Regional Mapping of Forest Heights using Multi-temporal Optical Stereo Imagery

Zijia Li[1,2*], Wenjian Ni[1,2], Zhiyu Zhang[1],Zhifeng Guo[1]

[1] State Key Laboratory of Remote Sensing Science, Aerospace Information Research Institute, Chinese Academy of Sciences, China

[2] University of Chinese Academy of Sciences, China

*lizijia20@mails.ucas.ac.cn

ABSTRACT

Forests constitute the backbone of terrestrial ecosystems, sequestering approximately 60% of the carbon in terrestrial ecosystems. Precise continuous regional forest canopy height mapping requires multi-angle optical satellite data. Most studies work on the extraction of forest canopy height using the stereo imagery acquired by repeat observation of a single satellite. However, in cloudy regions, using a single satellite for regional imaging can take over a decade. It is necessary to investigating regional mapping using synthesized stereo images from multiple satellites. This study reported the extraction of forest canopy height in the Daxing'anling region using multi-satellites and multi-temporal stereo imagery. Leaf-off season ZY-3 stereo images are employed for understory terrain elevation extraction, while leaf-on season GF-7 stereo image pairs are used for surface elevation extraction. A forest canopy height model is obtained by making difference between the two DEM and evaluated by reference canopy height. Results showed that the forest canopy height can be accurately estimated with a determination coefficients (R2) of 0.9. The paper also evaluates open source FABDEM(Forest And Buildings removed Copernicus DEM)'s accuracy in assessing understory elevation in the forest area. Extracted understory terrain elevation from leaf-off season ZY-3 stereo imagery is more stable, while FABDEM's elevation estimates are unstable. FABDEM overestimates in steep terrain and underestimates in flat areas, causing significant uncertainty in canopy height extraction.

Keywords: regional, understory terrain, northern forests, stereo Pairs, Daxing'anling

1. INTRODUCTION

Forests are an essential part of terrestrial ecosystems, covering more than 30% of the global land area. They not only support 80% of the animals, plants, and insects on land but also provide immeasurable value to humans(Pan et al. 2011; Pugh et al. 2019). The existence of forests is crucial for the well-being of people and the planet(Goldbergs 2021). Accurate tree height measurements are a fundamental parameter for assessing forest structure and play a crucial role in the estimation of forest carbon stock(Wallerman et al. 2010).

Current methods for observing forest structure at the regional scale are increasingly diverse. Forest structure applications based on vegetation spectral inversion are widely used, and with the advancement of deep learning technologies, the accuracy of forest canopy height retrieval continues to improve. The launch of spaceborne LiDAR satellites, such as GEDI and ICESat-2, provides globally sampled, precise forest canopy height information. In recent years, the integration of spectral data with spaceborne LiDAR data for forest canopy height extraction has developed rapidly. However, due to the saturation effect of spectral inversion, there is a tendency to underestimate the height of taller trees. Spaceborne optical multi-angle stereo pairs enable precise measurement of continuous regional surface elevation through parallax measurements between forward and backward-looking cameras. Since the 1990s, the rapid development of spaceborne high-resolution satellites has provided an unprecedented data foundation for forest structure information extraction based on spaceborne optical multi-angle data.

The utilization of stereo image pairs demonstrates commendable effectiveness in extracting DSM and canopy height, particularly in characterizing the vertical structure of forests with non-closed canopies (Neigh et al. 2016; Ni et al. 2015).

In recent years, optical multi-angle satellites have rapidly developed, providing a wealth of data for forest height extraction. Notable examples include SPOT5/HRS (Toutin 2006), ALOS/PRISM(Ni et al. 2012), ZY-3 (Ni et al. 2015; Ni et al. 2023), GF-7 (Du et al., 2023), Cartosat-1(Tian et al. 2013), PlanetScope(Huang et al. 2022), and the WorldView satellite series(Montesano et al. 2017). These satellites have laid a rich foundation for advancing forest height retrieval.

The limitation of stereo imagery in dense forest areas, specifically its inability to capture ground surface elevation, poses a significant obstacle, restricting its widespread use in regional forest biomass mapping(Ni et al. 2015). (Ni et al. 2023) have demonstrated the successful extraction of ground surface elevations in deciduous forests using UAV leaf-off stereoscopic imagery.

Cloud cover stands as a significant limitation in regional forest attribute mapping through stereoscopic imagery. Utilizing multi-sensor and multi-temporal data proves to be a viable alternative(Petrou et al. 2015). (Ni et al. 2023) further compared DSM derived from leaf-on stereoscopic imagery with DTM obtained from leaf-off stereoscopic imagery to produce Canopy Height Models (CHMs) in temperate deciduous coniferous forests. They considered the impact of image acquisition methods on the extraction of forest vertical structure, offering valuable guidelines for selecting multi-temporal data.

Optical multi-angle data acquisition is affected by weather conditions such as clouds and rain, making it difficult for a single satellite to cover an entire area in a short time, especially in cloudy and rainy regions. Additionally, for deciduous forests, variations in the timing of image acquisition can impact the accuracy of canopy height estimation(Dandois and Ellis 2013; DeWitt et al. 2017).

Therefore, this study aims to utilizes multi-satellite and multi-temporal optical stereo pairs to extract forest canopy height in Daxing'anling region. This study will integrate multi-satellite, multi-temporal optical multi-angle data to explore the accuracy of regional forest canopy height extraction. The research focuses on the following objectives: (1) Investigate the accuracy of forest canopy height estimation in deciduous forest areas using optical multi-angle data from different acquisition times. (2) Examine the differences between surface elevations derived from optical multi-angle data during the deciduous season and those obtained from the FABDEM model.

2. Main Body

The Daxing'anling region, located in northeastern Eurasia, has a temperate continental monsoon climate influenced by monsoons. During summer, humid air currents from the ocean bring moisture, and the complex terrain leads to frequent precipitation and cloudy weather. The Daxing'anling mountain range acts as a barrier, causing the moist air to rise and condense, which increases rainfall and cloud cover. This study aims to investigate the application of multi-source and multi-temporal satellite data for extracting forest canopy height information in the Daxing'anling region of China.

2.1 Test sites

Daxing'anling, nestled in northeastern China, experiences a cold temperate continental climate characterized by lengthy, harsh winters and brief, cool summers marked by considerable temperature fluctuations(Ni et al. 2015). This expansive region boasts a rich tapestry of diverse vegetation, encompassing not only coniferous, broadleaf, and mixed forests but also showcasing a plethora of dominant species such as spruce, larch, and birch. The topography of the region showcases a breathtaking variety, encompassing lofty mountains, undulating hills, verdant valleys, and serene lakes, creating a mosaic of landscapes. Elevations within this vast expanse range from several hundred to several thousand meters above sea level, solidifying its status as a prominent mountain range in Northeast China, offering a remarkable blend of ecological diversity and scenic grandeur.

2.2 Data

This study uses GF-7 stereo imagery on the leaf-on season to extract forest canopy DSM and ZY3 stereo imagery on the leaf-off season to extract terrain elevation. By combining multi-satellite stereo pairs from different seasons, this study generated a high-precision, full-coverage forest canopy height map in Daxing'anling.

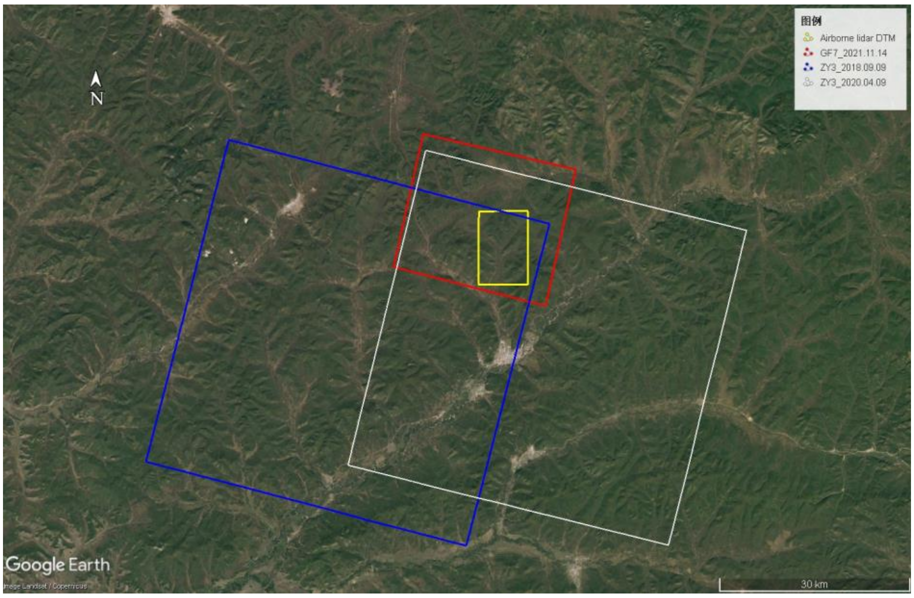

Fig. 1 Location of remote sensing data used in this study

2.2.1. ZY-3

The ZY-3 satellite, launched in January 2012, has a nadir-viewing panchromatic TDI CCD camera with a 2.1-meter resolution and forward- and backward-viewing panchromatic TDI CCD cameras with a 3.5-meter resolution(Fang et al. 2014; Ni et al. 2015; Ni et al. 2023). It captures imagery with a 52×52 km swath and a 22-degree intersection angle. The leaf-off ZY-3 imagery used in this study was captured on April 9, 2020, with a center at 121.6° longitude and 50.8° latitude. The leaf-on ZY-3 imagery used in this study was captured on September 9, 2018, also centered at 121.6° longitude and 50.8° latitude.

2.2.2. GF-7

Launched on November 28, 2019, the GF-7 satellite has two panchromatic cameras with a 0.7-meter resolution(Ni et al. 2024). It captures imagery with a 20-kilometer swath width and tilt angles of +26 degrees for the forward-viewing camera and -5 degrees for the backward-viewing camera(Zhu et al. 2021). The GF-7 stereo imagery utilized in this study was captured on November 14, 2021.

2.2.3. FABDEM

(Hawker et al. 2022) used machine learning to remove buildings and forests from the Copernicus DEM, creating the first global elevation map, FABDEM, with 1-arcsecond

(~30m) grid spacing that excludes buildings and forests. This study involves an assessment of the FABDEM data within the research area. FABDEM reduced the mean absolute vertical error in urban areas from 1.61m to 1.12m and in forests from 5.15m to 2.88m.

2.2.4. Aerborne DTM

ALS data was collected with a Leica ALS60 system on a Yun-5 aircraft from August 30 to September 14, 2012. The spatial coverage is shown in Fig. 1-a as a white polygon. The point density is 2–4 points/m². Accuracy checks using GCPs from RTK measurements showed RMS errors within acceptable limits (vertical error <15 cm, horizontal error <50 cm). The point cloud was manually classified into various types, including vegetation, buildings, and ground points, and a DTM with a resolution of 0.5 meters was generated based on the ground points.

2.3. Methodology

2.3.1. Processing of Stereo Imagery

Accurate geometric correction is essential prior to the stereo processing of imagery. By manually selecting control points, the Rational Polynomial Coefficients of high-resolution stereo pairs can be optimized.

The processing of stereo image pairs consists of four main parts: generating kernel images, dense matching of corresponding points between kernel images, triangulating to generate point clouds, and interpolating the point clouds to create a DEM. In this study, kernel images were generated based on affine transformations of corresponding points between stereo image pairs. The Semi-Global Matching (SGM) algorithm was employed for dense matching of stereo imagery to generate DEM data (Lee et al. 2019; Lee and Park 2020). Both the correlation kernel and subpixel kernel were set to 9×9, and a Census cost function with a 9×9 disparity calculation window was utilized. After dense matching, the generated disparity files were triangulated to produce point clouds, which were then interpolated using bilinear interpolation to create the corresponding DEM products. This work was performed using ASP software. The GF-7 and ZY-3 stereo pairs were utilized to generate a leaf-on season DSM and a leaf-off season DSM (including understory terrain).

2.3.2. Extraction of Regional Canopy Heights

The extraction of regional forest canopy height is divided into two parts. The first part involves extracting the understory terrain in deciduous forest areas. The second part assesses the ability of different satellite stereo pairs to depict the vertical structure of forests. The GF-7 stereo pairs acquired during the leaf-on season can effectively extract forest canopy height, while the ZY-3 stereo pairs obtained in the leaf-off season can capture understory surface elevation. Additionally, FABDEM serves as a reference for understory surface elevation. Consequently, the DTM extracted from the leaf-off season ZY-3 stereo pairs will be compared with the DEM provided by FABDEM to ascertain which product more closely approximates the true ground surface, using the DTM generated from airborne laser scanning data as a benchmark. This comparison will facilitate the evaluation of the reliability of each product in extracting forest canopy height. Furthermore, the study will assess the accuracy of tree height extraction from the CHM generated by integrating ZY-3 and GF-7 optical multi-angle data.

2.4. Results and Discussion

The results of this study are divided into two parts. The first part evaluates the accuracy of the open-source FABDEM and the DSM extracted from leaf-off ZY3 stereo pairs against the true DTM. The second part analyzes the performance of different sensors in capturing tree height by comparing DSMs extracted from stereo pairs of different sensors and acquisition times.

2.4.1. Comparison between FABDEM and Leaf-off ZY-3 DEM

Figure 2 illustrates the comparative performance of FABDEM and the leaf-off ZY-3 DEM in accurately depicting the understory terrain across two distinct deciduous forest regions. In Figure 2c, the forest canopy appears smaller and more uniform, indicating a relatively consistent vertical structure within this area. Conversely, Figure 2d showcases greater variability in canopy size, with larger canopies prominently positioned on the left side and significantly smaller canopies on the right side, highlighting the complexity and heterogeneity of forest structure.

As demonstrated in Figure 2a, the leaf-off ZY-3 DSM in the area characterized by smaller and more uniform canopies exhibits a high correlation with the reference DTM. This strong correlation suggests that the leaf-off ZY-3 DSM effectively captures the underlying terrain, indicating its reliability for understory assessments in uniform forest areas. In contrast, FABDEM displays greater instability, revealing either positive or negative systematic biases when compared to the reference DTM. This variability raises concerns regarding the consistency of FABDEM's performance in representing the true forest structure.

Figure 2b provides additional insights, where the right section reveals a strong correlation between the leaf-off ZY-3 DSM and the reference DTM, further confirming the reliability of this model. However, within the gray-shaded area, the leaf-off ZY-3 DSM exhibits larger errors, suggesting that specific conditions may hinder its accuracy. Figure 2e illustrates the leaf-off ZY-3 imagery corresponding to the 1100-1500 section along the x-axis in Figure 2b. A closer examination of the surface conditions in this region indicates that the forest density is lower, and the canopy size is larger in the gray-covered area. This observation implies that the varying tree canopy sizes lead to disparate radiative responses in the optical imagery, which subsequently contributes to errors during DEM extraction.

In summary, the findings indicate that FABDEM, which is derived from machine learning algorithms, exhibits random systematic errors that can manifest as either positive or negative deviations from the true terrain. This inconsistency calls into question the reliability of FABDEM for precise terrain modeling. In contrast, the accuracy of the leaf-off ZY-3 DSM is closely tied to the vegetation characteristics of the forest, underscoring the importance of understanding forest structure when evaluating the performance of different elevation models. These insights emphasize the need for careful selection of remote sensing data and methodologies to enhance the accuracy of understory terrain assessments in varied forest environments.

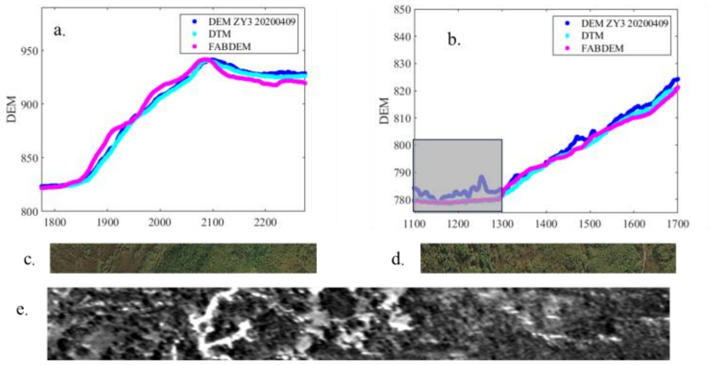

Fig. 2 Comparison between FABDEM and the leaf-off ZY3 DEM in the Daxing'anling. Figure e represents the leaf-off ZY-3 image corresponding to the 1100-1500 section along the x-axis in Figure b.

2.4.2. Comparison of CHM Extraction from Multi-source and Multi-temporal Stereo Imagery

Figure 3 comparatively illustrates the effectiveness of DSM extraction from stereo pairs captured by different sensors at different times, shedding light on the variations in performance based on sensor specifications and observational geometries. The GF-7 imagery boasts a resolution of 0.7 meters, which allows for a high level of detail in the resulting DSM.

In contrast, the ZY-3 imagery has a coarser resolution of 2 meters, potentially limiting its ability to accurately capture fine-scale features in the landscape. The GF-7 sensor employs a forward and backward viewing angle of approximately 30°, which enhances its capacity for depth perception and feature delineation. In comparison, the ZY-3 sensor utilizes three angles of observation—nadir, forward, and backward—with a convergence angle of 44° between the forward and backward views. These differing observational geometries play a crucial role in influencing the characterization of surface elevation in the DSM, as they affect the angle at which light interacts with the forest canopy and the resulting information captured in the imagery.

The two test sites illustrated in Figure 3 align with those presented in Figure 2, ensuring consistency in the analysis of forest structure across different methods. In Figure 3a, the segment from 1800 to 2100 represents a natural forest area, where, despite a three-year temporal gap between observations, there is no significant difference in the characterization of canopy height. This finding suggests that the structural characteristics of this natural forest remain stable over the observed period, reinforcing the reliability of the chosen methodology for assessing canopy height in such environments. Conversely, the gray-covered areas denote artificial forests, where both the leaf-on GF-7 DSM and the leaf-on ZY-3 DSM clearly indicate notable growth in forest canopy height over three years. This observation highlights the capability of these sensors to capture changes in vegetation structure, which is essential for monitoring forest dynamics.

Figure 3b depicts an area characterized by numerous forest gaps, revealing the advantages of high-resolution imagery in assessing forest structure. It is evident that the DSM extracted from the leaf-on GF-7 imagery is more detailed and provides a more accurate identification of these gaps, attributed to the sub-meter resolution of GF-7 imagery. The finer spatial resolution allows for better detection of small gaps within the forest canopy, enhancing the analysis of forest fragmentation and health. In contrast, the leaf-on ZY-3 DSM demonstrates weaker capability in identifying the forest gaps; for instance, the smaller gap at position 1490 was not detected, indicating limitations in capturing finer details. At position 1640, both sensors recognized the location of the forest gap, but the accuracy in characterizing the surface elevation of the gap varied significantly. The GF-7 sensor's superior resolution and sensitivity enable it to depict vertical structures with greater precision, which is critical for applications involving forest management and conservation. This comparative analysis emphasizes the importance of selecting appropriate sensors and understanding their observational characteristics for effective forest structure assessment.

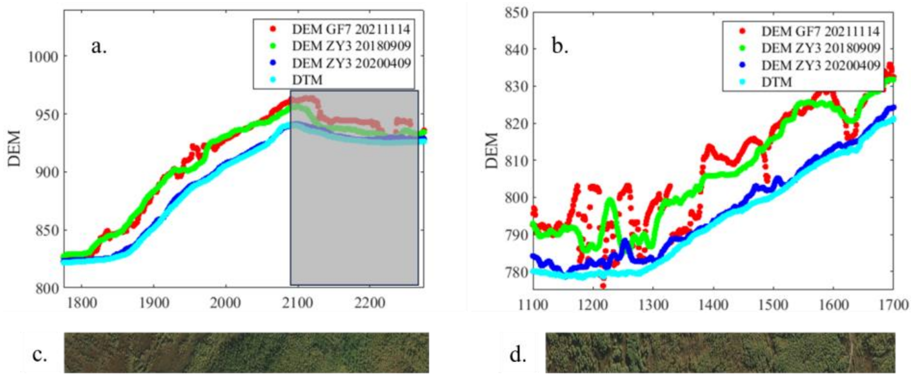

Fig. 3 Comparison of forest canopy height extraction using stereo pairs from different sensors and acquisition times.

Figures 4.a and 4.b present the precision analysis of the DEM extracted from the leaf-off ZY-3 imagery and FABDEM in terms of estimating forest height at the test site. Figure 4.a illustrates that subtracting the DSM derived from leaf-on season GF-7 imagery from the DEM obtained from leaf-off season ZY-3 imagery results in a CHM with a correlation of 0.9 and a root mean square error (RMSE) of 1.06 meters. From Figure 4.a, it can be seen that the DEM extracted from the stereo pairs exhibits high geometric accuracy in deciduous forest areas, leading to a more accurate assessment of canopy height. Conversely, Figure 4.b indicates that FABDEM is constrained by systematic biases, whether positive or negative, resulting in distinct clusters of points in the canopy height estimation.

The results illustrated in Figure 4.a suggest that the methodology employed for extracting the DEM is effective in accurately capturing the forest structure, as reflected in the close alignment between the extracted CHM and the actual canopy heights observed. This highlights the effectiveness of using stereo imagery in assessing forest canopy dynamics, particularly in regions characterized by deciduous vegetation.

In contrast, Figure 4.b reveals that the FABDEM is affected by systematic biases, which can manifest as either positive or negative deviations. These biases lead to the emergence of distinct clusters of points in the canopy height estimation, which indicates inconsistency in the height retrieval process. The presence of these clusters suggests that the FABDEM may not accurately represent the true forest structure, particularly in complex terrain or areas with varying forest density. This inconsistency underscores the need for careful evaluation of elevation products like FABDEM, particularly when they are used for applications involving forest height estimation. Overall, the analyses in Figures 4.a and 4.b provide valuable insights into the comparative performance of different elevation models, emphasizing the significance of methodological approaches in accurately assessing forest canopy height.

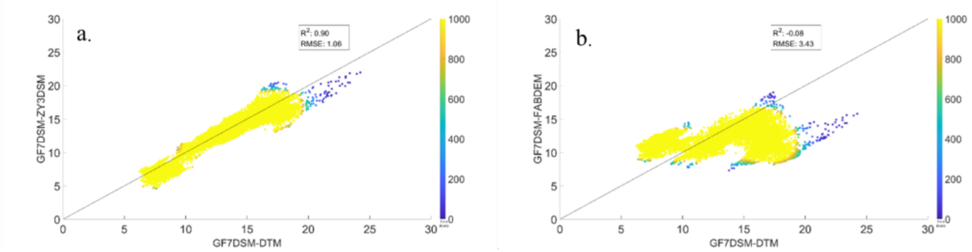

Fig. 4 Accuracy of forest height extraction from multi-source and multi-temporal stereo pairs

3. Conclusion

Given the lack of understory terrain data at a regional scale and the limitations of optical multi-angle satellite observations due to climatic factors such as clouds and rain, integrating multi-source data can indeed alleviate the issue of data scarcity in cloudy and rainy areas. This study explores and analyzes the effectiveness of multi-satellite and multi-temporal stereo image pairs in capturing forest structure. Additionally, it assesses the elevation accuracy of the open-access FABDEM.

Overall, FABDEM is found to be closely aligned with the true DTM. However, in areas with complex terrain, excessive data smoothing can result in a phenomenon of peak shaving and valley filling. Moreover, uncertainties in estimating the elevations of surface features such as forests and buildings can introduce systematic errors, either positive or negative, into the product itself. Despite these minor inaccuracies, FABDEM remains an excellent DTM product.

Furthermore, during the leaf-off season, factors such as forest height and canopy size significantly influence the precise extraction of understory DEMs. Thus, integrating the characteristics of different products to achieve a comprehensive depiction of global understory terrain represents a viable solution.

The observation geometry is highly sensitive to the characterization of the forest's vertical structure. In particular, the image resolution and viewing angles determine the accuracy of identifying small forest gaps. The sub-meter resolution GF-7 imagery outperforms ZY-3 imagery in both the quantity and precision of identified forest gaps.

Future work will build on these initial findings by expanding the analysis to cover the entire Daxing'anling region, where the integration of multi-satellite and multi-temporal data will be used to refine forest canopy height and biomass estimation. This broader application will contribute to regional carbon accounting efforts, offering more accurate data for forest management and climate change mitigation strategies. Of course, this study focuses exclusively on evaluating two optical multi-angle satellites from China. However, research on the accuracy of forest canopy height extraction using optical multi-angle simulated data is also rapidly advancing. Therefore, combining theoretical analysis with assessments using actual satellite data for forest canopy height estimation represents a key direction for future research.

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