Extended methods of automatic processing of multispectral airborne images of forest stand

S. Šumbera

Mendel University of Agriculture and Forestry, Faculty of Forestry and Wood Technology, Brno, Czech Republic

ABSTRACT: This study deals with the application of sophisticated methods of airborne multispectral images with high spatial resolution to describe the forest stand of Josefov valley. Quite a large part of suggested methods was extended and developed. The study determined the possibilities of polynomial transformation of four bands from MSK 4 camera to the identical position and use of subtractive color model according to the proposed sequence of channels to display a synthesis of these channels in natural colors. Classification of tree species was proposed for application by soft classifiers in Idrisi system. The edge detection method in gradient direction was improved by the iterative morphological operations to detect object boundaries as well as the methods of preliminary tree top and crown detection were applied and improved.

Keywords: remote sensing; aerial photographs; tree detection; image processing; anisotropy diffusion

The needs of forest inventory concerning the most accurate and objective characteristics of forest ecosystem are generally known. Multispectral images are sources of information on the landscape for forest planning. Nowadays their application under current conditions is bounded by both the visual interpretation and by the computer supervised and unsupervised classifications. There is no doubt about the methods being suitable for the needs of forest planning because of their objective resultant information (it means information without witness's personal evaluation) on the forest stand.

Images with high spatial resolution can provide further detailed information on the texture, shape, area, and mutual influence of the particular tree crowns and thus contribute to the high-quality processing and investment valorization of the image acquirement. A basic unit for this information is just an individual tree whose visual, automatic or semiautomatic identification serves as a key for approximation of the real tree characteristics.

Operators dealing with data obtained from remote sensing in current working conditions are often limited in their image processing work by the use of commercial software that offers only basic algorithms of image data processing. There are no special methods for forest images at their disposal, such as tree top or crown detection, special edge detectors, etc. The situation is caused by the algorithm nature representing an intelligence property and a form of expertise for the subject or the cost of implementation of these technologies is too high for common users. This was the reason to implement some of these algorithms into a software product that would facilitate tree top and crown detection as well as other processing steps being rarely available by common software.

The aim of this paper is to present and apply advanced methods for image processing especially designed for the needs of forest planning, such as edge detection, tree species recognition and individual tree top and crown estimation.

MATERIAL AND METHODS

The selected area was situated in the northern part of the Josefov valley reservation called Purkyně reservation and adjacent northern part of the forest stand. The locality is situated 5 km to the north-east of Adamov and in the locality represented by deciduous forests of the protected natural area Moravian Karst. A major part of the area is represented by the formation of 4D3 *Fageta dealpina*, 1CD3 *Corni-acereta campestris* and 3BC3 *Querci-fageta tiliae-aceris*.

The presented paper conforms to research aims of the Faculty of Forestry and Wood Technology, Mendel University of Agriculture and Forestry, Brno, No.434100005 (Ministry of Education, Youth and Sports).

Table 1. Basic properties of MSK4 camera sensor (ŠMIDRKAL 1989)

Half of the view angle (°)			F	Negative dimensions	Number of bands
α_x	α_y	α_{max}	(mm)	(mm)	
12.43	17.93	21.37	125	55 × 80	4

Table 2. View of the spectral bands of the MSK 4/II camera

Channel	Spectral band name	Wavelength (μm)	Filter (nm)
1	Blue	0.460–0.500	480
2	Green	0.520–0.560	540
4	Red	0.640–0.680	660
6	Near IR	0.790–0.890	840

Airborne images were made for Nature Protection Agency on 23. 7. 1990 in the daytime at 12.45–14.30 at the flying height of 4,500 m with forward 60% and lateral 30% overlap. The area was scanned in four spectral bands by MSK4 camera sensors. Tables 1 and 2 show the basic data on the camera. Due to this scale, the area covers 2.75 km^2 (1,375 m × 2,000 m). The area size without overlap is 0.77 km^2 (550 m × 1,400 m) and covers 28% of the total image surface. The northern part of Josefov valley is one square kilometer in size, Purkyně reservation takes 0.5 km^2 and is situated in the just forward overlap of scene number 535 28 and 535 29.

TRANSFORMATION AND COLOR SYNTHESIS

Each image of spectral band was digitized in spatial resolution of 600 dpi and intensity resolution of 256 levels of gray. In such resolution, there were approximately 90–120 pixels per one crown. Individual channels were transformed into identical position because of distortion of spectral cameras of MSK 4 sensors. Channels No. 4, 1, 6 were transformed into the position of channel No. 2. To fulfill this task projective and polynomial transformation of the third order was used with the nearest neighbor interpolation. The first one, projective transformation, requires six reference points at least and it does not compensate distortion caused by the area relief and camera lens displacement. The second one, polynomial transformation of 3rd degree, takes 10 reference points at least. It is suitable for distortion compensation caused by the area relief and camera lens displacement. If such a transformation takes place, a regular grid of reference points needs to be placed to avoid image distortion due to the higher order polynomial transformation effects.

The Descartes software for MicroStation was used for the transformation process due to the high performance features. The number of reference points was visually estimated to be between 15–20 locations regularly placed in the transformed area. Transformation accuracy was calculated according to the root mean square:

$$RMS(xy) = \sqrt{\frac{\Sigma(\Delta x^2 + \Delta y^2)}{(n-k)}}$$

$$\Delta x^2 = (x_1 - x_{orig})^2$$

$$\Delta y^2 = (y_1 - y_{orig})^2$$

where: x_1, y_1 – computed horizontal and vertical coordinates according to the transformation model,
x_{orig}, y_{orig} – horizontal and vertical coordinates of the original reference points,
n – number of reference points,
k – minimum number of reference points for transformation model.

COLOR SYNTHESIS

Color synthesis is an important part of the image pre-processing for the creation of training sets and multispectral classification. The number and type of synthesis components represent the number of spectral channels in the primary phase, and in the next one there can be some transformation channels of different modifications, for example vegetation indices, images from principal components analysis, etc. The Adobe Photoshop tool was used for color synthesis from the transformed images providing a suitable environment for image manipulation and visual interpretation. This platform makes it possible to create all possible combinations of the four channels in the RGB additive color model and provides a tool called Filter Factory for script programming. To this point a simple script for quickly changing the RGB channel order was developed for color synthesis variations. But the RGB color model can be composed of three bands only. To avoid this limitation of four channel images a subtractive color model CMYK was proposed together with subsequent transformation into RGB model. There is a review of all formed color models in Table 3.

VEGETATION INDICES COMPUTING

Once chlorophyll degenerates, its light absorption decreases in the red and near infrared bands causing yellow and red pigments to dominate. This is the opposite of the

Table 3. Review of the multispectral image color synthesis

• RGB synthesis

	Description	R	G	B
NAT I	Natural colors	4	2	1
NAT II	Health state synthesis	4	6	(1)
FALS I	False color	6	2	1
FALS II	False color synthesis II	6	2	4

• CMYK composition

	Description	C	M	Y	K
NAT III	Natural colors	4	6	1	2

reason for the increasing light reflectance in the band of 0.68 μm when defoliation takes place. Hence we use the 0.66 μm band as a red channel in RGB color model and 0.84 μm band in the green one; the increasing damage of trees causes a lower amount of the green component while increasing the red one (FAIMAN 1986). This principle forms a basis for vegetation indices computing. Their use is reduced by the spectrum variability of objects, which is caused by the factors of exposure, slope, illumination etc. Vegetation indices allow to discern vegetation from non-vegetation objects. This is the way to create a mask covering the vegetation only to make a classification process more precise. To fulfill this task a special script was formed in the Filter Factory environment to compute modified normalized vegetation indices according to the following equation:

$$VI_2 = \frac{(NIR - RED) \cdot S}{(NIR + RED) + A} + L$$

where: *NIR*, *RED* – channels No. 6 and 4.

The process of modification is based on the addition of the constants *S, A, L* for variable extension of brightness rate in the output image.

EDGE DETECTION

The edges represent both the boundaries of the current object demarcation (for example road construction) and a significant primary division of image segments. Edge detection and processing may optimize the whole classification process as well. Besides the specific spectral reflectance a closed segment boundary can provide some other characteristics, for example symmetry, orientation, texture characteristics, length of boundary, etc. and thus it contributes to the process of classification *per region.*

Edge detection was subdivided into three stages:

1. Image smoothing
2. Edge detection
3. Edge arrangements

1. Image smoothing by diffusion

A raw captured remote sensed image contains a number of minute edges being of no significance for detection on a certain scale. Therefore different degrees of Gaussian image smoothing are often used to reduce detail unnecessary information. A disadvantage of such linear filters is however a smoothing of important edges too. This paper benefits from the new anisotropy diffusion smoothing presented in the paper of MALIK, PERONA (1990). They proposed the anisotropy diffusion filter as a diffusion process that encourages intraregion smoothing while preserving interregion smoothing. They suggested the following equation in which the conduction coefficient *c* is not constant in space, but it is a function of the magnitude of the intensity gradient of the image:

$$\frac{\partial}{\partial t} I(x,t) = \nabla \cdot \Phi(x,t)$$
$$\Phi(x,t) = c(x,t)\nabla I(x,t)$$
$$c(x,t) = f\left(|\nabla I(x,t)|\right)$$

where: *I(x,t)* – the image,
x – refers to the image axes,
t – refers to the iteration steps,
Φ (x,t) – the flow function,
c(x,t) – the diffusion function.

By this process the amount of diffusion at each point in the image space is modulated by the function *c(x,t)* and the image gradient at that point. They choose to make *c(·)* a monotonically decreasing continuous function of the image gradient magnitude. Evaluation of this function in a moving window process makes it possible to define a smoothing amount for the central pixel according to the diffusion results of the eight closest neighboring pixels. An exponential function was used in this study as a decreasing function, but an inverse function of image gradient could be used as well:

$$c_1(x,t) = \exp\left(-\left(\frac{|\nabla I(x,t|}{K}\right)^2\right)$$

$$c_2(x,t) = \frac{1}{1+\left(\frac{|\nabla I(x,t|}{K}\right)^{1+\alpha}} \,|\, \alpha > 0$$

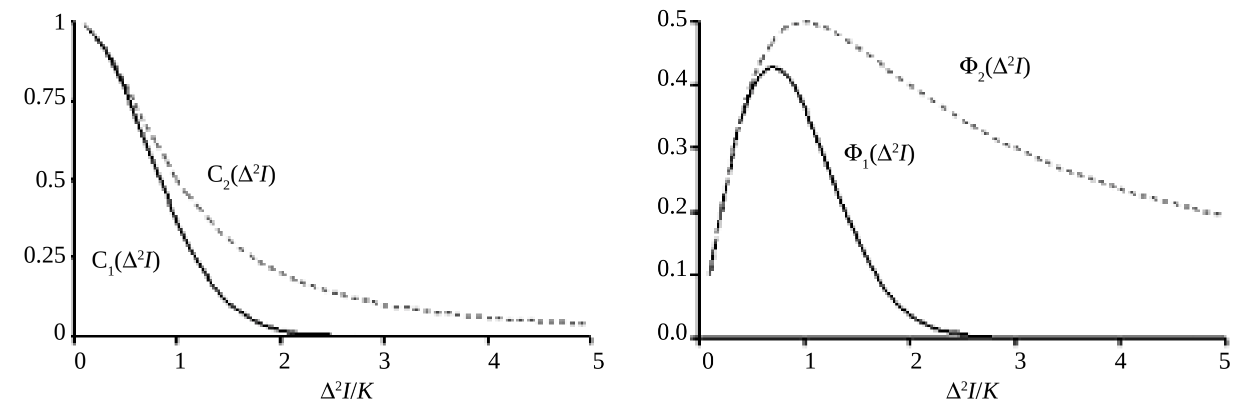

Fig. 1a) Dependence of the diffusion function on the image gradient. 1b) Dependence of the flow function on the image gradient

K is referred to as the diffusion constant. The function increases with the gradient to the point where $|\nabla I| \cong K$, and afterwards it decreases to zero. This function behavior implies that the diffusion process maintains homogenous areas where $|\nabla I| << K$ since the flow function is small in sections where $|\nabla I| << K$.

The highest flow is reached when the image gradient magnitude approximates to the value of K. Hence the coefficient K is applied to reflect to gradient magnitude produced by noise. The diffusion process can be used to decrease noise in images.

In this study a discrete implementation of the anisotropy diffusion was derived according to (GERIG et al. 1992):

$$I(t + \Delta t) = I(t + \Delta t \frac{\partial}{\partial_T} I = I(t) + \Delta t(\Phi_e - \Phi_w + \Phi_n - \Phi_s)|$$
$$\Delta t < -1$$

where: $\Phi_e, \Phi_w, \Phi_n, \Phi$ – denominate a flow function for pixels located in the n directions from the central pixel,
Δt – the integration constant.

To compute diffusion implies the increment of pixel flow located in the neighborhood of the processed pixel (Fig. 2).

2. Edge detection

The goal of the edge detection is to determine the pixels in the image in correspondence to the object boundaries seen in the captured scene. It is natural to define the edges as those points where the gradient magnitude assumes a maximum in the gradient direction. Thus the edges are defined by a differential geometric approach (LINDBERG 1993), also known as non-maximum suppression. For the purpose of the method explanation, it is possible to consider, for instance, an ideal tree crown in the sphere or cone shape supposing the illumination is vertically perpendicular to it. Then the tree crown is built up of isosurfaces (contours) gradually increasing from the tree top center. Next we introduce a new orthonormal coordinate system *(u, v)* at any image point where v-axis is parallel to the gradient direction of the pixel intensity L at the given point, and u-axis is perpendicular to it. It means u-axis is almost parallel to the tangent of the corresponding isosurface (Fig. 3):

$(\cos\alpha, \sin\alpha) = (L_{x,} L_y) / (L_x^2 + L_y^2)^{1/2}$.

The local directional derivative operators in this curvilinear coordinate system are as follows:

$\partial_{v'} = \cos\alpha\, \partial_x + \sin\alpha\, \partial_y$; $\partial_{u'} = \sin\alpha\, \partial_x + \cos\alpha\, \partial_y$.

At an arbitrary image point the gradient magnitude is equal to $\partial_v L$, marked as L_v below. The edge can be iden-

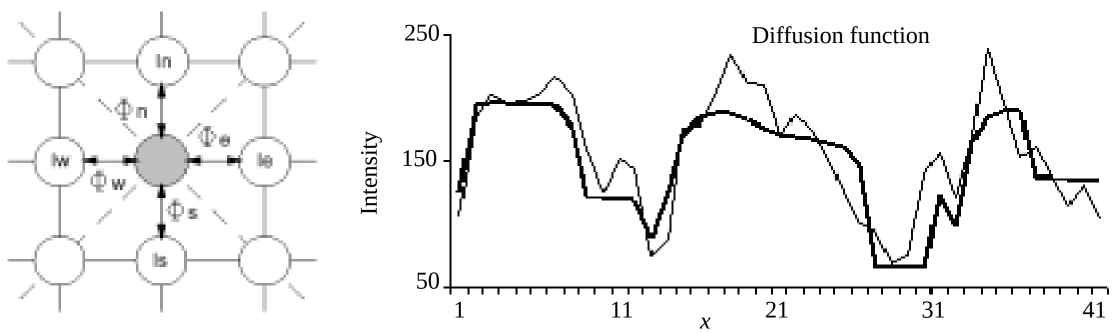

Fig. 2. On the left: A dependence of the computing of central pixel diffusion in the moving window on the value of the flow function of neighboring pixels. In, Iw, Ie, Is are the intensities of the adjacent pixels, adopted by GERIG et al. (1992). On the right: 1D diffusion function demonstration (a bold line) $K = 6$, $\Delta t = 0.1$, by 100 iterations

tified as a point, the first derivation of which in the gradient direction reaches the maximum (L_v = max), the second one is zero ($L_{vv} = 0$) and the third one is negative ($L_{vvv} << 0$). Here L_{vv} or L_{vvv} is computed as a result of transformation from curvilinear system to Cartesian system:

$$L_{vv} = \frac{L_x^2 L_{xx} + 2L_x L_y L_{xy} + L_y^2 L_{yy}}{\left(L_x^2 + L_y^2\right)}$$

$$L_{vvv} = \frac{L_x^3 L_{xxx} + 3L_x^2 L_y L_{xxy} + 3L_x L_y^2 L_{xyy} + L_y^3 L_{yyy}}{\left(L_x^2 + L_y^2\right)^{\frac{3}{2}}}$$

where: L_x, L_y and their combination – the derivation in the x,y directions.

Two passes of the moving window process realize edge detection. In the first pass the derivation values are calculated and in the second one an image gradient value is only displayed in areas satisfying the criteria mentioned above. Thus output edges from the process are marked by one of the 256 brightness values corresponding to the gradient magnitude rather than to be displayed only as binary image. In such a way significant edges can be detected easily from those of less importance, for instance by the method of thresholding.

3. Edge arrangements

The edge segments obtained by the differential geometric approach are obviously very often discontinued due to the heterogeneous nature of their adjacent regions. Then the complete object boundary delineation consists of composition of the different edge gradient values. This is the reason why the threshold method cannot detect the object boundary entirely. Thus morphological and conditional operators were introduced to be used in task of continuous object boundary linking:

- Joining nearly linked pixels;
- Removing small, isolated groups of pixels;
- Morphological thinning until the remaining edges are only one pixel wide;
- Optionally systematically removing the unconnected segments.

Joining nearly linked pixel is based on the filling of the gaps located between single pixels in eight directions counting the central pixel in the moving window. Morphological thinning is based on the binary comparison of structural elements sequence $B_{(i)} = \{B_{i1}, B_{i2}\}$ with the image where i signifies a sequence and B_1 is a subset of X (image objects) and B_2 is a subset of X^c (inversed image, it means the background). In the spot of coincidence of a structural element and the image, reducing by one pixel takes place. For one sequence, it is possible to express the operation in the following way (HLAVÁČ, ŠONKA 1992):

$$X \otimes B = (X \ominus B_1) \cap (X^c \ominus B_2)$$

$$X \ominus B = X \,|\, (X \otimes B)$$

where: $\ominus$ – morphological erosion,

$\ominus$ – morphological thinning,

$\otimes$ – means binary comparison (or hit or miss operation).

AUTOMATIC CLASSIFICATION

For the needs of supervised classification and for assessment of classification accuracy the training sets were taken on areas representing individual major object classes: Norway spruce *(Picea abies)*, Scots pine *(Pinus sylvestris)*, eastern larch *(Larix decidua)*, sessile oak *(Quercus petraea)*, crested beech *(Fagus sylvatica)*. Signatures were created based on spectral characteristics of those training objects for supervised classification. Idrisi system with applied signature formation facilitates advanced fuzzy signature creation. This process provides better understanding of object nature as well as a new concept of signature creation. A traditional way defines the signature as a spectral representative of the only one and unique object, while fuzzy signatures allow the creation of inhomogeneous signatures with relations to other objects. The following classifications were undertaken over the processed area of interest. The Idrisi module names are in the parentheses:

1. Unsupervised classification (CLUSTER, ISOCLUST)
2. Maximum probability basic classifier (MAXSET)
3. Supervised hard classification (MAXLIKE)
4. Supervised soft classification (BAYCLASS, BELCLASS).

While unsupervised and supervised classifications are commonly known, a very interesting role is played by a MAXSET hybrid classifier. Maximum Basic Probability Classifier belongs to the transition area between supervised and unsupervised classification. Although it is run as if it were a supervised classifier requiring training site data, in the end it behaves as if it were an unsupervised classifier because it can assign a pixel to a class for which no exclusive training data have been supplied (EASTMAN 1997).

The module is based on assigning the highest probability to the class involved in Dempster-Shafer theory of the class hierarchic structure. Dempster-Shafer theory defines the probability of an object occurrence in the area (hypothesis) according to the hierarchic structure derived from the basic frame of object resolution. The basic resolution can be an individual, relatively homogeneous entity such as spruce, pine, larch etc. Other objects under consideration are a combination of these basic classes, for example spruce-pine, spruce-larch etc. ranged in a hierarchic way. The complete hierarchic structure of these classes is taken into account by this classification using different class combinations. The classifier evaluates the probability of a pixel being in one of the classes defined in such a way. It can give rise to the image whose composition is formed not only by the classes defined in an unambiguous way but also by those classes the user did not consider thus providing information on missing training sites. MAXSET module belongs to the hard classifiers set but it can directly discern mixed pixels and this feature is one of the most important for an in-process classification assessment. Once a classification is processed, a very important step is to assess the percentage of occurrences of the composed classes. If the indicator is very high, it is necessary to find out whether all-important signatures have been defined and if they truly represent the object reflection. Post-classification arrangements run into the modal filter in Idrisi with a matrix of 5 × 5 pixels.

TREE IDENTIFICATION

Numerous theses were involved to the automatic crown identification mainly for forest management purposes. Among others essential methods need to be stated: POLLOCK (1996) proposed synthetic crown templates with respect to the crown shape and size, angle of sun illumination, and quantity of received and reflected light. These crown templates were then correlated to the forest image. LARSEN, RUDEMO (1998) enhanced the crown template to the camera scanner angle. GOUGEON (1995) adopted the method of tracing spectral minima located between crowns, known as "valley following". WALSWORTH, KING (1998) proposed to find the tree crown top as a union of "ridges" lines obtained by the double aspect technique in four directions. Tree crowns were estimated by the cost surface generation. CULVENOR et al. (1998) detected tree tops as the local brightest pixel and the region growing technique delineated tree crown. Similarly, DRALLE, RUDEMO (1996) understood the problem of tree top searching. Their activity lied in research on optimal image smoothing for tree counting providing best correspondence to the ground truth. BRANDTBERG (1999) studied the dependence of two-dimension variograms for texture detection and identified tree crowns by differential geometric operators. KORPELA (2000) determined tree tops from image stereopairs.

In spite of all the above mentioned the tree top and crown identification is still rather an unknown field in the current conditions of the Czech Republic. A set of basic methods for tree top identification was put forward in the present paper. No single algorithm is able to solve the complete task of tree finding and species classification (PINZ 1998). It is necessary to apply a hybrid approach of several stages. Based on these and other reasons mentioned in the introduction the majority of the methods were implemented to "Kernel Processor" (KP) software system forming a framework for tree identification. The problem of tree identification can be subdivided into two partial tasks:

a) Tree top searching,
b) Tree crowns delineation.

TREE TOP DETECTION

The main assumption for tree top identification is that the spectral reflectance (in the study only beech and spruce were considered) is higher than the rest of the crown and that the imagery was captured in the time of highest solar elevation. Under such conditions reflectance is decreasing downwards the tree top, thus the crown is presented in form of cone or oval shape. In such a way the tree top corresponds to the brightest crown point (NIEMANN et al. 1998) (Fig. 4). Tree crowns on high spatial resolution images usually do not represent ideal geometric shapes (spheres or cones) that could simplify tree top detection. This is the reason for the image to undergo homogenization by the smoothing process. Gaussian linear filter was applied to solve this problem.

The actual process of the tree crown searching was modified in this study. The main part of the algorithm is based on a filter in the moving window choosing the pixel with the brightest reflectance located in its center. In such a way, smaller or larger tree tops can be identified depending on the window size. The supplemental finer conditions were added to define the possible crown reflectance disproportion, for instance, an incorrect pixel in different places of an illuminated part of the crown. Furthermore, threshold values for the central pixel were determined to eliminate some amount of defectively demarcated crown tops. Finally, the algorithm enables to smooth the pixels outside the crown top:

$$\mathrm{S}\,f(p)\ \begin{cases} S\,f(p) = f(p) + K & max(q) <= f(p) \\ S\,f(p) = f(p) - K & min(q) => f(p) \\ S\,f(p) = G\,f(p) & \end{cases}$$

where: *max* – function for searching a pixel with maximum reflectance in the moving window,
min – function for searching a pixel with minimum reflectance in the moving window,

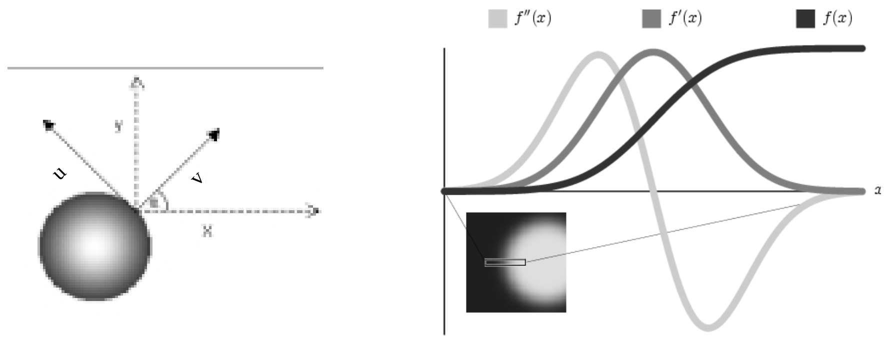

Fig. 3. Left: An orthonormal coordinate system *u, v* positioned on the outer isosurface (contour). Right: Relation of derivation to an edge, adopted from KINDLMANN, DURKIN (1998)

Gf(p) – function for smoothing, for example Gaussian smoothing,
f(p) – central pixel in the moving window,
f(q) – neighboring pixels in the moving windows,
K – constant to highlight a tree crown top.

Some tree tops might not be detected by the steps described, as either they lie in shadow, or their color properties do not match the given condition of the brightest central pixel. However, their number is quite low in comparison with tree tops detected by the above algorithm. An area-based template matching technique can look up such tree tops. This method determines the correspondence between a sample image (*t*) and the original image (*f*) according to the similarity of their gray level values. The sample (template) is derived from the original image where the tree tops were not yet identified. Thus this step is semi-automated. The size of sample image is either 3 × 3 or 5 × 5 pixels. The template matching between the sample and the compared part of the image is done by a normalized cross correlation formula:

$$\rho = \frac{\sum_{x,y}\left[f(x,y)-\bar{f}_{u,v}\right]\left[t(x-u,y-v)-\bar{t}\right]}{\sqrt{\sum_{x,y}\left[f(x,y)-\bar{f}_{u,v}\right]^2\sum_{x,y}\left[t(x-u),y-v)-\bar{t}\right]^2}}$$

where: f – the image,
Σ – the sum of pixel values computed according to the size and actual location of the template *t* positioned in *u, v* of the image,
$\bar{f}_{uv}$ – arithmetic mean *f(x,y)* at the place of the template actual location,
$\bar{t}$ – arithmetic mean of the template.

The values of relevant template matching should vary from 0.90 to 0.97 in locations where tree tops were found. The tree top was chosen from all correlation values using the method of the brightest pixel, it means the best correlation. In the case of duplicity in tree top identification a new filter was introduced performing duplicity removal. This filter application realized similarly by the moving window is based on the resultant image adaptation with special attention to the side effect of complementary conditions that can produce duplex tree top identification.

TREE CROWN DELINEATION

For the tree crown delineation the methods of spectral minima tracing and cost surface generation were adopted. The first one, also known as "valley following" (GOUGEON 1995), works as a filter in the moving window. In each processed area a procedure is run testing if the central pixel (i.e. the starting pixel for tracing) interferes with any neighboring pairs of minimum pixels. (In total four tests are run for horizontal, vertical, and two diagonal neighboring pixels.) If the condition is accomplished, the program recursively continues tracing in four main directions and tests and marks pixels using the same conditions. As the algorithms are incorporated into the moving window, all image pixels are tested as starting pixels for tracing. The individual steps of the entire process are outlined as follows:

1. Visual thresholding of image to separate the forest areas from the non-forested areas.
2. Scanning the image with 3 × 3 moving window to find local spectral minima.
3. For each found pixel to perform region growing for those areas satisfying the spectral minima criteria.
4. Joining nearly-linked crowns segments.
5. Morphologically thinning the image until the remaining crown segments are only one pixel wide.
6. Systematic removing of unconnected crown segments.

The second method of cost generation is linked to the preceding tree top detection. Located tree tops are used as a starting point for the crown filling, thus delineating its borders. For this filling a CostPush/CostGrow algorithm from the Idrisi for Windows software package was used. This algorithm uses a crown reflectance surface and calculates a cost distance surface. The movement from the tree top is realized in eight directions; it means that circular rings of distances are created around each tree top, depending on the (friction) crown surface (EASTMAN 1989). The output crown cost surfaces were then processed by the valley – following the above-mentioned algorithm.

IMAGE MANAGEMENT AND PROCESSING SOFTWARE DEVELOPMENT

The current software products facilitating remote sensing image processing result sometimes without any possibility to run special operations. The task of the user in such a case consists in further software development by him. Thus the software called "Kernel Processor" was developed for Windows NT platform, performing all necessary operations for the presented research. The software architecture is designed as complement enriching image processing operations and functions (e.g. Idrisi32 of the Clark Labs, Worcester, Ma). A basic module provides input/output operations into several image formats such as BMP, TIFF, and the format for Idrisi system – RST. The image processing functions are encapsulated into DLL libraries, which comply with a certain standard of the coding being similar to the user code applied in the ER-Mapper program. There is a user interface over this basic unit being able to cooperate with Excel office software and Idrisi system. Kernel Processor is a freeware; it can be installed without fee from an official page of the regional center IDRISI for the Czech and Slovak Republics or from the Links page of idrisi.com.

The management of raster data is maintained by the second developed application named Image Storage, providing the possibility to store raster files in Oracle database, allowing long transactions with the help of Workspace Manager and finally localizing raster positions using Oracle Spatial Cartridge. Workspace Manager provides a long transaction event framework built on

Table 4. Accuracy assessment of the channel transformation into the position of channel No. 2

Channel	Transformation Model	Number of points	STD X	STD Y	STD XY	RMS X	RMS Y	RMS XY
1	Polynomial-3	20	0.0564	0.1878	0.1801	0.1231	0.3769	0.3965
4	Projective	19	0.3113	0.3407	0.3388	0.5293	0.5384	0.7550
4	Polynomial-3	21	0.1378	0.1019	0.1187	0.3203	0.2398	0.4001
6	Polynomial-3	15	0.0214	0.0190	0.0264	0.6436	0.4857	0.8063

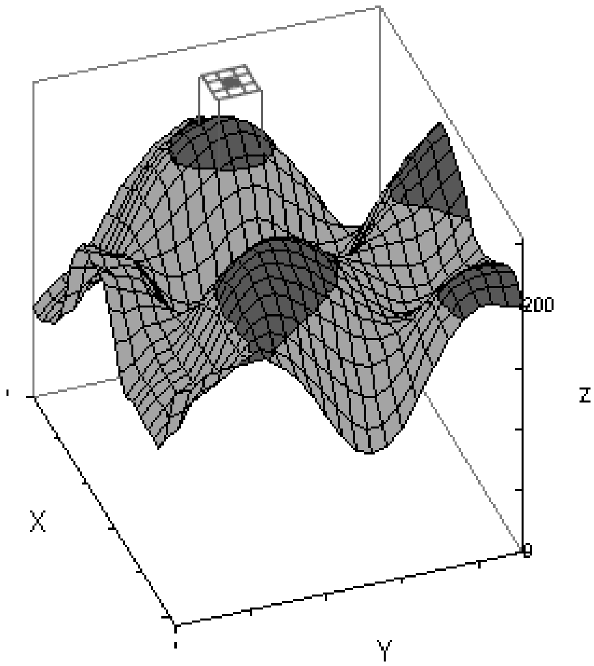

Fig. 4. Plot of image in 3D, where reflectance corresponds to *z*-axis. The moving window selects brightest pixels

the workspace management system. It uses a series of short transactions and multiple data versions to implement a complete long transaction event that maintains atomicity and concurrency (ORACLE 2001).

Both developed softwares were written in C++ language using MFC library, Visual Basic and Java.

RESULTS AND DISCUSSION

The accuracy of projective transformation using 19 reference points was acceptable from the visual point of view, but it is not the most accurate according to the root mean square (RMS). Therefore more accurate results from the polynomial transformation of the 3rd degree were used for further processing. In Table 4 both deviation indicator and RMS for particular transformed channels are shown being divided according to the axis. The lowest RMS was achieved by the first channel due to an easy identification of the reference points. A higher deviation in the sixth channel is on the contrary caused by a more difficult identification, for the sixth channel was of higher degree of brightness.

The color composition by a subtractive color model CMYK facilitated to make a synthesis out of all four channels. This untraditional way of synthesis turned out very advantageous for creating the training set with an observation possibility of object spectral characteristics in all four bands at the same time. Moreover, this synthesis allowed a natural visualization of objects in the image and provided a robust foundation for digital visual interpretation. The image quality of post-transformation of the CMYK synthesis into RGB color model did not lose quality and this transformation allowed to reduce four channels into three. This process presented a more natural way of visual interpretation and training set formation in comparison with channel number reduction by principal components analysis where the resulting components were not obviously radiometrically identical to the original channels. Computing of the normalized vegetation indices and synthesis of the state of health allowed to separate the vegetation cover from the non-vegetation land cover.

Detected edges by Laplacian operator of 9 × 9 pixels with subsequent threshold performance provided only rough boundaries of the main objects of the scene. Edge detection by a differential geometric approach especially in the gradient direction provided detection of more detailed object boundaries, but their discontinuity degraded the result. Therefore, other proposed operations of

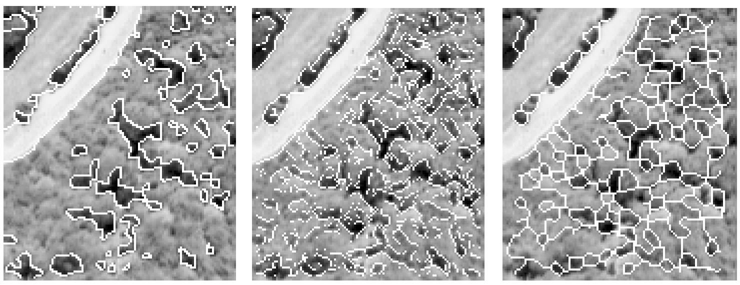

Fig. 5. Left: Detected edges by Laplacian operator of 9 × 9 pixels. In the middle: Edges detected by a differential geometry approach in gradient direction without arrangement. Right: Detected edges after proposed arrangement

morphological thinning, connection and elimination of small segments of the edges manifested to be useful for the final edge determination and achievement of a higher number of closed polygons (Fig. 5).

In the course of signature formation and spectral reflectance analysis in four spectral channels the larch class turned out to be difficult to be discerned from spruce. Neither was the separation of the oak signature from the beech one successful.

Unsupervised classification by ISOCLUST module facilitated the basic assessment of spectral groups of objects. These groups can be considered as basic objects of the image, suitable for further detailed identification, and can represent frames for basic object recognition for the MAXSET classifier. Results of this classification provided data of interest on the way of pine differentiation from spruce.

Hybrid classification by MAXSET module turned out very successful for the beginning of searching of different classes and for data acquisition on the assessed object signature accuracy. The resulting MAXSET classifier proved that the training sites for classes were well chosen because the representation of derived combinations reached only 6%.

BAYCLASS soft classifier tended to be the most accurate one based on Bayess theorem of probability. BAYCLASS reached 89% of success in the whole process of classification. Using this module it was possible to discern spruce with the classification accuracy of 98% and pine with 84%. In the case of particular classification of oak and beech the results get worse due to the different degree of crown reflectance, where some parts of the crown closure were overlapped in the spectral image. On the basis of the above mentioned, these two species were integrated in a mixed oak-beech class. This mixed class demonstrated 90% accuracy.

Generally, the whole classification by MAXLIKE module of maximum probability was of 87% and manifested only the slightest percentage of success compared with BAYCLASS module. The Larch indicated indiscernibility in the course of spectral reflectance characteristics. Thus this class was integrated with spruce.

BELCLASS classifier based on Dempster-Shafer theory did not bring about any significant differences in the accuracy compared with BAYCLASS and MAXLIKE ones.

Tree top detection based on the brightest pixel method tended to be very useful for tree crown identification. The image smoothing represents a very important feature. The main purpose of the crown smoothing is an approximation of the crown surface to a cone (in the case of spruce) or to a sphere (in the case of beech). Crown top searching with the use of iterative process proved to be very successful starting with the 7 × 7 pixels moving window which later diminishes to 5 × 5 and 3 × 3 pixels, followed by the process of further search refining according to the added conditions. The template method searching of tree tops provided solid foundations for generic tree identification. A disadvantage of the method consists in manual selection of tree crown samples from the input image serving as a template. The proposed highest correlation marking of resultant image allowed to identify those tree tops that were not identified by the previous method. According to the template size a preliminary tree crown size was set and delineated.

The accuracy of automatic detection of tree tops compared with manual detection depends on canopy thickness, tree species, image quality and smoothing quality. To assess the accuracy of the approach a subsample of the processed area, corresponding to approximately 10% of the entire area, was randomly selected. The locations of the individual tree crowns were manually interpreted within this area. A comparison of the two interpretations yielded a correspondence of 88–95%, depending on the crown density and tree size. After a visual revision and ground truth calibration the tree tops can be used for preliminary evaluation of the tree number per hectare in forest inventory. They can represent a starting point for further tree crown detection in this way.

Tree crown detection using the method of tracing spectral minima turned out to be a logical division of crown canopy. The divided canopy together with tree crown tops provides the basis for a detailed objective analysis of tree crown – it means analysis of both spectral and spatial characteristics. Thus image segmentation takes place where the proper segmentation process is *a priori* accommodated to the image scene character with a forest stand. For example it is possible to classify, cluster and create a layer of crown canopy for forest geoinfomation systems. It is worth paying attention to the relation between the edge detection, tree top and tree crown. If the tree top is formed by the brightest pixels and the crown contour is formed by the darkest ones, detected edges of tree crowns represent the highest changes in crown intensity from its darkest part to the brightest. Delineation of tree crown by means of crown cost surface production from its top was found to be a suitable method for assessment of the minimum surface the crown can occupy. The method depends on the full tree top detection (Fig. 6).

The problem for future development lies in assessment of the accuracy of image-based crown delineation algorithms. For this purpose special equipments like Field Map need to be used for ground truth estimation of the real crown shape.

Created applications were an important part of the whole project. Kernel Processor was a very successful and useful tool for verifying algorithms written in the user code. Compatibility of those codes with the user code of Er-mapper system facilitates to use the accessible algorithms of the system. A code architecture based on C code and user interface based on Visual Basic provides a quick environment for rapid application development. A negative feature of this application resides in unoptimized performance for large data amounts. Image Storage application is a prototype of hi-tech raster data management. Raster data storage in database via special database cartridge using a long transaction model and

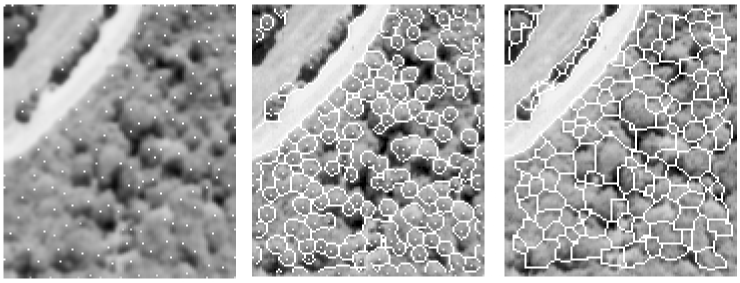

Fig. 6. Left: Detected tree tops. In the middle: Thresholded cost surface. Right: Crown delineation using the valley following method

spatial database operations for localization solved the problem of effective and safe image manipulation. Long transactions by Workspace Manager proved by its performance the suitability for image processing where it is possible to store individual stages of processed images in versioned tables. Oracle database in version 8.1.7. proved to be prepared for raster reading and storing directly from the database without any expressive time consumption compared to the file system.

CONCLUSION

This paper pointed out a possibility of extended processing of multispectral airborne forest images specially focused on edge detection and individual tree detection. Based on the presented results it is possible to draw the following conclusions:

- polynomial transformation provides more suitable results for misalignment elimination of MSK 4 multispectral camera than the projective one;
- a subtractive color model facilitates to make a synthesis of all four spectral bands in natural colors, being a valuable basis for training set selection and visual classification;
- normalized vegetation indices allowed to discern vegetation from non-vegetation objects, which is a promotion of successful picture segmentation;
- edge detection in the directional gradient of pixel intensities shows an applicable result of further morphological operation;
- it was not possible to classify larch successfully from a summer photograph. For larch classification it is obviously necessary to make a photograph during the spring season;
- separation of oak and beech classes was unsuccessful due to their common course of reflectance in all four channels and the characters of a mixture growth, so it was not possible to create a mask for only one type of species;
- automatic detection of tree crown tops by the method of the brightest pixel represents a significant contribution to tree number and location assessment. This detection should be supervised in a visual way or complemented by missing crowns and confronted with a real forest situation for example by GPS;
- crown delineation by tracing the spectral minima facilitates a logical segmentation of the image preparing the basis for more accurate object pixel classification,
- tree delineation by applied assessment methods constitutes a basis for further more convenient tree crown contours analysis;
- special image processing is hardly possible in the framework of the current software products for image processing; that is why it is necessary to apply these methods by help of the user's own experience. In order to fulfill this target it is possible to apply C/C++ programming language, providing quick processing and a possibility of using the resources of accessible library codes;
- any type of photographs (airborne or satellite) forms an important part of geoinformation systems. Thus the storage of all spatial data including its semantic characteristics will get on importance. We may also suppose that the long transactions in those databases will be essential for preserving the intermediate steps of image processing;
- the output of all steps of image processing results using these extended methods promises new possibilities of application of multispectral airborne images to the needs of forestry planning.

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Rozšířené metody automatického zpracování multispektrálních leteckých snímků lesních porostů

S. ŠUMBERA

Mendelova zemědělská a lesnická univerzita, Lesnická a dřevařská fakulta, Brno, Česká republika

ABSTRAKT: Studie se zabývá využitím a aplikováním rozšířených metod zpracování obrazu pro multispektrální snímky s vysokým prostorovým rozlišením na příkladu snímku lesního porostu Josefovské údolí. Významná část těchto metod byla rozšířena a naprogramována do vlastního softwaru. Studie poukázala na možnosti transformovat snímky z kamery MSK 4 do shodné polohy pomocí polynomické transformace a výsledné kanály sestavit podle navrženého pořadí do subtraktivního barevného modelu. Metoda detekce hran ve směru gradientu byla rozšířena o iterativní morfologické operace. Klasifikace druhového složení proběhla v systému Idrisi za použití měkkých klasifikátorů. Pro multispektrální snímek byla také navržena metoda detekce vrcholů a obrysů korun stromů.

Klíčová slova: dálkový průzkum Země; letecké snímky; detekce stromů; anizotropní difuze

Potřeba stanovení co nejpřesnějších a objektivních charakteristik lesního ekosystému pro lesnické plánování je obecně známá. Jedním z informačních zdrojů o území, které se při plánování používají, jsou letecké analogové multispektrální snímky. Tato studie navrhuje a aplikuje rozšířené metody zpracování těchto multispektrálních snímků, které mimo běžně využívané spektrální klasifikace spočívají v detekci hran, vrcholů a korun stromů.

Vybrané území pro zpracování leteckého snímku se nachází v severní části rezervace Josefovské údolí – rezervace Purkyňova a přiléhající severní část porostů. Lokalita se nachází asi 5 km na severovýchod od Adamova v listnatém porostu, který patří do CHKO Moravský kras.

Území bylo nasnímáno ve čtyřech spektrálních pásmech komorou MSK4/II v roce 1990. Negativy snímků byly digitalizovány s rozlišením 600 dpi při 256 odstínech šedi. Jednotlivé senzory kamery MSK 4 jsou nesouosé, proto byla věnována značná pozornost metodě geometrické transformace jednotlivých spektrálních kanálů do shodné polohy. Pro tento úkol byla navržena polynomická transformace za použití softwaru Descartes běžící na platformě MicroStation. Transformované kanály byly netradičně sestaveny do navržené sestavy v subtraktivní barevné syntéze, což přineslo možnost zobrazení všech čtyř kanálů místo tří kanálů, které se běžně používají v modelu RGB. Tento nový způsob syntézy se ukázal jako výhodný při tvorbě trénovacích množin, kdy byla možnost sledovat pohyb spektrálních charakteristik objektů ve všech čtyřech pásmech současně. Tato syntéza navíc umožnila přírodní zobrazení objektů na snímku, a tím i plnohodnotný podklad pro vizuální interpretaci

Významná diskontinua v intenzitách pixelů na zdigitalizovaném snímku se v této studii chápou nejen jako hranice běžně vylišitelných objektů, ale také jako ohraničení relativně homogenních segmentů snímku, které mohou mimo spektrální charakteristiky navíc poskytovat další informace, a tím významně přispět k procesu klasifikace *per region*. Pro snímek byla navržena metoda detekce hran ve směru gradientu intenzity pixelů spolu s vyhlazením metodou anizotropní difuze. Tato metoda umožnila stanovit detailní hranice, nicméně jejich diskontinuálnost velmi degradovala celkový výsledek. Z tohoto důvodu se navržené následné operace ztenčení, spojování a rušení malých segmentů hran ukázaly jako velmi přínosné pro stanovení konečných hran a dosažení většího počtu uzavřených polygonů. Nad snímkem proběhla detekce hran také pomocí Laplaceova operátoru o rozměrech 9 × 9 pixelů s následnou operací prahování. Tyto výsledky ovšem poskytovaly pouze hrubé obrysy hlavních objektů na snímku.

Spektrální klasifikace proběhla v systému Idrisi za použití jednak poměrně nových tzv. měkkých klasifikátorů založených na Dempster-Shaferově teorii (např. MAXSET, BELCLASS), jednak za použití klasických neřízených a řízených klasifikací. Výsledek neřízené klasifikace provedený modulem ISOCLUST poskytl zajímavé údaje z hlediska rozlišení borovice od smrku. Jako neodlišitelná dřevina se ukázal modřín, který průběhem odrazivostí v jednotlivých pásmech splýval se smrkem. Klasifikace modulem MAXSET se projevila jako velmi vhodný začátek pro zjištění neodlišitelnosti některých tříd a získání údajů o přesnosti definovaných signatur objektů. Výsledek klasifikátoru MAXSET prokázal, že definované trénovací množiny pro třídy byly dobře stanoveny, neboť zastoupení odvozených kombinací dosahovalo pouze 6 %. Neřízená klasifikace umožnila základní rozlišení spektrálních skupin objektů. Klasifikátor BELCLASS nepřinesl významné rozdíly v přesnosti oproti klasifikátoru BAYCLASS. Při klasifikaci se ukázal jako nejpřesnější měkký klasifikátor BAYCLASS založený na Bayesově teorému pravděpodobnosti, který dosáhl celkové 89% úspěšnosti klasifikace. Tímto modulem se podařilo odlišit smrk s přesností klasifikace 98% a borovici s 84% přesností. Výsledky jednotlivých klasifikací dubu a buku byly zhoršeny různým stupněm odrazivosti koruny, kdy část korun těchto dřevin se spektrálně překrývala. Z tohoto důvodu byly tyto dvě dřeviny sloučeny do třídy smíšení dub–buk.

Snímky s vysokým prostorovým rozlišením mohou mimo jiné podávat další informace týkající se textury, tvaru, rozlohy a vzájemného ovlivnění jednotlivých korun stromů, a tím přispět ke kvalitnějšímu zhodnocení investic do pořízených leteckých snímků. Základní jednotkou pro tyto informace je právě koruna stromu, jejíž ať už vizuální, automatická nebo poloautomatická identifikace je klíčem k aproximaci skutečných taxačních charakteristik porostu. Klasifikací jednotlivých korun stromů lze docílit také zpřesnění výsledků řízené klasifikace a vůbec zkvalitnění celkové segmentace obrazu. Pro detekci jednotlivých stromů byla navržena a rozšířena metoda nejsvětlejšího pixelu s použitím přídavných podmínek a metoda porovnání se vzorem následovaná výběrem nejvyšší korelace mezi vzorem koruny a snímkem. Kardinální význam pro úspěšnou detekci mělo prvotní vyhlazení snímku. Detekované vrcholy korun mohou být – po jejich vizuální revizi a doplnění o pozemní šetření – využity v lesnickém plánování pro předběžné zjištění počtu stromů na hektar. Dále mohou sloužit jako výchozí bod pro následnou detekci obrysů korun.

Pro detekci obrysů korun byly navrženy metody trasování frekvenčním minimem s následnou úpravou pomocí morfologických operací a metoda založená na vytvoření akumulačního povrchu koruny. Tyto detekce obrysů korun umožnily logicky segmentovat snímek, a tím připravit základ pro přesnější objektovou klasifikaci pixelů. Tyto prototypy obrysů korun mohou být východiskem pro zpřesnění reálného tvaru koruny.

Specializované zpracování obrazu není většinou v možnostech běžných softwarových produktů pro zpracování obrazu, proto je často nutné tyto metody aplikovat vlastními silami. Z tohoto důvodu byl vytvořen speciální software „Kernel Processor“, který umožnil jednotlivé algoritmy sestavit a realizovat v prostředí operačního systému Windows.

Snímky, ať už letecké, nebo družicové, jsou součástí geoinformačních systémů. Jestliže se v současné době uplatňuje ukládání prezentačních, sémantických a vektorových prostorových dat do databází, lze předpokládat, že význam ukládání a správy rastrových dat v těchto databázích také poroste. Dlouhé transakce hrají v těchto databázích významnou úlohu pro uchování jednotlivých stavů zpracování snímku. Pro tento účel byl vytvořen druhý nástroj s názvem „Image Storage“, který využívá nejmodernější technologie pro ukládání snímků do databáze Oracle s využitím dlouhých transakcí a prostorových operací pro lokalizaci. Oba produkty jsou volně šiřitelné a na vyžádání dostupné.

Výsledky ze všech procesů zpracování využívající tyto rozšířené metody prokázaly nové možnosti využitelnosti těchto snímků pro potřeby lesnického plánování.

Corresponding author:

Ing. STANISLAV ŠUMBERA, Mendelova zemědělská a lesnická univerzita, Lesnická a dřevařská fakulta, Lesnická 37, 613 00 Brno, Česká republika
tel.: + 420 5 45 13 40 16, fax: + 420 5 45 21 14 22, e- mail: ambrosa@mendelu.cz