Methods of digital photogrammetry in forest management in Slovakia

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ABSTRACT: The practical aspect of utilization of digital photogrammetry methods and their products in Slovak forestry is presented. We deal with the comparison of various data obtained by digital cameras, their accuracy, utilization and effectiveness for mapping. Based on presented results we summarize the main conclusions in the field of forest mapping. We also deal with the process of pan-sharpening for the preparation of image data for the interpretation and classification of forestry features. Also, the statistical characteristics of two photogrammetric projects with different geometric resolution photos (Ultracam D digital camera with ground sample distance of 10 cm and UltracamX digital camera with ground sample distance of 20 cm) from the same experimental area of the University Forest Enterprise Zvolen are described with the aim of finding an appropriate solution suitable for forest mapping. In both cases, the horizontal accuracy of the photogrammetric projects is presented. Finally, the process of true orthophoto generation and its utilization in forestry is the focus. Both experiments in this paper presented results which fulfil the accuracy standards defined by the state cadastre within the mapping of large scale maps. All projects, apart from the project of direct georeferencing, fulfilled the third accuracy class of mapping, so they can be used within cadastral mapping, land consolidations and, of course, within forested land mapping. Still, all the projects meet the accuracy requirements within the forest mapping standard, where the forestry features and forest spatial distribution units are mapped.

Keywords: pan-sharpening; aerial photos; aero-triangulation; true orthophoto; forest mapping

Forest management in Slovak forestry is undertaken according to forest management plans (care programmes for forests). Every year, approximately one-tenth of the state area must be renewed, that is about 4,500 km^2. Then the programmes are valid for the next ten years and are served by practical skilled forest managers who care about the forest sustainable development. Essential data needed for the creation of these plans are aerial photos and terrestrial surveying. This means that data collection techniques, their economy and effectiveness are very important tasks in Slovak forestry and research. Digital technology was introduced into forest mapping in 2001 as a substitution for older analogue technology. Nowadays, forest mapping is mostly undertaken using photogrammetric methods. Aerial photos are necessary in the process of forestry map creation and, in practice, during the acquisition of data on the forest condition. Forestry maps join the elements of topographic and thematic maps resulting in forest mapping related to an area of 1.998 million hectares, representing almost 40.6% of the state area.

The current period in photogrammetry is represented by an increasing interest in accurate spatial data acquisition. More often we meet with final products such as digital terrain models, digital surface models, true orthophotos and point clouds. These products are obtained using high quality cameras and scanners with high spatial resolutions.

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Their accuracy can be compared to terrestrial measurement, and they are also very efficient and less time consuming. Currently a project is solved in the National Forestry Centre and Technical University dealing with the photogrammetric evaluation of high resolution aerial photos (more than 10 cm geometric resolution), dense point clouds from airborne laser scanning, satellite images (WorldView-2) and hyperspectral data with the main aim to obtain precise information about forest for mapping and forest inventory. Many authors addressed the problem of the horizontal accuracy of orthophotomaps created from aerial photos obtained by modern aerial cameras (e.g. Potůčková 2004; Melichárek 2005; Chudý et al. 2007; Žíhlavník et al. 2007; Kardoš, Soľanka 2012) and the accuracy of photogrammetrically generated terrain models (e.g. Fryer et al. 1994; Prokešová et al. 2010). Terrestrial methods still have their place within the operations where higher accuracy is required (for example measurement and staking out of forest boundaries of individual owners).

Photogrammetric evaluation of stereo models created from high resolution aerial photos has reached the level of accuracy sufficient for most organizations which use spatial information.

Besides the geometric accuracy of aerial photos and the photogrammetric evaluation process, the ability to precisely identify the measured object is crucial for the final accuracy of mapping (Tomaštík, Žíhlavník 2011).

Modern digital aerial cameras offer both panchromatic and multispectral channels, so orthophotos created from such material can be used for interpretation and classification of features for various scientific disciplines.

A substantial amount of aerial photo utilization (e.g. Halvoň 2008) is within forest mapping and forest management, where the method of digital photogrammetry dominates in the digital photogrammetric workstations.

The main task of forest mapping is to create, update and publish thematic state maps with forestry content. Thematic maps create a basis for many forestry disciplines, mostly forest management and forest condition determination and are used in forest research and education. At present, mostly digital aerial photos with ground sample distance (GSD) of 20 or 30 cm and 60/30% overlap are used in forest mapping. They offer a good base to height ratio, and geometry and radiometry better than colour analogue photos at the scale 1:15000 scanned at 15 µm (e.g. Halvoň 2011).

Halvoň 2011 also described the economic aspect of utilization of digital aerial photos with GSD 20 cm in forest mapping. Costs of aerial photos with GSD 30 cm are only a bit lower than those of aerial photos with GSD 20 cm (fewer photos, but higher price), because different technology (due to the height of flight) has to be used. On the other hand, aerial photos with GSD 20 cm provide better accuracy for forest mapping and they can be used for solving the problem of blank areas in forestry. He also presented results of a comparison between high resolution satellite images and aerial photos for mapping. Because of the need of stereo-evaluation the final costs are lower for aerial photos and still the satellite sensors do not offer accuracy needed for the interpretation of forest spatial distribution units and for the determination of forest stand and individual tree characteristics and their main purpose is determination of the health state.

An important task in forestry is the interpretation of various remote sensing materials. They are used to interpret topographic features, and also for the determination of specialized forestry features for forest mapping. The current trend of remote sensing materials leads to ensure the geometric accuracy of depicted objects (e.g. Albertz 2001).

In recent years in Slovakia, the ownership of forest land has been restored to the original owners within land consolidation projects. A new unit of forest distribution has been created according to the ownership of forest land. Some forest boundaries have also become proprietary boundaries where the accuracy criteria of cadastral mapping must be fulfilled. The other boundaries of the forest spatial distribution units are measured and stabilized according to the standard of the digital map work. At present, digital photogrammetry offers an opportunity to achieve higher mapping accuracy so the problem of blank areas can also be solved – forested areas which are not registered as forest in the cadastre (Žíhlavník 2007, 2008).

Lately, only multispectral aerial photos have been used in institutions where forestry maps are created. Almost 90% of forest mapping is realized by evaluation of the actual condition shown in aerial photos. Photogrammetric evaluation of aerial images has a great tradition in Slovak forestry. The National Forest Centre with its departments creates various thematic forestry maps and is also responsible for updating and creating the large scale basic forestry map.

Orthophotos have their set place within forestry practice, also as a basis for geographic information systems (GIS), for forest planning and in the classification of the health state of forest stands. With the improvements in software applications and hardware for digital aerial photo processing, large amounts of aerial photos can be processed within one photogrammetric project in digital photogrammetric workstations. They also offer automatic digital elevation model (DEM) extraction using image correlation techniques.

At present, still more demands are placed on accurate digital aerial photos – mainly on their geometric, radiometric and spectral resolutions. With these improvements in digital photography we can obtain separated images representing the ground in a combination of various electromagnetic channels. This is possible due to the separated sensors on the camera module, which are filtered according to the desired wavelength. For example, the Vexcel UltraCam digital camera has eight lenses. Four lenses are used for panchromatic photography with higher resolution and four are used to produce normal colour and near infrared (IR) composites by photographing through filters, resulting in images with lower geometric resolution (Lillesand et al. 2008).

Then we can combine these images through the pan-sharpening process. Pan-sharpening or image fusion is a combination of a panchromatic (black and white) image with the higher geometric resolution and a multispectral (colour) image with the lower geometric resolution. The result is a single multispectral image with the geometric resolution of a panchromatic image. Pan-sharpening was developed mainly for the quality improvement of satellite images but with rising utilization of digital aerial cameras this technology is also used in aerial photogrammetry. For example, Vexcel, the developer of the UltraCam digital camera, recognizes four levels of image processing. In general, the customer obtains Level 3 image processing, meaning images after pan-sharpening in the desired colour representation [most often red-green-blue (RGB) composition].

In forestry research, we often meet with the specific demands for image data due to the interpretation and classification of the various objects of interest. Thus, it is important to have an opportunity to influence the final image syntheses. For this reason, Level 2 image processing (individual panchromatic and multispectral images) is used in forestry research. Specialized software is used (Ultramap, Geomatica Pansharp) to create multispectral syntheses with higher geometric resolution according to the demands of various forestry disciplines. Most often we use normal colour (RGB) and colour infrared (CIR) syntheses as the input to photogrammetric projects, where orthophotomaps in the same syntheses are created as the final product. Then they are overlaid with, for example, vector layers of forest stand boundaries, planned felling boundaries and colour age structures of forest stands, and thus digital forestry orthophotomaps are created for forest management.

Digital photogrammetry in forest mapping

Most of the mapping work in Slovak forestry (almost 90%) is undertaken by digital photogrammetry determining the boundaries of the forest spatial distribution units from the stereo models using digital stereoscopic hardware. The effectiveness and economy of photogrammetry in forest mapping reduce terrestrial measurements only where necessary (ground control point and check point measurements, forest detail invisible in the photos).

The reconstruction of photogrammetric bundles of rays is carried out in softcopy systems, where interior, relative and absolute orientation must be performed. Also, there is more automation, mainly in the point measurement, which leads to the processing of a larger amount of aerial photos in one block. Methods of image matching and image correlation which substitute manual pointing are commonly included in most photogrammetric software (Inpho, ImageStation, Leica). Point measurements are adjusted by standard methods of least square adjustment within the process of digital automatic aero-triangulation, which is the term most frequently applied to the process of determining the x, y, and z coordinates of individual points based on photo coordinate measurements (Wolf, Dewitt 2000).

Digital photogrammetry makes the work more effective and economic, which subsequently decreases the price of the final products. The main advantages of digital photogrammetry in forestry can be summarized as follows:

– digital photogrammetry includes algorithms for image processing (sharpening, filtering, compression etc.),
– known algorithms for solving classical photogrammetry (triangulation, photo orientation, orthoprojection) have been implemented and these processes are fully automated,
– digital automatic aero-triangulation allows the orientation of blocks of photos using fewer ground control points (GCPs), (approximately 1 GCP per 5 photos),
– the number of GCPs decreases if there are known parameters of exterior orientation for each photo, obtained from the GNSS (global navigation satellite system)/IMU (inertial measurement unit), which is a part of the camera at present,
– stereo models are immediately at the operator's disposal,

– the result of the vectorization of the stereo models is in digital form, so it can be combined with other layers in GIS.

True orthophotomaps in forest mapping

Orthophotomaps are highly used products which can be generated in softcopy photogrammetry. An orthophoto is a product which has the pictorial qualities of a photograph and the planimetric correctness of a map. Orthophotos are produced through a process of differential rectification (Wolf, Dewitt 2000).

Conventional orthorectification only considers the correction of tilt displacements and terrain relief displacements. True orthorectification procedures (e.g., Lohr 2003; Albertz, Wolf 2004; Wolf 2005; Chen, Li 2008) take into account ground objects for the correction of relief displacements and compensation for the hidden areas. Accordingly, true orthoimages provide the exact position of land objects.

Nowadays, airborne LIDARs (Light Detection and Ranging) are commonly used for the production of DEM, which provides the heights of all 3D objects in a scene and so they can be used for true ortho generation (e.g. Lohr 2003).

In the field of forest planning and forest spatial distribution, the problem of utilization of true orthophotos is current. Within forest land consolidation, the current task is to solve the increased requirements of the original owners for restoring the boundaries of their property (Žíhlavník 2007).

True orthophotos with very high resolutions could serve as a basis for the identification of boundaries for the purpose of their staking out. Relief displacement and leaning objects result in some parts of the orthophotos being invisible (e.g. boundaries of high forest stands, forest roads in forested areas) and so it is impossible to interpret boundaries in these areas.

A very important aspect in the process of true orthorectification is the existence of aerial images with higher endlaps and sidelaps. For this purpose, the recommended values are 80% endlaps and a minimum of 60% sidelaps, which allows objects to be viewed from all sides, so there will be no hidden areas during the process of true orthorectification.

MATERIAL AND METHODS

Aerial photos taken by the UltraCamD (Microsoft's UltraCam, Graz, Austria), digital camera with 80% endlaps and more than 30% sidelaps were used as the experimental material. The average scale of these photos was 1:11000; the average flying height was 1,620 m; the geometric resolution of the photos was 10 cm on the ground and 9 μm in the photo and the radiometric resolution of the photos was 8 bit after the process of pan-sharpening.

The next experimental materials were aerial photos taken by the UltraCamX (Microsoft's UltraCam, Graz, Austria), digital camera with 60% endlaps and 30% sidelaps, geometric resolution of 20 cm, average scale 1:27600, and average flying height 3,500 m. In both cases, the University Forest Enterprise in Zvolen was selected as the area of interest and data were available from the GNSS/IMU with a mean error of each coordinate of less than 0.1 m. For DEM generation we used Inpho's DTMaster and DTM/DSM (digital terrain model, digital surface model) Generator (Trimble Germany GmbH, Stuttgart, Germany). The 3D vectorization of the tops of the objects was undertaken in the Summit Evolution (DAT/EM Systems International, Anchorage, Alaska) and Microstation environment (Bentley Systems, Exton, Pennsylvania). True orthophotos were generated in the Inpho's OrthoMaster (Trimble Germany GmbH, Stuttgart, Germany) and the final output mosaic was prepared in the Inpho's OrthoVista (Trimble Germany GmbH, Stuttgart, Germany). Control and check points were signalized before the photo flight and their orthogonal coordinates were determined in the ETRS-89 coordinate system UTM (Universal Transverse Mercator) zone 34N projection. Coordinates were obtained by GNSS measurement using a TOPCON Hiper GGD device (Topcon Corporation, Tokyo, Japan).

The processing of the aerial photos in photogrammetric projects was carried out in the Inpho's photogrammetric system (Fig. 1). Most of the information needed for the projects was in the calibration protocols and some was measured terrestrially. The photogrammetric workflow in both photogrammetric projects was identical.

The first step in photogrammetric workflow is to set up project parameters in the ApplicationsMaster (coordinate system, photo strips, control and check points, approximate parameters of exterior orientation, focal length, average terrain elevation and the definition of blocks of photos) and edit the camera parameters (lens distortion, photo and camera orientation and coordinates of principal point). The next step in digital aerial triangulation is ground control and check point measurements. This step can also be carried out after automatic tie point extraction with least-squares adjustment of

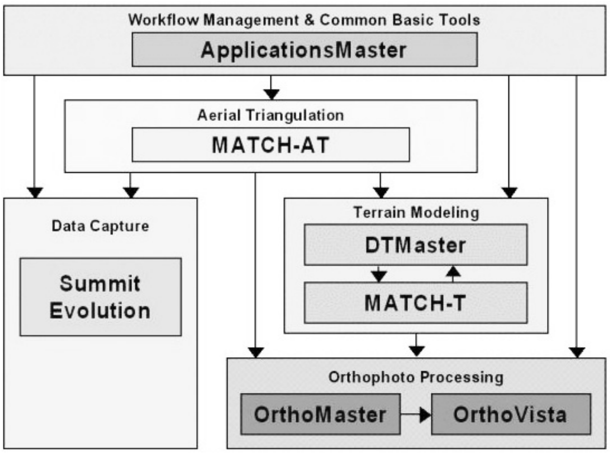

Fig. 1. Workflow in the Inpho's photogrammetric system

the blocks of photos. After reaching positive values on tie and pass points (the mean error of all measured pass and tie points is smaller than one-third of the size of the pixel) we can evaluate the accuracy of the photogrammetric project based on the statistical characteristics computed from the coordinates of the check points. Also, we obtained adjusted values of the exterior orientation parameters of all photos. The result is a stereo model with minimized vertical parallaxes. The absolute orientation of the stereo models was undertaken using aerial frame triangulation module. The final computed exterior orientation parameters for the individual photos were saved in the project and used in the next steps for DEM and orthophoto generation.

Nowadays, the use of GNSS/IMU for the direct georeferencing of airborne scanning devices is standard. Without this new technology, their application would nearly be impossible. The method of direct georeferencing allows the transfer of sensor or object data immediately into a local or global coordinate system, which makes their further processing possible. Such a system exists in the receivers of the GPS, on board and on the ground (reference stations), and the inertial system combined with a sensor, which determines angles and accelerations of the sensor with high precision. For conventional analogue aerial images, the aerial triangulation procedure is still preferred in the case of stereo plotting. But, for the generation of orthoimages, the method of direct georeferencing is more and more becoming of practical use (Schroth 2004).

For the purposes of the digital orthorectification of aerial photos, DEM had to be generated. We used Match-T (a DTM/DSM generator) to automatically generate DEM with variable grid widths (according to the Inpho photogrammetric system manual, dependent on the average scale of the photos and the pixel size). Digital orthorectification was undertaken in the OrthoBox module. Distortions of the aerial photos were removed by application of the DEM and the resampling of the original raster using bilinear interpolation. The final rasters – digital orthophotos – were then joined together into one continuous georeferenced mosaic by using seamlines.

Within the DEM generation, 3D vector layers were used, which contained roofs of buildings, the height distribution of forest stands and other features, such as ridges and edges. Software used these vector layers as the object shapes for DEM optimization and refinement, so it could be used for the true orthorectification.

Statistical methods used for data evaluation

To compute the *RMSE* (root mean square error), residuals (ΔX, ΔY), i.e. the differences in position between the source dataset (X^*, Y^*) and the co-located values from independent sources of higher accuracy, i.e. check points, (X, Y), were calculated. For the accuracy assessment we used standard statistical characteristics (reliability, precision, accuracy).

$$\Delta X = X^* - X \quad (1)$$

$$\Delta Y = Y^* - Y \quad (2)$$

In addition the mean error (*ME*) was used as a robust indicator for systematic error:

$$MEx = \frac{1}{n}\sum_{i=1}^{n}(\Delta X) \quad (3)$$

$$MEy = \frac{1}{n}\sum_{i=1}^{n}(\Delta Y) \quad (4)$$

The final accuracy represented by the *RMSE* was then computed as the square root of the average of these squared differences:

$$RMSEx = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta X)^2} \quad (5)$$

$$RMSEy = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta Y)^2} \quad (6)$$

$$RMSExy = \sqrt{\frac{1}{2}\left(RMSEx^2 + RMSEy^2\right)} \quad (7)$$

Since the application of these statistics assumes that the data follow the Gaussian distribution, residuals (ΔX, ΔY) were tested for normality. The normality assumption was not rejected, so the *ME* was computed. Its value was tested by the statistical *t*-test for significance. Then we could claim that with the 95% confidence level the residuals measured on the check points contain systematic error. To remove systematic error from the residuals, we had to subtract the inverse value of the *ME*. The precision of determination of point positions in the photogrammetric model is represented by the standard deviation, which means variability around the *ME*.

RESULTS AND DISCUSSION

Direct georeferencing and digital aero-triangulation of the block of aerial photos taken by the Ultracam D digital camera (GSD 10 cm)

Within the experiment we created four photogrammetric projects using digital automatic aero-triangulation in the Match-AT software. In each project, different numbers of GCPs were used for assessment of their influence on the horizontal accuracy of projects. In all projects, GNSS/IMU data were used. In forestry practice we meet with difficulties caused by variable and unclear forested areas, which negatively influence GCP signalization and measurement using the GNSS technology. For this reason we also created a project using direct georeferencing, without any GCP. The resulting accuracy of the aero-triangulation was assessed by measurements on the check points. Within all projects, we used 20 check points, which were suitably distributed over the area of interest. The accuracy of each project was characterized by the root mean square error (*RMSExy*). Next, its values were compared with the technical standard STN 01 3410 – the large scale maps (basic and thematic maps). This standard is used for the construction of basic large scale maps in Slovakia created in the third and fourth accuracy class of the map characterized by the accuracy of the *x*, *y* coordinates of planimetric points, from which mean coordinate error m_{xy} is computed. This error must not exceed the u_{xy} citeria according to the STN 01 3410 (Table 1). The fourth accuracy class is selected within the mapping of forest complexes mainly when using the photogrammetric mapping method.

The first project shows the results from direct georeferencing, the others from digital aero-triangulation using various numbers (4, 15, 29) of the GCP and GNSS/IMU data with approximate parameters of exterior orientation (Table 2). Large values of the *RMSE* within the direct georeferencing method have their bases in systematic errors – systematic shift as a consequence of the wrong determination of the projection of the centre position.

This is caused by the time synchronization and projection centre interpolation determined by the GNSS kinematic method. Internal accuracy of the integrated GNSS/INS system is: position 0.05 to 0.3 m, speed of carrier 0.005 m·s^{-1}, tilt 0.005° and azimuth 0.008° (Pavelka 2009).

The results confirm that increasing the number of GCPs using GPS/IMU parameters does not have a distinct influence on the horizontal accuracy of the aero-triangulation. The results also showed that only the minimal number of GCPs (4 full X, Y, Z GCPs) radically increased the accuracy of the photogrammetric project. Increasing the number of GCPs did not improve the quality significantly, which is important from the forestry aspect where the economic measurement at 4,500 km^2 of mostly forested areas per year is very important.

According to Jacobsen (2007), photos from digital aerial cameras often contain systematic errors as a consequence of their fusion from smaller parts [from CCD (charged coupled device) sensors] into one final image, which can be removed during block adjustment within the camera self-calibration. We obtained better *RMSE* results using the camera self-calibration methods in the direct georeferencing project (included in the Match-AT).

The results of individual projects show that four GCPs appropriately distributed over the block of photos are enough for digital automatic aero-triangulation using GNSS/IMU data. GNSS/IMU data also improve the successfulness of the image matching technique during the automatic pass and tie point extraction. Particularly in the large forested areas, we meet with the problem of GCP signalization and tie point extraction, which have improved since the introduction of digital data, with higher geometric and radiometric resolution which has been used in forestry practice. These

Table 1. Accuracy classes according to the STN 01 3410 standard – large scale maps

Mapping accuracy class	U_{xy} of positional points (m)
1	0.04
2	0.08
3	0.14
4	0.26

u_{xy} – criterion determining the positional accuracy of large scale maps

Table 2. *RMSExy* values of the photogrammetric project with and without camera self-calibration

Number of GCPs used	0	4	15	29
Without camera calibration	0.385	0.048	0.047	0.049
12_parameters	0.400	0.045	0.046	0.048
44_parameters	0.200	0.066	0.046	0.047

12_parameters, 44 parameters – number of parameters for camera self-calibration for compensation of systematic image errors

claims were also confirmed by the results obtained by Šadibol (2010).

The *RMSExy* values computed from check point coordinates in the projects where GCPs were used did not exceed the 2nd mapping accuracy class according to the standard used for mapping presented in Table 1. In the direct georeferencing project, the *RMSE* values exceeded the 4th accuracy class, but, in the project where 44 parameters of camera self-calibration were used, we fulfilled the criterion for the 4th mapping accuracy class. The obtained results are still suitable for the mapping of most forestry details (e.g. forest spatial distribution units, boundaries of forest stands) where specific criteria according to the standard of forestry digital map work creation are applied. These criteria allow the mapping of forestry features with up to 0.5 m horizontal accuracy.

Digital aero-triangulation of blocks of photos taken by the UltraCamX digital camera (GSD 20 cm)

Within this experiment we used digital aerial photos with lower geometric resolution (GSD 20 cm) and endlaps of only 60%. The sidelaps were the same as in the previous projects – 30%. These settings were used in forestry during the period of analogue aerial photography. The photogrammetric project was created in the Inpho's photogrammetric system and for quality assessment we used 22 check points distributed over the project area. GNSS/IMU data were used to make the photo processing more automated and so that image matching for pass and tie point extraction could be used. The final results after the block adjustment are presented in Table 3.

The results of the accuracy assessment confirm the theoretical assumption that the 3rd mapping accuracy class according to the technical standard STN 01 3410 can be achieved within the photogrammetric evaluation of the digital aerial images by the methods of digital photogrammetry. In this case, the residuals measured on the check points contained the systematic error with 95% probability, so it had to be removed. The systematic error probably originated from the inappropriate distribution of check points, which were mostly situated at the edges of the block of photos.

When we compare these results with the results obtained in the photogrammetric project, which contained the block of black and white analogue photos (Table 4) with a similar geometric resolution (GSD 25 cm) and overlap (60/30), we obtained significantly better results in the project where digital aerial photos were used.

From the effectiveness aspect, it is clear that digital photos offer higher quality, automation of work in softcopy systems, better radiometric resolution and more spectral channels in one flight. The presented results show that within forest mapping it is better to use digital aerial photos, because higher accuracy can be achieved at similar costs.

Table 3. *RMSE* values of the photogrammetric project with systematic error and with systematic error removed

Statistical characteristic	ΔX	ΔY	*RMSExy*
Sum	–1.743	–0.724	
Mean error	–0.079	–0.033	
Standard deviation	0.143	0.097	
T-test (frequency 22, critical value 2.08)	–2.537	–1.560	
RMSE	0.164	0.102	0.136
RMSE – systematic error correction	0.143	0.102	0.124

ΔX, ΔY – residuals, *RMSE* – root mean square errors for x and y coordinates, *RMSExy* – root mean square positional error

Table 4. *RMSE* values (in m) of the photogrammetric project consisting of black and white analogue photos

RMSEx	*RMSEy*	*RMSExy*
0.340	0.407	0.375

RMSEx, *RMSEy* – root mean square errors for *x* and *y* coordinates, *RMSExy* – root mean square positional error

True orthorectification using various DEMs

The last experiment focused on the generation of true orthophotos using various DEMs generated automatically from the created stereo models from the photogrammetric project mentioned in the previous chapter.

All used DEMs were automatically generated in the Inpho's DTM/DSM generator according to the standard settings presented in the DTM/DSM generator manual. Software automatically computed the grid width using the scale, number of pixels and geometric resolution of the aerial photos. DEMs were generated using automatic correlation techniques from stereo models with computed exterior orientation parameters.

Within DTM/DSM generation, 3D vector layers were used which contained roofs of buildings, height distributions of forest stands and other features, such as ridges and edges. The software used these vector layers as the object shapes for DEM optimization and refinement, so it could be used for the true orthorectification. Two DEMs were generated:

– DSM with a 0.7 m grid,
– DTM with modelled objects from the 3D vector layer in DTM Toolkit with a 2.7 m grid.

In the next step, generated DEMs were used for the true orthorectification process. The resulting orthophotos were checked for quality and the influence of the used DEM was assessed. The bicubic interpolation method was used for resampling within the rectification process. When DSM is used, the tops of the objects are placed in incorrect positions and orthophotos contain many hidden areas. Also, when the DTM with 3D object shapes was used, some hidden areas occurred (about 1% of whole orthophoto area) due to the inappropriate sidelaps of aerial photos (only 30%), which were used in the photogrammetric project. The minimum recommended sidelaps and endlaps are 60%.

Table 5. Horizontal accuracy of classic and true orthophoto

RMS (m)	*x*	*y*	*xy*
Classic orthophoto	2.44	3.40	2.96
True orthophoto	0.12	0.15	0.14

RMS – root mean square errors

The horizontal accuracy of the classic and true orthophoto presented in Table 5 was determined by differences between the positions of the tops of the high objects measured in the classic orthophoto, true orthophoto and terrestrial measurement by an electronic total station. High values of the *RMSE* represent relief displacements in the classic orthophotos.

From the effectiveness aspect, the preparation of a specialized DTM which contains object shapes is very time consuming. Manual vectorization of 3D object shapes can be substituted by laser scanning data. On the other hand, laser scanning offers points of clouds that can be filtered, while manual vectorization of object shapes gives exact line structures separated in several layers and can be used for any other analyses in the future. True orthophotos can be used mostly in forestry research (object oriented classification, forest stand characteristic determination, wood species determination). In practical forestry, they can be used within forest management (determination of forest area).

CONCLUSION

The main task of forest mapping is to create, update and publish thematic state map work with forestry content. Thematic maps create a basis for many forestry disciplines, mostly for forest management and forest condition determination, and are used in forest research and education. Traditionally, most information for forestry thematic map creation has been obtained by the photogrammetric evaluation of aerial photos. At present, about 90% of forest mapping is carried out using digital photogrammetry methods. Every year, one-tenth of the state area is mapped for the purpose of forestry map updating. At present, the whole area is photographed by modern digital aerial cameras. They offer higher quality imaging and thus faster processing in photogrammetric softcopy systems. In this article, we focused on three experiments which are current in forestry mapping. We dealt with a comparison of various data obtained by digital cameras, their accuracy, utilization and effectiveness for mapping. Based on the presented results we can summarize the following main topics.

Aerial photos are needed for forestry map creation. Currently, they cannot be replaced by the very high resolution satellite data (e.g. WorldView-2, GeoEye2). Unlike satellite data, aerial photos offer the higher geometric resolution needed for mapping of the variable forestry detail.

Both experiments in this paper presented results which fulfil the accuracy standards defined by the state cadastre within large-scale mapping. All projects, apart from the project of direct georeferencing, fulfilled the 3rd accuracy class of mapping, so they can be used within cadastral mapping, land consolidations and, of course, within forested land mapping. Still, all the projects meet the accuracy requirements within the forest mapping standard, where the forestry features and forest spatial distribution units are mapped.

Meeting these higher accuracy standards, digital photogrammetry supported by high resolution aerial photos can solve the problem of white and black areas in forestry and state cadastre register. White areas are forested areas, but in the cadastre register they have different attributes. Black areas are areas where forest should grow, they are registered as forest in the cadastre, but in reality they serve another purpose. These areas cause a problem within forest planning, which could be solved by the new mapping of such areas using high resolution photos.

In 2011, a new local coordinate system in Slovakia (SJTSK03) started to become valid. This new system removes all the negative aspects of the previous version, mainly positional shifts, and thus the state in cadastre vector maps is not identical to the new data obtained for the terrain by the precise GNSS devices. For this reason, new mapping of the area is currently in progress. Digital photogrammetry could solve this problem as it is a more effective method than terrestrial measurement (e.g. kinematic method of GNSS measurement, which has the problem of horizontal and vertical accuracy in forested areas). The results of the photogrammetric projects presented in this paper also support this theory. Aerial photos obtained by a digital camera with a 10 cm geometric resolution offer the horizontal accuracy of mapping which fulfils the 2nd accuracy class of mapping.

Photo interpretation has a set place within forest mapping, determination of the health status of forest stands and wood species determination. Present digital cameras offer data in various spectral channels, which improves the interpretation. Aerial photos processed in individual panchromatic and multispectral files are used in forestry research.

From the economic and effectiveness aspects, the aerial photos with a 20 cm geometric resolution created by a digital camera are an optimal solution for forest mapping and creation of forestry thematic map work. According to the results presented in this paper, aerial photos used in photogrammetric projects supported by GNSS/IMU data fulfilled the required accuracy. Moreover, a 20 cm GSD and a 60/30 overlap means fewer photos and a higher flight height, thus it is more efficient. Aerial photos with better GSD (10 cm) and overlap of more than 60% (e.g. 80/30, 80/60) are applicable in forestry research within classification and in determining forest stand characteristics. Higher overlap is also necessary for true orthophotomap generation. Their utilization in forestry is actually mostly in forest management (spatial forest distribution, forest mapping), automated classification and interpretation of the health status and wood species determination.

Much photogrammetry software is available which is capable of manually or automatically creating the DEM, vectorizing 3D layers and rectifying the distorted aerial photos. Also, there are algorithms with true orthorectification included. With the development of aerial photography technology and laser scanning, the best method of generating accurate true orthophotos is to take photos with high endlaps and sidelaps (for example 80% and 60%). Some companies also offer the taking of aerial photos and laser point cloud scanning simultaneously in one flight. At present, laser scanning data is starting to be used in forest mapping simultaneously with digital aerial photos. In the near future, the generation of true orthophotos will be more automated and will probably become widely used instead of classical orthophotomaps.

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