

Patterns from synergy

Dr Maurizio Santoro has developed a reliable method to accurately determine the volume of carbon sequestered in the world's forests from images obtained by remote sensing radar instruments



How does your work relate to the need to obtain direct and accurate measurement of carbon quantities stored in forests and vegetation, and their fluctuations?

My aim is to gain deeper understanding of what influences remote sensing observations of forests and vegetation, in particular synthetic aperture radar (SAR) remote sensing, because of the direct influence of vegetation structure on measurements. The ultimate objective is to set up a system where we obtain the most data from each observation that holds information on carbon stocks.

What is the broader significance of capturing and accurately interpreting these data?

Repeated observations of carbon stocks allow us to identify the direction in which our carbon balance is going, which has tremendous impact on regional, continental and global ecologies and economies. While the most reliable values of carbon stocks are derived from local measurements, these cannot give us the full picture, particularly in remote and inaccessible areas where the largest carbon stocks and sometimes most fragile ecosystems are located.

Can you explain the benefits of your BIOMASAR algorithm for retrieving forest growing stock volume (GSV)?

The algorithm relies on a concept developed during my PhD at Chalmers University of Technology, Sweden, and the University of Jena, Germany: if you obtain more observations of a single object, you can improve its characterisation by optimally combining the information content of each input channel. The BIOMASAR algorithm calibrates the model using synergy between Earth observation data products and some simple assumptions. Despite its crude approximations, we acquire some extraordinary results at radar frequencies typically neglected when targeting the estimation of forest variables.

Envisat was the largest Earth observation spacecraft ever built. Can you highlight its most interesting features?

We have mostly used Envisat's Advanced SAR (ASAR) because of its global and very dense coverage during the last decade. Hypertemporal observations served to generate an unprecedented wall-to-wall dataset of carbon stocks for the northern forests. We have found that such observations have unique features over water bodies as well.

The first SAR-based global dataset of open water bodies was recently generated by the European Space Agency (ESA) Climate Change Initiative Land Cover Project. In general, we believe that its unique time series can serve for hydrology studies, particularly in polar regions, thanks to almost daily observations at moderate resolutions (less than 1 km).

The spacecraft flew a large number of instruments, all operating at the same time, before becoming inoperative in 2012. It is unfortunate that its different observations have not been used in synergy so far. In terms of global thematic mapping, the operation of the ASAR instrument was by far the best when compared to other space-borne SAR

missions. The time series of ASAR observations, where available, are unique and deserve to be exploited more intensively.

Why is policy on SAR remote sensing data restrictive, with data access often proving difficult?

I am not in a position to explain the reasons, but most data are, and I fear will remain, in archives; there does not seem to be the will, nor sufficient engagement, nor funding, to make all archived image products available to the public. If this attitude persists, there won't be many additional chances for SAR-based solutions to contribute to relevant environmental themes.

Most SAR missions nowadays are commercial, so data are costly. Operating agencies could propose new services if they would let their satellites run 'just for science' and provide data without restrictions. In this respect, the open access policy of ESA-EC to Sentinel data is very much welcome.

Who are your principal collaborators and what have they added to your research?

Professor Christian Beer at the University of Stockholm, Sweden, was in need of a data product that could solve some issues in his work as a carbon modeller. He proposed generating wall-to-wall maps of GSV from space-borne SAR data. This triggered long discussions on the capabilities of existing data and tools. It was then my task to create the BIOMASAR approach.

Professor Christiane Schmullius at the University of Jena comes from the remote sensing community. We pooled our expertise to make BIOMASAR what it is today. BIOMASAR is not just SAR, but a system where several remote sensing data products are integrated, taking into account their information content.

In addition, the vision of ESA in funding the initial steps of BIOMASAR was crucial.

Seeing **the forest** for the trees

BIOMASAR has mapped the biomass in Northern Hemisphere forests with unprecedentedly high resolution and accuracy from satellite radar images



THE EARTH'S FORESTS extract carbon from the atmosphere and store it in their biomass; as carbon sinks, they thus play an essential role in the carbon cycle. Their growing stock volume (GSV), a measure of the volume of certain sized trees, living or dead, in a terrain, and how that volume is changing due to growth and felling, not only constitutes a fundamental variable for assessment of forestry carbon budgets, but also accurate information about the quantity of biomass in the world's forests and vegetation. How it changes over time provides key inputs to strategies for mitigating the effects of carbon emissions and land use changes on future climate. In this context, GSV is therefore also an important factor as the basis of above- and below-ground biomass quantity and density estimation.

The boreal and temperate forest ecosystems that cover large swathes of Canada, Russia, northern Europe and Alaska store a third more carbon per hectare than the forest systems of tropical regions, hence their biomass is crucial to the Earth's carbon cycle. Estimating the current and potential forest GSV in the Northern Hemisphere with any certainty, however, relies on accurate measurements of the composition of its forests. The feasibility of taking comprehensive *in situ* measurements on the ground is limited by the northern forests' vast impenetrability.

Measurement on the scale required via remote sensing approaches typically delivers only approximate levels of carbon storage capacity: "Most satellite-mounted observation systems provide only an indirect measure of carbon stocks," asserts Dr Maurizio Santoro, of the GAMMA Remote Sensing Research and Consulting company near Bern in Switzerland.

His research concentrates on space-borne data processing and analysis, as well as modelling the responses of forests and wetlands. Santoro recently developed an approach that overcomes the inherent uncertainties of radar space-borne remote sensing in retrieving reliable forest GSV data. The approach determines GSV estimates from the wavelength of the Advanced Synthetic Aperture Radar (ASAR) instrument and the structural and dielectric properties of forests: "I try to exploit the physics behind the measurements embedded in observations obtained by several remote sensors to get as close as possible to biomass information," Santoro explains.

THE BIOMASAR ALGORITHM

In the BIOMASAR project, funded by the European Space Agency (ESA) Support to Science Element, Santoro has validated his new method, using datasets of C-band backscatter collected in ASAR observations by the now-defunct Envisat Earth observation satellite. The observations covered terrain from 30-80°N that included three forest biomes – temperate broadleaf and mixed forests, temperate conifer forests, and boreal forests over three continents.

Backscatter signals obtained by ASAR instruments are sensitive to parts of the forest structure and yet resist interference from meteorological factors such as sunlight and cloud cover. Santoro's method exploits these strengths and applies an algorithm that links forest backscatter to GSV, employing a weighted combination of GSV estimates from individual backscatter measurements to maximise the information on forest structure in the backscatter measurement. The algorithm makes

use of a model similar to that of the 'water cloud', which deals with the effects of the water content of vegetation on backscatter data from radar systems.

The Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Continuous Fields product provides a mask for estimating unknown parameters, supplying central tendency statistics of backscatter for unplanted areas and those with high canopy cover. To improve certainty, the estimation is constrained to realistic GSV values, obtained from different inventories and other Earth observation datasets.

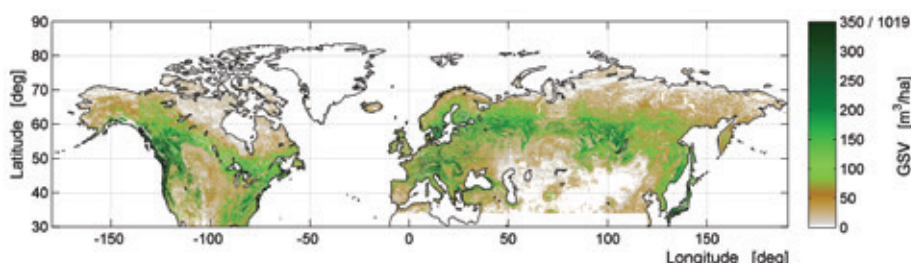
BIOMASAR MAPS OF BIOMASS

In BIOMASAR, Santoro and his colleagues amalgamated approximately 70,000 image strips acquired in ScanSAR mode by Envisat ASAR mostly between October 2009 and February 2011.

The images were multi-looked to a pixel size of 1 km, and terrain geocoded to a pixel size of 0.01°, then multi-channel speckle-filtered and normalised for effects on backscatter induced by slope. Unvegetated areas were masked out beforehand according to the GLC2000 land-use/land-cover map. GSV was then retrieved with the BIOMASAR algorithm on a pixel-by-pixel basis. The result was a map of the northern forest GSV at a resolution of 0.01°.

By integrating multiple images of the same terrain, the BIOMASAR algorithm was able to obtain very high resolution mapping of the northern forests and thus much more accurate measures of their carbon stocks than had ever been attained previously: "When we start combining information from multiple images, we reduce uncertainties," observes Santoro. "This is key in our work to overcome noise issues in individual observations."

GSV was consequently obtained in volumes of up to 1,000 m³ per hectare. The results were then compared with inventory-based data from Russia, Europe and the US, prior to making inter-continent and inter-biome carbon stock comparisons. The algorithm not only produces a low error rate of under 20 per



Growing stock volume (GSV) representative of the year 2010 estimated from Envisat ASAR observations of the backscattered intensity. Pixel size: 0.01°.



INTELLIGENCE

ESTIMATION OF FOREST GROWING STOCK VOLUME: POTENTIAL AND LIMITATIONS USING SPACEBORNE SAR

OBJECTIVES

To provide reliable and updated information on the distribution of forest resources using remote sensing. More generally, the objective is to develop applications of remote sensing data, using, in particular, spaceborne SAR data, to understand and monitor key processes of the Earth's environment where observations are lacking. Another objective is to promote SAR remote sensing as a mapping tool in large-scale studies of the terrestrial environment.

KEY COLLABORATORS

Professor Christian Beer, Department of Applied Environmental Science (ITM) and Bolin Centre of Climate Research, Stockholm University, Sweden

Professor Christiane Schmullius, Department of Earth Observation, Friedrich-Schiller University of Jena, Germany

Processing of ASAR data is done on ESA's Grid Processing on Demand G-POD environment (<http://gpod.eo.esa.int>).

Envisat ASAR data have been distributed under ESA's Category-1 project no. 6397.

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DR MAURIZIO SANTORO has been Project Scientist at GAMMA Remote Sensing AG, Switzerland, since 2006. His main duties include SAR data processing and applications for thematic cover mapping. He is Principal and co-Investigator for several international projects on the use of Earth observation for land cover mapping and monitoring.

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cent at regional scale, it also provides a new benchmark for improving carbon cycle models and monitoring systems.

TRANSLATING SCIENCE INTO POLICY

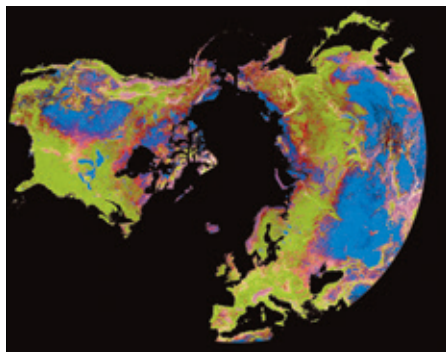
"It is always exciting when I see remote sensing images and products, the links among them and how all of this can help to fill a gap," Santoro enthuses. "This is exactly what happened when the BIOMASAR algorithm was developed." His initial brief was to use available data and simple tools, but he found, and continues to find, the availability of good data a major challenge. It is concerning that there are currently no firm guarantees of continuity in terms of satellite data provision: "Mostly we take what we can get," he laments. So, the availability of the large quantities

of high quality backscatter measurements acquired by Envisat ASAR from its frequent observations was fundamental to the viability of the BIOMASAR approach.

Santoro is now involved in the EU Seventh Framework Programme (FP7)-funded project GEOCARBON, which aims to lay the foundations for a Global Carbon Observing and Analysis System to support both science and policy. GEOCARBON is gathering high quality data on carbon dioxide and methane from *in situ* and remote sensing observations of the Earth's atmosphere, land and oceans to ensure their global consistency and sustainability, which will improve certainty and so their relevance for carbon policy making.

The maps derived using Santoro's algorithm and the data products on which they are based are now freely accessible on the BIOMASAR and GEOCARBON websites to anyone interested in the status and dynamics of forest resources on Earth. The BIOMASAR chain of ASAR data processing and retrieval of GSV is fully automated and no data training is required to calibrate the BIOMASAR model.

Apart from their utility for modelling future climate, Santoro sees potential applications including the generation of land use change or loss of biomass maps, and establishing preventative measures for major forest disturbances such as fires or deforestation.



False colour composite of average backscatter (red), minimum backscatter (green) and backscatter temporal variability (blue) from hyper-temporal Envisat ASAR observations. Credit: C Pathe, FSU Jena



Forest of Central Siberia.