Photogrammetrie • Fernerkundung • Geoinformation 5/2004, S. 413–422, 4 figs., 3 tab.

CARBON-3D – an International Earth Observation Mission for Global Biomass Mapping for an Improved Understanding of the CO_2 Balance

CHRISTIANE SCHMULLIUS, SÖREN HESE & WOLFGANG LUCHT, Jena

Keywords: remote sensing, biomass, Lidar, carbon, global change, biosphere models, CARBON-3D, CO_2

Summary: Understanding global climate change and developing strategies for sustainable use of our environmental resources are major scientific and political challenges. 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 mission will for the first time accurately estimate above-ground biomass globally, one of the most important parameters of the carbon cycle. Simultaneous acquisition of multi-angle optical with LIDAR (Light Detection and Ranging) observations is unprecedented. This innovative mission will 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.

Zusammenfassung: *CARBON-3D – eine internationale Erdbeobachtungsmission zur globalen Biomassenkartierung für ein verbessertes Verständnis der Treibhausgasbilanz.*

Das Verständnis des globalen Klimawandels und die Entwicklung von Strategien für die nachhaltige Nutzung unserer Umwelt sind die derzeit wichtigsten wissenschaftlichen und politischen Herausforderungen. Als Antwort auf einen Aufruf des Deutschen Zentrums für Luft- und Raumfahrt (DLR) zu einer nationalen Erdbeobachtungsmission schlagen die Friedrich-Schiller-Universität Jena zusammen mit der JenaOptronik GmbH die Mission „CARBON-3D“ vor, mit deren Daten erstmalig die terrestrische Biomasse, einer der wichtigsten Parameter des Kohlenstoffkreislaufs, präzise bestimmt werden kann. Der simultane Einsatz eines multidirektionalen optischen Sensors mit einem LIDAR-Sensor wird die Unsicherheiten über die Effekte von Abholzung und Wiederaufforstungen auf den atmosphärischen CO_2-Gehalt reduzieren. Dadurch wird eine entscheidende Validierungsgrundlage für die Modellierung der zukünftigen Entwicklung der CO_2-Quellen und -Senken durch Biosphärenmodelle gegeben.

1 Introduction

Understanding climate change processes and developing strategies for sustainable use of our environment to combat climate change on a global scale is a major scientific and political challenge. In response to a call of the German Aerospace Centre (DLR) the Friedrich-Schiller University Jena and the JenaOptronik GmbH proposed the EO-mission "CARBON-3D" for global biomass mapping.

CARBON-3D improves knowledge about spatio-temporal patterns and magnitudes of major carbon fluxes between land, atmosphere and oceans, and allows to quantify 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

1432-8364/04/2004/0413 $ 2.50

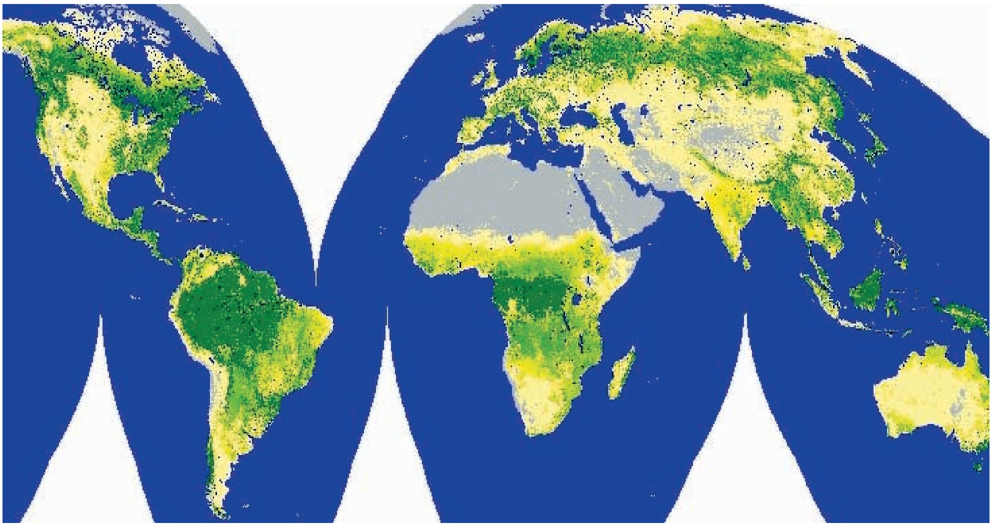

Fig. 1: Global tree cover in % (white: 0 %, dark green: 100 %) retrieved from NOAA AVHRR (DeFries et al. 2000). Uncertainties exist for global forest cover estimates (between 30 to 60 Mio km^2) and carbon stored in different types of forests (stock ranges from 100 to 400 t C/ha with biome).

greenhouse gas emissions, quantifying carbon stocks and changes is critical (Cihlar et al. 2002). Above-ground biomass stocks (Fig. 1) 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 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 BRDF 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 enables direct determination of vegetation height, the vertical structure of intercepted surfaces and the sub-canopy topography (Fig. 2). 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. Traditional predictive models require information on stem diameter to estimate biomass and volume. This parameter is a function of tree height

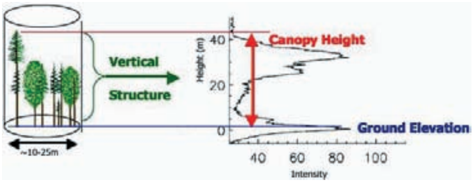

Fig. 2: Direct retrieval of vertical forest structure by LIDAR remote sensing (from Dubayah & Drake 2000).

and thus, could be inferred on the basis of LIDAR data.

Recent studies have proven the high benefit of large-footprint scanning airborne LIDAR: depending on the respective study area, total above-ground biomass as estimated from field data could be predicted from airborne LIDAR-derived metrics with R^2 values of up to 0,96 on biomass levels of 1300 t/ha which is far exceeding the capabilities of radar (LEFSKY et al. 1999).

For spatially consistent biomass assessment, information on horizontal biophysical forest parameters e. g. phenology and forest type is also essential. To gain such information the proposed CARBON-3D mission will be equipped with a multi-angle imager in the range of VIS/NIR/SWIR. 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).

2 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, 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.

Currently, the magnitude of the terrestrial carbon sink is considerably reduced by expanding land use. In the 1990ies, 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 provide crucial and unique data on vegetation biomass, vegetation productivity, and vegetation types and structure. Model-based extensions of these data will also allow estimations of soil carbon stocks and dynamics. 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 immensely benefit from the upscaling and validation data that will

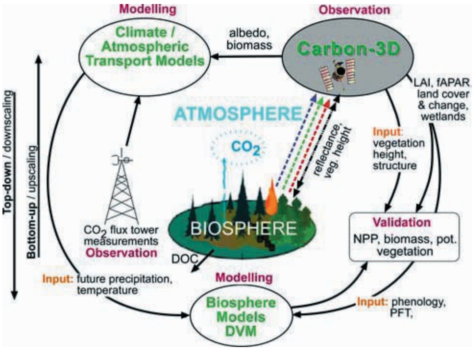

Fig. 3: Potential role of CARBON-3D in the observation and modelling strategy of the carbon cycle.

be available and it will be possible to assimilate the observations into these simulations (Fig. 3).

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 Carbon Fluxes – Scientific and Technological State of the Art

An observation system for carbon stocks and fluxes in vegetation consists of both, observations and modelling. Observations characterise spatial and temporal patterns of vegetation structure and activity, while modelling allows to infer from such observations a full carbon account of the surfaces viewed by computing the climate-dependent biogeochemical processes that contribute to the overall surface budget, including the dynamics of carbon pools not accessible to observation (e. g. in soils) (NEMANI et al. 2003). A side effect of such modelling is that the magnitude of evapotranspiration and resulting effects upon soil moisture can be estimated at the same time due to the close coupling of the carbon and water cycles in vegetation. The following three chapters describe how biomass and carbon fluxes are being determined.

3.1 *In-situ Biomass and Carbon Determination*

At the tree level, biomass cannot be assessed directly by non-destructive methods but is usually derived from measurements such as diameter-at-breast-height (dbh), tree height and wood density using conversion factors. These biomass estimation methods are relatively time-consuming and expensive, not uniformly standardized across the world, and are characterized in many regions by under-sampling. Uncertainty also arises from insufficiently validated allometric equations. Upscaling of inventory data to the continental scale remains a challenge (JANSSENS et al. 2003) and is possible only where the sampling density is sufficient (SHVIDENKO & NILSSON 2002).

Around 100 flux towers have been installed around the globe to directly measure net carbon exchanges above canopies. These measurements of net fluxes do not immediately allow a differentiation between CO_2 exchanges through vegetation and CO_2 exchanged by soils. An extrapolation of the obtained data to the continental scale (PAPALE & VALENTINI 2003) remains uncertain, but they provide valuable process understanding. Direct measurements of atmospheric CO_2 concentrations are undertaken at a network of stations. Their spatial differences can be inverted by taking into account wind and emission patterns as well as the effect of the oceans in order to deduce source-sink distributions for very large regions (BOUSQUET et al. 1999). The results suffer from a lack of regional pattern and insufficient sampling, but are extremely valuable as the only currently available independent information on large-scale net fluxes.

3.2 *Simulation of Biomass and NPP in Biosphere Models*

Carbon-fluxes between atmosphere and biosphere can be estimated using a range of global biosphere models that simulate the magnitude and geographical distribution of biomass and NPP (CRAMER et al. 1999). These models range in complexity from regressions between climatic variables and one or more estimates of biospheric trace gas fluxes to quasi-mechanistic models that simulate the biophysical and eco-physiological processes. Several different classification systems and descriptions of biosphere models exist in the literature (e. g. CRAMER et al. 1999, PRENTICE et al. 2000). The simplest differentiation is that into Static (Equilibrium) and Dynamic Vegetation Models

(SVMs and DVMs). SVMs are time-independent and assume equilibrium conditions in climate and terrestrial vegetation in order to simulate the global distribution of potential vegetation by relating the geographic distribution of climatic parameters to vegetation. DVMs are time-dependent process-based models that simulate the carbon balance of ecosystems under climatically induced changes to ecosystem structure and composition. The great strength of DVMs is their generality and predictive capability. By accurately representing the biophysical processes involved, they allow calculations of the long-term behaviour of vegetation systems under changing climate (Cramer et al. 1999, Prentice et al. 2000). In order to achieve this, they use generalised plant functional types (PFTs) to represent the state of vegetation in each grid cell and to simulate plant succession processes like establishment, tree growth, competition and mortality.

Fire occurrence is modelled based on natural probabilities as a joint function of vegetation and litter state and climate. The majority of models addresses the potential natural state of vegetation, though increasingly human processes are being incorporated, most notably agriculture. In mechanistic models, biogeochemical fluxes in the vegetation-soil system are computed on the basis of soil type, climate and atmospheric carbon dioxide concentration without additional reference to external data. Exchanges of water and carbon through the stomates of leaves are simulated as physiologically coupled water and carbon balances. Hydrological processes taken into consideration include percolation, evaporation, snow fall and permafrost. Carbon assimilation is calculated from numerical simulations of photosynthesis.

The carbon gained is used for plant respiration, growth and reproduction following allometric relationships that ensure functional and structural coherence. Carbon fluxes into the litter and soil are estimated from vegetation parameters. Computations of climatically dependent soil decomposition are used to calculate the net carbon balance of the vegetation-soil system as the difference between vegetation net uptake and carbon release from soils and through fire. Vegetation models have been shown to be able to reproduce a wide range of observed data from seasonal cycles of atmospheric carbon dioxide concentrations and growth rates to runoff and soil moisture, global vegetation patterns and satellite-observed trends in vegetation greenness (Wagner et al. 2003, Lucht et al. 2002). Due to their generalised nature, however, they are not fully capable of producing the full spatial and temporal detail of the real world, nor can human alterations of the land surface be inherently formulated as mechanistic processes.

Recently, a new type of regional vegetation models, which aim at combining process-based descriptions and available knowledge on individual landscapes in the form of a multi-layer GIS (Geo Information System) has been proposed (Shvidenko & Nilsson 2002).

3.3 *Biomass Determination by Remote Sensing*

Myneni et al. (2001) provides 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 data to biomass have been proven at low frequencies L- and P-band (Le Toan et al. 1992). 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, provide better vegetation characterisation and a sensitivity up to 400t/ha (METTE et al. 2003). No such system is foreseen yet for operational service in space.

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 subcanopy topography (DRAKE et al. 2002, LEFSKY et al. 1999). 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. 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 (Fig. 4) 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.

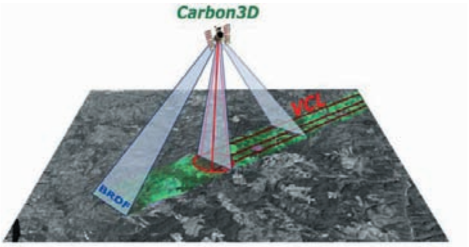

Fig. 4: CARBON-3D BRDF imager and VCL data acquisition configuration.

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 (Tab. 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).

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 subsystems, 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 (Tab. 2).

The instrument is designed to operate at an orbital altitude of 400 km $\pm$ 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

Tab. 1: BRDF instrument characteristics.

BRDF Instrument Description	
Sensor/FOV	Along-track capability/ ± 3.5° × ± 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 & 2,2 μm)
Radiometric Resolution	12 bits
SNR	200 : 1
Data rate	8 Mbps compressed
Design Lifetime	3 years

Tab. 2: VCL instrument characteristics.

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

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. Smaller footprints underestimate true canopy height (reduced probability of sampling the top of the canopy). Conversely, with larger footprints, similar to those of ICESat mission, the fraction of the total return contributed by the canopy top is greatly reduced, making height measurement inaccurate, especially in mature forests with great height variability.

5 CARBON-3D Data Products

CARBON-3D will provide level 1 (raw data), level 2 (post processed data: radiance, reflectance, vertical distribution of interception) and level 3 data (empirical or semi-empirical science algorithms that build the products) (Tab. 3). The combination of the BRDF and the LIDAR information will lead to new and innovative data products (3-dimensional structure of landcover with global coverage, improved landcover and vegetation type mapping, vegetation parameter re-

Tab. 3: Potentials of VCL and the Multi-Angle Imager for deriving vegetation parameters.

LIDAR – vertical	BRDF – horizontal	LIDAR & BRDF – 3D
• Vegetation height • Vertical distribution of intercepted surfaces • Subcanopy topography • Biomass • Crown volume • Stem diameter • Basal area • Forest age • Density of large trees	• Surface & spectral reflectance • Surface radiance • Surface emissivity • Albedo • Land cover mapping • Vegetation fraction • Phenology • Chlorophyll content • LAI, fAPAR, NPP	• 3-dimensional structure of land cover • Improved land cover and vegetation type mapping • Improved vegetation parameter retrieval (e. g. LAI) • Derivation of life form diversity

trieval (LAI) and life form and physiognomic diversity analysis (Tab. 3). Level 4 products (NPP, forest age) will be the output from the modelling science community.

The following list of applications are anticipated for the CARBON-3D products: global 3-D canopy structure maps, improved parameterisation of Global Circulation Models, improved parameterisation of bio-geochemical vegetation models, improved forest parameters and deforestation information for forest inventories, fire susceptibility, fuel accumulation, biodiversity/desertification/shrub encroachment research, detection of habitat features associated with rare or endangered species and the control of subsidised land use.

6 Relevance to International Science-orientated Programmes

Since the early 1990's, international organisations have been working towards the establishment of systematic, long-term observation systems. To facilitate progress in the challenge of obtaining and disseminating global carbon-cycle observations, space agencies and international research programmes have established a coordination mechanism: the Integrated Observing Strategy Partnership (IGOS-P). IGOS-P established a Terrestrial Carbon Observation theme (TCO) under guidance of GTOS. CARBON-3D directly serves the IGOS requirements and supplies the missing global biomass map as a solid prerequisite to carbon accounting.

Further international research with respect to the global carbon cycle is organised through the ESA Living Planet Programme including the Earth Observation Envelope Programme (EOEP) and the Earth Watch Programme (EWP), the Orbiting Carbon Observatory (OCO) mission and the Global Monitoring of Environment and Security (GMES).

7 Summary

CARBON-3D will be of outstanding importance for vegetation and carbon cycle studies as it provides the first instrument capable of retrieving accurate biomass information from regional to global scales using combined LIDAR – BRDF-imager data.

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 monodirectional 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.

Acknowledgement

Gratefully acknowledged is the work of all other members of the Carbon-3D proposal team: Ralph Dubayah, Mike Barnsley, Kathleen Neumann, Daniela Knorr, Tanja Riedel and Karin Schröter.

References

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

Barnsley. M.J., Allison, D. & Lewis, P., 1997: On the information content of multiple view angle (MVA) images. – Int. J. Remote Sensing, **18:** 1937–1960.

Bousquet, P., Peylin, P., Ciais, P., Le Quérè. C., Friedlingstein, P. & Tans, P.P., 1999: Regional changes in carbon dioxide fluxes of land and ocean since 1980. – Science, **290:** 1342–1346.

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. & Wickland, D., 2002: Initiative to quantify terrestrial carbon sources and sinks. – Eos, Transactions **83** (1): 1, 6–7.

Cramer, W., Kicklighter, D.W., Bondeau, A., Moore III, B., Churkina, G., Nemry, B., Ruimy, A., Schloss, A.L. and the participants of the Potsdam NPP Model Intercomparison, 1999: Comparing global models of terrestrial net primary productivity (NPP): overview and key results. – Global Change Biology 5, S1: 1–15.

DeFries, R, Hansen, M., Townshend, J.R.G., Janetos, A.C. & 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.

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

Dobson, M.C., Ulaby, F.T., Le Toan, T., Beaudoin, A., Kasischke, E.S. & Christensen, N., 1992: Dependence of radar backscatter on coniferous forest biomass. – IEEE Transactions on Geoscience and Remote Sensing, **30** (2): 412–415.

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

Dubayah, R. & Drake, J.B., 2000: Lidar remote sensing for forestry applications. – Journal of Forestry, **98:** 44–46.

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

Janssens, I.A., Freibauer, A., Ciais, P., Smith, P., Nabuurs, G.-J., Folberth, G., Schlamadinger, B., Hutjes, R.W.A., Ceulemans, R., Schulze, E.-D., Valentini, R. & Dolman, A.J., 2003: Europe's terrestrial biosphere absorbs 7 to 12% of European anthropogenic CO2 emissions. – Science, **300:** 1538–1542.

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

Lefsky, M.A., Harding D., Cohen W.B., Parker G.G. & 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, **67:** 83–98.

Le Toan, T., 1992: Relating forest biomass to SAR data. – IEEE Transactions on Geoscience and Remote Sensing, **30** (2): 403–411.

Lucht, W., Schaaf, C.B. & Strahler, A.H., 2000: An algorithm for the retrieval of albedo from space using semiempirical BRDF models. – IEEE Transactions on Geoscience and Remote Sensing, **38** (2): 977–998.

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

Lucht, W., Prentice, I. C., Myneni, R. B., Sitch, S., Friedlingstein, P., Cramer, W., Bousquet, P., Buermann, W. & Smith, B., 2002: Climatic control of the high-latitude vegetation greening trend and Pinatubo effect. – Science, **296:** 1687–1689.

Mette, T., Papathanassiou, K. P., Hajnsek, I. & 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. & Hughes, M. K., 2001: A large carbon sink in the woody biomass of Nothern forests. – PNAS **98**, 26: 14784–14789.

Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R. B. & Running, S. W., 2003: Climate-driven increases in global terrestrial net primary production from 1982 to 1999. – Science, **300:** 1560–1563.

Papale, D. & Valentini, R., 2003: A new assessment of European forests carbon exchanges by eddy fluxes and artificial neural network spatialization. – **9:** 525–535.

Prentice, C., Heimann, M. & Sitch, S., 2000: The carbon balance of the terrestrial biosphere: ecosystem models and atmospheric observations. – Ecological Applications, **10** (6): 1553–1573.

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, **25** (4): 483–511.

Shvidenko, A. & Nilsson, S., : Dynamics of Russian Forests and the Carbon Budget in 1961–1998: An Assessment based on Long-Term Forest inventory data. – Climatic Change, **55:** 5–37.

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

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

Wagner, W., Scipal, K., Pathe, C., Gerten, D., Lucht, W. & Rudolf, B., 2003: Evaluation of the agreement between the first global remotely sensed soil moisture data with model and precipitation data. – J. Geophys. Res., **108:** 4611.

Address of authors:

Prof. Dr. Christiane Schmullius,
Dr. rer. nat. Sören Hese
Friedrich-Schiller University Jena, Institute for Geoinformatics, Remote Sensing Section, Löbdergraben 32, D-07743 Jena
phone: ++49 30 948877,e-mail: {c.schmullius; soeren.hese}@uni-jena.de

Dr. rer. nat. Wolfgang Lucht
Potsdam Institute for Climate Change Impact, PO Box 601203, D-14412 Potsdam, Germany, phone ++49-331 2882533, e-mail: wolfgang.lucht@pik-potsdam.de

Manuskript eingereicht: Februar 2004
Angenommen: April 2004