Chapter 2
Literature Review

Over the past 10 years, the number of research activities in the field of radar remote sensing has increased considerably. To identify the main findings regarding SAR and forestry, a comprehensive review of the literature was conducted focusing on different SAR techniques and fusion of SAR information. Then, on the basis of the literature findings, the current issues in this regard were identified and the scope of this thesis was defined.

This chapter presents the literature review for this thesis and its objectives. The first section focuses on the remote sensing of temperate forests using SAR technology. This section particularly reviews the SAR backscatter intensity and SAR interferometry (InSAR), SAR polarimetry (PolSAR), polarimetric SAR interferometry (PolInSAR) and SAR tomography techniques. The second section deals with the methods applied for the fusion of SAR information from temperate forests. In this respect, the various approaches to combining SAR information are reviewed. The main objective of the present thesis is the estimation of *GSV* in temperate forests using SAR satellite imagery. The literature review focuses on temperate forests. However, some reports on boreal or tropical forests are also discussed to a lesser extent because these studies were also relevant to the assessment of SAR sensitivity in temperate forests. The reports on landcover or forest mapping are not always mentioned, and the fusion section reviews studies which focus on SAR information. After describing the literature findings, the last section of this chapter discusses the current issues identified from this literature review and introduces the objectives of this thesis.

2.1 SAR Remote Sensing of Forests

2.1.1 SAR Intensity

Radar remote sensing of forest biomass has been a domain of research since the early days of civilian imaging radar in the 1960s and the launch of the first SAR

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satellite Seasat in the 1970s (Leckie and Ranson 1998). The research activities in radar systems for forestry applications are attributed to the fact that radar microwaves are unaffected by weather conditions (Ulaby 1981; Imhoff et al. 1986; van der Sanden 1997) and solar illumination and are sensitive to the structure of the canopies (Imhoff et al. 1986). These capabilities together with the widespread use of and continuous surveys provided by spaceborne platforms make radar systems one of the primary domains of research in remote sensing for the estimation of forest biomass over a wide range of regions (Bergen et al. 1997).

2.1.1.1 SAR Parameters

Initially, investigations of radar imagery focused on gaining an understanding of the physical interactions between radar microwaves and forest canopies (Henderson and Lewis 1998). In particular, the microwave backscatter at different radar frequencies was considered. The examinations of conifer or broad-leaved forests mainly led to the same conclusions, i.e., there was a significant correlation between forest biomass and backscatter ($R^2 = 0.80 - 0.90$) at low radar frequencies (L-band, P-band) and poor correlation ($R^2 = 0.1 - 0.30$) with high-frequency systems (X-band, C-band) (Le Toan et al. 1992; Beaudoin et al. 1994; Rauste et al. 1994; Kasischke et al. 1995). Some researchers such as Imhoff (1995b) or Le Toan et al. (1992) analysed the relevant scattering mechanisms occurring at different frequencies and pointed out the limitations of different active systems. They showed that shorter wavelengths such as X-band and C-band are primarily scattered in forests by small components, typically foliage, twigs and branches of upper canopies. On the other hand, they indicated that the longer wavelengths (L-band and P-band) penetrate the canopy and are scattered by large elements such as branches and trunks, which constitute a major part of biomass. The analysis of P-band data presented a good correlation ($R^2 = 0.90$) between radar backscatter intensity and the main forest properties, including trunk biomass, age, basal area, diameter at breast height (*DBH*) and height (Le Toan et al. 1992; Mougin et al. 1999; Sandberg et al. 2011). Despite the improved correlation between low radar frequency and forest biomass, several studies showed that low biomass levels are also well correlated to short radar microwaves. This observation was highlighted in Wang et al. (1998), da Yanasse et al. (1997) among other studies, both of which concentrated on the correlation of C-band data to forest biomass and demonstrated the potential of this frequency band in the retrieval of biomass in early successional stages. With the penetration of short wavelengths being limited to the upper part of forest canopies, Hoekman and Varekamp (2001) also showed the potential of these wavelengths in the estimation of other forest biophysical parameters such as the forest canopy cover. In a tropical forest, it was possible to use the C-band to identify deforested areas as well as primary and secondary forests. Also, with respect to canopy cover, Natale et al. (2012) recently proposed a prospective study for future S-band missions, which involve the comparison of S-band and X-band data over a temperate forest. The researchers highlighted the higher performance of the S-band compared with the X-band in monitoring the canopy cover. Because longer wavelengths provide a better correlation between forest biomass and radar microwaves, some researchers have examined very high frequency (VHF) radar systems. For example, experiments employing the CARABAS VHF system have shown promising results (Fransson et al. 2000; Israelsson et al. 1997; Walter 1997). However, according to Goriachkin and Klovsky (1999), the exploitation of longer wavelengths such as P-band and VHF from space introduces new major technical difficulties (i.e. interference with other microwave sources, absorption of signals in the ionosphere), which limit the capabilities of a potential P-band or VHF future spaceborne sensor.

While investigating radar frequencies, researchers also noted the potential of using different microwave polarisations. For example, Le Toan et al. (1992), Dobson et al. (1992), Sader and Wu (1987) and Hussin et al. (1991) found that cross-polarisations (e.g. HV or VH polarisation) are more sensitive to forest canopies than like-polarisations (e.g. HH or VV polarisation). To support these observations, Beaudoin et al. (1994) developed a theoretical model for P-band backscatter. This study showed that cross-polarisation ($R^2 = 0.90$) is better correlated to forest biomass than like-polarisation ($R^2 = 0.75 - 0.85$). Moreover, the study demonstrated that HV backscatter is weakly sensitive to terrain conditions (soil moisture, roughness or local slopes) and HH polarisation is mostly returned as multiple trunk–ground interactions. Other researchers confirmed high direct surface scattering in HH or VV polarisation, especially under wet weather conditions (Ranson and Sun 2000; Balzter et al. 2002; Santoro et al. 2006). By comparing like-polarisations, many researchers have noticed dissimilarities between HH and VV. It was generally observed that HH polarisation presents higher backscatter than VV polarisation. This difference was related to several phenomena such as dihedrals (Dobson et al. 1992; Watanabe et al. 2006) or canopy absorption (van Zyl 1993; Santoro et al. 2009).

Because SAR remote sensing systems operate in the side-looking direction, scientists investigated the influence of varying look angles on backscatter intensity. With the help of simulations, researchers showed that backscatter generally decreases with increasing incidence angle (Sun et al. 1991; Westman and Paris 1987; Engheta and Elachi 1982). This trend could be verified using airborne and spaceborne SAR experiments (Magagi and Bernier 2002; Moghaddam and Saatchi 1993; Alasalmi et al. 1998; Rauste 1990; Ardila et al. 2010), which particularly highlight the importance of forest structure (i.e. density, canopy height, and branching structure) (Beaudoin et al. 1994; Imhoff et al. 2000) and ground layer characteristics (i.e. surface roughness and moisture) (Ardila et al. 2010; Westman and Paris 1987). In forested areas, it was especially noted that ground interactions were higher at steep incidence ($\theta = 20° - 30°$) angles, while canopy interactions were greater at shallow incidence angles ($\theta = 40° - 50°$) (Magagi and Bernier 2002; Rauste 1990; Sun et al. 1991; Westman and Paris 1987). On the basis of the considered frequency and polarisation, this observation suggested an increase in trunk–ground dihedrals with steep incidence angles (Rauste 1990; Sun et al. 1991; Westman and Paris 1987; Moghaddam and Saatchi 1993) and better sensitivity of SAR to biomass with the use of large incidence angles (Beaudoin et al. 1994).

From an analysis of the relationship between SAR backscatter intensity and biomass, it was found that the intensity generally increased with increasing biomass

Table 2.1 Saturation levels reported in literature for SAR backscatter intensity

Biome	Frequency	Saturation limit ($m^3 h^{-1}$)	Researchers(s)
Temperate	C	10–160	Imhoff (1995b), Rauste et al. (1994), Ranson and Guoqing (1994) and Wang et al. (1994)
	L	65–160	Dobson et al. (1992), He et al. (2012), Imhoff (1995b) and Rauste et al. (1994)
	P	>160–700	Dobson et al. (1992), Imhoff (1995b), Rauste et al. (1994) and Ranson and Guoqing (1994)
	VHF	>900	Melon et al. (2001)
Boreal	C	64	Fransson and Israelsson (1999)
	L	143	Fransson and Israelsson (1999)
	VHF	>550–625	Fransson et al. (2000), Imhoff (1995a) and Smith and Ulander (2000)
Tropical	C	30	Imhoff (1995a)
	L	65–160	de Araujo et al. (1999), Imhoff (1995a), Luckman (1997) and Rignot et al. (1997)
	P	>160	Imhoff (1995a)

When necessary, the density factor of 1.6 was considered to convert $t\,ha^{-1}$ to $m^3\,ha^{-1}$

until it reached a saturation level (Le Toan et al. 1992; Kasischke et al. 1995; Imhoff 1995b). The saturation of the SAR signal constitutes an important issue in the field of forest biomass estimation using radar data (Kasischke et al. 1997; Imhoff 1995a). Many previous studies attempted to define the saturation level and understand the different parameters contributing to the same (see Table 2.1). The values were reported either in $t\,ha^{-1}$ for dry biomass or $m^3\,ha^{-1}$ for stem volume (see Chap. 3 for the unit conversion).

As a rule, it was found that the saturation level increased at lower frequencies (e.g. L- and P-band) (Fransson and Israelsson 1999; Imhoff 1995b). Experimental analyses using the airborne NASA/JPL AIRSAR system over temperate and tropical forests indicated a saturation at 20, 40 and 100 $t\,ha^{-1}$ for C-, L- and P-bands, respectively (Imhoff 1995b). Other studies agreed on the limit of 10–160 $m^3\,ha^{-1}$ in C-band, 65–60 $m^3\,ha^{-1}$ in L-band and 160–700 $m^3\,ha^{-1}$ at P-band frequencies (see Table 2.1). In P-band, cases with no saturation were also reported (Rauste et al. 1994; Ranson and Guoqing 1994). The relative rapid saturation obtained at high frequency (small wavelength) was attributed to the large amount of foliage, twigs and small branches at the top of canopies, which considerably attenuated the signal. On the other hand, the saturation observed in L-band was primarily related to the smaller number of scatterers (large branches and trunk), which attenuated the EM microwaves to a lesser extent when compared with high-frequency systems (Le Toan et al. 1992). Consequently, by comparing the frequencies, it was finally noted that VHF sensors (Fransson et al. 2000; Melon et al. 2001; Smith and Ulander 2000) were the SAR systems which were affected to a lesser extent by the saturation effect.

In addition to the SAR frequency, the saturation point was investigated with various polarisations and incidence angles. For example, Watanabe et al. (2006) found that cross-polarised backscatter delays the saturation point to higher biomass level compared to like-polarisations, and Lu (2006) observed that a shallow incidence angle increased the saturation level, especially in low-frequency systems. It was shown that radar sensor configurations determined the biomass saturation level. However, as the forest structure influences the scattering mechanisms occurring in forests, numerous studies have also shown that the saturation level is site-dependent (Lu 2006).

The analysis of forest texture has been extensively investigated using optical remote sensing systems (Woodcock and Strahler 1987; Sarker and Nichol 2011; Kayitakire et al. 2006). With the development of high-resolution SAR sensors over the past decade, estimation of forest parameters using textures has attracted considerable research attention (Fukuda 2008; Wang et al. 2006). The most popular textural information refers to the gray level co-occurrence matrix (GLCM) defined by Haralick during the 1970s (Haralick et al. 1973). The publications dealing with the GLCM and forests mainly focused on tropical forests (Luckman et al. 1994, 1997; Oliver 2000), and, in particular, two studies demonstrated the potential of the Haralick parameters in improving the estimation of biomass in the tropics (Kuplich et al. 2005; Sarker et al. 2012). GLCM textures were also distinguished in boreal and temperate biomes for land classifications (Ulaby et al. 1986; Kurosu et al. 1999; Kurvonen and Hallikainen 1999) and retrieval of forest parameters (Weishampel et al. 1994; Champion et al. 2008) such as biomass (Champion et al. 2011; Kurvonen and Hallikainen 1999). One important issue in the examination of texture is the different scales of forest spatial patterns (Barros Filho and Sobreira 2008). To deal with the multiscalar textural property of a forest, researchers considered the concept of lacunarity ('gapiness' in Latin). This approach was initially described by Mandelbrot in 1983 and was subsequently further developed by Allain and Cloitre using the gliding box algorithm (Allain and Cloitre 1991; Plotnick et al. 1996). Lacunarity was investigated by a few studies which estimated forest parameters. However, only one of them was directly related to SAR imagery and temperate forests (Sun and Ranson 1998). The remaining studies mostly dealt with optical sensors and tropical forests (Malhi and Román-Cuesta 2008; Peralta and Mather 2000; Weishampel et al. 2001) or SAR sensors and landscape analysis (Plotnick et al. 1993; Hoechstetter et al. 2011; Henebry and Kux 1995; Kux and Henebry 1994; Mcintyre and Wiens 2000). In addition to the GLCM and lacunarity texture approaches, other methods were developed for investigating spatial patterns. A non-exhaustive list can be found in Kandaswamy et al. (2005) or Sarker and Nichol (2011).

2.1.1.2 Forest Properties

Realizing forest biomass estimation from SAR remote sensing systems requires thorough knowledge of radar principles and a very deep understanding of the forests and their environment. In this framework, many researchers sought to comprehend forest structural properties and their relationship with SAR backscatter (Beaudoin et al. 1994; Imhoff 1995a; Mougin et al. 1999; Kasischke et al. 1997; Ferrazzoli and Guerriero 1995). Considering forest structure, researchers often distinguished between three different classes, namely horizontal, vertical and branching structures (Spies 1998; Ferris and Humphrey 1999). The horizontal structure mostly referred to the basal area or stem density, the vertical structure concerned forest height or understory and the branching structure was denoted by the size shape or orientation of the branches and leaves at the canopy level (Kasischke and Christensen 1990; Wang et al. 1993; Mcdonald and Ulaby 1993).

First, with reference to the branching structure, to understand the complex relationship between radar backscatter and structural parameters of canopies, theoretical and semi-empirical models were developed. For example, Yueh et al. (1992) introduced a branching model which describes the backscatter of a soybean plant with its internal structure and the resulting clustering effects. This model was further used for modelling forest backscatter by combining it with the radiative transfer (RT) theory (Beaudoin et al. 1994; Hsu et al. 1994). In another example, Ferrazzoli and Guerriero (1995) focused on a physical model which relates geometrical tree properties such as the size of branches and their orientation with the backscattering coefficient. In this case, (1) deciduous leaves were represented by discs, (2) coniferous needles by thin cylinders and (3) branches and trunks by large cylinders. In general, the modelling of canopy structures confirmed the assumptions that tree morphological parameters have a significant impact on radar response (Mougin et al. 1993; Neumann et al. 2012).

As for the horizontal structure, researchers reported a significant contribution of the basal area and forest density parameters to the backscatter intensity (Brolly and Woodhouse 2012; Woodhouse 2006). For example, Dobson et al. (1995) observed that for equal biomass levels, there were clear variations between the backscatter responses of large, sparse forests and dense, young forests. More recently, Brolly and Woodhouse (2012) represented the forest as a collection of cylinders, which was therefore named ‘matchsticks’. Using the matchstick modelling approach, the researchers demonstrated that backscatter is not only sensitive to the quantity of biomass but also to the density and distribution of trees. On the basis of these findings, Woodhouse (2006) showed that backscatter intensity should increase until it reached an apparent saturation point, and then decrease with increasing quantities of biomass after the saturation level. These results, which were based on macroecology considerations, should provide further explanations regarding the unusual observations conducted by Rauste et al. (1994) in a conifer forest in Germany or by Ranson and Guoqing (1994) in a Northern mixed forest in Maine. They also highlight the differences between natural and managed forests and the importance of considering thinning and other forest-management activities in the implementation of a biomass-estimation methodology (Champion et al. 1998; Kuplich et al. 2000; Le Toan et al. 1992).

Among the vertical structural parameters of a temperate forest, forest height has been the subject of numerous studies. The height attribute was investigated using mainly InSAR or more advanced SAR techniques (discussed later in this section), although it potentially affects forest backscatter. At low frequencies, the vegetation beneath the forest canopy can be a source of considerable variability. However, this contribution has been discussed by few studies (Chauhan et al. 1991; Pulliainen et al. 1994; Silva and Dias 1996; Wang et al. 1998). For example, Wang et al. (1998) examined the backscatter variations induced by changes in forest floor properties. These studies reported the non-negligible contribution of the forest understory at the L-band frequency irrespective of the use of HH or VV polarisation. They also noted a decline in forest floor backscatter with increasing stem volume. At C-band frequencies, the same researchers showed that the forest floor contribution was significant for only steep incidence angles. A few studies have discussed the influence of forest understories on scattering mechanisms at the ground level. In particular for L-band data, it has been assumed that trunk–ground and crown–ground double bounces are significantly reduced owing to the attenuation of the canopy and roughness of the forest understory (Pulliainen et al. 1999; Karam et al. 1992; Santoro et al. 2006).

2.1.1.3 Forest Environmental Conditions

The environmental conditions in a forest affect radar backscatter and determine the growth properties of trees. In this context, several studies were conducted to highlight the effects of changing forest weather conditions on SAR backscatter intensity (Way et al. 1990; Rignot et al. 1994; Pulliainen et al. 1996). Bergen et al. (1997) focused on the influence of rainy precipitations on forest backscatter intensity. They showed that the amplitude of the signal generally increased with precipitation, especially at C-band frequencies, when compared with the case at L-band frequencies. Other researchers concentrated on soil humidity in forests. Wang et al. (1994) reported that at C-band frequencies, there was an increase in backscatter with increasing soil humidity. Simulations conducted to interpret these observations also showed that the increase in soil humidity for a biomass quantity extending between 40 t ha^{-1} and 100 t ha^{-1} was mainly presented as surface scattering. However, for a biomass quantity of greater than 130 t ha^{-1}, the effect of soil humidity was found to be insignificant, and volume scattering from canopies was the main contribution to the total backscatter. These variations in soil and vegetation humidity generally affected the backscatter dynamic range and reduced its sensitivity to the biomass quantity (Salas et al. 2002; Cartus et al. 2012). By considering winter radar measurements, some researchers examined the impact of snow on forest SAR backscatter. Dry snow cover was found to have an insignificant effect on C-band and L-band backscatter (Alasalmi et al. 1998). However, with the melting of snow, the variations in the dielectric properties of the snow led to an increase in the backscatter intensity (Santoro 2003; Arslan et al. 2006) and variations in the SAR signal at both C-band (Koskinen et al. 2010; Santoro et al. 2011) and L-band (Santoro et al. 2006) frequencies. The consideration of snow cover over forested areas at X-band frequencies is restricted to only a few studies. The first experiment was conducted using the HUTSCAT scatterometer over a boreal forest (Hallikainen et al. 1997). This study showed that ground backscatter contribution was dominant for dry snow, while tree canopy backscatter was the most significant factor under wet-snow or snow-free conditions.

The environmental conditions in both temperate and boreal forests change considerably within seasons. During summer, water is present in the form of liquid; however, during winter, the temperatures at high latitudes decrease leading to frozen conditions, which produce observations different from the aforementioned ones. Thiel et al. (2009) recently reported contrasting results between winter and summer intensities at L-band frequencies. They noted a decrease in backscatter during winter and showed that the environmental conditions were much more stable during winter (Ni et al. 2011) when compared with those during summer. The decrease in backscatter during winter was found to be related to the dielectric properties of the forest floor and forest canopy (Rignot et al. 1994; Way et al. 1990). Santoro et al. (2011) investigated the sensitivity of stem volume to radar backscatter at C-band frequencies. They pointed out that under frozen conditions, the attenuation of microwaves in canopies decreased and the sensitivity of SAR backscatter to biomass quantity improved because the C-band microwaves were mostly sensitive to the trees' main components (i.e. trunk and branches in the canopy). The results reported by Santoro et al. (2006) showed that unfrozen conditions were most suitable for estimating biomass quantity at L-band frequencies. This was explained by the greater sensitivity of L-band microwaves to forest features (e.g. branches and stems) with an unfrozen canopy.

In addition, while examining the temperature conditions in forested areas, researchers often refer to a diurnal freezing/thaw cycle. According to Kimball et al. (2004), this cycle appears in autumn or during spring, namely when the air temperatures alternate between frozen and unfrozen conditions during night and day time, respectively. Under frozen conditions, the dielectric constant of trees decreases; also, sapflow ceases and the water content of the trees reduces. However, when the air temperature during day time again rises above the freezing point, the dielectric constant increases, and with the reactivation of sapflow, the water content of trees also increases (Way et al. 1990; Kidd and Scipal 2003). As radar microwaves are sensitive to water, the diurnally changing water content and dielectric constant of trees influence the radar backscatter intensity signal and may have an impact on the estimation of biomass quantity. The effects of diurnal variations from the trunk and canopy water status on radar backscatter have been examined by several studies (Way et al. 1990; Kidd and Scipal 2003; Bartsch et al. 2006; Kimball et al. 2004; Schmullius 1997; Rignot and Way 1991). Owing to the daily repetition of the freeze/thaw effect, most of the researchers considered scatterometer evaluations instead of SAR measurements. Scatterometers can provide high-resolution temporal data when compared with those provided by SAR sensors. The results of these studies showed a consistent relationship between backscatter intensity and freeze/thaw diurnal cycles. However, it is noted that none of these studies presented the impact of the freeze-thaw cycles with varying water content statuses on the estimation of biomass quantity.

Topography accounts for significant variations in forest radar backscatter (Beaudoin et al. 1995; Holecz et al. 1995; Tanase et al. 2011; Park et al. 2012). These variations are due to different phenomena such as modification of the ground illuminated area, change in the incidence angle and modification of dominant scattering mechanisms. To deal with these topographic issues, studies have proposed various approaches, which range from simple cosine corrections (Hinse et al. 1988; Bayer et al. 1991; Leclerc et al. 2001; Rees and Steel 2001; Soja et al. 2010; Zhou et al. 2011) or images ratio to more rigorous methods (Ranson and Saatchi 1995; Ranson et al. 2001; Wever and Bodechtel 1998) based on the digital elevation model (DEM) (Small et al. 1997; Loew and Mauser 2007). The ground illumination area has the greatest impact on the backscatter intensity (Holecz et al. 1995). To correct this effect, Ulander (1996) suggested a correction based on the projection angle ψ evaluated from the DEM. Small et al. (1997) introduced the possibility of integrating the SAR scattering areas under DEM slope 'facets'. He further developed this approach in 2004 (Small and Meier 2004) and 2009 (Small et al. 2009) and summarised it recently in 2011 (Small 2011). This approach was tested and compared with the projection-angle approach by Frey et al. (2013) and was reported to be very effective, particularly in layover areas. The relationship between topographic variations and forest canopies remain under investigation. The potential effects of an undulated terrain on the nature of scattering mechanisms were reported in the 1990s (van Zyl 1993; Israelsson and Askne 1993; Amar et al. 1993). For instance, van Zyl (1993) showed that ground–trunk double reflections are a major contribution at P-band frequencies. However, in the presence of a slope gradient, the nature of the dominant scattering changed because of the new angle formed between the vertical extended trunks and the surface local slope. More recently, Castel et al. (2001b) suggested a semi-empirical correction for L-band or C-band frequencies, which takes the changing path length of the microwaves through the canopy into account. The results showed that the correction for the canopy optical path length improves the normalisation of the backscatter in hilly areas. SAR backscatter may be affected in a different way by the abovementioned topographic effects. In fact, the topography determines several abiotic factors such as solar radiation, water availability or wind direction, which directly influence the growth conditions of a forest (Luckman 1998; Williamson 1975; Kellogg and Arber 1981; Telewski 1995; Watt et al. 2004) and possibly lead to systematic trends in the backscatter intensity (Luckman 1998). To date, the relationship between forest backscatter and physiological effects related to the topography of a forest have been barely discussed. In most cases, these effects have been neglected by assuming that the forested areas are homogeneous.

2.1.1.4 Modelling Techniques

The modelling of biomass and the forest parameters related with SAR remote sensing systems has been the subject of numerous studies over the past few decades. These studies were based on different approaches (Saatchi et al. 2007; Martinez et al. 2000; Arslan et al. 2000; Castel et al. 2002; Svoray and Shoshany 2002).

The most common approach is empirical regression, which was mainly used to investigate the relationship between the SAR information (i.e. backscatter intensity) and the ground-measured biophysical parameters (Le Toan et al. 1992). For the most part, the studies which presented regression analyses dealt with nonlinear

Table 2.2 Summary of the main models and techniques for the backscatter

Approach	Model	Researchers(s)
Empirical regression	Linear	Dobson et al. (1992) and Hussin et al. (1991)
	Multiple linear	Harrell et al. (1997), Luckman (1997) and Ranson and Sun (1997)
	Non-linear	Balzter et al. (2003b), Magnusson et al. (2007), Morel et al. (2011) and Tsolmon et al. (2002)
Theoretical modeling	MIMICS (RT)	Mcdonald et al. (1990) and Ulaby et al. (1990)
	Santa Barbara (RT)	Wang et al. (1993, 1994)
	AMAP (RT)	Castel et al. (2001a)
	MIT/CESBIO (RT)	Hsu (1996)
	WBE (RT)	Brolly and Woodhouse (2013), West et al. (1999) and Woodhouse (2006)
	Branching (RT)	Yueh et al. (1992)
	Full wave (DBA)	Angot et al. (2002), Bellez et al. (2009), Israelsson et al. (2000), Oh and Sarabandi (2002), Nguyen et al. (2006) and Ziade et al. (2008)
Semi-empirical regression	WCM (RT)	Askne et al. (1995, 2003), Attema and Ulaby (1978), Cartus et al. (2012), Fransson and Israelsson (1999), Kurvonen and Hallikainen (1999), Martinez et al. (2000), Pulliainen et al. (1994), Richards (1990) and Santoro et al. (2003a, 2004, 2010)
Non-parametric	ANN	Benediktsson and Sveinsson (1997), Del Frate and Solimini (2004), Kimes et al. (1997) and Wang and Dong (1997)
	k-NNN	Guo et al. (2011) and Holopainen et al. (2009)

models as the biomass quantity was found to be non-linearly related to backscatter (Balzter et al. 2003b; Magnusson et al. 2007; Tsolmon et al. 2002; Morel et al. 2011). However, linear trends were also reported between forest parameters and SAR backscatter, motivating the use of simple (Dobson et al. 1992; Hussin et al. 1991) and multiple (Harrell et al. 1997; Luckman 1997; Ranson and Sun 1997) linear regressions (Table 2.2).

Another approach relied on the physics of scattering processes. This approach was essentially considered for describing and understanding forest backscatter. Many scattering models have been cited in previous studies and were essentially classified as RT and distorted born approximation (DBA) approaches (Le Toan et al. 2002). The RT approach is based on energy conservation and relies only on incoherent modelling techniques. Of the RT models, either the Michigan Microwave Canopy Scattering Model (MIMICS) (Ulaby et al. 1990; Mcdonald et al. 1990), Santa Barbara microwave model (Wang et al. 1993, 1994) or the model proposed by Karam et al. (1992) may be cited. Each of these models has specific characteristics such as continued multilayers (Ulaby et al. 1990), discontinued multilayers (Sun et al. 1991; Mcdonald and Ulaby 1993) or second-order scattering. Although the aforementioned models were shown to validate the empirical observations (Moghaddam and Saatchi 1993; Imhoff 1995a; Romshoo and Shimada 2001), they only briefly discussed the structural properties of trees' canopies. In this respect, Hsu (1996) contributed with the MIT/CESBIO model structural effects by considering the branching model Yueh et al. (1992) and Castel et al. (2001a) introduced the AMAP model and Woodhouse (2006) and Brolly and Woodhouse (2013) presented a modelling approach based on the coupling of the RT theory and a macroecological model (West et al. 1999). The DBA approach was less popular than the RT approach. However, contrary to the RT models, it has the advantage of dependence on electromagnetic waves, thus allowing the coherent modelling of vegetation parameters (Le Toan et al. 2002). The radar modelling of red pine proposed by Lang et al. (1994) and the modelling assessment of the coherent effects for forest canopies given by Saatchi and McDonald (1997) provide two examples of the DBA models. Owing to the great concern regarding the retrieval of biomass quantity by low-frequency systems (Le Toan et al. 2012), and the limited ability of RT models to account for multiple reflections, there has been renewed interest in improving DBA models (Nguyen et al. 2006; Oh and Sarabandi 2002; Bellez et al. 2009; Ziade et al. 2008; Israelsson et al. 2000; Angot et al. 2002). For example, Bellez et al. (2009) applied a coherent 'full wave' simulation of forested areas and successfully modelled the main forest scattering mechanisms, including multiple reflections, using the method of moments (MoM).

Empirical models can be easily inversed, but they are also very site-dependent, while physical models can provide accurate estimations but often require a large number of unknown parameters (Martinez et al. 2000; Castel et al. 2002). To combine the benefits of both these modelling approaches, a third approach applying semi-empirical models has been the subject of discussions. The most common semi-empirical model is the water cloud model (WCM), which was developed by Attema and Ulaby (Attema and Ulaby 1978). This model is based on the RT theory and describes a forest as a single homogenous layer comprising cloud droplets which attenuate the radar signal (Martinez et al. 2000; Richards 1990; Santoro et al. 2003a, 2004; Fransson and Israelsson 1999; Kurvonen and Hallikainen 1999; Askne et al. 2003). The main strength of the WCM is its simplicity, which allows a straightforward inversion of the model and prediction of forest biomass quantity (Woodhouse 2006). However, the WCM also presents some limits. For example, it does not consider forest structures and high-order scattering such as dihedrals (Cartus et al. 2012). In this regard, some studies have presented extended versions of the WCM. For instance, Askne et al. (1995) modified the WCM by introducing a variable which accounts for vertical and horizontal discontinuities (gaps). Pulliainen et al. (1994) replaced the area-fill factor by *GSV*, which is more common in the field of forestry. Taking into consideration the updated versions of the WCM, some recent studies such as Santoro et al. (2010) and Cartus et al. (2012) successfully applied the WCM to large-scale forest biomass estimations. Besides the WCM model, some researchers proposed semi-empirical models which considered specific forest conditions. For example, Arslan et al. (2000) proposed a backscattering model which incorporates forest stem volume and snow water equivalent, while Kurvonen and Hallikainen (1999) implemented a semi-empirical model based on stem volume and soil moisture.

Finally, non-parametric machine learning algorithms was applied by studies for the estimation of a forest's biophysical parameters. This approach employing algorithms such as artificial neural networks (ANNs) and k-nearest neighbour (k-NN) have been widely applied to landcover classifications and biomass estimations based on optical data (Franco-Lopez et al. 2001; McRoberts et al. 2007; Baffetta et al. 2009; Tomppo 2004; Tomppo et al. 2008, 2009). The non-parametric processing techniques present a major advantage when compared to the aforementioned approaches; they generally require no prior knowledge about the data distribution (Mas and Flores 2008; McRoberts et al. 2007). Despite this advantage and the numerous investigations undertaken with optical sensors, there are few studies employing such techniques for radar remote sensing in the field of forestry. Several researchers have tested the retrieval of forest parameters using ANNs (Del Frate and Solimini 2004; Kimes et al. 1997; Wang and Dong 1997; Benediktsson and Sveinsson 1997), while others have focused on the k-NN algorithm using combined SAR and optical (Holmström and Fransson 2003) or light detection and ranging (LiDAR) data (Tian et al. 2012). To date, only two studies based on SAR data (Holopainen et al. 2009; Guo et al. 2011) have involved the examination of k-NN for the assessment of forest parameters.

2.1.1.5 Estimation Accuracy

Taking into account the capability of SAR systems in retrieving biomass, several studies have shown the accuracy of the models. To do so, researchers generally applied the root-mean-square error (*RMSE*) or the relative *RMSE* (*rRMSE*) for comparing different test sites. The achieved accuracy depended primarily on the SAR system configuration, the forest properties environmental conditions and the modelling technique. An accuracy of approximately 20 % was considered to be reasonable for envisaging the application of SAR systems to forestry. The estimated *RMSE* differed between the studies. Using the Japanese Earth resources satellite (JERS-1) L-band data, Santoro (2003) found an *rRMSE* of 30–50 % and 40–60 % with and without multitemporal retrieval in a boreal forest, respectively. The variations were attributed to weather conditions. In this respect, Santoro showed that an accuracy of 20–25 % can be achieved (Santoro et al. 2003a, 2006) by considering dry and unfrozen conditions as well as a multitemporal approach. Similar results were obtained by Sandberg et al. (2011) and Magnusson et al. (2007) with ALOS PALSAR data. The best accuracy obtained with L-band backscatter was reported by Cartus et al. (2012), who recently showed that an *RMSE* of 12.9 t ha^{-1} can be obtained with PALSAR data. At P-band and VHF-band frequencies, the ranges of errors were 20–30 % (40–60 t ha^{-1}) (Soja et al. 2010, 2013; Sandberg et al. 2011) and 15–20 % (50–65 m^3 ha^{-1}) (Fransson et al. 2000; Smith and Ulander 2000; Folkesson et al. 2008), respectively. The higher relative accuracies given by low-frequency sensors when compared with high-frequency sensors were mostly explained by their subsequent saturation in high biomass ranges (Castel et al. 2002; Saatchi et al. 2007).

2.1.2 *SAR Interferometry*

The potential of InSAR in retrieving forest parameters was introduced in the mid-1990s. Mainly, two different topics were discussed, namely sensitivity of forest variables to interferometric coherence and derivation of interferometric forest height.

2.1.2.1 InSAR Coherence

The first investigations referring to interferometric coherence were given by Zebker and Villasenor, who observed temporal decorrelations over forested areas with an L-band 17-day repeat-pass Seasat sensor (Zebker and Villasenor 1992). C-band phase correlation properties were subsequently examined a few years later using the the first European remote sensing satellite (ERS-1) 35 days repeat-pass data. In particular, Askne et al. (1997) highlighted the main decorrelation mechanisms, and Floury et al. (1996) and Beaudoin et al. (1996) showed the relationship between coherence and forest biomass. The latter two studies clearly depicted a decrease in coherence with an increase in stand age and bole volume, respectively. This trend was also presented in different subsequent studies (Smith et al. 1998; Santoro et al. 1999). Luckman (1997) and Luckman et al. (2000) were among the first to compare ERS-1/2 tandem data (Smith et al. 1998; Koskinen et al. 2001; Santoro et al. 2002) and L-band 44-day repeat-pass JERS-1 (Eriksson et al. 2002, 2003; Cartus et al. 2005), respectively, using forest biomass. These studies depicted a monotonic decrease in coherence with increasing vegetation cover and a stronger correlation with coherence than with backscatter intensity. Subsequent studies on ERS-1/2 tandem and JERS-1 coherence confirmed the observed trends. Among these, some studies examined the saturation level obtained with coherence (see Table 2.3). It was generally observed that with C-band 1-day repeat-pass data, the coherence in some cases reached a saturation between 100 and 400 $m^3\,ha^{-1}$, while no saturation was observed in other cases. For example, Castel et al. (2000) reported no saturation in a coniferous forest in Southern France up to 400 $m^3\,ha^{-1}$, while Santoro et al. (2002) reported a saturation at 350 $m^3\,ha^{-1}$ for a hemiboreal forest located in Sweden. With regard to L-band systems, a limited number of studies were performed. Eriksson et al. (2003) and Luckman et al. (2000) reported saturation levels at 100–130 $m^3\,ha^{-1}$ and 150 $m^3\,ha^{-1}$, respectively, for JERS-1 44 days repeat-pass system. More recently, Thiel and Schmullius (2012) reported a saturation at around 100 $m^3\,ha^{-1}$ for ALOS PALSAR 46-day repeat-pass system.

The wide range of saturation levels reported in literature was explained by the sensitivity of coherence to weather conditions and to the perpendicular baseline (Smith et al. 1996; Pulliainen et al. 2003; Koskinen et al. 2001; Askne et al. 2003). In terms

Table 2.3 Saturation levels reported in literature for SAR interferometric coherence

Biome	InSAR	Saturation limit ($m^3 h^{-1}$)	Researchers(s)
Temperate	ERS-1/2	>100–400	Cartus et al. (2005) and Castel et al. (2000)
Boreal	ERS-1/2	>100–400	Askne and Santoro (2007), Fransson (2001), Santoro et al. (2002), Smith et al. (1998) and Wagner et al. (2000, 2003)
	JERS-1	>100–130	Eriksson et al. (2003)
	PALSAR	100	Thiel and Schmullius (2012)
Tropical	ERS-1/2	150	Luckman et al. (2000)
	JERS-1	150	Luckman et al. (2000)

When necessary, a density factor of 1.6 was considered to convert $t\ ha^{-1}$ to $m^3\ ha^{-1}$

of spatial baseline configurations, large perpendicular baselines were usually recommended (Floury et al. 1996; Skinner et al. 2002). For example, Askne et al. (2003) and Santoro et al. (2008) suggested a normal baseline in the range 100–250 m to improve the *GSV* retrieval accuracy with ERS-1/2. Although the recent SAR spaceborne platforms allow the use of repeat pass and complete polarisation systems, a limited number of studies have discussed forest coherence signatures at different polarisations. Wegmuller et al. (1996) briefly reported differences in coherence between like- and cross-polarisations. He noted that with airborne SIR-C L-band data, coherence values for HH and VV were very close, with a slightly higher coherence for HH. However, comparing HH and HV polarisations, the researcher noted an obviously lower coherence for cross-polarisation compared to co-polarisation. More recently, Tanase et al. (2010) compared ALOS PALSAR HV and HH channels for different burn severity ranges. The coherence for HV polarisation was also found to be generally lower than that for HH polarisation. These results were very recently confirmed by Simard et al. (2012). The dependence of interferometric coherence on incidence angle has been briefly discussed by Shimada et al. (2010). The study did not report any significant variation in coherence with incidence angle. However, another study reported that an incidence angle of greater than 45° should be chosen because at this angle, spatial decorrelations due to layover and shadow over topographic areas are limited (Bamler and Hartl 1998).

2.1.2.2 Forest Properties

As for radar backscatter, it has been shown that a forest's horizontal structure can complicate the retrieval of biomass. As for interferometric coherence, the horizontal structure plays a significant role. It was reported that the forest structure may influence the coherence to a greater extent than the forest type or composition (Santoro et al. 2005). Although a few studies have noted the importance of the horizontal structure (Askne et al. 1997; Santoro et al. 2005, 2007) and included it in their modelling approaches (Askne et al. 2003; Drezet and Quegan 2006; Santoro et al. 2007), the assessment of its effect on coherence is in its preliminary stages (De Zan et al. 2013).

2.1.2.3 Forest Environmental Conditions

With respect to weather conditions, it was demonstrated that in boreal forests and for ERS-1/2 tandem data, winter interferometric acquisitions were more stable than summer acquisitions (Askne and Santoro 2007; Eriksson et al. 2002; Manninen et al. 2000; Santoro et al. 2002, 2005, 2007; Thiel et al. 2009; Koskinen et al. 2001). As for L-band data, studies investigating JERS-1 interferometric coherence reported similar results, namely more stable conditions with winter acquisitions. As an example, for JERS-1 winter coherences, Eriksson et al. (2002) and Askne et al. (2003) showed a large dynamic range and small standard deviations, which indicated promising results for the estimation of *GSV*. Among the different weather parameters affecting coherence, wind was found to be significant (Dammert et al. 1995; Smith et al. 1996; Beaudoin et al. 1996; Askne et al. 1997, 2003); soil and canopy moisture (Drezet and Quegan 2006; Luo et al. 2000) in the presence of rain (Santoro et al. 2002; Pulliainen et al. 2003; Wagner et al. 2003; Simard et al. 2012) or snow (Askne and Santoro 2005; Pulliainen et al. 2003) and temperature (Askne et al. 2003; Pulliainen et al. 2003), which modulates the forest dielectric properties, were also found to affect coherence. On the basis of these parameters, Santoro et al. (2007) defined stable conditions as acquisitions with ‘no precipitation, no freeze/thaw, with temperatures constantly being at least a few degrees below zero and the presence of snow cover’ and ‘optimal conditions’ as the additional presence of a moderate breeze. Forest understories have been examined by a few studies such as Drezet and Quegan (2006) or Neeff et al. (2005) and was modelled by Neumann et al. (2010). Although forest understories contribute to interferometric phase decorrelation, this parameter remains under investigation. Finally, the atmospheric conditions usually change between two radar acquisitions. The presence of heavy precipitations during one of the acquisitions was found to decrease interferometric coherence (Li et al. 2007). This observation was shown to be particularly significant at high frequencies (i.e. X-band and C-band). Owing to the temporal decorrelation induced by varying weather conditions, several researchers (Smith et al. 1996; Eriksson et al. 2002, 2003, 2008) suggested the use of small temporal baselines or low-frequency systems. In addition to the normal baseline and weather conditions, topography was found to affect the interferometric coherence and *GSV* retrieval (Wegmuller and Werner 1995; Cartus et al. 2005; Tanase et al. 2010, 2011). Two main effects were distinguished, namely spatial decorrelation due to the non-overlapping fraction of the range spectral band and volume decorrelation due to the varying path length of the microwaves in canopies within different terrain slopes and aspects (Castel et al. 2000; Lee and Liu 2001). The first issue could be solved using common-band filtering (Gatelli et al. 1994; Cartus et al. 2005, 2008; Santoro et al. 2007), while the second issue has not yet been discussed in literature.

2.1.2.4 Modelling Techniques

For evaluating backscatter intensity as well, modelling of coherence was mainly classified as one of the three different approaches, namely empirical, semi-empirical and theoretical approaches. Table 2.4 summarises the principal publications referring to these approaches.

Empirical regressions were applied to coherence in several studies. As an example, Koskinen et al. (2001) and Smith et al. (1998) suggested the use of linear relationships to describe ERS tandem coherence. Fransson evaluated ERS coherence using multiple linear regressions (Fransson 2001), Eriksson described L-band coherence with an exponential relation (Santoro et al. 2003b; Eriksson et al. 2003, 2005) and Wagner implemented the SAR Imaging for Boreal Ecology and Radar Interferometry Applications (SIBERIA) algorithm using ERS tandem coherence and JERS backscatter data (Wagner et al. 2003, 2000). Although empirical models had been successfully applied in these studies, they were shown to be limited when interferometric pairs were acquired under various conditions, namely with changing weather conditions and a different perpendicular baseline. To deal with multi-seasonal and multi-baseline datasets, semi-empirical models needed to be considered. In this respect, the retrieval of the stem volume using SAR interferometric coherence has attracted considerable attention in literature, particularly by a small community of researchers who developed the interferometric water cloud model (IWCM) [see Askne et al. (1997, 2003) and Santoro et al. (2002) for the complete description]. The IWCM is a semi-empirical model which was introduced by Askne et al. (1995). This two-layer model is an extension of the WCM and defines forestvolume decorrelation as the sum of ground and vegetation contributions. This model has been extensively applied to C-band ERS-1/2 tandem data in different regions of the world such as Siberia (Santoro et al. 2005, 2007; Cartus et al. 2008, 2011), Scandinavia (Askne et al. 2003;

Table 2.4 Summary of the main models and techniques for the interferometric coherence

Approach	Model	Researchers(s)
Empirical regression	Linear	Koskinen et al. (2001) and Smith et al. (1998)
	Multiple linear	Fransson (2001)
	Non-linear	Santoro et al. (2003b) and Eriksson et al. (2003, 2005)
	SIBERIA algorithm	Drezet and Quegan (2006) and Wagner et al. (2000, 2003)
Theoretical modelling	COSMO	Thirion et al. (2006)
Semi-empirical regression	IWCM (RT)	Askne et al. (1995, 1997, 2003), Askne and Santoro (2005, 2007, 2009), Cartus et al. (2005, 2008, 2011) and Santoro et al. (1999, 2000, 2003a, 2005, 2006, 2007)
	HUT (RT)	Engdahl et al. (2004), Koskinen et al. (2001) and Pulliainen et al. (2003)

Askne and Santoro 2005, 2007, 2009; Santoro et al. 1999, 2000, 2003a, 2005) and North China (Santoro et al. 2006; Cartus et al. 2008). The model was also tested in Europe over the Thuringian Forest in order to evaluate the influence of topography on *GSV* estimation (Cartus et al. 2005). With respect to physical modelling, scattering models for vegetation are well documented in literature. However, few studies have provided a theoretical description of the relationship between interferometric phase and coherence with forest canopies and underlining soils. Askne et al. (1997) and Treuhaft et al. (1996) highlighted the relationship between interferometric phase and scatterings from vegetation canopies and ground. Sarabandi and Lin (2000) presented a coherent scattering model based on Monte Carlo simulations, which predicted the interferometric response of forests. Liu et al. (2008) combined a tree growth model with a scattering model based on the RT2 theory to simulate the interferometric coherence and to validate the main assumptions of the IWCM model. With reference to this study, it was found that there was a good agreement between the RT2 and IWCM models and confirmed that C-band data conformed to the assumptions of the IWCM model. Finally, more recently, Thirion et al. (2006) presented the COSMO coherent model, which was aimed at simulating complex radar images with a view to provide a tool for interferometric as well as polarimetric applications.

2.1.2.5 Estimation Accuracy

The interferometric coherence accuracies reported in the literature were mainly discussed for ERS-1/2 tandem acquisitions. The studies showed that coherence generally provided an *rRMSE* of 20–30 % (25–60 $m^3\,ha^{-1}$), which is significantly better than using the intensity information on average (Fransson 2001; Askne and Santoro 2007; Santoro et al. 2005, 2007; Cartus et al. 2008; Smith et al. 1998). In extreme cases, the *rRMSE* could increase beyond 48 % (Pulliainen et al. 2003) or even 60 % (Askne and Santoro 2007) and could also fall below 5 % (10 $m^3\,ha^{-1}$) (Askne et al. 2003). These results highlight the instability of the coherence due to weather conditions and the influence of the SAR acquisition configuration (perpendicular baseline) and forest properties. The L-band studies conducted by Eriksson showed that an *rRMSE* of 35–39 % could be achieved using a JERS-1 44 repeat-pass system.

2.1.2.6 InSAR Forest Height

In addition to using coherence to retrieve forest variables, estimation of tree height on the basis of interferometric phase has attracted considerable attention. The concept of extracting forest height using interferometric techniques was introduced by Hagberg et al. (1995), Wegmuller and Werner (1995), Rodriguez and Michel (1995), Ulander et al. (1995) and Dammert et al. (1995). These studies have proven that InSAR is a useful tool for estimating canopy height and forest biomass through allometric relations. Different approaches were proposed in literature for the retrieval of forest height (Balzter 2001; Balzter et al. 2007). The most common approach was the evaluation of the difference between InSAR elevation and a DEM. Kellndorfer et al. (2004) evaluated the feasibility of deriving vegetation canopy height from the Shuttle Radar Topography Mission (SRTM) C-band, namely the DEM derived in 2000 at C-band from the SRTM and National Elevation Dataset (NED), which is a reference surface available in the U.S. On the basis of preliminary investigations from Brown and Sarabandi (2003), Kellndorfer showed that it is possible to estimate the forest height with an *RMSE* of 1.1 and 4.5 m, respectively, for two different test sites. More recent studies have proposed additional methods by using SRTM C-band data (Brown et al. 2010; Sexton et al. 2009; Kenyi et al. 2009) and have investigated the feasibility of using SRTM X-band elevation data (Weydahl et al. 2007; Solberg et al. 2010; Walker et al. 2007) to derive forest height. Owing to variation in the position of the scattering phase center for different frequencies, the success of height retrieval was closely related to the frequency systems. The investigations showed that high frequencies were more suitable for estimating forest height because the scattering phase center was mostly located in the upper part of the canopies (Yong et al. 2003; Balzter et al. 2003a, 2007). However, low-frequency systems also appeared to have the potential to retrieve vegetation parameters (Lei et al. 2012). In addition to SAR frequency, some studies pointed out the influence of temporal decorrelation using repeat-pass systems. To limit the inaccuracies induced by changing weather conditions, it was recommended that single-pass interferometric systems be considered (Balzter et al. 2003a). With the availability of polarimetric interferometric SAR sensors, new methods based on full polarimetry were considered for the estimation of forest height. The literature review referring to these advanced techniques are discussed later in this chapter.

2.1.3 SAR Polarimetry

While the potential of polarimetry was demonstrated in the 1950s by studies on light scattering (Fabelinskii 1957), attention was directed toward radar polarimetric techniques in the early 1980s with the deployment of the first radar polarimetric sensor.

2.1.3.1 PolSAR Parameters

The first investigations of radar polarimetric data over vegetation cover were performed by Evans, 1986. The study highlighted the capability of full polarimetry to map forest cover by retrieving the density and structure of canopies. With the increasing number of sensors, which enable full polarimetric acquisitions (e.g. AIRSAR, PiSAR, E-SAR, SIR-C C/X, ALOS PALSAR, and RADARSAT-2), the number of publications in this regard exponentially increased in the subsequent years. These studies examined forest parameters using diverse techniques and polarimetric parameters. Some researchers directly compared forest biophysical parameters with the amplitude signal of linear polarisations (Herold et al. 2001; Balzter et al. 2002; Shimada et al. 2009). Other researchers explored polarimetric ratios (Mougin et al. 1999; Proisy et al. 2000), polarimetric phase difference (Ulaby and El-rayes 1987; Proisy et al. 2000; Kwok et al. 1993; Shimada et al. 2009; Ranson and Guoqing 1994; Thiel et al. 2007) and polarimetric coherence (Proisy et al. 2000). The outcomes mainly showed that polarimetric coherence decreased constantly with increasing vegetation density. However, the correlation of polarimetric coherence with biomass remained lower than the correlation shown by backscattering intensity with biomass in HV polarisation.

2.1.3.2 Modelling Techniques

There have been many expectations regarding the use of PolSAR in studies aimed at enhancing the knowledge of the scattering mechanisms occurring in forested areas and other landcovers. Various polarimetric decomposition techniques have been developed in this regard. Most of these can be divided into two categories. The first one is referred to as coherent decomposition, e.g. Pauli, Krogager (SHD), Cameron and Hyunen decompositions, while the second one is referred to as incoherent decomposition, e.g. eigenvector-based, Freeman–Durden and Yamaguchi decompositions. The eigenvector-based decomposition was introduced by Cloude (1985) and was performed on the popular Cloude–Pottier Entropy/Alpha unsupervised classification scheme (Cloude and Pottier 1997; Jong-Sen et al. 2004). Another renowned incoherent decomposition is the Freeman–Durden model (FDD) (Freeman and Durden 1998). In forested areas, this model distinguishes between three main scattering mechanisms, namely volume scattering from canopies, double bounces between ground and trunks and surface scattering from the underlying ground surface. Canopy volume scattering was modelled as a cloud of uniformed distributed dipoles with a fixed volume component in the coherency matrix. This provided potentially unrealistic negative values for the surface and double bounce scattering components (Sato et al. 2012; Cui et al. 2012). The FDD model has been widely used, and improvements have been proposed for the same by several studies (Freeman 2007; Yamaguchi et al. 2005, 2006; Arii et al. 2011; Sato et al. 2012; Cui et al. 2012). One significant contribution made by Yamaguchi et al. (2005) is the addition of a helix component to the FDD model (Yamaguchi et al. 2005). This fourth scattering component deals with targets which do not meet the reflection symmetry assumption of the FDD model, such as forests or man-made structures. Yamaguchi et al. (2005) also improved the model for forests by adding a vertically orientated volume scattering (Yamaguchi et al. 2005). Another important contribution to the FDD model was provided by Arii et al. (2011) and van Zyl et al. (2011) and more recently by Sato et al. (2012) and Cui et al. (2012), who proposed different solutions to the negative-power issue.

2.1.3.3 Forest Environmental Conditions

A topographic correction which is specifically dedicated to polarimetric datasets has been developed over the past decade. By performing topographic measurements from polarimetric SAR data (Schuler and De Grandi 1996; Schuler et al. 1998), Schuler highlighted that azimuth slopes need to be corrected and proposed a compensation method based on the variations in the EM wave orientation angle (Schuler et al. 1999). This method was further investigated in subsequent studies (Lee et al. 1999, 2000a, b, 2004) and was introduced as a de-orientation concept for the different target-decomposition algorithms (Xu and Jin 2005; An et al. 2010; Yamaguchi et al. 2011; Sugimoto et al. 2012; Lee and Ainsworth 2011). In addition to azimuth-slope corrections, a few studies focused on the forest radar signal over a topographic terrain. For example, Park et al. (2012) underlined the scattering mechanisms, and Villard et al. (2012) proposed a new backscattering coefficient for angular corrections of topography-induced scattering variations.

2.1.4 Polarimetric SAR Interferometry

While researchers have been actively developing separate algorithms for polarimetry and interferometry, over the past decade, there has been growing interest in coherently combining these two techniques to create SAR systems which are able to retrieve the three-dimensional structure of forest canopies. The joint use of polarimetry and interferometry is referred to as polarimetric interferometric SAR (PolInSAR). These instruments are particularly attractive because they provide an increased number of independent observables and, therefore, limit the complexity of the theoretical polarimetric models (Neumann et al. 2010; Praks et al. 2012a). The application of PolInSAR was first reported by Cloude and Papathanassiou (1997) and Cloude and Papathanassiou (1998), who suggested a coherent optimisation approach for separating the phase centers of different scattering mechanisms. These studies were further considered by Papathanassiou and Cloude (2001), who derived the formulation of a generalised complex interferometric coherence.

PolInSAR has become an important application for ecology and forestry as it can provide reliable estimates of forest height and biomass (Mette et al. 2002; Mette 2007; Hajnsek et al. 2009). Studies on PolInSAR focused on one parameter, namely forest height, but other components such as canopy extinction and ground-to-volume scattering ratio have also attracted considerable attention. The relationship between polarimetry and interferometry in the estimation of canopy heights is based on the concept that phase differences could be corrected using coherent wave scattering models (Cloude and Papathanassiou 2003). The best known PolInSAR model is the random volume over ground (RVoG) model, which is widely used in the scientific community because of the good tradeoff between its physical description and model complexity (Cloude and Papathanassiou 2003). RVoG was introduced by Treuhaft and Cloude (1999) and was further extended to full polarimetry by Papathanassion et al. (2000). This two-layer model was also described by Papathanassiou and Cloude (2001), who proposed an inversion algorithm and loci geometrical projection for plotting the complex coherence on an Argand diagram. The inversion of the RVoG model was developed for PolInSAR data (Cloude and Papathanassiou 2003). However, single-pol interferometric data were also considered under certain conditions, such as use of an external DEM, fixing of a forest extinction coefficient value and removal of the ground scattering contribution, which can be neglected at high SAR frequencies (Praks et al. 2007a, b, 2012a; Hajnsek et al. 2009; Garestier et al. 2008).

Several studies have demonstrated PolInSAR height estimation over temperate and boreal forests (Papathanassiou and Cloude 2001; Kugler et al. 2006; Mette 2007; Woodhouse et al. 2003; Garestier et al. 2008; Praks et al. 2007b). For example, Papathanassiou and Cloude (2001) used an L-band 10-min repeat-pass airborne system to show that it is possible to retrieve the forest height with a standard deviation of approximately 2.5 m. The RVoG model was assessed at different frequencies. Although a few publications reported P-band investigations (Garestier et al. 2008, 2009; Lee et al. 2009), most of the analyses concerned X-, C- and L-band frequencies (Kugler et al. 2006, 2007; Praks et al. 2007a; Mette and Papathanassiou 2004; Hajnsek et al. 2009). These studies showed that the accuracy of the inversed PolInSAR height depends on several factors. Among these factors, (1) forest height, (2) density and coefficient of extinction, (3) soil moisture, (4) terrain topography and (5) SAR frequency and temporal baseline have been discussed in literature (Hajnsek et al. 2009; Praks et al. 2012a; Lavalle 2009; Le Toan et al. 2012; Kugler et al. 2006). In repeat-pass PolInSAR systems, the temporal baseline consisted of one of the most limiting components (Lee et al. 2010; Neumann et al. 2010, 2012). The change in weather conditions or vegetation properties between two PolSAR acquisitions induces temporal decorrelation; thus, the forest height is overestimated and the phase deviation is increased, which affects the accuracy of height retrieval (Lee et al. 2009; Li and Guo 2012). To circumvent this issue, some studies have discussed the use of multi-baseline acquisitions (Lee et al. 2010; Neumann et al. 2010, 2012) or a combination of RVoG with a temporal decorrelation model (Papathanassiou and Cloude 2003; Li and Guo 2012; Lavalle et al. 2012). Although these methods improved the accuracy of the height estimates, they did not completely remove the temporal effect. In this context, the use of single-pass PolInSAR systems, such as the recently launched spaceborne TSX/TDX or future TanDEM-L systems, should be very promising (Kugler et al. 2010; Torano Caicoya et al. 2012; Praks 2012).

2.1.5 SAR Tomography

An extended approach to PolInSAR involves polarimetric SAR tomography. Introduced by Reigber et al. (2000) during the early millennium, this approach relies on the coherent combination of multi-baseline InSAR acquisitions and allows the localisation of scattering contributions along the vertical direction of the targets (Tebaldini and Rocca 2012). Tomography considerably extends the capabilities of SAR for the extraction of forest vertical structure information (Reigber 2001) and estimation of forest parameters such as biomass (Dinh et al. 2012). The studies related to SAR tomography are very recent and are focused on ameliorating the processing algorithms (Frey et al. 2007; Cloude 2006, 2007; Lombardini 2005; Tebaldini and Rocca 2009; Tebaldini et al. 2010; Zhang et al. 2012). However, the past three years have also seen a growing number of publications on the analysis of tomographic SAR data in forested areas (Frey and Meier 2010; Tebaldini and Rocca 2009, 2012; Tebaldini et al. 2010). For example, Tebaldini et al. (2010) and Tebaldini and Rocca (2012) compared the scattering contributions for P-band and L-band SAR tomography in a boreal forest. These studies reported a relatively uniform scattering distribution in L-band and a significant ground-level contribution in P-band in co-polar channels as well as HV polarisation. Frey and Meier (2010) reported similar results by investigating P-band and L-band datasets in a temperate forest. Dinh et al. (2012) evaluated the potential of tomographic SAR signals to retrieve biomass at a P-band frequency in a tropical forest and obtained the best sensitivity for a vegetation layer located above height of 30 ± 10 m and biomass quantities in the range 250–450 t ha^{-1} at a specific test site. These studies and future studies regarding tomography will be essential for the planned TanDEM-L, DESDynI and BIOMASS spaceborne missions.

2.2 Fusion of SAR Information

With the number of SAR techniques and datasets having increased over the past few years, there is a need to improve the estimation of forest parameters such as biomass by merging different sources of SAR information. The combination of SAR information in multiple ways was conceived. First, with reference to the different SAR techniques, a combination of two sensors for evaluating interferometric phase as well as the integration of polarimetry and interferometry in PolInSAR could be considered as fusion techniques. Therefore, publications describing InSAR, PolSAR, PolInSAR or Tomography approaches were seen in some cases as fusion approaches (Lavalle 2009). Then, researchers showed a variety of possible combinations by integrating different frequencies, polarisations, incidence angles or temporal acquisitions in a single fusion approach by using different SAR acquisition parameters. Finally, the approaches were combined in different ways such as using simple ratios, Bayesian rules, neural networks, multiple linear regressions or physical models.

The combination of various SAR acquisition parameters and the use of different fusion approaches provide the ability of improving the retrieval of forest variables. While the number of reports on SAR techniques is relatively large, the number of studies dealing with the fusion potential of SAR parameters remains limited. One of the most cited fusion methods involved combining multi-temporal datasets. In this regard, the researchers proposed diverse approaches such as merging (Goodenough et al. 2005), weighting (Santoro et al. 2003a, 2008, 2011; Askne et al. 2003; Askne and Santoro 2007) and linear combination (Quegan et al. 2000; Quegan 2001;

Bruzzone et al. 2004; Gineste 1999) of multi-temporal data. A combination of different SAR frequencies has been proven to increase saturation levels and reduce uncertainties in biomass estimates. For example, Englhart et al. (2011) recently demonstrated that combining X-band and L-band SAR data over a tropical forest using multi-regression models would increase the saturation level from approximately 100–300 $\mathrm{t\,ha^{-1}}$ and reduce the *RMSE* from approximately 110–79 $\mathrm{t\,ha^{-1}}$. The combination of different polarisations has been presented in a few studies, and it has been generally shown that the use of a polarisation ratio such as HH/HV improved the estimation of forest biophysical parameters (Wu 1987; Sarker et al. 2012; Mougin et al. 1999). No study has supposedly demonstrated the potential integration of multi-angle or multi-pass direction SAR data. One major issue for retrieving large scale biomass maps lies in the development of algorithms which are independent of ground inventory data. To solve this problem, some researchers have combined SAR and optical data (Santoro et al. 2010, 2011; Cartus et al. 2011, 2012). However, to date, although some studies have proposed the combination of backscatter intensity and coherence (Wagner et al. 2003, 2000), no study has reported the possibility of deriving *GSV* from only SAR information without considering reference data.

2.3 Open Issues and Scope of the Thesis

With respect to the literature review performed in Sects. 2.1 and 2.2, four different topics were identified as important issues in forest biomass estimation from remote sensing systems in temperate forests. The first issue is topography. Although it is known that topography affects the SAR signal and corrections for sloping terrains have been proposed, the effects of steep slopes in forests on the returned SAR signals remain under investigation (Castel et al. 2001a; Luckman 1998; Cartus et al. 2005, 2008; Castel et al. 2000). The second issue is the forest's horizontal structure, which directly refers to the results reported by Woodhouse (2006) and Brolly and Woodhouse (2012). The researchers introduced a new approach for the uncommon trend observed in several studies, namely a decrease in backscatter intensity with increasing forest biomass quantity (Rauste et al. 1994; Ranson and Guoqing 1994; Dobson et al. 1995; Woodhouse 2006). The third issue is the *GSV* range. Most studies examining the relationship between *GSV* and SAR data only considered forests with GSV values up to 400 $\mathrm{m^3\,ha^{-1}}$. However, temperate forested areas may show GSV values greater than 700 $\mathrm{m^3\,ha^{-1}}$. With the aim of estimating forest biomass wordwide, it is necessary to cover the different ranges of GSV and investigate the related effects on remote sensing systems. After reviewing several sensors used in forestry applications, Wulder et al. (2004) mentioned that 'the best sensor is often more than one sensor'. In this regard, the last issue highlights the significant potential of combining SAR information and the small number of studies published in this field. On the basis of the four aforementioned issues, the following objectives were defined for this thesis:

- Highlight the scattering and decorrelation mechanisms occurring in temperate forests with a topographic terrain;
- Examine potential effects related to forest horizontal structure and high *GSV* values;
- Determine the optimal SAR acquisition parameters for the estimation of forest *GSV*;
- Estimate *GSV* from spaceborne remote sensing sensors using algorithms presented in literature;
- Investigate and develop an integrated approach to deriving a *GSV* map from the fusion of SAR information.

The above objectives were formulated to provide answers to the open issues and to present novel scientific knowledge to the radar community. To limit the framework of this thesis, the investigations focused on X-band and L-band spaceborne data (see the SAR missions presented in Sect. 1.2). In addition, although PolSAR and PolInSAR techniques may be explored, greater attention will be paid on backscatter intensity and interferometric coherence data. Finally, as mentioned in Sect. 1.2, the examinations performed in this thesis were incorporated into the ENVILAND2 project and consequently also involved investigations of optical remote sensing. Owing to time constraints, only findings obtained from radar data are presented in this thesis.

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