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Potential of Multipolarization and Multifrequency Radar Images in Identification of Land Cover in the Eastern Amazon

Potencial da Multipolarização e da Multifrequência de Imagens de Radar na Identificação da Cobertura da Terra na Amazônia Oriental

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Abstract: The objective of the present work is to analyze the potential of synthetic aperture radar images to identify the different classes of land cover representative for the Eastern Amazon, in a protected area. Images distributed free of charge were analyzed referring to the ALOS PALSAR-2 (L-band, HH and HV polarization) and Sentinel 1A (C-band, VV and VH polarizations) sensors, referring to the month of November 2022, which were evaluated separately and integrated for identification, through machine learning classification, of the following classes: Forest Cover, Grassland Cover, Wet Fields and Water Cover. The results show that the targets of interest, in a representative environment of the Amazon, are better differentiated through the multifrequency integration and multipolarization between the C and L bands, allowing to achieve excellent classification accuracy and all the chosen classes presented satisfactory Kappa index.

Keywords: Backscatter; Amazon; Maranhão; SAR.

Resumo: O objetivo do presente trabalho é analisar o potencial de imagens de radar de abertura sintética para identificar as diferentes classes de cobertura de terras representativas para a Amazônia Oriental, em área de proteção. Foram analisadas imagens distribuídas gratuitamente referentes aos sensores ALOS PALSAR-2 (banda L, polarização HH e HV) e Sentinel 1A (banda C, polarizações VV e VH), referente ao mês de novembro de 2022, as quais foram avaliadas separadamente e integradas para identificação, através de classificação por aprendizagem de máquina, das seguintes classes: Cobertura Florestal, Cobertura Campestre, Campos úmidos e Cobertura Hídrica. Os resultados mostram que os alvos de interesse, em ambiente representativo da Amazônia, se apresentam melhor diferenciados através da integração multifrequencial e multipolarização entre as bandas C e L, permitindo alcançar acurácia de classificação excelente e todas as classes escolhidas apresentaram índice Kappa satisfatórios.

Palavras-chave: Retroespalhamento; Amazônia; Maranhão; SAR.

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1. Introduce

The Brazilian Amazon is going through intense changes in its land cover, where human action has contributed significantly to the alterations of this environmental system. Conversions of land cover into different uses have historically been motivated by different planning policies, settlement, and economic interests in the region.

Protected areas have stood out effectively in containing the transformations, especially in the face of deforestation (NUNES et al., 2015). In the Amazon, areas are distributed for different levels of protection, highlighting the Conservation Units (UC's), which total 335 areas, in addition to 338 Indigenous Lands (COELHO, 2022). Also, according to (NUNES et al., 2015), depending on the degree of restriction of the area, the effectiveness of containing deforestation vary.

Among the different categories of UC's, the group of Environmental Protection Areas (APA) is mentioned, defined as areas of sustainable use (allowed the rational use of existing natural resources and housing) and full protection (of high restriction), established by the National System of Conservation Units - SNUC (Federal Law 9985/2000).

Considering the importance of environmental services provided by protected areas, in addition to the need to ensure compliance with the laws that are intended for the preservation of such areas, initiatives for monitoring changes in land cover in Brazil emerged from the 80's and since then, the PRODES, DETER and TerraClass systems, supported by Remote Sensing, stand out.

Remote Sensing is the main support tool in the monitoring of extensive areas, in a comprehensive way and whose changes can occur suddenly, being, therefore, of great importance for the monitoring of the Amazon. However, it is important to highlight the limitations of detection in the Amazon region, due to the cloud cover over this area (ASNER, 2001; SALGADO et al., 2018), when observed through optical sensors. These characteristics motivated the use of RADAR (Radio Detection And Ranging) sensor systems as a precursor in the mapping of the Amazon region.

The first major initiative for cartographic mapping of the Amazon took place in Brazil, using an airborne X-band radar sensor, within the scope of the RADAM (radar in the Amazon) program, in the 1970s (AZEVEDO, 1971; IBGE, 2018). Such data was digitized in the early 2000s and made publicly available. Other initiatives are also observed in Amazonian countries, such as in French Guiana, with the "Guyana in the Clouds" program, using the ERS-1 orbital sensor (RUDANT, 1994). There are also other programs for the recognition of the Amazon, in the C band, aimed at the recognition of land cover and SAR imaging capacity in tropical forest areas, with the respective Globe-SAR (WOODING et al., 1994) and SAREX-92 (BROWN et al., 1996) programs.

The ability to image through radar sensor systems in humid tropical environments occurs with low or no atmospheric interference, considering the wavelengths used (from 2.5 to 120 cm). Target detection results from the interaction of the emitted energy with the surface, usually in the form of backscattering, which depends on surface parameters (such as roughness and dielectric properties) and wave parameters (such as local angle of incidence, wavelength and polarization) (JENSEM 2009; LEWIS AND HENDERSON 1998).

In the Amazonian context, initiatives supported by orbital radar data in coastal mapping are observed (TEIXEIRA; SOUZA FILHO, 2007; TEIXEIRA, 2011; GUIMARÃES, 2017) through the polarimetry of different sensors, in the mapping of floods with embedded (FUCHSHUBER, 2011) and orbital (FERREIRA, 2018) sensors, in the mapping of vegetation cover and Phyto physiognomies (NUNES, 2011; SAINTS; GONÇALVES, 2009), in patrolling and defense with an R-99 airborne sensor (ALVES et al., 2009), in the identification of deforested areas through L-band SAR sensors (SOUZA et al., 2012; ABOUD NETA et al., 2010), relief mapping through sensors operating in the P-band (TANAJURA et al, 2023), among other applications.

In the cartography of land use and land cover, different initiatives are observed in the Amazon using radar images (NEGRI, 2009; Azevedo et al., 2014; WIEDERKEHR, 2018; DINIZ, 2019; DAVID; RANGE; ADAMI, 2020). Land cover classes may have limitations in their detection due to aspects related to the absence of multitemporal, polarimetric and multifrequency data in the various sensor systems available (FURTADO et al., 2015). However, the increase in the temporal resolution of SAR sensor systems, at different frequencies and polarizations, in addition to the free availability of such data, has enabled applications integrating different sensor systems in tropical areas in the Amazon and in the Savanna/Amazon transition (EVANS et al., 2010).

Among the SAR data currently available, data from Sentinel 1A (S1A) and ALOS PALSAR 2 (ALOS2) deserve to be highlighted. The European Space Agency's (ESA) Sentinel 1A mission (operating in C-band) succeeded the ERS and ENVISAT missions, with the difference of having grand4e magazine capability and making it available free of charge. The Japan Aerospace Exploration Agency's (JAXA) ALOS PALSAR-2 mission (operating in L-band) succeeded its predecessors JERS-1 and ALOS PALSAR, launched in 1992 and 2006, respectively, and although initially restricted, in

2022 the agency announced the opening of data since 2014 for public access on its portal (https://www.eorc.jaxa.jp/ALOS/en/dataset/alos_open_and_free_e.htm).

In view of the atmospheric limitation that the Amazonian environment presents for imaging through optical sensors, and considering the public and current availability of differents microwaves imaging missions, this study evaluated the potential of SAR (Synthetic Aperture Radar), multifrequency and multipolarization images obtained by the Sentinel 1A (dual-pol: VH and VV) and ALOS PALSAR-2 (dual-pol: HH and HV) as an alternative in the discrimination of land cover classes in a protected area in the northeastern region of the Brazilian Amazon.

2. Study Area

In the Eastern Amazon, the Environmental Protection Area of the Baixada Maranhense (figure 1) is located, created through Decree Law 11.900/1991, and categorized as Sustainable Use (Federal Law 9985/2000), aiming at harmony between the maintenance of local biodiversity, sustainable development and the rational use of existing natural resources.

This protected area has as a striking feature a vast fluviomarine plain with flat topography, in which extensive portions of land are flooded during the rainy season and favor the emergence of extensive lakes which connect to the courses of the great rivers also present in the region. Such characteristics led the area to be declared a RAMSAR Site in 2000 (RAMSAR, 2020). There is also a very rich ecosystem of which it is possible to mention diversified fauna and flora, the presence of mangroves and babassu trees.

This area was chosen for this study due to the dynamics of transformation in its cover, with a strong emphasis on the loss of arboreal, secondary and forest vegetation cover, as indicated by data from the TerraClass Program for the years 2008, 2014 and 2020, with such areas being historically replaced by cultivated pastures whose intensification has been taking place in recent years (ALMEIDA et al., 2022). In this context, the boundaries of the Municipality of Turilândia were chosen as the study area to be a representative section of the landscape and the transformations mentioned above (figure 1).

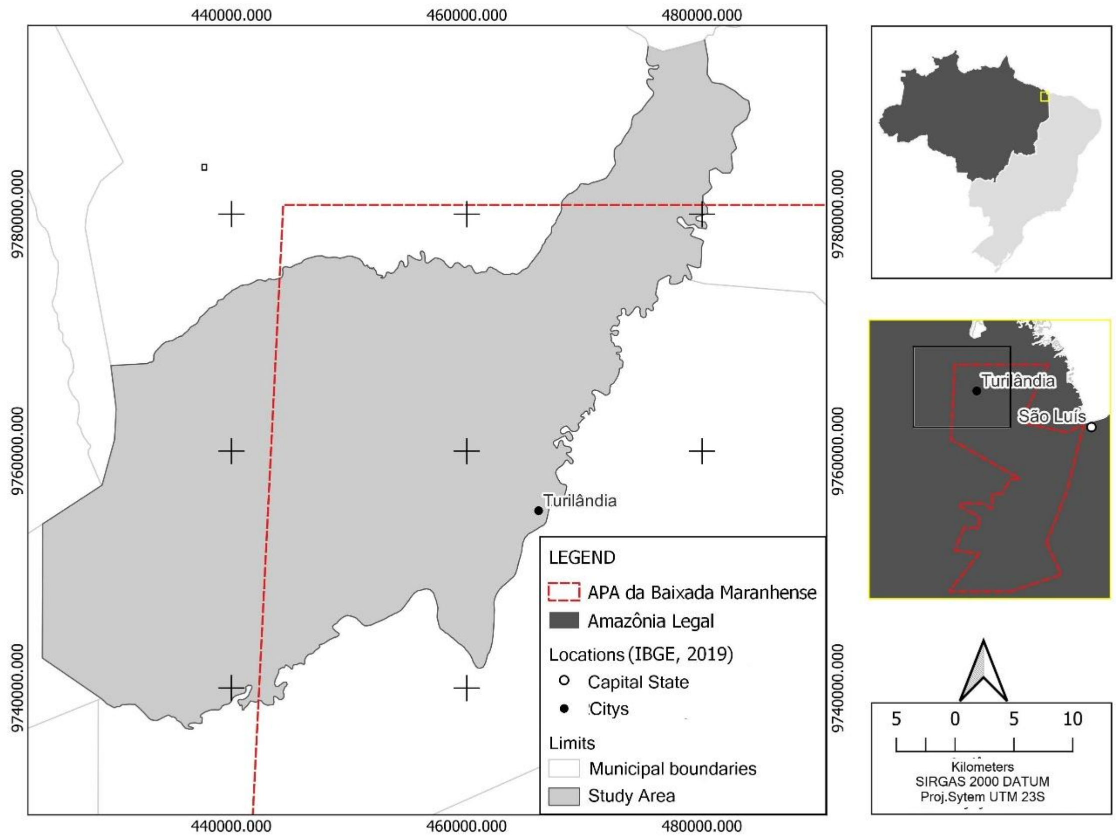

Figure 1 – Location of the study area.
Source: Silva et al (2024).

The municipality of Turilândia has approximately 1567 km², bordering Turiaçu, Santa Helena, Presidente Médici, Governador Nunes Freire, Bacurí and Serrano do Maranhão. This area is partially part of the Baixada APA, in its northwestern portion.

3. Materials and methods

Land cover classification was performed from SAR images and training samples. To increase the possibility of discriminating different coverage classes, assuming that the sensitivities are complementary, images from two different frequency sensors were used, each offering two different polarizations: Sentinel 1A (S1A) and ALOS PALSAR 2 (ALOS2). The procedures for processing SAR scenes are summarized in figure 2 and described below.

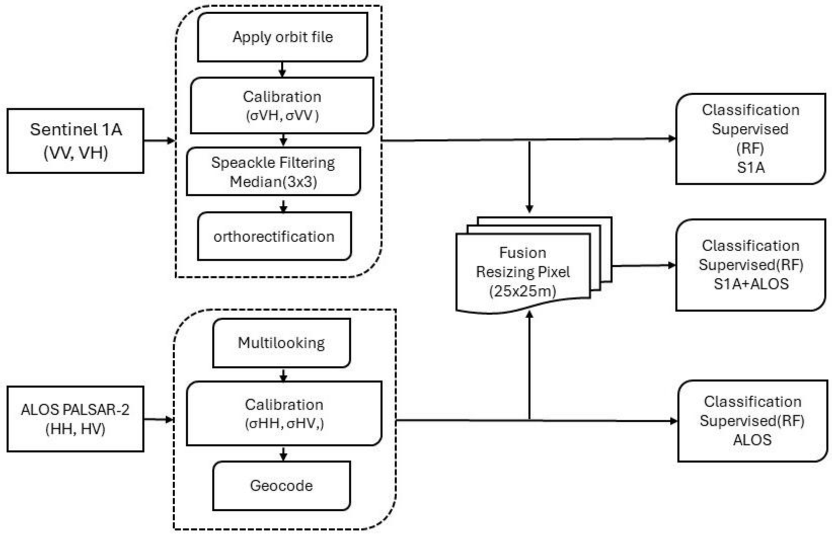

Figure 2 – Flowchart of processes applied to SAR scenes.
Source: Silva et al (2024).

A SAR S1A scene was acquired, dated 11/06/2022 (distributed free of charge in https://search.asf.alaska.edu/) acquired in Interferometric Wide mode - IW (in double polarization: VV and VH) at Ground Round Detection (GRD) level with amplitude data.

An ALOS2 scene was also acquired, dated 02/11/2022 (distributed free of charge from G-Portal Jaxa in https://gportal.jaxa.jp/) in ScanSar mode (with dual polarization: HH and HV) with Single Look Complex (SLC) level. This level contains amplitude and phase information.

For the S1A scene, the following scene correction procedures were applied, according to Filipponi (2019), in the SNAP 9.0 (Sentinel Application Platform) program:

(i) the application of precise orbits to update the information on the status of the platform (velocity and position) during the acquisition of the information;

II) Radiometric calibration in order to obtain the backscatter coefficients σVV and σVH (which characterize how much of the energy emitted towards the target returned to the sensor) through the Radar-Radiometric-Calibration module;

III) Reduction of the Speckle effect (with the Single Speckle Filter menu in 3x3 median) to remove the graininess of this effect, and;

IV) Orthorectification (with the support of the Terrain Correction module using 30 m Shuttle Radar Topography Mission (SRTM) data already incorporated into the application) and resampling to 25 meters in order to make it compatible with the PALSAR-2 scene.

For the ALOS2 scene, SLC scene transformation procedures were applied in amplitude. The processes were executed through ENVI IDL 5.6 and the SARASCAPE module, both temporarily provided by SulSoft Brasil, Harris' representative in Brazil, under the licenses ENVI+IDL 5.7 Evaluation - 7926-1881-2473-6822 and SARscape 5.6 Evaluation - 8289-8281-7265-3938. The processes were:

I) Multilooking was applied using the default SARscape standard (Range looks: 1, Azimuth Looks: 5 and pixel size of 25 m);

II) Radiometric Calibration and Geocoding to obtain the backscatter values (σHV and σHH), as well as to correct the geometry and topography of the scene. Radiometric calibration used JAXA (2014) recommendations (equation 01), where the calibration factors adopted were: CF1 = -83.0; A = 32, which were duly signaled in the Geocoding and Calibration algorithm. Geocoding included the orthorectification of the scene, with the 30 m Shuttle Radar Topography Mission (SRTM) model also incorporated into the SARSCAPE module.

$$\sigma = 10 * 10log_{10}(I^2 + Q^2) + CF - A \qquad \text{eq. 01}$$

The following complementary data were used: a) Interpretation key, composed of field information carried out in July 2023 (figure 3); b) Optical images of the LANDSAT-8 (from 29/09/2022) and CBERS 4A (from 29/10/2022) missions to support the sampling stage and; c) TerraClass Land Cover for the year 2020.

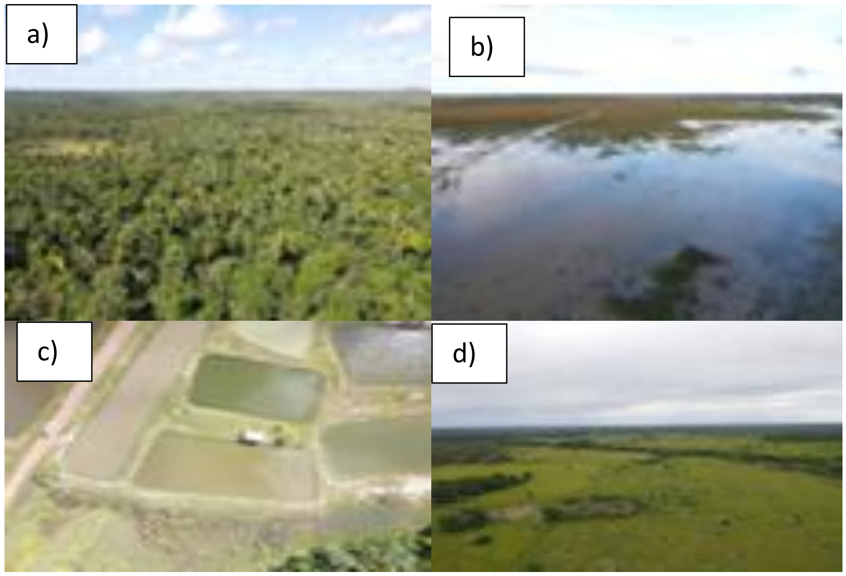

Figure 3 – Interpretation key for the study area. a) Forest Cover (FC); b) Wetlands (WT); c) Water Bodies (WB); d) Countryside Coverage (CC).
Source: Silva et al (2024).

The target classes adopted in this study were: (1) Forest Cover - CF (composed of Forest, Succession and Tree covers), (2) Grassland Cover - CC (formed by open and extensive areas, with the presence of grasses, managed pastures and agricultural crops), (3) Wetlands - WT (wetlands, topographically lowered and subject to seasonal flooding) and (4) Water Bodies - WB (including rivers, lakes, tanks for fish farming and weirs for thirst and supply). These classes were chosen because they are presented in large areas and repeatedly, are the result of land cover conversions and are more representative for the study area. In addition, it is noteworthy that the Wetlands of this UC are considered protected by local legislation (MARANHÃO, 1989).

Considering, initially, the fact that the area is located in a context of strong atmospheric interference, as it is located in the equatorial tropical zone, rainfall data from the Turiaçu Meteorological Station (closest to the study area) of the National Institute of Meteorology (INMET) were observed. These data show no precipitation in the days prior to the acquisition of the S1A scene and a small precipitation on the day before the acquisition of the ALOS2 scene (Figure 4).

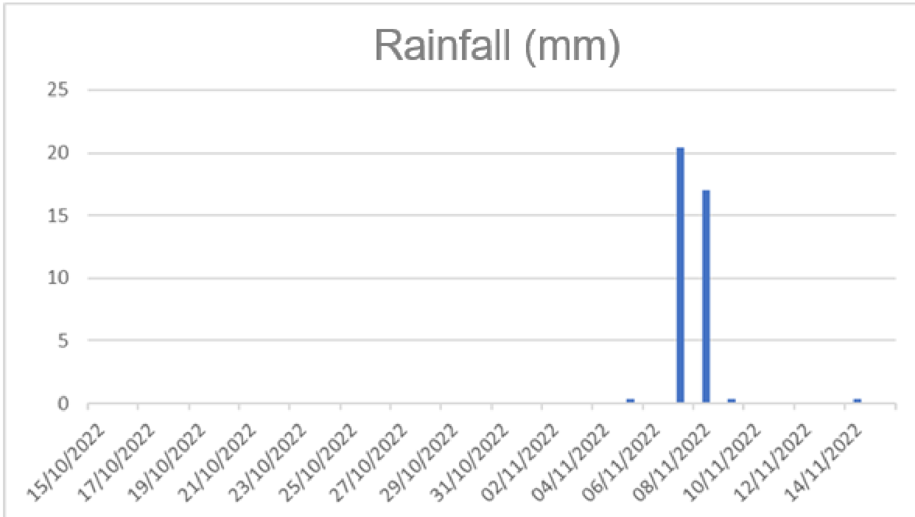

Figure 4 – Rainfall data for the months of October and November for the study area. Source: Silva et al (2024).

Precipitation records show days without heavy rainfall (figure 2) and, although there is a difference in dates between the ALOS2 and S1A products, it is assumed that there are no significant events to abruptly differentiate land cover between the dates of the scenes. Thus, this research assumes that the images are simultaneous.

Finally, the scenes were stacked and aligned in a SNAP environment. They were submitted to different combinations for supervised classification using the Random Forest (RF) algorithm, in the QGIS 3.28 LTR Software, through the Semi-Automatic Classification Plugin (CONGEDO, 2022) considering default parameters (training samples = 5000, trees = 10), and the Kappa statistics (LANDIS AND KOCH, 1977) and Global Accuracy of these processes were later evaluated. The statistical behavior of each of the classes in the different frequencies and polarizations was also evaluated in an exploratory way.

4. Results and discussion

The analysis of the backscatter values of the targets of interest demonstrates the behavior of the targets for the different polarizations and frequencies (Figure 5). The S1A presents backscatter values that vary, in the different polarizations, between ~ -24 dB and ~ -6 dB, with a good difference in water coverage. On the other hand, the ALOS2 sensor presents backscatter values ranging from ~ -34 dB to ~ -16 dB for both polarizations, standing out from the other targets at FC in HV and HH, and WB in HH.

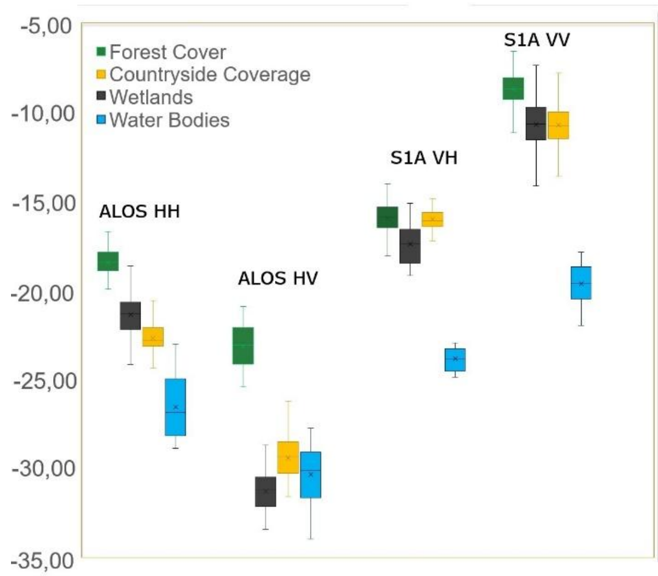

Figure 5 – Backscatter behavior (dB) of the targets in the different sensors approached.
Source: Silva et al., (2024).

The parallel polarizations, i.e., HH (ALOS2) and VV (in S1A), present higher backscatter values for all classes, with the exception of water body, and with emphasis on the FC class. This behavior stems from the interaction at the top (for S1A) and inside (ALOS2) of the canopy, interacting with leaves, trunks, and branches that make up the target. Similar behaviors are observed in experiments observed in the Amazon, for S1A (KYOHARA AND SANO, 2022) and in the Amazon/Savanna transition to ALOS 2 (SILVA et al., 2021).

Still on the backscatter behavior of targets, it is important to highlight the behavior of forest cover in the HV band, for ALOS 2. Shimada et al., (2014) identified that, in an experimental section of the Amazon, HV polarization, in ALOS 2, was able to better discriminate forest cover from non-forest targets.

Observing figure 3, it can be inferred that if a given class presents proximity in the behavior of the targets to a given sensor, the alternative of using another frequency and/or another polarization increases the possibilities of discriminating the targets.

When evaluating the isolated potential of each of the sensor systems for the chosen targets, by RF classification, through the Kappa index, it was found that they are capable of separating the targets with good (S1A) and very good (ALOS2) coefficients, according to Landis and Koch (1977) (Tables 1 and 2).

Table 1 – Confusion matrix with hit statistics obtained from S1A data.

S1A Confusion Matrix					
Class (Pixels)	**FC**	**CC**	**WB**	**WT**	**Total**
FC	16129	1824	11	56	18020
CC	9735	14586	17	742	25080
WB	39	29	9790	39	9897
WT	525	2428	183	2754	5890
Total	26428	18867	10001	3591	58887
Producer Accuracy [%]	88,9309	55,8514	89,4878	70,9791	-
User Accuracy [%]	89,5061	58,1579	98,9189	46,7572	-
Kappa of the Class	0,5919	0,4704	0,989	0,4518	-
Overall Accuracy [%]	86,9087				
Kappa	0,5459				

Source: Silva et al (2024).

Table 2 – Confusion matrix with hit statistics obtained from ALOS2 data.

ALOS2 Confusion Matrix					
Class (Pixels)	**CF**	**CC**	**CH**	**CU**	**Total**
FC	16129	1824	11	56	18020
CC	9735	14586	17	742	25080
WB	39	29	9790	39	9897
WT	525	2428	183	2754	5890
Total	26428	18867	10001	3591	58887
Producer Accuracy [%]	88,9309	55,8514	89,4878	70,9791	-
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Kappa of the Class	0,5919	0,4704	0,989	0,4518	-
Overall Accuracy [%]	86,9087				
Kappa	0,5459				

Source: Silva et al (2024).

For the ALOS 2 product, the CH and CF classes presented high Kappa values (0.9417 and 0.9358 respectively) and at the same time were the best when compared to the other classes. For the ALOS 2 product, the CH and CF classes presented high Kappa values (0.9417 and 0.9358 respectively) and at the same time were the best when compared to the other classes. S1A also presented water body as the class with the highest separation capacity from the other targets.

The integration of the S1A and ALOS2 data allows a classification that is both multi-frequency and multipolarization, which in turn presents a category improvement in the Kappa index, so that the value observed in this indicator suggests an excellent classification (Table 3). The Kappa of the classes is very good (WT) and excellent (WB, CC, FC).

The multi-frequency approach (C-band and L-band) presents a significant improvement in the identification of land cover, and adds to the results found in the Savanna (EVANS; COSTA, 2010) and in Savanna/Amazon transition areas (EVANS; COSTA, 2013) when ALOS (L-band) and ENVISAT (C-band) sensors are integrated.

Table 3 – Confusion matrix with hit stats obtained from S1A and ALOS2 integration.

S1A and ALOS2 Integration Confusion Matrix					
Class (Pixels)	**CF**	**CC**	**CH**	**CU**	**Total**
FC	22344	475	8	69	22896
CC	3314	17102	31	550	20997
WB	40	12	9872	34	9958
WT	730	1278	90	2938	5036
Total	95,7883	83,9662	93,1913	77,979	58887
Producer Accuracy [%]	97,5891	81,4497	99,1364	58,34	-
User Accuracy [%]	0,888	0,7777	0,9912	0,57	-
Kappa of the Class	95,7883	83,9662	93,1913	77,979	-
Overall Accuracy [%]	93,2278				
Kappa	0,8148				

Fonte: Silva et al (2024).

Although the Kappa values are good and very good, respectively, for S1A and ALOS 2, it is possible to verify the impact of this classification in its qualitative aspect (Figure 6). It is verified that the aspect of homogeneity of the targets interferes in the results.

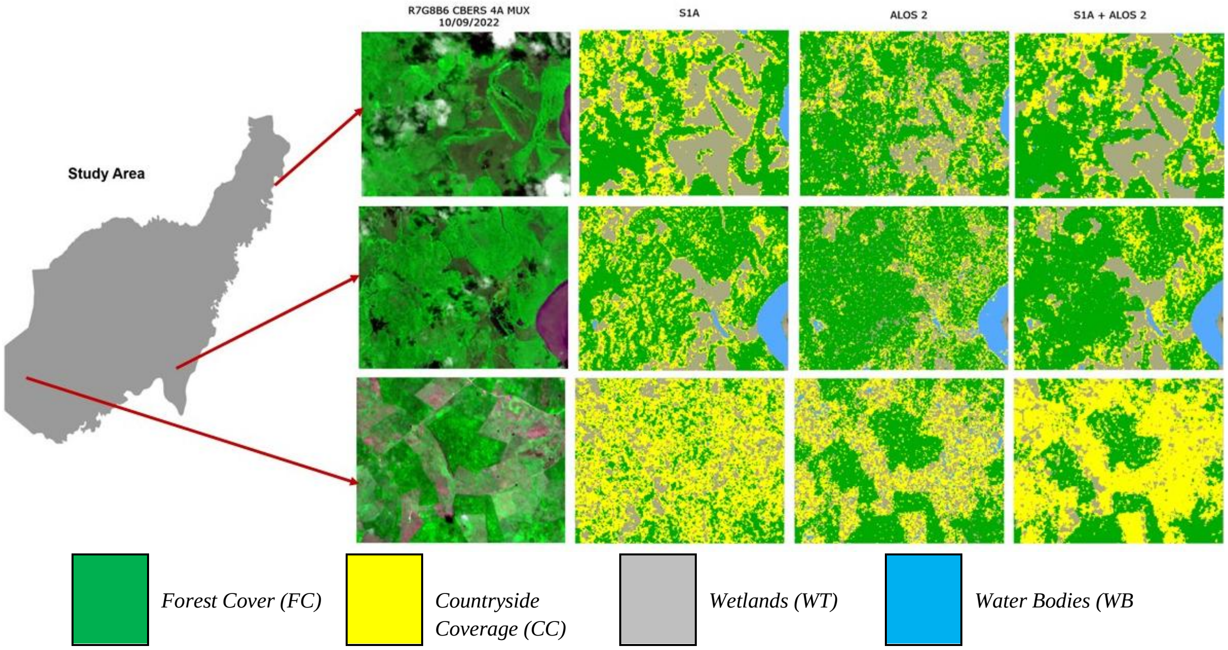

Figure 6 – Comparative sample between the results obtained in the different classifications.
Fonte: Silva et al (2024).

Very homogeneous areas, dominated by Forest Cover and Water Body, presented a better qualitative aspect, when observing the classification resulting from the S1A scene. For the S1A product, the identification of the FC class is limited in fragmented areas and with a strong presence of tree covers. On the other hand, in the ALOS2 product, the homogeneity of the FC class did not present the same limitation as in S1A, but the difficulty of the sensor system in identifying the WT class was verified. Such occurrences are related to the quantitative results of the extension of the classes obtained by the different classifications (Figure 7).

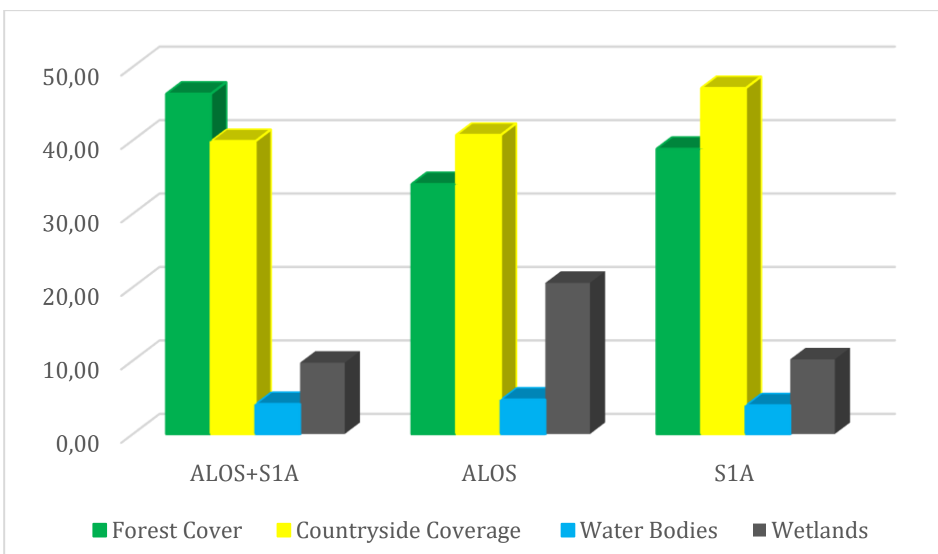

Figure 7 – Extent of land cover obtained by the different sources.
Source: Silva et al (2024).

Among the different combinations of products, the integration of ALOS 2 and S1A data showed the largest extension of area considered Forest Cover, as well as the smallest area referring to Wetlands. However, Water Bodies remains the only class without a relevant difference in the number of classes.

5. Final Considerations

The land cover classification presented in this research generated from ALOS2 was generally slightly higher when compared to S1A, highlighting the detection of the FC class in heterogeneous areas, although limited for the WT class. However, it is worth noting that the potential of S1A associated with the multitemporal aspect was not explored in this study, being an important characteristic of this sensor that currently has a temporal resolution of 12 days, in contrast to ALOS 2, with 46 days.

The integration between S1A and ALOS2 data, with a negligible temporal difference of acquisition (4 days), was able to separate land cover classes well in the extreme northeast portion of the Amazon, presenting itself as excellent (>0.8). However, although satisfactory in this context of integration, it is noteworthy that the WT class presented greater limitations when compared to the other classes, but it is still very good.

Further studies can be conducted to evaluate whether flood dynamics and/or moisture content can be related to the Kappa value obtained for the Wetlands (WT) class. Multitemporal classifications can be evaluated for this class, as it is a dynamic coverage.

The integrated product, using data referring only to the amplitude of the S1A and ALOS 2 sensors, was also able to generate satisfactory results for the Forest Cover class, an extremely important class, considering that the area is part of a Conservation Unit in a humid tropical zone.

It is worth noting that in the future, a separation of the Forest Cover Class into two others (Tree and Forest) can be evaluated to seek better levels of accuracy and its proximity to large monitoring projects, such as Mapbiomas and TerraClass.

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References

ABOUD NETA, S. R.; FREITAS, C. C.; DUTRA, L. V. Uso de imagens ALOS/PALSAR multipolarizadas para detecção de incremento de desflorestamento na Amazônia. Revista Brasileira de Cartografia, Uberlândia, v. 62, p. 417-431, 2010.

ALMEIDA, J. L.; BEZERRA, J. F. R.; SANTOS, J. R. C.; MORAES, M. M.; LISBOA, G. S. Avaliação das Mudanças no Uso da Terra da Bacia Hidrográfica do Rio Turiaçu na região amazônica maranhense. *Revista Brasileira de Geografia Física*, v. 15, n. 4, p. 1965-1977, 2022.

ASNER, G. P. Cloud cover in Landsat observations of the Brazilian Amazon. International Journal of Remote Sensing, v.22, n. 18, p. 3855-3862. 2001.

AZEVEDO, L.. Radar in the Amazon. Proceedings of the 7th International Symposium on Remote Sensing of Environment, *Center for Remote Sensing Information and Analysis*, Ann Arbor, p.2303-2306, 1971.

BROWN, R.J.; BRISCO, B.; D'IORIO, M.A.; PREVOST, C.; RYERSON, R.A.; SINGHROY, V. RADARSAT Applications: Review of GlobeSAR Program. *Canadian Journal of Remote Sensing*, 22: 404-419, 1996

CALDEIRA, C. R. T., POLIDORI, L., EL HAGE, M., COBACHO, O. C. M., BASTOS G. E., PIERRE, H., BALBAUD O. J. Comparação entre os Modelos Digitais de Terreno gerados por Radar em Banda P e LiDAR na Amazônia, um estudo de caso no Amapá (Brasil).: Comparison between Digital Terrain Models generated by P-Band Radar and LiDAR in the Amazon, a case study in Amapá (Brazil). Revista de Geociências do Nordeste, [S. l.], v. 9, n. 1, p. 59–70, 2023

CALDEIRA, C. R.; POLIDORI, L.; EL HAGE, M.; CALDEIRA, M. C. O; PIERRE, H. B. O. Comparação entre os Modelos Digitais de Terreno gerados por Radar em Banda P e LiDAR na Amazônia, um estudo de caso no Amapá (Brasil).: Comparison between Digital Terrain Models generated by P-Band Radar and LiDAR in the Amazon, a case study in Amapá (Brazil). *Revista de Geociências do Nordeste*, [S. l.], v. 9, n. 1, p. 59–70, 2023

COELHO, A, S. *POLÍTICAS PÚBLICAS E A CONFIGURAÇÃO DO BIOMA AMAZÔNIA NO ANTROPOCENO:* UMA ANÁLISE DO DESMATAMENTO EM MÚLTIPLAS ESCALAS DE ESPAÇO E TEMPO. Belém, 2022. 140f. Tese (Doutorado em Ciências Ambientais). Programa de Pós-Graduação em Ciências Ambientais, Universidade Federal do Pará, Belém-PA 2022.

CONGEDO, L. Semi-Automatic Classification Plugin: A Python tool for the download and processing of remote sensing images in QGIS. *Journal of Open Source Software*, 6(64), 3172, 2021.

DINIZ, J. M. F. de S. Avaliação do potencial dos dados polarimétricos Sentinel-1A para mapeamento do uso e cobertura da terra na região de Ariquemes-RO. Dissertação (Mestrado em Sensoriamento Remoto) - Instituto Nacional de Pesquisas Espaciais, São José dos Campos, 2019.

DINIZ, J. M. F. S., GAMA, F. F., ADAMI, M. Evaliation of polarimetriy and interferometry of sentinel-1A SAR data for land use and land cover of the Brazilian Amazon Region. Geocarto International, v. 37, n.15, p.1482-1500, 2020.

EUROPEAN SPACE AGENCY - ESA. *Sentinel-1: ESA's Radar Observatory Mission for GMES Operational Services, 2012*. Disponível em https://sentinel.esa.int/documents/247904/349449/S1_SP-1322_1.pdf Acesso em 18 de março de 2021.

EVANS, T. L., COSTA, M., TELMER, K., SILVA, T. S. F. Using ALOS/PALSAR and RADARSAT-2 to map land cover and seasonal inundation in the Brazilian Pantanal. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, v.3, n.4, p.560-575, 2010.

FERREIRA, G. H. S. Identificação de áreas inundáveis na porção sul de Roraima com auxílio de imagens de Radar. Dissertação de Mestrado do Programa de Pós-Graduação em Geografia da Universidade de Brasília. Brasília, DF, 2018.

FILIPPONI, F. Sentinel-1 GRD Preprocessing Workflow. *Proceedings,* v.18, n.11, 4p, 2019.

FLORENZANO, T. G. *Imagens de Satélite para Estudos Ambientais*. Ed Oficina de Textos, São Paulo, 2008.

FUCHSHUBER, E. M. AVALIAÇÃO DE TÉCNICAS DE CLASSIFICAÇÃO AUTOMÁTICA DE DADOS MULTIPOLARIMÉTRICOS NA BANDA-L DO SENSOR R99B-SAR PARA O MAPEAMENTO DE ÁREAS INUNDADAS NO LAGO DE COARI, AMAZÔNIA CENTRAL. Dissertação de Mestrado do Programa de Pós-Graduação em Geografia da Universidade Federal do Rio de Janeiro. Rio de Janeiro, RJ, 2011.

FURTADO, L. F. A., SILVA, T. S. F., FERNANDES, P. J. F., NOVO, E. M. L. M. and cover classification of Lago Grande de Curuai floodplain (Amazon, Brazil) using multi-sensor and image fusion techniques. ACTA AMAZÔNICA, v.45, n.2, p.195-202, 2015.

GUIMARÃES, U. S. Análise dos modelos digitais de superfície gerados por interferometria e radargrametria no estudo de ambientes costeiros amazônicos. Tese de Doutorado do Programa de Pós-Graduação em Ciências Cartográficas da Universidade Estadual Paulista. Rio Claro, SP, 2017.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATISTICA (IBGE). CONHECER, MAPEAR, DESBRAVAR: MEMÓRIAS DO PROJETO RADAM BRASIL. Gerência de Biblioteca e Acervos Especiais. - Rio de Janeiro : IBGE,

2018. Disponível em: https://biblioteca.ibge.gov.br/index.php/biblioteca-catalogo?view=detalhes&id=2101614. Acesso em 13 de outubro de 2023.

JAPAN AEROSPACE EXPLORATION AGENCY (JAXA). ALOS-2/PALSAR-2 Level 1.1/1.5/2.1/3.1 CEOS SAR Product Format Description (Handbook). 2014. 233 p. Disponível em: https://www.eorc.jaxa.jp/ALOS-2/en/doc/fdata/PALSAR-2_xx_Format_CEOS_E_r.pdf. Acesso em 13 de outubro de 2023.

JENSEN, J. *Sensoriamento Remoto do ambiente: uma perspectiva em recursos terrestres (2ed)*. São José dos Campos: Ed. Parênteses, 2009.

LANDIS, J. R.; KOCH, C. H. The measurement of observer agreement for categorical data. *Biometrics*, v. 33, n. 3, p. 159-174, 1977.

LEE, J. S.; POTTIER, E. Polarimetric Radar Imaging: From Basics to Applications. *CRC Press*, 2009.

LEI FEDERAL 9985/2000. Sistema Nacional de Unidades de Conservação. Disponível em: <http://www.planalto.gov.br/ccivil_03/leis/l9985.htm>. Acesso em: 06 Jan. 2022.

LEWIS, A. J., HENDERSON, P. M., HOLCOMB, D.W. RADAR FUNDAMENTALS: THE GEOSCIENCE PERSPECTIVE.IN: HENDERSON, P.M.; LEWIS, A. J. (orgs.). *Manual of Remote Sensing: Principles & Applications of Imaging Radar*. American Society for Photogrammetry and Remote Sensing, New York, p131-181, 1998.

MARANHÃO. Constituição do Estado do Maranhão. 1989. Disponível em http://www.al.ma.leg.br/arquivos/constituicaoma.pdf. Acesso em 13 de outubro de 2023.

MARANHÃO. Decreto Estadual 11900/1991 – CRIAÇÃO DA APA DA BAIXADA. Disponível em: <https://documentacao.socioambiental.org/ato_normativo/UC/303_20100823_145738.pdf>. Acesso em: 06 Jan. 2022.

NEGRI, R.G. Avaliação de dados polarimétricos do sensor ALOS PALSAR para classificação da cobertura da terra da Amazônia. 2009. 170 p. Dissertação (Mestrado em Sensoriamento Remoto) – Instituto Nacional de Pesquisas Espaciais, São José dos Campos, 2009.

NUNES, G. M.; Souza Filho, C. R.; Ferreira, L. G. Discriminação de fitofisionomias de floresta de várzea a partir do algoritmo Iterated Conditional Modes aplicado aos dados SAR/R99 (QUAD-POL/Banda L). *Revista ACTA AMAZÔNICA*, v. 41, n. 4, p. 471-480, 2011.

NUNES, T. S S., FERREIRA, L. V., VENTICINQUE, E. M. A importância das Unidades de Conservação e Terras Indígenas na contenção do desmatamento na Amazônia Legal Brasileira. IN: VIEIRA, I. C. G., JARDIM, M. A. G., ROCHA, E. J. P. (orgs.). *Amazônia em Tempo: Estudos climáticos e socioambientais*. Belém, Universidade Federal do Pará: Museu Paraense Emilio Goeldi: Embrapa Amazônia Oriental, 2015.

PARADELLA, W. R. O USO DE RADAR ORBITAL EM APLICAÇÕES AMBIENTAIS NA AMAZONIA BRASILEIRA: A AVALIAÇÃO DO RADARSAT NO PROGRAMA ADRO. *Anais VIII Simpósio Brasileiro de Sensoriamento Remoto*, p. 331-340, 1996. Disponível em: http://marte.dpi.inpe.br/col/dpi.inpe.br/lise/2005/01.07.13.54/doc/T212.pdf. Acesso em: 18 de março de 2021.

RAMSAR (2020). Ramsar Information Sheet. Disponível em https://rsis.ramsar.org/RISapp/files/RISrep/BR1020RIS_2002_en.pdf. Acesso em 13 de outubro de 2023.

RANGEL, M. E. S. CONTRIBUIÇÃO DOS DADOS INTEGRADOS DOS SISTEMAS SENSORES TM/LANDSAT-5 E ERS-1/SAR PARA O ESTUDO DE USO E COBERTURA DA TERRA NO NORDESTE DA ILHA DO MARANHÃ. Dissertação de Mestrado do programa de Pós-Graduação em Sensoriamento Remoto do Instituto Nacional de Pesquisas Espaciais. São José dos Campos, 2000.

RUDANT, J.P. 1994. French Guyana through the clouds: first complete satellite coverage. *ESA Earth Observation Quarterly*, 44: 1-6.

SALGADO, C. B., CARVALHO JÚNIOR, O. A. C., GOMES, R. A. T., GUIMARÃES, R. F. Cloud interference analysis in the classification of MODIS-NDVI temporal series in the Amazon region, municipality of Capixaba, Acre - Brazil. Sociedade & Natureza, v. 31, p. e47062, 2019.

SANO, E. E., MENESES, P. R., ALMEIDA, T. REFLECTÂNCIA DOS ALVOS NA FAIXA DE MICRO-ONDAS. IN: MENESES, P. R., ALMEIDA, T., BAPTISTA, G. M. M. (orgs.). *Reflectância dos materiais terrestres: análise e interpretação*. São Paulo, Oficina de Textos, 2019.

SANTOS, J. R; GONÇALVES, F. G. Polarimetric responses patterns and scattering mechanisms of forest targets from L-band radar. Revista Brasileira de Cartografia, Uberlândia, v. 61, n. 4, p. 391-397, 2009.

SHIMADA, M. et al. New global forest/non-forest maps from ALOS PALSAR data (2007-2010). Remote Sensing of Environment, Amsterdam, v. 155, p. 13-31, 2014.

SILVA, F. S.; PESTANA, A. L. M. Mapeamento da cobertura hídrica da microrregião da Baixada Maranhense com dados do sensor SAR Sentinel 1A. *Revista Brasileira de Sensoriamento Remoto,* v.1, n. 2, p.058-071, 2020.

TEIXEIRA, S. G Radar de abertura sintética aplicado ao mapeamento e reconhecimento de zonas úmidas costeiras. Tese de Doutorado do Programa de Pós-Graduação da Universidade Federal do Pará. Belém, PA, 2011.

TEIXEIRA, S. G.; SOUZA FILHO, P. W.; M. Análise de coeficientes de retroespalhamento de imagens multitemporais RADARSAT-1 na discriminação de ambientes costeiros tropicais das regiões da Baixada Maranhense. *Anais XIII Simpósio Brasileiro de Sensoriamento Remoto*, p. 5019-5026, 2007. Disponível em: http://marte.sid.inpe.br/col/dpi.inpe.br/sbsr@80/2006/11.15.18.31.40/doc/5019-5026.pdf. Acesso em: 18 de março de 2021.

WIEDERKEHR, N. C. MUDANÇA DE USO E COBERTURA DA TERRA A PARTIR DOS DADOS POLARIMÉTRICOS ALOS/PALSAR-2 EM UMA PORÇÃO DA FLORESTA NACIONAL DO TAPAJÓS E ÁREAS ADJACENTES. Dissertação de Mestrado do Programa de Pós-Graduação em Sensoriamento Remoto do Instituto Nacional de Pesquisas Espaciais. São José dos Campos, SP, 2018.

WOODHOUSE, I. H. *Introdution to Microwave Remote Sensing*. New York: CRC Press/Taylor & Francis, 2006.

WOODING, M.G.; ZMUDA, A.D.; ATTEMA, E. 1994. An overview of SAREX-92 data acquisition and analysis of the tropical forest environment, In: Longdon, N. (orgs.). *Proceedings of the Second Euro-Latin American Space Days,* European Space Agency, Paris, ESA SP-363: 57-68.