



Growing stock volume estimation from L-band ALOS PALSAR polarimetric coherence in Siberian forest



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ABSTRACT

This paper investigated the potential of L-band ALOS PALSAR full polarimetric radar data for forestry applications. In order to characterize the polarization response as a function of growing stock volume (GSV), weather conditions and different tree species in Siberian forests, the polarization phase difference between HH and VV polarizations and the magnitude of the polarimetric HHVV-coherence have been analyzed. Moreover, the retrieval accuracy of forest growing stock volume (GSV) has been evaluated. The investigations were conducted on forest stand level and maximum GSV was 350 m³/ha. Using multi-temporal L-band ALOS PALSAR polarimetric coherence data and extensive sets of the forest inventory data at a stand level, we observed a clear decrease of polarimetric coherence with an increase in GSV, with Pearson's correlation coefficient between -0.74 and -0.79 . The correlation improved to -0.87 for the forest stands with high relative stocking $>70\%$ (i.e. more homogeneous forest stand structure) and the sensitivity of the polarimetric coherence to GSV increased to ~ 250 m³/ha GSV. The polarization phase difference (PPD) also allowed forest to be discriminated from non-forest areas. Comparison of PPD during thawing and unfrozen weather conditions at the time of image acquisition revealed a higher contribution of a volume scattering at the latter conditions. In addition, differences in polarimetric coherence and phase difference were observed as a function of tree species. In particular, stands of larch typically exhibited a $+0.1$ polarimetric coherence under unfrozen conditions compared to aspen, birch and pine. There was also less variability in the PPD compared to other tree species, both under thawing and unfrozen conditions. An exponential model was used to characterize the polarimetric coherence behavior as a function of GSV. The retrieval of GSV was better under unfrozen conditions, with an RMSE of 33 m³/ha and R^2 of 0.73. The retrieval error was slightly higher (RMSE = 51 m³/ha and R^2 = 0.61) under thawing conditions. In the case of the forest stands with the area larger than 30 ha and the relative stocking of at least 70%, the GSV retrieval error decreased to RMSE of 16 m³/ha and to RMSE = 19 m³/ha respectively.

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1. Introduction

Siberian forests are a natural resource of global importance, both economically and ecologically. They already serve Russia and the world as a source of wood, a symbol of wilderness, and a critical stabilizer of the global climate. Siberian forests contain roughly half of the world's growing stock volume (GSV) of coniferous species (Nilsson & Shvidenko, 1998), making them a commercially and environmentally precious resource. GSV represents the volume of tree trunk per unit area, including bark but excluding branches and stumps and is

measured in cubic meters per hectare (m³/ha). Siberian forests suffer from several types of disturbances. A greater majority of damage is caused by timber extraction associated with the wood trade and careless logging practices (including over logging), excessive forest fires, acid rain and air particulate pollution. Forest degradation or deforestation increases the atmospheric CO₂ concentration, temperatures and also changes in precipitation which are likely to have an impact on climate change. Therefore, it is necessary to monitor Siberian forests on a large-scale, frequently and accurately. The traditional ground survey is useful for the local investigations but taking into account the vastness and remoteness of Siberian forests and also the lack of adequate infrastructure, forest inventories are not carried out frequently enough to provide information about the ecosystem. Moreover, ground-based surveys are very expensive and time consuming. To overcome this problem, a recommended solution is to use remote sensing techniques. In Siberia, optical remote sensing data are frequently affected by cloud cover, fog, mist or darkness for much of the winter period. However, radar remote sensing data are not sensitive to cloud cover and solar illumination and hence they provide year-round information on forest

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cover. Furthermore, they can deliver a data in polarimetric and interferometric modes. Moreover, SAR data can also be acquired over large areas and at a reasonably high temporal resolution. Due to their sensitivity to the geometric properties of the targets, radar data have been shown to be useful for retrieving forest biomass (Askne & Santoro, 2005, 2007; Balzter, Skinner, Luckman, & Brooke, 2003; Eriksson, Santoro, Wiesmann, & Schmullius, 2003; Harrell, BourgeauChavez, Kasischke, French, & Christensen, 1995; Harrell et al., 1997; Kuplich et al., 2000; Ranson & Sun, 1997; Saatchi & Moghaddam, 2000; Santoro, Askne, Smith, & Fransson, 2002; Santoro, Shvidenko, McCallum, Askne, & Schmullius, 2007; Santos, Lacruz, Araujo, & Keil, 2002; Santos et al., 2003; Tansey et al., 2004; Tsolmon et al., 2002; Wagner et al., 2003). SAR data acquired at L-band (23.5 cm) have also proved to be more useful than those acquired at higher frequencies (e.g., X and C-bands), largely because of greater sensitivity to the woody components. However, a limitation is that saturation occurs at higher levels of biomass (Hoekman & Quiñones, 2000; Le Toan, Beaudoin, Riou, & Guyon, 1992; Luckman, Baker, Kuplich, Yanasse, & Frery, 1997) i.e., after a specific biomass level, no further increase in radar backscatter intensity occurs.

1.1. SAR polarimetry for forestry applications

Radar polarimetry is the science of acquiring, processing and analyzing the polarization state of an electromagnetic field (Lee & Pottier, 2009). Polarimetric synthetic aperture radar (POLSAR) is an advanced technology that provides image data with phase (scattering matrix) information. Polarimetric data contain more information on the scattering objects than the conventional single and dual polarization data. One of the benefits of polarimetric data is that the backscattering mechanisms from scattering objects can be obtained which gives insight into their physical characteristics and can be used for their discrimination. Basic data examination techniques analyze polarimetric coherence or polarization phase difference. These parameters were not commonly used for the forest biomass estimation, although they provided some potential in particular for polarization phase difference which exhibited strong correlation with diameter at breast height (dbh) of the trees and the high sensitivity with forest biomass (Le Toan et al., 1992). Table 1 lists the polarimetric parameters which have been used for the estimation of forest structural parameters in the various studies.

Le Toan et al. (1992) used polarimetric data for the retrieval of forest biomass but only the relationship with polarization phase difference was described. Karam et al. (1995) took these results and developed a polarimetric scattering model for forest canopy using polarimetric coherence and polarization phase difference based on the radiative transfer formulation. Comparisons of the model with measurements from forest showed good agreements and gave a quantitative

understanding of the relation between these polarimetric parameters and the age of the trees in the forest and forest biomass. However, the site studied was comprised mainly of managed and homogeneous forest stands. Balzter et al. (2002) improved the accuracy of forest biomass estimation by implementing a simple regression model which was derived from the radar backscatter intensities and polarimetric coherence. Proisy et al. (2000) also incorporated the polarization phase difference and coherence for the retrieval of biomass up to 240 t/ha in mangroves forest. In particular, the polarimetric coherence exhibited a distinct sensitivity to forest biomass. Hoekman and Quiñones (2002) developed a specific approach for the interpretation of the complex polarimetric coherence across various radar frequencies. Thus, the authors were able to link these specific polarimetric coherence signatures to diverse forest types and biomass classes. Besides backscatter intensities, McNeill and Paiman (2005) considered polarization phase difference, polarimetric coherence and also alpha (average scattering angle) and entropy of the Cloude–Pottier decomposition (Cloude & Pottier, 1996) parameters for the estimation of forest stand age. Together with alpha and entropy, both young (2 years or less) and old (25 years or older) forests could be separated. The integration of the polarimetric information minimized the standard error of the estimation of forest stand age. Garestier et al. (2009) used another Cloude–Pottier decomposition parameter, anisotropy, which was linearly correlated with tree height up to 25 m when P-band data were used over pine trees. Alpha and entropy increased with height until 10 m, at which point they remained constant. Gonçalves et al. (2011) used airborne L-band SAR data to apply polarization phase difference, polarimetric coherence and the volume scattering component of the Freeman–Durden decomposition method (Freeman & Durden, 1998) in tropical forest. The authors performed multi-linear regression analysis using these polarimetric attributes for the estimation of GSV. The retrieval accuracy of GSV was about $RMSE = 20\text{--}29\text{ m}^3/\text{ha}$ and the saturation effect was not observed up to $308\text{ m}^3/\text{ha}$ GSV. Nevertheless, 24 plots (each plot size is 1 ha) were observed in this study and the lack of forest stands with GSV less than $155\text{ m}^3/\text{ha}$ and greater than $308\text{ m}^3/\text{ha}$ made determination of saturation level difficult.

Some studies showed the potential of tree species discrimination based on polarimetric data (Ranson & Sun, 1997; Watanabe et al., 2006). Watanabe et al. (2006) applied the Freeman–Durden decomposition model to forest in Tomakomai, Japan revealing that larch had a higher contribution of surface scattering and a lower contribution of double bounce and volume scattering. Using multi-frequency and polarimetric information, Ranson and Sun (1997) found that deciduous forests could be better discriminated using C-, L- and P-band AIRSAR data whereas better discrimination of coniferous forests was achieved using SIR C- and X-band data. However, the impact of tree species on polarimetric coherence and polarization phase difference has not yet been fully examined in these studies.

Table 1
List of polarimetric parameters for the estimation of forest structural parameters in different studies. In the 3rd column the same studies in different polarimetric parameters indicate that the retrieval was done using the combination of these corresponding polarimetric parameters.

Polarimetric parameters	Retrieve forest structural parameters	Studies
Polarimetric coherence or HHVV coherence	Polarimetric scattering model for forest canopies Improve the accuracy of forest biomass Forest biomass Biomass classes Age of the trees GSV estimation	Karam et al. (1995) Balzter et al. (2002) Proisy et al. (2000) Hoekman and Quiñones (2002) McNeill and Paiman (2005) Goncalves et al. (2011)
Polarization phase difference (PPD)	Diameter at breast height (dbh) of the trees. Polarimetric scattering model for forest canopies Forest biomass Age of the trees GSV estimation	Le Toan et al. (1992) Karam et al. (1995) Proisy et al. (2000) McNeill and Paiman (2005) Goncalves et al. (2011)
Cloude–Pottier decomposition (alpha, entropy and anisotropy)	Age of the trees Height of the trees	McNeill and Paiman (2005) Garestier et al. (2009)
Freeman–Durden decomposition	GSV estimation	Goncalves et al. (2011)

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