Monitoring of tropical forests using SAR data - Application to the Amazon region

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Abstract. Because of the importance role in the land use carbon emissions of tropical forests in general, and of the Amazon forest in particular, observing systems are needed for monitoring deforestation and for estimating forest biomass. Up to now, the existing monitoring programs rely mostly on optical remote sensing. With the recent and forthcoming availability of open and systematic SAR data, there is a need to assess the contribution of SAR data in observing systems. This paper examines the use of SAR data to observe Amazon forests, e.g. Sentinel-1 data for deforestation monitoring, ALOS PALSAR data for biomass retrieval in the Cerrado, and the future BIOMASS data for measuring the high range of biomass in dense rain forests. The promising results indicate that SAR data can be integrated in current monitoring programs.

Keywords: Forest above ground biomass, Tropical forest, Amazonia, Cerrado, L-band SAR, P-band SAR Biomass mission.

1. Introduction

Forests have an important role in tropical countries by providing renewable resources, raw materials and energy, maintaining biological diversity, and protecting land and water resources. Moreover, tropical forests hold a large fraction of the terrestrial carbon, and they thus play a major role in the global carbon cycle. When forests are cleared or degraded, the stored carbon is released to the atmosphere, and the carbon sinks are altered. Central to these carbon flux calculations is forest biomass, for which there are no agreed and updated reference source of global gridded biomass data. To quantify tropical forest biomass and its dynamics is therefore required for approaches to managing climate, e.g. of the UNFCCC initiative known as Reducing Emissions through Degradation and Deforestation (REDD+).

Studies have indicated that the land surface has acted as a strong global carbon sink over recent decades, with a substantial fraction of this sink probably located in the tropics, particularly in the Amazon, which contains the largest and most biodiverse tropical rainforest in the world. According to a recent study (Brienen et al., 2015) Amazon forests have acted as a long-term net biomass sink, but the authors also found a long-term decreasing trend of carbon accumulation, i.e. a decline of the Amazon sink. The results were based only on biomass data at 321 forest plots, and this highlights the needs to have systematic assessment of the spatial distribution of biomass in the future.

Along with deforestation area extent, biomass determines the potential for carbon emissions that can be released into the atmosphere when forests are cut. In Amazonia, cutting and burning of forest biomass are linked to expanding areas of agriculture and pasture.

The emissions from land use in tropical South America is important, accounting for half of the world land use emission in 2010 according to the Global Carbon Atlas (November 2016) http://www.globalcarbonatlas.org/en/CO2-emissions

Moreover, Brazil deforestation and agricultural expansion has occurred not only in the Amazon, but also in the neighboring Cerrado biome, a biodiversity hotspot comprised of dry forests, woodland savannas, and grasslands. In the last 40 years, land conversion in the Cerrado has been rapid and intense (Spera et al., 2016)).

As a summary, because of the importance of the tropical forests and in particular the Amazon forests in the world land use emissions, an observing system is essential for both detecting deforestation, measuring deforested areas, and for estimating the carbon stocks and dynamics.

Deforestation monitoring has been tackled in a number of programs in Brazil operated by INPE monitoring systems: the PRODES project monitors clear cut deforestation in the Brazilian Legal Amazon, mainly based on Landsat data, and has produced annual deforestation rates for the region since 1988. The Near Real-time System for Detection of Deforestation (DETER) based on MODIS data provides monthly information for immediate public awareness, the DEGRAD program reports on the forest degradation using Landsat data.

Regarding biomass mapping in Amazonia, the first systematic attempt to obtain large scale forest biomass was mostly derived from studies by Brown and Lugo (1992). The global distribution and amount of woody carbon stocks were based on spatial extrapolation of inventory measurements over forest ecosystems. In recent years, remote sensing data have been used for biomass mapping, also based on spatial extension of forest plot measurements. However, the methods suffer from the weak relationship to woody above ground biomass (AGB) of most remote sensing data used, and the limited number of training plots. The approach used in two recent pan tropical biomass maps consists to spatially extrapolate above ground woody biomass obtained from *in situ* inventory plots using ICESat GLAS transects, combined with MODIS data (Baccini et al., 2012) or combined with MODIS and Quick Scatterometer (QuikSCAT) data (Saatchi et al., 2011). These two biomass maps, being the first of their kind with such a large coverage, have been widely used. However, they show large uncertainties and significant regional biases, in particular in Amazonia (Mitchard et al., 2014).

Because of the difficulty to quantify biomass in tropical forests in general, and in Amazon region in particular, estimates of the total carbon stock in Amazonia range widely, from 70 to 120 PgC (Malhi et al. 2009;; Saatchi et al. 2007), with large variance in the spatial distribution of biomass (Nogueira et al. 2008, Saatchi et al. 2011; Baccini et al. 2012). The disagreement between estimates was already observed by Houghton et al., 2001, more than 15 years ago. Regarding the uncertainty in emissions, although it results from the deforestation process itself, uncertainty in the underlying original biomass remains the largest contributor to uncertainty in deforestation emissions (Aguiar et al. 2012).

In this paper, we examine the possibility to use SAR data to monitor deforestation and to measure biomass in tropical forests in general and in Amazon forest in particular. It has long been known that SAR data are promising for observing forests, but applications have been hampered by the lack of systematic and cost-effective SAR data. The situation has changed drastically with the current or near future SAR missions. Global mosaics of L-band ALOS and ALOS2 SAR data are made available yearly by the Japan Aerospace Exploration Agency (JAXA); ESA C-band Sentinel-1 data are open and available since 2014, with a repeat cycle of 12 days in Amazonia starting October 2016; ESA P-band Biomass mission designed for biomass measurements, with focus on tropical forests, will be launched in 2021.

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In the following, we will show the use of each data type for Amazon forest monitoring. The C-band Sentinel-1 data with short repeat cycle can be used for deforestation monitoring, L-band ALOS data can be used for biomass mapping in cerrado biome, and P-band Biomass data for measuring biomass of dense tropical rain forests.

2. Deforestation monitoring using Sentinel-1 data

Until now, C-band SAR data from ERS, RADARSAT, ASAR have not been extensively used for forest applications. This is due to the small dynamic range of the backscatter signal over forest cover, and the variable contrast between forest and deforested areas. The latter depends mainly on the ground conditions after deforestation (areas with remnant, soil moisture and roughness, regrowth..). Deforestation detection can be perturbed by various noises including speckle effect, environment conditions, in particular when limited number of data before and after deforestation is used. Using C-band SAR data for deforestation detection requires therefore a) a dense time series of data, b) a comprehensive methodology starting from the image pre-processing step. Figure 1 shows that deforested area can be detected in a Sentinel-1 time series images. In this example, the deforestation occurred between 17.04 and 03.08.2016. With the new Sentinel-1data systematic acquisition scenario starting October 2016, it is foreseen that deforestation event can be monitored every 12 days.

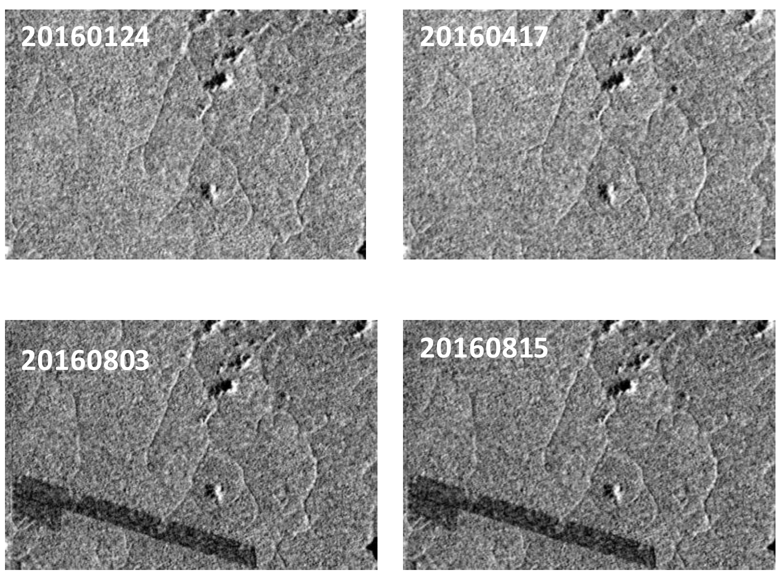

Figure 1. Time series of Sentinel-1 data show deforestation in the municipality of Colniza, in the North West of Mato Grosso (9.04°S / 59.21°W). The deforested area extent is of 10 km x 1 km (2 km at the tip).

Figure 2 shows an example of Sentinel-1 multi date images where new deforestation plots are detected in the outskirt of a region where agricultural fields have been settled. These examples have shown that deforestation could be detected using time series of Sentinel-1 data, not only large deforested areas (more than 6.25 ha), but also smaller area (1 ha or less), as shown in figure 2.

Automated disturbances detection methods are developed (Mermoz and Le Toan, 2016) and currently tested for Sentinel -1 data at CESBIO. However, when the images are adequately

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preprocessed, their interpretation could be performed by operators of the existing deforestation detection programs.

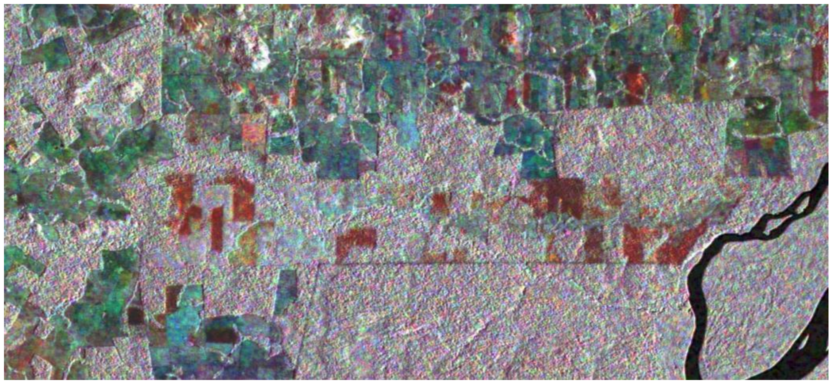

Figure 2. Sentinel-1 images over a location in Cotriguaçu (10.07°S/58.38°W15) Red: 15 August 2016 / Green: 2 0ctober 2016 / Blue: 14 October 2016. Based on the temporal variation of VH backscatter from January to October 2016, the red plots on this image indicate new deforested areas between 15/08/2016 and 02/10/2016.

3. Estimating AGB in Cerrado using L-band SAR data

Theoretical and experimental studies showed that L-band SAR data are sensitive to forest AGB until a saturation level is reached. This saturation generally occurs between 70 and 150 $Mg.ha^{-1}$, depending on studies carried out on different forest types. L-band SAR data are therefore well suited to above-ground biomass estimation for low biomass forests, in particular for savannahs and woodlands. This was demonstrated for a limited number of region or country in Africa and Australia (Carreiras et al., 2013, 2012;; Mermoz et al., 2014).

In the following, we will assess the use of L-band data for AGB estimation in Brasilian Cerrado. The L-band data are from the yearly PALSAR (2007-2010) and PALSAR-2 (2015-onwards) mosaics at 25m, built by JAXA. These data are freely available and facilitate the use of large dataset for forest monitoring (http://www.eorc.jaxa.jp/ALOS/en/palsar_fnf/fnf_index.htm).

The method for AGB estimating and mapping using PalSAR mosaics, described in Mermoz et al., 2014, and in Bouvet et al., 2016 comprises two steps. The first step consists in defining a direct model that relates the PALSAR backscatter to AGB, with the help of a selected set of field measurements. In the second step, a Bayesian inversion of this model is performed to produce the AGB map, taking into account of the different perturbing effects of environment (soil and vegetation moisture, topography), and forest structure. The approach uses is semi empirical models relying on the physical interpretation of the experimental results by means of scattering mechanisms. This approach requires a more reduced number of training plot data. Forest structure and environment effects will be treated as noise and considered in the uncertainty assessment.

Figure 3a shows the biomass map of NE Brazil obtained from ALOS-PALSAR data of 2010. Figure 3b presents the map of different Brazilian biomes. In the biomass map, AGB classes are displayed up to 80 Mg/ha, because of the L-band saturation. Figure 3c shows the histogram of AGB of the Cerrado region delineated using Figure 3b. It can be seen that a large part of Cerrado (31%) is in the low biomass class (AGB < 10 Mg/ha), indicating agriculture or pasture. The cerrado savannah type ranges from 20 to 70 Mg/ha (56% of the cerrado surface area), whereas the forest formations are in the range of 70 Mg/ha or more (13% of the cerrado surface area).

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Despite the lack of AGB map validation (expected to be done in a later phase, with suitable biomass plots in Cerrado), the range of cerrado AGB found here appears to be consistent with plot measurements in literature.

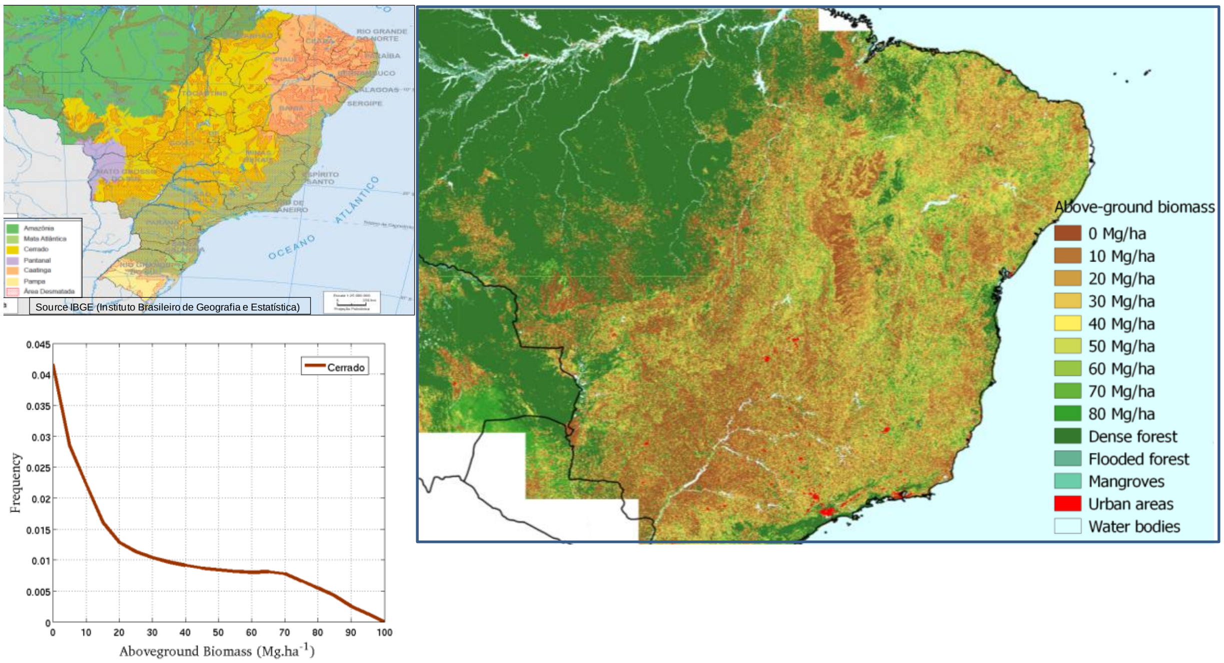

Figure 3. Figure 3a (Right): Above ground biomass (AGB) map (20 m resolution) generated using ALOS-PALSAR data of 2010. Source: CESBIO. Figure 3b (Top left): Map of Brazilian biomes (Source: IBGE). Figure 3c (Bottom left): histogram of AGB of the Cerrado region.

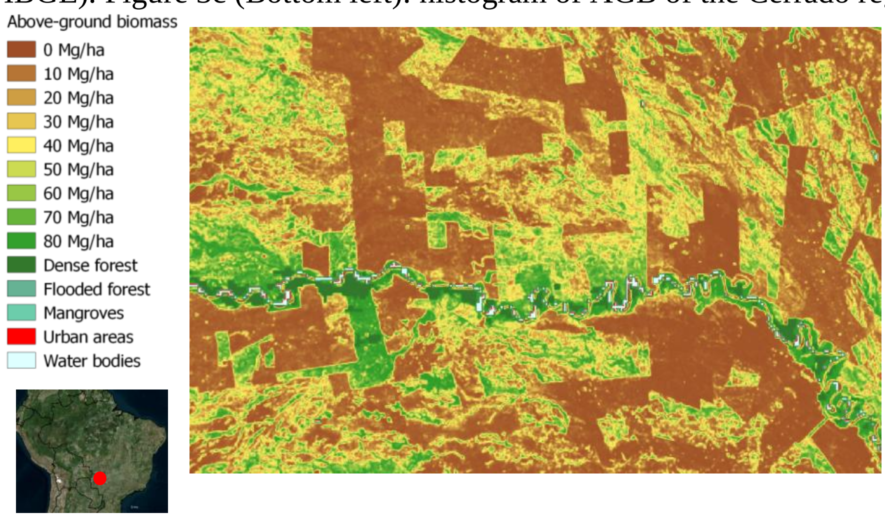

Figure 4. Detail of the Above-ground Biomass map in Figure 3 (18.19°S/55.26°W) 28x18 km

Figure 4 shows details of above-ground biomass in a small subset from Figure 3a. It can be seen that a significant part of the region is converted into pasture or agriculture (AGB < Mg/ha). The illustrations show that it is possible to map the biomass distribution of the whole cerrado at 25 m resolution, and more important, to follow the dynamics of biomass in cerrado and similar biomes (miombo, and other savannah).

4. Estimating of tropical forest biomass using P-band SAR- The BIOMASS mission

For the global carbon cycle, the most critical forest regions arein the tropics, where knowledge on biomass information is poor and biomass information is the most needed. However, estimating biomass of tropical rain forests characterized by high biomass density (up to 500 t ha^{-1} or greater) remained a challenging task. Studies have shown that P-band SAR systems have the highest potential for the retrieval of AGB in high-biomass areas. Numerous airborne surveys have been conducted for biomass mapping, in the absence of spaceborne missions. In Brazil, an airborne mapping project called "Radiografia da Amazonia" was implemented by the Brazilian government, based on radar surveys, in which the DTM (ground elevation) and the DSM (canopy elevation) are generated by P-band and X-band airborne SAR interferometry, respectively, in order to characterize both the topography and the forest structure in a single data set (Correia 2011). The difference between the two altimetric profiles provides an estimation of tree heights. Beyond classical cartographic application, some attemps have been made to use these data to detect illegal logging and assess biomass (Sambatti and Lubeck 2014).

With the P-band frequency allocation decided in 2004, the BIOMASS mission has been selected for mapping of biomass globally by the European Space Agency (Le Toan et al., 2011). The mission will carry a polarimetric P-Band SAR, capable of providing three types of measurements: polarimetric intensity (PolSAR), polarimetric interferometry (Pol-InSAR) and SAR Tomography (TomoSAR) to be used for the retrieval of forest biomass.

During the preparatory phase of BIOMASS activities, the algorithms to be employed for Above Ground Biomass (AGB) retrieval have been developed, using airborne and in situ data collected over boreal and tropical forests, with significant efforts put on the challenging biomass retrieval of the high biomass range in tropical forests (Biomass Report for Selection, ESA 2013). The following points can be noted:

1) The retrieval of AGB of dense tropical forest with AGB up to 500 t ha−1 using PolSAR requires particular attention on the topographic correction. The method developed in (Villard and Le Toan, 2014) has two aspects: changes in effective scattering area induced by slope and correction accounting for changes in polarisation orientation and change in relative contributions of volume scattering and double bounce scattering.

2) Pol-InSAR can provide height estimates. However, the accuracy of AGB retrieved from height depends on different factors, among them the relevance of the allometric equation to be used, resulting in a possible source of error for AGB estimates.

3) The combination of the two approaches, PolSAR and Pol-InSAR using a Bayesian approach yield improved AGB estimates.

4) Using SAR tomography (TomoSAR) providing the 3D distribution of backscatter , forest height, terrain topography, and AGB can be accurately estimated.

To assess the retrieval of AGB using these techniques we used data acquired by dedicated airborne campaigns. Over the tropical forests in S America, the data were acquired by the ONERA P-band airborne SAR over French Guiana in 2009, during the TropiSAR campaign. The results showed that it is possible to measure AGB with good accuracy up to 500 t ha-1 using either TomoSAR or a combination of PolSAR and PolInSAR. Figure 5 shows the biomass mapping results using P-band SAR tomography at the Paracou site in French Guiana for AGB values ranging from 250 to 450 t ha−1 (Ho Tong Minh et al., 2013). The algorithm has also been applied at an other site in French Guiana, and based on SAR data degraded to simulate BIOMASS data.

Currently, a network of *in-situ* forest plots is under investigation to serve in the Cal-Val Strategy, for which forest plots in Amazonia will have a key contribution.

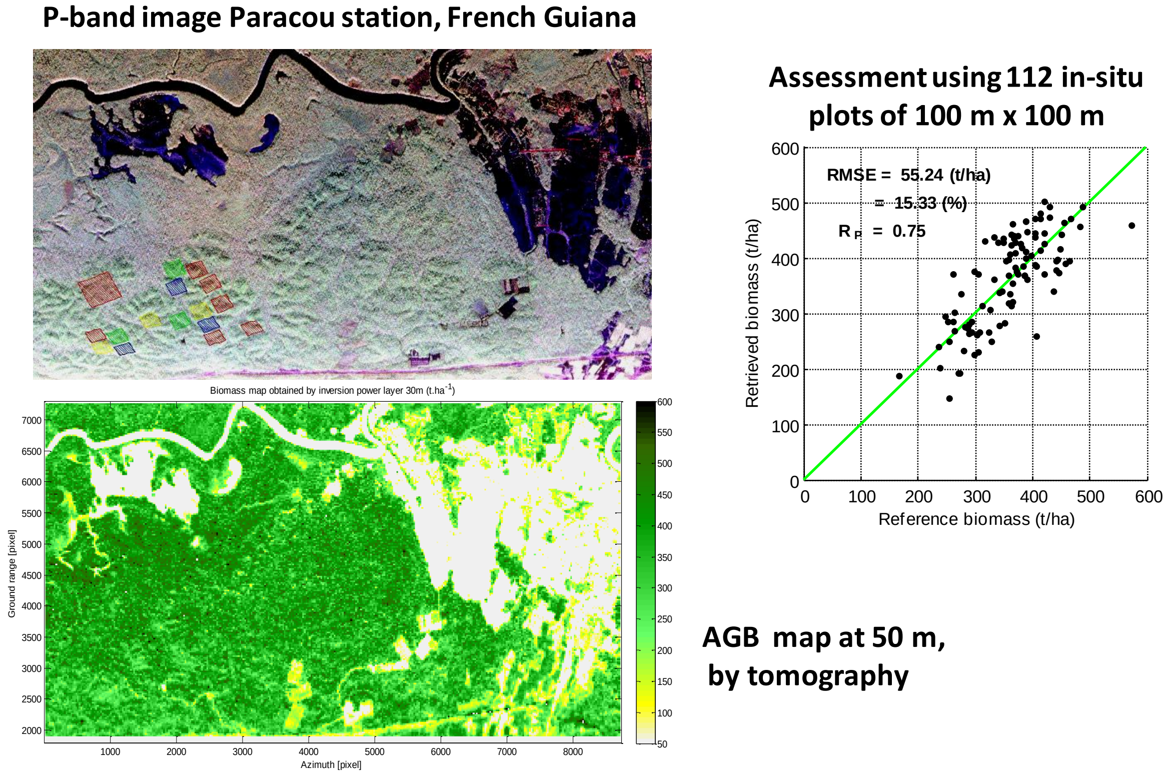

Fig.5: Bottom: Map of forest Above Ground Biomass (AGB) of the region of Paracou, in French Guiana, at 50 m resolution. The map is obtained using SAR Tomography result derived from P-band SAR data (Top) acquired during the ESA-CNES TropiSAR campaign. Left: AGB estimates assessment using in situ plot data. (Crédit: CESBIO-PoliMi).

5. Conclusions

This paper has examined the use of SAR data in forest observing systems, for deforestation monitoring, and for measuring biomass of tropical forests. The results shown are promising, despite the fact that operational methods consolidation and validation remain to be done. In Amazon region, the C-band Sentinel-1 data with a repeat frequency of 12 days will be optimal for bi-monthly disturbances detection, for deforested areas of large (> 6.25 ha) and small (1 ha or less) dimensions. This can complete well the current monitoring programs (e.g. PRODES and DETER) dealing with large deforested plots. The currently yearly available L-band SAR data from ALOS-PALSAR can be used for mapping of biomass for the Cerrado biome. Data from the forthcoming BIOMASS mission are expected to be used for bi-yearly mapping of biomass and carbon stocks of dense tropical forests, and monitoring their dynamics during the mission lifetime.

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