THE EARTH OBSERVATION MISSION CARBON-3D – A SYNERGETIC MULTI-SENSOR APPROACH TO GLOBAL BIOMASS MAPPING FOR AN IMPROVED UNDERSTANDING OF THE CO_2 BALANCE

S. Hese[a], C. Schmullius[a], R. Dubayah[b], W. Lucht[c], M. Barnsley[d]

[a] Friedrich-Schiller University Jena, Institute for Geoinformatics and Remote Sensing, Löbdergraben 32, 07743 Jena, Germany, (soeren.hese, c.schmullius) @uni-jena.de

[b] University of Maryland, Department of Geography, College Park, MD 20742, USA, dubayah@geog.umd.edu

[c] Potsdam Institute for Climate Change Impact Research, Telegrafenberg C4, Postfach 601203, 14412 Potsdam, Germany, wolfgang.lucht@pik-potsdam.de

[d] University of Wales, Swansea, Department of Geography, Singleton Park, Swansea, SA2 8PP Wales, UK, m.barnsley@swansea.ac.uk

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ABSTRACT:

To estimate the potential impact of global climate change an improved knowledge of the carbon cycle and its variability is essential. In response to an announcement of the German Aerospace Center (DLR) for a national Earth observation mission, the Friedrich-Schiller University Jena and the JenaOptronik GmbH proposed the EO-mission CARBON-3D. The data products of this multi sensor mission will for the first time accurately estimate above-ground biomass, one of the most important parameters of the carbon cycle. This mission will simultaneous acquire data with a multi-angle optical instrument and with NASAs Lidar system VCL (Vegetation Canopy Lidar). The second instrument onboard Carbon-3D is a BRDF-imager that extrapolates the laser-retrieved height profiles to biophysical vegetation maps using the horizontal, spectral information as well as multidirectional information. This innovative mission will greatly reduce uncertainties about net effects of deforestation and forest re-growth on atmospheric CO_2 concentrations and will also provide key biophysical information for biosphere models (DVMs – Dynamic Vegetation Models).

1 INTRODUCTION

In 2003 the Friedrich-Schiller University Jena and the JenaOptronik GmbH proposed the Earth Observation mission "CARBON-3D" for global biomass mapping combination the Lidar system VCL (Vegetation Canopy Lidar) with a BRDF (Bidirectional Reflectance Distribution function) - imager on one platform. CARBON-3D improves knowledge about spatio-temporal patterns and magnitudes of major carbon fluxes between land, atmosphere and oceans, and allows quantifying above-ground stocks. Since land use, land use change and forestry activities as well as vegetation response to enhanced levels of atmospheric CO_2 are major influences on greenhouse gas emissions, quantifying carbon stocks and changes is critical (Cihlar *et al.* 2002). Above-ground biomass stocks are also a key parameter in assessing the economic, conservation, and biofuel potential of land surfaces. The provision of a sensor that measures these stocks and their change in space and time is therefore paramount. The mission is also relevant for contributing key data on the environmental consequences of non-climatic global change resulting from continued global population growth, economic globalisation and expanding land use.

The technical innovation of CARBON-3D is the simultaneous operation of a LIDAR (NASA's Vegetation Canopy Lidar - VCL) with a multi-angle imager providing BRDF-information (Bidirectional Reflectance Distribution Function). CARBON-3D´s strength is the combined information on both, the fine-scale vertical structure of the canopy (through waveform analysis of the vertical laser profile) and biophysical properties of the surface targets (through multi-angular optical observation of vegetation targets with three-dimensional spatial structure). The spectral information allows extrapolation of the point measurements to complete spatial coverage.

Large-footprint LIDAR remote sensing is a breakthrough technology for the estimation of important forest structural characteristics. The waveform information (Fig. 1) enables direct determination of vegetation height, the vertical structure of intercepted surfaces and the sub-canopy topography. A critical issue and key requirement for accurate parameter assessment is the ability to identify precisely the top of the canopy, as well as the ground reference level.

Accurate retrieval of vertical forest parameters is essential as other biophysical forest characteristics, such as biomass, stem diameter and basal area, are modelled on the base of these measurements. Above-ground biomass is commonly modelled using the height information by performing regression analyses or applying allometric height-biomass relations (Drake *et al.* 2003). Traditional predictive models require information on stem diameter to estimate biomass and volume. This parameter is a function of tree height and thus, could be inferred on the basis of LIDAR data. One major limitation of stand-alone LIDAR systems is their capability to retrieve locally sparse information on vertical forest structure only. For spatially consistent biomass assessment, information on horizontal biophysical forest parameters e.g. phenology and forest type is essential. To gain such information simultaneously the proposed CARBON-3D mission will be equipped with the multi-angle imager in the range of VIS/NIR/SWIR.

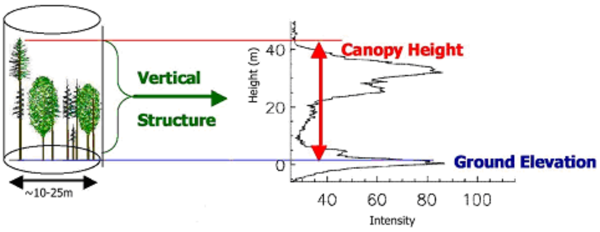

Figure 1. Direct retrieval of vertical forest structure by LIDAR remote sensing (from Dubayah & Drake 2000).

Driven mainly by the needs of NASA's MISR and MODIS mission, considerable work was done regarding the development of BRDF model inversion algorithms for vegetation, surface and climate parameter retrieval (Knyazikhin *et al.* 1998; Lucht *et al.* 2000). With the high spatial resolution of CARBON-3D it will be possible to exploit more complex BRDF models, i.e. physically-based approaches, for precise parameter retrieval. In addition, the use of Look-Up Table (LUT) techniques is expected to enable the derivation of the geophysical data products with a high accuracy (Barnsley *et al.* 2000).

Data provided by the BRDF-instrument onboard the CARBON-3D satellite are also required to extrapolate spatially, regionalizing the LIDAR point measurement on vegetation structure between the transects, and to regions where no LIDAR data exist. Developing ways of using optical data (i.e. the multi-angle imager data) for spatial extrapolation of forest structure as derived from locally sparse LIDAR data is central to the mission objectives.

2 STRATEGIC POSITIONING OF CARBON-3D

The role of vegetation in reducing atmospheric levels of CO_2 has been recognised in a number of international agreements (e.g. United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol) which specifically require countries to quantify their carbon stocks and changes. Plants store carbon in above- and below-ground biomass, 90 per cent of the above-ground carbon is stored in tree stems – which are being reduced through natural (diseases, wildfires, drought/flooding) and anthropogenic impacts (logging, pollution, human-induced fires) or vice-versa increased through regeneration or promoted growth associated with elevated CO_2 levels in the atmosphere (Wardle *et al.* 2003).

Currently, the magnitude of the terrestrial carbon sink is considerably reduced by expanding land use. In the 1990s, terrestrial uptake has been estimated to have been 1.6-4.8 billion tons of carbon per year (GtC/yr), a notable fraction of the 6.3 GtC/yr that have been emitted from fossil fuel burning. However, losses due to land use are estimated to have amounted to 1.4 to 3.0 GtC/yr, leaving the net uptake of carbon from the atmosphere by the biosphere to have been about 1.0 ± 0.8 GtC/yr (House *et al.* 2003). This sink is the result of the combined changes in carbon content of vegetation, litter and soils. Changes in the carbon flux from vegetation into the litter and soil pools can be estimated from the carbon pools in vegetation. The relative magnitudes of these fluxes demonstrate the importance of interactions between atmospheric composition, biospheric biogeochemistry and land use for determining the rate of climate change.

CARBON-3D will be an essential contribution to carbon cycle investigations by providing crucial and unique data on vegetation biomass, vegetation productivity, and vegetation types and structure (compare with Figure 2). Model-based extensions of these data will also allow estimations of soil carbon stocks and dynamics with unprecedented spatial detail, and hence the land surface carbon balance. Particularly, the spatial heterogeneity of carbon-related vegetation properties, such as the status of re-growth in intensely managed forests, will be quantified.

These products will fill substantial gaps in current continental-scale carbon assessments which are specifically related to problems of spatial heterogeneity and scaling, as well as reliable quantifications of pool sizes. By observing biomass around the globe, the proposed mission will build a much needed bridge between knowledge gained at sites and the spatially poor resolved information from atmospheric inversion studies (Janssens *et al.* 2003). Biogeochemical process models of vegetation and soil and the associated carbon and water fluxes will benefit from the upscaling and validation data that will be available and it will be possible to assimilate the observations into these simulations.

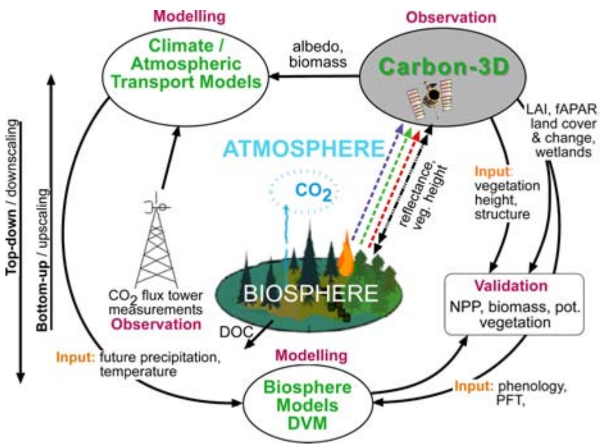

Figure 2. Role of CARBON-3D in the observation and modelling strategy of the carbon cycle.

Vegetation biomass is the direct result of vegetation productivity, that is, of the net carbon exchange between the atmosphere and the photosynthetically active tissues of plants. Estimates of net primary production will be improved by not only using estimates of absorbed light, as do current satellite-based algorithms, but also the observed vegetation structure in terms of types and age. This will provide a firm basis for the estimation of autotrophic respiration, a critical but highly uncertain

component of previous satellite-driven global model estimates of net primary production.
The implications of changes in biomass for the atmospheric greenhouse gas balance and the future evolution of climate change is critical. The temporal and spatial variations in observations of atmospheric CO_2 contain a strong biospheric signal. There is substantial evidence from model studies that the current role of the terrestrial biosphere as a net sink for CO_2, and therefore a brake on the build-up of anthropogenic CO_2 in the atmosphere could be reversed during this century as a result of climate change.

3 BIOMASS DETERMINATION BY REMOTE SENSING

Myneni *et al.* (2001) and Dong *et al.* (2003) provide examples of using optical remote sensing data to determine biomass with high spatial resolution at the continental scale using NDVI. Their method of correlating seasonally integrated measures of satellite-observed vegetation greenness with ground-based inventory data amounts to a spatial interpolation and extrapolation of the inventory data. While pioneering, the work is indirect in that direct space-based measurements of biomass are not available. The upscaling used relies on the unknown degree to which the sample of inventories used is representative of the whole of a continental area.

Correlations of Synthetic Aperture Radar (SAR) data to biomass have been proven at low frequencies L- and P-band (Le Toan *et al.* 1992; Ranson *et al.* 1997; Rowland *et al.* 2002, Ericsson *et al.* 2003) and at C-band using ERS-1/2 repeat-pass interferometry (Santoro *et al.* 2002) and combining ERS tandem interferometric coherence and JERS backscatter (Balzter *et al.* 2002; Wagner *et al.* 2003). Multi-polarimetric SAR data allow interpretation of the canopy structure up to 200t/ha above-ground biomass at P-band and 100t/ha at L-band (Dobson *et al.* 1992). Recently developed PolInSAR techniques, combining polarimetry and interferometry (Papathanassiou and Cloude 2001; Cloude and Papathanassiou 1998) provide better vegetation characterisation and a sensitivity up to 400 t/ha (Mette *et al.* 2003). No such system is foreseen yet for operational service in space but the PolInSAR techniques will be tested within the framework of the “Kyoto and Carbon Initiative” with PALSAR (Phased Array type L-band Synthetic Aperture Radar) data from ALOS (Advanced Land Observing Satellite) (Rosenqvist *et al.* 2001; Rosenqvist *et al.* 2003). ALOS is planned to be launched in 2005.

In contrast to the frequent attempts of using SAR for biomass estimations only a few airborne light detection and ranging (LIDAR) missions have been developed and validated: the Laser Vegetation Imaging Sensor (LVIS) and the Scanning Lidar Imager of Canopies by Echo Recovery (SLICER). Results of these studies have demonstrated that large-footprint LIDAR instruments show great promise in biomass estimation of tropical as well as temperate forests due to the information about the location of the intercepting surfaces and sub canopy topography (Drake *et al.* 2002a; Lefsky *et al.* 1999a; Lefsky *et al.* 1999b). Due to the correlation between light absorption and net carbon uptake by vegetation, a range of diagnostic methods exist for converting optical satellite observations into estimates of net primary production (e.g., Potter *et al.* 2003; Veroustraete *et al*. 2002; Nemani *et al.* 2003). The relationship between these quantities is considerably moderated by effects of temperature and soil moisture, limiting the accuracy of the assessment. The use of satellite data, however, ensures fine spatial and temporal detail. Derivation of biomass from these estimates requires use of a full biogeochemical process model.

4 DESCRIPTION OF THE MISSION

CARBON-3D is designed to ensure the overall science driven goal: global acquisition of a combined, synergistic BRDF-LIDAR-dataset to continuously map height profiles and reflectance to retrieve biomass. Required ground data will be obtained from terrestrial monitoring sites linked to worldwide observation networks and associated regional projects. The scientific project leader is coordinating ESA’s Landcover Implementation Office starting in 2004 and will be able to establish close links to global landcover validation activities and the CEOS landcover validation team. If CARBON-3D will be selected for the phase A and B study in 2004 and 2005 the system will be launched in 2009.

4.1 The CARBON-3D BRDF Sensor

The BRDF imager is a multispectral pushbroom imager that is sampling the Bi-directional Reflectance Distribution Function of the target scenery (Table 1). The mission design lifetime will be two years with an orbit of 390-410 km (with monthly reboost to 410 km using monopropellant hydrazine).

BRDF Instrument Description	
Sensor / FOV	Along-track capability / ±3.5° x ±2°
Directional Sequence	Between 3 and 7 angles (desirable) (+/- 50°, +/- 25°, 0°)
Spatial Resolution	Nadir: < 25 m, Off-Nadir: ~ 50 m
Image Swath	Swath: 50 – 100 km
Spectral bands	3 – 5 channels (blue, red, NIR, SWIR 1.6 µm & 2.2µm)
Radiometric Resolution	12 bits
SNR	200:1
Data rate	8 Mbps compressed
Design Lifetime	3 years

Table 1. BRDF instrument characteristics

The spatial resolution at nadir will be < 25 m to match the VCL resolution, allowing for approximately 50 m spatial resolution at the extreme off-nadir angles for BRDF angular acquisitions. The BRDF Imager will consist of two identical Three-Mirror-Anastigmat (TMA) imaging sub-systems, a nadir imager and an off-nadir imager.

4.2 *The Carbon-3D VCL Sensor*

The Vegetation Canopy LIDAR (VCL) instrument consists of 3 near-infrared laser beams (Table 2).
The instrument is designed to operate at an orbital altitude of 400 km ± 10%. That does require orbital maintenance every few weeks, but higher orbits have a significant impact on the quality of the received laser signal.
Laser altimetry is the only space-based remote sensing technique capable of measuring tree heights in closed canopies. Waveform analyses based on extensive airborne and spaceborne Laser altimetry have revealed the need for footprint sizes of about one to two canopy diameters. This guarantees a resulting reflection from the vertical top of canopies within the sampled area, as well as sufficient intra- and inter-tree gaps required to image the underlying ground.

VCL Instrument Description	
Lasers	3 Nd:YAG diode-pumped pulsed lasers at 1064 nm
Laser Pulses	242 pps (land), 10 mJ per pulse (EOL) (15 M, BOL)
Telescope	0.9 m f/1 parabolic mirror with 20 mrad total FOV and 0.3 mrad IFOV
Waveform Digitisation	250 Mega samples/sec
Resolution	25 m (60 µrad) footprint diameter, 400 km altitude
Track Spacing and Swath	4 km (3 tracks with 4 km spacing), swath: 8 km
Elevation Accuracy	~ 1 m in low slope terrain
Veg. Height Accuracy	~ 1 m limited by 100:1 pulse detection dynamic range
Design Lifetime	1 year, goal: 2 years

Table 2. VCL instrument characteristics

Sufficient laser output energy and dynamic range in the receiver are required to detect small (~ 1%) returns from the canopy top and, even in dense canopies, the underlying ground. Smaller footprints underestimate true canopy height (reduced probability of sampling the top of the canopy). Conversely, with larger footprints, similar to those of the ICESat mission (Ice, Cloud and land Elevation Satellite) with the Geoscience Laser Altimeter System (GLAS) (Zwally *et al.* 2002), the fraction of the total return contributed by the canopy top is greatly reduced, making height measurements inaccurate, especially in mature forests with great height variability (ICESat‘s primary scientific objective is to measure changes in elevation of the Greenland and Antarctic ice sheets as part of NASA’s Earth Observing System of satellites).

5 SUMMARY

CARBON-3D will be of importance for vegetation and carbon cycle studies as it provides the first instrument capable of retrieving accurate biomass information from regional to global scales.
Remote sensing only serves to diagnostically analyse the current state of the vegetation. It can neither analyse the actual flux of carbon through the system nor predict the future development and changes of vegetation patterns. Therefore, prognostic vegetation models are necessary for a prediction of future sources and sinks of carbon (Lucht *et al.* 2001).
The Multi-Angle Imager provides BRDF-data delivering more comprehensive land surface information in terms of its spectral, directional, spatial and temporal characteristics than data acquired from mono-directional observations (Verstraete *et al.* 1996; Barnsley *et al.* 1997; Diner *et al.* 1999; Asner 2000). The determination of the chemical and physical structure of land surfaces improves bio-physical modelling. Secondly, these data products improve existing vegetation parameters such as LAI, fAPAR, and NPP (Knyazikhin *et al.* 1998; Roberts 2001). Furthermore, a reliable computation of albedo is granted improving climate modelling. These data can only be achieved from a multi-angle instrument as on-board CARBON-3D.

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REFERENCES

Asner, G. 2000. Contribution of multi-view angle remote sensing to land surface and biogeochemical research. Remote Sensing Revision, vol. 18, 137-162.

Balzter, H., Talmon, E., Wagner, W., Gaveau, D., Plummer, S., Yu, J. J., Quegan, S., Davidson, M., Le Toan, T., Gluck, M., Shvidenko, A., Nilsson, S., Tansey, K., Luckman, A., and Schmullius, C. 2002. Accuracy assessment of a large-scale forest cover map of central Siberia from synthetic aperture radar, Canadian Journal of Remote Sensing, vol. 28, 6, pp. 719-737.

Barnsley, M.J., Allison, D., and Lewis, P. 1997. On the information content of multiple view angle (MVA) images. Int. J. of Remote Sens., vol. 18, 1937-1960.

Barnsley, M.J, Lewis, P., O'Dwyer, S., Cutter, M., Disney, M.I., Hobson P.D. & Lobb, D. 2000. Potentials of CHRIS-PROBA for mapping vegetation characteristics from space, Remote Sensing Reviews, vol. 19:171-189.

BMBF Bundesministerium für Bildung und Forschung 2001. Deutsches Raumfahrt programm. http://www.dlr.de/dlr/Raumfahrt/Index/drp.pdf, found on 07-23-03.

BMBF Bundesministerium für Bildung und Forschung 2002. Forschung für den Klimaschutz – Stand und Perspektiven - No. 160/2002, http://www.bmbf.de/pub/forschung_fuer_den_klima-schutz.pdf, (found 08.12-03).

Cihlar, J.R., Denning, S., Ahern, F., Arino, O., Belward, A., Bretherton, F., Cramer, W., Dedieu, G., Field, C., Francey, R., Gommes, R., Gosz, J., Hibbard, K., Igarashi, T., Kabat, P., Olson, D., Plummer, S., Rasool, I., Raupach, M., Scholes, R., Townshend, J., Valentini, R. and Wickland, D. 2002. Initiative to quantify terrestrial carbon sources and sinks. – In: Eos, Transactions, vol. 83, no. 1: 1, 6-7.

Cloude, S. R., and Papathanassiou, K. P. 1998. Polarimetric SAR interferometry, *IEEE Transaction on Geoscience and Remote Sensing*, vol. 36, 5, pp. 1551-1565, 1998.

Diner, D.J., Beckert, J.C., Reilly, T.H., Bruegge, C.J., Conel, J.E., Kahn, R., Martonchik, J.V., Ackerman, T.P., Davies, R., Gerstl, S.A.W., Gordon, H.R., Muller, J.-P., Myneni, R., Sellers, R.J., Pinty, B. and Verstraete, M.M. 1998. Multiangle Imaging SpectroRadiometer (MISR) description and experiment overview, *IEEE Transactions on Geoscience and Remote Sensing,* vol. 36: 1072-1087.

Diner, D.J., Asner, G.P., Davies, R., Knyazikhin, Y., Muller, J.-P., Nolin, A.W., Pinty, B., Schaaf, C.B., and Stroeve, J. 1999. New directions in earth observing: Scientific applications of multiangle remote sensing, Bull. Amer. Meteorol. Soc., vol. 80, 2209-2228.

DeFries, R, Hansen, M., Townshend, J.R.G., Janetos, A.C., and Loveland, T.R. 2000. A new global 1 km data set of percent tree cover derived from remote sensing, *Global Change Biology*, 6: 247-254.

DLR Deutsches Zentrum für Luft- und Raumfahrt 2003. Fachprogramme Raumfahrt – Aktualisierung, 2002/2003, http://www.eid.dlr.de/dlr/Raumfahrt/Fachprogramm_2003.pdf, found on 07-28.03.

Dobson, M.C., Ulaby, F.T., Le Toan, T., Beaudoin, A., Kasischke, E.S. and Christensen, N. 1992. Dependence of radar backscatter on coniferous forest biomass. – In: *IEEE Transactions on Geoscience and Remote Sensing*, vol. 30, no. 2: 412-415.

Dong, J., Kaufmann, R.K. Myneni, R.B., Tucker, C.J. Kauppi, P.E., Liski, J., Buermann, W., Alexeyev, V. and Hughes, M.K., 2003. Remote sensing estimates of boreal and temperate forest woody biomass: carbon pools, sources and sinks. – In: *Remote Sensing of Environment*, vol. 84: 393-410.

Drake, J.B., Dubayah, R. O., Clark, D.B., Knox, R.G., Blair, J.B., Hofton, M.A., Chazdon, R.L., Weishampel, J.F. and Prince, S. 2002a. Estimation of tropical forest structural characteristics using large-footprint lidar, *Remote Sensing of Environment*, vol. 79: 305–319.

Drake, J.B., Dubayah, R.O., Knox, R.G., Clark, D.B. and Blair, J.B. 2002b. Sensitivity of large-footprint lidar to canopy structure and biomass in a neotropical rainforest, *Remote Sensing of Environment*, vol. 81: 378 – 392.

Drake, J.B., Knox, R.G., Dubayah, R.O., Clark, D.B., Condit, R., Blair, J.B. and Hofton, M. 2003. Above-ground biomass estimation in closed canopy Neotropical forests using lidar remote sensing: factors affecting the generality of relationships. – In: *Global Ecology & Biogeography*, vol. 12: 147 – 159.

Dubayah, R. and Drake, J.B. 2000. Lidar remote sensing for forestry applications. In: *Journal of Forestry*, vol. 98: 44-46.

Dubayah, R., Knox, R., Hofton, M., Blair, J. B. and Drake, J. 2000. Land surface characterization using LIDAR remote sensing. - In: Hill, M. and Aspinall, R. (eds.), 2000: Spatial Information for Land Use Management. - International Publishers Direct, Singapore.

Eriksson, L. E.B., Santoro, M., Wiesmann, A., Schmullius, C. 2003. Multi-Temporal JERS Repeat-Pass Coherence for Growing Stock Volume Estimation of Siberian Forest, *IEEE Transactions on Geoscience and Remote Sensing,* vol. 41, No.7, pp.1561-1570, July 2003.

FAO Food And Agricultural Organization Of The United Nation (eds.) 2002. Global forest resources assessment 2000. – Main Report. FAO Forestry Paper 140, Rome, Italy.

House, J.I., Prentice, I.C., Ramankutty, N., Houghton, R.A., and Heimann, M. 2003. Reconciling apparent inconsistencies in estimates of terrestrial CO2 sources and sinks, Tellus, vol. 55B: 345-363.

Knyazikhin, Y, Martonchik, J.V., Diner, D.J., Myneni, R.B., Vertraete, M., Pinty, B., and Gobron, N. 1998. Estimation of vegetation canopy leaf area index and fration of absorbed photosynthetically active radiation from atmosphere-corrected MISR data. – In: *Journal of Geophysical Research*, vol. 103, 32239-32356.

Lefsky, M.A., Harding D., Cohen W.B., Parker G.G. and Shugart H.H. 1999a. Surface lidar remote sensing of basal area and biomass in deciduous forests of eastern Maryland, USA, *Remote Sensing of the Environment*, vol. 67: 83-98.

Lefsky, M.A., Cohen W.B., Acker, S.A., Parker G.G., Spies, T.A. and Harding, D. 1999b. Lidar remote sensing of the canopy structure and biophysical properties of Douglas-Fir Western Hemlock Forests, *Remote Sensing of the Environment*, vol. 70: 339-361.

Lefsky, M.A., Cohen W.B., Parker G.G. and Harding, D. 2002. Lidar remote sensing for ecosystem studies, *BioScience*, vol. 52, no. 1: 19 – 30.

Le toan, T. 1992. Relating forest biomass to SAR data, *IEEE Transactions on Geoscience and Remote Sensing*, vol. 30, no. 2: 403-411.

Lim, K., Treitz, P., Wulder, M., St-Onge, B. and Flood, M. 2003. Lidar remote sensing of forest structure, *Progress in Physical Geography*, vol. 27, no. 1: 88 – 106.

Lucht, W., Schaaf, C.B. and Strahler, A.H. 2000. An algorithm for the retrieval of albedo from space using semiempirical BRDF models, *IEEE Transactions on Geoscience and Remote Sensing,* vol. 38, no. 2: 977 – 998.

Lucht, W., Bondeau, A., Sitch, S., Cramer, W., Venevsky, S. and Thonicke, K. 2001. Synergistic use of satellite data and a dynamic model of the global biospheric carbon cycle 8th Int. Symp. Phys. Meas. Signat. in Remote Sensing, Aussois, France, January 8-12, p. 659-668.

Means, J.E., Acker, S.A., Harding, DJ., Blair, J.B., Lefsky, M.A., Cohen, W.B., Harmon, M.E. and McKee, W.A. 1999. Use of large-footprint scanning airborne lidar to estimate forest stand characteristics in the western cascades of Oregon, *Remote Sensing of Environment*, vol. 67, no. 3: 298 – 308.

Mette, T., Papathanassiou, K.P., Hajnsek, I. and Zimmermann, R. 2003. Forest biomass estimation using polarimetric SAR interferometry. - Proceedings of POLinSAR 2003, Frascati, Italy, January 14-16, 2003.

Myneni, R.B., Dong, J., Tucker, C.J., Kaufmann, R.K., Kauppi, P.E., Liski, J., Zhou, J., Alexeyev, V. and Hughes, M.K. 2001. A large carbon sink in the woody biomass of Nothern forests, PNAS, vol. 98, no. 26: 14784-14789.

Papathanassiou, K. P., and Cloude, S. R. 2001. Single-baseline polarimetric SAR interferometry, *IEEE Transaction on Geoscience and Remote Sensing*, vol. 39, 11, pp. 2352-2363.

Ranson, K. J., Sun, G., Lang, R. H., Chauhan, N. S., Cacciola, R. J. and Kilic, O. 1997. Mapping of boreal forest biomass from spaceborne synthetic aperture radar, *Journal of Geophysical Research*, vol. 102, no. D24: 29,599-29,610.

Roberts, G. 2001. A review of the application of BRDF models to infer land cover parameters at regional and global scales, *Progress in Physical Geography*, vol. 25, no. 4: 483 – 511.

Rojstaczer, S., Sterling, S.M. and Moore, N.J. 2001. Human appropriation of photosynthesis products, Science, vol. 294: 2549-2552.

Rosenqvist, Å., Ogawa, T., Shimada, M., and Igarashi, T. 2001. The ALOS Kyoto and Carbon Initiative - An introduction to CEOS, *Proceedings of 15th CEOS Plenary Meeting*, Kyoto, Japan, 6-7 November 2001, CEOS/15/CR/04, 2001.

Rosenqvist, Å., Shimada, M., Igarashi, T., Watanabe, M., Tadono, T., and Yamamoto, H., 2003. Support to multi-national environmental conventions and terrestrial carbon cycle science by ALOS and ADEOS-II - the Kyoto and Carbon Initiative, *Proceedings of IGARSS'03*, Toulouse, France, 21-25 July 2003.

Rowland, C., Balzter, H., Dawson, T., Luckman, A., Skinner, L. and Patenaude, G. 2002. Biomass estimation of Thetford forest from SAR data: potential and limitations. ForestSAT Conference August 2002, Edinburgh, UK.

Santoro, M., Askne, J., Smith, G., and Fransson, J.E.S. 2002. Stem Volume Retrieval in Boreal Forests with ERS-1/2 Interferometry, *Remote Sensing of Environment*, vol. 81, 1, pp.19-35, 2002.

UNFCCC 2000. A guide to the Climate Change Convention and its Kyoto Protocol, Bonn, Germany.

Veroustraete, F., Sabbe, H., and Eerens, H. 2002. Estimation of carbon mass fluxes over Europe using the C-Fix model and Euroflux data, *Remote Sensing of Environment*, vol. 83, 376-399.

Verstraete, M. M., Pinty, B., and Myneni, R. 1996. Potential and limitations of information extraction on the terrestrial biosphere from satellite remote sensing, *Remote Sensing of Environment*, vol. 58, 201-214.

Wardle, D.A., Hörnberg, G., Zackrisson, O., Kalela-Brundin, M. and Coomes, D.A. 2003. Long-term effects of wildfire on ecosystem properties across an island area gradient, Science, vol. 300: 972 – 975.

Yoshimura, M. and M. Yamashita 2001. BRF measurement onto tropical forest canopy. http://www.tropicanopy.org /project/pdf/cd-2.9(yoshimura).pdf (found on 09-16-03).

Zwally, H.J., Schutz, B., Abdalati, W., Abshire, J., Bentley, C., Brenner, A., Bufton, J., Dezio, J., Hancock, D., Harding, D., Herring, T., Minster, B., Quinn, K., Palm, S., Spinhirne, J. and Thomas, R. 2002. ICESat's laser measurements of polar ice, atmosphere, ocean and land, *Journal of Geodynamics*, vol. 34: 405-445.