) initiative to the extent that the term 'data policy', a key part of remote sensing policy, is deliberately avoided and only the term 'data sharing' is allowed (Achache 2006). This book examines a very wide variety of remote sensing data, techniques to process the data and applications of the data. This chapter looks at remote sensing policy, trying to disentangle the ways in which the organizations responsible for providing the data examined in later chapters have come to their different views. This chapter will concentrate on data policy because this is where remote sensing policy has the greatest impact on access to and use of remote sensing data, while commenting on wider policy concerns where appropriate. The chapter opens by examining remote sensing policy agreements reached at the global scale, and then goes on to examine the policies developed in the USA and Europe as major organizational actors in remote sensing. A review of selected national policies is used to highlight differences in approach to policy, for example India's very clear concern with national security, before the conclusion points to critical tensions such as pricing policy and the overall sustainability of remote sensing.

Whether in the public sector or the private sector Bentham's *Principle of Utility* is without doubt an unconscious characteristic of remote sensing. One could go even further along the road of utilitarianism and argue that the comments of the Roman senator Cicero are also applicable to twenty-first century remote sensing (Oxford 1981):

> Salus populi suprema est lex
> [The good of the people is the chief law]

GLOBAL SCALE REMOTE SENSING POLICY

United Nations principles on remote sensing

On 3 December 1986 the United Nations (UN) reached agreement on the *UN Resolution Relating to the Remote Sensing of the Earth from Outer Space* (Jasentuliyana 1988, von der Dunk 2002). This Resolution contains 15 principles on remote sensing that were agreed as a compromise between the perspective of state territorial sovereignty and the principle of the freedom to use outer space that is embodied in the Outer Space Treaty.[1] Those nations that had satellite remote sensing capability both wanted and needed freedom to capture remote sensing data for any and all parts of the Earth. Some of those nations that lacked a satellite remote sensing capability wanted to control access to the outer space above their territory in much the same way as they controlled the air space above their territory (Harris and Harris 2006). This approach of control envisaged the concept of ownership extending to a limitless distance above a nation's territory and would have invited all organizations that orbited remote sensing spacecraft to seek the permission of each and every country to allow orbital passes over their country. The compromise between the points of view of open access and control was the agreement of the 15 UN Principles on Remote Sensing. While all 15 principles are relevant to this book, four principles are particularly important.

> ***Principle I.*** *For the purposes of these principles with respect to remote sensing activities: (a) The term 'remote sensing' means the sensing of the Earth's surface from space by making use of the properties of electromagnetic waves emitted, reflected or diffracted by the sensed objects, for the purpose of improving natural resources management, land use and the protection of the environment.*

This first principle (of which only part (a) of five parts is reproduced here) provides a definition of the scope of the later principles. At the time of the agreement the UN principles were thought to apply to civil remote sensing only of the land surface, but since 1986 the term 'protection of the environment' has taken on a much wider meaning because of the concerns about climate change (IPCC 2007) and it is now difficult to identify which elements of the Earth system (ocean, ice, atmosphere, land) fall outside the scope of the protection of the environment. Principle I may therefore now be considered very wide in scope.

> ***Principle IV.*** *Remote sensing activities shall be … carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and stipulates the principle of freedom of exploration and use of outer space on the basis of equality. These activities shall be conducted on the basis of respect for the principle of full and permanent sovereignty of all States and peoples over their own wealth and natural resources, with due regard to the rights and interests, in accordance with international law, of other States and entities under their jurisdiction. Such activities shall not be conducted in a manner detrimental to the legitimate rights and interests of the sensed State.*

This principle strikes at the core of the dilemma noted above: the freedom of the use of outer space by those nations equipped to do so and the sovereignty that nations have over their own territory and resources.

> ***Principle XII.*** *As soon as the primary data and the processed data concerning the territory under its*

jurisdiction are produced, the sensed State shall have access to them on a non-discriminatory basis and on reasonable cost terms.

Principle XII means that space-faring nations cannot keep the remote sensing data collected by their space missions to themselves, and answers in part the question posed by Principle IV. Principle XII allows a state sensed by a remote sensing satellite to have access to the data collected by the satellite under three conditions: as soon as the data are produced; on a non-discriminatory basis; and on reasonable cost terms. None of these three conditions of access is tightly defined: the balance of issues around these three terms is discussed at length by Frans von der Dunk in Harris (2002).

Principle XIV. *… States operating remote sensing satellites shall bear international responsibility for their activities and assure that such activities are conducted in accordance with the provisions of the Treaty and the norms of international law, irrespective of whether such activities are carried out by governmental or non-governmental entities or through international organizations to which such States are parties. This principle is without prejudice to the applicability of the norms of international law on State responsibility for remote sensing activities.*

The UN principles were agreed between states, so are private companies and other organizations exempt? Principle XIV covers both governmental and non-governmental entities which brings private companies and other organizations into the scope and the legitimacy of the UN Principles. This principle therefore covers the authority of governments to grant licences to private companies such as DigitalGlobe and to participate in international organizations such as Eumetsat.

United Nations Charter Space and major disasters

As well as drawing up the set of 15 Principles the United Nations has been active in arranging major meetings of all UN member states to discuss the opportunities offered by the use of outer space. There have been three such major meetings called UNISPACE conferences. At the third UNISPACE conference in Vienna in 1999 the ESA and the French Space Agency (CNES) launched the idea of a UN Charter on Space and Major Disasters. The basic idea of the Charter is to provide a unified system of space data acquisition and delivery to those affected by natural or man-made disasters through the mechanism of authorized users. The UN Charter has two major objectives.

- Supply during periods of crisis, to states or communities whose population, activities or property are exposed to an imminent risk, or are already victims, of natural or technological disasters, data providing a basis for critical information for the anticipation and management of potential crises.
- Participation, by means of this data and of the information and services resulting from the exploitation of space facilities, in the organization of emergency assistance or reconstruction and subsequent operations.

Following the lead given by Europe other members have joined the Charter, namely Canada, India, Japan, the US National Oceanic and Atmospheric Administration (NOAA), US Geological Survey (USGS) and the participants in the Disaster Management Constellation of small satellites (Algeria, Nigeria, Turkey and the United Kingdom).

When a disaster strikes an authorized user can contact a single point to request satellite remote sensing data acquisition. The space agency members of the Charter then work together to plan image acquisitions and provide data of the disaster location to the authorized users free of all charges. Each year there are approximately 20–30 activations of the Charter, acquiring data of, for example, floods in Indonesia, a typhoon in the Philippines, an oil slick off the coast of Lebanon, an earthquake in Pakistan, the 2004 tsunami in the Indian Ocean and forest fires in Portugal. Further discussion on the use of remote sensing in disaster applications is given by Teeuw et al. (in this volume).

World Meteorological Organisation Resolution 40

A second policy related to remote sensing that is global in nature was that agreed by the World Meteorological Organisation (WMO) in 1995. At the Twelfth Meteorological Congress in Geneva in June 1995 the WMO passed 41 resolutions covering a wide range of its activities from the use of the Portuguese language to the Global Climate Observing System (WMO 1995). One of these resolutions, Resolution 40, states the WMO policy for exchanging meteorological data including remote sensing meteorological data. The policy applies to all 187 WMO member states and so is a policy that is global in reach. WMO Resolution 40 has at its core:

> As a fundamental principle …, WMO commits itself to broadening and enhancing the free and unrestricted international exchange of meteorological and related data and products.

Resolution 40 then provides advice to WMO member states on the practice of the resolution (WMO 1995):

> Members shall provide on a free and unrestricted basis essential data and products which are necessary for the provision of services in support of the protection of life and property and the well-being of all nations, particularly those basic data and products as … required to describe and forecast accurately weather and climate, and support WMO programmes.

Annexes to the resolution provide advice on how to implement the basic ideas of free and unrestricted access. The meteorological community has always practiced relatively unrestrictive exchange of weather data and this principle is followed through to cover meteorological remote sensing data. Resolution 40 is important in remote sensing policy because it provides a clear statement of one community's view of how remote sensing data should be regarded. There is an implicit assumption that meteorological remote sensing data are a public good (Samuelson 1954, Pearce 1995, Longhorn and Blakemore 2004, Miller 2007), an attractive idea in the development of the information society but an idea not without its problems such as financing the systems that deliver the data.

International Council for Science

In 2004, the International Council for Science (ICSU) published a report that is essentially a guidance document for science data policy (ICSU 2004). It covers all science data and information, identifying especially remote sensing data and biomedical data as exemplars of massive data sets that are presenting new challenges to science. The ICSU recommendations cover the roles of the public and private sectors in the production of scientific data and information, data rescue and safeguarding, interoperability, dissemination, intellectual property rights and funding. For remote sensing policy a key issue can be summed up in the recommendation on professional data management (ICSU 2004):

> The panel recommends that ICSU play a major role in promoting professional data management and that it foster greater attention to consistency, quality, permanent preservation of the scientific data record, and the use of common data management standards throughout the global scientific community.

This book is concerned with the acquisition, treatment and use of remote sensing data, yet these data are more than just digits. They are information resources about the state of the Earth, resources that are important in understanding the Earth both now and in the future. Professional approaches to data management will improve the access to remote sensing data and will improve the opportunity to gain a greater scientific and operational return on the large investments involved. The International Polar Year and the Electronic Geophysical Year (both having a focus on 2007–08) have been stimulated by the ICSU policy ideas in developing their own policies and frameworks for data, including policies on the legacy that will be left in the form of professionally archived data sets.

All users of remote sensing data benefit from improvements in policy definition because it means that the conditions of access are explicit and known. Initiatives such as Global Monitoring of Environment and Security (GMES) and Global Earth Observation System of Systems (GEOSS) increasingly rely on data that are robust and have a known pedigree, which in turn means that professional data management and clear data policies become essential to progress in the field of remote sensing.

UNITED STATES

The United States has the most developed and the most formal approach to remote sensing policy. The major national initiatives that incorporate remote sensing are frequently passed as national laws and are then subject to regular, formal review. The US has an overall law on access to all data produced by the Federal government. This is the Paperwork Reduction Act of 1995[2] that was made operational in the Office of Management and Budget (OMB) Circular A-130. The Act is relevant to remote sensing because it mandates that all data produced by the Federal government, including remote sensing data produced by federal agencies, should be provided to users with no restrictions and no copyright protection. This means that when a user acquires, for example, a Landsat ETM+ or a MODIS digital image then this data set can be provided to other users free of any copyright restrictions. By contrast this is not the case for SPOT (Satellite Pour l'Observation de la Terre) data which cannot be copied freely to other users by the initial purchaser. The general approach in the US is that the tax payer has paid once for remote sensing data and so to maximize the value of the data then they should be provided to as many users as can benefit from them with low barriers to use.

The US Climate Change Science Program (CCSP) was created in 2002 as a combination and integration of two government policy actions, the Global Change Research Act of 1990,[3] which was approved by Congress, and the Climate Change Research Initiative which was established by