

Postprint: Height Measurement of Cedar (*Cedrus deodara*) Stands Using UAV-Based 3D Photogrammetry

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Abstract

Plant community height is a crucial metric for characterizing plant communities, and its measurement provides essential data foundations for plant community diversity analysis, biomass estimation, and functional trait research. Traditional forest inventory primarily involves ecological surveyors conducting individual measurements through visual estimation or using laser altimeters, which is labor-intensive, time-consuming, and costly, making large-area plant community height surveys difficult to implement. In recent years, with the rapid development of Unmanned Aerial Vehicle (UAV) technology, low-altitude UAV photogrammetry and remote sensing techniques have emerged and been applied to crop plant height measurement and biomass estimation. However, accurately obtaining plant community height in mountainous areas with diverse vegetation types, numerous tree species, and complex terrain remains a significant challenge. Taking the gentle-sloped Yunnan University Chenggong Campus as the study area, this research selected artificially planted cedar (*Cedrus deodara* (Roxb.) G.Don) forests within the campus as the study object. A UAV platform equipped with a visible-light camera was utilized to acquire near-ground aerial imagery of the study area. Point cloud data obtained through high-resolution image matching and densification was used to generate a Digital Surface Model (DSM). Non-plant points were extracted based on point cloud classification to eliminate misclassified portions caused by blurred edges at vegetation-non-vegetation interfaces, and after interpolation, a Digital Terrain Model (DTM) was generated. By overlaying and subtracting DSM and DTM, a Canopy Height Model (CHM) was obtained, which yielded the height of each cedar in the study area. Subsequently, a laser rangefinder was used to measure the heights of 100 cedar trees within the sample plot, and these measured tree heights were used for accuracy validation against the tree height values derived from the CHM model generated by UAV aerial survey technology. The results demonstrated high

linear fitting between UAV-measured tree height values and laser rangefinder-measured values, with r^2 values above 0.904. This method, based on UAV imagery for spatial model generation and tree height extraction, is less affected by external environmental factors and more cost-effective than traditional tree measurement methods. It can be widely applied to various plant community survey and research efforts, demonstrating excellent application prospects.

Full Text

Preamble

Height Measurement of a Cedar (*Cedrus deodara*) Community Based on Unmanned Aerial Vehicle 3D Photogrammetry Technology

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Abstract

Plant community height is a crucial indicator reflecting plant community characteristics. Its measurement provides essential data for analyzing plant community diversity, estimating biomass, and studying functional traits. Traditional forest surveys rely on ecological investigators who visually estimate or use laser altimeters to measure each individual tree, which is labor-intensive and impractical for large-scale plant community height surveys. With the rapid development of unmanned aerial vehicle (UAV) technology, low-altitude UAV photogrammetry and remote sensing have emerged and been applied to crop height measurement and biomass estimation. However, accurately obtaining vegetation height in mountainous areas with diverse tree species and complex terrain remains a significant challenge.

This study selected the gently sloping Chenggong campus of Yunnan University as the research area and focused on an artificially planted cedar (*Cedrus deodara*) forest. Using a UAV equipped with a visible-light camera platform, we acquired near-surface aerial imagery of the study area. High-resolution image matching and encryption were used to generate point cloud data, from which a Digital Surface Model (DSM) was produced. Non-plant points were extracted from the point cloud classification, and sections misclassified due to edge ambiguity between vegetation and non-vegetation were eliminated. A Digital Terrain Model (DTM) was then generated through interpolation. The Canopy Height Model (CHM) was obtained by subtracting the DTM from the DSM, yielding the height of each cedar in the study area. To validate accuracy, we measured

the heights of 100 cedars using a laser rangefinder and compared these values with those generated from the UAV aerial survey.

The results demonstrated strong linear correlation between tree heights measured by UAV and laser rangefinder, with an r^2 value of 0.904. The method based on UAV imagery for spatial model generation is less affected by external environmental factors, more cost-effective than traditional tree measurement approaches, and shows excellent potential for widespread application in various plant community investigations.

Keywords: multi-rotor UAV; aerial photogrammetry; near-ground remote sensing; visible-light camera; standing tree height

Introduction

Plant height is an important indicator of plant community characteristics, providing a critical data foundation for plant community diversity analysis, biomass estimation, and functional trait research. In forest management, tree height is commonly used to determine timber volume and volume growth rate, making it an indispensable measurement in contemporary forestry surveys. With decreasing forest resources, accurate forest inventory has become increasingly important.

Traditional community height measurement methods typically employ hypsometers or laser rangefinders to estimate forest community height. These conventional approaches usually involve measuring only a few to several dozen trees to calculate an average, resulting in high labor intensity. While traditional aerial and satellite remote sensing can conduct large-scale forest parameter surveys, they suffer from low spatiotemporal resolution and significant cloud interference. New technologies have emerged in plant community height measurement, including polarimetric synthetic aperture radar interferometry, spaceborne LiDAR, MODIS data for canopy height retrieval, and airborne LiDAR point cloud data for tree height extraction. However, these techniques are costly, and spaceborne LiDAR still shows considerable deviation for large-scale ground object measurement. Although LiDAR's unique penetrability can obtain ground information through simple canopies to extract vegetation height, its application is limited. Data quality is significantly affected by forest density, especially wind speed, with relatively high-quality data only obtainable under calm conditions for low-density, low-crown-closure coniferous forests. The high cost of LiDAR sensors and imagery constrains broader application for acquiring forest and plant community structural characteristics.

With the rapid development of unmanned aerial vehicle (UAV) technology, UAV low-altitude photogrammetry and remote sensing (PaRS) has emerged. This technology offers high-resolution imagery, large data volumes, and has tremendous development potential for both commercial and scientific applica-

tions. Small, lightweight UAVs with flexible takeoff and landing capabilities and minimal climate impact have attracted increasing attention. UAV photogrammetry and remote sensing technology has also drawn interest from ecologists, particularly macro- and spatial ecologists. As a new platform, UAVs can carry various cameras and sensors, such as LiDAR scanners, multispectral imagers, hyperspectral imagers, and thermal imagers.

Salamí et al. noted that UAV aerial photogrammetry, with its low cost and ability to obtain high temporal and spatial resolution imagery using conventional digital cameras, serves as an excellent complement to traditional satellite remote sensing. UAVs have been widely applied in ecological monitoring research. Herwitz et al. used UAV survey systems to monitor 1,500 hm² of land long-term. Gonçalves et al. classified habitat ranges using UAV imagery. Puliti et al. conducted long-term monitoring of a coniferous forest in southern Norway using UAV survey technology, establishing regression models under different light transmission conditions and validating model feasibility for forest monitoring using multi-fold cross-validation. Li Deren proposed that establishing multi-scale ecological environment monitoring and evaluation technology systems using spatial information technology is fundamental for ecological protection, preventing degradation, and maintaining ecological security.

With the rapid development of photogrammetry technology, 3D modeling using conventional digital cameras has matured. Scholars have used UAV-mounted conventional digital cameras to acquire near-surface aerial photographs for tree height measurement and crop height measurement and biomass estimation. However, few reports exist on extracting coniferous tree heights in mountainous areas with diverse species and complex terrain using UAVs with ordinary digital cameras. Traditional remote sensing techniques for extracting forest information require substantial manpower and financial resources, have long information extraction cycles, and yield poor results. Yunnan Province has rich vegetation types, with coniferous forests covering approximately 35.54% of the province's area. Rapid monitoring of coniferous forests has long been challenging but is important for estimating biomass and ecological value.

This study proposes using a UAV carrying a visible-light camera to acquire aerial imagery, establishing spatial models from the image data, and using classified point data subtraction to extract coniferous tree heights in the experimental area. This method can be extended to other regions and enables rapid monitoring of relatively large-area forest communities, especially coniferous forest communities, providing important data for biomass estimation.

1. Study Area Overview

The study area is located near the School of Ecology and Environmental Science on the Chenggong campus of Yunnan University (24.828640°-24.829136°N, 102.855947°-102.856439°E). The overall terrain is a uniform gentle slope facing

northeast, with an elevation of 1,987 m (± 2 m) in the northeast and 1,984 m (± 2 m) in the southwest. The entire artificial forest covers approximately 4,203 m², primarily planted with cedar (*Cedrus deodara* [Roxb.] G. Don). The study area is mainly a polygonal artificial forest, surrounded by roads on the northeast side with a few miscellaneous trees at the edges. The imagery was captured on a clear day between 11:00 and 12:00 local time.

2. Research Data

2.1 Data Collection

To obtain effective data, we conducted comprehensive flight mission planning before data acquisition to ensure data quality and flight safety. Flight speed was controlled to match the camera's time-lapse shooting frequency. In this study, the flight speed was 4 m/s, with forward overlap exceeding 80% and side overlap exceeding 60%.

The UAV-mounted camera was a Sony ILCE-7R with a maximum sensor resolution of 7360×4912 pixels, minimum photosensitive cell size of 4.89 μm ×4.89 μm , fixed aperture of f/4, ISO 1000, and shutter speed of 1/1000 s. The lens had a fixed focal length of 35 mm. A six-rotor aircraft served as the flight platform, using the DJI Assistant 2 tuning software. A Holux M-241A GPS logger recorded the flight trajectory.

Ground control points were established in the main area, with a total of 10 points set across the entire area. Image overlap exceeded 60%, with effective overlap of 78% in the main area. Point cloud data density was 10.7848 points/m². The study area is in the northern hemisphere, and we used the Universal Transverse Mercator (UTM) projection, World Geodetic System 1984 (WGS84) coordinate system.

2.2 Geometric Correction

All lenses exhibit some geometric distortion, and the mounted camera was not a professional metric camera designed for photogrammetry. Without strict lens calibration, the captured digital images contained optical distortion errors. Factors causing geometric deformation include non-linear lens distortion and potential alignment errors in the image sensor array. This study used independent camera imaging without sensor array alignment errors, only inherent non-linear lens distortion.

Traditional geometric correction is time-consuming and labor-intensive. In this study, we used the camera's built-in function to compensate for distortion. Lens parameters were calculated in PhotoModeler software, and camera calibration model parameters were imported into Agisoft Lens to correct all images. The correction coefficients and errors are shown in Table 1.

Correction coefficients and correlation matrix

2.3 Image Enhancement

The camera automatically adjusts white balance, ISO, aperture size, and exposure time according to the shooting scene. Since flight altitude is typically tens or even hundreds of meters above ground, the target objects are effectively at infinity relative to the lens. Aperture size is locked and does not affect data accuracy, and there is no depth-of-field blur in the photos. Flights are generally conducted during clear, precipitation-free days. As long as the correct flight speed is maintained, exposure time does not affect data accuracy.

However, one situation can occur: if the previous photo was taken in sunlight and the camera's automatic adjustment has not yet adapted when the next photo is taken under cloud cover, the lighting environment changes, making the subsequent photo darker than the previous one. This affects image matching quality. Before processing, all photos underwent image enhancement. Images were imported into Agisoft PhotoScan, stacked, and the average exposure of the photo group was estimated to set brightness percentages, achieving uniform image enhancement.

[Figure 2: see original paper] Uniform color contrast before and after processing

2.4 Point Cloud Data Extraction

Aerial photos were imported and matched with time-corresponding GPS information to directly form flight trajectories and camera positions. After rapid photo alignment and vertex generation, we observed target generation and generated reports to check photo alignment. Overlap was high, especially in the main area. Ground control points were marked and located in the software, and a coordinate system (WGS84/UTM zone 48N) was introduced to assign coordinates to each point. Based on the point cloud data, more spatial information could be extracted, preserving numerous height details. The LAS format point cloud data is binary, can contain more information, and occupies relatively small storage space. This processing was implemented in the Agisoft PhotoScan software platform.

2.5 Plant Community Height Measurement

The point cloud data was sampled at a pixel size of 0.5 m, with each pixel taking the maximum value within its range to generate raster data. We used Multi-level B-Spline Interpolation, which balances shape smoothness and multi-level approximation accuracy. The RGB Vegetation Index (RGBVI) was calculated from visible light spectral bands: $RGBVI = (\text{green} - (\text{green} + (\text{red} + \text{blue}))) / (\text{red} + \text{blue})$. This index, based on hue and value mixing, effectively distinguishes vegetation from non-vegetation, facilitating non-plant point extraction from point clouds.

Point cloud data was reclassified with the new spectral index attribute. Using a point cloud sampling tool with a tolerance of 0.5 m, non-plant points were classified and extracted. The DTM Filter (slope-based) was used to eliminate misclassified edge sections between vegetation and non-vegetation, with an elimination scan radius of 0.5 m and allowed terrain slope of 10° , without setting confidence intervals. After interpolation, a ground raster data DTM was generated.

[Figure 3: see original paper] The RGBVI calculated according to the band

[Figure 4: see original paper] Extracted non-plant points and removed misclassified portions

The Canopy Height Model (CHM) was obtained by subtracting DTM from DSM, yielding the height variation model of the cedar canopy in the study area. This operation was completed in the SAGA-GIS software platform, with the flowchart shown in Figure 5.

[Figure 5: see original paper] The flowchart of extracting CHM

2.6 Community Height Accuracy Assessment

Using the R statistical software platform, we conducted linear correlation analysis between field-measured data and tree height data extracted by this method. All cedar heights in the study sample plot were measured using a laser rangefinder to validate the accuracy of heights extracted by the aerial survey method. A linear correlation analysis was established for accuracy validation.

The sample correlation coefficient r is calculated as: $r = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{[\sum(x - \bar{x})^2 \sum(y - \bar{y})^2]}}$

The coefficient of determination r^2 represents the proportion of y variation explained by x variation, with values ranging from 0 to 1, indicating the correlation degree between x and y .

3. Research Results

3.1 Experimental Area Digital Surface Model

Based on UAV aerial imagery, an overall point cloud model of the experimental area was generated. The point cloud data was sampled at 0.5 m pixel size and interpolated to generate the Digital Surface Model (DSM). According to non-vegetation points and eliminating edge misclassification, the Digital Terrain Model (DTM) was generated. The Canopy Height Model (CHM) was obtained by subtraction.

Using a laser rangefinder, we measured all cedar heights in the study area and compared them with heights extracted from the aerial survey. With aerial survey

data as the dependent variable and field-measured data as the independent variable, a linear function relationship was established. The regression results are shown in Figure 8, with the correlation coefficient $r^2 = 0.904$ after processing, indicating close agreement between measured and actual values.

[Figure 6: see original paper] Study area' s point cloud model

[Figure 7: see original paper] Digital Surface Model, Digital Terrain Model, Canopy Height Model

[Figure 8: see original paper] Results of the validation assessment comparing field-measured tree height and DSM-retrieved height of the 100 validation trees distributed over area

4. Discussion

Current methods for generating digital geographic models from UAV imagery include two primary approaches: generating models through absolute orientation point extraction and constructing regular grids based on Triangulated Irregular Networks (TIN). Both methods require substantial computation and high professional expertise. This study uses non-vegetation point interpolation to extract the local DTM, which is adaptable for large-scale field surveys.

The cedar height extraction achieved high accuracy, with correlation coefficient $r^2 = 0.904$ and small errors between measured and actual values. Compared with other methods, the tree heights obtained were very close to actual values.

Previous attempts at UAV-based tree height extraction include: (1) a forest measurement patent using the difference between true flight altitude at tree base and tree apex; (2) methods using stereo image pairs and rotation matrices to calculate tree height; and (3) airborne LiDAR technology for tree height measurement. These methods have limitations: the true altitude subtraction method requires radio altimeters; stereo image pair methods only work for individual trees and are unsuitable for large-area forest surveys; and LiDAR, while accurate, uses manual single-tree measurement and is also difficult to apply to large-scale surveys. LiDAR data quality is significantly affected by forest density and especially wind speed.

This study uses UAV-mounted digital cameras for rapid, large-scale community height surveys, which is more suitable for ecological field investigations. The method extracts tree heights through DSM-DTM subtraction analysis, is unaffected by forest density or weather conditions, and offers lower costs compared to LiDAR.

Similar to Zarcó-Tejada' s 2015 linear regression analysis of differences between statistical and field-measured data, and Beijing Forestry University' s relative error calculations and linear regression analysis of tree heights extracted from UAV imagery based on stereo image pairs, this study also uses linear regression

to validate differences between measured and actual values. Results show that errors are within acceptable ranges and measurements are close to actual values.

However, this method has limitations. Tree height extraction is affected by canopy occlusion, with occluded portions obtained through interpolation inference. When interpolating from non-vegetation points to vacant areas, edge data influences results. Although data is collected with ordinary digital cameras, there remains a precision gap compared to professional metric cameras even after correction. Visible-light cameras cannot capture data beneath the canopy, so currently only heights of plants in higher canopy positions can be extracted. Most current UAV platforms are used in relatively flat terrain with simple tree species, such as orchards and farmland.

This study's method can be extended to large-area coniferous forest height estimation, sparse tree-shrub-grass vegetation communities, and single vegetation community height extraction in areas with complex terrain and diverse plant species. The study introduced coordinates through ground control points, requiring high-precision positioning instruments for control point collection. In the future, high-precision positioning systems like RTK could obtain more accurate ground control points. Using high-resolution DSM that matches actual terrain would simplify operations. UAV flight processes are often affected by external and internal flight factors, causing attitude errors. High-quality attitude information can improve photo matching efficiency and accuracy, and more professional inertial navigation systems could compensate for these errors in the future.

5. Conclusion

With the development of geographic information science and related industries, demand for remote sensing data has grown dramatically across sectors, including ecology. For regional small-scale or fine-resolution ground features, traditional satellite remote sensing imagery cannot meet requirements due to resolution limitations. This study successfully extracted individual cedar heights in the research area and validated the method's reliability and accuracy through correlation analysis.

Compared with traditional survey methods, UAV aerial photogrammetry technology offers flexibility, short cycles, and particular advantages in complex field terrain inaccessible to humans. The technology continues to update and improve rapidly. While LiDAR is increasingly used in UAV-based tree measurement and can better obtain ground information for more accurate local digital geographic models, visible-light sensors offer advantages in low cost, rapid acquisition, and rich color information that LiDAR cannot match.

Through continuous experimentation, this study has developed an up-to-date UAV aerial survey workflow and improved the difference method for tree mea-

surement, significantly shortening work cycles. Compared with traditional field community quadrat surveys and forest inventories for obtaining forest tree and community heights and estimating biomass, UAV aerial photogrammetry is faster and potentially more accurate. Current UAV endurance can be compensated through route design and breakpoint flight, and multiple sampling can meet the needs of relatively large-area sampling. If combined with satellite remote sensing, these sampling results could enable larger-area forest community height measurement and even biomass estimation research in the future.

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