1

Data Acquisition

In this chapter, we focus on Synthetic Aperture Radar (SAR) data. We first provide an introduction to SAR systems and detail how data are acquired, whereas the main parameters related to SAR systems such as azimuth resolution and range resolution and the main acquisition modes are introduced. A simple introduction to radar systems is included to better deal with the interaction of the radar emitted and transmitted signals with targets. We pay special attention to signal backscatter due to its relation to speckle. A brief description of currently deployed satellite providing SAR data and useful tools to deal with freely accessible SAR data is also provided.

1.1 Introduction

Figure 1.1 summarizes this chapter in the context of this book: a sensor (Sensor) mounted in a spacecraft (a satellite, an aircraft, or a ground-based platform) captures signals *remotely* over the Earth's surface that is conveniently processed (Signal Processing) and transformed into data (Data). Users build models to deal with the data to suit their needs. Due to the inherent random nature of data (see Chapter 3), statistical modeling is of maximum interest and it seems to be the first approach to handling the data. *Speckle noise* (or just *speckle*) is a particular kind of *noise* that largely corrupts the SAR data, making it difficult to interpret acquired images. How speckle is related to image pixels is also accounted in this chapter. Once data have been properly processed, despeckling is a major issue (see Sections 5.1 and 5.2.2), it is when applications enter into play. From the many possible uses, image classification (see Sections 5.5, 5.6, 5.7, and 5.8) and image segmentation are the most common image processing tasks.

Remote observation of the Earth's surface can be done by using passive or active sensors (see Figure 1.2). A passive sensor (shown in (a)) does not emit any signal to the Earth's surface to collect data: it just receives the signal. Such signal is emitted by the Earth's surface in the form of radiation or is due to the reflected sunlight, or both phenomena. Cameras on satellites or on aircrafts are examples of passive sensors. However, active sensors (shown in (b)) first emit a signal that interacts with the Earth's surface and the reflected signal is detected by the sensor. This chapter (and this book), only deals with active sensors for the reason that acquisition system for collecting data discussed in this book uses them.

SAR Image Analysis — A Computational Statistics Approach: With R Code, Data, and Applications, First Edition.
Alejandro C. Frery, Jie Wu, and Luis Gomez.

Companion website: www.wiley.com/go/frery/sarimageanalysis

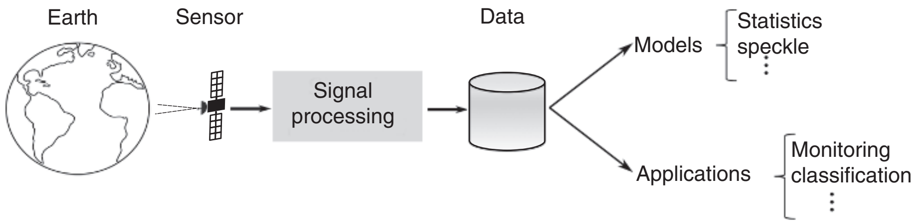


Figure 1.1 Remote sensing data acquisition and data processing.

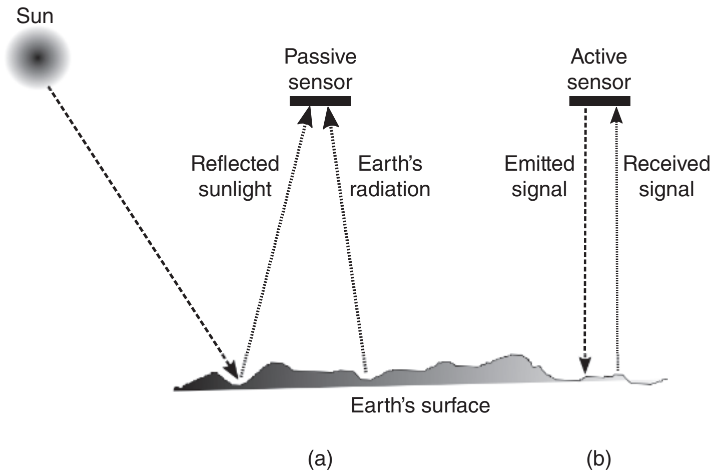


Figure 1.2 Passive sensor (a) and active sensor (b).

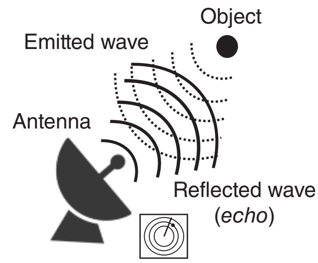
1.2 SAR

Synthetic Aperture Radar (SAR) sensors have a prominent role in remote sensing with microwaves. They can provide images with high resolution (up to centimeters on the ground), information about de dielectric and textural properties of the target, they operate without the need of sunlight, and are almost immune to adverse visibility conditions (clouds, rain, fog, etc.) Therefore, SAR systems are capable of providing high valuable data to users 24/7 all year round. That is possible because SAR systems use active sensors to illuminate the area under observation (as a difference with optical sensors, that use passive sensors and also are affected by atmospheric conditions, such as clouds, day/night cycle, rain, etc.) Before addressing the standard configuration of a SAR system, to better understand them first, we explain how a radar works.

1.2.1 The Radar

Radar (Radio Detection And Ranging) systems were developed for military use during the second World War for surveillance purposes. Radar rapidly motivated the studio of signal processing techniques and, also, encountered many new areas of applications. In the military area, it includes air-defense systems and antimissile systems, among others, whereas civil applications span from astronomy (radio-astronomy) to aircraft navigation (fight control

Figure 1.3 Simplified radar emitting-receiving operation.



systems, altimeter measures, etc.) In the particular area of remote sensing, radar was first used for monitoring precipitations and it soon stemmed as a very useful tool for geological observations.

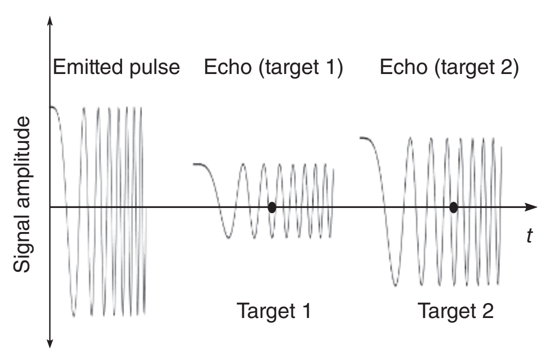
As it is generally known, radar operates by transmitting an electromagnetic signal (*the radar signal*) over an area (*illuminated area*) and getting information from the reflected signal (received signal) due to the illuminated object (target). So, the radar uses an active device (the emitting antenna) that, in most cases, is also the sensor that captures the reflected signal (see Figure 1.3).

Obtaining information from the received signal is not a trivial issue, and it requires deep knowledge of electromagnetic propagation, signal scattering, and signal processing. Fortunately, all this knowledge is available at present, after decades of intensive research over the past century. The generation of the signal to transmit as well as the amplification of the received signal (usually very weak) and other signal conditioning (filtering, quantization, analog-digital, digital-analog conversion, etc.) requires also the use of specific electronic systems also largely studied in the past. The transmitted pulse used is a *chirp* (see Figure 1.4): a signal that contains many frequencies, increasing (chirp-up), as in the case shown in the figure, or decreasing (chirp-down). The benefits of the chirp signal over a simple single-frequency pulse are:

- it provides better resolution,
- the area covered (illuminated) by the signal is enhanced,
- it is less affected by noise,
- the circuits used to generate such signal are relatively simple,
- the system requires less power.

In Figure 1.4 it is also shown the basic radar operation principle: each target reflects (scatters) the received signal in many directions, and the reflected signals toward the transmitter are the desirable ones that make radar work. As also illustrated in this figure, the reflected signal (echo signal) is a variation of the emitted one. Such variations in amplitude, wave

Figure 1.4 Simplified radar emitting-receiving operation using a chirp-up signal (emitted pulse).



shape, and frequency, are caused mainly by the physical properties of the targets. In this way, the return does not only provide information about the distance from the emitter (basic radar operation), but also valuable physical information (advanced systems such as SAR). Although the basic principle of radar operation is indeed simple to understand, radars are complex systems, and a deep knowledge of signal processing is required to fully understand how the echoes are finally converted into useful information. However, it is not difficult to understand that, as the emitter signal is totally known (the chirp signal), by comparing the emitter signal with the received one, targets placement can be easily estimated. This operation is done through the well-known matched filter that, in essence, performs the correlation between the emitted and the received echos.

After this brief introduction to the basic radar principles of operation, SAR systems are explained in subsection 1.2.2.

1.2.2 What is SAR?

An extensive set of specific mathematical and signal tools for radar applications were available early in the mid-fifties of the past century. They paved the way for new systems to come. SAR (Synthetic Aperture Radar) was invented by Carl A. Wiley in 1951 and, after solving many technical problems (especially ones related to keeping moving trajectory stable), the first acquired SAR image was obtained in 1957. The first SAR system on a space mission was aboard of the Seasat satellite launched in 1978. This first SAR observational system scanned along 126 million square kilometers of the Earth's surface from an altitude of 800km. The captured data resolution was 25 m (both in range and azimuth directions)[1]. It is worthy to mention that the NASA's space Shuttle carried an enhanced version of the Seasat satellite in 1981 collecting, in only three days, image data of about 10 million square kilometers of the Earth's Surface from an altitude of 245 km. Resolution of data was 40 m (both in range and azimuth directions). After that, most Shuttle missions incorporated enhanced SAR systems.

SAR systems are frequently placed on military and commercial aircrafts, reducing costs when compared to satellite deployments. A great advantage of airborne SAR systems is the greater flexibility in establishing data acquisition parameters such as the incidence angle and the resolution. Observation altitude is evidently lower so, the although the scanned area is also reduced, the resolution can be much better (https://ui.adsabs.harvard.edu/abs/2017EGUGA..1918019P/abstract). For a description of an airborne system see https://www.dlr.de/hr/en/desktopdefault.aspx/tabid-2326/3776_read-5691/. This airborne SAR system provides data with resolution of 20 cm in the azimuth direction and it is mounted on a Dornier DO228-212 aircraft. Boeing E-7 Wedgetail AWACS (Airborne Early Warning and Control), NATO (North Atlantic Treaty Organization) military planes include SAR systems (https://www.thedrive.com/the-war-zone/39451/top-air-force-general-in-the-pacific-wants-e-7-wedgetails-to-replace-e-3-radar-planes).

What is SAR? Among the many differences between a standard radar and a SAR, the most important are:

- SAR is not just a radar: it is an imaging radar system,
- SAR uses a sensor (or antenna) that is not fixed but it is moving as it emits signals and receives the echos.

1 These concepts are described in Section 1.2.4.

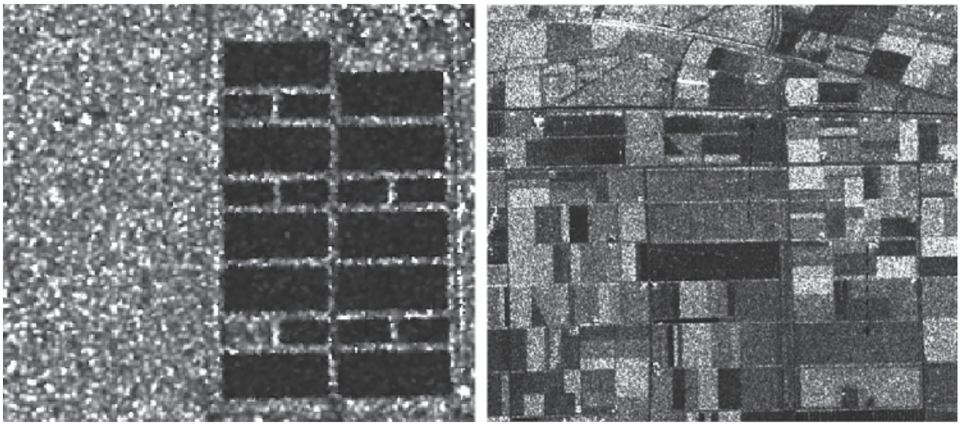


Figure 1.5 (a) An actual single-look image from the COSMO-SkyMed SAR sensor acquired on June 5, 2018 over the Amazon rainforest (black areas are fish ponds). The spatial resolution (in range and azimuth) is 3 m. (b) Airborne Synthetic Aperture Radar (AIRSAR) sub-image of Flevoland agricultural area in The Netherlands. It was obtained by the NASA / Jet Propulsion Laboratory AIRSAR platform in 1989 (azimuth resolution is 12.1 m and range resolution is 6 m). Source: NASA / Jet Propulsion Laboratory AIRSAR.

Therefore, SAR systems do not provide an *image* of the echos received, but, through the use of complex signal and image processing techniques, it obtains images (*photo-like*) of the illuminated area. It can be noticed that, although SAR images are somehow similar to natural images, they have a significant amount of noise (this will be discussed in Section 1.5). An example of SAR images (actual data) can be seen in Figure 1.5.

Figure 1.6 shows the same scene, the well-known San Francisco Bay area, as seen by an optical sensor and by a SAR. It is noted that, although both images are visually quite different, many targets are clearly recognizable in the SAR image (the ocean, the blocks of buildings, the forest and parks, the Golden Gate bridge, and the Alcatraz island are easily seen). Moreover, the Golden Gate is even more visible in the SAR image than in the optical one because metallic structures reflect the radar signal strongly. Note that the SAR image could have been acquired during the night or on a cloudy day.

As indicated above, the SAR antenna moves when emitting and receiving signals. In Figure 1.7 a simplified description the geometry of a SAR system is depicted. The sensor movement provides the high-resolution capabilities of the SAR, as well as it introduces complex calibration and stabilization challenges, fortunately, largely solved at present.

After this brief introduction to SAR, Section 1.2.3 focuses on particular details of actual SAR systems.

1.2.3 SAR Systems

As explained, a SAR sensor is an imaging radar system that emits pulses (electromagnetic waves) whose wavelengths are of the order of centimeters, ranging from about one meter to one millimeter corresponding to frequencies between 300 MHz to 300 GHz, respectively, as follows from,

$$f = \frac{c}{\lambda}, \tag{1.1}$$

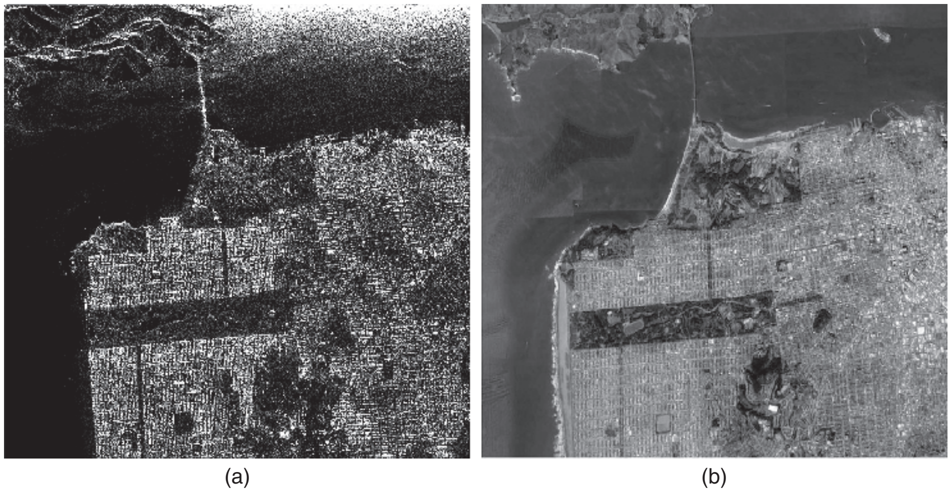


Figure 1.6 (a) NASA/JPL AIRSAR image for San Francisco Bay and the optical version, from Google Earth (b). The SAR image has spatial ground resolution of about 6.6 m in range and 9.3 m in azimuth. The images have not been registered (aligned) and some additional differences between them are due to geophysical corrections applied to the SAR data. Acquisition dates are not either the same.Source: (a) NASA/JPL AIRSAR and (b) Google Earth.

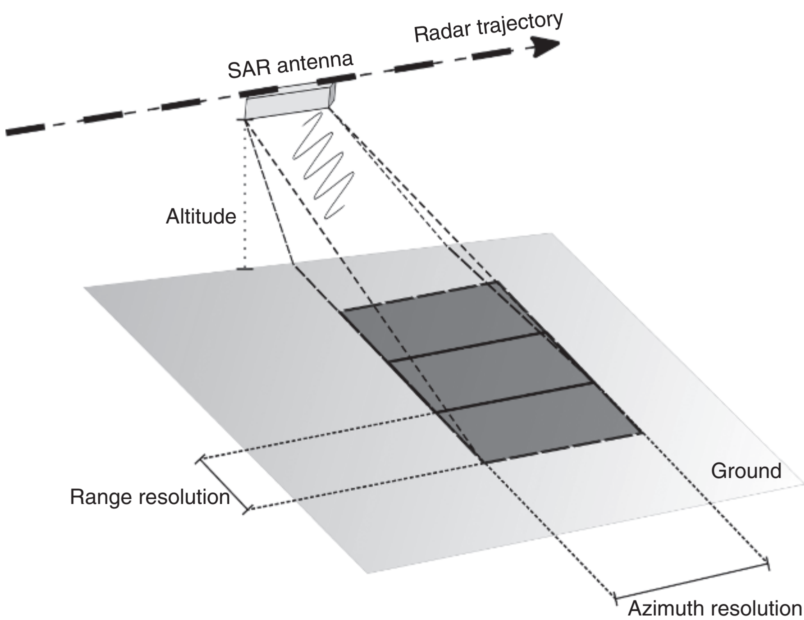


Figure 1.7 Synthetic aperture system (simplified description).

where c is the speed of the light[2] ($\approx 3 \times 10^8$ ms^{-1}) and λ is the wavelength of the signal (in meters). Figure 1.8 shows two waves with different wavelengths. The shorter the wavelength is, the more energy it has. Just to compare, the visible light ranges from 390 nm to 750 nm

2 All electromagnetic waves travel at speed c.

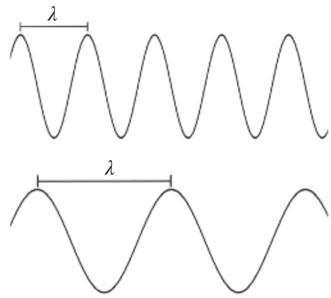


Figure 1.8 Two waves with different wavelengths (top wave has double frequency than the bottom wave).

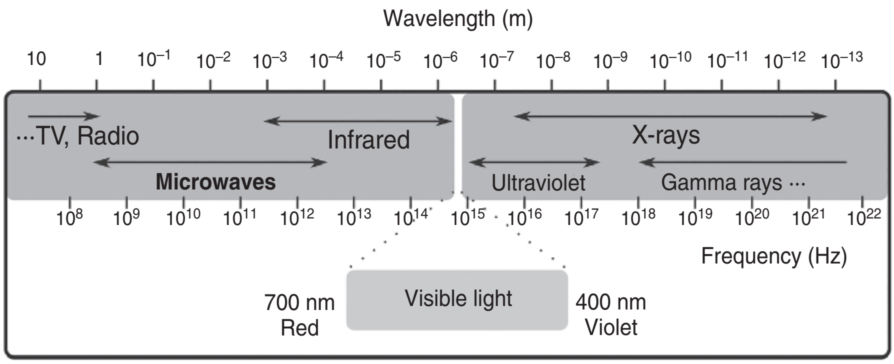


Figure 1.9 Electromagnetic spectrum.

(nanometers), whereas infrared radiation ranges from 750 nm to 1 nm (see Figure 1.9, where a region of interest of the electromagnetic spectrum is shown). Note also that as the wavelength diminishes (higher frequencies), the larger the resolution of the system is. Besides, microwave signals travel by line-of-sight (point-to-point).

Note also that, as mentioned above, what the sensor emits and receives is not a waveform like the one shown in Figure 1.8, but an electromagnetic signal like the one represented in Figure 1.10. This is of especial importance since both the electric and the magnetic components interact with the target providing, thus, much valuable (physical) information from the illuminated area. Additionally, the information collected by the sensor comes not only from the amplitude of the reflected signal but also from the change of its phase (this will be addressed below).

This book deals with SAR data in which the transmitted signal has a single polarization mode, unlike PolSAR (Polarimetric SAR) systems where several polarization modes participate. Nevertheless, it is convenient to have some knowledge of what signal polarization refers to.

Polarization (of a electromagnetic wave) refers to the orientation of the electric field during propagation respect to a reference. For convenience, the reference is chosen to be parallel to the Earth's surface on transmission, which is known as horizontal (H) polarization. For a general wave (see Figure 1.11), the horizontal polarization (H) indicates that the wave is oscillating within a horizontal plane as it propagates. The vertically polarized wave (V) oscillates within a vertical plane as it propagates. When the wave is not polarized, it vibrates in all planes orthogonal to the axis of propagation.

The electromagnetic wave, that is, the emitted and reflected radar signal, has two components (see Figure 1.10): the electric component (**E**), and the magnetic component (**B**), which

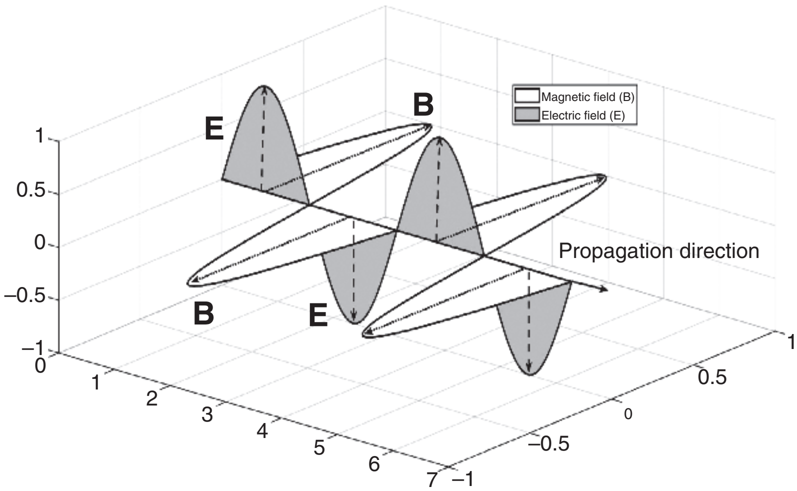


Figure 1.10 An electromagnetic wave (**E** and **B** vectors are orthogonal).

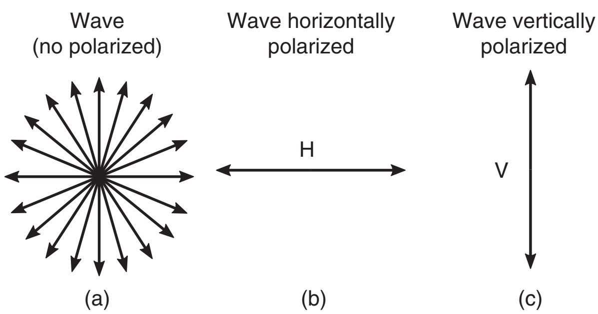


Figure 1.11 Not polarized wave (a), horizontal (b), and vertical polarization (c).

are orthogonal. In the radar's context, the polarization of a signal refers only to the orientation of the electric component, E, with respect to the emitter (antenna).

A radar antenna can be designed to send and receive electromagnetic waves with well-defined polarization. Two modes of radiation, horizontally (H) and vertically (V) polarized waves are possible. Figure 1.12 illustrates two sensors emitting an H wave (left) and a V wave toward the target. It is important to note that an emitted H wave, after being scattered by the target, may produce both H and V waves. The opposite is also true, an emitted V wave, after being scattered by the target, may produce H and V waves.

Therefore, the emitter can transmit either an H or a V wave. Additionally, the sensor detects only reflected H or V waves, depending on the established configuration (this can be dynamically modified). It is clear that the combination of emitted and detected waves produces four modes of radar operation:

Co-polarized modes: HH (signal emitted H, signal received H), and VV (signal emitted V, signal received V).

Cross-polarized modes: HV (signal emitted H, signal received V), and VH (signal emitted V, signal received H).

These modes of operation offer the user a vector related to each pixel of the image, so, better characterizing the target properties (target signature). As mentioned at the beginning of this

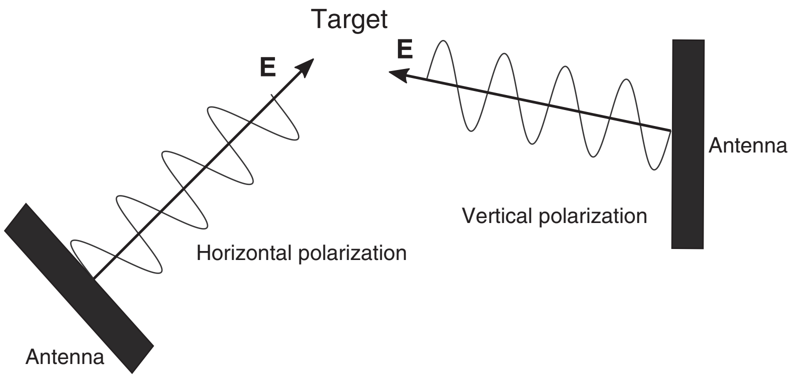


Figure 1.12 Illumination of a target by horizontal (a) and vertical (b) polarized waves.

section, PolSAR systems use such a rich combination of polarization modes providing much more information for targets than SAR systems that use a single-mode (single-polarization system or just "single-pol") that constitutes the object of this book.

The forthcoming description of modern deployed SAR systems requires the standard nomenclature related to the polarization modes:

- Single-polarization, or single-pol: transmits and receives a single polarization, typically the same direction, resulting in horizontal-horizontal (HH) or vertical-vertical (VV) imagery.
- Dual-polarization, or 'dual-pol': may transmit in one polarization but receives in two, resulting in either HH and HV, or VH and VV imagery.
- Fully polarimetric, polarimetric, or quad-pol systems alternate between transmitting H and V pulses, and receive both H and V, resulting in HH, HV, VH, and VV imagery. To operate in quad-pol mode the radar must pulse at twice the rate of a single- or dual-pol system since the transmit polarization has to alternate between H and V pulse by pulse.

Figure 1.13 summarizes the usual polarization modes.

Without entering much in explaining polarization mechanisms, which is beyond the scope of this book, it is known that:

- physical processes responsible for like-polarized HH or VV returns are related to quasi-specular surface reflections (calm ocean/water surfaces, i.e., without waves). Due to the specular reflection, the detected return signal is practically null, which is seen in the image as a black area (see the black large areas in the SAR image of San Francisco Bay image in Figure 1.6).
- HH and VV modes returns are stronger than cross-polarized (HV or VH) modes.
- Cross-polarized modes show less penetration effect (through canopy, sand, snow, or soil) than co-polarized modes.

Figure 1.14 shows the HH, HV, VV, and HH_VV (module) for an actual SAR image. As it can be seen, each polarization mode offers different information.

1.2.4 The Synthetic Antenna

The two first letters in SAR refer to *synthetic aperture* (or antenna) which is introduced in this section, as well as other important concepts related to the whole SAR system. To represent

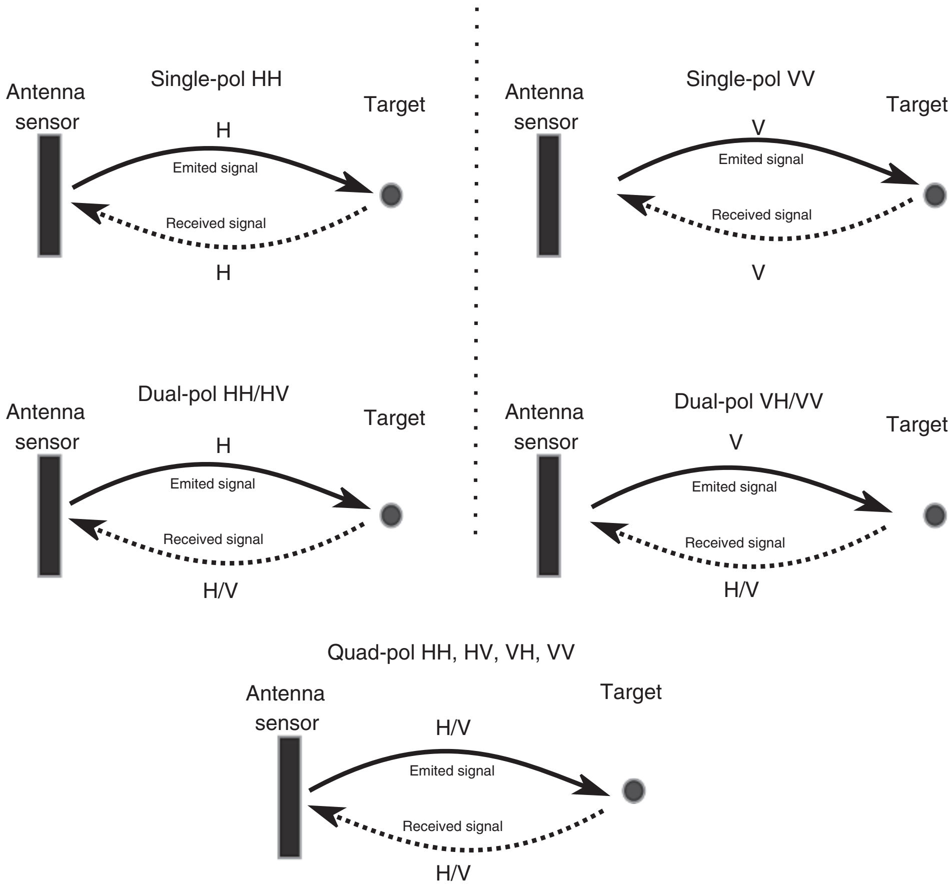


Figure 1.13 SAR common polarization modes.

ground objects that are, for instance, one meter apart as separate pixels within an image, the radar sensor needs to have the same spatial resolution: that is, one meter or less, which translates into the need of a large antenna (for the case of an orbiting satellite, such antenna would be of 15 km length!) if using a standard radar system. This is not the case, fortunately, when using SAR.

Figure 1.15 depicts a SAR system. First, note that the sensor is mounted on a moving platform (it can be a satellite, as the represented case, an airplane, a drone, as described by Koo and et al. (2012), or even a simple van, see Frey et al. (2013b)). For the case of the system shown in this figure, the radar system is mounted on a satellite, and it emits the electromagnetic signal to the ground (Earth surface), *illuminating* a region as it is moving along its orbit. The satellite is at an altitude (it could be around hundreds of kilometers or even much more), and it is moving following the radar trajectory. We show a *side-looking* observation system (other configurations are explained in Section 1.4). In this configuration, the radar is pointing perpendicular to the direction of flight. Two important concepts related to SAR imaging are also shown in this figure:

Slant range: is the side-looking direction of the antenna. It is perpendicular to the sensor's path (the along-track direction).

Azimuth: is the along-track direction, or also the perpendicular projection of the sensor line of flight on the ground.

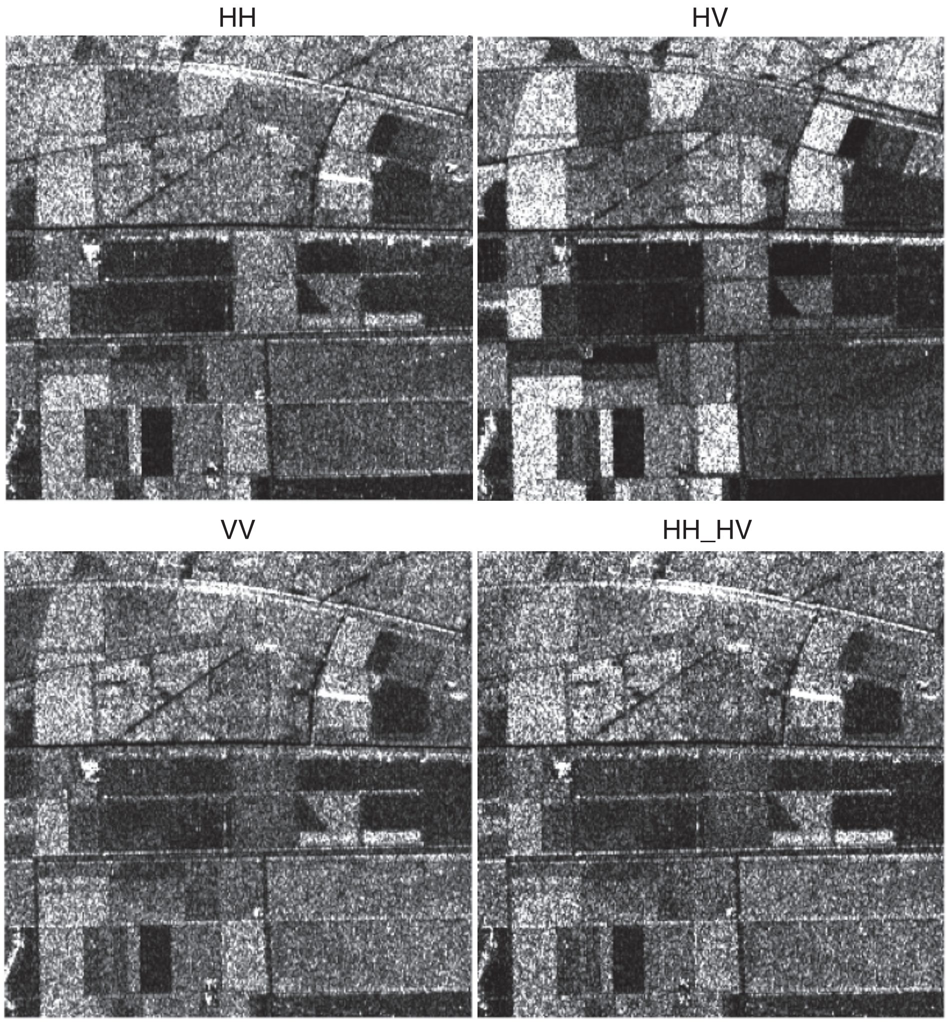


Figure 1.14 Example of polarization modes for an actual SAR image. The mode HH_VV indicates that the polarization used was quad-pol.

Therefore, the SAR antenna has its long axis in the flight direction (the azimuth direction) and the short axis in the range direction (slant range).

What defines a SAR system is the imaging technique employed. Figure 1.16 details the basic operation of a SAR system. As it can be seen, the forward motion of the antenna along the track direction is used to *synthesize* a much longer antenna. That is the reason for the system name SAR: Synthetic Aperture Radar[3]. At each antenna position, an electromagnetic pulse is emitted and the return echoes pass through the receiver and recorded for their post-processing. Figure 1.17 shows that the synthetic aperture (the sensor as it moves) collects many echoes from the same target. In this sequential way, the system operates as if it were using a larger antenna (the Synthetic Aperture Length). Figure 1.18 shows the synthetic aperture length. Note that the larger the antenna, the finer the detail the radar can

3 Aperture: from the Latin *apertus*, is translated as *open* or *opened*, and used in optics to name the opening through which light enters or exits an optical system. Note that microwaves are electromagnetic waves, so is light.

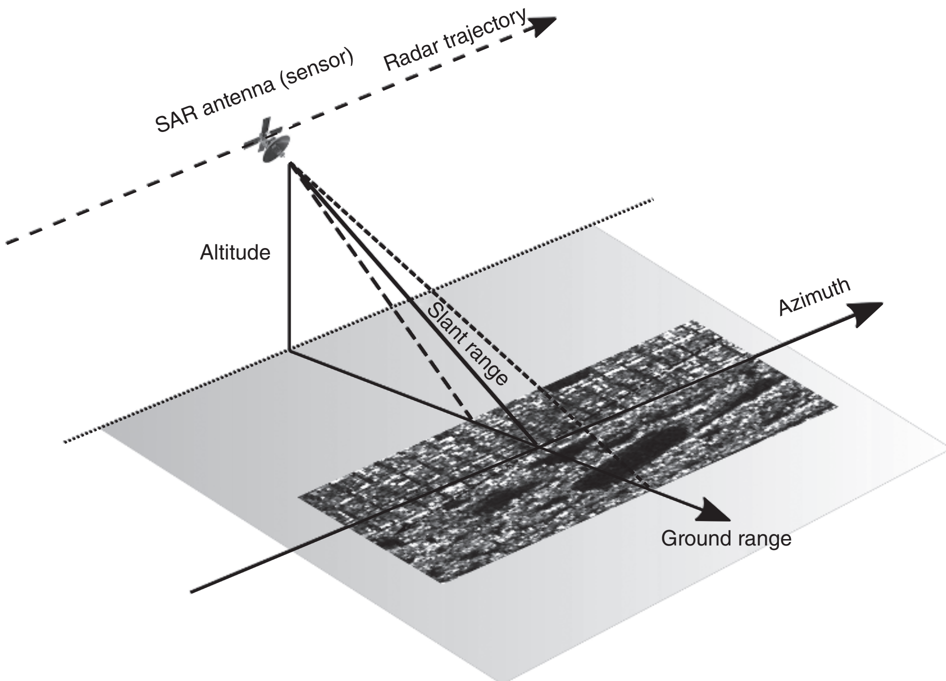


Figure 1.15 SAR acquisition geometry.

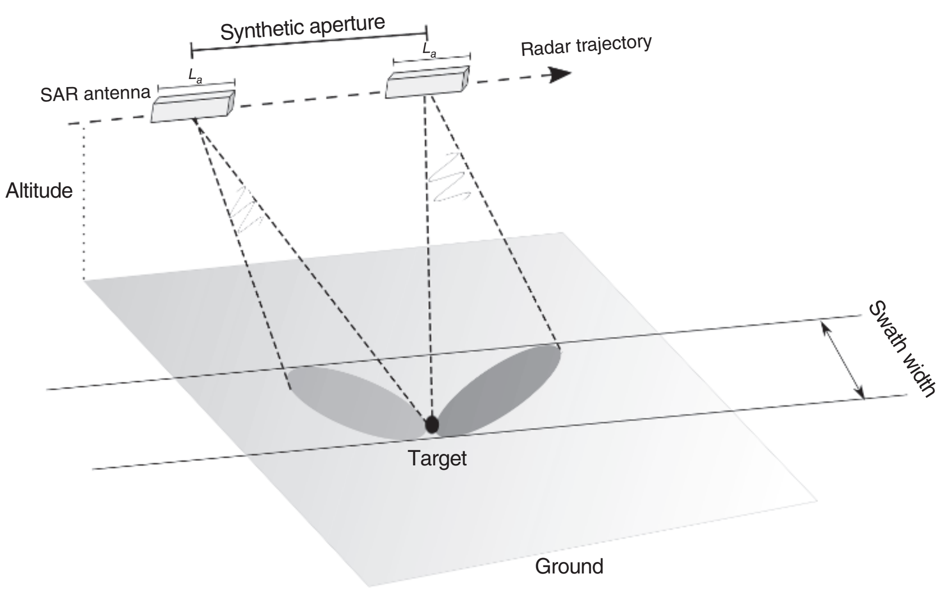


Figure 1.16 Synthetic aperture concept.

resolve. Therefore, by using a small antenna (which is a relevant issue when it is mounted on a moving platform), a high spatial resolution across large areas can be obtained.

From the stored echoes, the returned signal is converted to digital format and then processed to be later displayed. The processing is indeed complex, including many mathematical

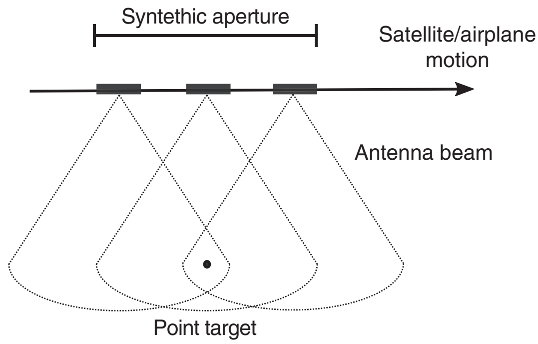


Figure 1.17 Synthetic aperture and radar beams.

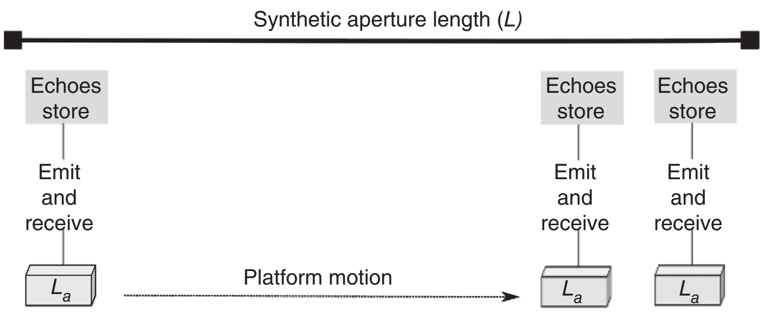


Figure 1.18 Synthetized antenna.

operations and specific signal processing methods that are mostly done in ground stations. The final result is a high-resolution image (see some actual SAR images in Figure 1.5) as it had been obtained by using a very long *physical*, antenna of length, for example, of 15 km or more.

It is interesting also to remark that, for a desired spatial resolution, the length of the antenna depends on the wavelength of the emitted signal. For instance, if using a C-band radar (which operates with a wavelength ≈ 5 cm), to obtain a spatial resolution of 10 m, a radar antenna longer than 4 km would be needed! Therefore, the benefits of the moving platform (satellite, aircraft or so) are clear.

The most common SAR bands and their main uses are collected in Table 1.1). More about spatial resolution is detailed in Section 1.3.

Table 1.1 Most used bands SAR.

Band	Frequency	Wavelength	Uses
X	8 GHz to 12 GHz	3.8 cm to 2.4 cm	High resolution (little penetration into vegetation): urban monitoring, ice and snow
C	4 GHz to 8 GHz	7.5 cm to 3.8 cm	SAR workhose (moderate penetration): change detection, global mapping, ocean observation
S	2 GHz to 4 GHz	15 cm to 7.5 cm	Agriculture monitoring and observation of high density vegetation areas
L	1 GHz to 2 GHz	30 cm to 15 cm	Medium resolution (high penetration): geophysical monitoring, vegetation and biomass mapping

1.3 Spatial Resolution

Spatial resolution is a key issue when dealing with acquired data. Lee and Pottier (2009) discuss in detail the following concepts.

Range resolution (slant range resolution): it is defined as the observable size of a ground pixel along the range direction (see Figure 1.19) and it is calculated as,

$$\delta_r = \frac{c\tau}{2}, \tag{1.2}$$

where c is the speed of light and τ is the duration of the transmitted radar pulse.

The projection on the flat ground plane of δ_r (see Figure 1.20) is known as the Ground Range resolution,

$$R_r = \frac{c\tau}{2\ \sin\theta}, \tag{1.3}$$

where θ is the look angle.

From the above expressions, note that:

- The range resolution is independent of the height of the platform (satellite, aircraft, etc.)
- The range resolution is infinite for an orthogonal direction of illumination (vertical look angle), and it improves as the look angle is increased.
- Finally, the range resolution improves as the bandwidth, BW, of the radar increases ($\tau = 1/\text{BW}$).

Azimuth resolution: it is defined as the observable size of a ground pixel along the azimuth direction (see Figure 1.19). The azimuth resolution, R_a, only depends on the length of the antenna,

$$R_a = \frac{L_a}{2}. \tag{1.4}$$

Therefore, the azimuth resolution is also independent of the height of the platform and improves as the antenna length is reduced.

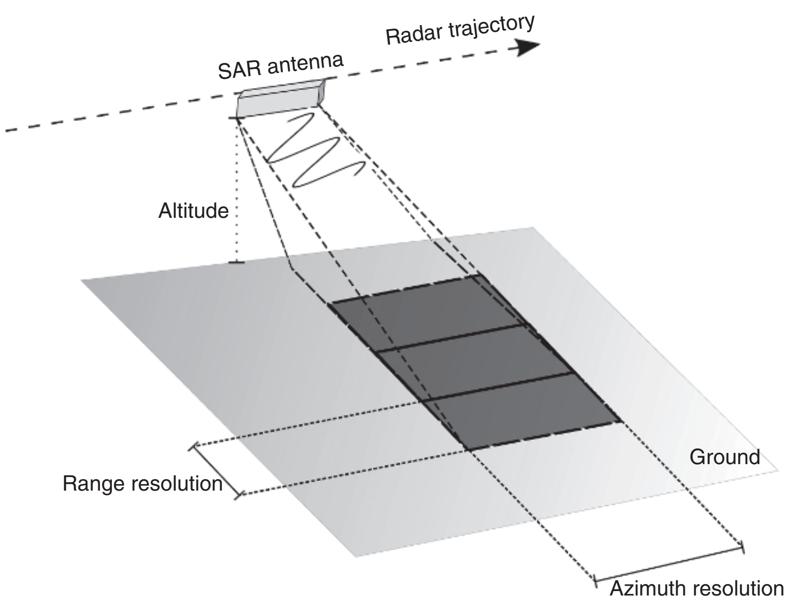


Figure 1.19 Range and Azimuth resolution.

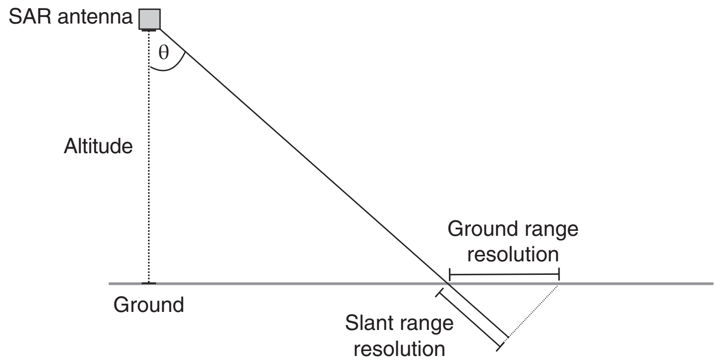


Figure 1.20 Slant range resolution and Ground range resolution.

1.4 SAR Imaging Techniques

In this section, a brief description of the most used SAR imaging techniques is provided. From the several available SAR acquisition modes, the most popular are:

Stripmap: (also known as *StripMap*): this corresponds to the conventional or original SAR mode (it was introduced in the early versions of SAR systems). As shown in Figure 1.21, the radar antenna is pointing at a fixed direction (fixed azimuth and observation angle) while moving along its flying path. Therefore, the ground swath is illuminated with a continuous sequence of pulses, the echoes are received and then, after processed, the image is formed. The azimuth resolution is notably increased because more echoes are received (multiple ones from the same target) than in a single scan. Strip mode is very useful to

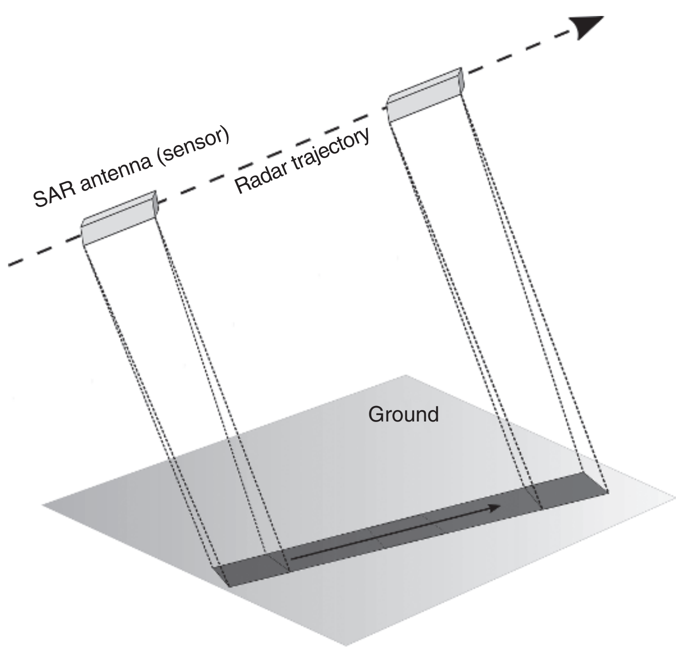


Figure 1.21 SAR stripmap acquisition mode.

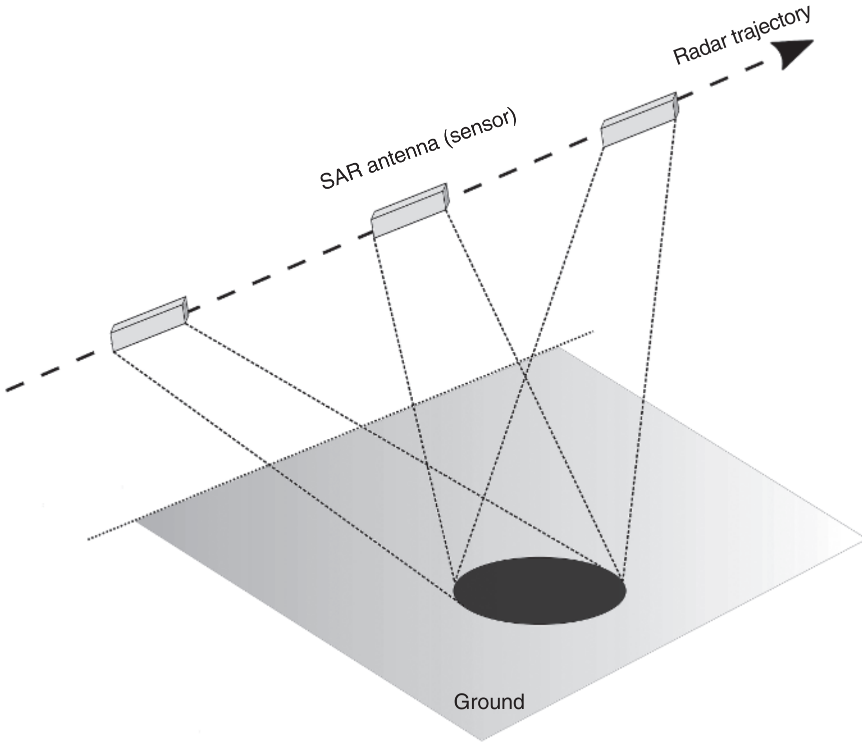


Figure 1.22 SAR spotlight acquisition mode.

obtain information of excellent resolution from large areas. Note that the radar antenna can be mounted on a satellite or on an aircraft.

Spotlight: (also known as *SpotLight*): this is the mode recommended for obtaining high-resolution images. As it can be seen in Figure 1.22, the antenna radar is pointing at a particular area and keeps illuminating just this area to get as many echoes as possible to increase both, the range and the azimuth resolutions significantly. Spotlight mode, as a difference from the stripmap mode, operates at the expense of spatial coverage. It is interesting to mention that the beam steering to irradiate on the specific area is either mechanically or electronically controlled to keep the radar radiation pattern constant on the target.

Scan: (also known as *ScanSAR*): in this mode, the radar antenna sweeps periodically into different orientations, thus, illuminating several subswaths areas (see Figure 1.23, covering a larger area than in the two previous modes explained above. Due to the synthetic aperture is shared between the subswaths areas, the reconstruction of the image requires mosaic operations. Also, it is important to remark that the azimuth resolution is much lower than for the stripmap and the Spot modes.

Stripmap and Spot imaging techniques are nicely explained in Soumekh (1999), through these examples (sic):

> "The stripmap SAR form of target area radiation is analogous to a scenario in which someone is trying to view *all* objects in a dark room with a flashlight. With the

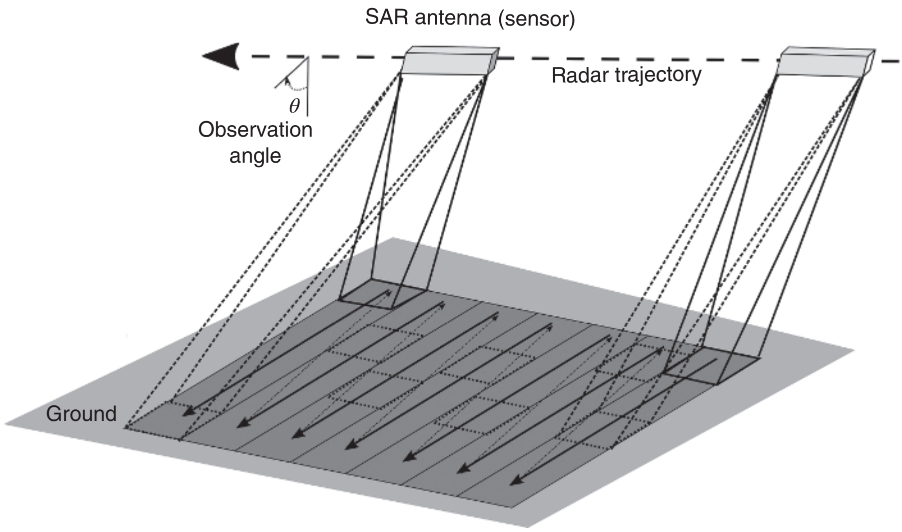


Figure 1.23 SAR scan acquisition mode.

> flashlight in his right hand (the radar on the aircraft), that person would move his right arm to *scan* the room with the light of the flashlight. This *preliminary* phase of the search is to provide the individual with a general feel for what the room contains. Similarly, stripmap SAR systems provide imaging information on the general condition and contents of, for example, a terrain area.
> Consider again the individual with the flashlight in a dark room. Once he locates an object of interest after scanning the beam of the flashlight throughout the room, he might go around that object with the flashlight to gather more information about it. This phase of search provides that individual with specific information about an object of interest, […] a similar task is performed by spotlight SAR systems to obtain detailed information on targets within a relatively small terrain area."

Also in this text, rich information about SAR is found, but sound knowledge of signal processing is required.

1.5 The Return Signal: Backscatter and Speckle

Speckle is a term inherently related to SAR images, and it is largely studied in this book throughout statistical methods. This book's contents are all intended to deal with speckle. Before explaining what speckle is about, first, the radar return signal is briefly accounted.

1.5.1 Backscatter

An important concept is the radar cross section (RCS), which measures the ability to detect an object by the radar, that is to reflect (*backwards* to the radar), part of the energy transmitted by the radar toward the illuminated area. The RCS is also known as the electromagnetic signature of the object and is denoted by σ. It is influenced by many factors, such as,

- the size of the target and mainly, its relative size respect to the wavelength of the radar signal,
- the composition of the target,
- the incident angle of the radar emitted signal,
- the polarization of the radar emitted signal.

The amount of reflected energy by an object depends both on its physical properties and on the properties of the radar signal used. The reflected signal is known as the backscattered signal.

In Figure 1.24) the signal detected at the sensor (the backscattered signal) formed as a convolution of the reflected signals by each illuminated target is illustrated. Note that the reflected signal is just proportional to the value of σ, keeping its original waveform.

In Figure 1.25), it is represented the same information as in Figure 1.24 but in a three dimensional model. As it can be seen, the many scatters within the illuminated area, reflect the radar signal by modifying the amplitude of the incident waves proportionally to their backscatter coefficients σ.

To conclude this brief introduction to the backscatter coefficient, it is important to note that, as explained above, the amount of energy backscattered depends on the composition of the target. Without entering the physical properties (percentage of humidity, metallic

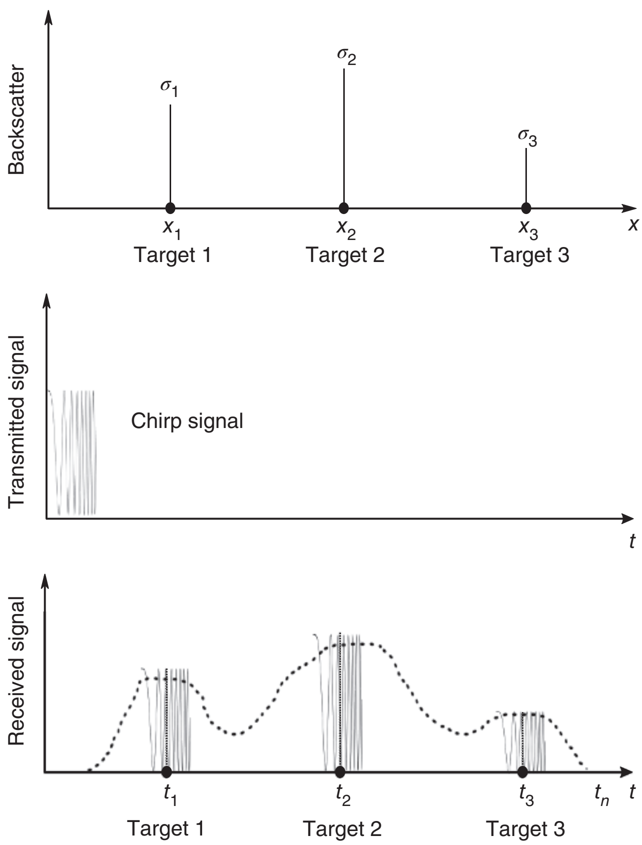


Figure 1.24 Unidimensional simplified model illustrating the detected signal (the echoed signal) from the convolution of the scattered signal by each target.

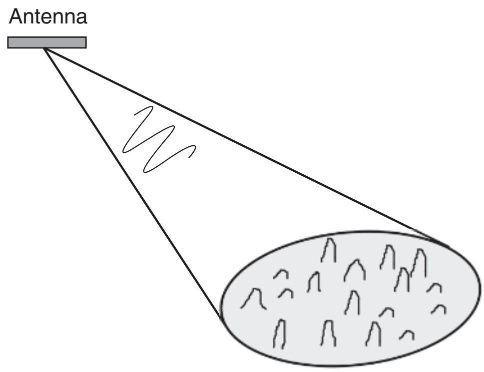


Figure 1.25 Multiple reflections (backscattered) from elementary scatters over an illuminated area.

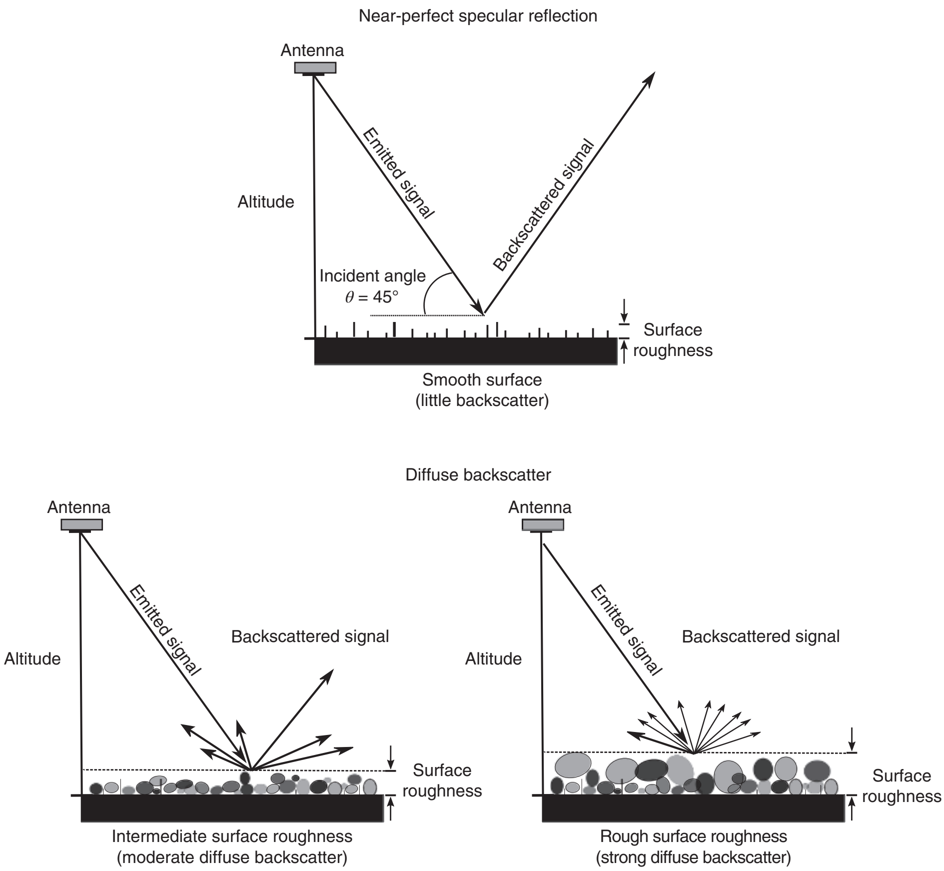


Figure 1.26 Backscatter and its relation to surface roughness.

components, etc.) and just focusing only on the size of the targets (when compared to the radar signal wavelength), three are the most important scattering mechanisms due to the surface roughness: the near-specular reflection, the near-diffuse, and the diffuse backscatter modes. These are shown in Figure 1.26).

In the case of near-specular reflection, no signal is received at the sensor, therefore, in the final image, it appears as a dark area (black pixels), as the black areas due to the calm ocean in

Figure 1.27 Zoom of the calm ocean from the San Francisco Bay SAR image (a), and the same area for the optical image (b).

Figure 1.6 (see a zoom of this image in Figure 1.27). The near and totally diffuse backscatter are due to reflections from objects of moderate and large size respectively and they will appear in the image brighter pixels (see, in this same image, the buildings and the forest area).

1.5.2 Speckle

Speckle statistical models are fully explained in Chapter 3. We address in this section the physical origin of speckle in SAR images.

An important characteristic of the radar signal in SAR systems is that they use a coherent signal[4]. A wave (signal, electromagnetic wave, light, etc.) is coherent when the phases of all waves at each point on a line normal to the direction of the beam propagation are identical. Usually, coherent light is monochromatic (single frequency) and a common practical source of such *light* is a laser or a radar signal. An example of coherent and incoherent signals (also known as non-coherent signal) is shown in Figure 1.28. From this image, it is clear

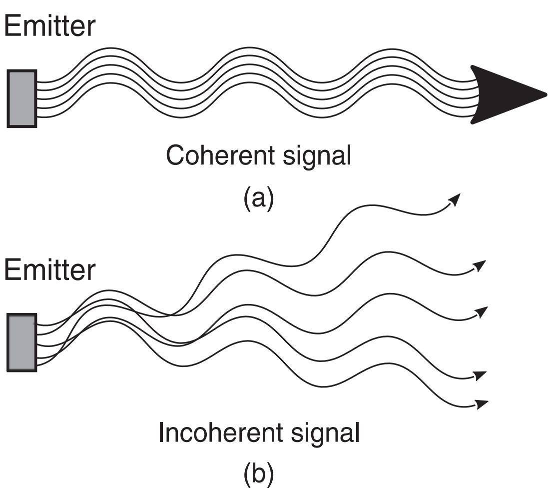


Figure 1.28 Coherent signal (a) and incoherent signal (b).

4 Not all radar systems use coherent signals (some systems use pseudo-coherent signals or also non-coherent signals).

that for the coherent signal, all phases are constant as the signal propagates. However, for the non-coherent signal, these phases are randomly distributed.

The benefits of using a coherent signal stem from the possibility of concentrating the emitted energy over the targets. Additionally, SAR data provides valuable information both in the amplitude and the phase of the received echoed signal. What defines a radar system as coherent or not comes from the type of transmitter used. The main advantage of a radar coherent system is that even very small phase shifts of the echo signals are detectable. Additionally, coherent radars also have a better signal-to-noise ratio than non-coherent systems. However, the use of coherent signals has an undesirable counterpart. After the the emitted signal interacts with the targets (see Figure 1.29), and from the fact that the used signal is coherent, backscattered signals may combine either in a destructive or a constructive way, or in a random combination of both definitive states. If this is extended to the real situation (as modeling in Figure 1.25) the consequence is that, from the multiple signal reflection due to the multitude of randomly located scatters, the received signal at the sensor is a sum of all those waved that, although coherent in frequency (all scattered signals have the frequency of the emitted radar signal), they are characterized by the absence of phase-coherence. Just as illustrated in Figure 1.29, for the case of destructive interference (waves are out of phase), a weak signal is received in the sensor. As for the constructive (waves are in phase), a strong signal is received. These mechanisms can be formulated mathematically through the sum of phasors (complex vectors) as it is explained in Chapter 3, and in more detail in the works by Yue et al. (2020, 2021b).

It is important to note that due to these mechanisms, many not-so-dark pixels will appear as black in the image. The same will occur to some not-so-bright pixels. This is the explanation of why the SAR images will look as corrupted with a salt-and-pepper noise. This characteristic granular pattern is what is known as speckle; it is easily visually recognizable. In a practical sense, a signal used in an imaging technique is considered to be non-coherent when no speckle effects are present in the final image and coherent when they are. The apparent

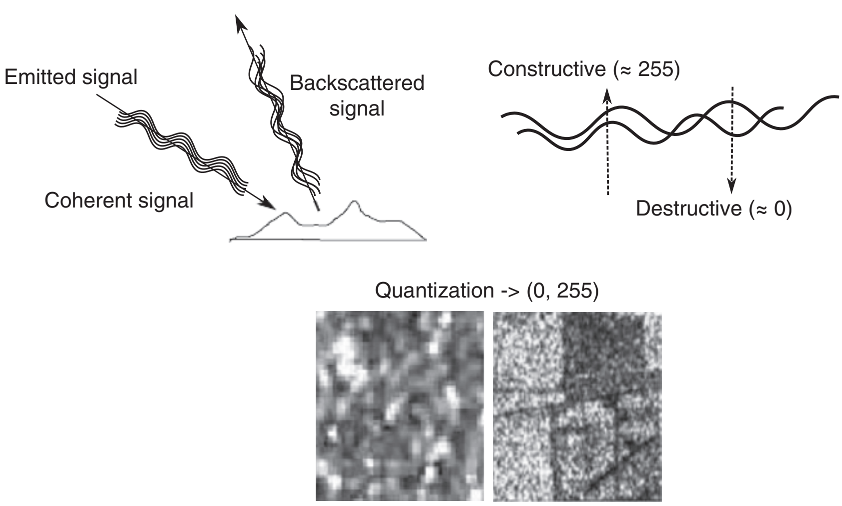


Figure 1.29 Constructive and destructive interference from using coherent signal. The constructive case (top right) will result in more white pixels (255), in a typical 8 bits quantization in the final image (bottom). The opposite occurs for the case of destructive case (more black pixels within the image). Both situations give the image a characteristic and easily visually recognizable granular pattern.

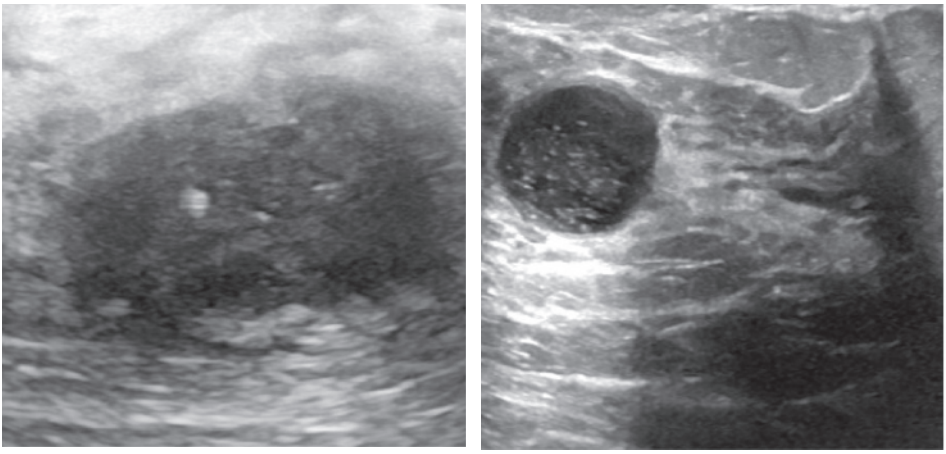


Figure 1.30 Actual breast ultrasound images. Source: From Breast Ultrasound Images Dataset, https://www.kaggle.com/aryashah2k/breast-ultrasound-images-dataset.

size of the scattering centers and that of the individual speckles observed in the image are related to the resolution limit of the acquisition system. Speckle is not exclusive of SAR images but it also appears in any imaging technique that uses coherent signals to form the image. Another well-known imaging technique largely affected by speckle is ultrasound-B (medical ultrasound images), laser, and sonar. An example of actual ultrasound images is shown in Figure 1.30.

From the above exposition, it is clear that speckle gives to final images a granular-like pattern, easily recognizable *visually* and it comes from illuminating the area under observation with a coherent signal. Speckle can hardly be considered noise as is the case of Gaussian noise in natural (optical) images, for it is not an added factor but a consequence of how the image is formed. If accepted that noise can be defined as a random or regular interfering effects that corrupt the quality of the data and the information it bears, speckle does not suit this definition. Regarding the particularities of the SAR imaging technique, speckle is a consequence of the resolution of the sensor, which is not sufficient to spatially separate (*resolve*) individual scatterers. Additionally, for the same acquisition conditions, an identical speckle pattern is obtained and, thus, it is not random.

In Goodman (1976), speckle is discussed from a physical point of view. This work is regarded as a seminal work, considered to be the first statistically modeling of speckle, which leads to the proposal of practical methods to reduce it. It can be said that the first speckle-reducing filters have been inspired by this work.

As explained above, each pixel in the final image is the result of the coherent superposition of all received signals from scatterers over the illuminated area. Indeed, from an image processing perspective, echoes within small parts of the illuminated area are jointly processed. Such small areas are termed *resolution cells*. The ensemble of the overall information from the resolution cells is what forms the final image. Besides, it can be assumed that the number and the distribution of the targets within each resolution cell are random (and unknown). A similar assumption holds for the physical composition of the targets and their sizes and textures. When one observes a SAR image, immediately will recognize its speckle content distributed within the whole image, showing a random alternation of bright and dark pixels due to the constructive and destructive patterns caused by the coherent illumination. Such

SAR image, being inherently a remote sensing image, typically will contain regions (usually large) related to homogeneous areas, such as agricultural soils, forest, roads, where the scatters within a resolution cell are almost uniform and, consequently, the speckle tends to be totally uncorrelated (randomly distributed). Such totally uncorrelated speckle areas (very common in SAR images) are known as fully developed speckle areas. However, this uncorrelated pattern is strongly modified by the geometric distortions due to the own nature of the SAR acquisition procedure (see Section 1.5.3); cf. Ref. (Yue et al., 2021a).

Although speckle contains information from the targets (indeed high-valuable information), speckle has a strong negative impact on the visual quality of SAR images, largely making it difficult their interpretation even for experts, not to mention the post-processing tasks (segmentation and classification), either manually or automatically (through machine learning techniques or deep learning approaches). Hence, speckle decreases the usability of SAR images since it makes it difficult to identify ground targets. Additionally, speckle content makes it difficult the estimation of the parameters that characterize the targets.

To mitigate the adverse effects provoked by speckle, many techniques have been researched over the past decades. Such efforts to reduce the speckle content within SAR images (and also in ultrasound medical images) is still ongoing. Basically, two are the techniques developed for despeckling (this is used term) SAR data:

The multilook approach consists of acquiring more images of the same illuminated area and to averaging all of them to reduce the speckle while preserving the amplitude level (Moreira, 1991). The approach is somehow similar to the HDR (High Dynamic Range) technique used in photography, where many photos are combined to improve the final result. In SAR, the images to be averaged correspond to images over the same illuminated area captured at different dates or taken from different look angles. A single-look SAR image indicates that one SAR image, whereas, for instance, a 4 Looks SAR image refers to a SAR image after averaging four (4) single-look SAR images. Although multilook technique notably improves the visual appearance of the image, it causes a loss of information caused by the averaging process. Indeed, multilook images seem blurred (the more blurred the higher the averages performed). That is, a single-look SAR image has a high speckle content (the maximum for that acquisition) but it also contains the maximum information (especially for edges and single targets). Examples of single-look SAR and 4-Look SAR images are shown in Figure 1.31. In summary, the multilook technique is easy to implement and it is very efficient in reducing speckle, but it also blurs the image in a similar way as a mean filter (boxcar filter) does. More on multilook technique, from a statistical perspective, is discussed in Chapter 3.

Filtering: reducing the amount of speckle by filtering the data (despeckling) is the other approach. The basic, but surprisingly very effective, median filter was first used and then replaced by more sophisticated filters. Along the past decades, many despeckling filters have been proposed, some of them, remarkably efficient (Lee et al., 2009). Essentially, a despeckling filter aims to reducing the speckle in large homogeneous areas while preserving image fine details (especially edges and bright scatterers, which are of particular importance in SAR). To that end, some methods (Lee et al., 2009, Kuan et al., 1985, Moschetti et al., 2006) explore pixels and close neighbors, and build local models from the data. Other methods (Cozzolino et al., 2014) explore larger areas (non-local filters). Yet other methods transform the data into a new domain through powerful imaging processing techniques, such as wavelet transform (Argenti and Alparone, 2002, Penna and Mascarenhas, 2019) or

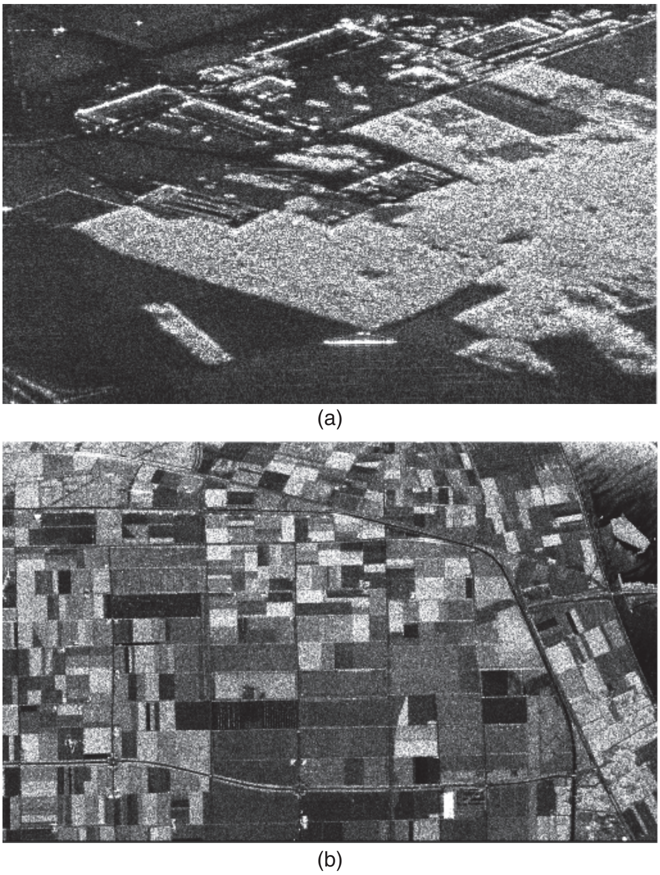


Figure 1.31 (a) Single Look SAR image (ESAR-HH, 1997 data) and (b) Flevoland (4-looks). In the latter, it can be identified the cultivated areas, some roads and even the small island. However, the interpretation of the single look image is a challenging task even for an expert.

total variation (Sun et al., 2021, Feng et al., 2014). The deep learning paradigm has irrupted recently into this challenging area with promising results (Ma et al., 2020). An example of despeckling a single-look SAR image by the simple median filter and the well-established Enhanced Lee filter is shown in Figure 1.32. Despeckling filters are studied in Chapter 5.

1.5.3 SAR Geometric Distortions

SAR systems, as often mentioned in this Chapter, are indeed complex system. Soumekh (1999), in the Preface, states

> "SAR is one of the most advanced engineering inventions of the twentieth century."

It is impossible in this Chapter to provide a whole explanation surrounding all technical aspects of SAR systems. Rather than that, our aim is reviewing those aspect which have a direct connection with speckle. SAR geometric distortions can be classified as:

- those caused by the side-looking nature of the SAR imaging system, which include effects as ground range nonlinearities, radar foreshortening, shadowing, and radar layover (explained below).

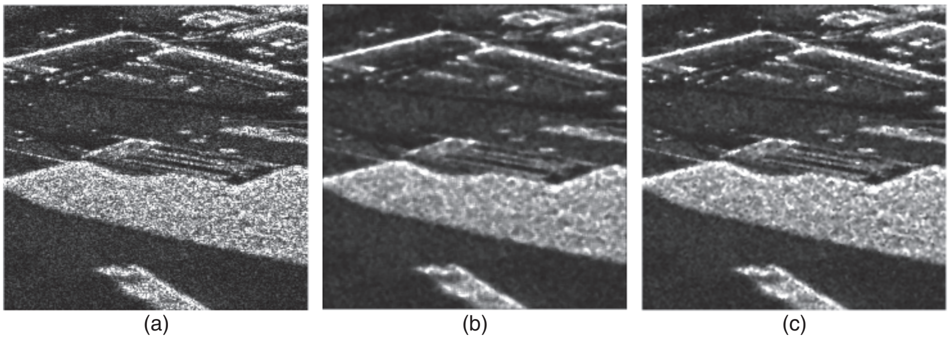


Figure 1.32 (a) Single Look SAR image (ESAR-HH, 1997 data) and (b) the filtered result by the median filter and (c) the result by the Enhanced Lee filter. It is clear that the latter performs better: image has more contrast (black areas appear blacker and bright areas, brighter) and fine details are better preserved.

- Distortion introduced during the data processing: it is due to approximations made to generate the final result (the image). They are mainly caused by errors in the estimation of the target phase or caused by wrong compensation for the Earth rotation during the acquisition time. The impact of these distortions depends on the precision of the algorithms used to obtain the final image.

In this section, only the first group of distortions are addressed. They are illustrated in Figure 1.33).

Details of the distortions caused by side-looking are:

Layover: the synthetic aperture (antenna) collects all the echoes from the targets within each resolution cell over the illuminated area. The ground coordinates are Azimuth and Range, being Azimuth the direction parallel to the flight movement of the antenna, and Range the orthogonal-to-movement direction. As the speed of the propagation of the emitted and received signals is finite (c, the speed of light), it is clear that targets along the range

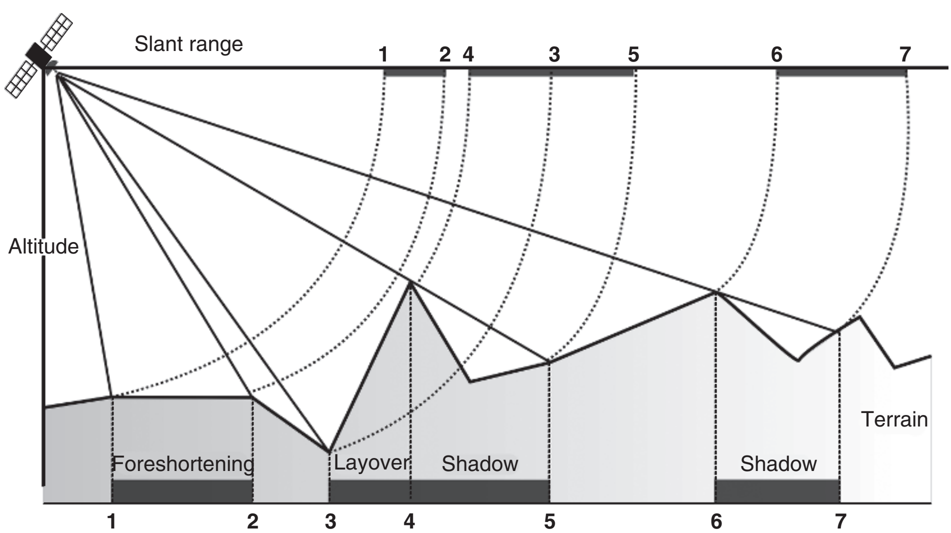


Figure 1.33 SAR geometric distortions.

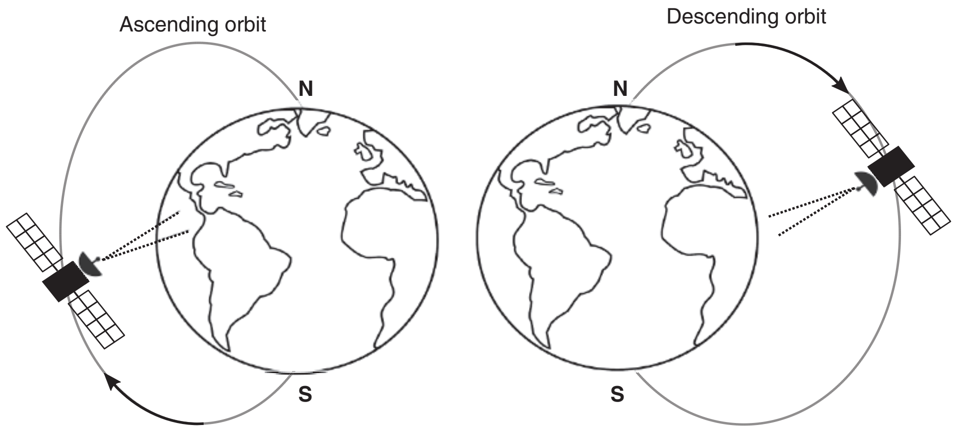


Figure 1.34 Ascending and descending polar orbits.

direction closer to the antenna will be captured first, so, in the final image, they will be represented also first. This is the desired situation for targets in the ground plane distributed with similar altitudes. However, for targets of different altitudes (see targets 3 and 4 in the ground plane in Figure 1.33), since the points located at a higher altitude are closer to the antenna than those at the base, they will be captured first and they will appear in the final image with a incorrect mapping (see, in the same figure, the mapping 3 → 4 and 4 → 3, when they should be mapped 3 → 3 and 4 → 4). This distortion is known as *layover*, and it is seen in SAR images that contain buildings or mountains. A SAR expert will visually recognize it easily.

Foreshortening: if the difference of altitudes among top and base points is not large enough, the mapping of the targets on the final image is correct but they will appear nearer (*compressed*) than they actually are in ground coordinates. This causes another SAR geometric distortion known as *foreshortening*. Such effect is represented in the figure (targets 1 and 2, which are correctly mapped, 1 → 1 and 2 → 2).

Shadowing: this is the last geometric distortion. See targets 4 and 5, and targets 6 and 7 in the figure. As its name suggests, the non-illuminated targets will not appear in the final image due to the absence of backscattering. For the case illustrated in this figure, the ground area from target 6 to target 7 will not be represented in the image and instead, a black area (black pixels) will be shown, which, obviously, does not agree with the actual scenario.

It is also important to note that two SAR images from the same illuminated area may show different kinds of geometric distortions mentioned above. That is, a shadow can be seen in one acquisition of an image and a different one in the other image due to the observation angle used in the acquisition. The same may happen for the foreshortening or/and the layover. This is because images can come from sensors with different observing angles. Note that some satellites operate in an ascending orbit and others in a descending one (see Figure 1.5.3). The information of the kind of orbit is usually known and it is useful when analyzing a SAR image.

These distortions can be significantly reduced if a three-dimensional model of the illuminated area is available and used to correct them. This is usually the case because most areas of interest have very accurate DEMs (Digital Elevation Models). Through image interpolation techniques, those corrections (terrain-corrected georeferencing) can be applied, at the

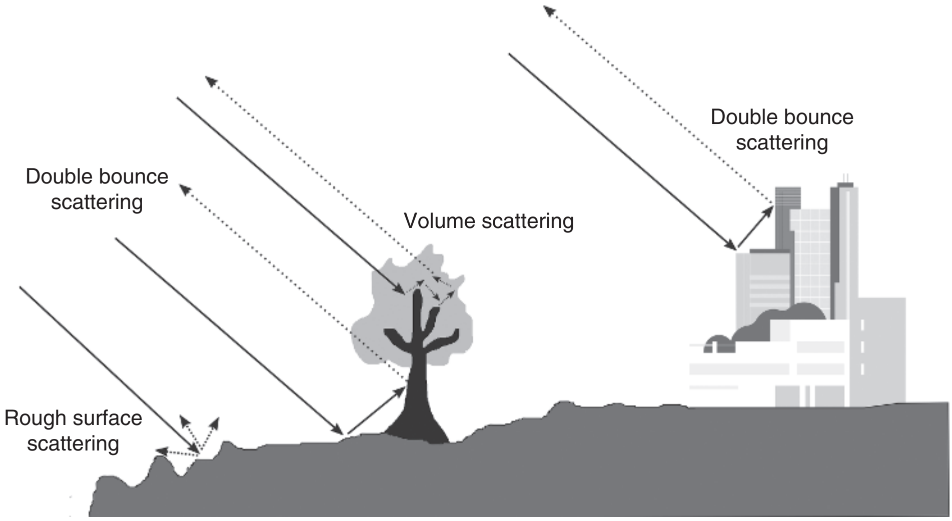


Figure 1.35 Scattering mechanisms.

cost of affecting the original spatial resolution (see, for instance, Frey et al., 2013a). Common software used for handling SAR images integrates these methods; cf. Section 1.7.

From these geometric interferences, a SAR image over a large illuminated area will commonly show the following types of areas:

- fully developed speckle regions, resembling a random pattern without visible structures. For the general case, the amplitude and the phase of the speckle field are statistically independent and the speckle phase are uniformly distributed over $(-\pi, \pi)$;
- in urban areas (with buildings), such regular pattern is less evident and it is replaced by a more complex pattern (shadowing and layover effects will manifest). Additionally, as illustrated in Figure 1.35, multiple reflections between ground and objects (trees, buildings, etc.) will be detected as stronger echoes in the sensor caused by the constructive interference from the reflected signals. Such double and multiple signal bounce scattering will be shown in the final image as very bright pixels, characteristic of SAR images. This scattering mechanism is, therefore, responsible for the illuminated side of objects which, in general, are mapped as strong bright pixels in the final image. It is also very common to identify shadows effects on the other side, along the range direction, where strong scatterers appear. Layover effects may cause the outstanding effect of mapping the buildings in non-natural disposition (the top of the building where the bottom should be or backward).

As mentioned, SAR images will show large variability, depending on the content of the illuminated area (see Figure 1.6, left). However, fully developed speckle areas and strong scatterers will play a decisive role when deciding the quality of a filtering operation performed on the image. This is discussed in the next chapters.

1.6 SAR Satellites

This section summarizes the SAR systems from the main Space Agencies. Special attention is given to spatial resolution and capabilities of those systems. Satellites equipped with SAR

Table 1.2 Overview of civilian SAR applications.

Area of application	Operation
Cartography	Topographic maps
	DEM (Digital Elevation Model)
Agriculture	Land cover monitoring
	Soil moisture measurement
Oceanography	Wind speed estimation
	Monitoring coastline changes
	Oil spill and maritime traffic surveillance
Hydrology	Flood monitoring
	Hydrological modeling
Geology	Landslide monitoring
	Geomorphological modeling
Forestry	Land use monitoring
	Detection of changes in vegetation
	Fire surveillance

Table 1.3 Some well-known SAR systems: a brief review.

Satellite	Country	Year	Band	θ (degrees)	Polarization	Range Resolution (m)	Azimuth Resolution (m)
SEASAT	EEUU	1978	L-Band	23°	HH	7.9	6
ERS-1/2	Europe	1991/95	C-Band	15° to 23°	VV	9.7	25
ENVISAT	Europe	2002	C-Band	15° to 45°	HH,HV,VH,VV	16.6	6

observation systems orbit the Earth in a sun-synchronous polar orbit, collecting data (amplitude and phase) day and night, independent of cloud coverage, with a revisiting period, of usually a few days. Table 1.2 presents an overview of some common civilian applications for SAR data.

Table 1.3 provides information about some well-known systems.

From this table, polarization modes have evolved from the single configuration (HH) to full polarization modes (HH, HV, VH, VV). The spatial resolution (both, in range and in azimuth) has also been notably improved.

Although this section focuses on main SAR systems, which are detailed above, for the sake of completeness, other relevant agencies (and SAR missions) are:

- Indian Space Research Organization (ISRO): RISAT-1
  - Year: 2012.
  - Polarization: dual.
  - Resolution: 3 to 50 meters, and one meter in Spotlight mode.
- Argentina's space agency (CONAE, Comisión Nacional de Actividades Espaciales): SAOCOM,
  - Year: 2018 (SAOCOM 1A), 2020 (SAOCOM 1B).

  - Polarization: HH, HV, VH, VV.
  - Resolution: 7 to 100 meters (SAOCOM 1A),.
- Korea Areospace Research Institute (KARI): KOMPSat-5,
  - Year: 2013.
  - Polarization: HH, HV, VH, VV.
  - Resolution: 20 meters (Stripmap mode) and one meter at high resolution mode.

We now provide details about the main SAR systems. We first present the European and American missions, followed by the Japanesse and Chinesse missions. It is recommended to visit the ESA (European Space Agency) website, (https://www.esa.int/) and, particularly, the Sentinel website (https://sentinel.esa.int/web/sentinel/home). For the COSMOS-Sky Med, it is recommended to visit (https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/cosmo-skymed) and for the RADARSAT, https://www.asc-csa.gc.ca/eng/satellites/radarsat/default.asp. For the TerraSAR-X, it is recommended to visit the website https://www.dlr.de/content/en/missions/terrasar-x.html, and for NASA's airborne and satellite-based systems, the website https://earthdata.nasa.gov/learn/articles/getting-started-with-sar. See the website https://directory.eoportal.org/web/eoportal/satellite-missions/a/alos-2 for more information about the Japanese mission, and https://eoportal.org/web/eoportal/satellite-missions/g/gaofen-3 for the Chinese mission. All the information summarized in this section has been extracted from those websites.

1.6.1 European Mission: Sentinel-1

The Sentinel missions include radar (SAR) and super-spectral imaging for land, ocean, and atmospheric observation and monitoring. Sentinel is part of the European Union's Copernicus program. Copernicus includes many missions carrying different sensors (Sentinel-1, Sentinel-2, Sentinel-3, Sentinel-4, Sentinel-5, and Sentinel-6), and with many near-future missions (Sentinel-7, Sentinel-8, Sentinel-9, Sentinel-10, Sentinel-11, and Sentinel-12) to be included in the second generation of Copernicus program. Sentinel-1 uses a SAR system and it is the one summarized in this section. Sentinel-1 mission consists of two twin polar-orbital satellites (*a constellation*) sharing the same orbital plane: the Sentinel-1A satellite (launched in 2014), and the Sentinel-1B satellite (launched in 2016), operating day and night. Both satellites carry a C-band SAR, which provides high-resolution imagery with high cloud penetrating capabilities. Sentinel-1 mission has a short revisit period, making it reliable for repeated wide-area monitoring. This is of particular interest for detecting and tracking oil spills and to mapping sea ice, as well as for detecting landslides and changes in the land uses. Through the Copernicus Hub (see Section 1.7), Sentinel-1 data are freely accessible. For each observation, precise measurements of spacecraft position and attitude are available. In particular, no distinction is made between public, commercial, and scientific uses, or between European or non-European users. Each Sentinel-1 satellite is expected to transmit Earth observation data for at least 7 years and have fuel on-board for 12 years.

Table 1.4 gathers a selection of the Sentinel-1 data of interest.

The SAR instrument onboard in the Sentinel satellites operate in one of the four exclusive modes:

Stripmap: the sensor provides continuous coverage with a ground resolution of 5 m $\times$ 5 m at a swath width of 80 km while the antenna beam is pointing to a fixed azimuth and elevation angle. This mode will only be operated on request for extraordinary situations.

Interferometric wide swath: this is a new type of Scan mode, called Terrain Observation with Progressive Scan (TOPSAR, with the purpose to reduce the drawbacks of the standard

Table 1.4 Some Sentinel-1 parameters.

Sentinel-1 parameter	Value
Polarization modes	Single (HH or VV)
	Dual (HH + HV or VV + VH)
Antenna length	12.3 m
Antenna width	0.82 m
Azimuth beam width	0.23°
Elevation beam width	3.43°
Elevation beam steering range	−0.9° to 0.9°
Maximum range bandwidth	100MHz
Apogee altitude	683 km
Repeat interval	12 days (175 orbits/cycle)

Scan mode. The basic principle of TOPSAR is the shrinking of the azimuth antenna pattern (along-track direction) as seen by a spot target on the ground. This is obtained by steering the antenna in the opposite direction as for Spotlight support. This acquisition mode is Sentinel-1's primary operational mode over land.

Extra wide swath: an extension of the interferometric wide swath mode to cover very wide areas (400 km) at a medium ground resolution of 20 m × 40 m.

Wave: in this mode, a set of stripmap scenes (known as *vignetes*), at regular spatial intervals of 100 km along-track are acquired. This mode is particularly well-suited for ocean applications, where data can be taken over large areas at low resolution.

1.6.2 European Mission: COSMO-SkyMed Systems

COSMO-SkyMed (Constellation of Small Satellites for Mediterranean basin Observation) is a 4-satellite constellation, operated by ASI (Agenzia Spaziale Italiana). The COSMO-SkyMed program, launched in 2007, represents, at present, the largest Italian investment in space systems for Earth Observation. Each satellite is equipped with an X-band SAR instrument, and the main goal of the mission is to provide global Earth observation for both, the military community and the civilian society (commercial and for institutions). The four satellites are in sun-synchronous polar orbits with a nominal altitude of 619 km and an orbital period of 97.2 min. The operating life of each satellite is estimated to be of five years, and the revisit period is of 16 days. The radar antenna is 1.4 m wide and 5.7 m long, operating at a center frequency of 9.6 GHz with a maximum radar bandwidth of 400 MHz. The polarization modes available are the same as for the Sentinel-1 mission: single and dual. Table 1.5 presents a selection of the COSMO-SkyMed data characteristics.

1.6.3 European Mission: TerraSAR-X

TerraSAR-X has been a remarkable European mission for observing the Earth promoted by the German Aerospace Center (DLR) and EADS (European Aeronautic Defence and Space Company) Astrium. The SAR satellite was launched in 2007 and became fully operational in 2008. It orbiting the Earth in a polar orbit at 514 km altitude. Then, in 2010, a twin satellite complemented the initial system, that became to be known as the TanDEM-X system,

Table 1.5 Cosmo-SyMed acquisition modes.

Mode	Swath km × km	Resolution (m) Range × Azimuth	Polarization
Stripmap (Himage)	40 × 40	3 × 3	Single HH or VV or HV or VH
Stripmap (Ping-Pong)	30 × 30	15 × 15	Alternating HH/VV or HH/HV or VV/VH
Spotlight-2	10 × 10	1 × 1	Single HH or VV
Scan (huge area)	200 × 200	100 × 100	Single HH or HV or VH or VV
Scan (wide area)	100 × 100	30 × 30	Single HH or HV or VH or VV

which acquires data for the worldwide and homogeneous DEM (Digital Elevation Model) high-valued data for mapping the Earth's surface. TerraSAR-X (also referred as TSX mission or TerraSAR-X1) is intended for both, scientific and commercial applications, operating at multi-mode and high-resolution X-band. Terra-SAR-X data have wide applications: hydrology, climatology, disaster monitoring, cartography (DEM generation of 2D and 3D maps) when it operates in interferometry and stereometry conditions, among others. Due to its short revisiting time (2.5 days) and access to any point on Eath, TSX mission is of enormous value for change detection of land use or even for monitoring large-scale construction projects. Some characteristics of the TerraSAR-X system are collected in Table 1.6.

Table 1.7, displays some parameters regarding the imaging modes of the TerraSAR-X system.

A collection of TerraSAR-X data is freely available for users at https://tpm-ds.eo.esa.int/oads/access/collection/TerraSAR-X.

1.6.4 Canadian and NASA Missions

First, the RADARSAT Mission is summarized, and then, some NASA missions are also briefly addressed. The RADARSAT Constellation Mission (RCM), launched in 2019, is Canada's new generation of observation satellites for scanning the Earth day or night in any weather

Table 1.6 TerraSAR-X system characteristics.

TerraSAR-X Parameter	Value
SAR antenna dimensions (length × height)	4.8 m × 0.80 m
Centre frequency	9.65 GHz ($\lambda = 3.1$ cm)
Resolution (maximum)	1 m
Polarization	HH, VV, HV, VH single or dual
Revisiting time	11 days

Table 1.7 TerraSAR-X acquisition modes.

Beam Modes	Scene size (width × length)	Maximal spatial resolution (m)
Stripmap	30 km × 50 km	3
Spotlight	10 km × 5 km	1
Scan	100 km × 150 km	16

conditions by using a constellation of three identical SAR satellites operating in C-Band. This constellation allows for a daily revisit of Canada's territory. It also allows daily access to ≈ 90 % of the planet and up to four times a day for the Artic.

RCM is the natural evolution of the previous RADARSAT program based on the RADARSAT-2 satellite (launched in 2007, yet active), but fully optimized (including a strong reduction of its size: half the size of its predecessors).

RCM data is used in many fields: maritime surveillance, agriculture, climate change monitoring, ecosystem monitoring, land use evolution, and even human impact on the Earth's surface.

Although RCM data are mostly restricted, certain image products are freely and openly available for worldwide users, under certain conditions.

However, for RADARSAR-2 mission, data is freely available after registration (see the website https://earth.esa.int/eogateway/missions/radarsat).

A full comparison of characteristics of RADARSAT-2 and the RCM is available on the website (https://www.asc-csa.gc.ca/eng/satellites/radarsat/technical-features/radarsat-comparison.asp), and Table 1.8, gathers some of those parameters.

Table 1.9 presents some parameters regarding the resolution capabilities of the RCM system. Similar parameters for the RADARSAT-2 are gathered in Table 1.10.

Apart from the Canadian mission, NASA's airborne and satellite systems provide also high-valuable SAR data for users (many of them freely). In Section 1.8, we present a brief introduction to some useful tools to access NASA's data.

It is also worth mentioning the NASA-ISRO SAR (NISAR) Mission (https://nisar.jpl.nasa.gov/mission/quick-facts/, to be launched in 2022 from India's Satish Dhawan Space Center in Sriharikota, India, into a near-polar orbit, which the purpose of monitoring climate

Table 1.8 RADARSAT-2-RCM system characteristics.

	Item RADARSAT-2	RADARSAT constellation
Altitude	798 km	586–615 km
High resolution (spotlight mode)	1 m × 3 m	1 m × 3 m
SAR antenna dimensions (length × height)	15 m × 1.5 m	6.75 m × 1.38 m
Centre frequency	5.405 GHz ($\lambda = 5.7$ cm)	5.405 GHz ($\lambda = 5.7$ cm)
Bandwidth	100 MHz	100 MHz
Active antenna	C-Band	C-band
Polarization	HH, VV, HV, VH	HH, VV, HV, VH Compact

Table 1.9 RCM acquisition modes.

Beam Modes	Nominal swath width (km)	Approximate resolution (m)
Low Resolution (100 m.)	500	100 × 100
Medium Resolution (50 m.)	350	50 × 50
Medium Resolution (30 m.)	125	30 × 30
Medium Resolution (16 m.)	30	16 × 16
High Resolution (5 m.)	30	5 × 5
Very High Resolution (3 m.)	20	3 × 3
Ship Detection	350	variable

Table 1.10 RADARSAT-2 acquisition modes.

Beam Modes	Nominal swath width (Km)	Maximal spatial resolution (m)
Standard	100	25
Wide	150	25
ScanSAR Narrow	300	50
ScanSAR Wide	500	100
Ocean Surveillance	530	Variable

change. This mission will scan the Earth's surface (land and ice-covered areas) with a visiting time of 12 days with a maximum resolution of 3 m. NISAR will become the first SAR satellite to use two microwave bandwidth regions: L-band ($\lambda = 24$ cm) and S-band ($\lambda = 9$ cm). By using such short wavelengths, this sensor will be able to observe changes in the Earth's surface of less than a centimeter in size.

1.6.5 Japanesse Mission

Japanese SAR systems include the L-band satellites under the general name ALOS (Advanced Land Observing Satellite): ALOS/AVINIR-2, PALSAR) and ALOS-2 (ALOS-2/ScanSAR). Data from these satellites, since 2019, are freely available. The main objective is to provide data continually for regional observation, disaster monitoring, environmental observation, and cartography. The ALOS/PALSAR (Advanced Land Observing Satellite Phased Array L-band Synthetic Aperture Radar) is an enhanced version of the JERS-1 (Japanese Earth Resources Satellite 1). It was launched in 2006, and it operates in a sun-synchronous orbit at an altitude of 691 km, with a 46-day recurrence cycle. The PALSAR sensor operates in a wide range of off-nadir angles and resolutions in a single-, dual-, and quad-pol mode.

The ALOS-2 SAR was launched in 2014 in a Sun-synchronous orbit, at an altitude of 628 km, with a revisiting time of 14 days. Some specifications for this satellite are collected in Table 1.11.

Table 1.12 presents some parameters regarding the resolution capabilities of the ALOS-2 system.

Table 1.11 ALOS-2 System Characteristics.

ALOS-2 Parameter	Value
SAR antenna dimensions (length × height)	9.9 m × 2.9 m
Centre frequency	9.65 GHz (λ = 3.1 cm)
Band (wavelength)	L-band (λ = 22.9 cm)
Resolution (maximum)	1 m (range) × 3 m (azimuth)
Polarization modes	Single / dual / full / compact

Table 1.12 ALOS-2 acquisition modes.

Beam Modes	Swath	Spatial resolution (m)
Stripmap	Ultra-fine: 50 km	3
	High-sensitive: 50 km (FP: 30 km)	6
	Fine: 70 km (FP: 30 km)	10
Spotlight	25 km × 25 km	3 (range) × 1 (azimuth)
ScanSAR	350 km	100

1.6.6 Chinese Mission

The Chinese Academy of Space Technology developed the Gaofen systems (Gaofen 1, Gaofen 2, up to Gaofen 14), and many powerful Gaofen satellites are in space since the launch of the first one, Gaofen 1, in 2013. The latter was a high-resolution optical observation satellite, and, in general, the main goal of the Gaofen mainframe relies on performing observations for disaster prevention and relief, geographical mapping, climate change monitoring, environment, and resource surveying, and also for precision agriculture support. However, Gaofen-3 is a SAR civilian satellite, that operates in the C-band, aiming to provide high-resolution images (land and ocean monitoring, disaster reduction, water conservancy, and meteorology) and disaster monitoring. It is in a Sun-synchronous orbit (like the RADARSAT-2 and Sentinel-1 systems), at an altitude of 755 km. Table 1.13 collects some of its parameters.

Table 1.13 Gaofen system characteristics.

Item	Value
Band	C-band
SAR antenna dimensions (length × height)	15 m × 1.5 m
Polarization	Single/Dual/Full
Acquisition modes	12
Swath width	10 km to 650 km
Spatial resolution	1 m to 500 m

Table 1.14 The 12 acquisition modes of Gaofen-3.

Acquisition Mode	Observation angle (°)	Resolution (m)	Swath width (km)	Polarization
Spotlight	[20, 50]	1	10×10	single
Ultra-fine Stripmap	[20, 50]	3	30	single
Fine stripmap	[19, 50]	5	50	dual
Wide fine stripmap	[19, 50]	10	100	dual
Standard stripmap	[17, 50]	25	130	dual
Narrow ScanSAR	[17, 50]	50	300	dual
Wide ScanSAT	[17, 50]	100	500	dual
Global observation	[17, 53]	500	650	dual
Quad-pol stripmap	[20, 41]	8	30	quad
Wide quad-pol stripmap	[20, 38]	25	40	quad
Wave	[20, 41]	10	5×5	quad
Expanded incidence angle	[10, 20]	25	130	dual
	[50, 60]	25	80	dual

Table 1.14 presents some parameters regarding for the twelve (12) observing modes of Gaofen-3, provided by the C-SAR (Complementary SAR) sensor.

1.7 Copernicus Open Access Hub

Information summarized in this section is from the website https://scihub.copernicus.eu/. To have a global understanding of the Copernicus program, it is recommended to visit the website https://www.copernicus.eu/en. According to those websites,

> Copernicus is the European Union's Earth observation program, looking at our planet and its environment to benefit all European citizens. It offers information services that draw from satellite Earth Observation and in-situ (non-space) data

It takes its name from the great well-known European scientist and astronomer Nicolaus Copernicus.

Copernicus program provides a vast amount of global data from different systems: satellites, ground-based, airborne and, seaborne, free and openly accessible to users.

How to access satellite data? Fortunately, this is an easy task using the Copernicus Open Access Hub, which provides complete, free and open access to data from Sentinel-1 (SAR) and other products (Sentinel-2, Sentinel-3, and Sentinel-5P).

For the case of interest of this book (SAR data), a brief description of Sentinel-1 data available from the Copernicus Open Access Hub is detailed below. Readers are strongly encouraged to register and experiment with the Copernicus' Hub to discover its enormous possibilities. Through an interface, it is easy to map any zone under satellite observation and to request for products (data), download them, and start using them. The data are free of charge to all data users (commercial users, scientific and general public) under the Sentinel Standard Archive Format for Europe (SAFE) format which is recognized by ESA tools (also free) like SNAP (see the end of this section). Data are available in single-polarization (VV or HH) for the Wave mode and in dual-polarization (VV+VH or HH+HV) or single-polarization for Stripmap, Extra Wide Swath mode, and Interferometric Wide Swath mode. The data are organized in levels:

Level-0: this can be considered the most complex data, not indeed easy to handle by new users, but, at the same time, they are of great value because they are SAR raw data.

Level-1 are data intended for most users and they come into two different products:

- **Level-1 SLC (Single Look Complex):** focused SAR data geo-referenced using orbit and altitude data from the satellite. This product includes a single look in each dimension (range and azimuth) in complex format.
- **Level-1 GRD (Ground Range Detected):** focused SAR data that has been detected, multi-looked, and projected to ground range. Its multi-look nature reduces strongly the speckle content (but it reduces the spatial resolution). For that reason, three resolutions are available (depending on the amount of multi-looking performed), Full, High, and Medium.

Level-2: it has several special products for ocean observation:

- **OSW (Ocean Swell) spectra:** a two-dimensional ocean surface swell spectrum that includes an estimate of the wind speed and direction per swell spectrum. OSW operates in Stripmap and Wave modes.
- **OWI (Ocean Wind Fields):** intended for monitoring surface wind speed and direction at 10 m above the surface (it operates in Stripmap, Interferometric Wide Swath and, Extra Wide Swath mode modes).
- **RVL (Surface Radial Velocities):** a ground range gridded difference between the measured Level-2 Doppler grid and the Level-1 calculated geometrical Doppler. RVL provides an estimate of the width of the ocean Doppler spectra.

ESA has developed several software tools (toolboxes), freely available, for handling Sentinel data; SNAP (Sentinel Application Platform) is one of them. SNAP can be downloaded from the website https://step.esa.int/main/download/snap-download/, and a full description is available at https://step.esa.int/main/toolboxes/snap/. It is strongly recommended to use SNAP to process downloaded data from Copernicus Open Access Hub. SNAP's interface contains a link to many tutorials that are recommended to visit.

Figure 1.36 shows the graphical interface of the SNAP tool and a SAR image to be processed with it. We present examples of processing actual SAR data with SNAP in Section 1.9.

In the website https://asf.alaska.edu/how-to/data-recipes/how-to-create-a-subset-of-a-sentinel-1-product/, an actual Sentinel 1 scene is fully processed to get the final VV and VH polarized images.

1.8 NASA Earth Data Open Data

NASA's airborne and satellite systems provide also highly-valuable SAR data for users (many of them freely), although, sometimes it can be challenging to use. For that reason, NASA's Earth Science Data Systems (ESDS) program and Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAACs) make available to users

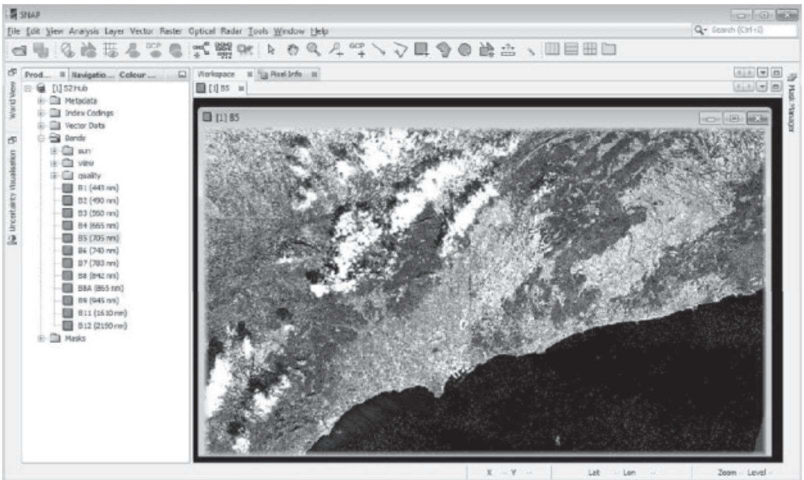


Figure 1.36 An example of processing SAR data with the SNAP tool.

a set of tools to overcome those difficulties. Users interested in accessing NASA's SAR data, are encouraged to visit the websites:

- https://earthdata.nasa.gov/learn/articles/getting-started-with-sar: provides an introduction to SAR and it details how to access to SAR data.
- https://worldview.earthdata.nasa.gov is a tool from NASA's Earth Observing System Data and Information System (EOSDIS) that provides the capability to interactively browse over 900 global, full-resolution satellite imagery layers and then download the underlying data.

1.9 Actual SAR Data Examples

This section is devoted to showing two actual SAR data sets (Sentinel-1) freely available. Data is downloaded from

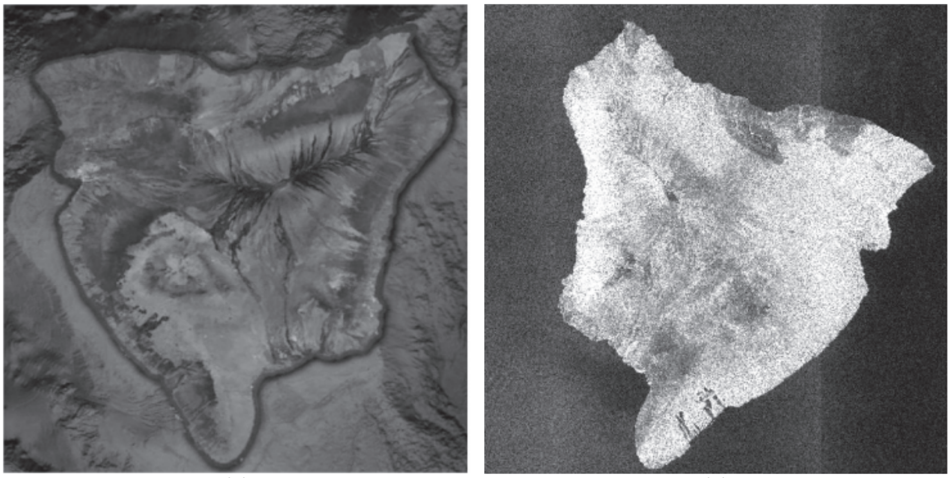
- Hawaii's Big Island (4 equivalent looks): from NASA Earth Data Open Data (https://asf.alaska.edu/how-to/data-recipes/how-to-create-a-subset-of-a-sentinel-1-product/),
- Other examples: some Sentinel-1 actual SAR data.

The purpose is not to give a SNAP tutorial but to show some results of interest.

1.9.1 Hawaii's Big Island

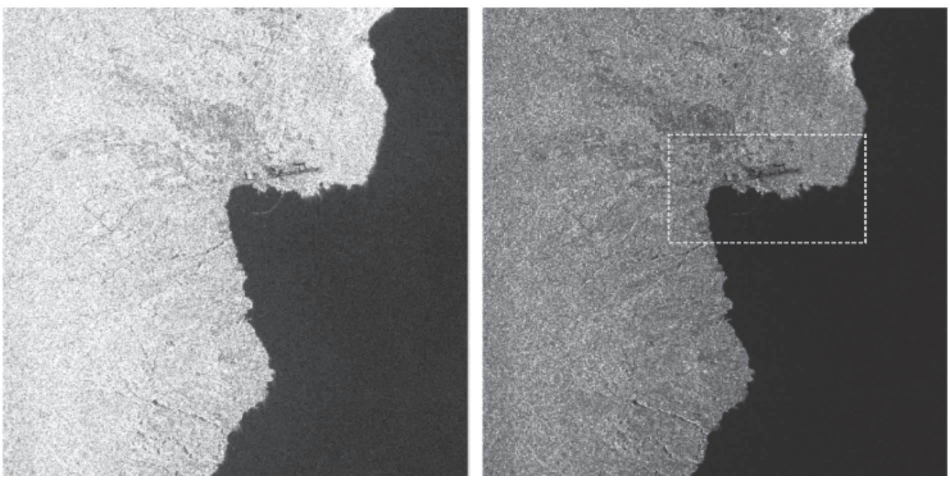
Figure 1.37 shows the Intensity VH band over Hawaii's Big Island as it is available. The optical image from Google Earth is also shown just to point out a typical issue: the SAR geo-spatial image orientation does not correspond with the optical image (it is also mirrored, that is, the left part should be the right part and the opposite). The optical image has been rotated to note more easily the mirroring effect. To correct this orientation flaw is an trivial task (a simple image co-registration operation would solve it).

A subset of the original image is taken (in SNAP by using the utility "Spatial Subset from View…"), and the images for the Intensity and Amplitude bands in the polarization VH can



(a) (b)

Figure 1.37 (a) Optical image from Google Earth of Hawaii's Big Island and the Sentinel-1 image (b).



(a) (b)

Figure 1.38 (a) Amplitude VH image and intensity VH image (b) for a subset from the original Sentinel-1 SAR data. See the next figure for a zoom of the dashed rectangle.

be seen in Figure 1.38. The differences between those data modalities, intensity and amplitude are addressed in Chapter 3, although, some clear differences are visible from the images.

From the many possibilities of the SNAP to work with satellite data, just some processing is done for the intensity SAR data. The common methodology includes:

- reading the data (already done). It is recommended not to uncompress the original downloaded data to save hard disk space. SNAP will handle the compressed data.
- the removal of the thermal noise from electrical fluctuations from the random thermal motion of electrons,
- steps for acquiring the satellite orbit file (to improve geo-coding and other capabilities),
- calibration to make that image pixels represent true radar backscatter values from the reflecting surface,

- terrain-flattenig to *flatten* the image, that is, to reduce the terrain-induced radiometric variations,
- terrain-correction step to apply a DEM (digital elevation model) to produce a map projected product,
- despeckling to reduce speckle content. SNAP includes the well-known Enhanced Lee filter mentioned above (Lee et al., 2009),
- write the transformed data to files.

Some of those steps are not required and sometimes other are depending of the nature of data (raw data, single-look-data, ground data, etc.) This done for the selected area shown in Figure 1.38 (the rectangle in dashed white lines). Figure 1.39 shows the processed image and its filtered version. As it can be seen, details are preserved, specially the bright scatters, while speckle has been reduced.

At last, SNAP can export the original SAR data bands (the data) and the processed bands in many formats. Among them, the one used in this book is the ENVI format (a file or files of binary data and a header file that collects all relevant information). This task can be done in SNAP as explained in Figure 1.40. The submenu "Bands extractor" opens from (Toolbar) Raster → Bands extractor.

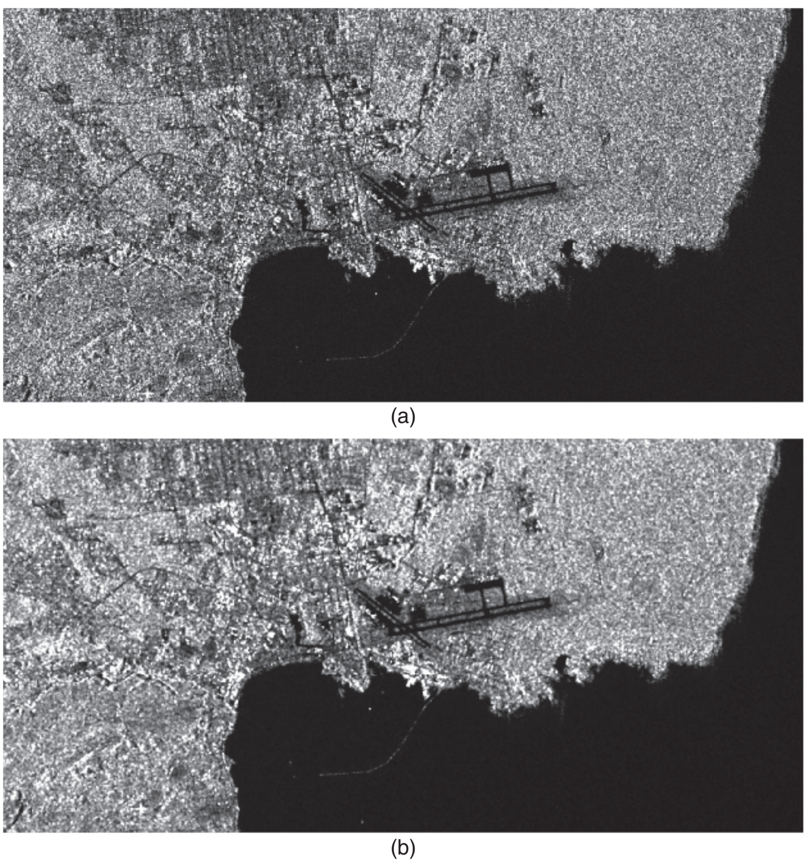


Figure 1.39 (a) Subset after applying some processing and the filtered image by the Lee filter(b).

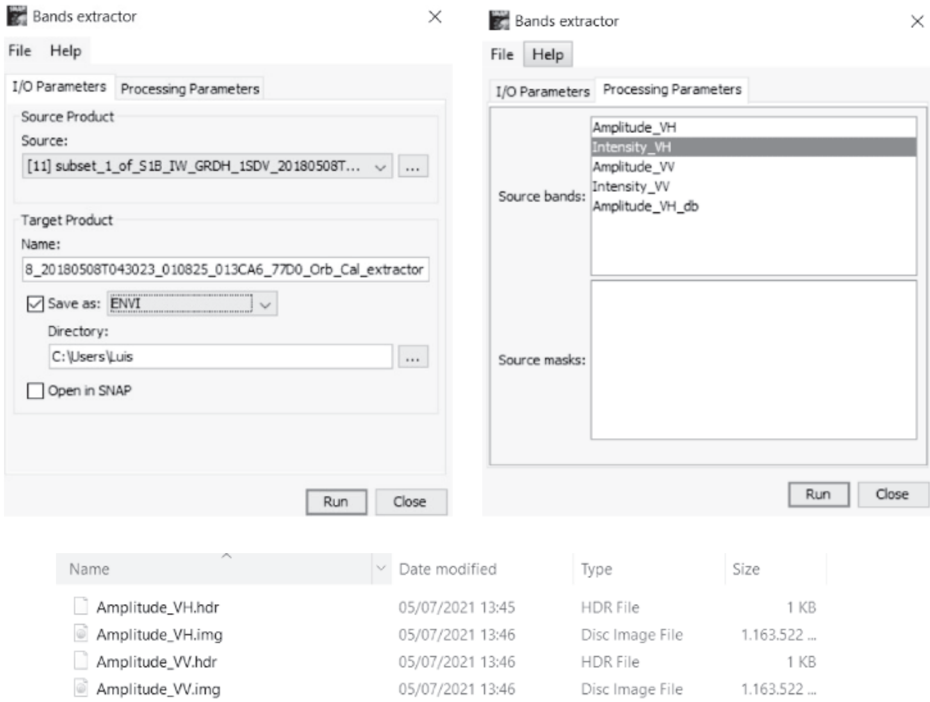


Figure 1.40 Exporting the bands from SNAP to ENVI format.

1.9.2 Other Examples

From the Copernicus Open Access HUB, some examples over Europe are selected and shown in Figure 1.41 and Figure 1.42.

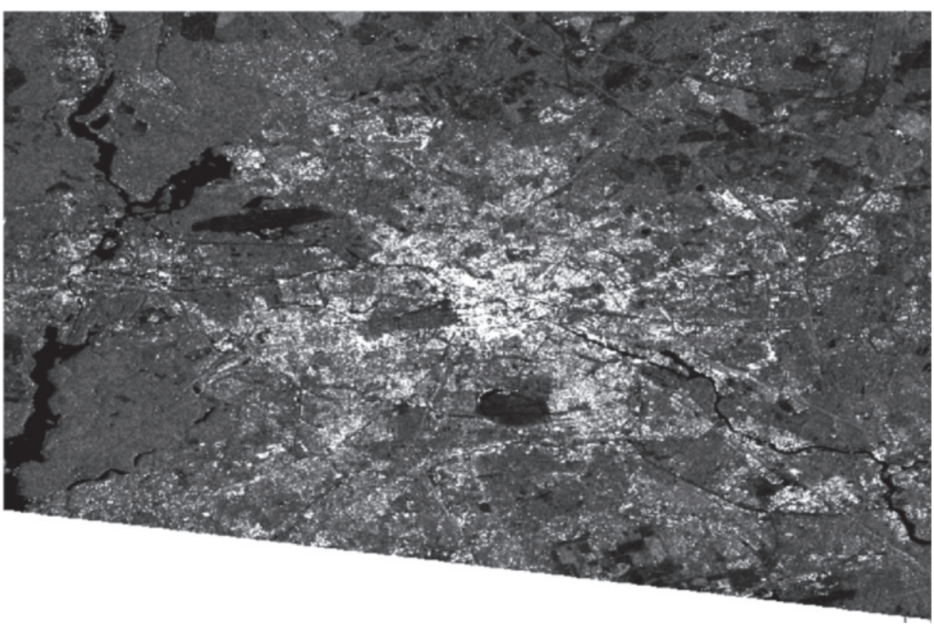


Figure 1.41 Low-resolution Sentinel-1 intensity-HH image over Berlin and surroundings (image has been processed with SNAP).

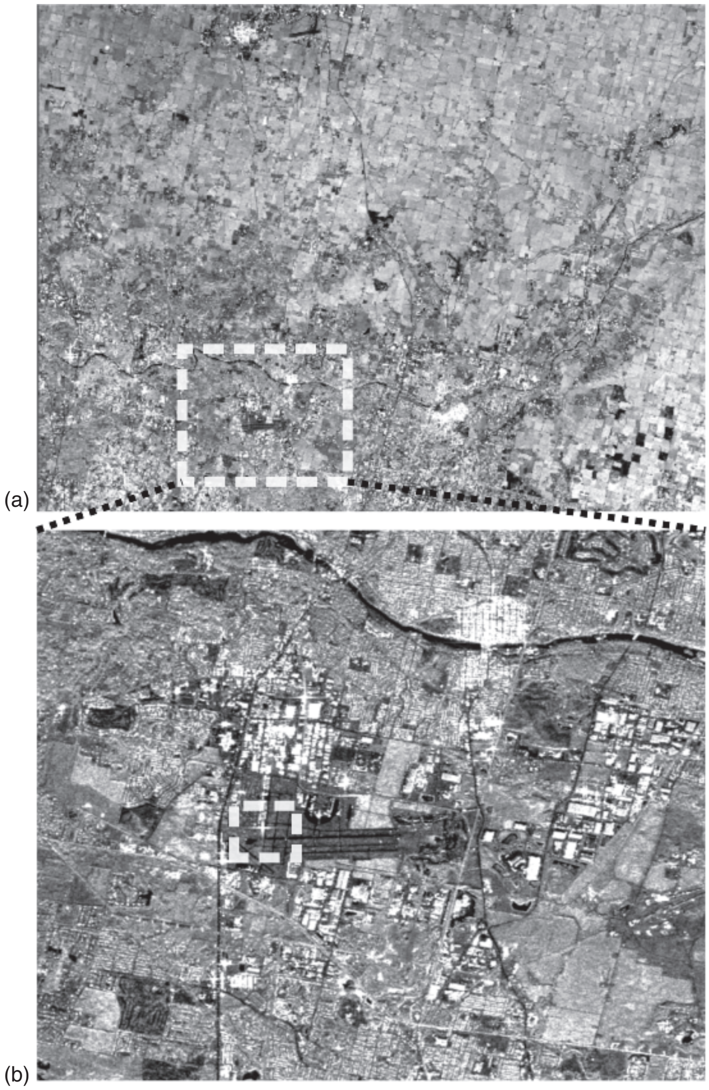


Figure 1.42 (a) High-resolution Sentinel-1 amplitude-HH image over Central Europe (image has been processed with SNAP). (b) The bottom image is a zoom of the indicated area, where a strong bright scatterer can be seen (within the dashed white rectangle).

Exercises

1 For a set of targets with backscatter coefficients, $\sigma_1 > \sigma_2 > \sigma_3$, and a given chirp-up radar signal, represent, in a one-dimensional plot, the received echoes.

2 In the assumption that the representation for Figure 1.33 is for an ascending-orbit satellite, represent the same for a descending-orbit satellite.

3 By using the Copernicus Open Access HUB, locate Sentinel-1 data and process them with the SNAP program.