ASSESSING THE IMPACT OF SEGMENT SIZE ON CANOPY HEIGHT ESTIMATION FROM NASA'S ICESAT-2 IN THE BRAZILIAN TROPICAL SAVANNA

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ABSTRACT

This study evaluates the effectiveness of NASA's ICESat-2 in estimating canopy height within Brazil's Cerrado (i.e., Brazilian tropical savanna), a critical biome undergoing rapid land-use change. By examining various segment sizes, from 25 to 100 meters, we assessed the accuracy of ICESat-2-derived canopy heights compared to UAV-LiDAR measurements in Cerrado climax forests. Our findings show that larger segment sizes (100 meters) improved estimation accuracy, as indicated by reduced mean difference and RMSD values, likely due to higher photon counts. This study demonstrates ICESat-2's potential for accurately capturing canopy height in dense tropical savanna, contributing valuable insights for forest biomass estimation and fire management applications. These results support the application of ICESat-2 in forest monitoring, with larger segment sizes recommended for optimal accuracy in similar ecosystems.

***Key words* —** Brazilian Savanna, photon-counting LiDAR, ATL08, ATL03, Remote sensing.

1. INTRODUCTION

The Brazilian tropical savanna, referred to as Cerrado, ranks as the second-largest habitat type in South America, following the Amazon biome, and covers approximately two million square kilometers, accounting for 23.3% of Brazil's land area [1, 2].

In recent decades, nearly half of the original vegetation of the Cerrado has been destroyed [3] and the remaining regions are subjected to ongoing environmental pressures due to the expansion of agricultural activities aimed at meeting the growing global food demand. To effectively understand the landscape configuration of biomass stocks and their variations, innovative monitoring approaches are essential in the Cerrado. Such strategies are crucial for developing reliable predictive models of vegetation dynamics and climate, which could aid decision-making and assist policymakers in formulating strategies for carbon markets and REDD+ initiatives worldwide [4].

Essential ecosystem parameters, including canopy height, which is associated with forest productivity and biodiversity, must be accurately measured to address gaps in our understanding of terrestrial ecosystems and their interactions with carbon cycle feedbacks in relation to future climate. This requirement can primarily be fulfilled through satellite observations, which has significantly advanced our ability to assess vegetation parameters over vast landscapes and capture the heterogeneity of ecosystem structure and function [5, 6, 7].

Among these technologies, NASA's Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) has emerged as a powerful tool for characterizing canopy heights across various forest types. ICESat-2 is a photon-counting LiDAR mission that was launched in September 2018, offering unprecedented high-resolution three-dimensional measurements globally along its track. With a smaller footprint of approximately 11 to 14 meters and six profiling beams (three strong and three weak), ICESat-2 provides enhanced along-track sampling capabilities compared to its predecessor, the original ICESat mission [8, 9, 10, 11]. Although ICESat-2's primary mission is centered on ice and land elevation, its potential for estimating canopy heights in various forest ecosystems has already been demonstrated in previous studies [12, 13], warranting further exploration.

To address existing knowledge gaps regarding the effectiveness of ICESat-2 in estimating canopy height within Brazil's tropical savannas, this study specifically evaluates how segment size impacts the accuracy of these estimates. By

analyzing various segment sizes, we aim to uncover the relationship between segment size and estimation accuracy, which is crucial for informing improved practices in the use of ICESat-2 data for forest monitoring and management.

This understanding can ultimately enhance the reliability of canopy height measurements and support more effective conservation and management strategies in these vital ecosystems. Furthermore, the findings from this study may encourage the broader application of ICESat-2 data for predicting forest biomass and aiding fire management strategies in the Cerrado region.

2. MATERIAL AND METHODS

2.1. Study area

The study was conducted in the Canto do Obrieni Privately Protected Area (PPA) of the Instituto Araguaia. The area comprises 240-hectares of pristine Cerrado climax forests with trees up to 25 meters in height, distinctive native grasslands and flooded forests [14]. The area is located in the state of Tocantins, in the Northern region of Brazil (Figure 1).

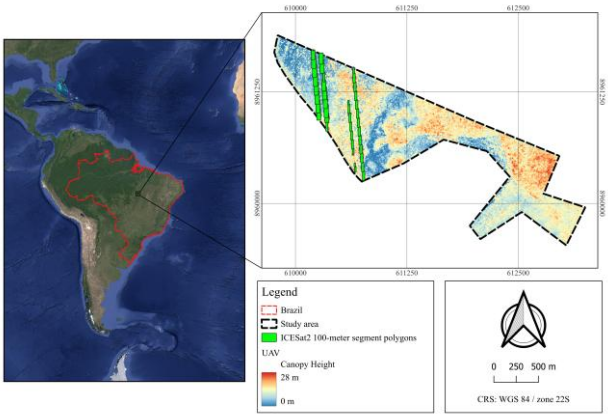


Figure 1. Location map of the study area and coverage of UAV-LiDAR data used for the validation effort.

2.2. UAV-LiDAR Data Collection and Processing

The UAV- LiDAR data were obtained in August 2024 with the DJI Zenmuse L1 sensor mounted on the Matrice 300 RTK UAV platform. The data from the Zenmuse L1 laser scanner were processed with the DJI Terra software before being finally exported in LAS format in the UTM coordinate system (EPSG 32722).

The next steps of LiDAR data processing utilized functions from LAStools [15]. High-density 3D point clouds were merged using the *lasmerge* tool and then clipped to the boundaries of the study area with *lasclip*. Following this, the *lasnoise* tool was employed to identify and remove spurious returns and ground returns were classified using *lasground_new*. A digital terrain model (DTM) with a 2-meter resolution was then generated using *las2dem*. The DTM was subsequently used to normalize the LiDAR point clouds (*lasheight*) and to create the canopy height model (CHM) with a 2-meter resolution. The CHM served as the observed canopy height for the validation of canopy height from ICESat-2.

2.3. ICESat-2 Data

ICESat-2 was launched in September 2018 to analyze the structure of Earth's ice, land, and vegetation [11]. The ATLAS instrument aboard ICESat-2 is a photon-counting system that operates six beams - three pairs of strong and weak beams - using green wavelength (532 nm) lasers, achieving a nominal footprint of approximately 13 meters [8, 10]. The algorithm for the Land and Vegetation Height data product (ATL08) derives terrain and canopy height information from the geolocated photon point cloud (ATL03), processed in 100-meter segments along the satellite's ground track [17]. The algorithm additionally computes several relative height metrics for each 100-meter segment. This generates a set of metrics per segment, representing canopy heights relative to the terrain surface, along with height variability measures and a collection of quality flags [18].

In this study, we utilized canopy height data from the study area between October 2019 and October 2024, ensuring sufficient data for comparison within the area and considering that the climax forests have not experienced significant canopy height changes over the past five years. Although the ATL08 height products provide various height measures, 98th percentile (P98) was selected as it is the standard metric output from the ATL08 product.

2.4. ICESat-2 Data Processing

Various segment sizes were tested to extract canopy height, with the help of the package ICESat2VegR [19] from R Programming language [20]. The ATLAS_dataFinder function was used to locate the exact granule(s) containing ICESat-2 ATLAS data for the study area within the date range mentioned above. Following this, the ICESat-2 ATL03 and ATL08 data were downloaded from the LP DAAC Data Pool using the ATLAS_dataDownload function. In the next step, the data were clipped to match the study area, and the photon attributes from ATL03 and ATL08 were joined and extracted using the ATL03_ATL08_photons_attributes_dt_join and rbindlist2 functions, respectively.

Finally, the ATL03_ATL08_segment_create function was employed to split the photons into segments of the desired length, and the ATL03_ATL08_compute_seg_attributes_dt_segStat function was used to calculate statistics (such as canopy height P98, the number of photons classified as ground, canopy, and top canopy, and the minimum and maximum

latitudes and longitudes of photons) from ATL03 and ATL08 labeled photons (classified as ground, canopy and top canopy) for each segment.

Only segments with 50 or more classified photons were included in the analysis, like the methodology employed in computing segment parameters for the Canopy Products from Algorithm Theoretical Basis Document (ATBD) [18].

2.5. Comparison of ICESat-2 P98 and CHM-UAV P90 canopy height values

The UAV-derived heights were spatially matched with the ICESat-2 height data by creating polygons for each ICESat-2 segment. The boundaries of these polygons were determined by the extreme photon coordinates, specifically the minimum and maximum latitudes and longitudes within each segment.

Subsequently, a 6.5-meter buffer was applied to each polygon to account for the footprint radius of the ICESat-2 satellite. After evaluating various metrics (including the mean and percentiles ranging from 50 to 98) the P90 heights from CHM pixels within each segment polygon were compared to the ICESat-2 canopy height P98 using a suite of descriptive statistics. The analysis incorporated the Pearson correlation coefficient (r), absolute (m) and relative (%) mean difference (MD%), and absolute (m) and relative (%) root mean square difference (RMSD). Furthermore, comparison plots were generated to evaluate the ICESat-2 canopy height estimates against those derived from the CHM.

3. RESULTS

The valid ICESat-2 data for the study area during the evaluated period were exclusively located in areas of Cerrado forest and for all data, there were analyzed 201 segments: 45 25-meter segments, 50 30-meter segments, 42 50-meter segments, 35 75-meter segments and 29 100-meter segments.

The quality of the ICESat-2 canopy height estimates and the scatter plots of canopy height are illustrated in Figure 2. In each of these figures, the black line denotes the one-to-one line, while the red line represents the mean bias of canopy height values estimated by ICESat-2.

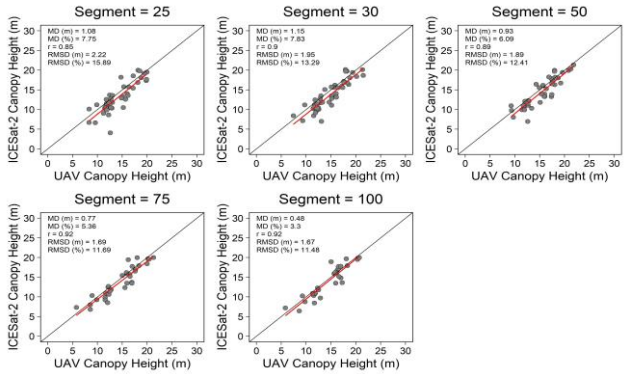


Figure 2. Agreement between ICESat-2 and ALS canopy heights at different segment sizes.

Across all segment sizes, ICESat-2 canopy height estimates consistently underestimated the canopy heights derived from CHM, as indicated by the positive mean difference values. However, increasing the segment size had a beneficial impact on improving the accuracy of these estimates. Notably, the mean difference for the 100-meter segment was less than half that of the 25-meter segment, and the RMSD was reduced by 0.55 meters. Additionally, the 25-meter segments had a mean photon count of approximately 75, while the 100-meter segments had a mean count of 187.

4. DISCUSSION

Since the 25-meter segments had a lower mean photon count than the 100-meter segments, it can be inferred that a greater number of classified photons can significantly diminish errors in estimating canopy height within forested regions. Furthermore, the observed positive skew in the errors may suggest a tendency for smaller photon counts to result in an underestimation of canopy height.

Previous studies comparing the ATL08 canopy height product to airborne LiDAR data also have reported that canopy heights are generally underestimated [17, 21]. This underestimation is likely due to an 11–13% chance of missing canopy tops, as identified by [10], who attributed the error to limitations in the computed canopy heights.

However, the results of this study indicate higher accuracy in canopy height estimates compared to previous studies using 100-meter segments. [10], examining boreal forest canopy heights, reported mean MD, MD%, and RMSD% values of 1.47 m, 9.13%, and 19.54%, respectively, though they were able to reduce the error by selecting strong beam/night/summer data (MD = 0.56 m, MD% = 3.18%, RMSD% = 13.75%). Similarly, [7], in their study across six biomes, reported mean MD and MD% values of 1.71 m and 15.9%, respectively.

The results of this study indicate strong performance of ICESat-2 in estimating canopy height, despite previously noted limitations identified by [17]. They reported potential underestimations due to ICESat-2's low photon return rates over vegetation surfaces (0–4 photons per pulse) and challenges with the ATL08 filtering algorithms in classifying non-terrain points. These factors increase the risk of missing canopy tops, which may lead to underestimations when compared to high-resolution airborne LiDAR. However, the improved accuracy seen in this study suggests that ICESat-2 can perform reliably under specific conditions or that data processing adjustments may help mitigate earlier challenges with ATL08 estimates.

The improved performance of ICESat-2 in estimating canopy height also can be attributed to the exclusive presence of data points in Cerrado forest, which exhibits denser canopy characteristics. According to [7], ATL08 canopy heights are more suitable for dense canopy environments. Thus, the

unique conditions of the study area likely enhanced the accuracy of ICESat-2 estimates.

Despite ICESat-2 not being explicitly designed for measuring vegetation structure, as is the case with the Global Ecosystem Dynamics Investigation (GEDI) mission, our findings indicate that ICESat-2 provides reliable canopy height data for monitoring Cerrado forests. This capability not only enhances regional forest monitoring efforts but also can contributes to the prediction of aboveground biomass (AGB), thereby supporting broader ecological studies and improving fire management strategies in the region.

5. CONCLUSION

This study emphasizes the importance of segment size in enhancing the accuracy of canopy height estimations derived from ICESat-2 data. The results indicate that larger segment sizes, particularly 100 meters, yielded more precise estimates and reduced error values. Therefore, we recommend that future research in similar ecosystems, especially within the Cerrado region, adopt larger segment sizes to take advantage of the increased photon counts associated with these measurements.

This study also underscores the potential of ICESat-2 for estimating canopy height in Cerrado forests. However, further research is necessary to investigate local factors such as forest type, terrain slope, canopy cover, ATLAS beam strength, and the timing of data collection (day versus night). Addressing these factors will improve the accuracy of future estimates and enhance the effectiveness of ICESat-2 in ecological research and resource management within Brazilian forests. Ultimately, this work establishes a benchmark for future investigations in estimating canopy height within Brazil's Cerrado forests.

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