Tackling high biomass in tropical forests through the BIOMASS mission

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Abstract

To improve our understanding of the carbon cycle, precise estimates of forest biomass are needed. High values of dense tropical forest biomass are particularly important, as they determine uncertainties in carbon stock assessment and carbon loss due to deforestation and forest degradation. However, estimating Above Ground Biomass (AGB) of tropical forests based on remote sensing systems remains challenging, most existing satellite systems are not sensitive to AGB in the high range. In this paper, we assess the use of P-band SAR tomography technique to provide AGB with reduced uncertainties in the range of 200-400 Mg.ha $^{-1}$. We present the expected contribution of the BIOMASS mission in estimating the carbon loss from deforestation and from forest degradation , and in providing the Digital Elevation Model under dense forests.

1. Introduction

Tropical forests occupy 45% of the world's total forests (FAO, 2020) and contribute more than half of terrestrial uptake of atmospheric CO2 (Stephens et al., 2007). However, forest degradation and deforestation result in the release of much of this otherwise stored carbon into the atmosphere. Due to the many uncertainties regarding forest carbon sinks and their possible transformation into carbon sources over time, it is essential to quantify how and where forests are changing and their subsequent implications for our climate.

To improve our understanding of the carbon cycle, it is necessary to accurately estimate forest biomass, which represents an indicator of stored carbon (about 50% of biomass is carbon). High biomass values in tropical forests are particularly important because they determine uncertainties in assessments of carbon stocks and carbon losses due to deforestation and forest degradation.

Tropical forests have a very complex 3D structure and the presence of large trees and dense canopy greatly complicates forest inventories. Furthermore, given the difficulty of conducting ground-based assessments over large areas, the use of remote sensing approaches is preferred to map forest biomass and its evolution over time. Additionally, dense tropical forests present a challenge when quantifying the underlying topography, which is necessary for forest ecology, hydrology, geomorphology, biodiversity, etc.

In this paper, we focus on high-biomass tropical forests and evaluate the use of P-band SAR to measure AGB in the high range. The contribution of the upcoming BIOMASS mission to estimating biomass loss due to deforestation and forest degradation will be considered, as well as its potential to provide a global digital elevation model of tropical forests.

The paper is organized as follows. The following sections present existing biomass maps (Section 2), an overview of the BIOMASS mission (Section 3), its state-of-the-art approach for biomass mapping in dense tropical forests (Section 4), and discuss the contribution of BIOMASS in estimating carbon loss due to deforestation and forest degradation (Section 5). Section 6 presents a secondary objective of the mission which is to provide the digital elevation model in high-biomass forests, and finally, the summary remarks are presented in section 7.

2. Existing biomass maps

In 2001, Houghton et al. compared several estimates of biomass for the Amazonian forests of Brazil, and found that estimates varied by more than a factor of two, and that the differences were greatest in high-biomass regions. Their comparison with 44 in situ sites yielded a very low correlation coefficient (0.04–0.35). Furthermore, estimates were inconsistent for high- and low-biomass regions in this Brazilian Amazon. where up to 65% of the old-growth terra firma forests have their Above Ground Biomass density AGB > 200 Mg ha^{-1}, and about 23% have AGB > 300 Mg ha^{-1} (Saatchi et al., 2007). (Note that Above Ground Biomass density AGBD, or AGB more commonly used in literature, is expressed in tonne/ha or Mg ha^{-1}) . Houghton et al. concluded that given the imminent need to determine carbon sources and sinks resulting from land-use change and natural processes, methods for determining biomass accurately, repeatedly, and inexpensively were urgently needed.

To estimate aboveground biomass, optical remote sensing uses proxies related to the optical spectral properties of the forest canopy, their temporal variations, their image texture, etc. These optical indicators, such as those provided by MODIS, Landsat and Sentinel-2, are not sensitive to AGB beyond canopy closure, which is the case for dense tropical forests. Spaceborne lidar data (e.g. ICESat GLAS, GEDI) are sensitive to canopy height. However, for high-biomass forests, the average tree height (e.g. per hectare) is weakly related to biomass. This is because biomass is stored in large proportions in a few emergent trees. In a study of old-growth forests, very large trees were found representing 2% of the stems, but 27% of the estimated above ground biomass (Clark et al., 1995). Radar measurements, resulting from interactions of radar waves with tree scattering elements, are more physically related to biomass, but their sensitivity to forest biomass depends on the radar frequen-

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cy. In the X and C bands, the scatterers are small tree elements, i.e. leaves, small branches, etc., and the radar signal saturates at low biomass values. In the L band, the scatterers are larger elements, making the radar backscatter sensitive to biomass up to saturation, which typically occurs between 70 and 150 Mg ha^{-1}.

With the increasing availability of data from current space sensors and advances in the ability to handle big data, several regional and global AGB maps of tropical forests have been produced, combining multiple satellite observations, in situ inventory measurements and airborne Lidar data (Saatchi et al. 2011; Baccini et al. 2012, Avitabile et al., 2016, Santoro et al., 2021).

Comparison of these global AGB maps shows that the spatial patterns and magnitude of AGB are well captured, but the gaps in AGB estimates are large, especially in high carbon stock forests with AGB > 250 Mg ha^{-1} (Santoro et al., 2021).

In the Brazilian Amazon, Tejada et al., 2020 compared pantropical-scale satellite maps, published by Saatchi et al. (2011), Baccini et al. (2012) and Avitabile et al. (2016), with AGB maps of the Brazilian Amazon published by Nogueira et al. (2015) and the Third National Communication of Brazil (MCT 2016) ; the latter two maps are based on field data extrapolated using vegetation classes. Their main conclusion is that current Amazonian biomass maps show substantial discrepancies in total biomass and its spatial distribution. The large differences between biomass maps are located in specific locations (western Amazon, Amapá, northeastern Pará), where there are larger areas with high biomass values.

These results show that two decades after Houghton et al., 2001, measuring AGB in high-biomass forests still remains a challenging task. In this context, we evaluate how the BIOMASS mission will provide AGB estimates with reduced uncertainties for high-biomass tropical forests, in order to achieve its objective.

3. Overview of the BIOMASS mission

The BIOMASS mission was selected by the European Space Agency (ESA) in 2013 as its 7th Earth Explorer mission, and the satellite is now for launch in 2025. The initial mission concept is described in Le Toan et al. (2011), and there have been major developments since that time (Quegan et al., 2019).

At present, mission completion is in sight, and launch is planned for 2025 on a Vega rocket from Europe’s Spaceport in Kourou, French Guiana. Figure 1 shows the artist view of the satellite, with a large deployable reflector, measuring 12 m.

The objectives of the mission are 1) to quantify the magnitude and distribution of forest biomass globally to improve resource assessment, carbon accounting and carbon models, and 2) to monitor and quantify changes in terrestrial forest biomass globally, on an annual basis or better, leading to improved estimates of terrestrial carbon sources (primarily from deforestation). These science objectives require the mission to measure above-ground forest biomass from 70° N to 56° S at spatial scale of 100–200 m, with error not exceeding ± 20% or ± 10 t ha^{-1} and forest height with error of ± 4 m.

To meet the measurement requirements, the mission will carry a P-Band polarimetric SAR (centre frequency 435 MHz with 6 MHz bandwidth) with interferometric capability,

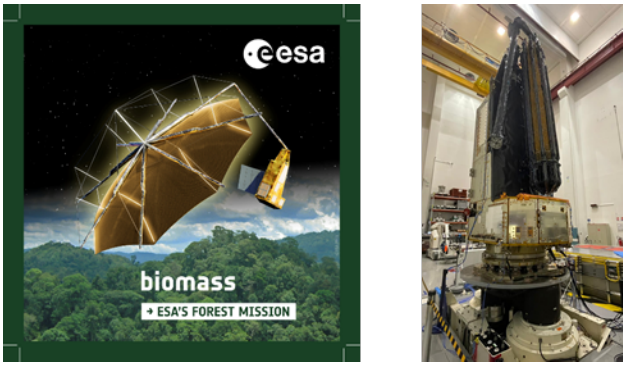

Figure 1. The BIOMASS mission. Left : artist view ; right : the assembled satellite.

With a wavelength of ~70 cm, P-band SAR has proven to be more adapted to measure the whole range of biomass in tropical forests, and the wave penetration depth is compatible with the height of the forest cover. In this way, the measured signal carries information about the forest structure and can be used to infer parameters such as forest biomass, forest height and underlying terrain topography.

Compared to all previous SAR systems, BIOMASS offers major advances in its use of three complementary technologies to provide information on forest 3D properties: polarimetry (PolSAR), polarimetric interferometry (Pol-InSAR) and tomographic SAR (TomoSAR) (Figure 2).

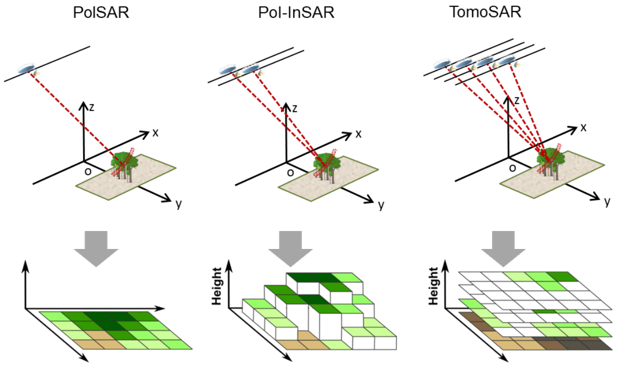

Figure 2. The three BIOMASS measurement modes, namely Polarimetry (PolSAR), polarimetric interferometry (Pol-InSAR) and tomographic SAR (TomoSAR).

BIOMASS operates in a dawn-dusk, Sun-synchronous orbit at a mean altitude of 666 km and an inclination of around 98°. A dawn (06:00) ascending node time minimises any adverse effects of the ionosphere on the radar signal and that of the fast change in dielectric properties of tree woody elements due to sap flow (Hamadi et al., 2013).

After launch in 2025, there will be a 6-month commissioning phase, followed by an 18-month phase of global TomoSAR coverage (where ‘global‘ should be understood as subject to the restrictions of the Space Object Tracking Radar (Carreiras et al., 2017)). During this phase, the effects of temporal decorrelation, rain, and ionospheric disturbances on TomoSAR will be assessed and the first AGB maps will be realised.

In the subsequent interferometric phase, Pol-InSAR coverage will be carried out every nine months until the end of the 5.5-year mission. Dual-baseline PolInSAR ground cancelling technique will be used to reduce ground scattering, and information gained from the TomoSAR phase will be used to improve forest height and AGB estimation for the rest of the mission lifetime. For all phases, accurate and representative in-situ datasets are needed for algorithm training and product validation. For BIOMASS and other missions (including GEDI and NISAR), a strategy was proposed for a coordinated, global in situ data network to ensure data availability throughout the life of the missions.

Additionally, major mutual gains will be made by combining BIOMASS data with data from other missions that measure forest biomass, structure, height and change, in particular, the changes associated with deforestation and forest degradation.

To summarize, the BIOMASS mission is expected to provide a much needed improvement in estimates of biomass in high carbon stock forest, and subsequent carbon stock loss due to deforestation and degradation of tropical forests, and thus improve the assessment of the terrestrial carbon balance**.**

4. The BIOMASS TomoSAR to measure high biomass

During the BIOMASS preparation phase, experience gained from airborne campaigns and tower experiments has led to new developments in the retrieving of 3D forest structure from polarimetric SAR interferometry (Pol-InSAR) and SAR tomography (TomoSAR).

During the tomographic phase, the system orbit will be adjusted to collect multiple acquisitions at the same sites, characterized by small baselines and a repetition interval of about a few days (3 days), thus allowing a reconstruction of the vertical structure of the forest. The tomographic processing then allows the conversion of the multi-baseline stack of SAR images into a multi-layer stack of SAR images, where each image represents the complex reflectivity associated with a layer at a certain height in the forest above the ground. (Minh D. H. T. et al., 2013).

The backscatter intensity of different TomoSAR 10 m vertical layers was analyzed as a function of AGB. As expected, at the ground level, backscatter intensity is weakly or negatively correlated with AGB and vary strongly with topographic slopes. From the ground floor to the upper layers, the best correlation was found between AGB and the tomographic intensity at 30 m. This was observed with the TomoSAR data acquired at different forest sites during the airborne campaigns in French Guiana and in Gabon.

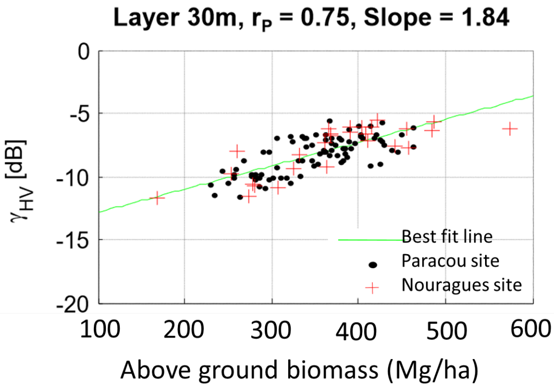

Figure 3. Relation between the radar backscatter intensity of the TomoSAR 30 m layer and AGB from 1 ha in situ plots at Paracou and Nouragues forest sites in French Guiana.

Figure 3 shows a result obtained at the Paracou and Nouragues forest sites in French Guiana. The backscatter intensity at the TomoSAR 30 m layer is strongly related to the in situ AGB (rp = 0.75) and the sensitivity observed at the two different forest sites was about 55 t/ha per dB over the AGB value range of about 230 to 500 Mg ha−1 (Minh D. H. T. et al, 2016).

The first reason for this finding is that the ground disturbance is primarily cancelled out in tomographic intensity at 30 m. The second reason is of ecological order. In a dense tropical forest, four layers can be found: 1) the overstory above 40 m containing the crown layer of (few) emergent trees, 2) the main canopy, a layer of 20-40 m, centered at approximately 30 m, which contains tightly packed tree tops and their branches, 3) the understory, and 4) the forest floor. The canopy layer is the main site for the exchange of heat, water vapor, and atmospheric gases. Below the canopy, there is little direct sunlight due to light extinction through the canopy layer. For these reasons, the layer centered at 30 m is expected to contain the majority of leaves, and a large proportion of woody elements which contribute to the total AGB.

5. Expected contribution of BIOMASS to improve the estimates of forest carbon loss

5.1 Carbon loss by deforestation

The UNFCCC framework on REDD+ (Reducing Emissions from Deforestation and Forest Degradation in Developing countries) encourages developing countries to take actions for reducing emissions in the forestry sector. For receiving performance-based payments countries need – among others – to implement national forest monitoring systems and mechanisms for Measuring, Reporting and Verification (MRV) of achievements in avoiding deforestation and in related emission savings.

According to IPCC guidelies, the approach for estimating emissions from deforestation or forest degradation can be based on Activity Data (AD) and on Emission Factors (EF):

$$Emissions = AD \text{ x } EF$$

where AD = change since the last reporting in forest area due to deforestation (in ha) and EF = emissions expressed in tC/ha. The Emission factors represent the Carbon (hence biomass) stored in the forest before deforestation. The key variable involved in the calculation is the Above Ground Biomass, and the change in forest area accessible from forest inventory and from Remote Sensing (IPCC, 2019).

However, despite progresses in deforestation monitoring and in AGB mapping, large discrepancies in estimates of C emissions are observed between studies.

We focus on the case of Amazon forests, where the important carbon sink seems to be in decline. Recent studies indicate a possible shift from sink to source regionally, although there are large discrepancies from many studies using different methodologies (bottom-up, e.g. using inventory data, top-down techniques, e.g. using aircraft CO2 vertical profiles, and a wide variety of global, regional and inversion models. In contrast, the bottom up approach suggest a small carbon sink over 2010-2020 (Gatti et al., 2021, Ometto et al., 2014; Tejada et al., 2020, 2023).

In order to assess the carbon loss by deforestation, we use the data on annual deforested area from Terra Brasilis PRODES (https://terrabrasilis.dpi.inpe.br/en/), and the AGB map of Ometto et al., 2023, produced using the airborne Lidar database collected from aircraft flying over the Brazilian Amazon region.

Figure 4 shows the evolution of a) the annual deforested area according to TerraBrasilis PRODES, and b) the corresponding average AGB loss in deforested areas calculated using the AGB map of Ometto et al., 2023. Figure 4 shows that between 2017 and 2022, an increase is observed for both the deforestation area and the average AGB of the deforested area. This shows that deforestation affects forests with higher biomass than those deforested in the past, as deforestation fronts reach the heart of the basin. In 2023, a drastic decrease in the deforestation area is observed, as well as a slight decrease in the average AGB.

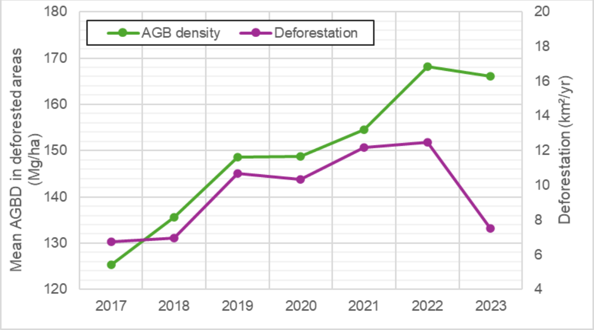

Figure 4. Evolution of a) annual deforested area according to TerraBrasilis PRODES, and b) corresponding mean AGB loss in deforested areas calculated using AGB map from Ometto et al., 2023.

The AGB loss due to deforestation calculated using the PRODES database and the AGB of Ometto et al., 2023 is compared with the AGB estimates from available remote sensing-based pantropical maps. The comparison in Table 1 shows that a) all estimates show an increase in biomass loss from 2017 to 2022, followed by a decrease from 2022 to 2023, b) the range of AGB loss values differs considerably between the estimates. It is understood that the assertion of a regional shift from carbon sink to carbon source will depend greatly on the AGB estimate to be used in carbon accounting. For example, the reduction in AGB loss in 2023, compared to 2022, ranges from 79.5 Mt to 151.2 Mt corresponding to approximately 40 MtC and 75 MtC, a factor of 1.87 which counts in the calculation of the carbon emission source.

	Total AGB loss (Mt)			
	Ometto	Saatchi	Avitabile	Bacchini
2017	87,8	146,6	148,8	182,9
2018	97,1	155,0	153,3	194,5
2019	161,5	240,2	250,4	297,5
2020	156,8	230,8	236,2	287,4
2021	191,8	273,7	280,6	344,1
2022	213,2	291,3	304,4	367,2
2023	133,7	179,7	190,8	226,0

Table 1: AGB loss in Brazilian Amazon due to deforestation estimated using deforestation areas by PRODES, and AGB values at pixels detected as deforested areas from 2017 to 2023 by Ometto et al (2023), Saatchi et al. (2011), Baccini et al (2012) and Avitabile (2016).

With AGB estimates provided by the BIOMASS mission with 20% accuracy in deforestation-prone areas, carbon loss due to deforestation should be better assessed by remote sensing.

5.2 Carbon loss by forest degradation

Recent studies show that forest degradation, neglected in remote sensing-based approaches, could also explain the decline in the forest carbon sink observed by top-down approach. However, the impacts of forest degradation are understudied, largely because international emission reduction programs have focused on deforestation, which is easier to detect and therefore more easily monitored. Improving knowledge of greenhouse gas emissions from forest degradation will be essential to better understand and seize opportunities to combat climate change. In fact, tropical forest degradation is estimated to be responsible for 25% of forest carbon emissions (Pearson et al., 2017) and approximately 20% of tropical forests are disturbed by logging activities that can then lead to forest degradation (Hubau et al., 2020).

In contrast to deforestation, selective logging represents a more diffuse disturbance where only a subset of trees (the most economically valuable) are harvested. Typically, the AGB of wood harvested ranges about 30 Mg ha^{-1} to 100 Mg ha^{-1} .

Several authors have attempted to address the challenges of using satellite data to estimate forest disturbances caused by selective logging in tropical regions. The majority of approaches use high-resolution images (i.e., spatial resolution between 10 and 30 m) to detect large canopy openings and features such as road networks to monitor forest degradation (Hethcoat et al., 2019, Dupuis et al., 2023). However, the link between the degree of forest degradation and forest biomass loss is still poorly studied.

In this paper, we address the question of how P-band Tomo-SAR can estimate the AGB of a degraded forest to improve the calculation of carbon loss and the resulting carbon emission to the atmosphere.

The site under study is the Paracou experimental site located in a lowland tropical rain forest in French Guiana (Dubois-Fernandez et al., 2012) (Figure 6). 15 permanent plots of 6.25 ha each and one plot of 25 ha in which all stems ≥ 10 cm DBH (Diameter at Breast Height) were mapped and regularly surveyed. From 1986 to 1987, the plots were logged according to one of three different treatments. Treatment 1 (T1) was a selective logging which removed an average of 10 timber trees per hectare (DBH ≥ 50 or 60 cm). Treatment 2 and 3 were selective logging with resp. about 30 and 45 trees removed per hectare (DBH ≥ 40 cm) (Sist et al., 2012).

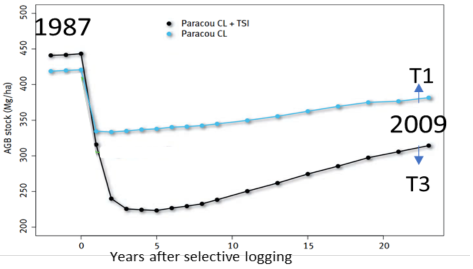

Figure 5 : 23-year AGB dynamics before and after selective logging in 1987, for plots with T1 Treatment (10 trees removed per hectare), and T3 (45 trees removed per hectare). Adapted from Sist et al., 2012.

Before logging, AGB is in the range of 420-440 Mg ha^{-1}. The minimum AGB of T1 is observed 1 year after logging (320 Mg ha^{-1}) and in T3, 4 years after logging (220 Mg ha^{-1}), due to additional tree mortality.

The data indicate that the 10 trees removed from T1 contain 100 Mg ha^{-1}or 24% of the plot AGB, and the T3 treatment causes a loss of 220 Mg ha^{-1}, or 50% of the plot AGB. After reaching the minimum values, the dynamics of AGB, resulting from tree growth rate, tree recruitment and tree mortality, increases with a higher rate in T3 than in T1. In the year of P-Band TropiSAR experiment (2009), i.e. 22 years after selective logging, the AGB of the T1 and T3 plots are respectively 380 and 280 Mg ha^{-1}, or 90% and 63% of their pre-logging values.

The data indicate that the loss of AGB due to forest degradation is far from negligible and must be accounted for in carbon emissions. More than twenty years after logging, the AGB of this forest site covers an overall range of 280 to 440 Mg ha^{-1}, which is a challenge for existing remote sensing systems.

In this context, we assess the sensitivity of P-band TomoSAR to different degrees of forest degradation.

Figure 6 shows the map of the Paracou site in French Guiana, and the AGB map produced from P-band SAR tomography. The selective logging experiment plots are located in the bottom right of both images.

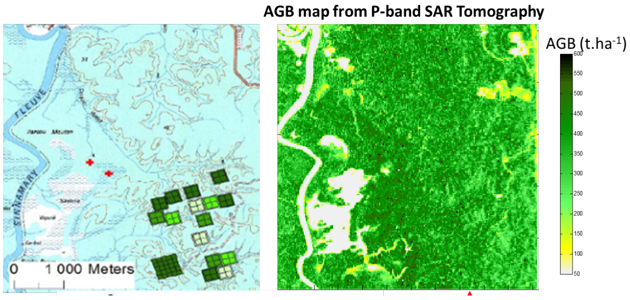

Figure 6. Left : map of Paracou site in French Guiana, where a long term selective logging experiment has been conducted (very dark green plots : intact forest, from dark green, light green to white : plots with treatment T1, T2, T3). Right : map of AGB derived from P-band SAR tomography

Figure 7 shows the comparison between retrieved AGB and in situ AGB, where the range of AGB for degraded forest plots under 3 selective logging T1, T2, T3 are well distinguished from intact forest T0.

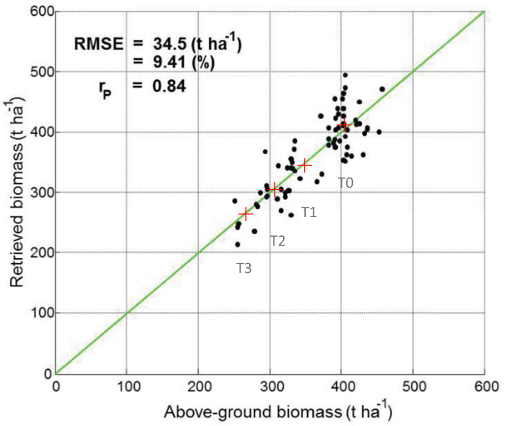

Figure 7. Comparison between retrieved AGB using P-band SAR tomography and in-situ AGB for plots of intact forest (T0), and plots having increasing degree of forest degradation caused by selective logging T1, T2 and T3. The red crosses on the 1 :1 green line are the in situ AGB values of T0, T1, T2 and T3 plots at the time of the SAR data acquisitions.

5.3 Expected contribution of the BIOMASS mission

The results obtained above, for loss of biomass due to deforestation and to forest degradation have been assessed, taking into account a) the limited pulse bandwidth of 6 MHz, b) ionosphere disturbance, c) temporal decorrelation in particular due to environment effects such as rain, wind, diurnal and seasonal variation (Essebtey,et al., 2021). The overall simulation results show that at a resolution of 4 ha, BIOMASS can provide AGB in the range of 200-400 t/ha with 20% accuracy (Minh et al., 2015, Tebaldini et al., 2019).

The results indicate that data acquired by BIOMASS will contribute significantly to national communications on GHG to the UNFCCC, in which not only deforestation, but also forest degradation.

Specifically, for each country *a* and above ground carbon stock B_a, the forest emissions or removals, ER_a, are computed as a simple carbon stock change (IPCC 2006):

$$\begin{aligned} \mathrm{ER}_a(t_i) &= -\Delta C_a(t_i) \\ &= -[B_a(t_i) - B_a(t_{i-1})] \end{aligned}$$

(The minus sign is used to adhere to the convention of considering emissions to be positive fluxes to the atmosphere, and vice versa).

For deforestation and forest degradation, BIOMASS should provide AGB loss directly, without the need to detect deforested and degraded areas.

6. Digital Elevation Model under tropical forests

A secondary objective of the BIOMASS mission is the estimation of the digital elevation model (DEM). Three-dimensional representations of terrain elevations are poorly accessible by satellites for heavily forested terrain (Polidori et al., 2022). In tropical forests, DEMs are needed to a) identify suitable terrain for agriculture, settlement, b) to model water flow, watershed boundaries and potential floodplains, c) to identify areas subject to erosion and soil degradation, or d) to understand the distribution of habitats and biodiversity for conservation planning. In addition, the DEM provided by tomography during the BIOMASS TomoSAR phase is needed in the subsequent interferometry phase, as the AGB retrieval algorithms during this phase will rely on ground topography to compensate for slope or to reject ground backscatter.

Currently, airborne lidar has become the most effective technique in forest areas. It provides a dense and accurate point cloud that represents both the canopy and the terrain. However, the lidar coverage is limited to local or regional use.

Space-based SAR imagery has been used to produce DEMs based on SAR interferometry and PolInSAR, the latter with the use of signal polarization. However, existing SAR systems used for DEM generation (e.g. SRTM, Tandem X) operate at short wavelength in the X and C bands, which limits their use in forest terrain. The signal interacts only with the upper layer of the forest and, moreover, the signal is highly decorrelated by the movement of small tree elements between two acquisitions

At P-band, the radar waves penetrate through dense vegetation, from the top to the ground. As stated above, using tomography technique, it is possible to separate the contributions of different layers in a vertical reflectivity profile, including the top layer for tree height, and the ground layer for DEM.

Figure 8 shows the DEM obtained using SAR tomography in the Paracou forest in French Guiana (El Hage et al., 2022).

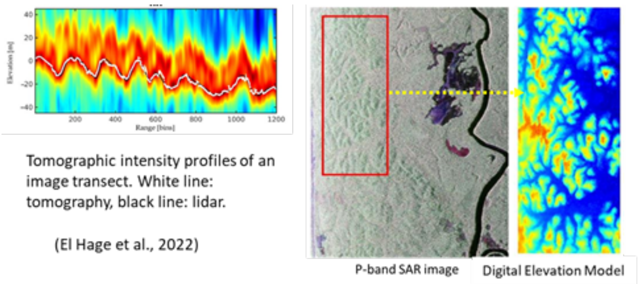

Figure 8. A tomographic intensity profile (left image), the P-Band SAR image (center), and the Digital Elevation Model from P-band TomoSAR.

The DEM obtained by P-band SAR tomography (Figure 8) is comparable to the airborne lidar reference, indicating the high potential of BIOMASS to provide DEM under tropical forests on a global scale, while airborne lidar has limited coverage.

7. Summary remark

In summary, the BIOMASS mission is expected to significantly improve estimates of carbon emissions in tropical forests by reducing uncertainties related to carbon loss due to deforestation and forest degradation. Furthermore, BIOMASS has the potential to provide the global DEM in these dense forests.

However, the performance in terms of spatial configuration remains to be evaluated. Resolution effects due to the 6 MHz bandwidth, ionospheric effects and temporal decorrelation have been evaluated in simulation studies, but the overall performance of the BIOMASS mission will be assessed once the system is in orbit.

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