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Forest canopy height and carbon estimation at Monks Wood National Nature Reserve, UK, using dual-wavelength SAR interferometry

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Abstract

Forest canopy height is a critical parameter in better quantifying the terrestrial carbon cycle. It can be used to estimate aboveground biomass and carbon pools stored in the vegetation, and predict timber yield for forest management. Polarimetric SAR interferometry (PolInSAR) uses polarimetric separation of scattering phase centers derived from interferometry to estimate canopy height. A limitation of PolInSAR is that it relies on sufficient scattering phase center separation at each pixel to be able to derive accurate forest canopy height estimates. The effect of wavelength-dependent penetration depth into the canopy is known to be strong, and could potentially lead to a better height separation than relying on polarization combinations at one wavelength alone. Here we present a new method for canopy height mapping using dual-wavelength SAR interferometry (InSAR) at X- and L-band. The method is based on the scattering phase center separation at different wavelengths. It involves the generation of a smoothed interpolated terrain elevation model underneath the forest canopy from repeat-pass L-band InSAR data. The terrain model is then used to remove the terrain component from the single-pass X-band interferometric surface height to estimate forest canopy height. The ability of L-band to map terrain height under vegetation relies on sufficient spatial heterogeneity of the density of scattering elements that scatter L-band electromagnetic waves within each resolution cell. The method is demonstrated with airborne X-band VV polarized single-pass and L-band HH polarized repeat-pass SAR interferometry using data acquired by the E-SAR sensor over Monks Wood National Nature Reserve, UK. This is one of the first radar studies of a semi-natural deciduous woodland that exhibits considerable spatial heterogeneity of vegetation type and density. The canopy height model is validated using airborne imaging LIDAR data acquired by the Environment Agency. The *rmse* of the LIDAR canopy height estimates compared to theodolite data is 2.15 m (relative error 17.6%). The *rmse* of the dual-wavelength InSAR-derived canopy height model compared to LIDAR is 3.49 m (relative error 28.5%). From the canopy height maps carbon pools are estimated using allometric equations. The results are compared to a field survey of carbon pools and *rmse* values are presented. The dual-wavelength InSAR method could potentially be delivered from a spaceborne constellation similar to the TerraSAR system.

Keywords: Synthetic Aperture Radar (SAR); Interferometry; Tree height; Canopy height; Carbon; LIDAR

1. Introduction

The long-term net carbon flux between terrestrial ecosystems and the atmosphere has been dominated by changes in forest area and changes in forest biomass per hectare resulting from management and regrowth (Houghton, 2005). These processes are thus vital for understanding the global carbon balance. The quantification of carbon content in forest ecosystems is important for forest management, climate science and verification of international environmental treaties. Forests and woodlands interact with the carbon cycle through photosynthesis, respiration and disturbance events (fire, windfall, insect damage and logging). There are still considerable quantitative uncertainties in the magnitude of the carbon sink in different regions and the contribution of different processes to the overall carbon cycle (Schimel et al., 2001), which could be reduced through better estimates of terrestrial, biotic carbon pools such as forest ecosystems.

Increasing awareness of risks associated with climate change has led to international measures trying to limit the increase of greenhouse gas (GHG) concentrations in the atmosphere. The UN Framework Convention on Climate Change and the

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Kyoto Protocol aim at a reduction of greenhouse gas emissions to prevent dangerous climate change. Af-, Re- and Deforestation measures are accountable under the Protocol. The possible uses of remote sensing in verifying the Kyoto Protocol are discussed by Rosenqvist et al. (2003). Terrestrial vegetation, mainly forest, is being discussed as a potential carbon sink with the important function of stabilizing GHG concentrations. The Marrakech Accords to the Kyoto Protocol define "forest" as a "minimum area of land of 0.05–1.0 ha with tree crown cover (or equivalent stocking level) of more than 10–30% with trees with the potential to reach a minimum height of 2–5 m at maturity *in situ*...". From 2008, nations are required to report human activities that affect their national GHG inventories. To achieve a full carbon account, information is needed on the carbon stocks in forest. In forestry, canopy height is often used to estimate forest biomass and carbon pools, as the quantities are functionally related. Field-based top height measurements are used in estimating timber yield from yield class models by the UK Forestry Commission (Forestry Commission, 1981). The aboveground carbon content of the forest can be estimated using knowledge of forest canopy height and allometric equations (Patenaude et al., 2002). Here, we define *forest canopy height* as the height of the highest vegetation components above ground level, *mean stand height* as the mean canopy height of a forest stand, *tree height* as the height of the tip of the stem of an individual tree, *top height* of a forest stand as the average total height of the 100 trees of largest diameter at breast height per hectare and the *interferometric scattering phase center height* from InSAR as the vertical location within the canopy from which most of the backscatter signal is returned.

Forest canopy height can be estimated using remote sensing techniques, particularly stereophotogrammetry, LIDAR and Synthetic Aperture Radar (SAR) interferometry (InSAR), including polarimetric interferometry (PolInSAR). Patenaude et al. (2005) give an overview of approaches for above-ground forest carbon stock estimation including RADAR and LIDAR (Light Detection and Ranging).

Three basic approaches of biomass mapping from SAR can be distinguished and are described below: approaches based on backscatter, coherence and phase.

1.1. Backscatter based approaches

Backscatter intensity is the energy that is received by the SAR sensor after transmission of an energy pulse to the target. The total backscatter from a forest target consists of contributions from a number of basic physical scattering mechanisms, specifically volume scattering from the canopy, rough surface scattering from the ground and double-bounce scattering from trunk-ground interactions. These scattering mechanisms contribute to the return signal at specific polarization combinations, and depend amongst other factors on the electromagnetic wavelength. Radar backscatter intensity has been used to estimate woody biomass of forest (Kasischke et al., 1997), forest biomass (Le Toan et al., 1992), forest aboveground dry biomass (Rignot et al., 1994) and timber volume (Balzter et al., 2002a). Backscatter typically increases with increasing forest biomass, but this function saturates at a wavelength dependent biomass density, which limits the usefulness of SAR for this application (Imhoff, 1995). The form of the functional relationship between backscatter and biomass depends heavily on vegetation structure, which can confuse the retrieval of biomass. A backscatter modeling study using MIMICS-I for L-band radar for dry and wet peat swamp forest found that the canopy layer contributed significantly to radar backscatter, but some L-band radiation also penetrated through the canopy to the ground layer, as shown by significant trunk-ground contributions in both flooded and non-flooded peat-swamp forest (Aziz & White, 2003). A multitemporal analysis of SEASAT and JERS-1 SAR over a coniferous forest plantation showed that L-band backscatter difference is sensitive to tree growth over an 18 year period (Balzter et al., 2003). Hyyppä and Hallikainen (1996) present results from the helicopter-borne HUTSCAT ranging scatterometer at C- and X-band (polarimetric) over Finnish boreal forest stands, which showed a tree species dependent retrieval accuracy of tree height. Tree height of pine stands could be estimated more accurately than deciduous, spruce or mixed stands. From 3° to 40° incidence angle the retrieval accuracy decreased. The profiling capabilities of this instrument mean that ground elevation can be estimated from the signal, even though a certain amount of noise means that digitizing the surface can be more accurate. Martinez et al. (2000) relate HUTSCAT data to a radiative transfer model coupled to a tree structure model.

1.2. Coherence based approaches

Coherence based approaches are based on the estimation of the complex correlation coefficient between two SAR acquisitions. The coherence is the magnitude of the complex correlation coefficient, while the interferometric phase is defined as an angular measurement. Coherence based approaches are based on the observation that interferometric coherence under certain conditions is related to forest biomass. Forest stem volume was retrieved from multitemporal interferometric ERS 1 and 2 C-band tandem coherence under winter conditions over forest test sites in Finland and Sweden by Askne and Santoro (2005), who conclude that the error level for large forest stands (>2 ha) in a well managed and homogeneous boreal forest may be expected to be in the 15% to 25% range, deteriorating for small and heterogeneous stands. The superior performance of winter coherence over summer coherence for stem volume retrieval was also found by Pulliainen et al. (2003). At L-band, multitemporal JERS-1 data showed that interferometric wintertime coherence with a 44 day temporal baseline is suitable for estimations of growing-stock volume in boreal forest in Siberia (Eriksson et al., 2003). Tansey et al. (2004) present a forest growing stock classification algorithm based on the information content of both ERS tandem coherence and JERS backscatter that gives classification accuracies of greater than 70% for test sites in Sweden, Siberia and the UK.

1.3. Phase based approaches

Phase-based InSAR techniques exploit the interference patterns (so-called fringes) of two electromagnetic waves to