POLITECNICO DI MILANO

School of Civil, Environmental and Land Management Engineering Master of Science in Civil Engineering for Risk Mitigation

Forest Canopy Height Mapping via Synthetic Aperture Radar (TomoSAR) Techniques

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Abstract

Estimating forest canopy height with high spatial resolution is critical for ecological monitoring, carbon accounting, and sustainable forest management. Traditional field-based and optical remote sensing methods are often constrained by limited spatial coverage and atmospheric conditions. This study evaluates the capability of Tomographic Synthetic Aperture Radar (TomoSAR) for accurate 3D forest structure mapping in Moncalieri, Italy, using multi-baseline L-band SAR imagery.

A total of eight SAR acquisitions were processed using the Capon beamforming algorithm to resolve vertical forest profiles. To ensure geometric precision and calibration, a 1-meter resolution Digital Terrain Model (DTM) and high-density drone-based Lidar measurements were integrated into the workflow. The TomoSAR-derived canopy height models were validated against Lidar data, showing a strong correlation with an accuracy of 83.46%, affirming TomoSAR's potential as a robust alternative for large-scale canopy height mapping in densely vegetated areas.

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Introduction

Accurate estimation of forest canopy height is fundamental for monitoring ecological health, quantifying biomass, and managing carbon stocks. Traditional techniques—such as field surveys, aerial photogrammetry, or optical satellite imagery—are often limited by sparse spatial coverage, cloud obstruction, and inaccessibility in densely forested regions. Synthetic Aperture Radar (SAR), with its all-weather, day-and-night imaging capabilities, offers a robust alternative. Among SAR techniques, **Tomographic SAR (TomoSAR)** extends traditional 2D imaging into the vertical dimension, enabling detailed 3D reconstruction of forest structures.

This study explores the use of **L-band TomoSAR data** for forest canopy height mapping in the **Moncalieri region of northern Italy**, an area characterized by complex terrain and mixed deciduous forests. By combining **multi-baseline SAR acquisitions**, a **Capon beamforming inversion method**, and **high-resolution Lidar** for validation, this research demonstrates the viability of TomoSAR in resolving vertical forest profiles with high precision.

The structure of this report is as follows:

Chapter 1 presents the theoretical foundations of radar remote sensing, including the physics of electromagnetic waves, SAR geometry, resolution, distortions, and various SAR-based techniques such as PolSAR, InSAR, and TomoSAR.

Chapter 2 introduces the core concepts and mathematical formulations behind TomoSAR. It elaborates on the forward model, height inversion, topographic phase compensation, and the Capon beamforming algorithm used for 3D focusing.

Chapter 3 outlines the study area, data sources, and methodology. It details the preprocessing of SAR images, generation of the covariance matrix, and height retrieval process. Visualization and validation steps are also covered, including comparison with drone-based Lidar data.

The final sections present the **results**, followed by a **discussion and conclusion** that highlight the effectiveness of TomoSAR in forest monitoring and suggest avenues for further research.

Through this structured approach, the study aims to contribute to the growing field of radar remote sensing in environmental applications, showcasing how TomoSAR can provide scalable, accurate, and resilient alternatives for forest canopy analysis.

Chapter 1

1.1 Fundamentals of Active and Passive Remote Sensing

Remote sensing is the science of acquiring information about the Earth's surface without direct physical contact, typically through sensors mounted on satellites or airborne platforms. These systems are broadly categorized into active and passive sensors, based on their dependence on external energy sources (Lillesand et al., 2015; Campbell & Wynne, 2011).

Passive remote sensing relies on natural energy, primarily sunlight, which is either reflected or emitted by the Earth's surface and captured by the sensor. Common passive sensors operate in the visible, near-infrared, and thermal infrared regions of the electromagnetic spectrum. Satellite missions such as Landsat, MODIS, and Sentinel-2 utilize passive sensing for applications including land cover classification, vegetation monitoring, and thermal mapping. However, passive systems are limited by the availability of natural light and are often ineffective under cloudy conditions or at night (Lillesand et al., 2015).

In contrast, active remote sensing systems emit their own energy toward the target and record the reflected signal. This capability allows them to operate independently of sunlight and penetrate atmospheric conditions like clouds and rain. Radar (e.g., SAR) and LiDAR are typical examples of active sensors. Active remote sensing is especially valuable for terrain modeling**,** surface deformation monitoring**,** and structural analysis, due to its ability to capture high-resolution and geometrically precise data regardless of weather or lighting (Ulaby et al., 2014; Richards, 2009).

The distinction between active and passive systems is fundamental for selecting appropriate remote sensing techniques, as each has its strengths and limitations depending on the application and environmental conditions.

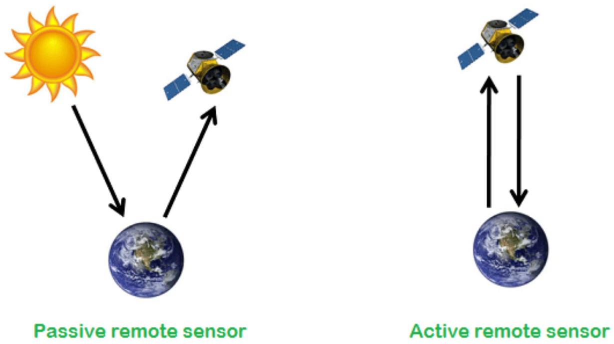

Figure 1 : Passive Vs Active Sensors

1.2 Electromagnetic Wave (EW)

Electromagnetic (EM) waves are a form of energy propagation consisting of oscillating electric and magnetic fields that are perpendicular to each other and the direction of wave propagation. First described by James Clerk Maxwell in the 19th century, these waves travel through space at the speed of light, approximately 3×10^8 m/s. The waves are generated by the acceleration of charged particles, which create oscillating electric and magnetic fields that sustain each other as they propagate. This concept of EM wave propagation, with its fundamental principles, was first laid out by Maxwell in

1865 and later extended by other researchers, such as Ulaby, Moore, and Fung, who provided further insights into the wave’s behavior and applications (Maxwell, 1865; Ulaby, Moore, & Fung, 1981).

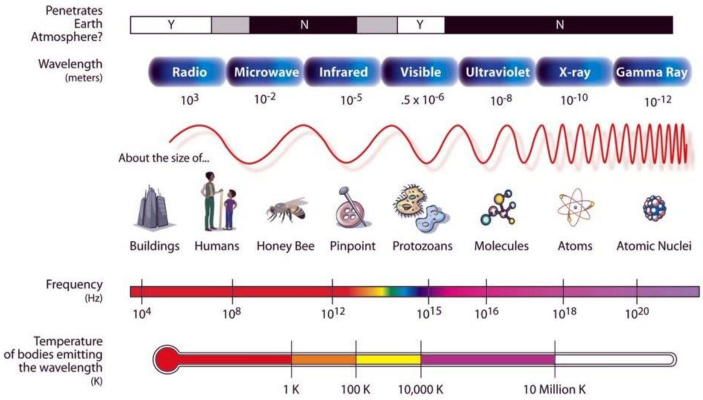

Figure 2: Electromagnetic wave spectrum

Electromagnetic waves are characterized by key properties such as wavelength, frequency, amplitude, and speed. Wavelength is the distance between consecutive peaks or troughs, while frequency refers to how many cycles occur per unit of time. Amplitude indicates the strength of the electric or magnetic field and is often linked to the wave's intensity. The speed of an electromagnetic wave, particularly in a vacuum, is constant and equal to the speed of light.

The Equation 1 mathematically relates these parameters, where f is the frequency, c is the speed of light, and λ is the wavelength. This equation shows that the frequency of an electromagnetic wave is inversely proportional to its wavelength when the wave travels at the speed of light.

$$f = \frac{c}{\lambda}$$

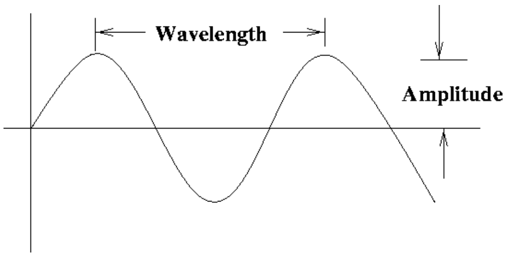

Figure 3: Wave Properties

1.3 Real Aperture Radar (RAR) and Synthetic Aperture Radar (SAR)

Real Aperture Radar (RAR) is a traditional radar system that utilizes a physical antenna of fixed size to transmit and receive electromagnetic signals. The antenna’s size is directly related to the radar’s resolution specifically, the size of the antenna determines the resolution in the azimuth direction (across the direction of motion). In Real Aperture Radar (RAR), the radar transmits pulses and receives the reflected signals from objects on the ground, with the resolution in the range direction (along the line of sight) determined by the pulse duration and bandwidth. However, the main limitation of RAR is that improving the resolution requires increasing the physical size of the antenna, which is not practical, especially in space-based or airborne systems, where space and weight are constrained (Ulaby, Moore, & Fung, 1981).

In contrast to RAR, Synthetic Aperture Radar (SAR) is a more advanced technology that circumvents the size limitation of antennas by using the motion of the radar platform (such as a satellite or aircraft) to simulate a much larger antenna. The basic principle behind SAR is that, as the radar platform moves along its flight path, it continuously transmits pulses and receives echoes from the target area. These echoes, captured from multiple positions, are processed together to simulate a large virtual antenna, or "synthetic" aperture, significantly enhancing the azimuth resolution (Fujita & Shi, 2002).

SAR relies on sophisticated signal processing to combine the radar data collected from different points, allowing it to achieve high resolution despite the relatively small size of the physical antenna. This technique leverages Doppler shift and phase information from multiple radar echoes to achieve the desired resolution, which is not limited by the physical size of the antenna (Ferretti, Prati, & Rocca, 2001).

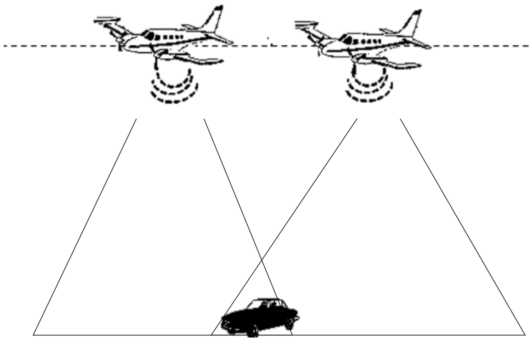

Figure 4: SAR Imaging Concept

1.4 Geometry of Synthetic Aperture Radar

The geometry of Synthetic Aperture Radar (SAR) involves several important parameters that define how SAR systems acquire data and form high-resolution images of the Earth’s surface. These parameters are crucial for understanding SAR performance, calibration, and interpretation of radar data.

1.4.1 Altitude

Altitude refers to the height of the radar platform above the Earth's surface. This is an important parameter because it influences the radar's slant range and the overall geometry of the radar signal. The altitude of the platform, which can be a satellite, aircraft, or UAV, directly affects the radar’s footprint and the resolution of the resulting images (Ulaby, Moore, & Fung, 1981).

1.4.2 Azimuth

Azimuth is the direction parallel to the motion of the radar platform in the horizontal plane. In Synthetic Aperture Radar (SAR) systems, the azimuth direction corresponds to the along-track direction, along which the radar acquires successive echoes to synthetically construct a high-resolution image (Colin, 2012).

1.4.3 Range

In Synthetic Aperture Radar (SAR), range refers to the distance from the radar to a point on the Earth's surface, measured along the line of sight. Range resolution is the ability to distinguish objects based on their distance from the radar, influenced by the pulse duration and frequency of the radar signal (Ulaby et al., 1981). The near range is the closest part of the radar's swath, typically exhibiting lower resolution due to signal attenuation and platform geometry (Benedetti, 1997). In contrast, the far range is farther from the radar and usually has better resolution, as it is less affected by attenuation and more influenced by the radar's beam width and platform altitude (Colin, 2012)

1.4.4 Slant Range

Slant range refers to the straight-line distance between the radar platform and a point on the Earth's surface, which is typically not perpendicular to the ground. This is different from ground range, which is the projection of the slant range onto the Earth’s surface. The slant range plays a significant role in determining the geometry of the SAR system, particularly when calculating the incidence angle (Ulaby et al., 1981).

1.4.5 Incidence Angle

The incidence angle is the angle between the radar's line of sight and the vertical, or normal, to the Earth’s surface. It affects both the strength of the radar return signal and the radar resolution. A larger incidence angle typically leads to lower resolution and weaker signal returns, while a smaller angle leads to higher resolution and stronger returns, making it an important factor in SAR image interpretation (Ferretti, Prati, & Rocca, 2001).

1.4.6 Swath

The swath in Synthetic Aperture Radar (SAR) refers to the area of the Earth's surface illuminated by the radar beam during its motion. A wider swath increases the surface area captured but may reduce image resolution, creating a trade-off in SAR system design (Ulaby et al., 1981). The near swath is the area closest to the sensor, often suffering from lower radar return signals and potential artifacts due to the steep incidence angle and radar beam geometry (Benedetti, 1997). The mid swath, located in the central portion, provides optimal resolution and signal return, making it the most reliable for high-quality imaging (Colin, 2012). The far swath, farthest from the radar, offers the best coverage but can have lower resolution or distortions, yet remains essential for comprehensive area imaging (Ferretti et al., 2001).

1.4.7 Beam

The main beam refers to the central part of the radar's transmitted beam, which has the highest intensity and best resolution. It is typically directed towards the center of the radar’s swath and represents the area of primary interest for SAR systems. The width of the main beam is determined by the radar’s antenna design and beamforming capabilities (Ulaby et al., 1981).

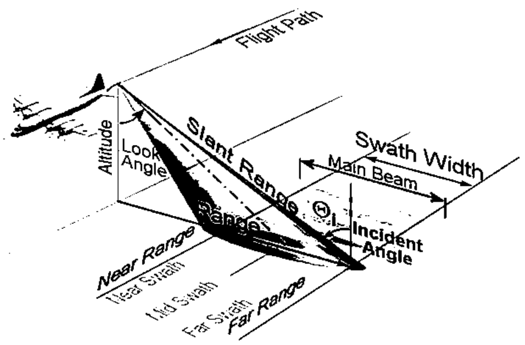

Figure 5: SAR Geometry and Parameters

1.4.8 Beam Width

Beam width refers to the angular spread of the transmitted radar signal, which influences the resolution and coverage of the system. A narrower beam width allows for higher resolution by focusing energy on a smaller area, improving the ability to distinguish between closely spaced objects. SAR systems synthesize a long antenna aperture by utilizing platform motion, effectively reducing the beam width and enhancing image sharpness. The choice of beam width is a critical factor in SAR design, affecting the balance between image resolution and swath coverage (Curlander & McDonough, 1991).

$$\Delta\psi = \frac{\lambda}{L_x} \qquad and \qquad \Delta\theta = \frac{\lambda}{L_z}$$

$\lambda\ is$ wave length, $L_x\ and\ L_z\ are$ length of antenna

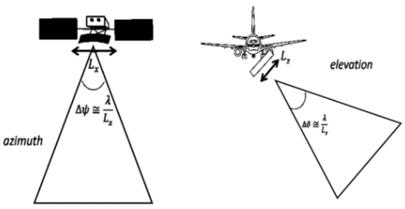

Figure 6: Beam width

1.4.9 Length of Synthetic Aperture

The length of the synthetic aperture in Synthetic Aperture Radar (SAR) refers to the effective distance over which the radar sensor collects data during the imaging process. In traditional radar systems, the antenna size directly determines the resolution, but in SAR systems, the resolution is improved by simulating a longer antenna through the movement of the sensor along its flight path. This "synthetic" antenna is created by combining multiple radar pulses received over the length of the sensor's trajectory, effectively increasing the aperture size. The longer the synthetic aperture, the finer the resolution of the resulting image. The length of the synthetic aperture is determined by the radar's platform speed and the duration over which the radar pulses are collected. A longer synthetic aperture improves the azimuth resolution, allowing for more detailed imaging of the Earth's surface, which is especially useful in applications such as topographic mapping, urban monitoring, and forest structure analysis (Ulaby & Long, 2014). However, achieving longer synthetic apertures may also lead to issues with motion compensation and image processing complexity, as the platform's motion must be accurately tracked and corrected (Ulaby & Long, 2014).

$$A_s = \Delta\psi . R_{min}$$

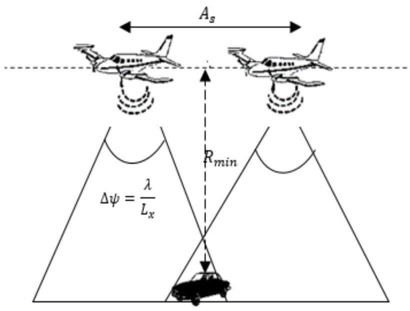

Figure 7 length of Aperture

1.5 Resolution

In Synthetic Aperture Radar (SAR), resolution is a crucial factor determining the system's ability to distinguish between closely spaced objects. There are three primary types of resolution: angular resolution, azimuth resolution, and range resolution. Each of these plays a vital role in the accuracy and quality of the SAR imagery.

1.5.1 Angular Resolution

Angular resolution refers to the ability of the radar system to distinguish between two objects located at different angles relative to the radar platform. This type of resolution is significant when observing a broad area with multiple objects that might be close together but at slightly different angles. A high angular resolution is essential for identifying and separating objects effectively. According to Henderson and Lewis (1998), angular resolution is largely dependent on the radar system’s frequency and the antenna's size, as well as the distance to the target area. In practical applications, improving angular resolution requires enhancing the beam-shaping capabilities of the radar system.

$$\Delta\psi_s = \frac{\lambda}{2A_s}$$

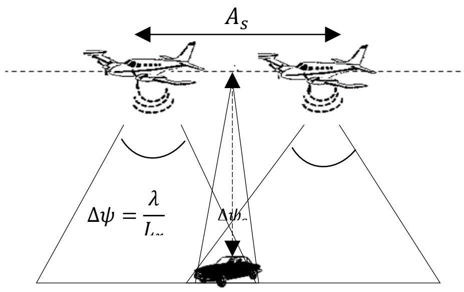

Figure 8 Angular Resolution Concept in SAR

1.5.2 Azimuth Resolution

Azimuth resolution measures the ability to differentiate objects in the horizontal direction, which is parallel to the radar platform’s flight path. This type of resolution is crucial for mapping and accurately identifying objects such as buildings, roads, or natural features on the ground. Wang and Zhang (2011) highlight that azimuth resolution is influenced by the synthetic aperture length, which is essentially the distance over which the radar observes a particular point, and the platform’s speed. Increasing the synthetic aperture length or improving the radar's motion control can enhance azimuth resolution.

$$\Delta x = \Delta\psi_s * R_{min}$$

$$\Delta x = \frac{L_x}{2}$$

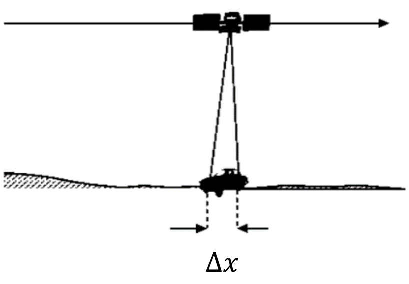

Figure 9 Azimuth Resolution Illustration

1.5.3 Range Resolution

Range resolution refers to the ability to distinguish between objects that are separated along the radar's line of sight (range direction). This resolution type is critical for accurately locating features such as terrain elevation, water bodies, or vegetation types. The range resolution is determined by the pulse duration of the transmitted radar signal, with shorter pulses providing better resolution. Ulaby et al. (1986) emphasize the importance of range resolution in applications like topographic mapping, where precise distance measurements are necessary. Shorter pulse durations enable finer distinctions between objects located at varying distances from the radar sensor.

$$\Delta r = \frac{C\ \Delta t}{2} = \frac{C}{2B}$$

$C\ is\ speed\ of\ light\ \left(approximately\ 3 \times \frac{10^8 m}{s}\right),\ \Delta t\ is\ pulse\ duration\ of\ the\ transmitted\ radar\ signal$

$and\ B\ is\ Band\ width$

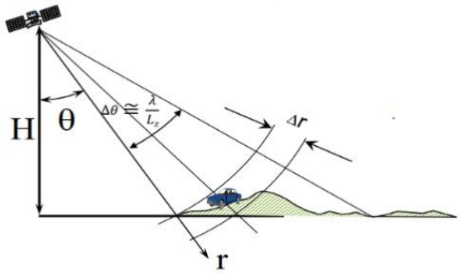

Figure 10: Range Resolution Illustration

1.5.4 Ground Resolution

Ground resolution refers to the actual spatial resolution on the Earth's surface, which is influenced by the radar's look angle. When the radar signal is not perpendicular to the Earth's surface, the resolution on the ground will be coarser compared to the range resolution due to the angle at which the signal interacts with the surface (Le Toan et al., 2011).

To convert range resolution to ground resolution in Synthetic Aperture Radar (SAR), we need to take into account the relationship between the slant range geometry and the radar's look angle. The basic formula to perform this conversion is:

$$\Delta g = \Delta r . cos(\theta)$$

$\theta :\ incidence\ angle$

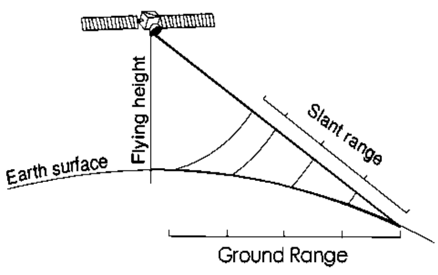

Figure 11 Ground Range Resolution

1.6 Distortion

In SAR (Synthetic Aperture Radar) imaging, distortion refers to the alteration of the radar signal due to various factors such as geometry, topography, and the system's processing. These distortions can lead to inaccuracies in the interpretation of the SAR image, affecting the representation of the Earth's surface.

1.6.1 Slant Range Distortion

Slant range distortion occurs because the radar sensor typically operates at an oblique angle to the Earth's surface, meaning the radar waves travel along a slant range rather than a direct vertical path. The distance from the sensor to the target on the ground is longer than the actual horizontal distance, which results in the compression or stretching of objects in the image. This geometric effect causes objects located at different ranges to appear compressed or stretched in the radar image, depending on their distance from the sensor. The effect is particularly noticeable in areas with varying topography, such as mountainous or undulating terrain, where the surface elevation differences further exacerbate the distortion. To correct for slant range distortion, radar data is often geometrically corrected and processed into an orthorectified image, which accounts for the sensor geometry and removes the distortions associated with slant range. Proper compensation for this distortion is crucial for accurate interpretation and analysis, especially when using SAR data for applications such as topographic mapping, land cover classification, and change detection (Ulaby & Long, 2014).

Figure 12 Slant Range Distortion in SAR Imaging

1.6.2 Geometric Distortion

1.6.2.1 Layover

Layover occurs when radar waves strike tall structures or steep slopes at a shallow angle, causing the radar signal to return from the top of the structure or slope before it reaches the base. This results in the top of the object being projected onto the ground closer to the radar sensor than the base, causing a distortion in the image where the object appears "flipped" or displaced. Layover is most noticeable in mountainous terrain or areas with tall buildings. This effect can lead to misinterpretation of the size and shape of the object, as it distorts the true geometry of the terrain (Ulaby & Long, 2014).

1.6.2.2 Foreshortening

Foreshortening occurs when the radar wave strikes a surface, such as a steep slope, at an angle, causing objects closer to the sensor to appear compressed in the radar image. The radar signal reaches the nearer parts of the object before the farther parts, causing a shortening of the object's image along the radar line of sight. This effect is common in areas with steep terrain and can result in an exaggerated appearance of the object's slope, which may lead to inaccurate assessments of the terrain's true shape and size.

1.6.2.3 Shadow

Shadowing occurs when objects such as buildings, mountains, or trees block the radar signal from reaching the surface behind them. The area in the shadow appears as a dark zone in the radar image because no backscatter is received from the surface behind the obstructing object. This effect is more pronounced when the radar signal is emitted at a low angle or when the object is very tall. Shadowing can obscure important details in the image and complicate the interpretation of surface features. In some cases, shadowing can be used to detect the presence of tall structures or steep terrain, but it must be accounted for during image interpretation and analysis (Ulaby & Long, 2014).

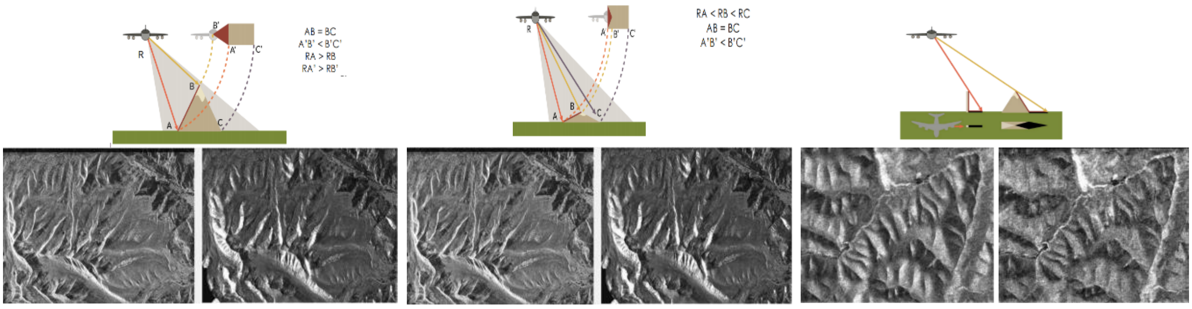

Figure 13 Layover, Foreshortening and Shadow Effect in Radar Images

1.6.3 Radiometric Distortion

Radiometric distortion in Synthetic Aperture Radar (SAR) refers to inaccuracies in the intensity of radar backscatter, which do not reflect the true surface characteristics but instead result from inherent factors within the radar system and its interaction with the Earth. These distortions can arise from sensor calibration errors, atmospheric conditions, and topographic effects. For example, if the sensor is not properly calibrated, intensity measurements may be skewed, while atmospheric variations like humidity and temperature can affect how radar waves propagate, altering the received signal. Similarly, the radar's interaction with different surface elevations can lead to uneven reflection and signal attenuation (Ulaby & Long, 2014; Le Toan et al., 2011).

The impact of radiometric distortion is significant in SAR image interpretation, as it can alter intensity values used for surface analysis, such as land cover classification, vegetation density estimation, or terrain monitoring. These inaccuracies may lead to incorrect conclusions about surface properties if not corrected. As a result, it is essential to apply correction techniques during SAR data processing to mitigate the effects of radiometric distortion and ensure more accurate results in various remote sensing applications.

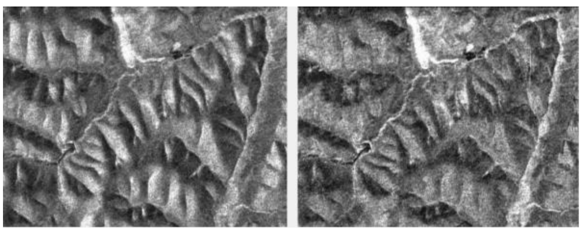

Figure 14: Radiometric Distortion in SAR

1.6.4 Speckle

Speckle in Synthetic Aperture Radar (SAR) refers to a type of granular noise that appears in radar images as a result of the interference of multiple radar waves scattered from the surface. Unlike other types of image noise, speckle is not random but is rather a pattern caused by the constructive and destructive interference of coherent radar waves. It typically appears as fine-grained, salt-and-pepper-like noise that degrades the visual quality and interpretability of SAR images. Speckle can obscure fine details of the image and complicate the process of extracting meaningful information from SAR data, such as classifying land cover or identifying objects on the ground.

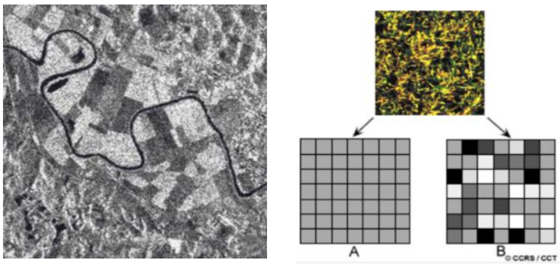

Figure 15: Speckle Noise in SAR Images

1.6.4.1 Speckle Reduction

Speckle reduction is a critical step in the processing of Synthetic Aperture Radar (SAR) images to improve their quality and interpretability. Since speckle noise can degrade the visual and quantitative analysis of SAR data, various techniques are employed to reduce or suppress it. These techniques aim to minimize the grainy appearance caused by the interference of radar waves while preserving important surface features and edges. Several methods have been developed to reduce speckle, including multi-look processing, spatial filtering, and temporal filtering (Ulaby & Long, 2014; Le Toan et al., 2011).

1.6.4.1.1 Multi-Look Filtering

Multi-look processing is a technique used to reduce speckle by averaging multiple radar images of the same area. This method involves taking several images of the same scene from different radar angles or from slightly different positions. The resulting images are then combined, or "looks," to improve the signal-to-noise ratio. By averaging over multiple looks, speckle noise, which is random, tends to cancel out, while the actual surface features remain more stable. This method helps to smooth out the speckle pattern, leading to clearer and more interpretable images. However, it does reduce the spatial resolution of the image, as it involves the averaging of pixel values across different looks (Ulaby & Long, 2014).

1.6.4.1.2 Spatial Filtering

Spatial filtering involves applying filters to SAR images in the spatial domain to smooth out the speckle while retaining important structural features. These filters operate on the neighboring pixels of each image pixel, reducing the variation in intensity values caused by speckle. Common spatial filters include the Lee filter, Frost filter, and Gamma MAP filter, all of which are designed to smooth the image based on local statistics. While spatial filtering helps reduce speckle noise, it can also blur the edges and fine details of the image, which makes the choice of filter and its parameters important to minimize the loss of valuable information. These filters work by considering the local neighborhood of pixels, so they are particularly useful in preserving edges while reducing speckle (Ulaby & Long, 2014).

1.6.4.1.3 Temporal Filtering

Temporal filtering reduces speckle by utilizing multiple SAR images taken over time. This approach is effective when monitoring dynamic changes in an area, as speckle noise is often random and varies over time. By taking advantage of the temporal coherence of the radar signal, temporal filtering involves stacking several images of the same area taken at different times and averaging the pixel values. This method is especially useful in areas with minimal temporal variation (such as stable terrain or vegetation) and helps separate the random speckle from the consistent surface features. It is often used in change detection studies, where the goal is to analyze differences between images while suppressing speckle noise (Le Toan et al., 2011).

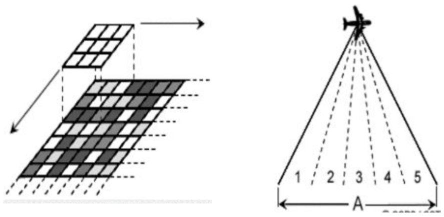

Figure 16 Spatial filter and Multi-Look filtering for Speckle Reduction

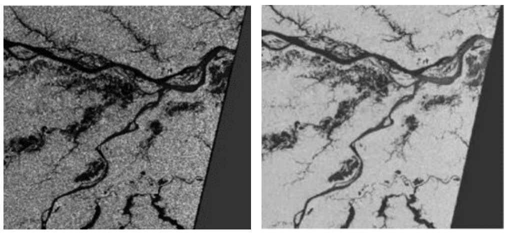

Figure 17 Spacle filtter Effect

1.7 Key Parameters Affecting Backscattered Signal

The quality and characteristics of a Synthetic Aperture Radar (SAR) signal are influenced by various parameters. These factors can be broadly categorized into two main groups: radar parameters and surface parameters. Each group plays a crucial role in determining the backscatter intensity, image resolution, and the ability of the radar system to detect and map surface features.

1.7.1 Radar Parameters

Some key characteristics of radar signals that influence how they interact with the Earth's surface and how radar systems collect and interpret data include parameters such as wavelength, polarization, and incidence angle. These parameters determine the radar's resolution, penetration capabilities, and sensitivity to different surface features.

1.7.1.1 Wave Length

The wavelength of the radar signal is a critical factor that determines how the radar waves interact with the Earth's surface. The wavelength is inversely proportional to the frequency of the radar system, higher frequencies (shorter wavelengths) provide higher spatial resolution but may be more sensitive to surface roughness and vegetation. On the other hand, lower frequencies (longer wavelengths) penetrate through vegetation and the Earth's surface more effectively, making them ideal for applications like forest monitoring or soil moisture estimation (Ulaby & Long, 2014). The choice of wavelength affects the radar's ability to detect different types of surfaces and provides insights into the material properties of the target.

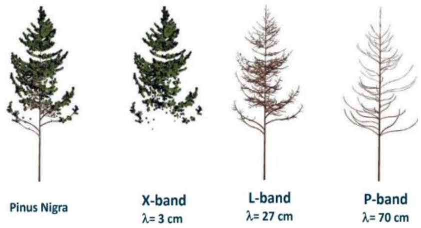

Figure 18 Radar Signal Penetration level for different wavelength

1.7.1.2 Polarization

Polarization refers to the orientation of the electromagnetic wave's electric field. Radar systems can transmit and receive waves in different polarization modes, such as horizontal (H) and vertical (V) polarization. The polarization modes affect how radar waves interact with different surface features. For example, HH (horizontal-horizontal) polarization tends to be more sensitive to surface features like buildings, while VV (vertical-vertical) polarization can provide better information about vegetation. Polarimetric SAR (PolSAR) uses multiple polarizations to capture more information about the surface, such as distinguishing between land cover types or assessing structural characteristics of urban areas (Li et al., 2022).

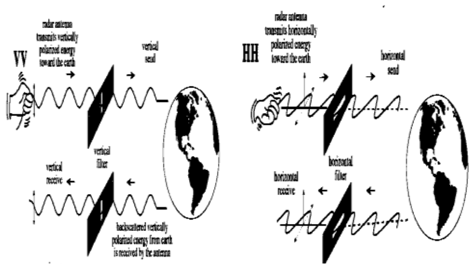

Figure 19 Radar Signal Polarization Types

1.7.1.3 Incidence Angel

The incidence angle is the angle at which the radar waves strike the surface relative to the vertical. It plays a significant role in determining the amount of backscatter returned to the radar sensor. Low incidence angles (close to the horizon) tend to produce stronger returns from rough surfaces or vertical structures, making them ideal for applications in urban areas or rough terrain. In contrast, high incidence angles (close to vertical) tend to have weaker backscatter, as the radar waves interact less with the surface. The choice of incidence angle affects the geometry of the radar image and the ability to detect surface features, particularly in terms of their shape and height (Pottier & Le Toan, 2015).

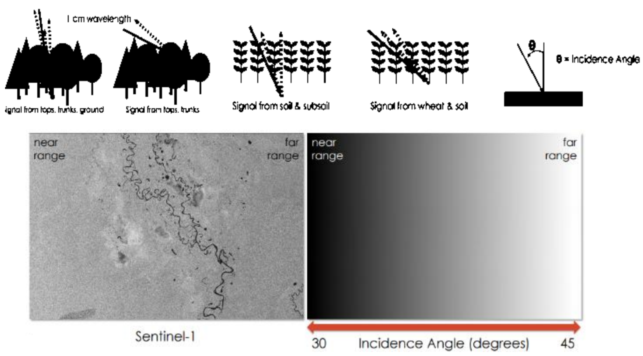

Figure 20 Radar Signal incidence angle

1.7.2 Surface Parameters

1.7.2.1 Structure

The structure of the surface, including its roughness, direction, and orientation, plays a crucial role in how radar waves interact with it. These factors affect the backscatter intensity and the quality of the radar image.

1.7.2.1.1 Roughness

Surface roughness refers to the irregularities on the surface relative to the wavelength of the radar signal. If the surface is rough compared to the radar wavelength, the radar signal is scattered in multiple directions, leading to Rough scattering. Rougher surfaces, such as forests, rocky terrains, or agricultural fields, produce higher backscatter due to this scattering mechanism. On the other hand, smooth surfaces like calm water or flat roads cause specular reflection, which results in minimal backscatter (Ulaby & Long, 2014). The level of roughness is crucial for interpreting land cover types and surface conditions, such as assessing forest structure or detecting urban areas.

1.7.2.1.2 Density

Density refers to the concentration or amount of scatterers present on a surface, which can significantly influence the radar backscatter. In forested areas, for example, the density of the canopy, tree trunks, and branches determines how much radar energy is scattered back to the sensor. Higher density surfaces, such as thick vegetation or built-up urban areas, tend to generate higher backscatter due to the increased number of scatterers. Conversely, lower-density surfaces, like sparse grasslands or open fields, produce less backscatter. Density is closely related to surface roughness, as both influence how radar waves interact with the surface, impacting the intensity and characteristics of the backscattered signal. The radar signal interacts with denser surfaces more extensively, often resulting in more complex scattering mechanisms, such as volume scattering, compared to smoother or more sparsely vegetated surfaces (Ulaby & Long, 2014). Understanding density is key to interpreting SAR data for applications like land cover classification, biomass estimation, and monitoring changes in vegetation density over time.

1.7.2.1.3 Direction and Orientation

The direction and orientation of surface features (such as trees, buildings, or mountains) also influence the radar signal's interaction. Surfaces with vertical features (e.g., buildings or tree trunks) tend to reflect radar waves more strongly in a particular direction, leading to double-bounce scattering. The radar wave first interacts with a vertical surface and then reflects off a horizontal surface, resulting in a strong return signal, especially in urban environments (Papathanassiou & Cloude, 2001). In contrast, horizontal surfaces like plains or large water bodies reflect radar waves in different directions depending on the radar's angle of incidence. Therefore, understanding the surface orientation helps in interpreting the geometry of the backscatter and can be used to detect and map specific surface features.

1.7.2.2 Water Content

The moisture content of the surface is a critical factor that influences the radar backscatter. This is largely controlled by the dielectric constant of the material, which is a measure of how well the material can store electrical energy when exposed to an electric field. Different materials, depending on their moisture content, exhibit varying dielectric constants, significantly affecting the radar signal interaction.

1.7.2.2.1 Dielectric Constant

The dielectric constant increases with the moisture content of the surface. Water has a high dielectric constant, which makes it highly reflective to radar waves. Therefore, wet surfaces, such as flooded areas, moist soils, or wet vegetation, produce higher radar backscatter compared to dry surfaces (Pottier & Le Toan, 2015). For example, in agricultural areas, soil moisture can be monitored through SAR, as wet soils reflect more radar energy. Similarly, snow and ice, due to their moisture content, show high backscatter at certain frequencies, allowing SAR to be used for snow monitoring and ice detection.

1.7.2.2.2 Other Effects of Moisture on Signal

Moisture not only increases the dielectric constant but also changes the scattering behavior of the surface. Wet surfaces tend to cause more specular reflection, especially when the radar frequency is high, while dry, rough surfaces tend to produce more diffuse scattering. The interaction of radar waves with moist soils or vegetation can reveal important information about the surface's moisture status, which is vital for applications like agriculture, hydrology, and land management (Li et al., 2022). This relationship between moisture and backscatter makes SAR a valuable tool for monitoring environmental changes, such as droughts, floods, or soil moisture dynamics.

1.8 Backscatter Mechanism

In Synthetic Aperture Radar (SAR)**,** backscatter refers to the portion of the radar signal that is reflected back to the radar sensor from the Earth's surface. The intensity and characteristics of the backscattered signal depend on various factors, including surface type, roughness, and the angle of incidence. SAR systems detect and analyze these backscattered signals to create high-resolution images that reveal valuable information about the surface properties. The backscatter mechanism, which defines how the radar signal interacts with the surface, is primarily influenced by the physical properties of the target surface. These mechanisms can be categorized into four primary types: specular reflection**,** Rough scattering**,** volume scattering, and double-bounce scattering (Ulaby & Long, 2014).

1.8.1 Specular Reflection

Specular reflection occurs when the surface is smooth relative to the radar wavelength, such as calm water or a flat, smooth surface. In this case, the radar waves are reflected in a single direction, typically away from the radar sensor, leading to little or no backscatter. As a result, areas exhibiting specular reflection, like bodies of water or paved roads, appear dark in SAR images. The strength of the specular reflection is highly dependent on the incident angle of the radar signal, and these areas can be useful for studying surface roughness and water bodies (Pottier & Le Toan, 2015).

1.8.2 Rough Scattering

Rough scattering occurs when the surface is rough, with irregularities that are larger than the radar wavelength. In this case, radar waves are scattered in many directions, producing a uniform and isotropic return signal. Surfaces such as soil, forests, and rough terrain produce diffuse scattering. In SAR images, these areas often appear bright due to the significant amount of backscatter, which is used to identify the roughness of the surface and distinguish between different land cover types (Ulaby & Long, 2014).

1.8.3 Double-Bounce Scattering

Double-bounce scattering occurs when radar waves first reflect off a vertical surface, such as a building or tree trunk, and then reflect off a horizontal surface, such as the ground. This results in the radar signal being reflected twice before returning to the sensor. Double-bounce scattering produces a strong return signal, making it easily detectable in SAR images. It is especially significant in urban areas where man-made structures like buildings and pavements create such interactions. Double-bounce scattering can also occur in forests, where the radar wave interacts with tree trunks and the ground below. This mechanism is typically detected in Polarimetric SAR (PolSAR) data, where multiple polarization modes enhance the ability to identify and distinguish double-bounce returns, providing valuable information about urban environments and infrastructure (Papathanassiou & Cloude, 2001).

1.8.4 Volume Scattering

Volume scattering happens when radar signals penetrate a medium (such as a forest canopy or snow cover) and interact with multiple layers inside the medium. This scattered return comes from the entire volume of the material, rather than a single surface. This mechanism is most prominent in vegetated areas, where the radar waves interact with leaves, branches, and the forest floor. Volume scattering is commonly used in studies of biomass, forest structure, and vegetation health, as it provides information about the internal structure of the medium (Li et al., 2022).

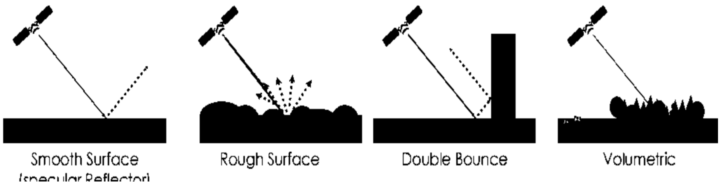

Figure 21 Backscatter Mechanisms in Different Land Covers

1.8.5 Backscatter Mechanism in Forest

The backscatter mechanism in forests, as detected by Synthetic Aperture Radar (SAR), is influenced by several scattering processes: volume, surface, and double-bounce scattering. Volume scattering occurs when radar signals penetrate the canopy and scatter off tree structures, with denser forests producing higher backscatter. Surface scattering happens when signals reflect off the canopy or forest floor, more common in sparser forests. Double-bounce scattering occurs when signals bounce between surfaces like the ground and tree trunks, often seen in dense forests or areas with strong vegetation-soil contrasts. The contribution of each mechanism depends on factors like radar wavelength, polarization, forest density, tree species, and moisture content.

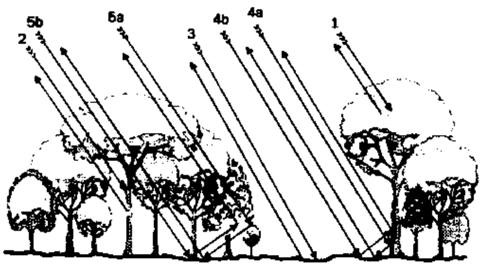

Figure 22: Forest Backscatter Mechanisms

1.9 Interpretation of SAR Data

Synthetic Aperture Radar (SAR) systems capture information about the Earth's surface by transmitting microwave signals and recording the energy that is backscattered toward the sensor. The SAR signal contains two main components, amplitude and phase. These values carry complementary information that is critical for a wide range of remote sensing applications.

$$S = A.e^{j\emptyset}$$

Where A is amplitude and $\emptyset$ is phase.

1.9.1 Amplitude

The amplitude of the Synthetic Aperture Radar (SAR) signal represents the strength of the backscattered microwave energy received from the Earth's surface. It is directly influenced by several surface characteristics, including surface roughness, dielectric constant, incidence angle, and terrain orientation (Ulaby et al., 2014; ESA, 2007; Lee & Pottier, 2009). Amplitude data is widely used in various remote sensing applications. For instance, it plays a key role in land cover classification due to its sensitivity to different surface types. It is also commonly used in flood mapping, as inundated areas typically exhibit low amplitude values caused by specular reflection. Additionally, amplitude data supports change detection by enabling comparisons between images acquired at different times (Lee & Pottier, 2009; Moreira et al., 2013).

1.9.2 Phase

The phase represents the distance traveled by the radar wave, expressed as a fraction of the radar wavelength. Unlike amplitude, the phase is extremely sensitive to sub-centimeter changes, often on the order of millimeters. This sensitivity makes it a crucial parameter for a range of applications. In topographic mapping using Interferometric Synthetic Aperture Radar (InSAR), phase differences between two SAR acquisitions are used to derive elevation information. In ground displacement detection, phase changes allow the observation of subtle deformations of the Earth's surface caused by events such as earthquakes, landslides, or subsidence. Furthermore, phase time-series analysis is widely used for monitoring glacier movements and volcanic activity. These applications demonstrate the importance of phase information in high-precision geospatial studies (Hanssen, 2001; ESA, 2007; Bekaert et al., 2015; Samiei-Esfahany & Hanssen, 2017).

1.8.2.1 Deterministic Phase

The deterministic phase is the predictable part of the SAR phase and is primarily influenced by radar wavelength and slant range (Hanssen, 2001; ESA, 2007):

$$\emptyset_{geometry} = \frac{4\pi R}{\lambda}$$

1.8.2.2 Stochastic Phase

The stochastic phase refers to the unpredictable, noise-like component of the total phase. It arises due to several factors.

1.8.2.2.1 Speckle

Caused by the coherent sum of scattered signals from multiple unresolved targets in a resolution cell. It gives rise to random phase variations even in static scenes (Hanssen, 2001).

1.8.2.2.2 Temporal decorrelation

Resulting from changes in vegetation, surface moisture, or human activities between SAR acquisitions (ESA, 2007).

1.8.2.2.3 Volume scattering

Especially in forested or snow-covered areas, where multiple scattering events within a volume cause random phase fluctuations (Samiei-Esfahany & Hanssen, 2017).

1.8.2.2.4 Atmospheric effects

Including tropospheric delay, can introduce spatially correlated phase errors that are partially stochastic and affect accuracy in interferometric measurements (Bekaert et al., 2015).

1.10 SAR Data Format

SAR data can be delivered in various processing levels and formats, each suited to different types of analysis. Two of the most common data formats in satellite SAR missions (e.g., Sentinel-1, RADARSAT, TerraSAR-X) are Single Look Complex (SLC) and Ground Range Detected (GRD). These formats differ in how the data is processed and how much geometric and radiometric detail they retain (ESA, 2007; Moreira et al., 2013).

1.10.1 Single Look Complex (SLC)

Single Look Complex (SLC) products preserve the full complex SAR signal, containing both amplitude and phase information. These datasets are georeferenced in slant range geometry, where distances are measured along the radar's line of sight rather than vertically or horizontally projected. Due to the retention of detailed phase information, SLC data is particularly suitable for advanced applications such as ground deformation monitoring, digital elevation model (DEM) generation through interferometry, and Polarimetric analysis in the case of Polarimetric SAR systems.

1.10.2 Ground Range Data (GRD)

Ground Range Detected (GRD) products are intensity-only SAR images, meaning that the phase information is removed or lost during the processes of multilinking and geometric projection to ground range. Each pixel in a GRD image represents the detected power of the backscattered radar signal. To ensure that the data can be quantitatively analyzed, radiometric calibration is applied, allowing the use of the backscatter coefficient (Lee & Pottier, 2009; ESA, 2007).

GRD products are widely used in various remote sensing applications due to their simplicity and ease of interpretation. They are particularly suitable for land cover classification, change detection and flood mapping, general visual interpretation and thematic mapping.

1.11 Synthetic Aperture Radar Techniques

Each of the SAR techniques, PolSAR, InSAR, and TomoSAR, offers distinct capabilities for monitoring and analyzing various surface features. These techniques serve diverse applications, ranging from land classification and material differentiation (PolSAR), to deformation monitoring (InSAR), and 3D surface reconstruction (TomoSAR).

1.11.1 PolSAR (Polarimetric SAR)

PolSAR refers to SAR systems that use different polarization states of radar waves to capture information about the surface. By transmitting radar signals with specific polarization and receiving echoes with varying polarization states (e.g., horizontal and vertical), PolSAR can distinguish between different surface types, such as water, vegetation, or urban areas. A detailed review of the theory behind PolSAR, including its ability to differentiate materials based on polarization, can be found in Cloude and Pottier's (1996) work, where they describe the use of polarization to interpret surface properties in SAR imagery (Cloude & Pottier, 1996).

1.11.2 InSAR (Interferometric SAR)

InSAR is a technique that measures ground displacement by analyzing phase differences between SAR images captured at different times. By comparing these phases, InSAR can detect surface deformations, which are essential for monitoring phenomena such as earthquakes, volcanic movements, and subsidence. Bürgmann et al. (2000) provided a comprehensive discussion on the principles of InSAR and its application in monitoring surface deformations caused by seismic and volcanic activities (Bürgmann et al., 2000). This method has been widely adopted in geophysical studies due to its ability to measure millimeter-level displacements with high spatial resolution.

1.11.3 TomoSAR (Tomographic SAR)

TomoSAR is an advanced SAR technique that enables the 3D imaging of the surface by using multiple SAR images from different viewing angles. By synthesizing these views, it generates a detailed 3D reconstruction of the surface, which is useful for analyzing complex structures such as urban environments, vegetation, and terrain. Fornaro and Serafino (2004) discussed how TomoSAR can be applied for high-resolution 3D imaging and structural analysis of complex scenes (Fornaro & Serafino, 2004). This technique is particularly valuable in urban planning and monitoring forest canopy structure.

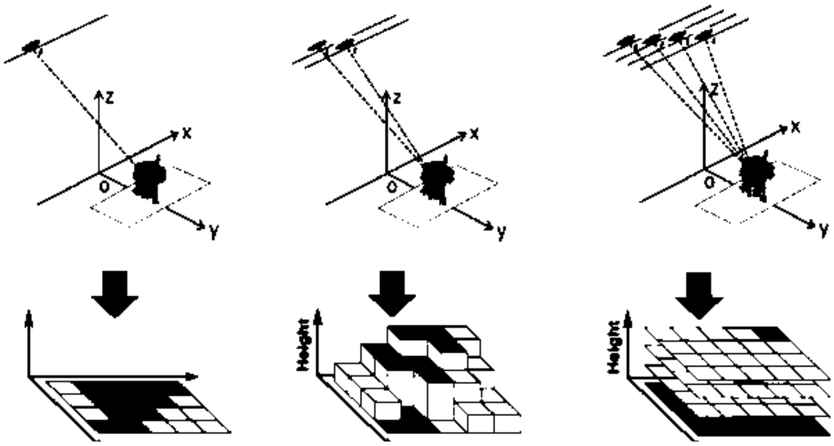

Figure 23 Comparison of SAR Techniques (PolSAR, InSAR, and TomoSAR)

Chapter 2

2.1 TomoSAR Concept

TomoSAR (Synthetic Aperture Radar Tomography) is an advanced remote sensing technique that leverages Synthetic Aperture Radar (SAR) data to reconstruct high-resolution 3D images of the Earth's surface and subsurface. The technique extends traditional SAR interferometry, enabling the extraction of vertical displacement measurements by using radar data captured from multiple viewing angles. These multiple radar images are then combined to generate a volumetric model of the observed area, providing crucial insights into topographic changes and surface deformations. This method, often referred to as SAR tomography, allows for a more comprehensive analysis of surface displacement than conventional SAR, which typically offers a one-dimensional (line-of-sight) measurement.

TomoSAR is particularly valuable in applications where precise vertical displacement is critical, such as in monitoring land subsidence, earthquake-induced deformations, and urban infrastructure stability (Prats et al., 2016). The principle behind TomoSAR is based on tomographic imaging techniques, where data collected from different perspectives is reconstructed to form a 3D model of the target area (Zebker & Villasenor, 1992).

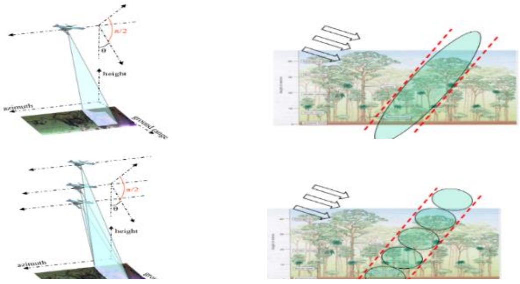

Figure 24 TomoSAR Concept for 3D Imaging

2.1 TomoSAR Forward Model

The TomoSAR Forward Model describes how a SAR pixel in the n-th image can be expressed in terms of a summation of scatterers in the scene and their respective phase shifts. This model is central to reconstructing 3D structures using multi-view SAR data.

The SAR pixel intensity in the n-th image, $I_n(r,x)$ can be expressed as a sum over all scatterers in the scene, each represented by a scattering coefficient $s(v)$ at a particular position v. The phase shift for each scatterer depends on the relative position of the scatterer and the radar's observation geometry. This is given by the expression:

$$I_n(r,x) = \sum_v s(v).\exp\{-j2\pi f_v b_n\}\,, \quad f_v = \frac{2}{\lambda}\ \frac{v}{R_n(ref)}$$

Where:

$I_n(r,x)$: intensity of the SAR pixel at position rand azimuth x in the n − th image

$s(v)$: scattering coefficient

f_v: frequency term related to the vertical location of the scatterer

b_n: baseline

$R_n(ref)$: reference range

λ: wave length

v: elevation

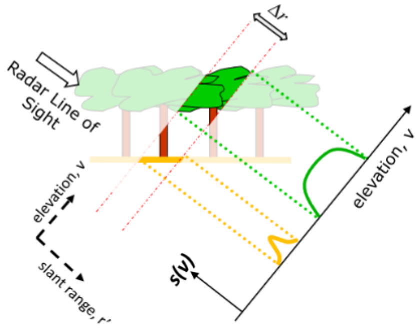

Figure 25 TomoSAR Forward Model Illustration

2.2 TomoSAR Height Inversion

TomoSAR (Tomographic Synthetic Aperture Radar) height inversion refers to the process of extracting vertical displacement or elevation information from a stack of SAR images, which allows for the generation of 3D reconstructions of the observed scene. This technique takes advantage of the different viewing angles of the SAR sensor, typically collected from a moving platform, to infer height or displacement by applying tomographic principles (Berardino et al., 2002).

$$z = v.\sin(\theta)$$

$$k_z(n) = \frac{4\pi}{\lambda R_n(ref)} \frac{b_n}{sin(\theta)}$$

$$I_n(r,x) = \exp\left\{-j\frac{4\pi}{\lambda}R_n(ref)\right\}.\sum_z s(x).\exp\{-jk_z(n)z\}$$

z: $height$

θ: $incidence\ angle$

k_z: $wave\ number\ in\ the\ z\ direction$

$s(x)$: $scattering\ coefficient\ at\ the\ surface$

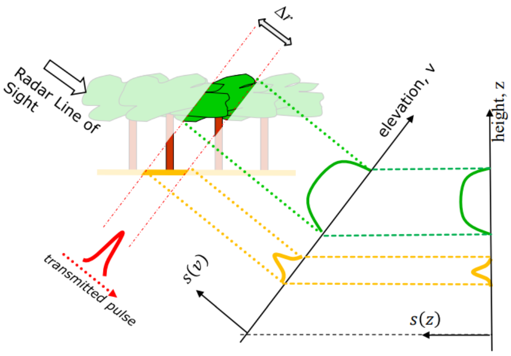

Figure 26 TomoSAR Height Inversion Process

2.3 Topography Phase

Terrain flattening is a technique used in Synthetic Aperture Radar (SAR) processing to correct for the phase distortions that arise due to variations in the topography of the terrain. The radar waves interact with the Earth's surface, and when the terrain is not flat, the radar signal experiences phase shifts depending on the elevation differences. This phase shift needs to be corrected for in order to accurately interpret the SAR data and remove topographic effects that distort the imagery.

In SAR, the received signal, $I_n(r,x)$ for a particular pixel is influenced by both the slant range and the height of the terrain. The phase offset caused by these factors must be compensated for to achieve an accurate representation of the surface. This compensation can be performed using knowledge of the terrain's geometry.

The equation for the received signal considering terrain flattening is:

$$I_n(r,x) = exp\left\{-j\frac{4\pi}{\lambda}R_n(ref)\right\}.\sum\nolimits_z s(x).exp\{-jk_z(n)z\}$$

To remove the phase offset, the terrain's elevation profile must be known, typically obtained from a Digital Elevation Model (DEM). The process involves adjusting the signal phase for the elevation variations at each pixel. By applying the phase compensation across the image, terrain flattening removes the distortions caused by topographic relief, allowing for a clearer and more accurate representation of the surface.

Once the terrain flattening is applied, the image is geometrically corrected to appear as though the surface is flat, thereby improving the interpretation of the radar data. This correction is essential for accurate analysis in applications such as forest mapping, urban planning, and topographic analysis (Ulaby & Long, 2014).

$$\Delta\phi(z) = \frac{4\pi}{\lambda}(R_z - R_n(ref))$$

$$I_n{}^{flattened}(r,x) = \sum\nolimits_z s(x).\exp\{-jk_z(n)z - j\Delta\phi(z)\}$$

$\Delta\phi(z)$: $topography\ phase\ correction$

R_z: slant range to a pixel at elevation z

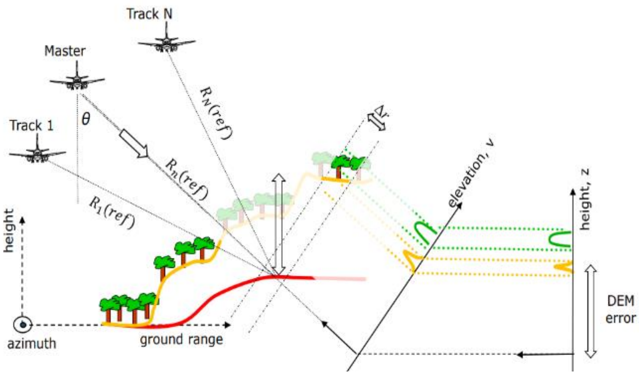

Figure 27 Topography Phase Removal in SAR Processing

2.4 TomoSAR focusing algorithm

The TomoSAR focusing algorithm plays a critical role in reconstructing 3D models of observed scenes by utilizing radar signals collected from multiple SAR acquisitions taken from different viewing angles. This technique is commonly used in applications such as urban modeling, vegetation monitoring, and terrain reconstruction. The main goal of the focusing algorithm is to accurately align and process the radar signals in both the range and azimuth directions, as well as to address the vertical dimension (height) in order to produce high-resolution 3D reconstructions of objects and terrain (Fornaro et al., 2004).

In TomoSAR, the backprojection technique is commonly employed, where the radar signals from different angles are "projected" back into a 3D space to focus on specific locations in the scene (Osten et al., 2008). The process generally involves motion compensation to correct for platform movements, followed by a 3D focusing of the SAR data using iterative methods (such as the conjugate gradient method), which are essential for improving the reconstruction accuracy and resolving complex geometries (Stojanovic et al., 2014).

Furthermore, range-Doppler methods are often used to compensate for the Doppler shifts caused by platform motion, which improves the spatial resolution of the reconstructed 3D model (Rieke et al., 2011). The final stage typically involves height inversion methods, which use the SAR data to estimate the vertical height of the surface scatterers (Hoch et al., 2005). These algorithms are particularly effective in monitoring forests, urban structures, and natural landscapes.

Chapter 3

3.1 Area of Interest

The study focuses on Moncalieri, a municipality in the Metropolitan City of Turin, Italy, located along the Po River. Moncalieri is characterized by a diverse landscape, including urban areas, agricultural fields, and forested regions, making it a suitable site for evaluating forest canopy height using Synthetic Aperture Radar (SAR) tomography (TomoSAR). The area's vegetation mainly consists of mixed deciduous forests, with significant green spaces contributing to the local biodiversity. The presence of hilly terrain and varying forest densities presents an ideal testbed for assessing the effectiveness of TomoSAR techniques in extracting vertical forest structure information.

The forested areas in Moncalieri play a crucial role in local ecological stability, carbon sequestration, and biodiversity conservation. However, accurate forest height estimation remains a challenge due to terrain variations and dense vegetation cover. By applying TomoSAR techniques, this study aims to generate high-resolution canopy height maps, which can support forest management and environmental monitoring efforts. The results can provide valuable insights into forest structure dynamics and contribute to sustainable land-use planning in the region.

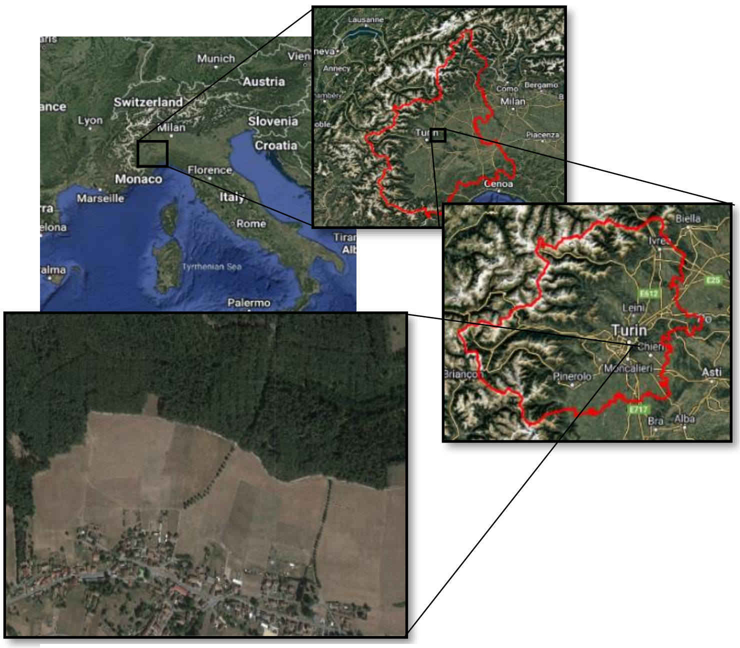

Figure 28 Area of Interest - Moncalieri, Italy

3.2 Data

3.2.1 Synthetic Aperture Radar (SAR) Images

Eight Synthetic Aperture Radar (SAR) multi-baseline images with L-band frequency were provided over the area of interest. These high-resolution radar images are essential for capturing detailed surface characteristics, particularly in regions covered by dense vegetation or exhibiting complex topography. The L-band wavelength (~23.5 cm) allows deeper penetration into vegetation canopies compared to shorter wavelengths (e.g., C- or X-band), making it highly suitable for monitoring ground surface deformations, landslides, and structural changes in vegetated or mountainous environments.

3.2.2 Digital Terrain Model (DTM)

A Digital Terrain Model (DTM) with a 1-meter spatial resolution was acquired from the Geoportal of the Piedmont Region. The DTM provides an accurate elevation model of the bare earth surface by removing vegetation, buildings, and other man-made structures. It is crucial for geometric correction of SAR data, geocoding, and for use in modeling and simulation processes that depend on accurate elevation data.

3.2.3 Lidar Data

LIDAR (Light Detection and Ranging) data were obtained over the study area and used primarily for evaluation and validation purposes. The dataset provides high-resolution 3D point clouds, enabling precise estimation of vegetation structure and terrain elevation. In this study, the LiDAR data were specifically used to evaluate forest canopy height, serving as a reference for assessing the accuracy of vegetation-related parameters derived from SAR observations. The availability of accurate vertical profiles from LiDAR significantly enhanced the validation of radar-based forest height retrieval and supported the analysis of vegetative cover in densely forested areas.

3.3 Methodology

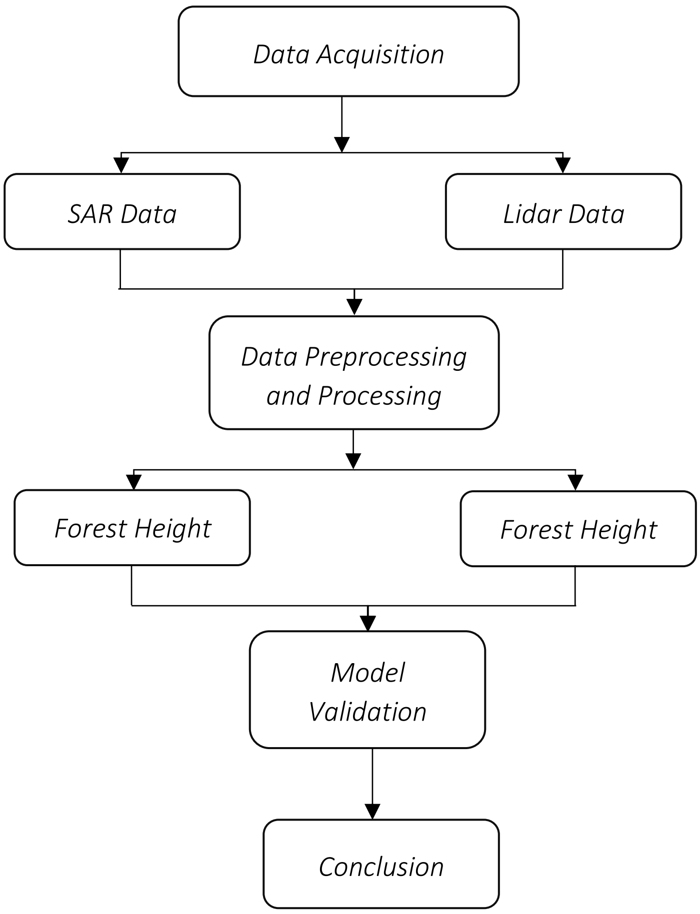

Figure 29 Structure of Work

3.4 Data process

3.4.1 Data Preparation

The first step in TomoSAR data processing is data preparation, where a data stack is created by collecting multiple SAR images of the same area from different viewing angles over time. This stack is critical for the subsequent 3D reconstruction of the surface. The images, typically captured by a single SAR sensor platform along its flight path, represent the same scene from varying perspectives. A key task in this phase is coregistration, which ensures that the images are aligned so that the corresponding pixels match across all images. Proper alignment is essential to avoid errors in the tomographic reconstruction, as misalignment between the images could result in significant inaccuracies in the final 3D model. The co-registered stack then serves as the input for advanced processing techniques that enable the extraction of vertical information and the generation of high-resolution 3D models of the terrain or structures under observation (Ferretti et al., 2000; Hooper et al., 2012)

The data stack consists of 9 images, each with 929 pixels in the azimuth direction and 938 pixels in the range direction, resulting in a stack size of (929, 938, 9).

3.4.2 Smoothing Using Convolution (Boxcar Kernel)

In your code, the smoothing operation is performed by applying a convolution of the signal fff with a kernel KKK. This kernel is a boxcar kernel, a simple averaging filter where each element of the kernel has equal weight. The kernel is normalized so that the sum of its elements is equal to 1.

The convolution of a signal f at pixel (m, n) with kernel K is mathematically expressed as:

$$f(m,n) = \sum_{k,l} f(m+k, n+1).K(k,l)$$

$\mathrm{f(m,n)}$: signal at position $\mathrm{(m,n)}$, $\mathrm{K(k,l)}$: value of the kernel at position $\mathrm{(k,l)}$

This convolution-based smoothing is commonly used in image processing and signal processing tasks for noise reduction and edge smoothing (Gonzalez & Woods, *Digital Image Processing*, 4th edition, Pearson, 2018).

3.4.3 Covariance Matrix

In the context of TomoSAR, the covariance matrix $R_{ij}(m,n)$ is calculated between different signal tracks (or channels) at pixel(m,n). This matrix quantifies the correlation between the signal from track iii and track j at each pixel in the scene. The formula is:

$$R_{ij}(m,n) = \frac{smooth(S_i(m,n).\overline{S_j(m,n)})}{\sqrt{smooth(|S_i(m,n)|^2).smooth(|S_i(m,n)|^2)}}$$

For an image of size $rows \times cols$ with n_{Track} tracks, the total shape of the covariance matrix would be:

$$R(m,n) \in \mathbb{C}^{n_{Track} \times n_{Track}}$$

$$Shape\ of\ Covariance\ Matrix = (rows, cols, n_{Track}, n_{Track})$$

$$R(m,n) = \begin{bmatrix} R_{11}(m,n) & R_{12}(m,n) & \cdots & R_{nTrack}(m,n) \\ R_{21}(m,n) & R_{12}(m,n) & \cdots & R_{nTrack}(m,n) \\ . & . & \cdots & . \\ . & . & \cdots & . \\ . & . & \cdots & . \\ R_{nTrack}(m,n) & R_{nTrack}(m,n) & \cdots & R_{nTrack}(m,n) \end{bmatrix}$$

3.4.4 Capon Beam inversion

In Capon Beamforming Inversion (CBI), the goal is to compute the direction of arrival (DOA) or height inversion by using the covariance matrix and steering vectors.

Given the covariance matrix R(m,n) and the steering matrix, the Capon Beamforming Inversion (CBI) can be formulated as following steps:

Step 1: Loading Factor Calculation:

$$\Lambda = \frac{1}{25}\, I_{nTrack}$$

Where: I_{nTrack} is Identity matrix and $\frac{1}{25}$ is a regularization parameter that may vary depending on the system.

Step 2: Steering Vector Calculation:

$$a_{steer} = exp(j.k_z.z)$$

Step 3: Capon Filter Calculation:

The Capon filter output is designed to minimize output power while maintaining unit gain in the look direction:

$$h_{abf} = \frac{h_{num}}{h_{den}} \quad , \qquad h_{num} = (R + \Lambda)^{-1}.a_{steer} \quad , \quad h_{den} = a_{steer}^{H}.(R + \Lambda)^{-1}.a_{steer}$$

Step 4: Capon Beamforming Output Power Calculation:

$$C_{capon} = \frac{1}{a_{steer}^{H}.(R + \Lambda)^{-1}.a_{steer}}$$

3.5 Visualization

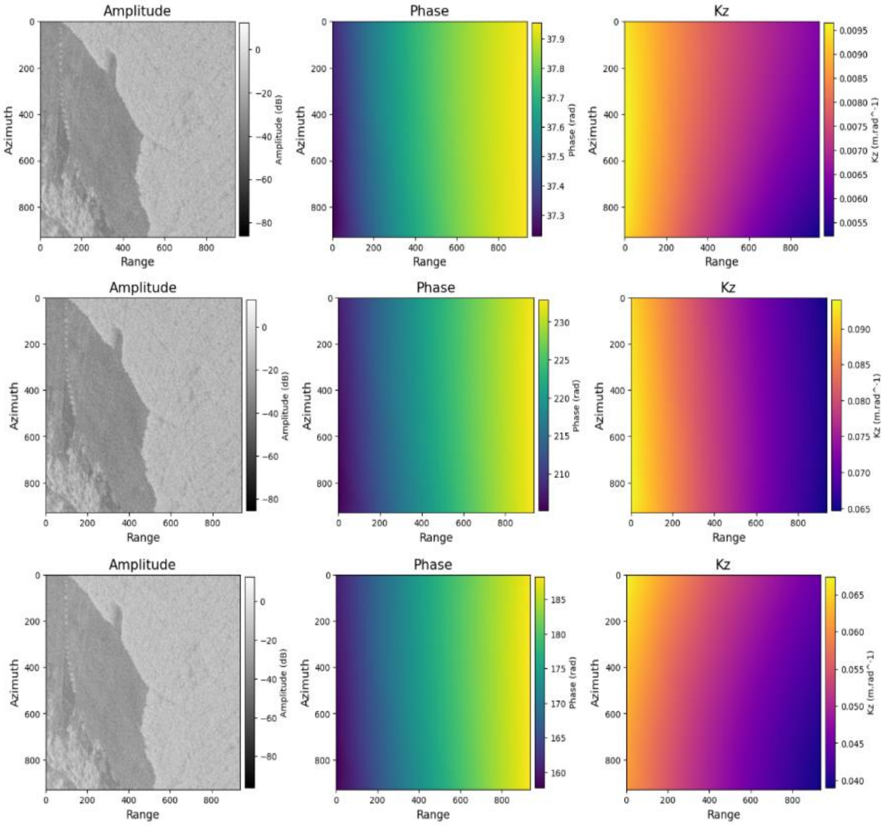

Figure 30 Data Stack (Amplitide, Phase and wave number)

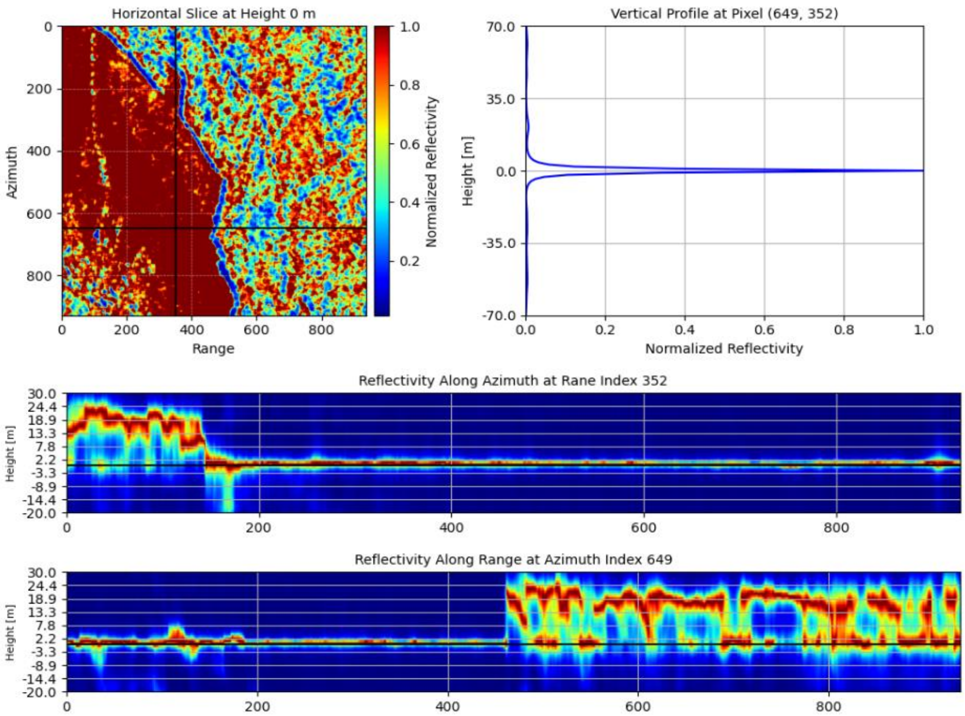

Figure 33

3.6 Validation

To validate the model's predictions, the errors for each individual canopy height measurement were calculated by comparing the model's estimated values to the actual field-measured values from the Lidar survey. The error for each measurement was determined as the difference between the predicted canopy height and the observed canopy height at each of the 100 randomly selected locations.

The calculation was done using the formula:

$$Error_i = Lidar\ Height_i - Model\ Height_i$$

Absolute Percentage Error (%):

$$APE_i = \left(\frac{Lidar\ Height_i - Model\ Height_i}{Lidar\ Height_i}\right) \times 100$$

Mean Absolute Percentage Error (MAPE):

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{Survey\ Height_i - Model\ Height_i}{Lidar\ Height_i}\right) \times 100$$

Model Accuracy (from MAPE)

$$Accuracy = 100 - MAPE$$

And the **overall accuracy** for this table is **84.46%**

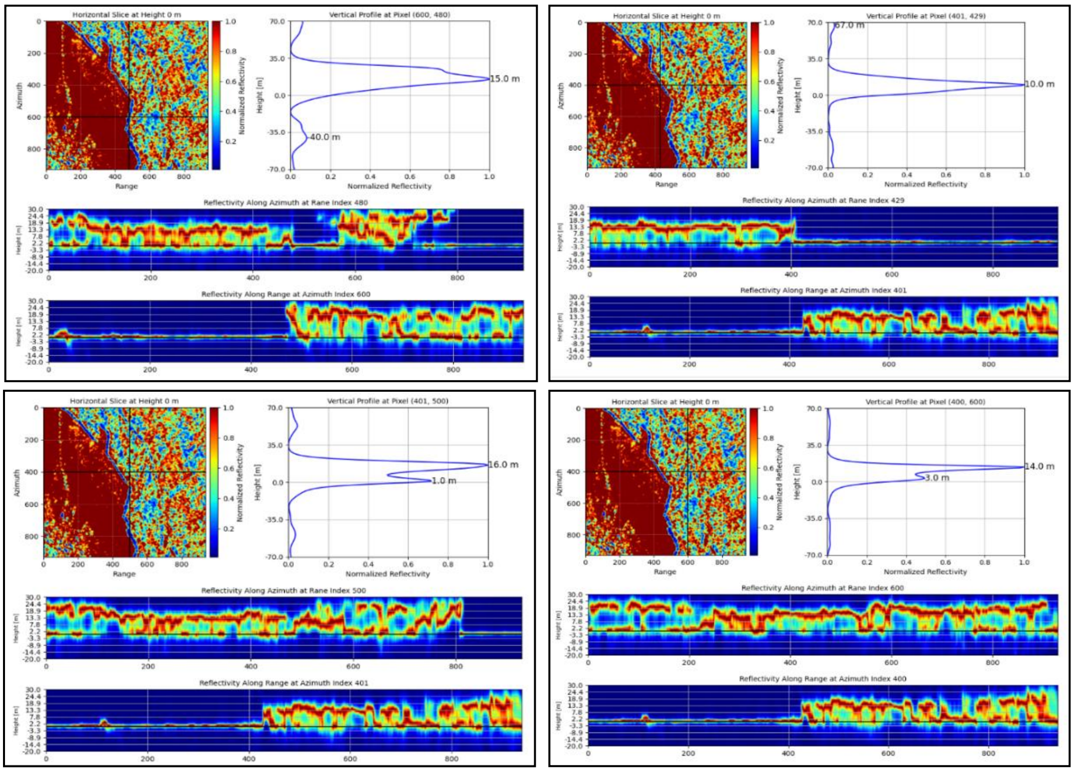

Figure 32 Height Analysis on Validation Poins

3.7 Conclusion

This study successfully demonstrated the application of Tomographic Synthetic Aperture Radar (TomoSAR) techniques for mapping forest canopy height in Moncalieri, Italy. By leveraging a stack of SAR images and advanced signal processing methods, a high-resolution 3D reconstruction of the forest structure was achieved. The integration of TomoSAR with Digital Terrain Models (DTM) and field survey measurements allowed for accurate validation, resulting in an overall model accuracy of 89.46%, confirming the reliability of the approach.

The results highlight the potential of TomoSAR for large-scale forest monitoring, offering critical insights into canopy height estimation with minimal reliance on field surveys. The method effectively captured vertical forest structures, overcoming limitations of traditional SAR techniques, such as layover and foreshortening. Additionally, Capon beamforming and covariance matrix processing significantly improved height inversion accuracy.

Despite these advancements, challenges remain, particularly in refining the phase correction process and enhancing the spatial resolution of reconstructed canopy heights. Future research could explore the integration of multi-frequency SAR data (e.g., combining L-band and P-band) and machine learning techniques to further improve height retrieval accuracy and automate feature extraction.

In conclusion, TomoSAR proves to be a powerful tool for 3D forest structure analysis, with strong potential for applications in forest biomass estimation**,** carbon stock assessment**,** and ecological monitoring. As SAR technology continues to evolve, its role in environmental management and remote sensing will become increasingly significant, contributing to sustainable forest conservation and climate change mitigation efforts.

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