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Status and future of laser scanning, synthetic aperture radar and hyperspectral remote sensing data for forest biomass assessment

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ABSTRACT

This is a review of the latest developments in different fields of remote sensing for forest biomass mapping. The main fields of research within the last decade have focused on the use of small footprint airborne laser scanning systems, polarimetric synthetic radar interferometry and hyperspectral data. Parallel developments in the field of digital airborne camera systems, digital photogrammetry and very high resolution multispectral data have taken place and have also proven themselves suitable for forest mapping issues. Forest mapping is a wide field and a variety of forest parameters can be mapped or modelled based on remote sensing information alone or combined with field data. The most common information required about a forest is related to its wood production and environmental aspects. In this paper, we will focus on the potential of advanced remote sensing techniques to assess forest biomass. This information is especially required by the REDD (reducing of emission from avoided deforestation and degradation) process. For this reason, new types of remote sensing data such as fullwave laser scanning data, polarimetric radar interferometry (polarimetric systhetic aperture interferometry, PolInSAR) and hyperspectral data are the focus of the research. In recent times, a few state-of-the-art articles in the field of airborne laser scanning for forest applications have been published. The current paper will provide a state-of-the-art review of remote sensing with a particular focus on biomass estimation, including new findings with fullwave airborne laser scanning, hyperspectral and polarimetric synthetic aperture radar interferometry. A synthesis of the actual findings and an outline of future developments will be presented.

1. Introduction

The mapping of forests, from local to global in terms of their status and development is of increasing importance. This is due to the high competition within the wood market, as indicated by studies (UNECE, 2007) which predict a rising market demand for wood products and especially for wood-based bioenergy. There is also a growing need for information to improve the sustainability of our forests with regard to climate change issues. Within the last few years, carbon sequestration is a key topic within the climate change discussion. Forests are known as one of the major sinks for carbon. In order to estimate carbon sequestration, the mapping of forest biomass and the monitoring of changes over time is needed. Apart from biomass modelling, biomass assessment can also monitor change due to deforestation, which is another output of the mapping process. The important role of remote sensing within the forest mapping in general and biomass assessment in particular is expressed by several scientific activities. These are the significant European contributions towards remote sensing techniques: the 2.3 billion euro program GMES (Global Monitoring for Environment and Security) is one as well as a number of projects like TREES 3 (Tropical Ecosystem Environment Observation by Satellite) (TREES, 2010) and FRA (Forest Resource Assessment) (FRA, 2010).

The limitations of using remote sensing data for biomass mapping are related to data and appropriate method availability. The methods used today refer mainly to multispectral optical data sets. Visual interpretation and digital classification methods for optical data are described, but often cannot fulfil the information requirements in regard to timeline and quality. Multi-sensoral approaches or mapping approaches, based on polarimetric radar interferometry, fullwave laser or hyperspectral data, are not yet sufficiently developed to fill these gaps of information. However, there are a number of missions planned inside and outside of Europe which will, within the next decade, provide increased sets of polarimetric repeat pass or single pass synthetic aperture radar data, hyperspectral optical data or airborne fullwave laser data. Space-borne fullwave laser systems are also being considered and it is most likely that there will be a space-borne system designed or even in orbit within the next decade. The IceSat/GLAS (Ice, Cloude and Land Elevation Satellite/Geoscience Laser Altimeter System) system has already proven its suitability for forestry applications (Harding and Carabajal, 2005; Lefsky et al., 2005; Rosette et al.,

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2010). A study on earth observation future requirements provided by the British National Space Centre (QuintiQ, 2003) identified, for environmental studies, imaging radar and LiDAR as essential data sets. Low-frequency SAR, polarimetric SAR and profiling LiDAR are the most requested future systems by the users for vegetation canopy characterisation and biomass estimations.

Using remote sensing methods, biomass is normally defined as the above-ground phytobiomass (organic mass of plants). The biomass definition used in this paper stands for the above-ground phytobiomass. Measurements of biomass estimation can be divided into direct or indirect methods. For direct estimations, a relationship between the signal response registered by the remote sensing device and the biomass is determined, using techniques like multiple regression analysis, k-NN classification, neural networks or statistical ensemble methods. The indirect methods for biomass measurements are derived from remote sensing-based forest estimations, such as tree height, crown closure and tree or stand type as a major input. These are then used as an input to estimate stand mean diameter, stand age and wood volume. In the end, wood volume is multiplied by a biomass expansion factor (BEF) for the final biomass estimation (Cháidez, 2009). The value of the BEF depends mainly on the tree species and tree age. The aforementioned indicates that the forest height, forest closure and forest type are the best predictors for good biomass estimations. Previous studies have shown that forest canopy surface structure metrics (specifically height and crown cover) are highly correlated with biomass (Yáñez et al., 2008; Tiemann, 2007; Lefsky et al., 2001). Tiemann (2007) showed that the best nonlinear model is a combination of height, standard deviation of height and brightness index from optical data. He did not explicitly integrate crown closure but the brightness index is a mixed indicator for crown closure and forest type. Compared to the terrestrial biomass sample plot estimations with the best model, he achieved an R^2 (coefficient of determination) of 0.6.

2. LiDAR data for forest biomass mapping

An extended overview on the status of small footprint, multiple point or fullwave LiDAR data for general forest applications is provided by Hyyppä et al. (2009), Dees and Koch (2008) as well as by Mallet and Bretar (2009). They show that the information related to height or structure of forests can be extracted with high quality. There exist several approaches to estimate biomass from LiDAR data. One of the pioneering studies is from Nelson et al. (1988) using the tree height as a LiDAR derived parameter. Most authors concentrate on the above-ground biomass (Lefsky et al., 1999). Lefsky et al. (2001) explained 84% of the above-ground biomass variance by regression from the LiDAR measured canopy structure. Overall, the study gives a good overview for large-area carbon storage estimation. Popescu (2007) managed to explain 93% of the biomass using individual tree metrics. The only known study focusing on the below-ground biomass is from Næsset (2004), in which they used regression methods to explain 86% of the below-ground and 92% of the above-ground biomass. For biomass estimation from LiDAR data, the indirect approach is often chosen. This means that tree heights are first calculated from LiDAR (Nelson et al., 1988), and then wood volume is modelled based on this (Straub et al., 2009) and finally expansion factors are applied to estimated biomass. Tokola (2009) combined LiDAR in a two-stage stratified sampling, showing an RMSE of 18% for biomass and carbon estimation.

The space-borne fullwave laser system ICESat/GLAS has also been used to derive biomass parameters and canopy height for large areas (Lefsky et al., 2005; Pang et al., 2008). However, there are still information gaps particularly around intensity, amplitude or waveform parameter for forests information extraction. In addition, most of the studies carried out with LiDAR are focused on sub-boreal forest systems, such as Scandinavian forest types dominated by spruce and pine. Hardly any investigations exist on temperate, dry or tropical forests. LiDAR turned out to be one of the most applicable remote sensing techniques for forest monitoring (Hyyppä et al., 2009) due to the information that can be obtained on the vertical structure of the vegetation cover compared to optical sensors (Dubayah and Drake, 2000).

New developments in the field of laser technologies and analyzing methods are needed for further progress. Potential technology not yet on the market and totally unexplored for forest applications include, flash LiDAR with laminary sensors providing image products, and the synthetic aperture LiDAR (SAL), which is currently tested by NASA/DARPA (Defense Advances Research Agency). The development of the flash LiDAR technology will in future cover large areas from a high altitude with high density data (Steinvall et al., 2008). SAL Photon counting systems would also improve the operating distance and provide enhanced modelling approaches. Brown et al. (2005) describe an extended DIRSIG (Digital Imaging and Remote Sensing Image Generation) model which generates active laser radar simulations. In the future, this model will be able to track the polarization state, the phase distribution and the spectral structure of the photons. The performance of the multi-wavelength LiDAR was tested for biomass assessment based on simulations (Morsdorf et al., 2009). They simulated multispectral fullwave LiDAR data and tested the usability of these data for mapping the photosynthetically active biomass based on a virtual forest stand. They demonstrated that multi-wavelength LiDAR data would greatly improve the accuracy of measurements for photosynthetically active biomass. The multi-pulse in air technology on the market by Leica (Roth and Thompson, 2008) and Riegl (2010) enlarges considerably the point density. This increases the accuracy of height and crown volume measures on a single tree basis and consequently will improve biomass estimation. The major technological development within the last few years for airborne LiDAR is fullwave high density systems, providing 20 or more points per m^2 and a high number of reflections along the wave or the full waveform. In addition, there are systems working with multiple look angles which can improve single tree delineation as well as crown volume estimations, according to different shooting directions (Fig. 1). These technological developments allow new features to be extracted. Intensity as an information source also attracts more and more attention, especially for species identification.

Forest cover is one of the basic pieces of information used to estimate forest biomass. In the REDD (reducing greenhouse gas emissions from deforestation and degradation in developing countries) (GOFC-GOLD, 2009) source book, forest cover is defined as—forest versus non-forest boundary. Until now, to our best knowledge there are no studies on the usage of LiDAR for deforestation monitoring. However, the studies from Wang et al. (2007) and Straub et al. (2008) demonstrate the successful usage of LiDAR for—forest versus non-forest classification. This indicates LiDAR as an ideal tool for exact deforestation monitoring. Straub et al. (2008) successfully demonstrated that full waveform LiDAR data can be effectively used for forest delineation. Fullwave LiDAR systems allow the extraction of several single laser returns per laser beam. By Gauss fitting those echoes with a certain amount of pulses per laser beam together with information on their range, amplitude and width can be extracted. Based on the reflection distribution, Straub et al. (2008) separated large areas into regions of vegetation with trees and others. After this, they partitioned the total area into equal grids and classified each grid within the tree vegetation area. This classification included forest height, tree crown cover, minimum width of forest area and minimum total size of forest area. The class of trees outside forests are further divided into single trees or groves. Finally neighboring grids with the same class

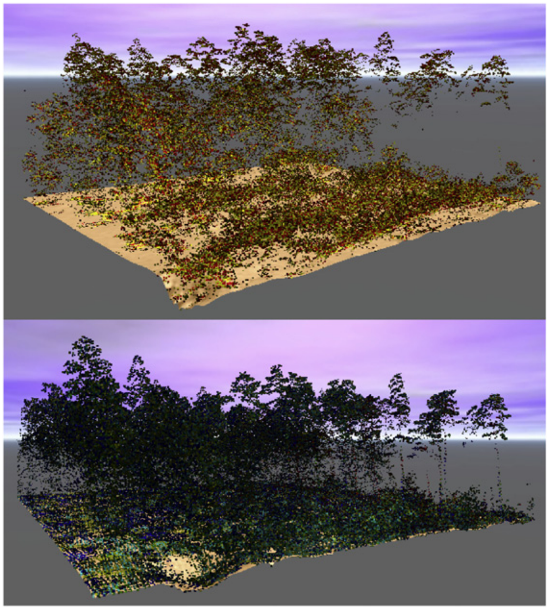

Fig. 1. High density data with different viewing angles (+/−30°, 16–22 points per m^2, Light Mapper 5600) at test site Karlsruhe, Germany.

membership are grouped together as one area. Referring to the formal and stringent forest definitions in Germany, they achieved an accuracy of more than 97% (Fig. 2).

In general, not only biomass status but monitoring of biomass changes is also required. According to the REDD definition, this is associated with deforestation and forest degradation. While the change in biomass due to deforestation can be assessed relatively correctly, the estimations of biomass changes due to the degradation processes are quite difficult to measure. Optical data are not sufficient since the difference in reflectivity together with natural variations between forest and degenerated forest is often not significant (DeFries et al., 2006). Even if there are no publications focusing on degradation monitoring with LiDAR, its applicability can be deduced from related studies. Change detection with LiDAR data has been analysed in a few studies with different objectives. Wulder et al. (2007) compared canopy attributes within a time interval of 5 years. They found that within a short time period of 5 years it is critical to map tree growth for large forest areas, due to the high impact of error sources not related to tree growth. They found segment-based changes in canopy attributes, providing spatially explicit indications of forest growth and depletion. However, the difference in the magnitude of these changes was significantly greater for depletions than it was for growth. Therefore, in an area-based approach, LiDAR reflectance features indicating growth can be leveled out by depletions. Hyyppä et al. (2009) describe problems which can occur in a plot-wise or single tree-based assessment of changes. These problems refer to matching with different data sets, changes in forests due to management measures (e.g. thinning) or natural damages (e.g. windfall, insects) and sensor-dependent affects. For biomass, the natural variations during the year have also to be considered. There are currently no publications describing how reliable and accurate biomass changes can be estimated, based on LiDAR data. There are some investigations into height and volume change assessment in boreal forest situations by Yu et al. (2008) who compared three different methods: individual tree top differencing, digital surface model (DSM) differencing and canopy height distribution differencing. The results show that for tree height differencing the individual tree top approach works best, while for volume change assessment, the combination of all three methods gave best results.

Recent publications indicate that in spite of the underestimation of single tree numbers based on LiDAR data it is beneficial to estimate the proportion of tree species by the single tree approach and apply species specific models in mixed forest for the estimation of biomass. Rowell et al. (2009) show that for biomass equations which can be fine-tuned to a single species, an improved overall prediction accuracy is possible. According to the R^2 values they measured, they achieved a decrease of the error within the range of 25–50% compared to generalized models. Straub and Koch (forthcoming) reported that models which include the mean crown area, derived from single tree delineations together with tree height metrics and broadleaf/conifer proportion, provide better wood volume, diameter and age estimations than without the single tree information. In their investigation, the observed error for stem volume estimation using variables for height and vegetation structure was about 30% (RMSE [%]) in richly structured, mixed stands. This is in the same range of the errors reported for pure conifer stands (Breidenbach, 2008) in South Germany and close to the errors measured for pure and more homogeneous conifer stands in Finland (Packalen and Maltamo, 2006). These results demonstrate the potential of the integration of single tree information with area-based measures or statistics for an improved quantification of biomass.

Investigations show that the missing information on tree species from LiDAR data is a weakness for biomass estimations. However, the separation of broadleaf trees and conifers is possible with high levels of accuracy from LiDAR data. For the separation of broadleaf and conifer, either height differences of the major reflection layers in leaf-off status (Dees et al., 2006; Liang et al., 2007; Koch et al., 2009) or intensity values (Ørka et al., 2009; Kim

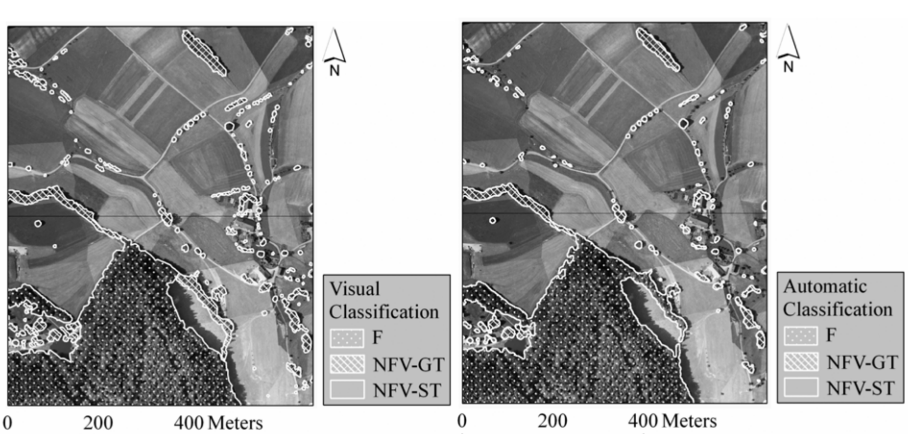

Fig. 2. Result of the visual classification (left) and automatic classification (right) (Straub et al., 2008).

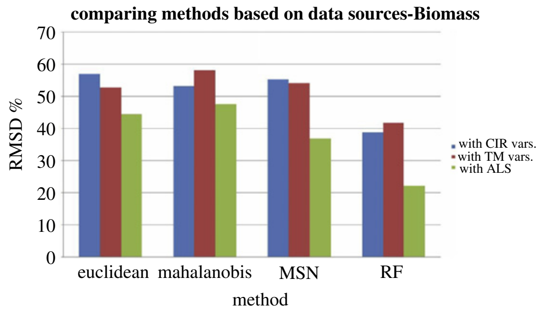

Fig. 3. RMSE % in optical and LiDar data using different k-NN methods compared to random forest at test site Karlsruhe, Germany.

et al., 2009) are used. For the methods using height differences in leaf-off status, the overall accuracies are higher than 90%, while for intensity data alone or in combination with structural features, the results differ between 70% and 80%. The intensity-based classification between the broadleaf and conifer seems better in leaf-off status than under the leaf-on condition (Brandtberg, 2007). A combination of intensity and echo width also seems to improve the classification accuracy in discriminating broadleaf from conifer trees (Reitberger et al., 2008). Not many investigations exist on further discrimination of tree species based on LiDAR features. Vauhkonen et al. (2010) reported for the classification of Scots pine, Norway spruce and deciduous trees an accuracy of 78% using alpha shape metrics and variables based on height and intensity distribution. For the classification they used the k-most similar neighbor and the random forest method and found not much difference in the results. Höfle et al. (2008) indicated that it is possible to use mean echo width to separate larch from deciduous trees. They used airborne LiDAR data produced by a RIEGL LMS-Q560 full waveform laser scanner during the winter and spring season 2006/2007 under leaf-off conditions. Following a classification of coniferous and deciduous trees, Hollaus et al. (2009) used the standard deviation of the echo width per crown to further separate spruce from larch. Heinzel and Koch (forthcoming) attempted to separate dominating tree species based on high density, fullwave laser data during leaf-on status. They computed a high number of waveform, structural and intensity-based parameters and with linear discriminant analysis they selected the top ten variables. They achieved an overall accuracy of over 80% for spruce, pine, beech and oak separation. The investigation showed that reflectance points close to the surface contribute best to the discrimination of tree species and that intensity and echo width of single return echoes are most important.

Wu et al. (2009) reported on direct biomass estimations based on full waveform-derived metrics achieving accuracies of around 73%. Investigations by Latifi et al. (forthcoming) showed that with LiDAR data, direct biomass estimations using a variety of different methods are superior to optical data. The random forest algorithm provided compared to different k-NN methods the best performance (Fig. 3).

The publications indicate that with increasing availability of new laser data, advanced methods are being developed integrating the geometric and physical-based LiDAR features to better exploit the wealth of information for different applications in forestry. In respect of biomass mapping, the study shows the potential of the new data quality, but the extraction of features for biomass estimations has just started.

3. Synthetic aperture radar for forest biomass mapping

SAR (synthetic aperture radar) data are of high interest for forest biomass mapping (Dobson et al., 1992; Rignot et al., 1997; Santoro et al., 2002a,b; Ranson and Sun, 1994; Thiel et al., 2006) especially for reasons of their relative weather independence. There are numerous publications on the use of radar data for forest cover and biomass assessment. For forest cover mapping and biomass estimations, three basic approaches based on SAR data are used: backscatter, coherence and phase-based approaches. If the measurement of biomass mapping is based on backscatter values or on coherence, then there exist clear limitations. Limiting factors are the roughness of the objects in relation to the wavelength, the weather influence at different data take times (Zhou et al., 2008), the exact co-registration and the saturation. If indirect methods are used to estimate biomass, the most important single forest variable is the tree or canopy height. Only SAR interferometric techniques such as repeat–pass or single pass interferometry (InSAR) and polarimetric interferometry (PolInSAR) can provide such information using radar data.

In the past, approaches based on backscatter intensities have been used to establish a relationship with biomass. The results show that a direct relationship with biomass is difficult to establish for areas which contain wood volumes greater than 100–150 m^3/ha. L-band JERS-1 data were used in forest biomass estimation (Fransson and Israelsson, 1999; Rauste, 2005). Fransson and Israelsson (1999) obtained R^2 values of 0.57…0.60 between the exponential of stem volume and radar differential backscattering coefficient σ^0 in three JERS scenes. However, they respectively estimated the saturation point (the amount of stem volume after which an increase in stem volume cannot be observed as an increase in σ^0) at 136, 130, and 157 m^3/ha in these three scenes. Rauste (2005) estimated the saturation point at 150 m^3/ha. The RMSE in stem volume estimation varied from 44.79 to 61.25 m^3/ha in three summer-time JERS scenes with stem volumes between 0–364 m^3/ha. However, in many forested areas the stem volume per hectare is clearly above this saturation point.

Today, polarimetry and interferometry has a strong research focus, not only to map deforestation and degradation as an input for biomass calculations, but also to get better relationships with direct biomass estimations. The most prominent project during the last few years within the European community was the SIBERIA (SAR Imaging for Boreal Ecology and RADAR Interferometry Applications) project. In this project, different space radar data in the C- and L-band domain were tested. Gaveau et al. (2003) reported that coherence images under winter conditions are much more sensitive to changes in woody biomass (biomass of the wooden parts of plants) than the C- and L-band backscatter intensity. They demonstrated the boreal forest woody biomass mapping capabilities of coherence images for very large areas. However, the results relate to boreal conditions and rather low wood volume which is very different to what can be expected in temperate, sub-tropical and tropical regions. Thiel et al. (2009) investigated the mapping of different forest areas based on winter coherence data and summer intensity values of the L-band ALOS/Palsar data. In this study, they reported that based on L-HV intensity values and winter coherence values, the forested land can be delineated and classified from other land cover types. Within the forested area, a separation of older and younger clearing areas was also possible using the backscatter information of L-HH and HV polarization together with coherence information. They demonstrated that using an object based classification for forest areas in Siberia, a separation with a classification accuracy of around 90% was possible. However the coherence calculations were based on a winter situation which only exists in some forest growing regions. The use of L-band backscatter alone for deforestation was also not appropriate for studies over tropical rain forest (Almeida-Filho et al., 2007). The integrated use of multi-angle and multi-mode L-band data however proved to increase the accuracy in land cover identification in the tropics, in comparison to single-angle and single-mode L-band data (Langner et al., 2008). At C-band, Smith and Askne (2001) reported that backscatter intensity is of little use for mapping of deforestation as a result of clear cutting. With repeat pass interferometry in short repeat cycles, the assessment of clear cuts greater 4 ha was possible with a success rate of 95%. The first instance of detecting changes in forest cover using ALOS/Palsar L-band data based on backscatter intensity information only was reported by Fransson et al. (2008, 2007). They found that there is a difference in the fine beam dual mode (look angle 34°) for HH- and HV backscatter between the forested stands and the clear cuts. The signature analysis also showed that for data acquired under different environmental conditions and viewing geometries, the fine beam mode HV-backscatter, acquired under unfrozen conditions and shallower look angles, is useful to indicate forest change. This underlines the importance of the polarimetric information as accessible today and in future from satellite-based systems.

A comprehensive overview of the phase-based approaches is provided by Baltzer et al. (2007). The phase-based techniques exploit the interference patterns of two electromagnetic waves to estimate the topographic height of the scattering phase centre. The location of the scattering phase centre depends on vegetation structure, scattering mechanisms and sensor characteristics. Leave, branches, stems and ground are the scatterers in the forests. Which part of the forest interacts most strongly with the radar wave depends on the wavelength, the polarization, incidence angle and of course on the vegetation itself, like thickness and density of the crown area. PolInSAR (Polarimetric Synthetic Aperture Interferometry) systems will be of increasing relevance for forest applications because there will be data available which provide single pass conditions in the near future (TerraSAR-X with TanDEM-X). Under these conditions, it should be possible to extract better height information over forests. Height is one of the important input variables when estimating the biomass. The allometric equations for biomass estimations are of high quality also in dense stands when height is one of the input variables. Therefore, a method which provides the extraction of heights from Earth observation data is of high interest. One approach in the future might be the extraction of height data using the phase information from new InSAR or PolInSAR systems. Most of the recent investigations on phase-based extraction of forest height used experimental airborne data to avoid problems with temporal and atmospheric decorrelation (Balzter, 2001; Askne et al., 2003; Askne and Santoro, 2005). A phase-based interferometric approach was used by Baltzer et al. (2007), in which they used an E-SAR campaign L-band HH for ground height and Xband VV for canopy height measurements. They report that in open forests, the L-band HH polarization can be used to calculate the ground height and the X-band VV polarization to derive canopy heights from forests. They achieved a relative error to LiDAR canopy height of around 29%.

Only few investigations exist for space borne data (Papanthanassiou et al., 2000). Interferometric SIR-C shuttle radar data at C- and L-bands were studied over the tropical rain forest by Rignot (1996). At the L-band, the RMS difference in inferred topographic height between the forest and adjacent clearings was 5 m, equivalent to the height noise.

As mentioned before, repeat–pass InSAR is limited in its accuracy by temporal decorrelation caused by changes in temperature, orientation angle of the scatterer and moisture changes between the two SAR acquisitions. Papathanassiou and Cloude (2003), Zhou et al. (2008) and Lee et al. (2009) have studied the effects of temporal decorrelation. Lee et al. (2009) reported that temporal decorrelation even within 1 day leads to high overestimations in forest height. The temporal decorrelation is not one constant value but depends strongly on forest height and wind-induced motions. In the long term, events like changing ground conditions, water content or fellings will also increase decorrelation. A study conducted by Kellndorfer et al. (2004) to determine the feasibility of vegetation canopy height measurements from data collected during the 2000 Shuttle Radar Topography Mission (SRTM) with a C-band InSAR instrument, suggested that a minimum mapping unit of approximately 1.8 ha is needed to achieve acceptable estimates under repeat–pass conditions. Papathanassiou and Cloude (2001) described a coherent scattering model for single baseline polarimetric SAR data which can be inverted to estimate canopy height. Currently, the model is based on airborne data in which the temporal decorrelation is neglected, but may be transferred to single pass EO data when it is available.

In the future, there is an opportunity to apply all these findings to satellite data, when TanDEM X data are available. De Zan et al. (2009) simulated TanDEM-X with different baselines to test different models for forest height and structure extraction. They report that even with only three to four interferograms, they can reconstruct a profile which might give sufficient height and forest structure information to support biomass estimation. The extraction of reliable heights from interferometric phase-based measurements would significantly improve the performance of the biomass estimation based on SAR data. A number of different models can be tested for the extraction of height from phase-based interferometric measurements if the respective single pass data are available. The most well-known model is the random volume over the ground model. Zhou et al. (2009) describe the use of the model and how height measurements can be improved using single pass multi-baseline PolInSAR data.

A recent approach to extract forest height and stand structure from radar data is the use of tomographic methods (Guillaso and Reigber, 2005; Cloude and Papathanassiou, 2008). Here a real 3D imaging of the scene is obtained by creating an additional synthetic aperture in elevation, using a coherent combination of images acquired from parallel flight tracks. There are not many investigations on the SAR tomography for forests and they all are at a very early research stage. One of the few applications on forests is based on multi-baseline airborne P-band data by Frey et al. (2008). They report that for the P-band the high intensity values are, as expected, located on the ground level. However they point out that high intensity values within tomographic images are accompanied by considerable side lobes and ambiguities in the normal direction. They see the suppression of the ambiguities as a main challenge in order to improve the quality of tomographic images. With the TanDEM mission also tomographic campaigns will be started. Therefore, can be expected that tomographic methods will be more intensively investigated in the future for radar-based forest applications. However, it should be remembered that this method contains many problems which still need to be resolved.

4. Multi- and hyperspectral data for forest biomass mapping

Optical satellite data only provide good results in the discrimination of largely differing biomass classes. For the biomass estimation, parameters referring to the near infrared, such as brightness and wetness, are relevant (Roy and Ravan, 1996). Rahman et al. (2007) demonstrated the suitability of optical data based on Landsat ETM to estimate the severe changes to forest biomass and carbon sequestration due to forest degradation using a statistical approach with dummy variables. Small changes in biomass and mapping of differences at a high biomass volume level with optical data are difficult due to the loss of correlation. Degradation processes can be assessed by very high resolution satellite data based on pattern changes. Pattern changes can indicate subtle biomass changes (GOFC-GOLD, 2009). Biomass mapping can be improved by species and health status information. A better assessment of this information might be possible with hyperspectral data. Darvishsefat et al. (2002) tested Hymap data to classify different mixture grades between conifers and deciduous stands. They used unmixing methods and came up with a separation of qualitative mixture grades. Buddenbaum et al. (2005) tried to separate different species and tree densities in conifer stands. They achieved a classification accuracy of 74% using advanced geo-statistical methods.

In recent years, the use of hyperspectral data has been validated for biomass applications. This was also supported by hyperspectral satellite-based systems which deliver hyperspectral data in relatively high spatial resolution, like the Hyperion, CHRIS/Proba or the future EnMap system (launch 2013). The expectations for hyperspectral data are improved species identification, a better mapping of biochemical status of trees and the possibility of estimating biomass directly from the data. Many papers have been published to analyze suitable band and vegetation indices for tree species classification (Buddenbaum et al., 2005; Dian et al., 2009; Dudeni et al., 2009; Debba et al., 2009; Odagawa and Okada, 2009; Apan et al., 2009). However, the robustness of the indices in general is not demonstrated and the indices are often difficult to interpret. In addition, end-member methods are used for tree species separation using hyperspectral data. The methods have proved to be quite valuable (Darvishsefat et al., 2002). A combination of an angular and an end-member approach resulted in an overall species classification accuracy of 74% for trees in the African savannah (Cho et al., 2009). However, the existing spectral libraries needed for the end-member method do not really serve the complex forest situation for detailed species discrimination in temperate or tropical forests. Multiangular information is used for further tree species discrimination and also for the assessment of structural and biochemical parameters (Simic and Chen, 2009). This might have increasing relevance for forest parameter extraction in future work with hyperspectral data. The assessment of the LAI and the biochemical status of forest or forest trees is a major research field using hyperspectral data. Schlerf et al. (2005), Schlerf (2006), Darvishzadeh et al. (2008), Huber et al. (2008) and Xue and Yang (2008) produced some of the publications in which they have analyzed the extraction of biochemical and LAI information from hyperspectral images. They all confirm that there exist strong relationships between certain vegetations indices and the biochemical status of the trees. However, the indices vary between different investigations. The LAI is strongly correlated with the reflectance and can be described quite well with a number of vegetation indices. Le Maire et al. (2008) described a set of indices to extract the canopy leaf biomass from Hyperion data. However, the assessment of the above-ground biomass seems difficult on the basis of hyperspectral data. Schlerf (2006) even states that the above-ground biomass cannot be retrieved from hyperspectral data, because there is only a poor relationship between stem biomass and the vegetation indices. The reflectance inversion models he tested underestimated the stem density in dense forests. He recommends the use of a combination of different remote sensing data for the above-ground biomass estimations. A future development in the use of hyperspectral data for biomass estimations might be the use of inverse modelling, but these investigations are still at an early stage. Zhang et al. (2008) reported a strong correlation (R^2 of 0.9) of inverted and measured leaf reflectance in the visible and near infrared. However with the modified PROSPECT inversion model only an R^2 of 0.4 was obtained for leaf chlorophyll content. In general, the future use of hyperspectral data for the above-ground biomass estimations will most probably be coupled with other types of remote sensing data. A direct estimation of the above-ground biomass based only on hyperspectral data is not likely, especially in stands with high biomass.

5. Multi-sensoral data for forest biomass mapping

Recently, the use of multi-sensoral data for forest applications has gained interest, because the use of multi-sensoral data together with improved methods may overcome some of the problems which are faced with single data sets. Few investigations have been carried out in multi-sensoral techniques for forest biomass estimations. However, due to the different wavelength used, data collection techniques and processing methods, the information which can be extracted is complementary and improves the quality of requested information. For biomass estimations, the tree or forest type, the crown coverage, the forest layer structure and the height is of imminent importance to achieve reliable estimations. For the direct derivation of biomass from remote sensing data, no single data type can fulfil all requirements and is limited by different frame conditions, weather, saturation and other bio-physical conditions. The suitability of diverse remote sensing data types for certain forest parameters will compel the use of multi-sensoral data sets to deliver the requested biomass mapping products. The use of multi-sensoral data will also be of increasing interest due to the fact that more systems will be available in space.

In general, the multi-sensoral approach with optical and LiDAR data improves the wood volume estimation and based on this, the biomass assessment. This is mainly due to the complementary information content of the data, like tree species type from optical data and the height information from LiDAR data. The extraction of the tree-type information is difficult with LiDAR data alone; therefore, many investigations combine LiDAR data with optical data sets. Straub et al. (2009), Dees et al. (2006) and Maltamo et al. (2006) provide examples of research which utilised the combination of LiDAR with optical data to improve wood volume estimates. In general, the combination of LiDAR and optical data is aimed at an improved species identification based on structural and spectral information (Holmgren et al., 2008; Hill and Thomson, 2005; Koukoulas and Blackburn, 2005; Persson et al., 2004). A number of investigations have been carried out, mostly based solely on airborne data, but also airborne LiDAR and space borne optical data have been used in combination. Chen and Hay (2009) developed a statistical approach which correlates height measurements based on LiDAR transects with the Quickbird image features and transfers the height information with the help of Quickbird images to a wall-to-wall mapping. Results show a good model performance with an RMSE of 6.6 m on average for the area. Further analysis of different transect numbers showed that with a subset of LiDAR transect samples (about 44% coverage) a similar performance to that using LiDAR data for the entire study site was possible. Mcinerney et al. (2010) combined LiDAR data with data from medium resolution IRS (Indian Remote Sensing) satellite to predict canopy height for a larger area. They identified band 1 and 4 of the satellite imagery as the best variables to assign height estimations from LiDAR with the k-NN method to areas not covered by LiDAR. They report a relative RMSE between 28% and 31% and conclude that no good results have been achieved by the combination of LiDAR and optical satellite data.

Quite often, combinations of radar and optical data have been tested. Moghaddam et al. (2002) combined AirSAR data with Landsat TM data and achieved better results than with the single data sets. A multi-sensoral approach for radar data and optical data was also carried out by Treuhaft et al. (2003, 2004). They estimated forest biomass from multi-altitude, airborne, C-band SAR interferometry based on density profiles and normalized them by the leaf area index from airborne hyperspectral optical imagery. This gave a forest canopy leaf area density as a measure for biomass. Banskota et al. (2009) tested BioSAR data, a radar system specifically designed for the estimation of biomass, in combination with imaging LiDAR data for biomass assessment.

They found neither BioSAR nor imaging LiDAR alone were good predictors for biomass. The best results were achieved with the combination of the two data sets. For the combined data set, they achieved an R^2 between 0.76 and 0.8. Hyde et al. (2007) reports about tests on low-frequency BioSAR data in comparison to LiDAR for pine biomass assessment. For the best five-variable RaDAR model 81.8% (R^2) are explained while for the best one-variable LiDAR model 93.3% (R^2) of the biomass variation is explained. They conclude that there is only little or no gain combining radar with LiDAR. One approach, which combines radar and LiDAR for vegetation mapping and biomass estimation, is the DesDynl mission project of NASA (DesDYNL project website, 2008). In this project, the information from airborne and space borne radar data are combined with the information derived from the IceSAT/GLAS system. For the estimation of biomass or C stock in the future, probably the use of multi-sensoral data will be of increasing interest due to the fact that more systems will be available and the better quality of information they deliver. In order to increase the usage of the multi-sensoral approach, methods are needed which allow the combination or fusion of the data. For example Klonus and Ehlers (2009) used data fusion techniques with TerraSAR-X and optical data.

6. Conclusion and beyond the state-of-the art

There are numbers of new space missions anticipated which in general will launch several very high resolution optical satellites, using cheaper and smarter technology than today. The most significant missions will be the Pleiades of CNES, the TopSat UK, CBERS China and the mission under the Indian Resource Program. All these missions will deliver very high resolution optical data in the VIS/NIR and will improve the global coverage of very high resolution optical data.

Future radar imaging missions, such as Sentinel 1 with C-Band, the TerraSAR-X/TanDEM-X mission, the RadarSat program of the Canadian Space Agency and the radar mission by the Jaxa organization in Japan, will provide a wealth of new radar data which is complementary in wavelength, polarization and spatial resolution to the existing once. This will provide a good basis to develop further methods for forest coverage mapping based on imaging radar data. The forest height extraction from imaging satellite radar data is not operational today and needs further investigation. A likely advance will be the availability of single pass data from space and low-frequency polarimetric systems like that designed for the BIOMASS (Kellndorfer, 2009) mission. This is designed to perform biomass estimations based on P-band PolInSAR data. Such a system would give complementary information to other radar imaging systems. The higher temporal coherence of P-band data will provide more reliable height measurements as an input for biomass estimations. For forest biomass estimations, the modelling of forest heights from radar interferometry will be an important step forward. In this respect, the radar tomography may become a leading technological approach.

New data will also be provided in the future from hyperspectral systems. This data can help improve the information on the tree type, LAI and biochemical status. The space missions expected in the future are the EnMap, the PRISMA and, in the medium resolution part, the MERIS mission. In particular, tree species and leaf area information from hyperspectral data can play an important role as input for biomass estimation.

For biomass estimation, the IceSat/GLAS system has also proved valuable. There is a new mission planned for IceSAT/GLAS II in 2015 (NASA, 2007). Even though this is the only currently scheduled mission with a space-borne LiDAR system, it can be expected that the topic will receive increasing attention from other space agencies. Airborne LiDAR has proved its importance and suitability for reliable biomass estimations; therefore, the integration of LiDAR data is of great interest also for large area biomass inventories. Developments in airborne LiDAR systems are expected to reach the market within the next decade. Due to the expected technical innovations and the performance of LiDAR data for biomass assessment, it can be assumed that LiDAR will play a prominent role in biomass estimations. The importance of LiDAR data is confirmed by a number of investigations which repeatedly showed higher performance of LiDAR data compared to other data types. The altimetric information combined with physical values like the intensity derived from LiDAR is suitable for predicting canopy structure and consequently biomass estimations.

If the different remote sensing systems are compared for biomass mapping, the major advantage of optical satellite imagery is its availability for a time period of more than three decades previous and its spectral sensitivity for species identification. The problems highlighted with optical data, are those of frequent mapping in cloudy areas and the loose correlation between spectral response and biomass, especially in classes with high biomass volume. The main issue today in estimating biomass from SAR data is the temporal decorrelation. Temporal decorrelation makes it difficult to calculate height or coherence based on interferometric methods. For the direct method approach, the saturation which occurs with higher biomass restricts the application of radar data to forest areas with low biomass volume. The sensitivity to roughness makes it additionally difficult for high-frequency data to find a clear boundary between forest and non-forest areas. For LiDAR, its weaknesses are the relative high costs, the nearly complete restriction to airborne platforms and an existing knowledge gap on the interactions between LiDAR beams and vegetation. For LiDAR and Radar, there are still a lot of possible improvements in the development of the sensor technology, as well as of the methodologies for information extraction. For optical data, the angular reflectance effects and the best use of hyperspectral data still need to be fully investigated.

A major challenge within the next years is also the more intensive development of integration models for multi-sensoral data. For the upcoming technological innovation in the field of radar, hyperspectral and LiDAR data, new algorithms and methods need to be developed and tested as single data sets and in combination. In the future, more data modelling for a better understanding of the interactions between the actively or naturally emitted radiance and the forest is required. A challenge is to understand the interactions under various forest conditions. A thorough understanding of these interactions will lead to new and particularly more robust information processing algorithms and statistical models. Great care needs to be taken in the development of robust methods; only robust algorithms which can be applied under different natural growing conditions will open up new operational applications.

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