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Part I

The Importance of Image Registration for Remote Sensing

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Introduction

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Despite the importance of *image registration* to data integration and fusion in many fields, there are only a few books dedicated to the topic. None of the current, available books is dedicated exclusively to image registration of Earth (or space) satellite imagery. This is the first book dedicated to this topic. The book surveys and presents various algorithmic approaches and applications of image registration in remote sensing. Although there are numerous approaches to the problem of registration, no single and clear solution stands out as a standard in the field of remote sensing, and the problem remains open for new, innovative approaches, as well as careful, systematic integration of existing methods. This book is intended to bring together a number of image registration approaches for study and comparison, so remote sensing scientists can review existing methods for application to their problems, and researchers in image registration can review remote sensing applications to understand how to improve their algorithms. The book contains invited contributions by many of the best researchers in the field, including contributions relating the experiences of several Earth science research teams working with operational software on imagery from major Earth satellite systems. Such systems include the Advanced Very High Resolution Radiometer (AVHRR), Landsat, MODerate resolution Imaging Spectrometer (MODIS), Satellite Pour l'Observation de la Terre (SPOT), VEGETATION, Multiangle Imaging SpectroRadiometer (MISR), METEOSAT, and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS).

We have aimed this collection of contributions at researchers and professionals in academics, government or industry whose work serves the remote sensing community. The material in this book is appropriate for a mixed audience of image processing researchers spanning the fields of computer vision, robotic vision, pattern recognition, and machine vision, as well as space-based scientists working in the fields of Earth remote sensing, planetary studies, and deep space research. This audience represents many active research projects for which the collaboration between image processing researchers and Earth scientists is essential, as the

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former try to solve the problems posed by the latter. A common language is not only appropriate but also needed. Our intent is to ensure that the material is accessible to both audiences. We have strived to provide a broad overview of the field, ranging from theoretical advanced algorithms to applications, while maintaining rigor by including basic (mathematical) definitions and equations.

In the Introduction we focus mainly on the basic essence of image registration and the main rationale for its pursuit in the domain of remote sensing. The individual contributions in the rest of the book cover extensively various ways in which image registration is carried out. Specifically, we will describe applications for which accurate and reliable image registration is essential, and briefly review their corresponding challenges. We will then define remote sensing, describe how remote sensing data are acquired, and consider characteristics of these data and their sources. Finally, we will summarize the overall contents of the book, and provide definitions of selected general terms used throughout the chapters.

1.1 A need for accurate image registration

Earth science studies often deal with issues such as predicting crop yield, evaluating climate change over multiple timescales, locating arable land and water sources, monitoring pollution, and understanding the impact of human activity on major Earth ecosystems. To address such issues, Earth scientists use the global and repetitive measurements provided by a wide variety of satellite remote sensing systems. Many of these satellites have been launched (e.g., the Earth Observation System (EOS) AM and PM platforms), while the launch of others is being planned (e.g., the Landsat Data Continuity Mission (LDCM)). All these systems support multiple-time or simultaneous observations of the same Earth features by different sensors. Viewing large areas of the Earth at very high altitudes by spaceborne, remote sensing systems provides global measurements that would not be available using ground or even airborne sensors, although these global measurements often need to be complemented by local or regional measurements to complete a more thorough investigation of the phenomena being observed.

Image registration for the integration of digital data from such disparate satellite, airborne, and ground sources has become critical for several reasons. For example, image registration plays an essential role in spatial and radiometric calibration of multitemporal measurements for obtaining large, integrated datasets for the long-term tracking of various phenomena. Also, change detection over time or scale is only possible if multisensor and multitemporal data are accurately calibrated through registration. Previous studies by Townshend *et al.* (1992) and Dai and Khorram (1998) showed that even a small error in registration may have a large impact on the accuracy of global change measurements. For example, when

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looking at simulated data of MODIS at 250-m spatial resolution, a misregistration error of one pixel can produce a 50% error in the computation of the Normalized Difference Vegetation Index (NDVI). Another reason for integrating multiple observations is the resulting capability of extrapolating data throughout several scales, as researchers may be interested in phenomena that interact at multiple scales, whether spatial, spectral, or temporal. Generally, changes caused by human activity occur at a much faster rate and affect much larger areas. For all these applications, very accurate registration, that is, *exact pixel-to-pixel matching of two different images or matching of one image to a map*, is one of the first requirements for making such data integration possible.

More generally, image registration for remote sensing can be classified as follows:

(1) *Multimodal registration*, which enables the integration of complementary information from different sensors. This suits, for example, land cover applications, such as agriculture and crop forecasting, water urban planning, rangeland monitoring, mineral and oil exploration, cartography, flood monitoring, disease control, real-estate tax monitoring, and detection of illegal crops. In many of these applications, the combination of remote sensing data and Geographic Information Systems (GISs), see, for example, Cary (1994), and Ehlers (1995), shows great promise in helping the decision-making process.
(2) *Temporal registration*, which can be used for change detection and Earth resource surveying, including monitoring of agricultural, geological, and land cover features extracted from data obtained from one or several sensors over a period of time. Cloud removal is another application of temporal registration, when observations over several days can be fused to create cloud-free data.
(3) *Viewpoint registration*, which integrates information from one moving platform or multiple platforms navigating together into three-dimensional models. Landmark navigation, formation flying and planet exploration are examples of applications that benefit from such registration.
(4) *Template registration*, which looks for the correspondence between new sensed data and a previously developed model or dataset. This is useful for content-based or object searching and map updating.

Scientific visualization and virtual reality, which create seamless mosaics of multiple sensor data, are other examples of applications which are based on various types of registration, in particular, multimodal, temporal, and viewpoint registration.

1.2 What is image registration?

As a general definition, image registration is the process of aligning two or more images, or one or more images with another data source, for example, a map

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containing vector data. An image is an array of single measurements, and alignment is provided by a mathematical transformation between geometric locations in two image arrays. To be mutually registered, two images should contain overlapping views of the same ground features. In the basic case, one image may need to be translated, or translated and rotated, to align it with the other. The problem of image-to-image registration is illustrated in Fig. 1.1, which shows a reference image, extracted from an IKONOS scene over Washington, DC, with a corresponding translated and rotated image. In later chapters we will consider complex transformations, beyond translation and rotation, for alignment of the images.

Image registration involves locating and matching similar regions in the two images to be registered. In manual registration, a human carries out these tasks visually using interactive software. In automatic registration, on the other hand, autonomous algorithms perform these tasks. In remote sensing, automated procedures do not always offer the needed reliability and accuracy, so manual registration is frequently used. The user extracts from both images distinctive locations, which are typically called *control points* (CPs), tie-points, or reference points. First, the CPs in both images (or datasets) are interactively matched pairwise to achieve correspondence. Then, corresponding CPs are used to compute the parameters of a geometric transformation in question. Most available commercial systems follow this registration approach. Manual CP selection represents, however, a repetitive, laborious, and time-intensive task that becomes prohibitive for large amounts of data. Also, since the interactive choice of control points in satellite images is sometimes difficult to begin with, and since often too few points, inaccurate points, or ill-distributed points might be chosen, manual registration could lead to large registration errors. The main goal of image registration research, in general, is to improve the accuracy, robustness, and efficiency of fully automatic, algorithmic approaches to the problem. Specifically, the primary objective of this book is to review and describe the main research avenues and several important applications of automatic image registration in remote sensing.

Usually, automatic image registration algorithms include three main steps (Brown, 1992):

(1) Extraction of distinct regions, or *features*, to be matched.
(2) *Matching* of the features by searching for a transformation that best aligns them.
(3) *Resampling* of one image to construct a new image in the coordinate system of the other, based on the computed transformation.

Automatic approaches differ in the way they solve each step. One algorithm may extract simple features, but use a complex matching strategy, while another may use rather complex features, but then employ a relative simple matching strategy. Chapter 3 provides a survey of many current automatic image registration methods,

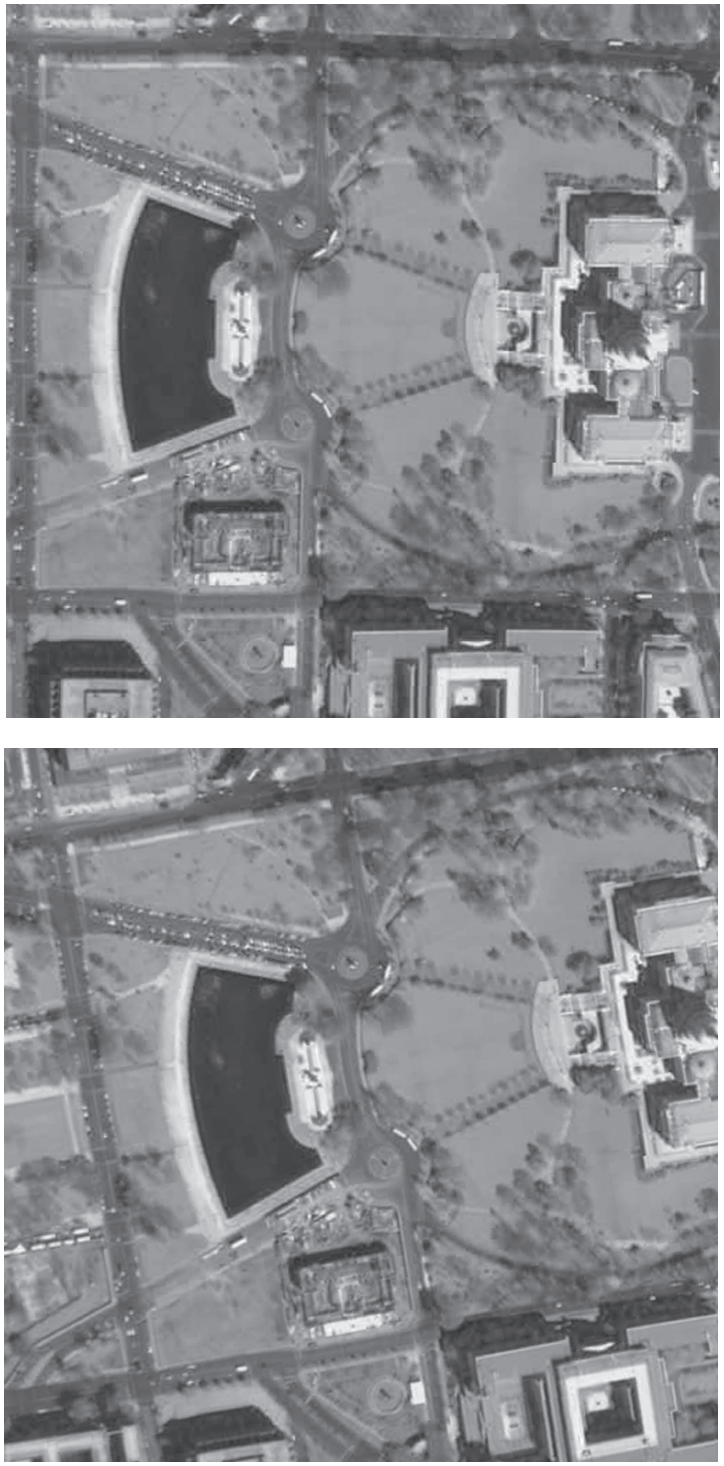

Figure 1.1. A reference image and its transformed image, extracted from an IKONOS scene acquired over Washington, DC. See Plate 1 in color plates section. (IKONOS satellite imagery courtesy of GeoEye. Copyright 2009. All rights reserved.)

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focusing mainly on their feature extraction and matching steps. Additional chapters discuss particular algorithmic approaches, and several other chapters describe ground control systems successfully implemented for satellite systems.

This book mainly deals with feature extraction and matching. While feature extraction and matching must be integrated, resampling is performed post-matching and can be handled relatively independently. For some applications, this step is replaced by an indexing of the incoming data into an absolute reference system, for example, a (latitude, longitude) reference system for Earth satellite data. Doing so preserves the original data values, which can be important for scientific applications. When several data sources are integrated, the resampling step can be replaced or supplemented by the fusion process. Finally, an automatic method may have two resampling stages. A temporary stage is used during matching to increase the similarity of the two images, but its results are discarded while a second, more accurate phase is used for the production of the final image product.

More generally, for all the applications described in Section 1.1, the main requirements from an image georegistration system are accuracy, consistency (i.e., robustness), speed, and a high level of autonomy that will facilitate the processing of large amounts of data in real time. With the goal of developing such a system, the purpose of this book is to examine the specific issues related to image registration in the particular domain of remote sensing, and to describe the methods that have been proposed to solve these issues. Before describing these methods, we first look at how remote sensing data are being acquired.

1.3 Remote sensing fundamentals

Remote sensing can be defined as the process by which information about an object or phenomenon is acquired from a remote location (e.g., an aircraft or a satellite). More specifically, satellite/sensing imaging refers to the use of sensors located on spaceborne platforms to capture electromagnetic energy that is reflected or emitted from a planetary surface such as the Earth. The Sun, as all terrestrial objects, is a source of energy. The sensors are either *passive* or *active*, that is, all energy which is observed by passive satellite sensors originates either from the Sun or from planetary surface features, while active sensors, such as radar systems, utilize their own source of energy to capture or image specific targets.

All objects give off radiation at all wavelengths, but the emitted energy varies with the wavelength and with the temperature of the object. A *blackbody* is an ideal object that absorbs and reemits all incident energy, without reflecting any. According to Stefan-Boltzman's and Wien's displacement laws (Lillesand and Kiefer, 1987; Campbell, 1996), a *dominant wavelength*, defined as the wavelength at which the total radiant exitance is maximum, can be computed for all blackbodies.

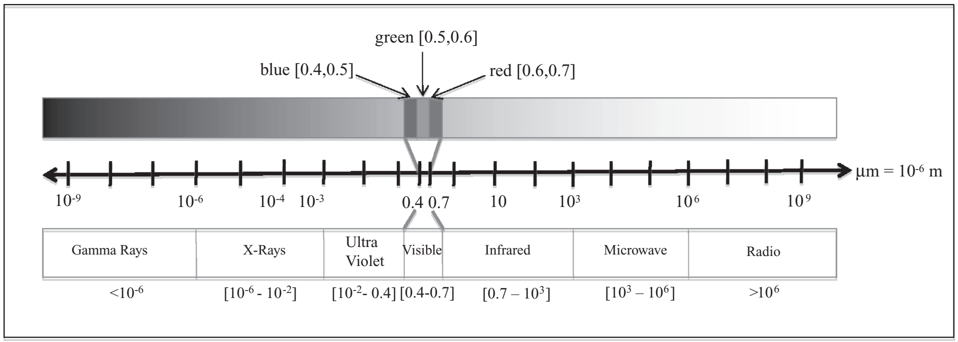

Figure 1.2. Electromagnetic spectrum. See Plate 2 in color plates section.

Assuming that the Earth and the Sun behave like blackbodies, their respective dominant wavelengths are 9.7 mm (in the infrared (IR) portion of the spectrum) and 0.5 mm (in the green visible portion of the spectrum). This implies that the energy emitted by the Earth is best observed by sensors which operate in the thermal infrared and microwave portions of the electromagnetic spectrum, while Sun energy which has been reflected by the Earth predominates in the visible, near-infrared and mid-infrared portions of the spectrum. As a consequence, most passive satellite sensing systems operate in the visible, infrared, or microwave portions of the spectrum (Lillesand and Kiefer, 1987; Le Moigne and Cromp, 1999). See Fig. 1.2 for a summary of the above electromagnetic spectrum wavelengths definitions.

1.3.1 Characteristics of satellite orbits

Different orbiting trajectories may be chosen for a satellite depending on many requirements, including the characteristics of the sensors, the data acquisition frequency, the required spatial resolution, the necessary ground coverage, and the type of observed phenomenon. The two most common orbiting modes are usually referred to as *polar orbiting* and *geostationary* (or *geosynchronous*) satellites. A polar orbit passes near the Earth's North and South Poles. Some examples are the Landsat and SPOT satellites whose orbits are almost polar, passing above the two poles and crossing the Equator at a small angle from normal (e.g., 8.2° for the Landsat-4 and Landsat-5 spacecraft). If the orbital period of a polar orbiting satellite keeps pace with the Sun's westward progression compared to the Earth's rotation, these satellites are also called *Sun-synchronous*, that is, a Sun-synchronous satellite always crosses the Equator at the same local Sun time. This time is usually very carefully chosen, depending on the application of the sensing system and the type of features which will be observed with such a system. Atmospheric scientists prefer observations later in the morning to allow for cloud formation, whereas researchers performing land studies prefer earlier morning observations to minimize cloud cover. On the other hand, a geostationary satellite has the same angular velocity as the Earth, so its relative position is fixed with respect to the Earth. Examples of geostationary satellites are the Geostationary Operational Environmental Satellite (GOES) series of satellites orbiting the Earth at a constant relative position above the equator.

1.3.2 Sensor characteristics

Each new sensor is designed for specific types of features to be observed, with requirements that define its spatial, spectral, radiometric, and temporal resolutions. This term of *resolution* corresponds to the smallest unit of granularity that can be measured by the sensor. The spatial resolution corresponds to the area on the ground from which reflectance is integrated to compute the value assigned to each pixel. The spectral resolution relates to the bandwidths utilized in the electromagnetic spectrum, and the radiometric resolution defines the number of "bits" that are used to record a given energy corresponding to a given wavelength. Finally, the temporal resolution corresponds to the frequency of observation, defined by the orbit of the satellite and the scanning of the sensor.

One of the main characteristics of sensors is their signal-to-noise ratio (SNR), or the noise level relative to the strength of the signal. In this context, the term *noise* refers to variations of intensity which are detected by the sensor and that are not caused by actual variations in feature brightness. If the noise level is very high compared to the signal level, the data will not provide an optimal representation of the observed features. At a given wavelength λ, the SNR is a function of the detector quality, as well as the spatial resolution of the sensor and its spectral resolution. Specifically,

$$(S/N)_\lambda = D_\lambda \beta^2 (H/V)^{1/2} \Delta_\lambda L_\lambda, \tag{1.1}$$

where

D_λ is the sensor detectivity (i.e., a measure of the detector's performance quality),
β is the instantaneous field of view,
H is the flying height of the spacecraft,
V is the velocity of the spacecraft,
Δ_λ is the spectral bandwidth of the channel (or spectral resolution), and
L_λ is the spectral radiance of the ground features.

Equation (1.1) demonstrates that maintaining the SNR of a sensor at an acceptable level often requires tradeoffs between the other characteristics of the sensor.

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For example, to maintain the same SNR while improving the spatial resolution by a factor of four (i.e., decreasing β by a factor of two), we must degrade the spectral resolution by a factor of four (i.e., increase Δ_λ by a factor of four). Note that there are additional factors not accounted for in Eq. (1.1), such as atmospheric interactions that also affect the signal-to-noise ratio.

Another way of characterizing Earth remote sensors is by the number of spectral bands of each sensor. In general, most Earth remote sensors are multispectral, that is, they utilize several bands to capture the energy emitted or reflected from Earth features. The addition of panchromatic imagery, which is usually of significantly higher spatial resolution than that of multispectral imagery in the visible part of the spectrum, provides higher quality detail information. Similarly, the number of bands in Landsat-4 and 5 was increased from four to seven (relative to Landsat-1 and 2) to include bands from the visible and thermal-IR range. The Landsat series was further extended with the introduction of Landsat-7, which contains an additional panchromatic band. Other sensors which provide coregistered, multispectral-panchromatic imagery are the Indian Remote Satellite-1 (IRS-1) sensor and SPOT.

Ideally, if a sensor had an infinite number of spectral channels, each observed area on the ground would be represented by a continuous spectrum and, therefore, could be identified from a database of known spectral response patterns. Practically, adding more bands and making each of them narrower is the first step towards realizing this ideal sensor. However, as previously explained by Eq. (1.1), it is very difficult to increase the number of bands without decreasing the signal-to-noise ratio. Due to recent advances in solid-state detector technology, it has become feasible to increase significantly the number of bands without decreasing the signal-to-noise ratio. This has led to the rise of new types of sensors, known as hyperspectral sensors. Usually, the criterion by which a sensor is regarded a multispectral or hyperspectral sensor is the number of bands (which can be as low as ten). Hyperspectral imaging refers typically to the simultaneous detection in hundreds to thousands of spectral channels, covering evenly a limited portion of the electromagnetic spectrum. The aim of hyperspectral sensors is to provide unique identification (or *spectral fingerprints*) capabilities for resolvable spectral objects. The NASA Earth Observing-1 (EOS-1) Hyperion sensor, launched in 2000, is the first spaceborne civilian hyperspectral sensor still flying. It spans 220 contiguous spectral bands from the visible to the infrared range (corresponding to a wavelength range of 0.4–2.5 mm). Hyperion data are currently used for scientific objectives related to land cover/land use activities, such as monitoring the global environment (e.g., deforestation) and climate change, disaster management, etc. Its targeting abilities complement those of other sensors, like MODIS, with a wider swath but lower spatial resolution.

Examples of different spectral and spatial resolutions are given in Table 1.1, with a focus on the operational Earth remote sensing systems described in Part IV of this book (Chapters 14–22). The table also provides information about the bandwidths and spatial resolutions of these sensors, whose spectral wavelength varies from the visible to the thermal-IR range.

Finally, another difference between sensors deals with their scanning mechanisms. Most Earth sensors utilize either across-track scanning or along-track scanning systems. Both types of scanning acquire data in scan lines that are perpendicular to the travel direction of the spacecraft. However, while cross-track scanners use a scanning mirror that rotates as it acquires the data, along-track scanners have a linear array of sensors that are “pushed along” the direction of travel (hence the term *pushbroom scanners*). Both types of scanning introduce errors that are corrected as part of the systematic correction step, although these corrections may include inconsistencies in the data radiometry, thereby creating errors in the registration process. Additional information about remote sensing can be found in several introductions to remote sensing, for example, Lillesand and Kiefer (1987), Campbell (1996), and Short (2009).

1.4 Issues involved with remote sensing image registration

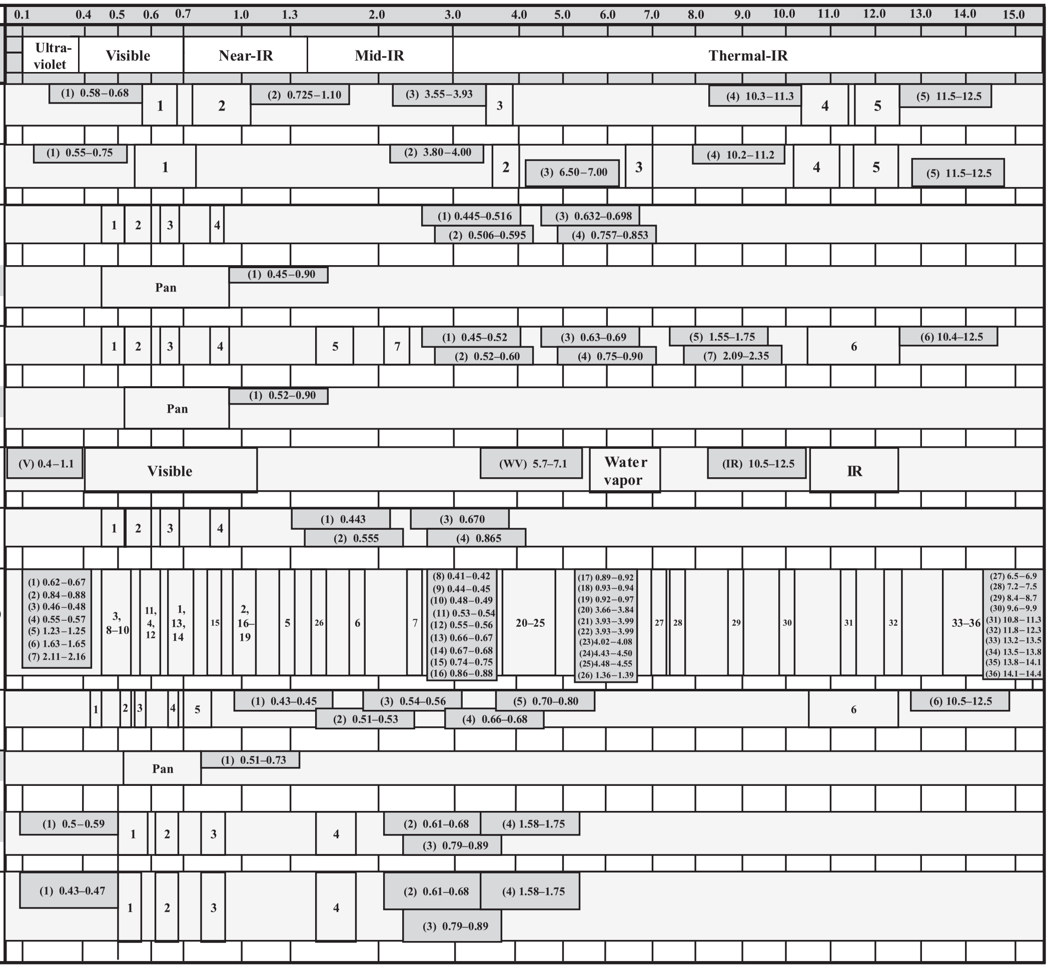
Once the data are collected and packaged, they are transmitted to the ground where they are unpacked and processed in a ground processing station. Another scenario involves more processing on board the spacecraft but in any case, after transmission from the satellites, raw data are usually processed, calibrated, archived, and distributed with some level of processing. Most of NASA’s satellite data products are classified according to the following data levels (Asrar and Dozier, 1994):

- *Level 0 data* are the reconstructed raw instrument data at full resolution.
- *Level 1A data* are reconstructed, time-reference raw data, with ancillary information including radiometric and geometric coefficients.
- *Level 1B data* are corrected Level 1A data (in sensor units).
- *Level 2 data* are derived geophysical products from Level 1 data, at the same resolution and location, e.g., atmospheric temperature profiles, gas concentrations, winds variables, etc.
- *Level 3 data* correspond to the same geophysical information as Level 2, but mapped onto a uniform space-time grid.
- *Level 4 data* are model output or results from prior analysis of lower-level data.

In Chapters 2–14 of this book, we will usually refer to image registration as performed on Level 1B data, which means that the spatial coordinates of image data have been computed according to a systematic correction using ancillary/ephemeris

Table 1.1 *Spatial and spectral characteristics of all operational sensors described in Part IV (Chapters 14–22)*

Instrument (Spat. Resol.)	*Number of Channels*	
AVHRR (1.1 km)	5 Channels	(1) 0.58–0.68 (2) 0.725–1.10 (3) 3.55–3.93 (4) 10.3–11.3 (5) 11.5–12.5
GOES (1 km:1, 4 km:2, 4&5, 8 km:3)	5 Channels	(1) 0.55–0.75 (2) 3.80–4.00 (3) 6.50–7.00 (4) 10.2–11.2 (5) 11.5–12.5
IKONOS (4 m)	4 Channels	(1) 0.445–0.516 (2) 0.506–0.595 (3) 0.632–0.698 (4) 0.757–0.853
IKONOS Panchromatic (1 m)		(1) 0.45–0.90
Landsat-5&7/ TM&ETM+ (30 m, except Ch6: 120 m)	7 Channels	(1) 0.45–0.52 (2) 0.52–0.60 (3) 0.63–0.69 (4) 0.75–0.90 (5) 1.55–1.75 (7) 2.09–2.35 (6) 10.4–12.5
Landsat7-Panchromatic (15 m)		(1) 0.52–0.90
METEOSAT (V:2.5 km, WV&IR:5 km)	3 Channels	(V) 0.4–1.1 (WV) 5.7–7.1 (IR) 10.5–12.5
MISR (275 m to 1.1 km)	4 channels x 9 cameras = 36	(1) 0.443 (2) 0.555 (3) 0.670 (4) 0.865
MODIS (Ch1–2:250 m; 3–7:500 m; 8–36:1 km)		(1) 0.62–0.67 (2) 0.84–0.88 (3) 0.46–0.48 (4) 0.55–0.57 (5) 1.23–1.25 (6) 1.63–1.65 (7) 2.11–2.16 (8) 0.41–0.42 (9) 0.44–0.45 (10) 0.48–0.49 (11) 0.53–0.54 (12) 0.55–0.56 (13) 0.66–0.67 (14) 0.67–0.68 (15) 0.74–0.75 (16) 0.86–0.88 (17) 0.89–0.92 (18) 0.93–0.94 (19) 0.92–0.97 (20) 3.66–3.84 (21) 3.93–3.99 (22) 3.93–3.99 (23)4.02–4.08 (24)4.43–4.50 (25)4.48–4.55 (26) 1.36–1.39 (27) 6.5–6.9 (28) 7.2–7.5 (29) 8.4–8.7 (30) 9.6–9.9 (31) 10.8–11.3 (32) 11.8–12.3 (33) 13.2–13.5 (34) 13.5–13.8 (35) 13.8–14.1 (36) 14.1–14.4
SeaWiFS (1.1 km)	8 Channels	(1) 0.43–0.45 (2) 0.51–0.53 (3) 0.54–0.56 (4) 0.66–0.68 (5) 0.70–0.80 (6) 10.5–12.5
SPOT-5-HRV Panchromatic (5 m)	1 Channel	(1) 0.51–0.73
Spot-5-HRG (10 m, except Ch. 4: 20 m)	4 Channels	(1) 0.5–0.59 (2) 0.61–0.68 (3) 0.79–0.89 (4) 1.58–1.75
VEGETATION (1.165 km)	4 Channels	(1) 0.43–0.47 (2) 0.61–0.68 (3) 0.79–0.89 (4) 1.58–1.75



data from the spacecraft. In short, by determining where the satellite is pointing while acquiring an image, the image can be given approximate ground coordinates. This type of correction is also sometimes referred to as *navigation*, since it is based on a *navigation model* that takes into account parameters such as the type, orientation, and shape of a satellite orbit (Logsdon, 1997).

During satellite ground processing, image registration is typically used for *precision correction*. The navigation model may have systematic or random errors, and it does not report where the satellite is pointing within the desired accuracy. Precision correction is the process of correcting these errors by registering an image to known ground features (such as a specific coastline or river). In other words, while systematic correction is model-based, image registration is feature-based. Depending on the age and the type of remote sensing systems, the accuracy of the systematic correction can be within a few pixels up to a few tens of pixels. Recent navigation models that utilize information from the Global Positioning System (GPS) (El-Rabbany, 2002) are usually accurate within a few pixels. Nevertheless, errors might still occur, for example, during a spacecraft maneuver. In contrast, the desired, ultimate accuracy is typically on the order of fractions of a pixel. For example, it is crucial for registration applications such as change detection to reach subpixel accuracy. Thus, image registration is used in all remote sensing systems to refine the initial geolocation accuracy to the desired subpixel accuracy level.

Although many image registration methods have been developed in other domains, such as applied medical imaging, very few automatic methods – let alone an underlying, systematic approach – exist within a remote sensing framework. The reason for this is related mainly to issues that are very specific to the remote sensing domain, and are summarized below.

Remote sensing vs. medical or other type of imagery Compared to medical images, remote sensing imagery offers various characteristics that make image registration more difficult.

(1) *The variety in the types of sensor data and the conditions of data acquisition*. A technique that appears to work accurately on satellite imagery acquired at a given time over some given location may not perform as well on data from the same sensor at other times or over another location.

(2) *The size of the data*. For example, a typical Landsat scene is of size 7000 × 7000 pixels on average, containing 7 bands whose wavelength varies from the visible to the thermal infrared range. Handling such amounts of data in real-time must take into account computational requirements such as speed and memory. As a consequence, the implementation of such methods on parallel, distributed or even onboard computers must be considered.

(3) *The lack of a known image model*. Similarly to fiducial points, a very rough sketch of a city, containing a river or a network of roads, can be utilized as a global model to initiate the registration. However, this usually lacks the amount of detail and the degree of invariance to atmospheric conditions and seasonal variations that would be needed for subpixel registration accuracy.

(4) *The lack of well-distributed "fiducial points" resulting in the difficulty to validate image registration methods in the remote sensing domain*. Although, it is possible to use well-known landmarks such as the Washington Monument or the Tour Eiffel ("Eiffel Tower") as fiducial points, such landmarks are very rare, and are not evenly distributed around the globe. The key factor in any accuracy assessment of remote sensing data is linked to the ability to gather ground reference data independently of the remote sensing data themselves. The most reliable fashion would be to record actual GPS locations of various sites on the ground and link them to recorded image data. To be sufficiently accurate, though, millions of such locations should be recorded, and so this approach could become very tedious and prohibitively expensive. Additionally, depending on the time between the on-site ground reference gathering and the imaging of the area, the validity of the ground reference data may be lessened due to anthropomorphic or natural influences. Another approach is to compare the digital image with other sources of ground reference data, such as air photos or appropriate reference maps, provided that the features of interest are detectable using these sources. The degree of correspondence between the ground reference data and the measurement derived from the sensor data can then be compared for accuracy assessment. Other assessment methods, including manual registration, the use of synthetic data, and round-robin measurements, are discussed in later chapters, in particular, Chapter 14.

Navigation error Several types of errors may occur in the navigation-based correction, thus resulting in registration errors of the Level 1B data. First, errors may be introduced in the input parameters during spacecraft maneuvers. Sometimes these errors are not detected and corrected until a few days or even a few weeks after the maneuver. Additional errors occur when the spacecraft and the sensor themselves age and perform differently from the way they were modeled in the navigation model. All these errors generally do not impact the data distributed at a later time, since regular checks are usually performed using *ground control points* (GCPs). These errors affect, however, data being used in real or near-real time, for example in efforts that support disaster relief. More generally, these errors affect all data being transmitted in a *direct readout* mode, that is, data transmitted almost immediately after acquisition to any receiving station within the satellite footprint.

Atmospheric and cloud interactions The atmospheric effects on data fidelity depend on the distance travelled by the radiation through the atmosphere and on the

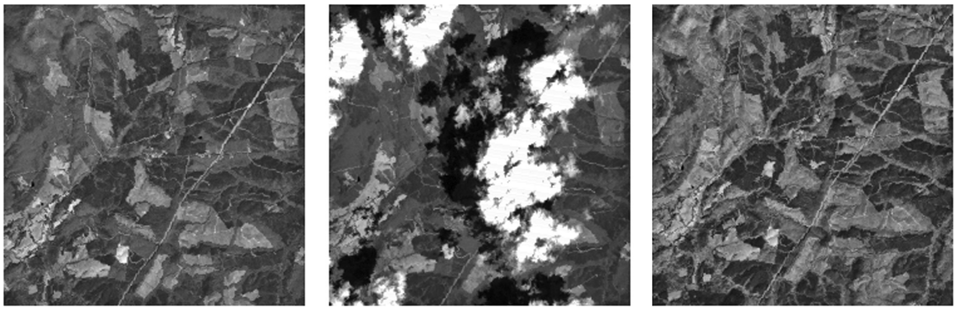


Figure 1.3. Three Landsat images over Virginia acquired in August, October, and November 1999. (Courtesy: Jeffrey Masek, NASA Goddard Space Flight Center.)

magnitude of the energy signal. The two main atmospheric effects are *scattering* and *absorption*. Earth remote sensors usually concentrate their observations within some *atmospheric windows* that are defined outside of the wavelengths of maximum atmospheric absorption. For each sensor, the spectral bands or *channels* are defined within these atmospheric windows while focusing on the phenomena to be observed. Most of the atmospheric effects, including atmospheric humidity and the concentration of atmospheric particles, are corrected by physical models, although effects related to altitude or local and temporal weather during data acquisition are usually not included in these models.

Another issue related to registration of remote sensing images deals with cloud interactions. When performing image registration, recognizing and discarding cloud features is often considered an important preprocessing step.

Multitemporal effects We distinguish between natural effects and human-induced effects that occur over time. The former consist of, for example, different lighting conditions due to the change in the Sun angle during the year. Also, the viewing angle of the instrument can change from pass to pass. And with seasonal changes, the surface reflectance varies with weather conditions, and land cover is altered as crops appear in different stages and deciduous trees change. Figure 1.3 illustrates the above type of effects. It shows three Landsat images (with cloud cover) over the same area of Virginia taken at three different months in 1999.

To all these natural temporal effects must be added human-induced effects related to activities such as urban development, agricultural practices, and deforestation. Figure 1.4, which shows two Landsat images taken over Bolivia in 1984 and 1998, illustrates the human-induced changes that can be observed over time. In view of the above multitemporal effects, whether natural or human-induced, certain features may not be visible from one image to the next, and may thus induce registration errors.

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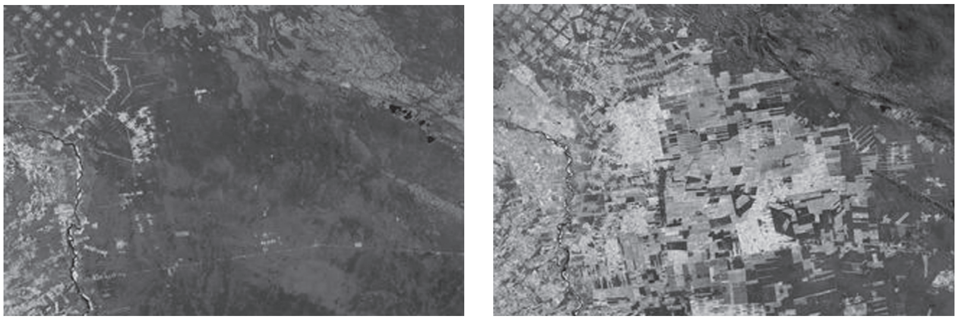

Figure 1.4. Human-induced land cover changes observed by Landsat-5 in Bolivia in 1984 and 1998. See Plate 2 in color plates section. (Courtesy: Compton J. Tucker and the Landsat Project, NASA Goddard Space Flight Center.)

Terrain/relief effect Another source affecting the registration of remote sensing imagery is the topography or the terrain. Various terrain features will be represented by variations in image brightness, in different ways, depending on the angle of illumination. This means that depending on the slope of the geographic relief, the characteristics of the sensor and the satellite orbit, and the time of the day, terrain relief effects might appear very differently in the images to be registered. Large topographic variations can be corrected using a terrain model but small local effects will still be present.

Multisensor (having different spatial and spectral resolutions) When dealing with multiple sensors, with different geometries and various spatial, spectral, radiometric and temporal resolutions (as described in Subsection 1.3.2), it is necessary to address the following image registration issues:

(1) Choice of geometric transformations that respond to various spatial resolutions and different scanning patterns.
(2) Extraction of image features that are invariant to radiometric differences due to multispectral and multitemporal resolutions.
(3) Choice of relevant channels when performing band-to-band registration (corresponding to approximate similar regions of the electromagnetic spectrum).

Figure 1.5 shows an example of terrain features observed at different times by the Landsat-7 Enhanced Thematic Mapper (ETM) and IKONOS over the Colorado Mountains. Note that some of the relief details are seen with IKONOS but not with ETM. This inconsistency is attributed to the different spatial resolution of the two sensors (i.e., 30 m for Landsat and 4 m for IKONOS).

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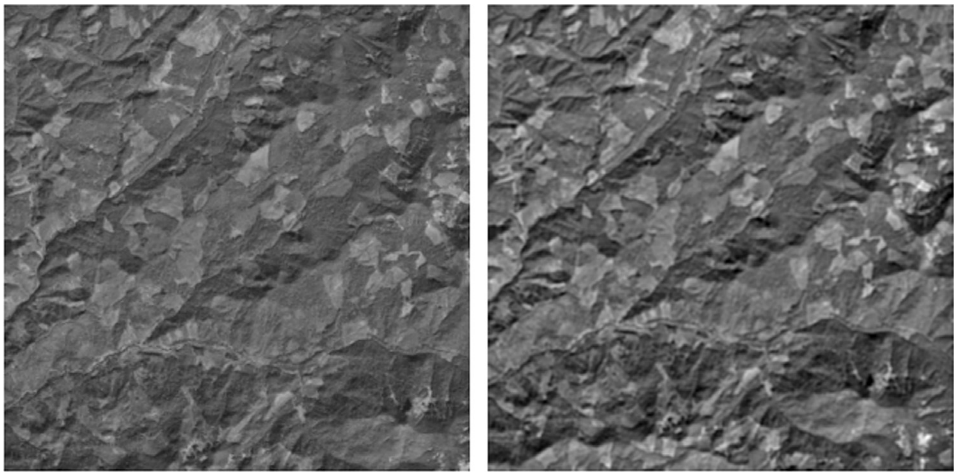

Figure 1.5. Two near-infrared bands of Landsat-7 (left) and IKONOS (right) taken over the CASCADES area, Colorado. (Courtesy: Jeffrey Morisette, USGS and EOS Validation Core Sites.)

1.5 Book contents

Overall, the book consists of four main parts. In Part I (Chapters 1–3), image registration for remote sensing is defined, explained, and surveyed. Chapter 2 examines the effects of misregistration on validation efforts. Other important misregistration effects (not described in Chapter 2) are those affecting change detection (Townshend *et al*., 1992; Dai and Khorram, 1998), and those that relate to weather forecasting, as well as political and legal issues, such as management of water resources or precise localization of property boundaries. Many of these topics are described in recent *IEEE Geoscience and Remote Sensing Symposium (IGARSS)* conferences. Chapter 3 provides a general overview of image registration, with special emphasis on the domain of remote sensing. In particular, it provides an extensive survey of current image registration methodologies, in the context of remote sensing.

Part II (Chapters 4–6) describes different possible choices of similarity metrics (Step (1) in Section 1.2), namely correlation, phase correlation, and mutual information. Methods based on these similarity measures are described from both a theoretical and practical standpoint, including their performance on synthetic and real data. Part III (Chapters 7–13) investigates Step (2) defined in Section 1.2. Specifically different choices of features (e.g., points, wavelets, contours, etc.) are discussed, and various feature-matching techniques and strategies, involving, for example, a hierarchical, multiresolution approach, robust feature matching, and different types of optimization. Finally, Part IV (Chapters 14–22) describes several remote sensing systems – most currently operational – with applications spanning many Earth remote sensing domains, such as land cover, meteorology, and geological and ocean studies, to name a few. The sensors that are studied in this part include IKONOS, Landsat, AVHRR, SPOT, and VEGETATION, which all focus mainly on land cover and urban studies; SeaWiFS, geared towards ocean color; GOES and METEOSAT, used for weather applications; and MISR and MODIS, which provide information about land surface and the atmosphere, at regional and global scales, for studies of the Earth climate.

1.6 Terminology

This section describes some of the terms used in the various chapters of the book, as the readers might find it useful to refer to this (alphabetically sorted) glossary when reading some of the subsequent chapters.

- ***Along-track scanning***

Uses a linear array of sensors that are “pushed along” the direction of travel (hence the term “pushbroom scanners”).

- ***Ancillary data***

Refer to the data from sources other than remote sensing that are used to analyze remote sensing data.

- ***Control point (CP) or ground control point (GCP)***

A point on the Earth surface whose location is known very accurately and that is used to georeference image data.

- ***Cross-track scanning***

Uses a scanning mirror that rotates as it acquires the data (hence the name “whiskbroom scanners”).

- ***Distributed Active Archive Center (DAAC)***

Centers that process, archive, and distribute data and products from NASA’s past and current Earth-observing satellites and field measurement programs. There are currently 12 DAACs, each serving a specific Earth system science discipline.

- ***Earth Observing System (EOS)***

A coordinated series of polar-orbiting and low-inclination satellites for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans.

- ***EOS data levels***

Level 0 data are the reconstructed raw instrument data at full resolution.
Level 1A data are reconstructed, time-reference raw data, with ancillary information including radiometric and geometric coefficients.
Level 1B data are corrected Level 1A data (in sensor units).
Level 2 data are derived geophysical products from Level 1 data, at the same resolution and location, e.g., atmospheric temperature profiles, gas concentrations, or winds variables.
Level 3 data correspond to the same geophysical information as Level 2, but mapped onto a uniform space-time grid.
Level 4 data are model output or results from prior analysis of lower-level data.

- ***Ephemeris data***

A set of parameters that are acquired onboard the spacecraft and that can be used to calculate accurately the location of a satellite.

- ***Field of view (FOV)***

The angle over which the sensor observes and records data.

- ***Geostationary (GEO) orbit***

A constant and circular orbit above the Equator, in which the satellite travels, in the same direction and at the same speed as the Earth, thus appearing to be *stationary* with respect to a specific location on the Earth.

- ***Geosynchronous orbit***

An orbit around the Earth whose period matches the Earth's rotation period, i.e., each point on the Earth is observed at the same time every day. A geostationary orbit is a special case of a geosynchronous orbit.

- ***Hyperspectral imaging***

Simultaneous detection or sensing in hundreds to thousands of spectral channels, covering almost completely a limited portion of the electromagnetic spectrum.

- ***Instantaneous field of view (IFOV)***

The smallest solid angle through which a sensor is sensitive to radiation. It is also related to the spatial resolution of the sensor and to its altitude.

- ***Line spread function (LSF)***

A detector's response to light from an ideal light source; defines the apparent shape of an object as it appears in the output image.

- ***Low-Earth orbit (LEO)***

An orbit of altitude lower than 2000 km.

- ***Medium-Earth orbit (MEO)***

An orbit usually above a low-Earth orbit and below a geostationary orbit (i.e., above 2000 km and below 35 786 km).

- ***Multispectral imaging***

Simultaneous detection in several bands (usually less than 10 or 20) covering separate portions of the electromagnetic spectrum.

- ***Point spread function (PSF)***

A measure of the geometric performance of an optical system; defines the apparent shape of a point as it appears in the output image.

- ***Polar orbit***

An orbit passing near the Earth's North and South Poles.

- ***Pushbroom scanner***

See along-track scanning.

- ***Radiometric resolution***

The number of "bits" used to record a given amount of energy corresponding to a given wavelength.

- ***Spatial resolution***

The area on the ground utilized to compute the value assigned to each pixel.

- ***Spectral resolution***

The bandwidths utilized in the electromagnetic spectrum.

- ***Sun-synchronous satellite***

A polar orbiting satellite that keeps pace with the Sun's westward progression compared to the Earth rotation; a Sun-synchronous satellite always crosses the Equator at the same local Sun time.

- ***Temporal resolution***

Corresponds to the observation frequency, defined by the orbit of the satellite and the scanning of the sensor.

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- ***Troposphere***

The lowest layer of the atmosphere; up to 10 km above the Earth and right below the stratosphere.

- ***United States Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS)***

Responsible for the processing systems that capture, correct, and distribute land remote sensing data, such as Landsat data products.

- ***Whiskbroom scanner***

See cross-track scanning.

1.7 Conclusion

As stated at the beginning of the Introduction, this book is aimed at several types of readers, including Earth scientists, image processing researchers, engineers, instructors, and students. With contents evolving from general overview material to theoretical descriptions of the separate components of image registration to specific studies of operational systems, the book chapters can be read sequentially, similarly to a textbook, or any one chapter can be read at a time, out of order, depending on the needs of the readers. We hope that readers will enjoy the material presented, as much as we enjoyed putting it together.

References

Asrar, G. and Dozier, J. (1994). *EOS: Science Strategy for the Earth Observing System*. New York: American Institute of Physics (AIP) Press.

Brown, L. G. (1992). A survey of image registration techniques. *ACM Computing Surveys*, **24**(4), 325–376.

Campbell, J. B. (1996). *Introduction to Remote Sensing*, 2nd edn. New York: Guilford Press.

Cary, T. (1994). A world of possibilities: Remote sensing data for your GIS. *Geo Info Systems*, **4**(9), 38–42.

Dai, X. and Khorram, S. (1998). The effects of image misregistration on the accuracy of remotely sensed change detection. *IEEE Transactions on Geoscience and Remote Sensing*, **36**(5), 1566–1577.

Ehlers, M. (1995). Integrating remote sensing and GIS for environmental monitoring and modeling: Where are we? *Geo Info Systems*, 36–43.

Le Moigne, J. and Cromp, R. F. (1999). Satellite imaging and sensing. In J. G. Webster, ed., *The Measurement, Instrumentation and Sensors Handbook*. Boca Raton, FL: CRC Press, pp. 73.42–73.63.

El-Rabbany, A. (2002). *Introduction to GPS: The Global Positioning System*. Norwood, MA: Artech House, Inc.

Lillesand, T. M. and Kiefer, R. W. (1987). *Remote Sensing and Image Interpretation*, 2nd edn. New York: John Wiley & Sons.

Logsdon, T. (1997). *Orbital Mechanics*. New York: John Wiley & Sons.

NASA Earth Science (2008). *Earth Science Data Terminology and Formats*. http://nasascience.nasa.gov/earth-science/earth-science-data-centers/earth-science-data-terminology-and-formats.

Short, N. M. (2009). *The Remote SensingTutorial*. http://rst.gsfc.nasa.gov/; also NASA Reference Publication 1078 and Library of Congress Catalog Card No. 81–600117.

Townshend, J. R., Justice, C. O., Gurney, C., and McManus, J. (1992). The impact of misregistration on change detection. *IEEE Transactions on Geoscience and Remote Sensing*, **30**(5), 1054–1060.