Chapter 2

Principles of SAR Image Formation

SAR is the abbreviation of *Synthetic Aperture Radar*, primarily a side-looking pulsed coherent radar on board of a moving platform (mostly an aircraft or a satellite) used to collect the amplitude and the phase of the backscattered signals of the earth's surface. The collected complex data sets are combined in the computer into a high resolution SAR image.

SAR images are very different from the visual or infrared images commonly used in remote sensing. In fig. 2.1 a SAR image[1] of the airfield of Oberpfaffenhofen is shown. Fig. 2.2 shows a image in the visual band of the same area.

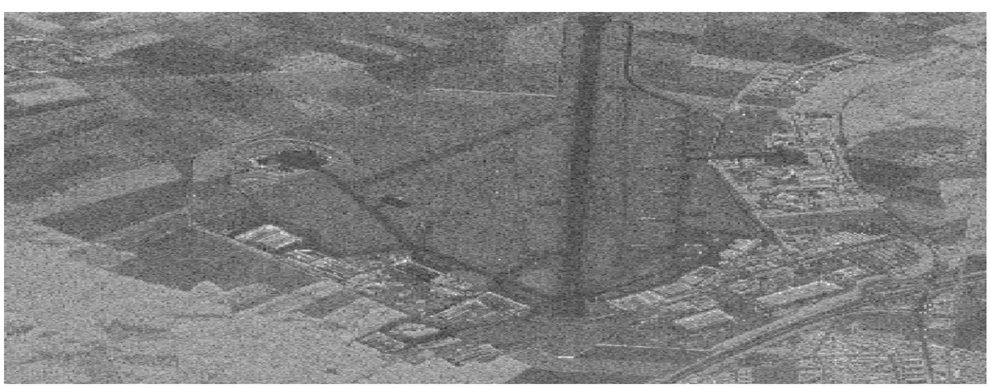

Figure 2.1: Part of an L-band HH-polarised E-SAR image of the area around Oberpfaffenhofen airfield (©DLR)

[1] L-band, HH-polarised image acquired by the E-SAR system of the German Aerospace Center DLR

Figure 2.2: Part of a visual image of the area around Oberpfaffenhofen airfield (courtesy DLR)

The main differences between SAR images and conventional electro-optical images (visual to infrared), used for remote sensing, are:

- the much longer **wavelengths** in SAR ($\lambda = 1cm - 1m$) as opposed to visual ($\lambda = 400 - 700nm$) and thermal infrared ($\lambda = 3 - 14\mu m$) ,
- the image **acquisition geometry**: SAR is side-looking while most electro-optical systems are near nadir -looking (almost straight down),
- the fact that SAR uses **coherent radiation**,
- the fact that SAR is an **active sensor**, i.e. it emits radiation and measures the signal (amplitude and phase) reflected in the direction of the sensor while electro-optical sensors either measure the energy emitted by the sun and reflected by the earth's surface or the energy emitted by objects on the ground (thermal radiation).

The current chapter describes the main principles of SAR image formation as well as the characteristics of the resulting images. The first section describes radar imaging, then the SAR concept is explained and in the last section some particular characteristics of SAR images are discussed.

2.1 Radar Imaging

In radar imaging of the earth's surface an electromagnetic wave, with a wavelength between a few centimeters and a few decimeters (microwaves), is sent to the earth.

The microwave part of the electromagnetic spectrum is subdivided in bands designated by letters. Table. 2.1 presents the frequency and wavelength range for the different bands as well as some typical wavelengths used in remote sensing. The atmosphere is nearly transparent for electromagnetic waves with a frequency below 20Ghz. For this reason K and Ka bands are not used in remote sensing. Note that at high frequency (above the X-band frequency), rain may attenuate or scatter significantly radar signals [4].

Name	Frequency Range (Ghz)	Wavelength Range (cm)	Typical Wavelength (cm)
P band	0.3 - 1	30 - 100	70
L band	1 - 2	15 - 30	23
S band	2 - 4	7.5 - 15	9.6
C band	4 - 8	3.8 - 7.5	5.3
X band	8 - 12.5	2.4 - 3.8	3
Ku band	12.5 - 18	1.7 - 2.4	-
K band	18 - 26.5	1.1 - 1.7	-
Ka band	26.5 - 40	0.75 - 1.1	-

Table 2.1: Wavelength bands in the microwave part of the electromagnetic spectrum

The energy scattered by the elements on the earth's surface and falling back onto the radar, is measured and used to build the radar image.

The returned energy depends on radar system properties (wavelength, power, size of the illuminated area, direction of illumination, polarisation and antenna characteristics) as well as on properties of the terrain that is imaged (conductivity, permittivity, roughness of the terrain, presence of deterministic scatterers, and of the subsurface or the vegetation cover up to a depth where the radar wave is attenuated to a negligible amplitude). Both types of properties are closely interrelated; for instance the used radar wavelength has its impact on the penetration depth in soil or vegetation as well as on the "apparent roughness" of the terrain. The term "apparent roughness" is the roughness of the terrain relative to the used wavelength.

If the radar is calibrated, it provides an estimate of the *radar reflectivity* or *backscattering coefficient* of the scene. The radar reflectivity of a distributed target is the ratio of the scattered electromagnetic power to the incident power, per unit area.

The value of this backscattering coefficient, measured in a given position of the terrain, depends on the radar frequency, incidence angle (local incidence angle) and polarisation. For a given set of radar system parameters the radar reflectivity of a given surface is determined by the electrical properties of the surface and the type of scattering mechanism the surface induces on the radar wave.

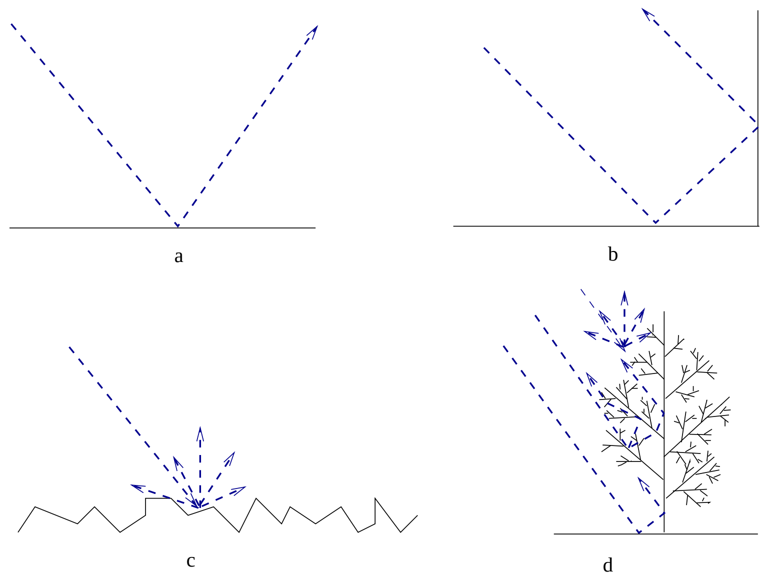

Figure 2.3: Examples of scattering mechanisms: a. Specular reflection by a smooth surface b. Double bounce scattering c. Scattering by a rough surface d. Scattering by trees or large vegetation

In figure 2.3 some frequently occurring scattering mechanisms are presented. They are briefly described below:

- **Specular reflection by a smooth surface**: If a radar wave falls onto a smooth surface, the surface behaves as a mirror. In the case of a side-looking radar this means that almost all energy is scattered away from the radar. The result is a dark region in the image. This is the reason why roads and lakes in wind-still conditions appear dark on a SAR image.

- **Double bounce scattering**: On the other hand a pair of smooth surfaces that form a straight angle with each other (e.g. walls of buildings and the ground) and that are facing the radar, reflect almost all the energy back into the direction of the radar because of the *double bounce scattering* that occurs between the two surfaces. This is one of the reasons why buildings are characterised by very bright lines corresponding to the walls facing the radar.

- **Rough surface scattering**: Rough surfaces produce scattered waves in a lot of different directions and the amount that gets scattered back into the direction of the radar mainly depends on the distribution of the orientation of facets composing the surface. This is called *rough surface scattering*. The fact whether a surface seems rough for a given radarwave depends on the wavelength of the radar; in general a surface is rough when the height variations are of the order of or larger than the radar wavelength.

- **Volume scattering and scattering by forests**: In forests a mixture of different scattering mechanisms can occur: surface scattering either from the top of the trees (canopy) or from the ground, double bounce scattering between the ground and the tree trunks and a multiple scattering when the wave gets trapped in the branches of the tree (*volume scattering*). The proportion of each of these effects in the measured backscattering depends on the wavelength of the radar as well as on physical properties of the forest (height of the canopy, surface density of the trees, roughness and water content of the soil, etc...). Generally, for the same forest, the longer the wavelength, the easier the radiation will penetrate through the canopy and therefore the higher the proportion of double-bounce and volume scattering will become.

More information about scattering mechanisms can be found in [5, 6, 7]

2.2 The SAR Concept

The concept of SAR has allowed to drastically improve the resolution of side-looking radar (SLAR) images. In fig. 2.4 the geometry of a side-looking radar is illustrated.

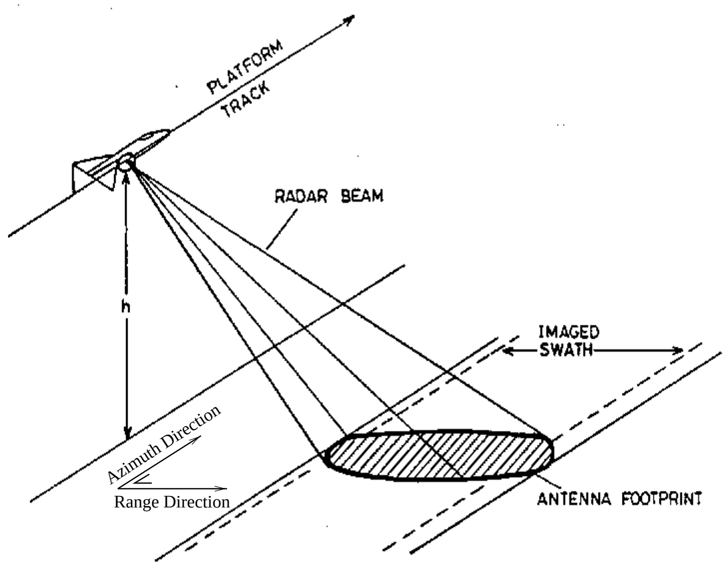

Figure 2.4: Side-looking radar geometry (reproduced from [8])

Current SAR systems attain an image resolution that is comparable to that of optical or infrared images. Optical and infrared systems currently attain a spatial resolution between 1 m and 2 m. This is sufficient to detect isolated houses, roads and some footpaths in bare terrain, i.e. sufficient for cartographic applications at scale 1/10000. The SAR concept has allowed radar imaging systems to attain a similar resolution.

In order to understand the concept of SAR we will first look at the factors determining the resolution in the across-track or *range direction* and in the along-track or *azimuth* *direction* for "real aperture" side-looking radars. For both cases we will then discuss improvements applied in SAR processing. The next two sections are devoted to this.

2.2.1 Resolution in Range

The spatial resolution is defined as the ability to discriminate point targets. For a pulsed radar the resolution in range is linked to the duration of the pulse. The principle of range resolution is illustrated in fig. 2.5.

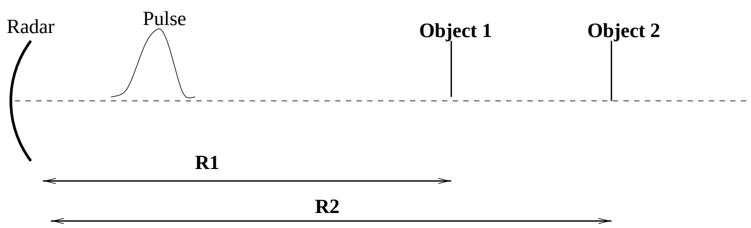

Figure 2.5: Principle of Range Resolution

If the (slant) range to the first point target is R_1 it will take a time R_1/c for the radar wave to reach the target. The total trip (to the radar-target-radar) will take a time:

$$t_1 = \frac{2R_1}{c}. \tag{2.1}$$

The radar will start receiving the echo from the point target at t1 seconds after the start of the transmission of the pulse. The echo will last the length of the pulse τ (-3dB width). Two point targets will be resolvable in range only if the difference in range between them is sufficient for their two echos not to overlap. This means that the end of the echo returned by the first target must reach the radar before the beginning of the echo returned by the second target reaches the radar (fig. 2.6)

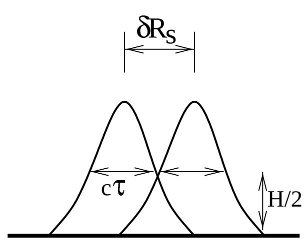

Figure 2.6: Link between range resolution and pulse width

The smallest resolvable distance along the slant range direction is thus:

$$\delta R_s = \frac{c\tau}{2}. \tag{2.2}$$

This minimal resolvable distance is measured in *slant range*, i.e. in the direction of sight of the radar. It is independent of range or wavelength. The corresponding minimal resolvable distance projected on the ground (*ground range*) is given by:

$$\delta R_g = \frac{\delta R_s}{sin(\theta_i)}, \tag{2.3}$$

where θ_i is the *incidence angle*. In radar literature the complement of the incidence angle is often used and either called the *depression angle* θ_d or *grazing angle* θ_g (see fig 2.7).

The ground resolution depends thus on the incidence angle which means that the size of the pixels in the range direction changes over the swath of the radar. The resolution in ground range improves with increasing incidence angle and thus also with increasing range. For a typical airborne radar the swath corresponds to an incidence angle ranging from about 30 to 60^o. This corresponds to a change in pixel size by a factor of 1.72 between near range (this is the point of the swath that is closest to the radar) and far range (the other extremity of the swath).

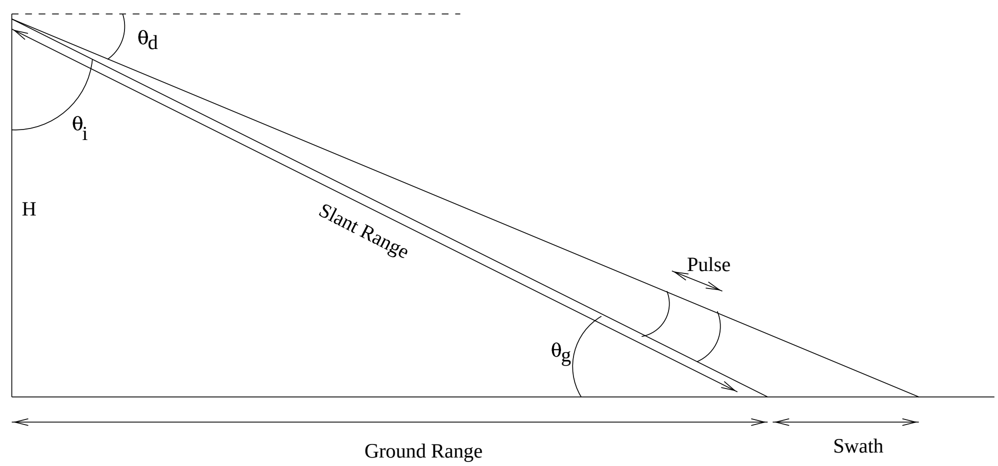

Figure 2.7: Range resolution of side-looking pulse radars

Typical pulse lengths are of the order of $1\mu s$. According to equation 2.2 this corresponds to a slant range resolution of 150 m which is a lot higher than the resolution of around 1 m we would like to achieve. In order to improve the resolution in range we need to shorten the pulse-length. This poses excessively high power and hardware requirements for SAR systems in satellites and airplanes. The solution commonly adopted in spaceborne and most airborne SAR systems is the so-called pulse compression. In pulse compression the emitted signal within a single pulse is coded (modulated). Signal processing techniques are then used to demodulate the received echo. Thus an extended frequency modulated long pulse is used instead of a short pulse to reduce hardware requirements and the signal processing techniques allows to compress the emitted long pulse into short spikes with intensity proportional to that of the extended echo. The principles of pulse compression are explained in more detail below.

The idea is to emit a frequency modulated signal called *chirp*:

$$\begin{aligned} p(t) &= A\ exp\left[i2\pi(f_0 t + \tfrac{1}{2}\alpha t^2)\right] \quad -\tfrac{\tau_p}{2} \leq t \leq \tfrac{\tau_p}{2} \\ &= 0 \qquad\qquad\qquad\qquad\qquad\qquad otherwise \end{aligned} \tag{2.4}$$

where f_0 is the carrier frequency of the used radar and τ_p is the length or duration of the (rectangular) pulse. Note that the form of the modulation function that is presented here is just an example. Other types of modulation functions are used in SAR.

The instantaneous frequency is then:

$$f = \frac{1}{2\pi}\frac{d\phi(t)}{dt} = f_0 + \alpha t. \tag{2.5}$$

Figure 2.8 shows the effect of the frequency modulation. From top to bottom the graphs represent the signal at radar frequency, the rectangular pulse, the frequency modulation function and the result on the radar signal.

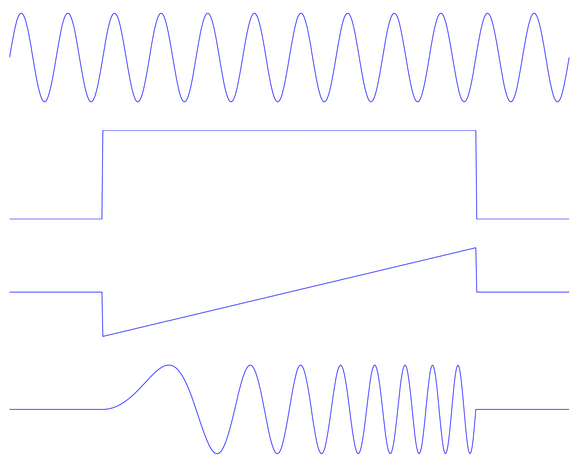

Figure 2.8: Linear frequency modulation (Chirp)

This means that within one pulse the time is further "coded" as a change in frequency. Processing the returned signal involves striping off the carrier frequency and performing a correlation with a copy of the transmitted signal (matched filtering, see also annex B).

The pulse duration after demodulation can be shown to be equal to $1/\alpha\tau_p$. On the other hand $\alpha\tau_p$ is the bandwidth B_p of the modulation, τ_p being the duration of the pulse during which the modulation is applied and α the rate of change of frequency over this duration. The chirp thus results in an effective pulse length of $\tau_{eff} = 1/B_p$ and the achieved range resolution is therefore:

$$\delta R = \frac{c}{2B_p}. \tag{2.6}$$

A modulation bandwidth of 100 MHz is a typical value and this corresponds to an effective pulse length of:

$$\tau_{eff} = \frac{1}{B_p} = 10ns, \tag{2.7}$$

with a corresponding resolution in slant range of 1.5 m

2.2.2 Resolution in Azimuth

For a real aperture radar the azimuth resolution is given by $R_0\psi_a$ where R_0 is the range to the imaged surface and ψ_a is the azimuth beam-width. As a rule of thumb the radiation from an antenna spreads out over an angle:

$$\psi_a = C^{st}\frac{\lambda}{d}, \tag{2.8}$$

where λ is the wavelength the radar uses and d is the dimension of the antenna. The constant C^{st} depends on the form of the antenna but is close to 1. For a radar with an antenna of 1 m mounted on an aircraft flying at an altitude of 3000 m above the ground and looking at an incidence angle of 45^o the azimuthal resolution thus varies between 127 m in X-band ($\lambda = 3$ cm) and 975 m in L-band ($\lambda = 23$ cm).

The only way to achieve a resolution of 1 m in azimuth is to increase the dimensions of the antenna. In the numerical example above we would need an antenna with a size of 127 m (for the X-band radar) to 975 m (L-band). This is clearly impossible. The idea of SAR is to synthetically create a very long antenna by making use of the motion of the radar platform. This is illustrated in fig. 2.9.

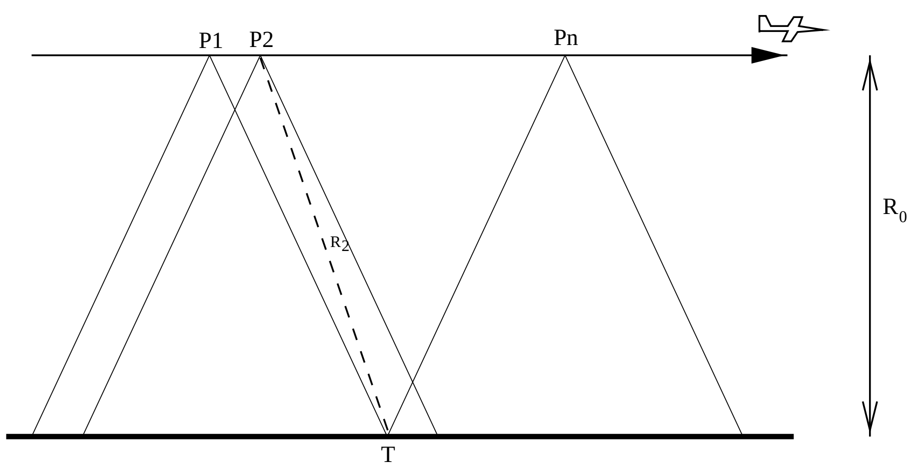

Figure 2.9: Working principle of the SAR

Suppose we wish to make an image of the point target T on the ground. We fly past the point and acquire an image as soon as the point T comes into the radar-beam (fig. 2.9). As the radar-platform continues its motion, the point will remain in the radar beam for a while. In fact it will remain visible for the radar as long as the platform displacement from the point P1, where T becomes visible for the first time, is smaller than the size of the footprint (i.e. the projection on the ground of the main lobe of the radar beam) of the (real) antenna. To generate the synthetic antenna, at each position P_i of the radar-platform an image is acquired and stored. The combination of all these images allows to simulate the image that would be seen by a radar array antenna of which the size is the distance between Pn and P1. However, there is an important difference between the synthetic array and a real array of the same size [9]. In a real array the pulses are emitted at the same time from all the array elements, in SAR they are emitted sequentially. In SAR the second pulse is only emitted after the first pulse has been transmitted and received. Consequently the returns received by successive elements of the synthetic array differ in phase by amounts proportional to the differences in the round-trip distance from each element to the target T and back again. The antenna gain pattern will thus be produced by the round-trip phase shift between successive array elements which is equivalent to the pattern of a real antenna with twice the spacing between elements of the synthetic array and thus twice the size.

Let the dimension of the synthetic antenna be L_s. The azimuth resolution is then [2]

$$\delta Az = R_0 \frac{\lambda}{2L_s}. \tag{2.9}$$

The largest possible dimension of the synthetic antenna is equal to the footprint of the real antenna, thus $L_s^{max} = R_0 \frac{\lambda}{d}$. This gives for the optimal achievable azimuth resolution:

$$\delta Az = R_0 \frac{\lambda}{2L_s^{max}} = \frac{d}{2}. \tag{2.10}$$

This means that the best possible resolution in azimuth that can be obtained by SAR processing is equal to half the size of the real antenna and thus independent of range and wavelength.

The difficulty in the SAR processing is that the images obtained at different positions of the radar platform need to be combined taking into account the phase differences caused by looking at a given point from different positions. Lets look at this in somewhat more detail. If we acquire an image at points P_1... P_n of the radar-platform, the signal that we get back from the point T will be proportional to the radar cross section of the point and the phase of the signal, as compared to the transmitted phase, will have shifted by a factor proportional to the range between the target T and the radar. When the latter is in P_j this results in:

$$S_T(j) = \sqrt{\sigma_T} e^{[i(\Phi_{Trans} + 2kR_j]}, \tag{2.11}$$

with $k = 2\pi/\lambda$. If R_0 is the smallest distance between the radar and the point T, then the range in the other points along the radar track is given by:

$$R_T(t) = \sqrt{R_0^2 + V^2 t^2}, \tag{2.12}$$

where V is the speed of the radar platform. This can be expanded as:

$$R_T(t) = R_0 \left[1 + \frac{1}{2} \frac{V^2 t^2}{R_0^2} - \frac{1}{4} \frac{V^4 t^4}{R_0^4} + ... \right]. \tag{2.13}$$

Usually only the two first terms are kept because dividing by high powers of R_0 makes the higher order terms negligible. The signal received from the point target is thus:

$$S_T(t) = \sqrt{\sigma_T} e^{\left[i(\Phi_{Trans} + 2kR_0 + k\frac{V^2 t^2}{R_0} \right]}. \tag{2.14}$$

[2] Please note that in this expression the 4dB beam-width is used instead of the usual 3dB beam-width which would be $0.44 R_0 \frac{\lambda}{L_s}$

This expression has again the form of a frequency modulated signal. The change of frequency is now given by:

$$f(t) = \frac{1}{2\pi}\frac{d\phi(t)}{dt} = \frac{2V^2}{\lambda R_0}t. \tag{2.15}$$

This is called an *azimuth chirp* and the demodulation, also called azimuthal focusing or azimuth compression can be done in a way analogous to the range compression. Note that the frequency modulation in azimuth is in fact a Doppler shift.

Remark also that the azimuth chirp depends on the range to the target. The range compression must therefore be completed before the azimuth compression can begin.

2.3 Special SAR Image Properties

2.3.1 Imaging Geometry

The typical geometry seen in SAR images is mainly due to the fact that the radar looks at the earth in a slanted direction. In the previous section the effect of the change of range resolution on the image due to variations in incidence angle over the swath was already mentioned. For space-borne systems this effect is very small as typically the incidence angle over the swath would vary by only about 2^o . However for airborne systems where sometimes the incidence angle varies by more than 40^o, the effect is very noticeable.

In SAR images, or more generally in images acquired by a side-looking radar, some other geometrical distortions occur. The main reason for these distortion is the fact that the radar measures ranges as the time needed for a radar pulse to return from the earth to the radar. Changes in elevation of the imaged point therefore cause distortions. They are discussed in the next paragraphs.

Backscatter and the Local Incidence Angle

For a given type of terrain feature the backscattered signal depends on the *local incidence angle* of the radar beam. As mentioned before this can vary over the swath, even if the terrain is completely flat. However, variations due to changes in the slope of the terrain (local topography) also produce changes in strength of the backscattered signal. Fig. 2.10 illustrates this effect. In the figure θ_i is the incidence angle a given point of the slope would have (due to the position in the swath) if the local topography would be horizontal. θ_i^{Local} is the actual local incidence angle of the point due to the combined effect of the terrain slope and position in the swath.

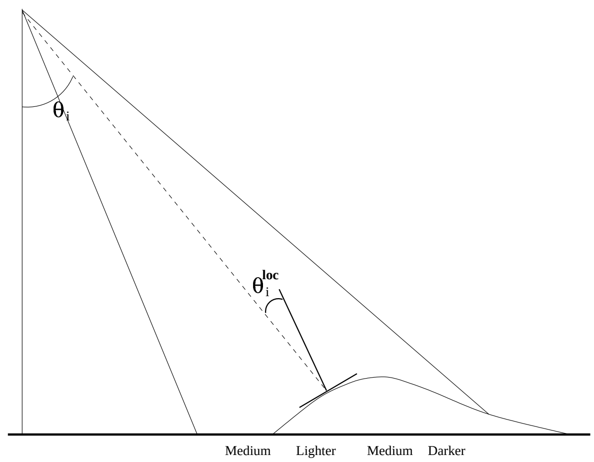

Figure 2.10: Variation of local incidence angle with topography

If the landcover over the considered region is uniform and the main scattering mechanism is surface scattering, this will result in a change of measured radar reflectivity as illustrated in the figure, i.e. surfaces with lower local incidence angle will appear brighter in the image.

Shadowing, Foreshortening and Layover

Shadowing occurs at locations of a slope away from the radar that is steeper than the sensor depression angle. Shadows appear as dark (zero signal) spots in the image. Any changes in intensity in shadow zones are solely due to system noise or side lobes of the radar.

Foreshortening occurs when a steep slope faces the radar. The effect of this is that the range differences between two points on the slope is smaller than they would be in a flat terrain. Foreshortening thus produces an across-track compression of the radiometric information.

Layover is related to foreshortening and occurs if the slope is even higher. If the slope of a mountain for instance is higher than the incidence angle (for horizontal terrain) of the radar, the top of a mountain will have a smaller range to the radar than its slope or even some of the valley points in front of the mountain. Moreover, in layover regions the radiometric information is the result of a superposition of the response of many objects. This gives rise to very bright spots in the image.

Fig. 2.11 illustrates the effect of layover and shadowing. Also notice that the slope of the mountain facing the radar will appear very short on the SAR image while the shadow will appear very long.

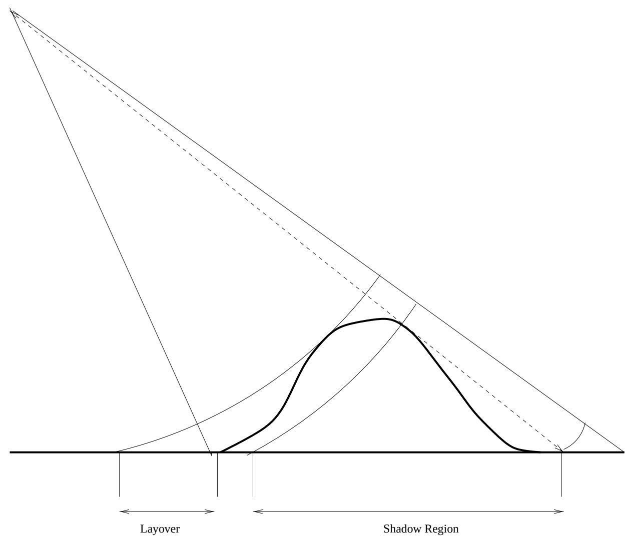

Figure 2.11: Layover and shadow effect

Please note that the three effects mentioned in this paragraph occur in mountaneous areas but also, and certainly in high-resolution radar images, in villages where slopes are 90^o. This is one of the reasons for the typical appearance of buildings on a SAR image, i.e. a bright corner facing the radar and a dark one oriented away from the radar.

All vertical structures such as buildings and forests produce foreshortening, layover and shadowing. This means that the edges of such objects can only be used for geocoding or registration purposes as a first approximation. For increased accuracy of registration, features with a low 3D structure, such as boundaries between fields or roads, must be used.

2.3.2 Speckle

One of the characteristics that immediately draws the attention when looking at SAR images is the fact that they appear to contain a lot of noise. The noise-like characteristic of these images that can be found in any image produced by a coherent imaging system (e.g. laser, sonar, ultrasound) is called *speckle* and is in fact an interference phenomenon.

In distributed targets each resolution cell of the imaging system contains a large number of discrete scatterers. As the wave interacts with the target, each individual scatterer contributes a backscattered wave with a phase and amplitude change (fig: 2.12), so the total returned wave is:

$$\overrightarrow{A} = Ae^{i\Phi} = \sum_{i=1}^{N} A_k e^{i\Phi_k}. \tag{2.16}$$

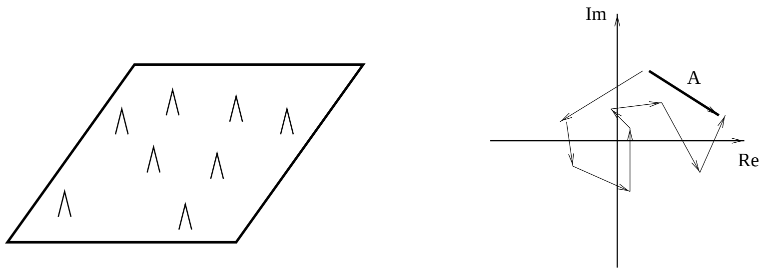

Figure 2.12: Individual scatterers in a resolution cell (left) and resulting phasors (right)

The resolution in range is typically many times the wavelength of the radar. Hence, even if all elementary scatterers were identical, the waves scattered from them have very different path lengths. The individual scatterers therefore produce a very different phase in the incident wave. The resulting phase is uniformly distributed in $[-\pi, \pi]$.

The sum in 2.16 can now be seen as a random walk in the complex plane where each step A_k is in a completely different direction. This problem is thoroughly treated in many books about SAR (e.g. [10, 11]) as well as in [12] which treats about laser speckle.

2.3.3 Image Quality

A SAR image, at first sight, can seem of poor quality. In comparison to optical images it seems noisy (due to the speckle) and is geometrically distorted. In fact these are qualitative subjective statements and a SAR image can actually contain much more information than an optical image of apparently "good" quality. The purpose of image quality measurement is to replace a subjective assessment of image quality with some objective measurements. The objective assessment of image quality results in a set of numbers, each one describing a particular feature of quality. In the following sections we briefly describe some image quality measurements.

Spatial Resolution

Spatial resolution in a SAR image is usually defined as the extent of a point target in the image. It is characterised by the system's impulse response function (IRF). The IRF is the two-dimensional final image response to a strong point target fixed on the (rotating) earth. The spatial resolution is defined as the width where the intensity of the IRF reaches 50 % of its peak value (-3dB width). It is expressed in meters in the along-track (azimuth) and across-track (range) direction. In order to measure the spatial resolution of a SAR image, it is necessary to have an isolated, small, bright target on a low-reflectivity, uniform background. Often artificial targets are placed on a suitable background. The most common type of artificial target is a trihedral corner reflector which usually consists of three (triangular or square) metallic plates joined together at right angles. They reflect an incident beam back along the transmission path.

Radiometric Resolution

Radiometric resolution of a system describes its ability to discriminate between neighbouring radiometric levels. This can be particularly difficult in SAR images due to the presence of speckle. The radiometric resolution is measured on a large uniform region. In the power (intensity) image (see chapter 4) the average μ and standard deviation σ of the speckle in such a uniform region is measured and the radiometric resolution γ is defined as:

$$\gamma = 10log\left[\frac{\mu+\sigma}{\sigma}\right]. \tag{2.17}$$

For a single-look intensity image this is a constant because for such an image $\mu = \sigma$ as we will see in sect. 4.1.4. The only way to improve the radiometric resolution is by reducing the speckle. This can be done by a technique that is called multi-looking or sub-aperturing. Here the data is pre-processed in azimuth over different sub-apertures or looks and the resulting individual looks are incoherently summed to give the final SAR image. This is equivalent to the incoherent averaging over a neighbourhood in each image. Multi-looking thus reduces the spatial resolution. The radiometric resolution can thus only be improved at the expense of the spatial resolution.

Ambiguities

An ambiguity is an undesired signal return whose signature for the SAR can not be distinguished from the desired return [13]. The main cause for these ambiguities is the existence of side-lobes in the radar antenna pattern. The SAR processing is based on the processing of the return signal from the main lobe of the antenna. The energy from the sidelobes also reaches the earth and can also be reflected back into the radar. Although the energy emitted in the sidelobes is much lower than that of the main lobe, they can result in "ghosts" in the image. This is for example visible on images of a region with low radar backscattering coefficient (e.g. a water surface). Sometimes in such areas a return from a region with a much higher radar return (e.g. a city), located at a completely different position is seen in the image. The main types of ambiguities are enumerated below.

- **Range Ambiguities**

  Range ambiguities are caused by targets outside the main swath of the radar, whose slant range differs from that of the desired target by a multiple of the pulse repetition distance $D = c/2 * PRF$. They can occur when returns from previous of succeeding pulses arrive at the same time as the return from the desired pulse. This can be caused by the returns of sidelobes of the antenna pattern in elevation. Ambiguous returns can come from "swaths" positioned between nadir and the desired swath and between the desired swath and the radar horizon.

- **Azimuth Ambiguities** Azimuth ambiguities are returns from targets whose Doppler frequencies differ from the Doppler frequencies of the desired targets by multiples of the pulse repetition frequency. They are due to reflections from azimuth antenna sidelobes of the radar.

Both types of ambiguities are characterised by ambiguity ratios. An ambiguity ratio is the proportion of the energy in a resolution cell that is due to ambiguous targets to the total energy received in that resolution cell. It is measured on large distributed targets.

2.3.4 Image Calibration

As is the case for all measurement systems, the data gathered by a SAR system need to be calibrated in order to take into account distortions by the instrument (the SAR receiving and emitting chain antenna) and the "transmission channel" (the path between radar and target) [14]. The calibration is necessary in order to be able to compare target properties measured at different positions, incidence angles, polarisations, frequencies or times.

Radiometric calibration consists in establishing the relationship between the received signal and the radar backscattering coefficient σ^o of the objects on the ground. For radiometric calibration artificial targets, mainly trihedral corner reflectors (see sect. 3.6.1), with known radar backscattering cross-sections are used.

The aim of *polarimetric calibration* is to estimate the scattering matrix of the targets on the ground from the signals received in the different polarisations (see chapter 3). For the polarimetric calibration artificial targets can also be used. Polarimetric calibration involves phase calibration, crosstalk removal and finally absolute amplitude calibration and channel gain balance [15].

2.4 Lessons Learned

We have seen that SAR images are very different from visual or infrared images. The main difference are due to the side-looking imaging geometry, the presence of speckle and the fact that, mainly due to the long wavelength that is used, the SAR image is determined by completely different physical characteristics of the objects on the ground.

Important consequences of the side-looking image acquisition geometry is the occurrence of foreshortening, layover and shadowing. These result in a loss in accuracy of both spatial and radiometric information. In particular, objects with a high 3D structure can not be localised precisely using a single SAR image. This fact will have its influence on the image registration strategy discussed in chapter 8.

The presence of speckle makes conventional image processing algorithms fail on SAR images. However, the characteristics of speckle, to be discussed in chapter 4 can be used for developing image processing algorithms as will be shown in chapter 5.

The next chapter is devoted to polarimetry and will describe the supplementary information that is delivered by polarimetric SAR images.