SUMMARY OF PROFESSIONAL ACHIEVEMENTS

dr inż. Krzysztof Stereńczak

Forest Research Institute

Sękocin Stary 2017

DIPLOMAS AND DEGREES

Mar 8, 2011	**Ph.D. in Forest Sciences** Faculty of Forestry, Warsaw University of Life Sciences - SGGW Supervisor: dr hab. Krzysztof Będkowski, prof. SGGW Doctoral thesis title: " Using airborne laser scanning data for assessing density in one layer pine stands" („*Wykorzystanie danych lotniczego skanowania laserowego do określania zagęszczenia drzew w jednopiętrowych drzewostanach sosnowych*").
May 18, 2010	**Master of Science in Geographical Information Science** Center for Geoinformatics, Paris-Lodron University of Salzburg (European Master, UNIGIS) Supervisor: prof. dr hab. Jacek Kozak Master thesis title: "Accuracy of Digital Terrain Models generated from laser scanning data under forest conditions".
May 19, 2006	**Master Engineer in Forestry** Faculty of Forestry, Warsaw University of Life Sciences - SGGW Supervisor: dr hab. Krzysztof Będkowski, prof. SGGW Master thesis title: "The Update of Digital Forest Map Based on Selected Sites in Rogów Forest District" („*Aktualizacja leśnej mapy numerycznej na przykładzie wybranych obiektów Nadleśnictwa Rogów*").

ADDITIONAL EDUCATION

2007-2009	**Jagiellonian University in Kraków,** Post-Graduate Studies in Geographic Information Systems UNIGIS**.**

INFORMATION ON EMPLOYMENT IN RESEARCH AND SCIENTIFIC INSTITUTIONS

Dec 1, 2012 - to date	**Forest Research Institute**, ul. Braci Leśnej 3, Sękocin Stary, 05-090 Raszyn – Researcher (Assistant Professor)
Jun 1, 2011- Nov 30, 2012	**Faculty of Forestry, Warsaw University of Life Sciences - SGGW**, ul. Nowoursynowska 159, Budynek 34, 02-776 Warszawa – Researcher (Assistant Professor)
Mar 1, 2006 - Jun 30, 2006	**Forest Research Institute**, ul. Braci Leśnej nr 3, Sękocin Stary, 05-090 Raszyn – Process Engineer

SCIENTIFIC ACHIEVEMENT FORMING THE BASIS FOR THE HABILITATION PROCEDURE

The scientific achievement forming the basis for the habilitation procedure under art. 16 item 2 of the Act of March 14, 2003 on Academic Degrees and Titles as well as Degrees and Titles in Arts (Journal of Laws No. 65, item 595, as amended) consists of a series of five original academic publications entitled

Digital Terrain Model interpolated from airborne laser scanning data– Its Accuracy and Application in Forestry

Of which I am the main author:

- **Stereńczak K.**, Zasada M., Brach M. 2013. Influence of terrain slope, model pixel size and stand structure on accuracy of DTM generated under pine stands from LIDAR data. *Baltic Forestry,* 19(2): 252-262.

  IF_{2013}: 0,304/Pts $MNiSW_{2013}$: 15

- **Stereńczak K.**, Kozak J. 2011. Evaluation of digital terrain models generated from airborne laser scanning data under forest conditions. *Scandinavian Journal of Forest Research*, 26: 374-384.

  IF_{2011}: 1,197/Pts $MNiSW_{2011}$: 30

- **Stereńczak** K., Ciesielski M., Bałazy R., Zawiła-Niedźwiecki T. 2016. Comparison of various algorithms for DTM interpolation from LIDAR data in dense mountain forests. *European Journal of Remote Sensing*, 49: 599 – 621.

  IF_{2016}: 1,533/Pts $MNiSW_{2016}$: 15

- **Stereńczak K.**, Będkowski K. 2011. Using digital terrain model and digital surface model for stands classification basing on their species and vertical structure. *Sylwan*, 155 (4): 219-227.

  IF_{2011}: 0,159/Pts $MNiSW_{2011}$: 15

- **Stereńczak K.**, Moskalik T. 2014. The possibilities of using a LIDAR-based Digital Terrain Model and single tree segmentation data to determine an optimal forest skid trail network. *iForest - Biogeosciences and Forestry*, 8: 661-667.

  IF_{2014}: 1,269/Pts $MNiSW_{2014}$: 25

Total: IF: 4,462/Pts MNiSW: 100

DESCRIPTION OF RESEARCH OBJECTIVES OF WORKS SUBMITTED FOR THE HABILITATION PROCEDURE AND ACHIEVED RESULTS

Attempts have been made for a long time to describe/measure the Earth's surface layout, locally frequently referred to a landform. The willingness to explore the detailed terrain shape results from the fact that is has an enormous impact on human activity in many areas. Practically, most aspects of human activity require the detailed knowledge of the Earth's surface. The Earth's surface layout also has the impact on climate. The climate affects, to a various degree, the shape of ecosystems, and in particular, the diversity of biocenose.

Methods enabling the measurement of Earth's shape and surface have been developed for years. At first, they were terrestrial methods, and after airborne and satellite technologies emerged, the measurements may be carried out with those tools. The current methods based on remote sensing data acquired from satellites enable relatively accurate representation of the global Earth's shape and surface. As for smaller areas, the Earth's surface measurement is carried out using aerial images or airborne laser scanning nowadays. Airborne laser scanning revolutionized and significantly improved the accuracy of the Earth surface's measurements, also enabling such activity in areas covered by vegetation.

To simplify, the digital terrain model (DTM) is a digital mapping of the surface/Earth. A more specific, the digital terrain model is can be defined as a numerical representation of a terrain surface, usually created by a set of appropriately selected points (XYZ) of its surface and interpolation algorithms enabling reconstructing its shape in a given region (Gaździcki 2001[1]). As a result of transforming the airborne laser scanning point of cloud, a digital surface model (DSM) is also created. DSM is an image of the terrain with objects located on its surface and permanently connected to the ground. By subtracting the corresponding pixels in the DSM and DTM, a normalized digital surface model (nDSM) is created, which shows the height of all objects on the earth surface. In forests, this model presents mainly the height variation of trees and stands, hence it is often used in various types of analyzes. nDSM in forest conditions is also defined as the canopy height model (CHM).

Two types of digital terrain models are used in spatial information systems (GIS): a raster model and a vector model. In order to represent the terrain surface, the raster model uses a matrix of elements frequently called grid cells. Each cell stores an average height value of the primary field, whose dimensions depend on the adopted DTM spatial resolution. The resolution has a significant impact on the manner of surface characteristic features' mapping. The larger the pixel (grid cell), the lower the detail level of model resolution and the capacity to open detailed features in it. The benefits of raster model include the ease of its processing and simple data recording. The vector model is most frequently represented with the use of a triangulated irregular network (TIN). Triangle peaks represent the elevation. The benefits of this model include the large precision level and the capacity to represent details. The literature also describes hybrid models, which utilize positive features of both abovementioned models.

Nowadays, a digital terrain model is the most frequently and widely used remote sensing material. There are two main trends related to the use of the digital terrain model. First of all, it is an element of different types of indexes which describe the variability of landform; and secondly, it is a reference for determining the height of objects on the surface of the earth.

[1] Gaździcki J. 2001. Leksykon geomatyczny. Polskie Towarzystwo Informacji Przestrzennej. Warszawa. (in Polish)

From the emergence of the digital terrain model generated based on airborne laser scanning data, the studies of its accuracy have commenced. Most studies on digital terrain model's accuracy carried out by now focused on open areas, therefore a large amount of information is available on variables affecting the accuracy of the digital terrain model. At the same time, there is a limited number of studies whose objective would include the analysis of the digital terrain model's accuracy in forest areas.

Several groups of factors affecting the digital terrain model's accuracy may be specified. The first group includes features related to the performance of photogrammetric flight and the type of scanner used for the acquisition of point cloud data. Another factor, which affects the quality of a digital terrain model, is the manner of point data processing, above all their filtering and the algorithm used for the interpolation of terrain surface. An important factor determining a model accuracy is the environment where a given model is acquired. In general, it may be stated that a digital terrain model for an area that is not covered by vegetation is more accurate than a digital terrain model acquired for the area which is not covered by vegetation. The characteristic features of vegetation, i.e. among others the height and density, determine the number and spatial distribution of laser signals which can reach the ground.

In addition, the high-density terrain model is gradually becoming a tool used for forest area management. It constitutes a frequent element of decision support systems (*Decision Support Systems*, DSS). It is also the primary remote sensing material used for describing selected features of the forest environment. In most studies on the application of remote sensing data in forestry, in particular, laser scanning, a digital terrain model is used for the normalization of a point cloud or the creation of altitude crown model – for the purpose of single trees' detection. The processing results are further used to determine features of individual trees (height, crown volume, etc.) or the whole stands (resources, biomass, structure, etc.).

The main purpose of the series of articles, which constitute the basis for the habilitation degree application, was at least partial filling of a gap in the knowledge on the digital terrain model's accuracy, including in the mountain areas, as well as factors which affect the accuracy in forest conditions. The purpose of the series of articles was also to indicate new ways for the use of terrain models in forestry. Therefore, the impact of model resolution and data acquisition time were analyzed, further, the effect of species composition and stand structure were investigated, and finally, the impact of point cloud filtering and the application of various algorithms for a digital model interpolation on its final accuracy was studied. In the second part of the presented cycle, the acquired experience was used in order to specify determinants of a digital terrain model's accuracy for their practical use in forest environment classification, with regard to its structure and species composition. In addition, the application of a model was indicated in planning thinning treatments, which is one of the most important elements of stands' maintenance.

The basic purpose of the series of articles was to gain new knowledge on how forest environment may influence the accuracy of a digital terrain model, with the account given to other factors affecting the final result. Due to the high variability of forests in the world (structures, species composition, management manner), different landforms, the availability of different airborne laser scanning systems, the application of various ALS data filtering methods and different algorithms for digital terrain model interpolation, it is difficult to compare the results. The number of study works, which discuss the accuracy of different methods of interpolation and point cloud filtering in a forest environment, is limited. Forest is special environment because it is difficult to carry out the visual interpretation of a registered point cloud to correct possible errors. Most previous studies, which dealt with the problem, analyzed the accuracy of a digital terrain model from the point of land use classes (e.g. forest, urban area, field). Forest is however very complicated environment of changeable structure, therefore, it is important to determine how such variability determines the accuracy of a digital model, and what the most important factors are which determine the accuracy of a digital model in various forest conditions.

A significant factor which determines the accuracy of digital terrain model is the acquisition time of airborne laser scanning data which is further used for interpolation. As a rule, airborne laser scanning data is acquired during a leafless and snowless period. On the other side, data for the need of vegetation study is acquired during a vegetation period. At that time, apart from leaves on trees, the ground is covered with ground vegetation. Very few studies have been carried out in the world, mainly in Scandinavia, which refers to the accuracy of a digital terrain model generated from airborne laser scanning data acquired at different times of a vegetation period.

Apart from investigating the accuracy of the digital model, its practical use for forest operations is also important. DTM may constitute the source of information on the landform, therefore it has a great potential for managing forest environment. Its use relates to the need to implement relevant procedures and processing so that the resulted information enabled undertaking optimum management decisions.

Study purposes focused on the following questions:

1) To what extent different development phases of pine stands affect the accuracy of a digital terrain model?
2) How does a digital terrain model's resolution affect its accuracy, and what are the differences between a model generated based on data acquired during spring and summer time, with the account given to a stand structure?
3) How do a filtering strategy and an applied interpolation algorithm affect the accuracy, and which factor determines to the greatest extent the accuracy of terrain model in forest conditions in areas where the landform is characterized by high variability?
4) Do terrain models generated based on data acquired during different vegetation periods enable the stands' classification into coniferous and deciduous ones, as well as single- and multiple storied ones?
5) How does a digital terrain model and information on the position of individual trees affect the optimization of skidding routes in a forest?

A detailed description of study results included in individual publications:

1) **Stereńczak K.**, Zasada M., Brach M. 2013. Influence of terrain slope, model pixel size and stand structure on accuracy of DTM generated under pine stands from LIDAR data. *Baltic Forestry,* 19(2): 252-262.

A stand structure and soil surface are factors which determine the accuracy of digital terrain model in the forest. The factors are related to the type of forest environment and its management manner. If one wishes to investigate the impact of a stand structure on the accuracy of digital terrain, it is necessary to include the impact of other factors, particularly the surface cover, in such analyses. Such experiment was conducted in relation to pine stands located in fresh coniferous forest habitats. This is one of the dominating forest habitat types in Poland. In such habitats, the soil cover is characterized by small size and cover, as a result of which a low impact of this factor on a digital terrain model interpolation may be assumed. The experiment was carried out in four stands of the total area of 5 hectares and the respective age of 2, 8, 28, and 109 years, where a Scots pine (*Pinus silvestris* L.) comprised 100% of species composition. 30% of the selected stands' area was covered by a dune, which enabled considering in the analysis the terrain slope's impact on the accuracy of a digital terrain model. As a result, the total area was divided into 8 sub-areas of a different stand structure and a flat or sloping surface.

For the experiment needs, GPS reference measurements were made using GNSS RTK Topcon HiperPro equipment. Each base point was measured for two hours. Based on those points, 468 reference points were established, which constituted the reference to digital terrain model analyses. The accuracy of reference points established in the field in every level was less than 5 centimeters.

Analyses were carried out for six digital terrain model resolutions, where pixels' sizes were respectively as follows: 0,5; 1; 2; 3; 4; 5, and 10 m. The terrain models were generated from airborne laser scanning data acquired on May 2-3, 2007.

For comparison purposes, generated raster pixels were used, which corresponded to the position of reference points measured in the field. In addition, models were filtered with an averaging filter of the 3x3 pixels window size. As previously, pixels corresponding to points measured in the field were used for comparison. The purpose of filtering was to answer a question whether slopes cause additional errors in the generated models' values.

In a comparative analysis, a generalized line model was applied for repeated measurements. In order to present the distribution of differences between compared values, a mean error and a root-mean-square error were estimated.

The study results showed the following:

- The distribution of errors for rasters of investigated resolutions differed significantly from the normal distribution, and it had the negative skewness.
- The accuracy of studied models is improved along with the increase of their resolution.
- Pixel values from the original model and the filtered model do not differ significantly in the flat area.

- It was stated that in a flat area, RMSE, ME, and 68th percentile of differences between terrestrial measurement, and the value of a corresponding pixel from DTM have very similar values and trends.
- The values of differences among individual stands are not statistically significant, but the value of *p* statistics was low (0.069), and thus it was close to the assumed importance level.
- All analyzed percentile values had a similar trend for individual stands, apart from a young forest stand, where the trend was opposite.
- Taking a stand type and a terrain type into account showed that for flat areas, the applied error measurements had similar trends and values.
- It was proven that the best results of model interpolation were achieved in the youngest stands and in older age classes. The 28-year-old young forest stand turned out to be the most difficult environment for laser beams to penetrate, and therefore the results of terrain model interpolation were the worst here.
- It was proven that a mean error and the value of 68th percentile of differences value have very similar values in analyzed model resolutions, and 95th percentile of differences value is very susceptible to large error values that arise from time to time. The use of different measurements in error evaluation may result in conclusions on the terrain nature.

2) **Stereńczak K.**, Kozak J. 2011. Evaluation of digital terrain models generated from airborne laser scanning data under forest conditions. *Scandinavian Journal of Forest Research*, 26: 374-384.

The multitemporal analyses with the use of digital terrain models generated based on airborne laser scanning data include errors that result from differences in the vegetation development in a given area. Depending on the species composition, structure, and age of vegetation it may be assumed that the differences have various values. The hitherto literature includes very few examples of analyses, which compare a digital terrain model acquired at different times of a vegetation period, and due to which it was possible to acquire the knowledge on the phenology's impact on the accuracy of DTM in forest conditions. In addition, different model resolutions were investigated and differences between them on two data acquisition dates.

The studies were carried out in Uroczysko Głuchów – a part of the SGGW Experimental Forestry Station in Rogów. 95 reference points were measured in the field in various stand types (mainly: pine, oak, alder, birch, and larch) aged 30 to 120. Points were measured using an electronic tachometer. The accuracy of measured points was ±9 cm in a horizontal plane, and ±4 cm in a vertical plane.

The stand features such as the number of layers, species, and crown cover were estimated in the field during measurements. In addition, aerial photos of 15 cm resolution were used. Data acquired and processed in such a manner constituted the basis for further studies.

Airborne laser scanning data, which formed the basis for digital terrain model interpolation, was acquired on May 1-2 and August 18, 2007, r. The first data set was referred to as a spring flight, the other as a summer flight. Both datasets were processed to reach the form of digital terrain models with the same interpolation algorithm settings. For both dates, digital terrain models were generated of the following resolutions: 1, 2, 3, 5,10, and 20 m.

Due to the fact that two airborne laser scanning data sets differed from each other in respect of point density, it was checked whether these differences might have an impact on the accuracy of the digital terrain model. As a result of the test carried out in the forest area and in open space, it was stated that both point cloud densities may be considered the same since only for a digital terrain model of 1 m resolution a difference between both models was statistically significant with a significance level $\alpha=0.05$.

The accuracy of both models was estimated with a mean error and a root-mean-square error, and the impact of individual factors on error values was examined through the analysis of variances (ANOVA).

The study results showed the following:

- For the total of all investigated cases, values in models overstated altitude by 8 cm on average.
- 96% of errors were within the range ± 1m, and the error distribution was close to normal, however, Shapiro-Wilk test rejected such an assumption (with $\alpha=0.05$).
- A mean error adopted values from -0.18 m for 1 m resolution raster, to +0.21 m for 20 m pixel raster. This means that a model decreased in relation to reference measurements in line with the increase of pixel size.
- The range of errors reached the largest values for a 20 m model raster size and the least ones for a model with 3 m raster size.
- A mean error for models with a pixel size from 1-5 m did not differ significantly statistically, as in the case of 10 and 20 m models. Statistically significant differences appeared between those groups.
- Errors in summer models had more than doubled scope than in the case of spring models.
- As a result of errors' averaging for individual resolutions, both the value of a mean error, as well as the value of a root-mean-square error showed a high determination coefficient (R^2 within a range from 0.889 to 0.999).
- No statistically significant differences were stated between accuracies of models in single and multi-storied stands.
- A correlation coefficient between errors in summer and spring models was high for single storied stands i.e. r=0.809. For multi-storied stands, it was r=0.481.
- From the point of error modeling, single-storied and coniferous stands provide more stable results, therefore error value assumptions may be more certain. In multi-species and deciduous stands, the seasonal nature causes greater differences, and forecasting errors are less reliable.

3) **Stereńczak** K., Ciesielski M., Bałazy R., Zawiła-Niedźwiecki T. 2016. Comparison of various algorithms for DTM interpolation from LIDAR data in dense mountain forests. *European Journal of Remote Sensing*, 49: 599 – 621.

Many factors determine the accuracy of a digital terrain model in a forest. They relate to data acquisition, the complexity of forest environment, and the processing manner of acquired airborne laser scanning point cloud. The study mainly deals with the last two groups of factors. As far as site features are concerned, the following were taken into consideration: the number of stand storeys, the slope, the height of groundcover, the type of surface (in the forest, outside forest, roads). During data processing, 3 filtering methods and 15 digital terrain model interpolation algorithms were used with various settings. In addition, the angles of laser beams were analyzed with reference to a digital terrain model. Ultimately, 24 best terrain models from particular variants were used.

The study was carried out in the south-west of the country, in Platerówka and Lubań municipalities. The reference data used in the study was acquired with a GPS receiver (RTK geodetic class) in 23 stands. The species composition was dominated by spruce (9 stands), and also included pine (4 stands), maple (4 stands), beech (3 stands), and ash, oak, and birch (1 stand each). The stands aged from 29 to 114. The land was severely undulating, and the altitude was from 232 to 375 m above sea level.

The airborne laser scanning data was acquired with a RIEGL LMS-Q680i scanner in August 2012. Further, the data was processed and classified with TerraSolid software. After various digital terrain models were generated, their accuracy was specified in relation to reference GPS measurements. In the assessment of accuracy, bias and root-mean-square error (RMSE) values were used. Differences in the obtained results were specified with a t-test with a significance level of $\alpha=0.05$.

The study results showed the following:

- The land slope, and particularly the type of vegetation covering the ground, are the most important factors affecting the accuracy of a digital terrain model in dense forests in mountain areas. The larger the slope and the higher groundcover, the errors are larger.
- All methods of digital terrain model interpolation may deliver results of similar accuracy, provided that their optimal settings were specified.
- A bias and a root-mean-square error (RMSE) are twice as high in open areas covered with vegetation than in case of roads.
- Error values grow along with the increase of scanning angle. Due to the cover of strips, errors are minimized at strips' ends.
- In the studied case, there was no quality profit when a DTM was ordered at the company professionally dealing with data acquisition and processing. The achieved filtering and interpolation results were at least as good as the results received from the commercial company.

4) **Stereńczak K.**, Będkowski K. 2011. Using digital terrain model and digital surface model for stands classification basing on their species and vertical structure *Sylwan*, 155 (4): 219-227.

The experimentally observed differences between models, resulting from environmental conditions, as well as the influence of seasonal forest variability, have a negative impact on the process of among others stand height assessment. The existing conditions may be used in order to gain other forest-related information. In the study, authors investigated whether it is possible to use dependencies between terrain models and digital surface models to automate the process of stands' classification based on their vertical and species structure. The basis for such classification was formed by the theoretical set of relations between DTM and DSM models of coniferous and deciduous stands, taking into account the impact of a vegetation period and the vertical composition of stands.

The research was carried out based on stands in Uroczysko Głuchów, a part of the Experimental Forestry Station in Rogów, which belongs to Warsaw University of Life Sciences. In the studies, the results of laser scanning carried out on May 2-3, July 9, and August 30, 2007, were used. FALCON II laser scanner from TopoSys company was applied for scanning. Data in the form of a raw point cloud was analyzed with TreesVis software, which enables airborne laser scanning data processing. In order to generate a digital terrain model, point clouds including only so-called last echoes were used, and to generate a digital surface model, clouds including so-called first echoes were used. Models were generated in 1 m spatial resolution, with elevation rounded up to 1 cm.

In the first phase of the experiment, a hypothesis was formed that a season (spring, summer) causes that between coniferous and deciduous and mixed stands there is a statistically significant difference of mean elevation values (elevation) of digital terrain model (DTM), digital surface model (DSM), and crown height model (CHM). For this purpose, within the borders of every stand, the mean elevation values were calculated from "spring" and "summer" models. ANOVA analysis was performed with Statgraphics packet to evaluate the significance of differences between the mean values. It was stated that there is a statistically significant difference between a group of 48 coniferous stands and 39 deciduous and mixed stands for DTM and DSM. The experiment result gave rise to the attempt to use the information to classify the vertical and species structure of stands.

To make sure that the processed data is not distorted by other factors (e.g. inappropriate calibration of laser point clouds), two groups of control points were introduced in the analysis – meadows and hard surfaced roads. The selection of those was justified by the assumption that DTM and DSM models, as well as the resulting differential digital surface models (DSM – DTM) generated for them, should not show differences resulting from the seasons of the year.

The purpose of the second part of the experiment was to verify whether the vertical structure (layer) of stands has an impact on the created DTM, DSM models and a resulting CHM model. Due to the stereoscopic analysis of aerial images, it was possible to indicate coniferous, as well as deciduous and mixed stands of the single and two-storied structure. In the presented experiment, considering the first layer of a stand, deciduous and multi-species stands were joined by one group. As previously, differences were analyzed between mean values of DTM, DSM, and CHM models, calculated for "spring" and "summer" variants. For the construction of a discriminant function, all models were used, which enabled the greater accuracy of classification.

The study results showed the following:

- The proposed methodology allows dividing stands into coniferous, and deciduous and mixed with 71 % accuracy (total accuracy).
- The proposed methodology allows dividing stands into single and double-storied ones. The achieved accuracy was approx. 71-79 % (total accuracy).
- Differences between DTMs (summer and spring) show that lower stand layers and groundcover have the impact on the position (elevation) of interpolated layers.
- No bias or the impact of other factors was stated in the analyzed data, which was proven based on results achieved for 45 control sites located in meadows and roads.

5) **Stereńczak K.**, Moskalik T. 2014. The possibilities of using a LIDAR-based Digital Terrain Model and single tree segmentation data to determine an optimal forest skid trail network. *iForest - Biogeosciences and Forestry*, 8: 661-667.

A digital terrain model generated as a result of airborne laser scanning data interpolation is the material which provides very accurate information on the landform in a forest environment. Therefore, the material may constitute the basis for planning various management activities. It is also used for planning maintenance works and wood harvesting, mainly in estimating the possible uses of specific technologies.

The studies referred to the opportunities to use a digital terrain model and the results of individual tree crowns' detection for optimizing skidding routes' designation. The analysis was carried out based on 170 pine stands in Uroczysko Głuchów, a part of the Experimental Forestry Station in Rogów, which belongs to Warsaw University of Life Sciences. In the studies, the results of airborne laser scanning carried out on May 2-3, July 9, and August 30, 2007, were used. FALCON II laser scanner from TopoSys company was applied for scanning. Data were processed in the form of a digital terrain model and a digital surface model. As a result of terrain models' processing, a crown height model was achieved, which was further subject to detection process of individual tree crowns. Subsequent analyses used a digital terrain model and trees' detection results.

In the study, a set of rules was developed, which, based on spatial data and its processing, the theoretical network of skidding routes, and additional criteria, were used for the optimization of skidding routes. The optimization related to operational routes used in a typical thinning method with skidding and thinning performed with harvesters. The aim of optimization was to indicate, before going on site, which areas are unavailable for adopted solutions (due to too large slopes). It was also assumed that routes should be planned in such a manner so that the number of removed trees was the least, among others, due to the use of existing gaps in stands.

As a result of the study, it was stated that:

- The length of skidding routes network decreased by approx. 2% for a traditional harvesting method and it practically remained unchanged for the mechanized method (insignificant difference of approx. 0.06%).

- As a result of optimization, planned numbers of removed trees also changed insignificantly (by 2.8% for a traditional method, and by 0.55% for a machine method). Percentiles were similar for the volume and biomass. The above differences were not statistically significant at $\alpha=0.05$.
- Despite insignificant changes in relation to the original structure of skidding routes' network, sites unavailable for specific technologies were recognized. Account should be taken of the fact that the analyzed area covered a small area, and it was relatively flat. Other results should be expected in mountain areas, where the use of DTM would allow the exclusion of areas with too large land slopes and would enable planning other maintenance cutting methods, at the stage of planning.

The most important study findings included in the series of publications:

- The landform, also in forest conditions, is an important factor which affects the accuracy of the digital terrain model. A mean error and the median of differences for points on slopes was, on average, 3 times higher than for points in a flat area.
- The study results showed that the most important factor, which affects the accuracy of digital terrain model in dense forests in mountain areas is mainly ground vegetation.
- Forest structure is a factor which determines the accuracy of the digital terrain model. The largest errors were observed for stands in an early growth phase when young forests are compact. An early-growth phase (young plantation) and a period after slackening (from polewood) do not cause such great errors of the digital terrain model. A young forest turned out to be the most difficult environment for laser beams to penetrate, and as a consequence, the results of terrain models' interpolation were the least accurate.
- The DTM error values reached about 10-30 cm for spring DTMs and about 30-60cm for summer DTMs; errors were clearly related to output resolution and increased with increasing pixel size; overestimation of elevation, typical for higher resolutions, was turning into underestimation for output pixel size >10 m. No statistically significant differences were stated between accuracies of models obtained from airborne laser scanning data acquired at different times of a vegetation period for up to 5 m pixel models. For 10 and 20 m pixel models, statistically significant differences were noted between two data acquisition dates. This means that both point cloud filtering, and indirectly forest structure affect the result.
- The impact of data acquisition date was different for various stands. Summer models were characterized by a greater range of random errors and a greater bias. One-layer stands were more sensitive to the season of data acquisition than were multilayer stands, as were larch and alder stands in comparison to pine and oak stands. This may be caused by the fact that in dense multi-storied stands, light conditions are similar all the time, and little light reaches the forest floor, which limits the growth of ground vegetation or underbrush. In addition, a dense forest structure limits the number of laser beams reaching the forest floor, regardless of whether there are leaves on trees. In single-storied stands, the quantity of light reaching forest floor is larger, although it may vary throughout a vegetation period. Since in coniferous stands light conditions do not vary considerably throughout a vegetation period, in deciduous stands variations are substantial, which affects the growth of ground vegetation. This means that in areas where vegetation changes occur seasonally, the leafless condition may not be an optimum time for acquiring ALS data to develop a digital terrain model. An example may be some oak-hornbeam habitats, where wood anemone or wild garlic appear on the ground for a while in the spring.
- A mean error and the value of the 68^{th} percentile of differences have very similar values for models of various analyzed pixel sizes, and the 95^{th} percentile is very susceptible to appear from time to time large values of errors related to the impact of land slope or vegetation structure. The application of various statistical measures in the assessment of a digital terrain model error may lead to a conclusion regarding the landform (a diverse terrain, or a flat area). The use of percentiles is more appropriate in cases where the data (errors/differences) distribution is not normally distributed and skewed.

- Different filtration strategies resulted in different ground-point densities. In general, the point cloud was dense and offered a very effective reflection of topography in the study area. The densest point cloud used for the interpolation of DTM does not guarantee the best accuracy. Differences were nevertheless very small (about 1-2cm). BIAS and RMSE for all DTMs, interpolated from denser data, assume the highest value. This result leading to the conclusion that too many off-ground points were preserved in the ground-point cloud and used in DTM interpolation.
- All methods of digital terrain model interpolation can provide results of similar accuracy if their optimal settings were applied. The studies showed that in the investigated case, there was no significant difference in the quality of DTM submitted by commercial providers and the results of self-performed works.
- The proposed methodology related to the use of terrain models to classify stands into classes: deciduous dominant and mixed species, and coniferous separately, reaches 71 % accuracy (overall accuracy). The proposed methodology related to the use of terrain models to classify stands into single and double-storied ones reaches 71-79 % accuracy (overall accuracy). In both cases, results confirmed that a stand structure influences the quality of digital terrain models. As a result, it is possible to use this constant influence in the classification.
- DTM and the results of single trees' detection enable the optimization of skidding routes layout. The length of skidding routes network, after the optimization, decreased by approx. 2% for a traditional harvesting method and it practically remained unchanged for the mechanized method (insignificant difference of approx. 0.06%). As a result of optimization, planned numbers of removed trees also changed insignificantly (by 2.8% for a traditional method, and by 0.55% for a machine method). Percentiles were similar for the volume and biomass. The above differences were not statistically significant at $\alpha=0.05$. DTM, already at the stage of planning, enabled indicating sites which are unavailable or prevent the use of certain technologies even in flat areas. More significant results could be achieved in mountain areas where terrain height differences are larger than in the examined area of Uroczysko Głuchów.

OVERVIEW OF OTHER SCIENTIFIC AND RESEARCH, DIDACTIC, AND ORGANIZATIONAL ACHIEVEMENTS

The course of my academic work prior to the award of the Ph.D. degree.

My scientific interests grew during my studies at the Faculty of Forestry, Warsaw University of Life Sciences - SGGW. I began studying in 2000 and graduated in 2006. During the studies, I decided to take a one year off due to the necessity to take up paid employment. Upon the restoration of financial condition, I was able to prepare a master degree thesis titled: "*The Update of Digital Forest Map Based on Selected Sites in Rogów Forest District"*. The supervisor of my work was dr hab. inż. Krzysztof Będkowski, prof. SGGW. I completed the master degree program at the Faculty of Forestry with a very good grade. Still, during the period of study, I decided to continue my scientific work.

In 2007, I commenced doctoral studies at the Faculty of Forestry, Warsaw University of Life Sciences - SGGW. I got involved actively in research studies carried out at the Department of Geomatics and Spatial Planning (10 projects), among others on the application of laser scanning in forestry. Supervised by dr hab. inż. Krzysztof Będkowski, professor of SGGW, I prepared a doctoral thesis, honored by the Council of the Faculty of Forestry, titled: *"Using airborne laser scanning data for assessing density in one layer pine stands".* Research studies, which resulted in the doctoral dissertation, were supported, among others, by Mazovia Doctoral Scholarship granted under the Integrated Operating Program for Regional Development, Measure 2.6 "Regional Innovation Strategies and Transfer of Knowledge", financed from the European Social Fund. In addition, the doctoral thesis was also supported by the funds from the Ministry of Science and Higher Education in the years 2009-2011 grant no. N N309 113237, title: "The Application of Airborne Laser Scanning Data to Determine Trees' Density in Single-Storied Pine Stands" (project manager: dr hab. inż. Krzysztof Będkowski, prof. SGGW).

In parallel with the doctoral studies, in the years 2007-2010, I commenced UNIGIS study program in the English language, which was carried out jointly by the University of Salzburg (Austria) and the Jagiellonian University. I completed the studies at the highest possible level (European Master), and I was granted a degree of Master of Science in Geographical Information Science and Systems. My dissertation was sent to the international competition of master theses – UNIGIS International Association 2010 Academic Excellence, where it took the 6th place.

During doctoral studies, I was heavily involved in the scientific activity. My scientific, as well as popular science achievements at that time, included 33 literature items. They comprised multiple study papers, prepared individually or with co-authors, published in monographies, scientific journals, and conference materials. The first research paper was published in 2006. In addition, during doctoral studies, I gave 16 conference lectures/seminars, 6 of which were in the English language. I attended 6 international summer schools. I completed 2 additional e-learning courses (the first one at the University of New Brunswick (Canada), and the other under the European Spatial Data Research Network), 3 training courses. I was granted 3 travel scholarships to conferences in China and the US. In a period from September 19, 2007, to February 14, 2008, I was at ERASMUS doctoral scholarship at the University of Freiburg (Germany).

When applying for Mazovia Doctoral Scholarship, my scientific achievements were awarded the highest rank out of all applications in "Environment" category, which was honored by a letter of congratulation from the Marshal of the Mazovia Province Adam Struzik. I was also awarded "the Best Paper Award", as a co-author of an honored article in the young scientists' session (Youth Forum), during the 21st ISPRS Congress in Beijing in June 2008. In November 2009, I was granted the Scopus-Perspektywy Young Researcher Award founded by Elsevier B. V. and the Education Foundation Perspektywy – 1st place in "Environment" category.

The course of my academic work upon the award of Ph.D. degree (overview of scientific and research achievements other than those which constitute the basis for the habilitation degree application).

After being awarded a Ph.D. degree in forest sciences, I was employed at the Department of Geomatics and Spatial Planning, Faculty of Forestry, Warsaw University of Life Sciences – SGGW (July 2011). After several months, I commenced my research work at the Forest Research Institute (December 2012), which I continue to date.

Since 2011, I have been involved in the performance of 10 research programs (financed by the Ministry of Science and Higher Education, as well as the General Directorate of the State Forests), as their tasks coordinator or main performing contractor, and in three projects as the manager (projects financed by the National Centre for Research and Development, The European Union, the National Fund for Environmental Protection and Water Management, and the European Space Agency). The execution of the following two projects was particularly important to me:

- The implementation project of REMBIOFOR "Remote sensing based assessment of woody biomass and carbon storage in forests", co-financed from the funds of the National Centre for Research and Development, within the program "Natural environment, agriculture and forestry" BIOSTRATEG, under the agreement no. BIOSTRATEG1/267755/4/NCBR/2015. The project is executed by the consortium of 8 institutions: Forest Research Institute (Consortium Leader), the General Directorate of the State Forests (business partner), Warsaw University of Life Sciences – SGGW, the Institute of Dendrology PAS in Kórnik, Poznań University of Life Sciences, University of Agriculture in Kraków, Wood Technology Institute in Poznań, Institute of Geodesy and Cartography in Warsaw. I am the main Author and Project Manager. The project budget is PLN 20,968,761.00.
- LIFE+ ForBioSensing PL project "Comprehensive monitoring of stand dynamics in Białowieża Forest supported with remote sensing techniques", which is co-financed from the European Commission funds under EU financial instrument LIFE+ and the funds of the National Fund for Environmental Protection and Water Management (NFOŚiGW) No. of Agreement with the EC: LIFE13 ENV/PL/000048; No. of Agreement with NFOŚiGW: 485/2014/WN10/OP-NM-LF/D. The project is the first as a comprehensive project, which extensively analyses the condition and dynamics of stands in Białowieża Forest. I am the main Author and Project Manager. The project budget is PLN 16,857,123.00.

Over 120 people are involved in the described projects, which, apart from extensive knowledge, requires me to have considerable organizational and management skills, which I develop continuously. In the described period, I completed courses and received the following certificates, among others: PRINCE2 Practitioner, AgilePM Practitioner, "People Management in

Research Project" under the project "STER dla B+R" No. UDA-POKL.04.02.00-00-022/11, the training co-financed from the European Social Fund under the Human Capital Operational Programme, Priority IV "Higher Education and Science", Measure 4.2 "Development of R&D system staff qualifications and improving the awareness of the role of science in economic growth", "Risk Management", and "Self-Management in Time".

My research activity in the years 2011-2017 focused on three main subject areas:

1) Prediction of tree and stand characteristics with use of laser scanning data,

2) Examination of forest species composition and forest health condition with use of remote sensing data,

3) Examination of selected tree and stand variables with use of unmanned aerial vehicles.

Ad.1 Prediction of tree and stand characteristics with use of laser scanning data

Due to the continuous development of technologies and the emergence of new tools, which may potentially be used for more detailed, faster, or cost-effective forest measurement, the need arises for continuous studies on their practical use. In carried out studies, apart from technical aspects, it is necessary to take into account the fact that forests in Poland have their specific characteristics, among others, with regard to management manner, species composition or structure. The below mentioned studies carried out in different teams mainly refer to aspects related to the use of laser scanning data in forestry. Some of the below presented studies are the continuation of my works carried out during the doctoral studies, and they use results developed in my doctoral dissertation. In the studies, carried out primarily with prof. Stanisław Miścicki, we focused on the use of results of airborne laser scanning data processing for the need of inventorying the basic valuation feature of forest i.e. the volume of stands. The studies, which we performed, enabled for the first time in Poland, to draw up a detailed inventory of a large forest complex i.e. the Stolowe Mountains National Park with the use of airborne laser scanning data (Project title: "The development of a method to measure forest resources supported by airborne laser scanning (by the case of a protected mountain area)"). There, the bases were formed for the method of inventorying resources, which is currently developed under NCBiR BIOSTRATEG program project ("Remote sensing based assessment of woody biomass and carbon storage in forests –REMBIOFOR").

- In the review section on airborne laser scanning, a brief description was included of the history and certain technical aspects of the technology. In a part related to the history, the most important facts were mentioned regarding the uses of airborne laser scanning in the studies of forest environment in Poland. The technology description section includes a brief of characteristic features of the main system variables i.e. sensor types, scanning frequencies, and density of point cloud. Further, the most important products were discussed, obtained as a result of airborne laser scanning, and data features were presented, which constitute the basis for analyses presented in the monography.

  Stereńczak K. 2011 Airborne laser scanning. [w] K. Będkowski (red.) Forest in raster model of spatial data, Wydawnictwo SGGW, Warszawa, p. 63-74.

- Data acquired as a result of airborne laser scanning was used for investigating the ability to detect trees in a point cloud. In order to verify the method, sample plots located in

Milicz Forest District were used. The tested approach to trees' detection is therefore advanced since it uses a point cloud, and not a digital surface model or crown height model, so it constitutes 3D, not 2.5D analysis. The results of trees' detection for individual areas varied depending on the species (from 60 to 85.7% of correctly detected trees) and age (from 57.1 to 100% of correctly detected trees).

Gupta S., Weinacker H., Stereńczak K, Koch B. 2013 Single tree delineation using airborne LIDAR data. European Scientific Journal, 9(32): 405-435.

- The accuracy of tree height estimation using single tree detection results was analyzed. The experiment was carried out in pine stands (*Pinus silvestris* L.) in Milicz Forest District. The studies showed that a mean height of stands estimated based on airborne laser scanning data was underestimated by approx. 0.82 m (nearly -5%), and the upper value was underestimated on average by 2 m (-9%). The obtained accuracy of segmentation was comparable to other works, and it seems that it had no negative impact on stands height estimation.

  Stereńczak K., Zasada M. 2011. Accuracy of tree height estimation based on LIDAR data analysis. Folia Forestalia Polonica, ser. A, 53 (2): 123–129.

- A possibility was investigated related to the use of a crown height model (CHM) to estimate the height and density of stands. Both valuation variables were first specified for the so called basic fields (raster cells) of 5 and 20 m. Values obtained for individual sizes of raster cells were averaged for the whole patches. Apart from specifying variables, which are significant from the economic point of view, the presented methodological solutions enabled the separation of homogeneous stand fragments in the whole forest complex area. Results developed based on data from CHM were compared with values specified based on forest management. The highest coefficient of determination was obtained for a variant, in which the mean height was estimated based on all raster cells fully included inside the patches. Slightly worse results were obtained for a variant, in which all raster cells crossing the patch space were taken into account. Similar trends were observed for the maximum height, but the coefficients of determination adopted slightly higher values i.e. R^2=0.81. As for such feature as trees' density per space unit, the applied method enables recording and indicating the spatial differentiation of this feature in patches' area.

  Stereńczak K., Będkowski K. 2011: Stand Height and Density. [w] K. Będkowski (red.) Forest in raster spatial data model, Wydawnictwo SGGW, Warszawa, p. 78-90.

- With two sets of airborne laser scanning data acquired for the area of the Experimental Forestry Station in Rogów, an analysis was carried out related to the possibilities of recording height increase during one vegetation period. The data were acquired in May and August 2007, i.e. at the beginning and at the end of intensive growth of trees. The growth was estimated at the stand level, and it was averaged in height classes. The results showed that data acquired through airborne laser scanning enable the detection of a one-year increase in trees' height.

  Stereńczak K., Mielcarek M. 2014. Assessing one year pine growth at stand level with single tree detection based on ALS data. Proceedings of the 6th Precision Forestry Symposium: The anchor of your value chain. Edited by Pierre Ackerman, *Elizabeth Gleasure and Hannél Ham, 3-5 March 2014, Stellenbosch University, Stellenbosch, South Africa, 16-18.*

- The subject of analysis was the dependency between a tree diameter at breast height and selected variables of tree crowns estimated through airborne laser scanning. The experiment was carried out in pine stands (*Pinus silvestris* L.) in Milicz Forest District. The results showed that the best set of features to estimate the dependency between tree thickness and crown characteristics turned out breast height cross sections as a dependent variable and a crown projection surface as an independent variable. The relation between tree thickness and crown parameters was important, but relatively weak (R^2 from 0.33 to 0.52). The best results were achieved for so called "pouring" algorithm, by means of which tree detection takes place in close connection with the crown morphological structure, hence such an improvement of results. The accuracy of analysis was also affected by other trees and stands' features, as well as the accuracy of tree detection, which never adopts 100% value. Despite a relatively low force of a relation between tree cross sections and the crown projection surface, it is possible to create an unburdened model for the need of automatic estimation of tree diameters at breast height.

  Zasada M., Stereńczak K., Brach M. 2011. Relationship between dbh and crown characteristics derived by airborne laser scanner. Sylwan, 155 (11): 725–735.

- The analysis featured on the selected tree and stand attributes, which were estimated and measured with airborne LIDAR scanning system, with regard to their suitability for remote and automated estimation of stand volumes. Attributes specified for single trees based on a crown height model (CHM) were analyzed. The studies were carried out in the mountain area, in the south-western part of the Stolowe Mountains National Park. The analysis featured on 7 attributes or attribute groups specified based on a crown height model and stand segmentation into individual crowns. The variability of dependent feature – stock volume in test areas – was best described by such independent variables as: the average height of trees and a product of the sum of crown volume and the sum of tree height within the plot. A multiple correlation coefficient was high ($R=0.820$ $p<0.001$). A strong dependency between the volume in terrestrial sample plots and features in airborne LIDAR sample plots (excluding intermediary features such as e.g. stand age) indicates that it is possible to apply a double sampling inventory method for forests which are strongly varied, and close to natural, occurring in the national parks. The presented method was an integration of area based and individual tree detection method. It was one of the first studies of this type in the world.

  Miścicki S., Stereńczak K. 2012. Using crown height model based characteristics in double sampling Method of forest stock inventory. Annals of Geomatics (Roczniki Geomatyki) X, 5(55): 47-54.

- Further extension of works on the use of airborne laser scanning data was the analysis of the impact of plot size, tree selection manner (crowns) in the sample plot, and the set of variables used for model development. Calculations were made four times taking into account the size of the sample and the manner of trees (crowns) selection for a sample. It was stated as a result of analyses that it is advisable to use airborne LIDAR sample plots of the size corresponding to the mapping of terrestrial sample plots. If larger plots were used, the consequence was a decrease in the calculation results of dependency between the volume or tree density measured in the field, and features measured within airborne LIDAR samples. It was stated that a better way to classify trees for airborne LIDAR sample is a "centroid" method, i.e. the one which takes account of whether a tree crown centroid is inside the sample plot. The studies showed that "the total of crown volumes" is an airborne LIDAR feature particularly useful for calculating trees' volume and density. Other attributes: height (upper or average), number of trees visible in imaging or the total of tree heights may also be used, and are of similar importance for explaining dependencies between the variable value of features measured terrestrially (volume and tree density), and the variable value of features measured within airborne LIDAR sample plots.

Mścicki S., Stereńczak K 2013. A two-phase inventory method for calculating standing volume and tree-density of forest stands in central Poland based on airborne laser-scanning data. Forest Research Papers (Leśne Prace Badawcze) 74 (2): 127–136.

- The analysis featured on the impact of crown size (crown's horizontal projection) on the result of volume modeling in sample plots. For this purpose, selected sample plots in the Stolowe Mountains National Park were investigated. It was proven that the manner of estimating crown coverage and variables describing the volume estimated on this basis, affect the determination coefficient during model creation, and increase volume estimation error. In addition, the manner of selecting trees for the sample plot also causes slight differences in the determination coefficient between volume, which is modeled, and the one specified in the field considered as the reference. An important result of the study was the empirical statement of the need for detection and discarding from the analyses dead trees in a study area of sample plots.

  Stereńczak K., Miścicki S. 2012. Crown delineation influence on standing volume calculations in protected area. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XXXIX-B8, 441-445.

- Based on the analysis of 3043 trees in 30 sample plots of over 20 m diameter, studies were carried out on the impact of mutual shadowing of trees on the estimation basal area, and the number of trees, if a measurement was made of the terrestrial laser scanning or the relascope from one position (in the center of sample plot). The studies were carried out in the Experimental Forestry Station in Rogów, which belongs to Warsaw University of Life Sciences, and focused on the use of terrestrial laser scanning in forestry practice. The results showed that it is possible to create a theoretical model describing tree visibility along with the extension of a plot radius with regard to mutual shadowing of the trees. It was stated that the number of trees hidden from a measuring person or a laser beam grows along with the increase of sample plot's radius, which also means the growth of an error in the estimation of tree number and other related attributes of the stand. In addition, it was proven that there is no relation between a percent value of a visible sample plot (unshaded) and the estimated basal area. In practice, this means that it must not be assumed that trees, especially those which are close to a measurement position, shadow most part of the plot, which causes that fewer trees are visible than are really present, and opposite. It was also proven that on plots with up to 15 m radius for specifying a basal area, an average of 5% error is made, which confirms the statement that with a sample plot radius equal 15 m, a relatively insignificant and acceptable error is made in estimating tree number and the stand's basal area.

Zasada M., Stereńczak K., Dudek W., Rybski A. 2013. Horizon visibility and accuracy of stocking determination on circular sample plots using automated remote measurement techniques. Forest Ecology and Management 302: 171–177.

- The consequence of the above described studies was further work, which focused on the accuracy of determining selected parameters related to breast height diameters' distribution in pine stands with the terrestrial laser scanning. It was assumed that despite it was stated in the previous studies that the number of trees hidden from a measuring person or a laser beam emitted by a scanner, grows along with the increase of a sample plot radius, it must not at the same time mean the increase of error in estimating other stand parameters, e.g. a mean and average breast height diameter, variability, or parameters of various breast height diameter distribution. In order to verify this hypothesis, data from 27 pine sample plots and 2671 trees were used. For all concentric plots of 5, 10, 15, and 20 m radius, the following attributes were estimated: the number of trees per hectare, the least and the greatest breast height diameter, the arithmetic mean of breast height diameters, the average breast height diameter, standard deviation of breast height diameters, 25th, 31st, 50th, 63rd, 75th, and 95th percentile of breast height diameters, distribution skewness and kurtosis, which were considered as the reference. For every plot a tree-trunk distribution plan was developed, which was further used for estimating stand's breast height diameter distribution based on trees visible from the center of the plot at a distance of 5, 10, 15, and 20 m. The results were further compared to reference values (estimated based on measurements of all trees on a plot of the assumed radius). It was stated that the average breast height diameter, standard breast height diameters' deviation, and distribution percentiles specified based on all trees and trees visible in circular sample plots of up to 20 m radius do not differ significantly from each other. Skewness and kurtosis are not significantly different in plots with a radius of 5 and 10 meters. For the 15 m radius plot, the difference was significant for about 15% of the analyzed plots.

  Zasada M., Stereńczak K. 2013. Accuracy of the selected tree diameter distribution parameters assessed using terrestrial laser scanning in Scots pine stands. Sylwan, 157(12): 883-891.

Ad 2. Examination of forest species composition and forest health condition with use of remote sensing data

Another research issue I was dealing with upon the award of a Ph.D. degree was the use of spectral information to analyze species composition and health condition of forests. I carried out studies in this area using various types of data, characterized by different spectral, spatial, and radiometric resolution. In this subject, I focused on standard levels of data acquisition: airborne and satellite, which are currently used operationally. Below, I describe two review papers published recently, which comprehensively summarize the current potential of remote sensing and the knowledge on remote sensing data type classification, with particular attention given to hyperspectral imaging.

- The possibility of using remote sensing data was analyzed to estimate possible threats to communication routes from nearby dead trees. The studies were carried out in the

Polish part of Białowieża Forest. Three different variants of remote sensing data integration with other spatial data were analyzed in the paper. In the first variant, multispectral images classification results were used exclusively. In the second variant, the classification information was combined with information on trees' height from a digital forest map. In the third variant, the classification results were integrated with the results of airborne laser scanning data segmentation. The purpose of data integration was to combine information on the location of standing dead trees with the information on their heights. As a result, it was possible to assess whether a tree standing near a communication route would cause a real threat if it fell down in that direction. The analysis showed that the most reliable data, which enabled the assessment of possible risk to communication routes from the side of standing dead trees, was the information where airborne laser scanning data was used. Apart from specifying the exact location of those trees, it was also possible to indicate the ones which threaten the larger number of routes. The results of studies were implemented in practice by the General Directorate of the State Forests.

Stereńczak K., Kraszewski B., Mielcarek M., Piasecka Ż. 2017. Inventory of standing dead trees in the surroundings of communication routes – The contribution of remote sensing to potential risk assessments. Forest Ecology and Management, 402: 76-91.

- The optimum spatial resolution of satellite images was investigated in view of their suitability for detection of dead trees. The studies were carried out in the area of Beskid Żywiecki, in Ujsoły Forest District. The basis for analyses was an airborne orthophoto of 0.5 m spatial resolution. For research purposes, multispectral images were simulated of the following field pixel dimensions: 1 m, 2.5 m, and 5 m corresponding to currently operating satellite systems (among others Pleiades, SPOT5, RapidEye). Some processing was performed on every image, which was the introduction to classification, and the supervised classification was further carried out. The results of classification were compared to data obtained as a result of visual interpretation of original output image. Ranges marked by the observer constituted references. It was stated as a result of studies that the worst results were achieved for an image of 5 m resolution. In the case of the smaller pixel value, the resulted accuracy was very good i.e. around 90%. The analyzed phenomenon of spruces' dieback mainly refers to older age classes. Taking a pixel size into account, the achieved accuracy, and the investigated phenomenon, it was stated that the pixel size at the level of 2.5 m is sufficient to identify dead trees. The value complies with the detection theory stating that the size of a searched subject should be approx. twice as large as the size of a pixel of the image used in such analysis.

  Pluto-Kossakowska J., Osińska-Skotak K., Stereńczak K. 2017. Determining the spatial resolution of multispectral satellite images optimal to detect dead trees in forest areas. Sylwan 161 (5): 395–404.

- The study investigated the dependency between the optimization of classification parameters of aerial images acquired with an UltraCam-D camera and the accuracy of tree crown detection in semi-desert areas of Zagros in Iran. Settings of the following algorithms were optimized: support vector machines (SVM), artificial neural networks (ANN), and object based image analysis (OBIA) using Taguchi method. Analyses revealed that the adopted method of optimization fulfilled the purpose, and it may be recommended for use in similar circumstances. The best classification results after the optimization were attained by object based image analysis (OBIA) method, as far as accuracy and precision, as well as specific purpose and individual nature are concerned. Other methods achieved slightly worse results.

Erfanifard Y., Stereńczak K., Behnia N. 2014. Parameter optimization of image classification techniques to delineate crowns of coppice trees on UltraCam-D aerial imagery in woodlands. Journal of Applied Remote Sensing 8(1), 083520. doi:10.1117/1.JRS.8.083520.

- Separate studies focused on the development of classification methodology basing on RapidEye (BlackBridge) remote sensing data, which will be used in the detection of bark beetle infected trees in the Sudety and the Beskidy mountains, where Norway spruce (*Picea abies* (L.) H.Karst) is a dominating species. Another issue verified in the study was the impact of a date when BlackBridge images were acquired on the accuracy of dead trees' detection. The classification was carried out of the following data sets created from the following respective channels: 2,3,4,5; 1,2,3,4,5; 5,4,3; 5,4,2; 5,3,2. Vegetation indices (NDVI, RENDVI) were also used for classification, which resulted in the following sets of classified data: NDVI; RENDVI; 4, NDVI, 2; 3, NDVIRE, 2. The highest accuracy of classification was achieved with the Maximum Likelihood algorithm. The season of year influences significantly the classification of imaging as regards stands condition assessment, as well as the separation of stand types. The highest accuracy in the classification of dead trees was achieved for satellite imaging coming from the summer period when a tree assimilation apparatus is fully developed. Spring and fall photographs enable correct classification of deciduous stands. The total accuracy of classified photographs for the study area from the year 2012 was 0.53, on average, and from the year 2013 - 0.69.

  Kycko M., Stereńczak K., Bałazy R. 2016. Detection of bark beetle infected trees with BlackBridge image on the example of the Sudety and the Beskidy mountains. Sylwan, 160 (9): 707-719.

- The extensive review of literature summarized current knowledge and the possibilities of using remote sensing data in tree species classification on different scales (tree group level, single tree level, and tree branches level). It was shown that the number of studies focusing on tree species classification had been constantly growing for the previous four decades. Several promising approaches may be found, which achieved high classification accuracies locally. Just a few examples of species classification were used for areas of large geographical extent. Tree species inventories over large geographic extents are still one of the greatest challenges of this research field. Furthermore, only a few studies systematically described and analyzed variables, which determine the variance in the remote sensing signal record and thereby enable or hamper species classifications. Most research works are local studies using specific data and focusing on achieving the best possible accuracy. The conclusion of the study is a need for further knowledge of classification process and understanding whether it gives worse results in certain circumstances.

  Fassnacht F.E., Latifi H., Stereńczak K., Modzelewska A., Lefsky M., Waser L.T., Straub C., Ghosh A. 2016. Review of studies on tree species classification from remotely sensed data. Remote Sensing of Environment, 186: 64–87.

- In the article, possibilities were examined in relation to species classification using hyperspectral data in a temperate zone. The purpose of the review was to examine current knowledge on the classification of forests in Poland. In the summary of the performed works, it was stated that atmospheric correction of hyperspectral data is not necessary. It was stated that the higher total classification accuracy was achieved when the number of used spectral ranges was limited. The highest accuracy of stand species classification is achieved by applying SVM (*Support Vector Machines*). Furthermore, the integration of hyperspectral data with ALS data may result in the improvement of classification accuracy. It was recognized that information, which is the most frequently used for this purpose, is tree height. It was proven that coniferous species are characterized by higher discernability. It was finally emphasized that the practical use of hyperspectral data requires further development of technology, a considerable decrease of prices and/or thorough economic analysis of profits resulting from the use of hyperspectral data in forest management. The study was the first one of this type in Poland.

  Wietecha M., Modzelewska A., Stereńczak K. 2017. Airborne hyperspectral data for the classification of tree species a temperate forests. Sylwan, 161 (1): 3–17.

Ad 3. Examination of selected tree and stand variables with use of unmanned aerial vehicle

The reason for which I separated a chapter related to the use of unmanned aerial vehicle (UAV) was mainly due to the fact that studies in this area are definitely of experimental nature. One may get the impression that in a sense the issues described in this section line up with the ones described above. However, the limits of UAV technology make it very specific, which distinguishes it from airborne and satellite materials. Civilian and commercial UAV technology has still very limited possibilities of forests' imaging (short flight time, problems related to the ability to start and land in large forest complexes, weather conditions), which significantly limits the ability to use them. On the other side, the height of flights and the detail level of acquired materials provide new opportunities that were previously unavailable with airborne or satellite sensing. The below described studies were carried out mainly with dr hab. inż. Krzysztof Będkowski, and were of pioneer nature in Poland. The experiences are described in the first section of the below review. Further, I give new experiences related to the attempt to use UAV to detect cones.

- The studies were carried out to evaluate the possibility of using non-metric multispectral digital photographs acquired by cameras carried by an unmanned aerial vehicle, to analyze selected dendrometric variables of trees in pine stands. The research works were performed in four stands in Uroczysko Głuchów, a part of the Experimental Forestry Station in Rogów, which belongs to Warsaw University of Life Sciences. During field works, the size of crown horizontal projection and breast height diameter was measured for 56 trees. Ortho-mosaics were used to vectorize (specify the range of) pine crowns, which were previously subject to on-site inventory. The vectorization was performed in two variants: by recording ranges of compact crowns, i.e. the ones without single protruding branches, and the whole crowns. The studies revealed that a relation between a breast height cross-section area measured in the field and a tree crown range vectorized on an ortho-mosaic showed high values of a determination coefficient R^2=0.78. The last phase of crown horizontal projection's analyses was comparing the results of vectorization with the measurement of breast height cross-section area in the field. A determination coefficient (R^2) was respectively: for the whole crowns 0.80, and for the compact crowns – 0.68. The studies revealed high quality of images performed from the low altitude, due to which the evaluation results were close or better than the simplified measurement in the field. The settled dependencies may be applied for the purpose of stand inventories e.g. in post-disaster areas or the areas which are difficult for field inventories.

Stereńczak K., Będkowski K. 2012. Evaluation of the ortho-mosaic obtained by unmanned aerial vehicle to determine selected dendrometric variables of trees in pine stands. Archives of Photogrammetry, Cartography, and Remote Sensing (Archiwum Fotogrametrii, Kartografii i Teledetekcji), vol. 24: 345-355.

- The purpose of the study was to present the idea of using the quasi-object-based method of images' classification for the classification of trees per species with imaging data acquired by unmanned aerial vehicle in the fall season. The investigated stands mainly comprised Scots pine, sessile oak, and single birch and red oak trees. A tree description feature was the mean value of crown image brightness (DN), which was estimated separately for every species and spectral range. Gathered data was further treated as signatures obtained from training fields in supervised classification. The ability to distinguish tree species with the proposed method of class standards (based on valued describing the whole crowns) was compared to multispectral pixel classification. It was stated based on the achieved results that the proposed quasi-object-based method would enable better distinction between species than the pixel method.

  Będkowski K., Stereńczak K. 2012. Outline of semi object-based analysis of multispectral aerial images and it's use to determine species composition of forest stands. Annals of Geomatics (Roczniki Geomatyki) X, 5(55): 19-26.

- The purpose of studies with the use of aerial photographs was to identify red oak individual trees and other species based on the digital analysis of selected spectral features of images taken by digital non-metric Sigma DP2 cameras, which took images in four spectral ranges: blue, green, red, and infrared. Cameras were carried by AVI-1 unmanned aerial vehicle. Pictures were taken on October 17, 2011. Two methods for the automatic recognition (classification) of photographs were tested: the minimum distance and the maximum likelihood. The best results were obtained for the classification of pine and birch respectively. The differentiation between red oak and other oaks was difficult due to the fact that in the final stage of the growing season it is spectrally very similar to sessile oak, with leaves colored in brown.

  Będkowski K., Stereńczak K. 2012. Recognition of Red oak Quercus rubra L. on aerial photographs taken in the final stage of the growing season. Proceedings of the Center for Nature and Forestry Education in Rogów (Studia i Materiały CEPL w Rogowie), 14., 4(33): 168-177.

- The studies focused on the use of aerial photographs to estimate phenological phases of fall discoloration of sessile oak leaves. The applied pictures were taken by digital non-metric Sigma DP2 cameras, which took images in four spectral ranges: blue, green, red, and infrared. Two observers performed visual classification of 556 oaks, based on a dominating color of trees, into three groups of crowns: green, yellow, and brown. As a result, it was stated that there was a great compatibility between observers (79.7%), therefore the phenomenon of the phenological variability of oak may be registered on the level of individual trees with the use of UAV.

Będkowski K., Stereńczak K 2013. Sessile oak (Quercus petraea (Mattuschka) Liebl.) trees variability according to an analysis of multispectral images taken from UAV – first results. Ecological Questions 17: 25-33.

- The study focused on the use of non-metric multispectral digital images acquired by cameras carried by unmanned aerial vehicle (UAVs) to assess the density of crown assimilation apparatus in Scots pine stands. Pictures were taken October 2011. During the field data acquisition, 272 pine trees were evaluated and classified into 10 classes based on the crown density. These results were compared with the average pixel brightness in four spectral channels B, G, R and IR, collected in three variants – the whole crown, the compact part of the crown (after so-called protruding branches have been eliminated), and the central part of crowns of 0.63 m radius. Studies have shown that brightness of images of tree crowns belonging to different defoliation classes varies. This especially refers to the class of trees with a very high degree of defoliation and dead trees. The degree of stabilization can be observed in class 5, which means that a further increase in crown density does not increase the spectral reflectance.

  Stereńczak K., Będkowski K. 2013. Assessment of the Scots pine (Pinus sylvestris L.) crowns density based on multispectral images obtained by unmanned aerial vehicle. Ecological Questions 17: 89-99.

- The studies on the application of data acquired by unmanned aerial vehicle to evaluate the abundance of cones were of a trial nature. So far, the Authors have not found any other published studies which would deal with a similar subject. First, a decision support system was analyzed and planned, whose purpose would be the support of an assessment process of seed crops, and the development of an application that would allow for the distribution of available seed bases within the seeding regions. Another purpose of the study was to verify the ability to use unmanned aerial vehicle to assess the number of cones on a single tree depending on a tree crown imaging manner. As a result, it was proven that diagonal images are best suited to assess the number of cones on individual trees. Orthogonal pictures taken from above the trees are characterized by a large systematic error. However, they are much easier to acquire. We have also indicated the need for further studies, in particular, with the use of picture blocks from the same area.

  Stereńczak K., Mroczek P., Jastrzębowski S., Krok G., Lisańczuk M., Klisz M., Kantorowicz W. 2016. UAV and GIS based tool for collection and propagation of seeds material – first results. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B8, 663-667.

Since 2011 (when I was awarded a Ph.D. degree), I have been an author and co-author of 19 papers indexed by Thomson Reuters (a journal from List A of the Minister of Science and Higher Education/MNiSW), 13 papers from List B of MNiSW, 2 monographies, 10 chapters in monographies, and 14 popular-science papers. Papers were quoted (before December 20, 2017) 67 times in Web of Science Core Collection database, Thomson ReutersTM (H-index = 5). The total Impact Factor of papers published by me, as per their publishing year (after 2011), is 26.670. The total number of points, according to MNiSW scoring, achieved since 2011 is 611. In addition, the total Impact Factor of articles published by me, without taking account of the series (after 2011), is 22.208, and the total number of points according to MNiSW scoring is 511.

My research/scientific achievements have been recognized, among others, by:

- The Minister of Science and Higher Education through granting me a scholarship for outstanding young scholars in 2015,
- Director of Forest Research Institute through granting me a 2nd degree annual award for scientific publications with the affiliation of Forest Research Institute in 2014 and 2016,
- The Rector of Warsaw University of Life Sciences – SGGW through granting me the 2nd Degree Individual Award for scientific achievements in 2011,
- Council of the Faculty of Forestry, who honored my doctoral dissertation in 2011.

In 2016, Forest Research Institute was granted the Polish Intelligent Development Award (*Polska Nagroda Inteligentnego Rozwoju*) in category: Research Units (*Jednostki Naukowe*). The performance of the above described projects was recognized: REMBIOFOR "Remote sensing based assessment of woody biomass and carbon storage in forests" and LIFE+ ForBioSensing PL project "Comprehensive monitoring of stand dynamics in Białowieża Forest supported with remote sensing techniques".

Since 2011, I have presented the results of studies at various national and international conferences, seminars, and workshops (the total of 118 presentations, including 38 oral (including 13 at international conferences), 26 posters (including 8 at international conferences), and 54 other speeches (including 12 at international meetings)).

My expertise was recognized and used, among others, in the works of a task performance team for the development of guidelines for using remote sensing techniques in the State Forests, appointed by the General Director of the State Forests (Decision No. 56 of July 31, 2012 of the General Director of the State Forests). The purpose of the team was to develop guidelines, which would specify terms of processing and interpret remote sensing data (aerial, satellite, and terrestrial photographs taken in different techniques and spectral ranges) referred to forest areas' analyses. In addition, I was a co-author of the "Recommendation regarding the acquisition, processing, analysis and use of LIDAR data in order to identify archaeological heritage resources under the AZP program" commissioned by the National Heritage Institute.

I endeavor to participate in initiatives of broader geographic extent. I am a member of the Global Forest Biodiversity Team – the international team of scholars dedicated professionally to studies on biodiversity of forest communities and mechanisms that shape them globally. I am also a member of The Forest Observation System – an international cooperation to establish a global in-situ forest biomass database to support satellite earth observation systems. In addition, due to my involvement, data from LIFE+ ForBioSensing project was used for the calibration of Global

Ecosystem Dynamics Investigation Lidar (GEDI) – a satellite laser scanning system developed by NASA to monitor the directions and changes in forest ecosystems globally.

Apart from the scholarship prior to the award of a Ph.D. degree, I have also extended my knowledge during a short-term trip abroad to the Swiss Federal Research Institute WSL in 2013. In addition, except for training related to management, I attended 13 courses to develop my competences in relation to broadly understood geomatics and statistics.

In addition, my knowledge and experience were also used during training courses, which I conducted for forest administration and companies dealing with forest inventory, on the application of remote sensing information in nature analyses.

Since 2011, I have written 34 reviews of research studies and abstracts for scientific journals, including those indexed by Thomson Reuters™, i.e.: Canadian Journal of Forest Research (1), Scandinavian Journal of Forest Research (1), Remote Sensing (3), IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (1), Computers and Electronics in Agriculture (1), European Journal of Remote Sensing (1), Forest Systems (1), Dendrobiology (1), Folia Forestalia Polonica Series A-Forestry (7), Folia Geographica Socio-Oeconomica (1), Acta Scientiarum Polonorum series Geodesia et Descriptio Terrarum (1), Forest Research Papers (Leśne Prace Badawcze) (1), Miscellanea Geographica (1), Annals of Geomatics (Roczniki Geomatyki) (1), Archives of Photogrammetry and Remote Sensing (Archiwum Fotogrametrii i Teledetekcji) (2), Proceedings of the Center for Nature and Forestry Education in Rogów (Studia i Materiały Centrum Edukacji Przyrodniczo-Leśnej w Rogowie) (1), Environment Remote Sensing (Teledetekcja Środowiska) (1), and The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences – abstracts (8).

I have always attempted to be an active member of research organizations. I was a member of the audit commission at the Club of Remote Sensing of Environment, Polish Geographic Society (Klub Teledetekcji Środowiska Polskiego Towarzystwa Geograficznego), as well as a secretary of IUFRO TF Education in Forest Science in the years 2011-2014, and a chair (Chair: 2016-2020) and a co-chair (Co-Chair: 2012-2016) of the following work groups respectively: V/5 and VI/5 at the International Society for Photogrammetry and Remote Sensing (ISPRS Working Group respectively V/5 and VI/5).

I am a supporting academic supervisor of five doctoral students i.e.: A. Modzelewska, M. Mielcarek, T. Hyczy, M. Ciesielski, and A. Olpenda, whom I support with my experience and knowledge together with professors of recognized scientific standing in Poland i.e.: dr hab. Krzysztof Będkowski, prof. at the University of Lodz, and prof. dr hab. Tomasz Zawiła-Niedźwiecki.

The results of my projects have been presented, among others, on the radio and television, as well as in local and national magazines, such as TV Białystok, Radio Białystok or Puls Biznesu.

Organization and teaching activity

During my studies at the Faculty of Forestry, Warsaw University of Life Sciences – SGGW, I was a year group representative and a leader of Student Government at the Faculty of Forestry. I participated actively in the works of the Scientific Research Group of Forestry Students.

During my doctoral studies, I worked to the benefit of science and doctoral students' environment at Warsaw University of Life Sciences – SGGW. I held the position of a member and a leader (2008-2010) of Ph.D. Students' Council at SGGW. I was, among others, a member of the Rector's Grant Committee and a member of Audit Committee at the national organization representing doctoral students i.e. National Representative of Ph.D. students (Krajowa Reprezentacja Doktorantów) (2009-2010). I was involved in organizing several scientific conferences, among others, due to my commitment, the Faculty of Forestry at Warsaw University of Life Sciences – SGGW was granted a right by the International Society for Photogrammetry and Remote Sensing to organize in 2009 a prestigious undertaking, i.e. the International Summer School, combined with the Scientific Conference. In the years 2008 -2012, I was a co-chair of the student organization operating within the International Society for Photogrammetry and Remote Sensing Student Consortium.

Within the framework of my doctoral studies, I conducted academic courses at the Faculty of Forestry, GIS and Spatial Management Post-Graduate Studies at SGGW: Introduction to Photogrammetry and GIS, Photogrammetry and GIS, Remote Sensing and Photogrammetry, Geomatics, Spatial Information Systems and Information Technologies.

After I was granted a Ph.D. degree in forest sciences in 2011, I conducted various academic courses in the Polish and the English language for full-time and extramural students, at Forestry and Land Management Programs on the following subjects: "Introduction to Photogrammetry and Spatial Information Systems", "Photogrammetry and Spatial Information Systems", "Forest Geodesy and Spatial Information Systems", "Photogrammetry and Remote Sensing", "Geomatics in Forestry", "Information Technologies", "Management of Nature", "TLS in Forestry", and "Contemporary Remote-Sensing-Based Inventory Methods"(special module) – Forest Information Technology". Since the award of a Ph.D. degree in forest sciences, I have been a supervisor of 5 master's theses and 1 engineer's thesis at the Faculty of Forestry, Warsaw University of Life Sciences - SGGW. In addition, I was the second supervisor of a master's thesis at AGH University of Science and Technology in Kraków, and 1 diploma thesis at the Military University of Technology.

I have also developed my expertise through organizing conferences and summer schools. I organized and co-organized 4 conferences (including 1 international - EARSeL 3rd Workshop SIG on Forestry, on September 15-16, 2016 in Kraków, Poland) and 6 international summer schools in Poland, the United States, and Turkey. I was a chairman of the Organizing and Scientific Committee of 1st International Scientific Conference of LIFE+ ForBioSensing PL Project Comprehensive monitoring of stand dynamics in Białowieża Forest supported with remote sensing techniques titled: "Current condition of Białowieża Forest based on the first results of ForBioSensing LIFE+ project". I was also a chairman of the Organizing Committee and a Member of Scientific Committee of the conference: "Cultural heritage in the Białowieża Forest, research state, and prospect".

Since I derived great satisfaction from working with students, I was actively involved in works of students scientific research groups at the Faculty of Forestry, Warsaw University of Life Sciences – SGGW i.e.: Research Group of Foresters, whose I was a tutor in 2010 and 2011, and Spatial Management Research Group.

I am involved in the works of the Forest Research Institute. Apart from active promotion of the Institute in different fields (Earth Days, Science Festival), I am a Member of Scientific Council at Forest Research Institute and a member of Science Committee within its framework.

Sękocin Stary, December 20th 2017

Krzysztof Stereńczak