Chapter 5. Preprocessing in remote sensing

5.1 Introduction

Remote sensing images from spaceborne sensors with resolutions from 1 km to < 1 m become more and more available at reasonable costs. For some remote sensing sensors already large archives for periods over 20 year are available via the World Wide Web (e.g., Landsat, NOAA-AVHRR). This has resulted in the application of remote sensing in a large number of application fields ranging from agriculture, environmental monitoring, forestry to oceanography.

However, the remote sensing data acquisition process is affected by several factors that can decrease the quality of the images collected. This may have an impact on the accuracy of the image analysis. Image rectification and restoration aims to correct distorted and degraded image data to create a more faithful representation of the original scene. This step is often termed preprocessing because it normally precedes the actual image analysis that extracts information from an image for a specific application (see chapter 5: Image processing). Typical preprocessing operations include (1) radiometric preprocessing to adjust digital values for the effect of for example a hazy atmosphere, and/or (2) geometric preprocessing to bring an image into registration with a map or another image.

Although certain preprocessing procedures are frequently used, there can be no definitive list of “standard” preprocessing steps. Each application of remote sensing data requires individual choices on the preprocessing steps required. However, keep in mind that preprocessing changes the original data. Therefore, the choices should tailor preprocessing to the data at hand and the needs for the specific application, using only those preprocessing operations essential to obtain a specific result. For example, early image analysis in remote sensing often directly employed the digital numbers (DNs) produced by the sensor to estimate land surface variables like Leaf Area Index (LAI). It is now realized that for an accurate quantification of surface variables, preprocessing steps are required to convert DNs to physical quantities like radiance and reflectance. This means that when you would like to compare remote sensing images, taken at different observation dates and times (different atmospheric conditions) and at different altitudes with different sensor systems, then preprocessing must be performed.

In this chapter we describe the basic concepts of preprocessing in remote sensing. We will give some examples of regularly occurring distortions in remote sensing images and give an overview of the most common techniques for radiometric and geometric preprocessing. Finally, we will present some recent developments in image quality assessment that can be used to assess images prior to the analysis and automatic preprocessing chains as applied for MODIS. The chapter will focus on the preprocessing of optical remote sensing data. For preprocessing of other types of remote sensing data (e.g., thermal), handbooks as listed in the last section of this chapter can be consulted.

5.2 The spectral preprocessing chain

To correct remotely sensed data, internal and external errors must be determined. Internal errors are created by the sensor itself. They are generally systematic (predictable) and stationary (constant) and may be determined from prelaunch or in-flight radiometric calibration measurements. External errors are due to platform perturbations, and the
influence of the atmosphere and specific characteristics of the remotely sensed object, which are variable in nature. *Atmospheric correction* and *geometrical correction* are the most common preprocessing steps to account for external errors in remotely sensed imagery.

Often remote sensing data (e.g., Landsat, NOAA-AVHRR) are represented in DNs when they are purchased from the data providers. A digital number (DN) is nothing more than a measure for the strength of an electrical current which is produced by a light-sensitive cell. The more energy falls on the sensor, the stronger the electrical current, which is stored with a larger DN (after AD-conversion). However, for many quantitative applications, instead of DNs, measurements of absolute radiances are required. For example, such conversions are necessary when changes in absolute reflectance of objects are to be measured over time using different sensors (e.g., multispectral sensor on Landsat-3 versus the one on Landsat-5). Also, these conversions are important for the development of mathematical models that physically relate image data to quantitative ground measurements (e.g., vegetation characteristics like LAI and biomass, and water quality data).

The raw data or DNs as acquired by the remote sensing sensor depend on the characteristics of the detector and the amount of energy received. The electromagnetic energy that reaches the sensor in the case of optical satellite sensors, is originating from the sun (Figure 5.1). There are several pathways how this electromagnetic energy or light from the sun reaches the sensor (Schott, 1997). The most important ones are:

- Direct reflected light: photons that originate from the sun, pass through the atmosphere, are reflected from the earth’s surface, and propagate back through the atmosphere to the sensor (pathway A);
- Skylight: photons that originate from the sun, are scattered by the atmosphere, and are then reflected by the earth to the sensor (pathway B);
- Air light: photons that originate from the sun are scattered by the atmosphere and are directly reflected to the sensor without reaching the earth (pathway C)

The summed energy of these pathways results in the *upwelling spectral radiance at the top of the atmosphere* (TOA). This energy is represented by the remote sensing sensor in the form of DNs.

![Figure 5.1: Various pathways of electromagnetic energy originating from the sun as received by the satellite remote sensing sensor (after Schott, 1996): pathway A: directed reflected light; pathway B: skylight; and pathway C: air light.](image-url)
Several pre-processing steps are required to convert DNs to absolute radiance values or surface reflectance. These steps are represented in the so-called **spectral pre-processing chain**. Figure 5.2 shows how the spectral representation of a remotely sensed spectrum changes during the different preprocessing steps (Ustin et al., 2004). In this case the spectrum is represented by a vegetation pixel. In the upper left panel you see how the spectral reflectance of this pixel looks like when it is measured on the ground with a field spectrometer (so-called **reflectance at top of canopy**). The upper right panel in Figure 5.2 shows the “true” upwelling spectral radiance for this pixel measured at the top of the atmosphere (at the elevation of the satellite sensor). In other words this is the amount of energy which the sensor measures for one specific area (the pixel area) of the earth surface. The middle panel illustrates how this radiance is measured by the sensor in the form of digital numbers. In a next step, the so-called **radiometric calibration**, these data must be calibrated to account for instrument performance, resulting in a simplified radiance spectrum (lower left panel of Figure 5.2). You can see that the form of this curve approximates the true radiance at the top of the atmosphere (upper right panel). By taking into account the original solar irradiance, it is possible to transform the calibrated radiance at the sensor to **reflectance at top of atmosphere** (not shown in figure).

Figure 5.2: Example of preprocessing of measured at sensor spectra to surface reflectance (after Ustin et al. (2004). Upper left: typical plant canopy spectrum measured in the field. Upper right: Upwelling spectral radiance at the top of the atmosphere. Middle: Digital number count measured by the sensor. Lower left: Calibrated at sensor radiance. Lower right: Derived surface reflectance after atmospheric correction for a vegetated pixel. Missing wavelength segments in derived surface reflectance indicate areas of atmospheric water vapor absorption where no energy is measured.
Finally, to derive surface spectral reflectance we have to account for atmospheric influence (Figure 5.1). By using an atmospheric correction procedure we can account for the scattering and absorbing properties of gases and particles in the atmosphere. In the lower right panel of Figure 5.2 the resulting surface reflectance spectrum of the vegetated pixel after correction is shown. This spectrum shows a close match with a plant reflectance spectrum as measured in the field (upper left panel of Figure 5.2). In the following paragraphs the different steps of the spectral preprocessing chain will be described in more detail.

5.3 Radiometric correction

The radiance measured by a sensor (Figure 5.2) for a specific object on the earth is influenced by factors as changes in scene illumination, atmospheric conditions, viewing geometry, and instrument response characteristics. Through the application of radiometric correction techniques we are able to reduce and calibrate the influence of these aspects. In this paragraph we will explain the different steps of the radiometric correction process which are dependent upon the characteristics of the sensor used to acquire the image data. The atmospheric correction procedure is presented in a separate paragraph.

Cloud cover is often a problem in optical remote sensing. This problem can be overcome by taking a sequence of images (say on five consecutive days) and cutting and pasting together an image that represents a cloud-free composite (e.g., MODIS NDVI product: 16 days). However, for this application it is necessary to correct for differences in sun elevation and earth-sun distance. The sun elevation correction accounts for the seasonal position of the sun relative to the earth. The earth-sun distance correction is applied to normalize for seasonal changes in the distance between the earth and the sun. The parameters for these corrections are normally part of the ancillary data supplied with the image and depend on date and time of image acquisition.

Another radiometric data processing step required for quantitative applications is the process that converts recorded sensor digital numbers to an absolute scale of radiance (watts per steradian per square meter) which is independent of the image forming characteristics of the sensor (e.g., integration time, band centre, intensity of input signal). Normally, detectors are designed to produce a linear response to incident spectral radiance. Figure 5.3 shows the linear radiometric response function typical of an individual Landsat TM channel (band). The figure shows that increasing DN values correspond to increasing radiance values for the indicated TM channel. When a sensor is built, accurate measurements of the radiometric properties of the response function are made before the sensor is sent into space. This is called preflight calibration. Each spectral band of the sensor has its own response function, and its characteristics can be monitored after the launch of the sensor in space using onboard calibration lamps (in-flight calibration). In this way changes in the sensor calibration during its operational use can be monitored and if required adapted for.

Figure 5.3 shows that for the Landsat TM sensor the relationship between radiance and DN values can be characterized by a linear fit (Lillesand et al., 2004):

\[
DN = A_0 + A_1 \times L
\]

where DN is the recorded digital number value, \( A_1 \) is the slope of the response function (channel gain), \( L \) is the measured spectral radiance, and \( A_0 \) is the intercept of the response function (channel offset). In Figure 5.3, LMIN is the spectral radiance corresponding to a DN response of 0 and LMAX is the minimum radiance required to generate the maximum DN.
This means that LMAX represents the radiance at which the channel saturates. The inverse of the radiometric response function can be used to convert a measured DN in a particular band to absolute units of spectral radiance. For most sensors, these so-called preflight coefficients, channel gain and offset, are provided by the sensor builders and they can be found in remote sensing handbooks.

Figure 5.3: Radiometric response function for an individual TM channel (from Lillesand et al., 2004).

5.4 Image noise removal

A special kind of error in remote sensing images related to sensor characteristics is called image noise. Image noise is any unwanted disturbance in image data due to limitations in the sensing, signal digitization, or data recording process. It can be the result of periodic drift or malfunction of a detector, electronic interference between sensor components and intermittent data losses in data transmission and recording sequence of an image (Lillesand et al., 2004). Noise can either degrade or totally mask the true radiometric information content of a digital image. In most cases these kinds of errors can already be deduced from a visual check of the raw DN data (Figure 5.4). Specialized procedures are available to remove or restore image noise features. When it is know that certain types of image noise occur for a sensor, often this information will be provided by the data provider or it is restored before delivery of the image. Well-known types of image noise in remote sensing are:

- **Striping or banding** is a systematic noise type and is related to sensors that sweep multiple scan lines simultaneously. This stems from variations in the response of the individual detectors used within each band. For example the radiometric response of one of the six detectors of the early Landsat MSS sensor tended to drift over time (Figure 5.4 left). This resulted in relatively higher or lower values along every sixth line in the image data. A common way to destripe an image is the histogram method (Lillesand et al., 2004).
- Another line-oriented noise problem is **line drop**, where a number of adjacent pixels along a line (or an entire line) may contain erroneous DNs (Figure 5.4 right). This problem is
solved by replacing the defective DNs with the average of the values for the pixels occurring in the lines just above and below.

- **Bit errors** are a good example of random noise within an image. Such noise causes images to have a “salt and pepper” or “snowy” appearance. This kind of noise can be removed by using moving neighborhood windows, where all pixels are compared to their neighbors. If the difference between a given pixel and its surroundings exceeds a certain threshold, the pixel is assumed to contain noise and is replaced by an average value of the surrounding pixels.

![Figure 5.4: Examples of image noise showing (left) the striping effect for Landsat MSS and (right) dropped lines for Landsat TM (adapted from ccrs.nrcan.gc.ca).](image)

### 5.5 Atmospheric correction

As indicated in Figure 5.1, the composition of the atmosphere has an important effect on the measurement of radiance with remote sensing. The atmosphere consists mainly of molecular nitrogen and oxygen (clean dry air). In addition, it contains water vapour and particles (aerosols) such as dust, soot, water droplets and ice crystals. For certain applications of remote sensing, information on the atmospheric conditions are required to determine ozone and N$_2$ concentrations as indicator for smog or for weather forecast. However, for most land applications the adverse effects of the atmosphere needs to be removed before remotely sensed data can be properly analyzed. The atmosphere affects the radiance measured at any pixel in an image in two different ways. On the one hand, it reduces the energy illuminating the earth surface for example through absorption of light. This affects the direct reflected light: pathway A of Figure 5.1. On the other hand, the atmosphere acts as reflector itself, the resulting diffuse radiation is caused by scattering (pathway B and C of Figure 5.1). This means that the most important step in atmospheric correction is to distinguish “real” radiance as reflected by the earth surface from the disturbing path radiance originating from atmospheric scattering. When meteorological field data on the composition of the atmosphere during the image acquisition are available, it is possible to reduce these effects using atmospheric correction models.
Several atmospheric correction models are available which vary a great deal in complexity. In principle they correct for two main effects: **scattering and absorption**. Scattering can be described as disturbance of the electromagnetic field by the constituents of the atmosphere resulting in a change of the direction and the spectral distribution of the energy in the beam. Three kinds of scattering effects can be distinguished:

- **Rayleigh scattering** is generated through the influence of air molecules on radiation. This Rayleigh scattering is wavelength dependent, with shorter wavelengths showing larger scattering effects. This wavelength dependency explains for example why we see the sky as blue. Blue is located at shorter wavelengths and thus scattered more than green and red which are located at larger wavelengths. As a result in every direction you look, some of this scattered blue light reaches your eyes. Since you see the blue light from everywhere overhead, the sky looks blue.
- **Mie scattering** is the result of the influence of aerosols on radiance. Aerosols are small solid or liquid particles that remain suspended in the air and follow the motion of the air within certain broad limits. The considered particles have a diameter of 0.1 to 10 times the influenced wavelength. Aerosols are the most uncertain factor in calculating solar radiation on the ground. They are highly variable in size, distribution, composition, and optical properties.
- **The non-selective scattering**, finally, is not dependent on the wavelength of the radiation. The relevant particles, like dust, smoke and rain, are much larger than the wavelength. This type of scattering is of minor importance on a clear day.

Absorption takes place due to the presence of molecules in the atmosphere. Their influence on the attenuation of radiation varies highly with wavelength. Di-atomic oxygen (O$_2$), di-atomic nitrogen (N$_2$), atomic oxygen (O), nitrogen (N) and ozone (O$_3$) are the five principal absorbers in the ultraviolet and visible spectrum. Of the gases that absorb solar electromagnetic radiation in the infrared wavelengths, the most important are H$_2$O, CO$_2$, O$_2$, N$_2$O, CO, O$_3$ and N$_2$. Some wavelengths are being absorbed completely: e.g., far-ultraviolet (<0.20 μm) by atomic and molecular oxygen, nitrogen and ozone. Others are hardly being absorbed. These form the so-called atmospheric windows. For example, the bands of the Landsat-TM have been chosen, as good as possible, within these windows.

A simple method to correct for atmospheric effects like haze in an image is the so called **darkest pixel method** (Liang *et al.*, 2001). In this method objects are identified from which we know they have very low reflectance values (and thus have a dark appearance in the image). For example, the reflectance of deep clear water is essentially zero in the near-infrared region of the spectrum. Therefore any signal measured over this kind of water represents signal originating from the atmosphere only (path radiance). To correct for the atmospheric haze, the measured signal value is subtracted from all image pixels in that band. Figure 5.5 shows the result of a more complex atmospheric correction method for a Landsat TM image (Liang *et al.*, 2001). This method also accounts for aerosol composition of the atmosphere and so-called adjacency effects. The final result of an atmospheric correction procedure are surface reflectance values for all image pixels which can be used for further image processing, e.g., classification and variable estimation (LAI).
5.6 Geometric correction

The previous paragraphs have mainly focused on correction of remote sensing images in the spectral domain. However, also distortion in the spatial domain is usually occurring during remote sensing data acquisition. Geometric correction of remote sensing is normally implemented as a two-step procedure. First, those distortions are considered that are systematic. Secondly, distortions that are random, or unpredictable, are corrected. Systematic errors are predictable in nature and can be corrected using data from the orbit of the platform and knowledge of internal sensor distortion. Common types of systematic distortions are: scan skew, mirror-scan velocity, panoramic distortions, platform velocity, earth rotation, perspective (Jensen, 1996). Most commercially available remote sensing data (e.g., Landsat, SPOT) already have much of the systematic error removed.

Unsystematic errors are corrected based on geometric registration of remote sensing imagery to a known ground coordinate system (e.g., topographic map). The geometric registration process involves the identification of the image coordinates of ground control points (GCP), clearly discernible points (e.g., road crossings), in the distorted image and an available map. The well-distributed GCP pairs are used to determine the proper transformation equations. The equations are then applied to the original (row and column) image coordinates to map them into their new ground coordinates. This approach is called image-to-map registration. An alternative would be to register one (or more) images to another image, the so-called image-to-image registration. This procedure is often applied for multitemporal image comparison when for example land cover changes are monitored using Landsat TM images. Different resampling methods can be applied to calculate the new pixel values from the original digital pixel values in the uncorrected image. An overview of these resampling methods is given in chapter 7 of the handbook Introduction to Geographic Information Systems of Chang (2006).
Space-based sensor platforms are usually geometrically stabilized such that the only motion of the platform during the imaging is the along-track motion of the spacecraft (e.g., platform velocity). Aircraft sensors are often not stabilized so that the orientation of the aircraft can change from one line to the next, or, in extreme cases, even from pixel to pixel within a line (Schott, 1996). An overview of possible distortions due to aircraft movement is given in Figure 5.6. Pitch and yaw effects are generally relatively constant errors typically removed in preprocessing. Roll effects may vary considerably on a line-to-line basis and can be corrected using measurements from a gyroscope. Figure 5.7 shows an image before and after roll compensation was performed using signals recorded from a gyroscope. The roll effect is especially observed in the buildings in the left part of the image.

Figure 5.6: Geometric distortions due to aircraft orientation. Gray boundaries represent nominal coverage; black boundaries represent actual coverage (from Schott, 1996).

Figure 5.7: Example image before (left) and after (right) lines were shifted to correct for roll distortion of an airborne sensor acquisition (from Schott, 1996).
5.7 Recent developments in preprocessing

With the increasing use of remote sensing for global monitoring of the earth (e.g., using the medium resolution MODIS and MERIS sensors), it becomes very important to know the quality of the images that are acquired and compared with each other. To facilitate the quality assessment of remote sensing images and products, recent developments are aiming at the standardization of the preprocessing process. This means that for a specific remote sensing sensor automated processing chains are developed that process the acquired images from raw data to surface reflectance and finally to a set of higher order products (NDVI, LAI, albedo etc.). A good example of this approach is the development of the processing chain for the Moderate Resolution Imaging Spectrometer (MODIS). Specific preprocessing software is developed to generate standard products which can be applied in a broad range of application fields (modis.gsfc.nasa.gov). An important strength of this approach is that automated image quality checks are built in and the quality of every image is described and made available to the user.

5.8 References and further reading


Websources

http://ccrs.nrcan.gc.ca/resource/index_e.php: remote sensing tutorials available from Natural Resources Canada (NRCan)

http://modis.gsfc.nasa.gov/: home page for the MODIS satellite sensor

http://envisat.esa.int/instruments/meris/: home page for the MERIS satellite sensor