# Synergism of optical and radar data for forest structure and biomass

## Sinergismo entre dados ópticos e de radar da estrutura da floresta e biomassa

Sassan S. Saatchi[1]


## Abstract

The structure of forests, the three-dimensional arrangement of individual trees, has a profound effect on how ecosystems function and carbon cycle, water and nutrients. Repeated optical satellite observations of vegetation patterns in two-dimensions have made significant contributions to our understanding of the state and dynamics of the global biosphere. Recent advances in Remote Sensing technology allow us to view the biosphere in three-dimensions and provide us with refined measurements of horizontal as well as vertical structure of forests. This paper provides an overview of the recent advances in fusion of optical and radar imagery in assessing terrestrial ecosystem structure and aboveground biomass. In particular, the paper will focus on radar and LIDAR sensors from recent and planned spaceborne missions and provide theoretical and practical applications of the measurements. Finally, the relevance of these measurements for reducing the uncertainties of terrestrial carbon cycle and the response of ecosystems to future climate will be discussed in details.


**Key words:** LIDAR; structure of forest; biomass and carbon.


## Resumo

A estrutura de florestas, o arranjo tridimensional de árvores individuais, tem um efeito profundo sobre o funcionamento dos ecossistemas e do ciclo do carbono, água e nutrientes. Repetidas observações de satélite óptico de padrões de vegetação em duas dimensões trouxeram contribuições significativas para a nossa compreensão do estado e da dinâmica da biosfera global. Recentes avanços na tecnologia de Sensoriamento Remoto nos permitem ver a biosfera em três dimensões e nos fornecer medições apuradas da estrutura horizontal, bem como a vertical das florestas. Esse artigo fornece uma visão geral dos recentes avanços na fusão de imagens ópticas e de radar para avaliar a estrutura do ecossistema terrestre e biomassa. Em particular, o trabalho concentra-se em sensores radar e LIDAR de recentes missões espaciais planejadas e fornece aplicações teóricas e práticas das medições. Por fim, a relevância dessas medidas para reduzir as incertezas do ciclo de carbono terrestre e de resposta dos ecossistemas ao clima no futuro será discutida em detalhes.


**Palavras-chave:** LIDAR; estrutura florestal; biomassa e carbono.

1 Jet Propulsion Laboratory 4800; Oak Grove Drive Pasadena, CA 91109; Email: Saatchi@jpl.nasa.gov

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## Introduction

We cannot account for the ultimate fate of more than one-third of the 6 billion tons of carbon we emit into the atmosphere each year. This so-called "missing carbon" (2-3 PgC $yr^{-1}$) represents the uncertainty in our understanding of the carbon budget. Indirect analyses of atmospheric data and models suggest that the sink is in terrestrial ecosystems, but direct measurements have not demonstrated such a sink. Several studies in recent years have discussed this problem and the urgency for understanding the terrestrial sources and sinks of carbon (Houghton et al., 2009). These studies have prompted the interest in quantifying the carbon budget of forested landscape because the biomass of forests and woodland ecosystems constitute the main component of terrestrial carbon pool. However, a methodology for measuring the various components of carbon pool and fluxes of forests remain a significant and highly debated research issue. The common approach is to multiply estimates of above ground biomass for each ecosystem by estimates of the ecosystem's aerial extent. Not surprisingly, this approach gives rise to large uncertainties in terrestrial carbon budget because of the heterogeneity of forest ecosystems, the dynamics of carbon storage, and the ever-changing area of forested ecosystems as a result of disturbance and recovery.

The main scientific challenge in the global carbon cycle is therefore to reduce these uncertainties. Synoptic, internally consistent measurement of multi-dimensional ecosystem structure that can be used to estimate above-ground biomass (and potentially total biomass) and to characterize disturbance impacts and recovery processes in terrestrial ecosystems are important in reducing these uncertainties. These measurements also provide important ecosystem attributes that are influenced by canopy structure (e.g., sustainability, biodiversity, ecosystem services). Therefore, there is a broad interest in forest aboveground biomass, the functional consequences of multi-dimensional ecosystem structure, and in using structure to elucidate process.

Remote sensing is the most promising technique to measure and monitor the forest structure and biomass components on a global scale. Radar and LIDAR sensors, working at different regions of the electromagnetic spectrum, are capable of these measurements. Full-waveform LIDAR (also referred to as laser altimetry) measurements at near-infrared laser frequencies resolve height and vertical profiles with relatively fine vertical resolution. Current technology laser altimetry for spaceborne platforms has the limitation of being a profiler than an imager and can only sample the global forest biomass. Synthetic Aperture Radar (SAR) measurements at P-band are sensitive to forest volume, basal area, and biomass components because of its capacity to penetrate into the forest canopy. Both sensors may have problems with saturation in densely foliated forests and there are varying degrees of technological and algorithm maturity for either techniques. However, the synergism of the two measurements for providing a globally consistent measurement of forest biomass and 3-D structure are yet to be explored. In particular, for spaceborne applications, the measurements from the sensors must have the accuracy and the spatial and temporal characteristics that are useful for resolving the scientific challenges of global carbon cycle. Algorithms that are directly intended to derive forest structure need to be developed and refined. The robustness of these algorithms in different environmental conditions and different measurement configurations as well as scaling issues also needs attention and analysis.

## Forest structure and biomass

Given a sample of tree diameters and appropriate allometric functions, one can estimate the biomass of a forest as the summation of the biomass of the trees comprising the forest. There are some important scale-related implications in this simple procedure. Averaging the forest biomass reduces the variation seen in the biomass estimates of individual trees. There is evidence that for many forests an aggregation of about 1 ha provides a significant amount of variability reduction (WEISHAMPEL et al., 1994; SHUGART et al., 2000). At smaller spatial scales variability in forest biomass is large, suggesting that there are significant forest features that are seen at one spatial scale and not others (CHAVE et al., 2003) Figure 1). While averaging results from small size plots reduces the variance due to error in the tree-biomass-estimation procedure, it also masks biomass variability resulting from spatial structural variability (WEISHAMPEL et al., 1994). This variability arises from tree-to-tree competitive interactions that often occur at the scale of a large canopy tree. To understand the significance of structure on forest biomass, two cases are discussed: 1. the even-aged stands with one species of tree and 2. forest biomass in complex stands with mixed-age structure and multiple species.

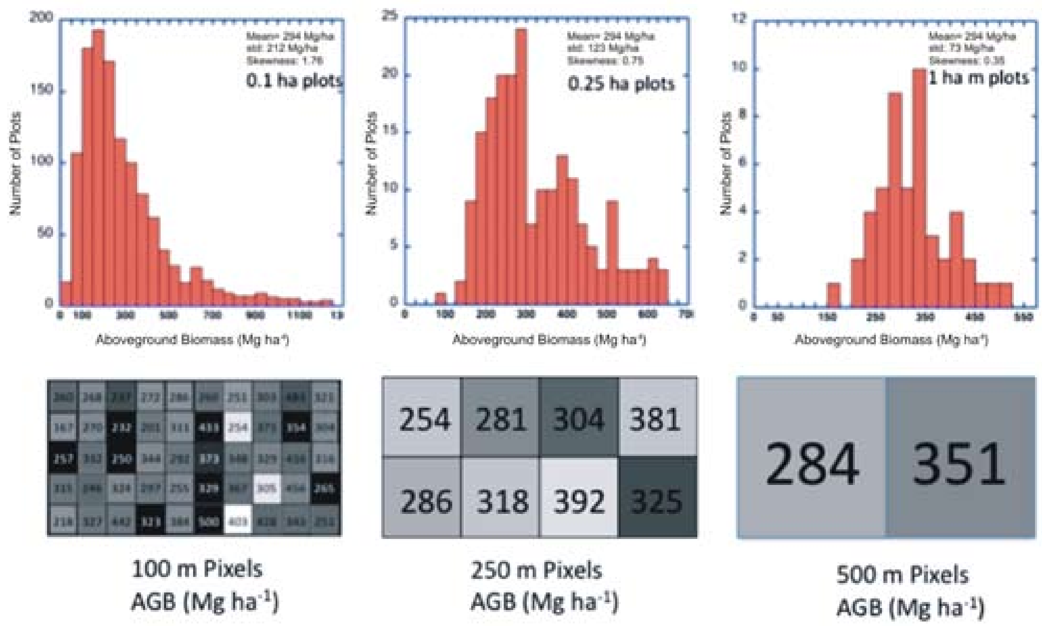


**Figure 1.** Above-ground biomass distribution in subplots within a 50 ha permanent plot in tropical wet forests of Barro Colorado Island, Panama. The distribution is skewed and unsymmetric at 0.1 ha representing the gap-dynamics and almost symmetric and normal at 1.0 ha representating forest structure at equilibrium. By increasing the size of subplots to 250m and 500m, the values of biomass show less variability

Single-species, even-aged stands also occur as natural forests. For the vast boreal forest, one finds extensive forest recovering from wildfires that are dominated by single species and of the same age. For most of the northern and mid-latitude forests, average height of forest stands is considered an indicator of site quality and growth potential and is usually derived from the forest age height relationship (KIMMINS 1987; KIRA, 2001). However, height alone does not provide the aboveground biomass of natural forests with the required precision for carbon management. In a recent study of northern and mid-latitude forests, it was found that average height can be used as a proxy for large-scale biomass variations and is a critical factor for controlling the magnitude of regional biomass density (FANG et al., 2006). Data from individual forest plots indicate that average height can explain approximately 60% of biomass variation on the regional scales (FANG et al., 2006; see Figure 2).

For multi-species and mixed-aged forests such as in tropics, the predictive power of height can become weaker in mature or old-growth forests. There, dominant trees often do not show any appreciable height growth and height may even decline in senescing but still dominant canopy trees. However, diameters continue to increase, adding to the biomass of trees. In boreal forests, maximum biomass can approach 400 $Mgha^{-1}$ although average biomass may be only 40 $Mgha^{-1}$ (BOTKIN and SIMPSON 1990). Similarly in temperate and topical forests, the average biomass may be 200 $Mgha^{-1}$ and 330 $Mgha^{-1}$ respectively (BROWN et al., 1991), but the maximum biomass may reach 2500 $Mgha^{-1}$ in Pacific Northwest of US or 690 $Mgha^{-1}$ in tropical Asia. The relative contributions of diameter and height in determining the forest biomass have been evaluated with recent allometric equations developed for tropical forests (CHAVE et al., 2005). Disturbance and recovery of forest ecosystems are essential to the understanding of the temporal dynamics of the biomass development in mature forests and its role in the global carbon cycle (See HOUGHTON et al., 2009). The mature forest should have patches with all

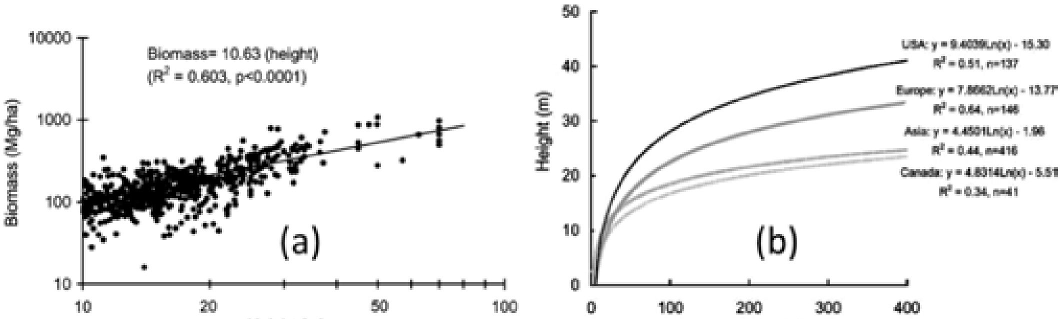


**Figure 2.** Average forest height predicts the aboveground biomass of even-aged and managed forests of northern mid latitude forests: (a) continental scale relationship of biomass and average height from 645 forest plots with a canopy taller than 10m to represents closed canopy forests, (b) Relationships between mean forest age and forest height for the northern regions (USA, Canada, East Asia, and Europe), suggesting the highest overall site quality is in USA forests, followed by European, Asian, and Canadian forests (FANG et al., 2006)

stages of gap-phase dynamics and the areal proportions of each should reflect different gap-replacement stages. This has significant implications for the apparent dynamics of forests when viewed at different spatial resolution. The spaces between the "teeth" in the saw-tooth curve are determined by how long a particular tree lives and how much time is required for a new tree to grow to dominate a canopy gap. At a landscape-scale, the overall biomass dynamic (Figure 3b) is determined by summing the dynamics of the parts of the mosaic (summation of several saw-tooth curves). If there has been a synchronising event, such as a clear-cutting, one would expect the mosaic biomass curve to follow four stages of development.

## Biomass carbon estimation

Allometric equations are transfer functions to estimate the tree biomass from structural measurements (DBH, Height, Crown Size, etc.). These estimators or equations have been developed using trees sampled from isolated sites or from small regions. Often, the equations are specific to individual species or group of species with growth characteristics of a region with specific climate, soil and hydraulic conditions, hence extending such equations to other species or regions will introduce uncertainties in estimating the biomass. As a result, there are inherent errors in estimating forest biomass at large scales using the site specific estimators. These errors include: (1) the use of coefficients derived for one species to another species, (2) sample trees and wood densities are not representative of target population because of size range and stand conditions and (3) statistical errors in estimating coefficients or form of the estimators (JENKINS et al., 2003). Other factors such as inconsistent standards and methodologies in both sampling and development of equations and measurements and data processing errors also impact the use of equations for large-scale forest biomass or carbon assessments. The propagation of errors from individual tree measurements to biomass equations depends on the spatial scale of the analysis(CHAVE et al., 2004).

## Remote sensing of forest structure

In general, there are two types of Remote Sensing techniques: passive and active. There are a variety of subtle differences between these techniques. Passive sensing refers to sensors that detect or measure the reflected or emitted electromagnetic radiation from natural sources (radiation from the sun in terms of visible and infrared photons, thermal, or microwave energy). Active sensing refers to sensors that detect reflected responses from objected irradiated from artificially-generated energy sources, such as photons in LIDAR (LIght Detection and Ranging ) and microwave energy in Radar (RAdio Detecting And Ranging) sensors. Measurements from passive sensors are related to the hemispherically integrated reflection from the surface in all directions and hence are less sensitive to the vegetation structure, but more to optical properties (in visible and infrared wavelengths) and moisture (in thermal and microwave wavelength). However, several passive optical sensing techniques have been used to estimate vegetation canopy structure, horizontal variations from texture variations, or land cover extent and changes. Active sensors, on the other hand, measure reflection in one direction by penetrating into the vegetation canopies and hence are more sensitive to the arrangement of

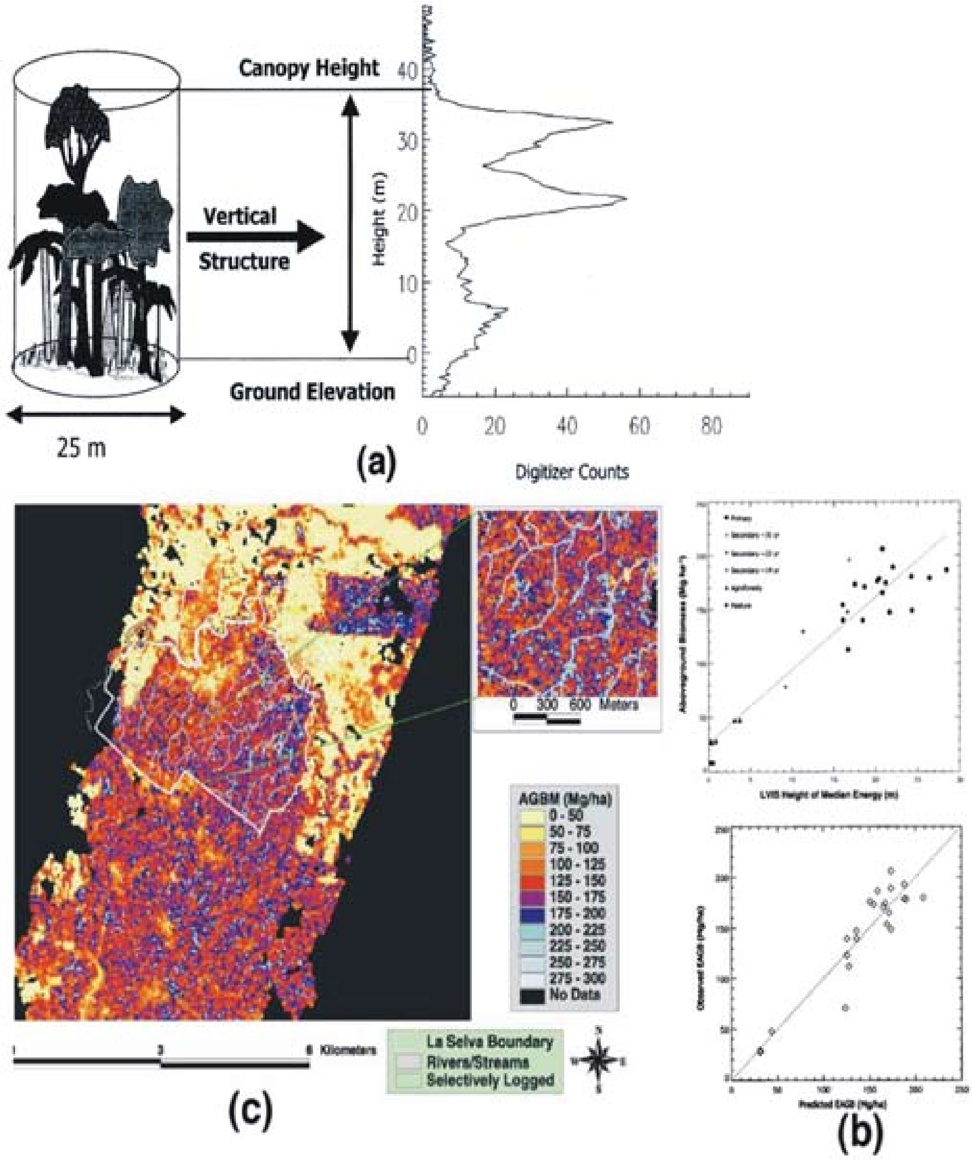


**Figure 3.** LIDAR measurement of forest biomass

*a. Conceptual basis of LIDAR remote sensing with resulting return waveform where the amplitude of pulse is a function of the area of reflecting surface (leaves and branches) at that height;*

*b. Above ground biomass estimation from the HOME metric derived from LIDAR backscatter and allometric equation;*

*c. Image of above ground biomass predicted from LVIS data over the La Selva Biological Station in Costa Rica (DRAKE et al., 2002a).*

objects (structure) on their propagation pathway. Radar and LIDAR sensors are currently being proposed as promising active-techniques for a globally consistent and spatially resolved measurement of the vegetation three-dimensional structure and the above ground woody biomass from space and providing spatial data on vegetation structure, biomass and their changes due to disturbance and recovery processes.

**LIDAR Remote Sensing**

LIDAR systems are laser altimeters that measure the distance between the sensor and a target through the precise measurement of the time between the emission of a pulse of laser light from the sensor, and the time of detection of light reflected from the target. In the more technologically-advanced LIDAR systems, the power of the entire returning laser signal is digitized, resulting in a waveform that records the vertical distribution of the backscatter of laser illumination from all canopy elements (foliar and branches) and the ground. The use of relatively large footprints (10-25m) in current airborne systems is optimized to recover returns from the top of the canopy and the ground in the same waveform (and there is no decrease in spatial resolution in forested regions), yet be small enough to be sensitive to the contribution of individual crowns (Figure 3).LIDAR systems can accurately estimate height and vertical profile of forest structure (BLAIR; HOFTON, 1999; DRAKE; WEISHAMPEL, 2000; LEFSKY et al., 1999). Empirical relations between these measurements and the forest biomass, make LIDAR an important Remote Sensing tool for forest inventory. These relationships are similar to the allometric equations used in field studies (NIKLAS, 1994). The primary difference is that instead of relating height or diameter of individual trees to biomass, the relationship is between LIDAR-derived canopy height (or other LIDAR metrics) and the total aboveground biomass of all trees within the area of interest (e.g., a field plot or resolution cell) (e.g., LEFSKY et al., 1999; DRAKE et al., 2002b, 2003). As such, LIDAR instruments provide a wealth of data suited for estimation of biomass in a variety of forest ecosystems. However, the nature of the physical relationship between LIDAR measurements and metrics and actual forest ground data (tree DBH, density, and volume) are yet to be established (DRAKE et al., 2002b). Most biomass estimates from national forest inventory and plot data are given by allometric equations in terms of tree DBH or volume. This creates the uncertainties often observed between LIDAR measurements and forest biomass. In addition, depending on the LIDAR power, and resolution, the backscatter signal may saturate in densely foliated forests and the total height of the forest may be retrieved unless in areas of canopy gaps.NASA airborne LIDAR sensors, SLICER (Scanning LIDAR Imager Of Canopies By Echo Recovery, retired in 1996) and LVIS (Laser Vegetation Imaging Sensor) both provide full waveform laser altimetry and provide similar measurements, with different resolution and imaging capabilities (BLAIR et al., 1999; PARKER et al., 2001). However, current spaceborne LIDAR technology is limited to sampling and profile measurement. In a realistic spaceborne configuration a LIDAR system with three-beams cannot cover more than 2 percent of the Earth's land surface during a 3-year mission lifetime. Therefore, the current generation of flying and planned spaceborne LIDAR sensors are only capable of measuring a small fraction of the forest biomass directly and must be combined by other

Remote Sensing data to provide a wall-to-wall coverage of forest structure and heterogeneity.

**Radar Remote Sensing**

Synthetic Aperture Radar (SAR) sensors operate at microwave region of frequency spectrum and like LIDAR sensors are part of active Remote Sensing techniques. Forest structure and biomass exert the primary control over SAR backscattering measurements because penetration of low frequency microwave signals into the forest canopy, sensitivity to wood density, and the size of the forest's scattering components (stems, branches, and leaves) (DOBSON et al., 1995; RANSON et al., 1995). In addition to the radar frequency, the polarization diversity of the radar systems allows measurements directly related to the geometry of the forest components. In the past two decades several experiments with airborne and spaceborne high-resolution SAR systems at various frequencies (C-band: 5.3 GHz or ≈ 6 cm, L-band: 1.25 GHz or ≈ 25 cm, and P-band: 0.4 GHz or ≈ 68 cm) have produced estimates of above ground forest biomass. Results from these studies show radar backscatter is a direct measurement of forest biomass. However, in forests with dense foliage, the attenuation of radar waves and the absorption of the incidence and scattered energy reduce the sensitivity of the backscatter to forest structure and biomass (Saatchi and Moghaddam, 2000). Radar sensors operating in interferometric modes provide additional information about the vertical structure of forest (ASKNE et al., 1997, CLOUDE and PAPATHANASSIOU, 1998; SARABANDI and LIN, 2000). However, most radar systems operate with limited wavelengths, polarization, and interferometric capabilities. NASA's AIRSAR is the only system to provide unique measurements of forest structure with fully polarimetric measurements in three wavelengths (P-, L-, C- bands) and interferometric modes at both L-band and C-band. P-band radar images are the most useful data for measuring biomass of old growth forests and are the main focus of our research in this proposal. However, it is generally understood that including other bands may improve the biomass estimation accuracy (SAATCHI; MACDONALD; RIGNOT, 1997; SAATCHI; MOGHADDAM, 2000; RANSON et al., 2003). Furthermore, interferometric measurements correlates well with the forest height can be combined with polarimetric data to provide forest 3-D structure in addition to biomass (Figure 4).

P-band SAR sensors are technologically mature and can be used for spaceborne applications. Such sensors are capable of providing high-resolution images (25-100m) globally for measuring forest structure (basal area, volume) and biomass and with frequent repeat cycle (e.g. every 30 days) for monitoring disturbance and recovery in forested ecosystems. In densely foliated tropical forests, P-band SAR may also saturate and lose its sensitivity to total forest biomass. Synergism with other measurements such as LIDAR height and vertical profile may improve the biomass estimation from SAR.

In addition to measuring one-time biomass densities, imaging Radar provides the capability of monitoring biomass changes resulting from forest disturbance (ROWLAND et al., 2002; MITCHARD et al., 2009). Acquiring multi-temporal images at different polarizations and wavelengths allows detection of deforestation resulting from clear-cutting, forest fires and insect disturbance, wind damage and to some extent

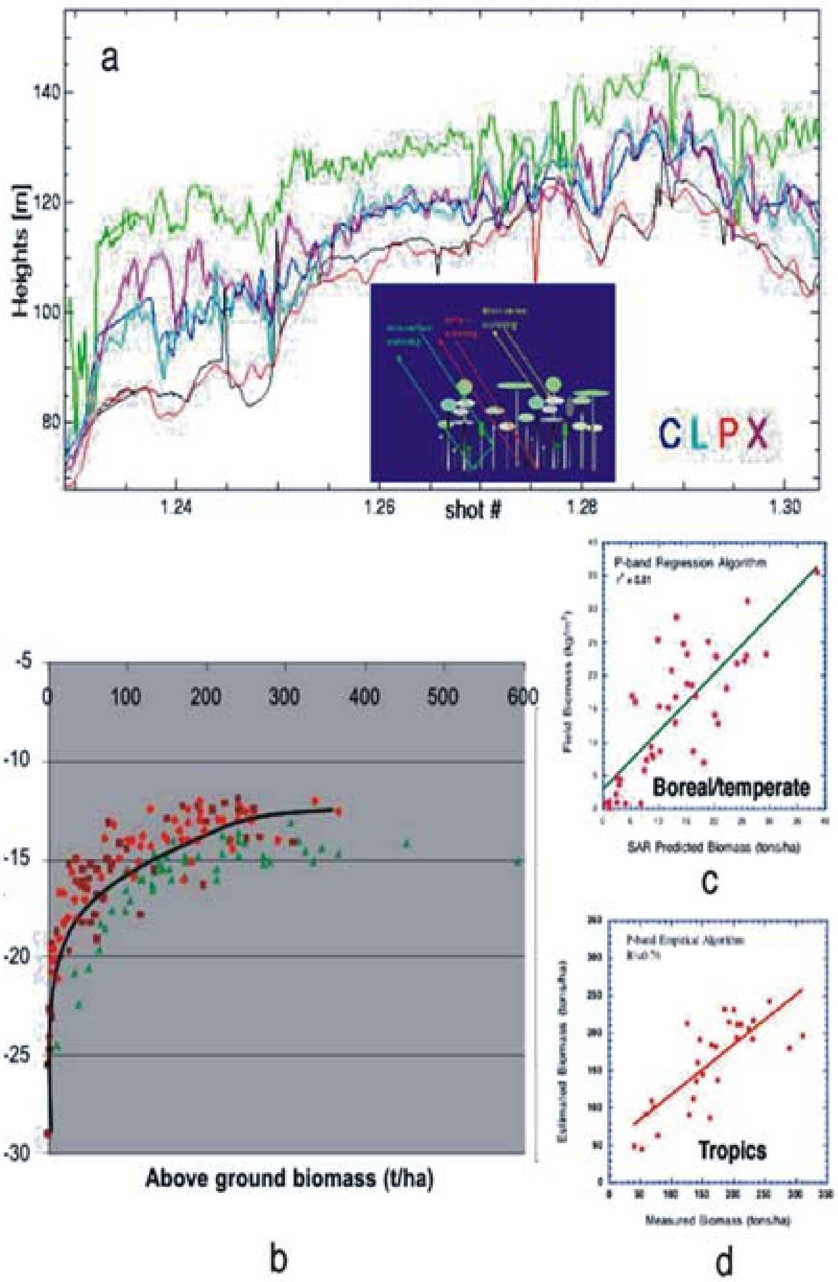


**Figure 4.** P-band radar measurement of forest structure

*a. Radar foliage penetration at different wavelengths in comparison with LIDAR first and last return over a dense forest (above 200 tons/ha).*
*b. Direct relationship of P-band HV polarization and above ground biomass derived from several experiments in boreal temperate and tropical forests.*
*c. Comparison of ground and estimated biomass over boreal and temperate sites using regression models*
*d. Comparison of ground and estimated biomass over tropical forest sites using regression models*

changes in forest structure (SAATCHI and RIGNOT, 1997; COUTURIER et al., 2001; SIEGERT et al., 2001; SALAS et al., 2002; RANSON et al., 2003). The results from these studies summarize the accuracy of monitoring forest disturbance and recovery by Radar backscatter measurements and highlight various sources of errors and ambiguities. However the results generally indicate that backscatter polarimetric measurements can potentially monitor disturbance modes in most global forested ecosystems.

## Fusion of LIDAR and radar

Some forest characteristics cannot be determined accurately from modeling or inference from LIDAR or radar data only. In these cases, the data from either sensor can be fused with information from either sensors or other Remote Sensing data. Most fusion studies are performed between radar and traditional passive optical sensors. This is primarily due to the fact that the LIDAR data have not been available widely for public use. However with the recent availability of LIDAR measurements from NASA sponsored sensors such as LVIS over forests with existing radar and ground data, fusion of these sensors have become feasible. In addition, several aspects of the physics of the measurement and the sensitivity to different forest structures make the sensors the best candidate for data fusion:

1. Both are active Remote Sensing sensors and perform the measurements in preferred transmitted and received geometry. Passive sensors measure the diffused reflection of light or microwave energy averaged over all incident directions and are therefore less sensitive to forest structural features.

2. LIDAR sensors measure the backscatter power of the transmitted laser pulse at close to nadir look angles and are sensitive to height and vertical profile of forest when intercepted by top and bottom of the forest within the sensor footprint. Radar sensors on the other hand, measure the backscatter power of the transmitted radar pulse at off-nadir (e.g. 20-50 degrees) along the range direction and are sensitive to the volume and wood density of intercepted tree stems and branches within the resolution cell.

3. LIDAR measurements, performed at optical wavelengths, are affected by some clouds and have limited coverage whereas radar sensors perform measurements at all time regardless of atmospheric condition.

4. Space-based measurements by LIDAR sensors provide samples of forest structure at high spatial resolution with some repeatability. Whereas, radar is an imaging instrument with comparable resolution and high repeatability.

The potential of data fusion between the two instruments is shown in results obtained over La Selva tropical forest in Costa Rica (DUBAYAH et al., 2004; SAATCHI et al., 2007). By including the LIDAR and radar measurements in a statistical estimation of forest above-ground biomass, the results were improved over all biomass ranges and in particular over stands with high biomass density (Figure 5).

## Concluding Remarks

Reducing carbon emissions from deforestation and degradation (REDD) in developing countries is an important component of global climate change mitigation. One of the key scientific challenges of REDD

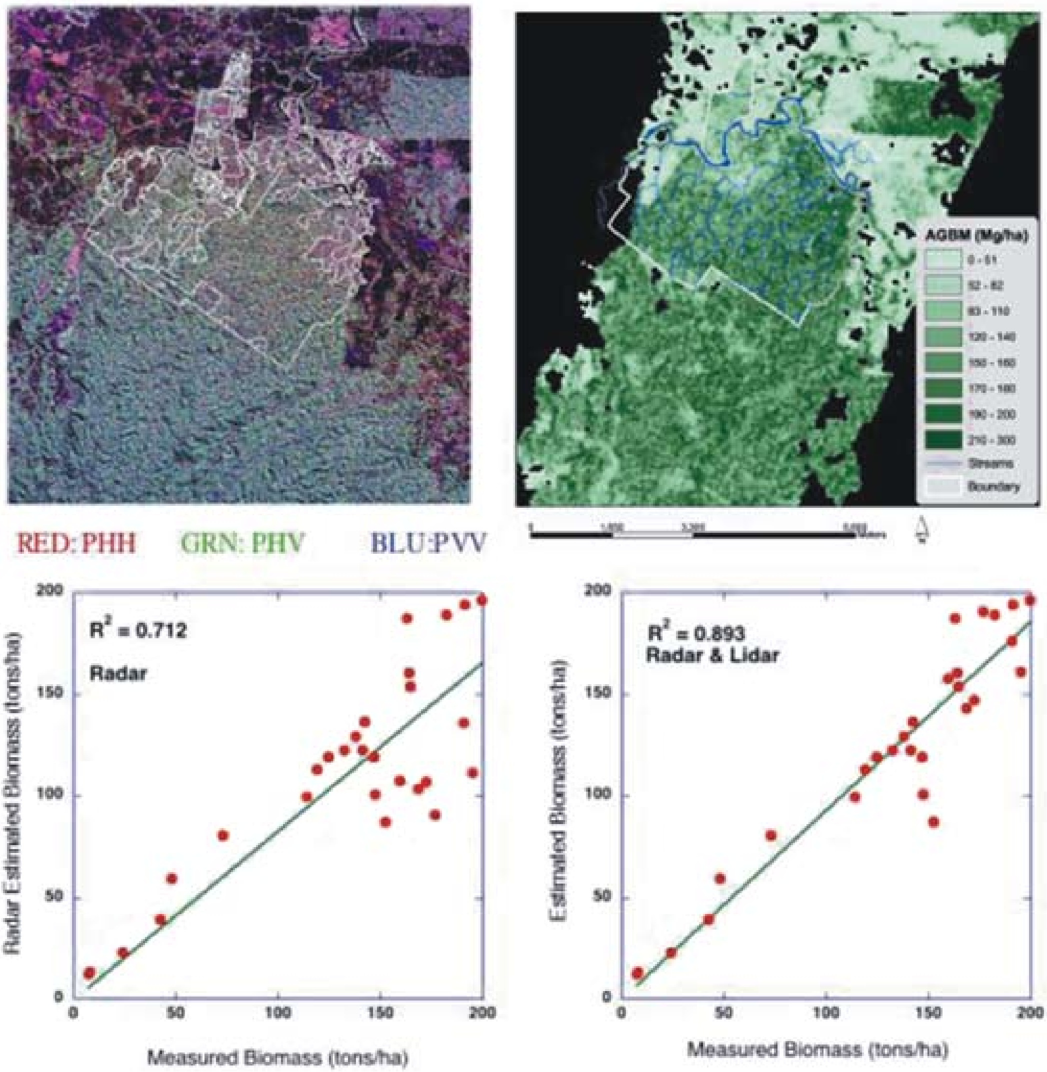


**Figure 5.** Fusion of P-band SAR and LVIS LIDAR data over the La Selva Biological Station in Costa Rica. Top left and right images are AIRSAR P-band and LVIS image mosaic respectively. The biomass estimation and the data fusion is performed statistically. The estimation accuracy improved from 70% to approximately 90%

is to quantify the carbon stored in forests and the amount released to the atmosphere as a result of deforestation and degradation. Both quantities are vital for developing a sound MRV (Measurement, Reporting, and Verification) globally and particularly in tropical regions. Forest biomass and its changes are considered the fundamental measurements required for establishing REDD mechanisms and MRV systems. Remote sensing, particularly with active Remote Sensing, provides a capability to quantify the structure of forest systems by direct measurement of indicators of structure.

Future spaceborne missions, DESDynl and BIOMASS, designed by NASA and ESA (European Space Agency) will provide the required data to assess the carbon stocks in forests and its changes by the end of the decade (2020). These measurements are performed by L-band SAR and LIDAR sensors in DESDynl and P-band SAR in BIOMASS. The DESDynI mission, as recommended by the National Research Council Decadal Survey (NRCDS), will provide previously unavailable information about terrestrial ecosystems, worldwide. The sensors provide complementary information about forest structure such as volume, basal area, height, and aboveground biomass (AGB) at various temporal and spatial scales. Although, there has been a general agreement on the value of synergism between the two sensors, no specific methodology has been recommended to integrate the datasets for measuring forest structure and its dynamics.

## References


ASKNE, J. I. H.; DAMMERT, P. B. G.; ULANDER, L. M. H.; SMITH, G. C-band repeat-pass interferometric SAR observations of the forest, **IEEE Transactions on Geoscience and Remote Sensing**, v.35, n.1, 25-35, 1997.

BLAIR, J. B., RABINE, D.L.; HOFTON, M.A. The Laser Vegetation Imaging Sensor (LVIS): A medium-altitude, digitisation-only, airborne laser altimeter for mapping vegetation and topography. **ISPRS Journal of Photogrammetry and Remote Sensing**, 54:115–122, 1999.

BOTKIN, D. B.; SIMPSON, L. G. Biomass of the North-American boreal forest - a step toward accurate global measures, **Biogeochemistry**, 9(2), 161-174, 1990.

BROWN, S.; GILLESPIE, A. J. R.; LUGO, A. E. Biomass of tropical forests of South and Southeast-Asia, **Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere**, 21(1), 111-117, 1991.

CHAVE, J. et al. Tree allometry and improved estimation of carbon stocks and balance in tropical forests, **Oecologia**, 145(1), 87-99, 2005.

CHAVE, J.; CONDIT, R.; AGUILAR, S.; HERNADEZ, A.; LAO, S.; PEREZ, R. Error propagation and scaling for tropical forest biomass estimates, **Philosophical Transactions of the Royal Society of London Series B-Biological Sciences**, 359(1443), 409-420, 2004.

CHAVE, J.; CONDIT, R.; LAO, S.; CASPERSEN, J. P.; FOSTER, R. B.; HUBBELL, S. P. Spatial and temporal variation of biomass in a tropical forest: results from a large census plot in Panama, **Journal of Ecology,** 91(2), 240-252, 2003.

CLOUDE, S. R.; PAPATHANASSIOU, K. P. Polarimetric SAR interferometry, **IEEE Transactions on Geoscience and Remote Sensing,** 36(5), 1551-1565, 1998.

COUTURIER, S.; TAYLOR, D.; SIEGERT, F.; HOFFMANN, A.; BAO, M. Q. ERS SAR backscatter - A potential real-time indicator of the proneness of modified rainforests to fire, **Remote Sensing of Environment,** 76(3), 410-417, 2001.

DOBSON, M. C.; PIERCE, L. E.; SHARIK, T. L.; BERGEN, K. M.; KELLNDORFER, J.; KENDRA, J. R.; LI, E.; LIN, Y. C.; NASHASHIBI, S.; SARABANDI, K.; SIQUEIRA, P. Estimation of forest biophysical characteristics in Northern Michigan with SIR-C/X-SAR, **IEEE Transactions on Geoscience and Remote Sensing,** 33(4), 877-895, 1995.

DRAKE, J. B.; WEISHAMPEL, J. F. Multifractal analysis of canopy height measures in a longleaf pine savanna. **Forest Ecology and Management**, 128(1-2), 121-127, 2000.

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. D. Estimation of tropical forest structural characteristics using large-footprint lidar. **Remote Sensing of Environment**, v. 79, n. 2-3, p. 305-319, 2002b.

DRAKE, J. B.; DUBAYAH, R. O.; KNOX, R. G.; CLARK, D. B.; BLAIR, J. B. Sensitivity of large-footprint lidar to canopy structure and biomass in a neotropical rainforest, **Remote Sensing of Environment,** v. 81, n. 2-3, 378-392, 2002a.

DRAKE, J. B.; KNOX, R. G.; DUBNAYAAH, R. O.; CLARK, D. B.; CONDIT, R.; BLAIR, J. B.; HOFTON, M. Above-ground biomass estimation in closed canopy neotropical forests using lidar remote sensimg: factors affeeting the generality of relationships. **Global Ecology and Biogeography**, v. 12, n. 2, p. 147-159, 2003,

DUBAYAH, R. O.; DRAKE, J. B. Lidar remote sensing for forestry, **Journal of Forestry**, 98(6), 44-46, 2000.

DUBAYAH, R.; BLAIR, J. B.; BUFTON, J.; CLARK, D.; JAJA, J.; KNOX, R.; LUTHCKE, S.; PRINCE, S.; WEISHAMPEL, J. The vegetation canopy lidar mission, in land satellite information in the next decade II: sources and applications, **American Society for Photogrammetry and Remote Sensing,** Bethesda, MD, pp.100-112, 1997.

DUBAYAH, R.;HURTT, G. C.; DRAKE, J. B.; MOORCROFT, P.; PACALA, S.; FEARON, M.Beyond potential vegetation: combining lidar, remote sensing and a height-structured ecosystem model for improved estimates of carbon stocks and fluxes. **Ecological Applications**, v. 14, n. 3, p. 873-883, 2004.

FANG, J.; BROWN, S.; TANG, Y.; NABUURS, G. J.; WANG, X.; SHEN, H. Overestimated biomass carbon pools of the northern mid-and high latitude forests, **Climatic Change**, 74(1-3), 355-368, 2006.

HOUGHTON, R. A.; HALL, F.; GOETZ, S. J. Importance of biomass in the global carbon cycle, **Journal of Geophysical Research-Biogeosciences**, 114, 2009.

JENKINS, J. C.; CHOJNACKY, D. C.; HEATH, L. S.; BIRDSEY, R. A. National-scale biomass estimators for United States tree species, **Forest Science**, 49(1), 12-35, 2003.

KIMMINS, J. P. **Forest ecology**. London: Macmillan, 1987. 531 p.

KIRA, T. **Forest and environment:** an approach to global environmental issues. Shin-Shisosha, Tokio, 2001.

LEFSKY, M. A.; HARDING, D. J.; COHEN, W. B.; PARKER, G. G.; SHUGART, H. H. Surface lidar remote sensing of basal area and biomass in deciduous forests of eastern Maryland, USA. **Remote Sensing of the Environment,** v. 67, p. 83-98, 1999.

MITCHARD, E. T. A.; SAATCHI, S. S.; GERALD, F. F.; LEWIS, S. L.; MEIR, P. Measuring woody encroachment along a forest-savanna boundary in Central Africa, Article Number 8, **Earth Interactions**, 13, 2009.

NIKLAS, K. J. **Plant allometry:** is there scaling of form and process. Chicago: University of Chicago Press, 1994.

PARKER, G. G.; LEFSKY, M. A.; HARDING, D. J. Light transmittance in forest canopies determined using airbone lidar altimetry and in-canopy quantum measurements. **Remote Sensing of Environment**, v. 76, p. 298-309, 2001.

RANSON, K. J.; SAATCHI, S.; SUN, G. Q. Boreal forest ecosystem characterization with SIR-C/XSAR, **IEEE Transactions on Geoscience and Remote Sensing**, 33(4), 867-876, 1995.

RANSON, K. J.; SUN, G.; KHARUK, V.I.; KOVACS, K. Valiadation of surface height from Shuttle Radar Topography Mission using Shuttle laser altimeter. **Remote Sensing of Environment**, v.88, n.4, p. 401-411, 2003.

ROWLAND, C.; BALZTER, H.; DAWSON, T.; LUCKMAN, A.; SKINNER, L.; PATENAUDE, G. **Biomass estimation of Thetford forest from SAR data**: potential and limitations. ForestSAT, Edinburgh, 5-9 August 2002, Forest Research, Forestry Commission, CD-ROM.

SAATCHI, S.; HALLIGAN, K.; DESPAIN, D. G.; CRABTREE, R. L. Estimation of forest fuel load from radar remote sensing, **IEEE Transactions on Geoscience and Remote Sensing**, 45(6), 1726-1740, 2007.

SAATCHI, S. S.; RIGNOT, E. Classification of boreal forest cover types usingSAR images, **Remote Sensing of Environment**, 60(3), 270-281, 1997.

SAATCHI, S. S.; MOGHADDAM, M. Estimation of crown and stem water content and biomass of boreal forest using polarimetric SAR imagery, **IEEE Transactions on Geoscience and Remote Sensing,** 38(2), 697-709, 2000.

SALAS, W. A.; DUCEY, M. J.; RIGNOT, E.; SKOLE, D. Assessment of JERS-1 SAR for monitoring secondary vegetation in Amazonia: I. Spatial and temporal variability in backscatter across a chrono-sequence of secondary vegetation stands in Rondonia, **International Journal of Remote Sensing**, 23(7), 1357-1379, 2002.

SARABANDI, K.; LIN, Y.C. Simulation of interferometric SAR response for characterizing the scattering phase center statistics of forest canopies. **IEEE Transaction on Geoscience and Remote Sensing**, v. 39, p. 115-125, 2000.

SIEGERT, F.; RUECKER, G.; HINRICHS, A.; HOFFMANN, A. A. Increased damage from fires in logged forests during droughts caused by El Niño. **Nature,** v.414, p. 437-440, 2001.

SHUGART, H. H.; CAYLOR, K. K.; DOWTY, P.; EMANUEL, W. R. Approaches for the estimation of primary productivity and vegetation structure in the Kalahari region. In: Ringrose, S. and R. Chanda (eds.) **Towards Sustainable Natural Resource Management in the Kalahari Region**. University of Botswana Press, 2000.

WEISHAMPEL, J. F.; SUN, G. Q.; RANSON, K. J.; LEJEUNE, K. D.; SHUGART, H. H. Forest textural properties from simulated microwave backscatter - the influence of spatial-resolution, **Remote Sensing of Environment**, 47(2), 120-131, 1994.