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Precision of measuring the height of trees in various ways

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Abstract. This study investigated the precision of measuring the height of trees using different methods. The paper evaluates the possibilities of using the stereophotogrammetric method to determine tree height indicators using unmanned aerial vehicles (UAV) in the conditions of a mature pine stand. The study compares the results of measuring the height of Scots pine trees with altimeters and height indicators determined from remote sensing data obtained using UAVs. In total, the study investigated six diverse ways to measure the height of growing trees. Experimental data on the height of the model trees were collected by three different altimeters (hand-held ground instruments) and the Phantom 4 Pro UAV. The use of UAVs involved optical capture and data collection using on-board equipment. Methods for determining the height of trees based on the results of processing data collected by quadcopter attachments were used. Specifically, the authors of this paper used the method of measuring the height of trees from a point cloud based on one-way vertical survey of model trees and calculating a digital crown height model (CHM) based on aerial photography of horizontal spans over a tree stand. The results of mathematical analysis of the conducted studies demonstrate the highest precision of the method using CHM to determine the height of growing trees. The value of the average random error in measuring the height of model trees using CHM was under 2%. The next most precise method of determining tree height was the TruPulse 360B laser-optical device, which demonstrated the highest precision among height meters. The use of the TruPulse 360b for ground-based measurements and the CHM method (based on UAV optical imaging data) yielded better results that meet the height precision standards for industrial inventory. Methods for determining the height of trees based on optical survey data from UAVs can be used for survey, inventory, forest management, and other works related to forestry and monitoring changes in forest ecosystems

Keywords: unmanned aerial vehicle, aerial photography, stereophotogrammetry, canopy height model, altimeter

Introduction

One of the main forest inventory indicators for determining forest productivity is the average height of tree stands. Instrumental measurement of tree height during a full-scale survey of a forest area is mandatory and requires considerable time and effort, especially in complex tree stands with dense understorey and undergrowth. These and other factors affect the precision of measurements, both in flat terrain and in mountainous areas. The error in measuring the height of trees and calculating the average

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height of the stand directly affects the determination of such indicators as site index class, height category, stock of the tree stand and its change.

Altimeters by measurement technology are divided into three groups: trigonometric and geometric principles of operation and optical. Altimeters of the trigonometric principle of operation are always basic, i.e., they require recording the distance from the point of measuring the height of the trunk to the tree on site. At the same time, the height is measured by viewing angles to the base of the tree and its top. The geometric principle of measuring the height of trees is based on the rules of similarity of triangles. Optical altimeters are constructed based on the laws of optics (Myroniuk et al., 2019). If there is no correction for the slope of the terrain, the inclination of the tree, the shape of the crown, this can lead to considerable errors in measuring the height of a growing tree (Bragg, 2008).

Recent decades have seen a widespread use of laser-optical devices that are designed to measure the height of a tree and are based on the use of built-in elements, specifically an inclinometer and a laser rangefinder. Apart from the height, other measurements can be made, which gives these devices advantages over others.

With the technological advance, new ways to determine the parameters of growing trees based on remote sensing data have emerged (Forsman et al., 2016; Guimarães et al., 2020; Magnussen et al., 2016; Maselli et al., 2014; Mulla, 2013), which do not require direct height measurement.

Unmanned aerial vehicles (UAVs) are widely used for optical imaging or laser scanning to collect data for local tasks in rural areas (Eskandari et al., 2020) and forestry (Guimarães et al., 2020). Improving photogrammetry methods and algorithms for image processing helps improve the precision of constructing a dense point cloud, which serves as the basis for digital models of relief and terrain, as well as 3D models of spatial objects. As a result, the precision of the results of decrypting environmental objects also increases.

Modern demands of society for the precision and relevance of information on forest resources require a review of the methods of forest inventory used in practice (Myroniuk et al., 2018), and the introduction of remote data collection into the practice of forest inventory is one of the principal modern trends in the development of forest inventory methods (Myroniuk et al., 2019). That is why it is relevant to justify the effectiveness and precision of determining the height of trees in forest areas using the data of remote sensing of the Earth using UAVs compared to the use of altimeters.

The purpose of this study was to test various methods and devices for measuring the height of trees in natural conditions and establish the possibility of using stereophotogrammetry methods to determine the height of trees from optical data collected using UAVs.

Materials and Methods

The experimental plot of this study was the principal use felling area in the Irzhavets Forestry of the State Enterprise "Nizhyn Forestry" (block 30, allotment 9) in the territory of Chernihiv region.

The study was conducted in an 80-year-old tree stand of site index class I^a with a composition of 7Ps3Qr and a relative density of 0.7, which grows in the conditions of a fresh hornbeam-oak-pine sudubrava ($C_{2\ \text{гд}}C$). The average diameter of the experimental stand was 44 cm.

The object of the study was the precision of measuring the height of trees using various methods and devices.

The study was conducted in three stages. The first stage involved selecting 30 model trees, assigning and applying unique identification numbers to their trunks. Height measurements of growing trees were made with *Suunto PM-5, Haglof EC II-D* and *TruPulse 360B* laser range finder-altimeter according to the instructions for use and measurement work (Laser Technology Inc., 2017).

During the second stage, a *Phantom 4 Pro* UAV was used to perform optical imaging. Remote sensing data was processed using Agisoft Metashape software (Agisoft Metashape, 2019).

To directly determine the height of trees, a method for measuring the height of trees and shrubs using UAVs was used (Bidolakh et al., 2018; Bidolakh et al., 2019). The UAV was installed at the level of the collar of a growing tree, which was subject to measurement. Subsequently, the UAV was manually raised to the top of the tree, the centre of the sight of its camera, calibrated parallel to the horizon, and aimed at the highest point of the tree. Under this condition, the attributive data of the photo of the top of the tree contained spatial information about coordinates and height, which was automatically calculated by the GPS module (labelling method – *AM*) (Bidolakh et al., 2019).

To use photogrammetry methods to create spatial 3D models based on photographs, vertical equidistant photographic evidence of the entire axis of the trunk of the model tree was taken, with filming at equal intervals of UAV altitude gain. A total of 1,671 photos were taken for this method and 17 vertical lifts were performed for 30 model trees. This was conditioned upon the group spatial arrangement of some model trees.

As a result of photo processing, a point cloud of a model tree or tree group was created (Fig. 1) (Agisoft Metashape, 2019). Each of the points in such a cloud had corresponding spatial coordinates in each system. The calculated point cloud contained enough spatial information to display a growing tree in a 3D editor to determine its height. The metric coordinate system WGS 84/UTM zone 36N (EPSG:32636) was used in the study. Measurements were performed by manually setting the beginning and end of a segment of interest using the linear measurement mode in Agisoft Metashape software. In manual mode, the highest point of the crown of the corresponding model tree was selected, from which the distance to the level of the collar was determined (method marking – *PC*).

Figure 1. Height measurement from a point cloud (PC method)

Additionally, tree height was determined using the crown height model (*CHM* method), which involved obtaining height based on a set of aerial photo processing operations to obtain rasters of the digital elevation model (DEM) and surface (DSM), as well as calculating the output raster of the crown height model *CHM*=DSM-DEM. To create digital models, two horizontal spans were made over the tree stands at an altitude of 70 and 90 meters. As a result, 251 aerial photos were obtained, based on which a dense cloud of points was calculated using Agisoft Metashape software, and they were classified by pertinence to land or trees. The calculated *CHM* raster was analysed using the Spatial Analyst tool package of the ArcGIS software, using the "Focal statistics" filter to determine height (Holiaka et al., 2018). The coordinates of the model trees were superimposed on the raster, which were determined from aerial photography materials by visual identification of the individual number of the model tree printed on the trunk. According to the given coordinates, the height values were read on the *CHM* raster image. Considering the displacement of the treetop from the perpendicular growth axis, the search radius for maximum values was set to 0.75 m.

The third stage of the study consisted in control measurements of the trunk length of 30 felled model trees and the height of the stumps using the *South PD-520N* laser range finder (Table 1). Diameters were measured at breast height (1.3 m) using a *Haglof* "Mantax blue calipers" measuring fork. The sum of the length of the trunk of the felled tree and the height of the stump was an indicator of the true height value of each model tree separately. The distribution of the measured values of the height of model trees by thickness degrees (Table 1) is characterized by a representation of model trees on the experimental plot.

Table 1. Distribution of model trees by height and diameter at breast height

Degree of thickness, cm	**Height, m**							
	29	**30**	**31**	**32**	**33**	**34**	**35**	**36**
32			1					
36			1	1				
40	1	4	1	1			1	1
44		1			1	2		1
48					1	1	1	1
52			1	1			1	
56					1	1		
60				1		1	1	

Distribution of model trees by height and diameter at breast heightIn general, during the study, height indicators were determined using six different methods for each of the 30 model pine trees in the growing state and 30 true height values of each model after felling (Table 2).

Results and Discussion

Table 2 presents the height data obtained by different methods for each of the 30 model trees and their true values.

The results of statistical data processing (Table 3) allow evaluating the advantages and disadvantages of using different methods of measuring growing trees that were used in this study. The highest measurement error was found for the *AM* method – 1.84, the lowest was 0.41 for *Haglof EC II-D*. The systematic measurement error was the largest for *Suunto PM-5* – 133.67 m, and the smallest – 11.96 m for *CHM*. The average random error, respectively, was the highest for *Suunto PM-5* – 2.01 and the lowest – 0.64 for *CHM*.

Table 2. Results of measurements of model trees using different methods

Model tree No.	Diameter, cm	Growing tree height measuring method, m						True tree height value, m
		Haglof EC II-D	*Suunto PM-5*	*TruPulse 360B*	*AM*	*PC*	*CHM*	
1	48.4	33.00	31.00	30.20	33.50	34.27	32.46	33.06
2	40.4	31.40	32.50	31.30	33.70	33.43	32.56	32.43
3	41.1	26.10	27.00	26.80	31.80	32.83	29.72	29.59
4	48.9	34.40	35.00	33.00	34.60	34.79	33.18	34.09
5	58.3	33.30	36.60	32.60	35.60	35.93	34.33	34.35
6	53.0	34.20	32.60	33.50	36.80	36.46	34.58	33.47
7	44.2	31.30	30.40	32.50	36.30	35.85	32.52	33.22
8	38.0	27.90	26.50	28.50	32.10	31.69	29.79	30.73
9	34.7	30.70	26.50	30.70	33.20	33.07	31.13	32.37
10	46.0	31.70	32.00	32.60	34.80	34.64	31.53	33.81
11	56.2	36.20	35.50	33.70	38.00	37.13	34.71	35.22
12	52.9	32.80	32.00	33.50	36.80	36.04	33.94	34.45
13	38.4	31.30	29.50	28.20	28.90	31.79	29.96	30.48
14	51.1	29.60	28.60	29.20	30.70	31.11	29.53	30.50
15	59.2	32.20	32.50	31.40	34.10	34.30	31.76	32.33
16	42.4	29.20	29.50	28.80	33.30	31.12	29.89	29.67
17	38.2	30.40	31.50	28.40	27.60	28.05	27.97	28.71
18	39.8	29.50	27.80	29.30	31.60	30.06	29.61	29.73
19	39.1	33.40	33.00	31.00	32.30	29.39	30.00	30.45
20	51.9	32.10	31.50	34.30	35.50	35.13	34.03	34.88
21	44.8	33.80	33.50	34.80	37.80	34.85	34.51	35.60
22	32.9	30.40	30.50	30.40	35.70	30.20	30.79	31.32

Table 2, Continued

Model tree No.	Diameter, cm	Growing tree height measuring method, m						True tree height value, m
		Haglof EC II-D	***Suunto PM-5***	***TruPulse 360B***	***AM***	***PC***	***CHM***	
23	48.9	37.50	37.50	35.40	38.40	35.65	35.15	36.33
24	49.8	35.10	35.50	34.60	37.30	34.27	34.43	34.70
25	39.5	35.00	34.50	34.50	39.30	37.38	34.99	35.90
26	57.8	38.10	38.50	36.90	40.20	38.85	36.31	35.48
27	45.7	34.90	35.50	32.00	35.70	33.17	33.52	33.70
28	41.5	34.30	34.30	32.80	38.00	34.46	34.56	35.30
29	40.0	29.90	29.20	28.70	31.70	31.30	30.13	30.23
30	53.9	32.20	33.50	30.90	33.90	33.79	31.34	31.98

Table 3. Results of statistical processing of the obtained tree height values

Statistical indicators	Tree height measuring method					
	Haglof EC II-D	***Suunto PM-5***	***TruPulse 360B***	***AM***	***PC***	***CHM***
Arithmetic mean	32.40	32.13	31.68	34.64	33.70	32.30
Mean square deviation	2.73	3.21	2.51	3.02	2.56	2.22
Standard error	0.50	0.59	0.46	0.55	0.47	0.40
Volatility ratio, %	8.42	9.98	7.91	8.73	7.59	6.86
Measurement error	**-0.41**	-0.67	-1.12	**1.84**	0.90	-0.51
Systematic error, m	69.60	**133.67**	25.28	58.04	47.16	**11.96**
Average random measurement error	1.45	**2.01**	0.88	1.41	1.28	**0.64**

The results obtained in this study, as well as research data from (Bidolakh et al., 2018; Bidolakh et al., 2019), further confirmed the study results in (Williams et al., 1994) regarding the highest precision of hand-held laser measuring devices.

The measurement error of laser devices is associated with the interference of side branches in aiming the laser at the top of the model tree, which is especially observed in conditions of growth and development of a sparse stand. Trees in such stands of mature and over-mature age have a wide tent-shaped crown, where the highest point of the top of the tree is not always located in the centre of the crown and causes an underestimation of height (Fig. 1).

The *TruPulse 360B*'s issue of underestimating height readings with laser altimeters is illustrated in Figure 2, where the height indicators of the main number of model trees have underestimated values.

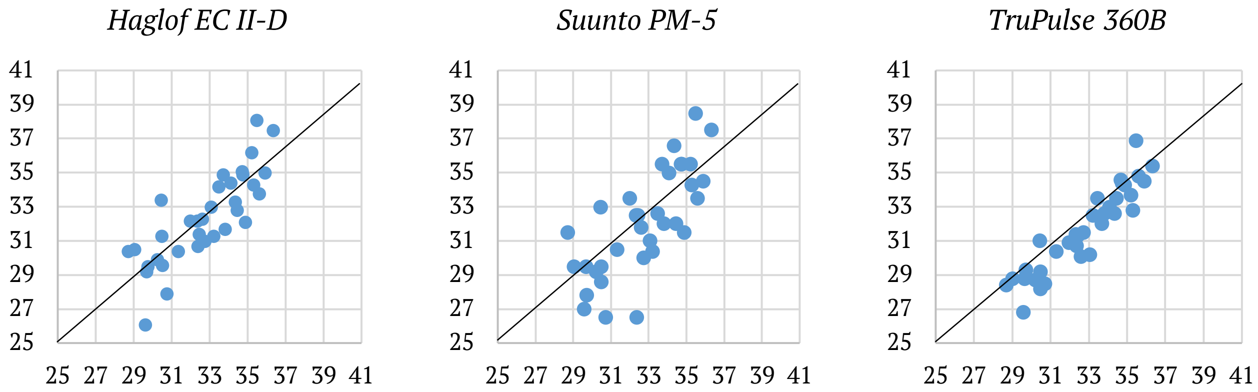

Figure 2. Comparison of the results of tree height measurement using altimeters

The use of the *Suunto PM-5* optical altimeter involves the use of two basic distances (15 and 20 m) and is characterized by the impreciseness of the height indicators of model trees. The specificity of using the *Haglof EC II-D* trigonometric altimeter compared to the *Suunto PM-5* has the advantage of the ability to arbitrarily change the base distance, which increases the precision of measurements. An increase in the base distance for the *Haglof EC II-D* may lead to a deterioration of the visibility of the top of the model trees and an increase in the time required to find a satisfactory sighting location. Most often, problems with viewing the top of a tree arise in conditions of a dense tree stand and rolling terrain. When discussing the precision of methods for tree height measurement involving UAVs and the advantages of using *CHM* for tree stands, it should be noted that there are a significant number of methodological approaches to determining and specifying the parameters of growing trees, which are presented in (Guimarães et al., 2020) and (Sadeghi & Sohrabi, 2019).

When comparing the precision of height determination methods using UAVs (Fig. 3), one should note that creating a CHM requires the least amount of time to collect data in the field.

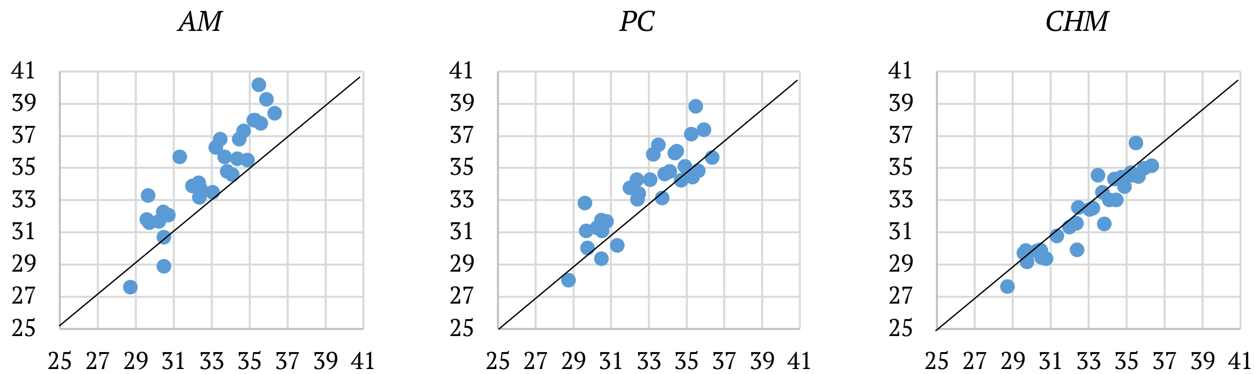

Figure 3. Comparison of height measurement using UAVs

An added advantage of *CHM* is that there is no need for a highly skilled UAV operator to pilot under the tree canopy, in contrast to the *AM* method (Bidolakh et al., 2018) and the creation of a growing tree point cloud by the PC method. In addition, the weak point of remote methods using UAVs in pine stands is their dependence on the correctness of determining geographical and spatial coordinates by the GPS module, due to the obstruction of signal passage through the forest canopy. Due to an unstable signal, the time spent on clarifying coordinates and constantly correcting them increases, which is recorded in the photo metadata. The specificity of the pine stand could lead to an increase in errors and deviations compared to the data for the beech stand (Bidolakh et al., 2019). Specifically, the average random error in the study of measurement precision was 0.72, and the systematic error was 15.03 m for European beech trees (*Fagus sylvatica* L.) in a deciduous stand with a composition of 10 Fs and a density of 0.4 (Bidolakh et al., 2019), and for Scots pine (*Pinus sylvestris* L.) trees in the stand under study, the average random measurement error was 1.41, while the systematic error was 58.04 m (Table 1).

Figure 4 shows the numbers and spatial location of model trees on the experimental plot according to the established coordinates. Additionally, Fig. 4 shows a coordinate grid, a legend (scale) of height values with gradation by colour. The results of height determination from the *CHM* raster image after using the "Focal statistics" filter (Fig. 4) were compared with other methods of height measurement based on aerial photography materials (Fig. 3). The obtained values are characterized by a considerable overestimation of the height indicators for the *AM* and *PC* methods. The height indicators found by the *CHM* method have the smallest deviations and are placed grouped regarding the true values of the height of the model trees.

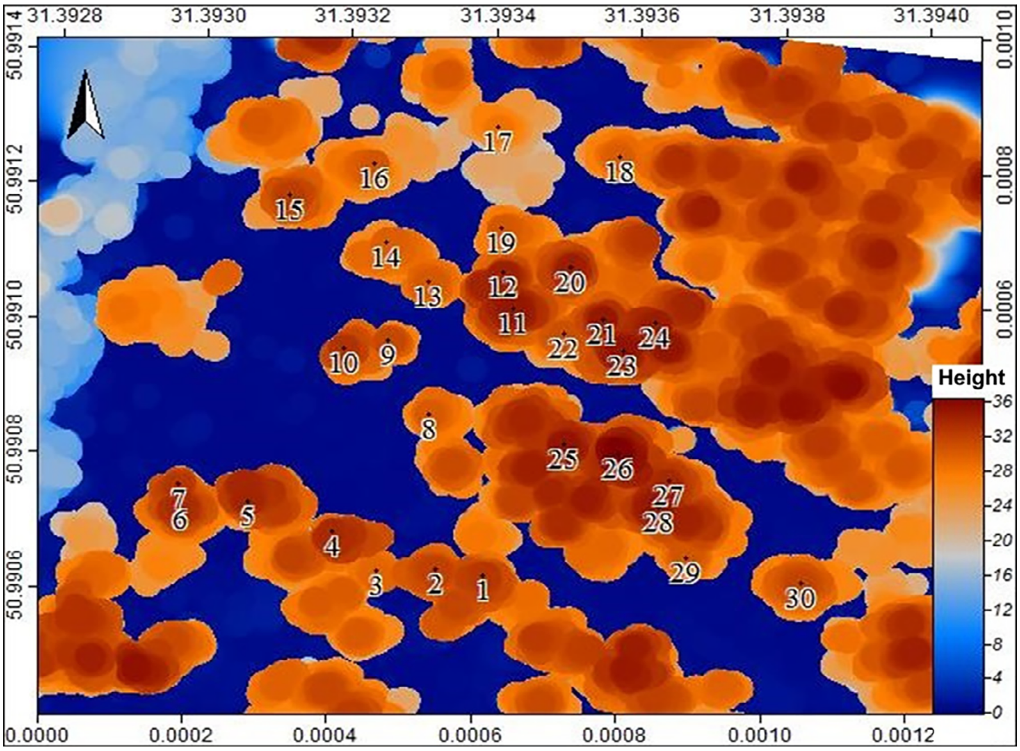

Figure 4. CHM after using the "Focal statistics" tools

CHM was the most precise of all the methods of measuring growing trees considered in this study. The *TruPulse 360B* laser-optical instrument was the most precise of the handheld ground altimeters. The mean random error of measurement for *TruPulse 360B* was 0.88 and for *CHM* was 0.64. First of all, this is explained by the independence of the *CHM* from the actions of the operator, i.e., the human factor in the measurement is minimized.

The advantage of ground-based manual altimeters is the ability to quickly obtain the height value of the measured tree on site. The use of optical imaging using a UAV requires time to process and analyse the raw data using specialized software. On the other hand, if it is necessary to establish the height of a considerable number of trees in the stand, the use of stereophotogrammetry methods has substantial advantages, which include less time spent on field work, the availability of information about the height of all identified trees, diverse possibilities in working with the obtained results; restriction of the area of interest (polygon, allotment), where inventory indicators are automatically set and simulated. In addition, when processing materials, aerial photos acquire a digital terrain model, which can later be used to create a scheme for developing a cutting area. Furthermore, the use of UAVs to determine the height of trees leaves an archive of records of the measurement process, which can be an additional tool for quality control of forest inventory operations.

Conclusions

Comparison of different methods allowed evaluating the precision of measurements and establish the advantages and disadvantages of height measuring devices that are actively used on the territory of Ukraine. The capabilities of UAVs for height measurement show the advantages and prospects of using optical surveying using UAVs to obtain data during inventory, forest management, and survey work in forest areas.

The analysis of the results of using the *CHM* method showed the least impact of the human factor on the results, since the height of trees is measured with minimal operator involvement, which is essential for quality control of the implementation of economic measures and their design.

The value of the average random error for *CHM* was less than 2%, which allows determining the height of trees in pine stands with high precision and meets the requirements for production inventory according to the "Instructions for the regulation of the forest fund of Ukraine" (2014).

Further study is required to estimate the impact of the quality of signals from satellite positioning systems, under the forest canopy, on the precision of determining the height of trees using on-board UAV equipment in coniferous stands compared to deciduous ones.

The accumulation of ultra-high-resolution raster data obtained using UAVs allows increasing the ability to monitor forest stands and detect changes in their structure at the local level (forest area, block, stratum).

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Точність вимірювання висоти дерев різними способами

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Анотація. Дослідження присвячено перевірці точності вимірювання висоти дерев різними способами. В роботі оцінено можливості використання стереофотограмметричного методу для визначення показників висоти дерев за допомогою знімання з безпілотних літальних апаратів (БПЛА) в умовах стиглого соснового деревостану. Проведено порівняння результатів вимірювання висоти дерев сосни звичайної висотомірами та показників висоти, визначених за даними дистанційного зондування, отриманих за допомогою БПЛА. Загалом у дослідженні було розглянуто шість різних способів вимірювання висоти ростучих дерев. Дослідні дані про висоту модельних дерев збирали трьома різними висотомірами (ручними наземними приладами) та БПЛА Phantom 4 Pro. Застосування БПЛА полягало в оптичному зніманні та збиранні даних за допомогою бортового обладнання. Використано способи визначення висоти дерев, які спираються на результати оброблення даних, зібраних навісним обладнанням квадрокоптера. Зокрема, застосовано вимірювання висоти дерев із хмари точок, побудованої на основі одностороннього вертикального знімання модельних дерев, та розрахунок цифрової моделі висоти крон (CHM) за даними аерофотознімання горизонтальних прольотів над деревостаном. Результати математичного аналізу проведених досліджень демонструють найвищу точність способу з використанням CHM для визначення висоти ростучих дерев. Значення середньої випадкової помилки вимірювання висоти модельних дерев для CHM становило менше ніж 2 %. Наступним за точністю визначення висоти дерев був спосіб вимірювання за допомогою лазерно-оптичного приладу TruPulse 360B, застосування якого продемонструвало найвищу точність з-поміж висотомірів. Використання TruPulse 360B для наземних вимірювань та способу CHM (за даними оптичної зйомки з БПЛА) показало кращі результати, які відповідають нормативам точності визначення висоти для виробничої таксації. Способи визначення висоти дерев за даними оптичної зйомки з БПЛА можуть використовуватися для проведення обстежувальних, інвентаризаційних, лісовпорядних та інших робіт, які пов'язані із веденням лісового господарства та моніторингом змін у лісових екосистемах

Ключові слова: безпілотний літальний апарат, аерофотознімання, стереофотограмметрія, модель висоти крон, висотомір