DIGITAL SURFACE MODEL AND ORTHO-IMAGES GENERATION FROM IKONOS IN-TRACK STEREO IMAGES

IZDELAVA DIGITALNEGA MODELA POVRŠJA IN ORTOPODOB IZ STEREO POSNETKOV IKONOS, ZAJETIH V ISTEM PRELETU

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ABSTRACT

The paper describes the generation of a digital surface model (DSM) and orthoimages from panchromatic and multispectral Ikonos stereopairs. It assesses the suitability of the images for vegetation height mapping of a large area and the applicability of the results for various spatial analyses. The processing steps involved stereo bundle adjustment with various sets of ground control points, digital surface model extraction, orthoimage generation and evaluation of the results. Although both multispectral and panchromatic stereoimages were processed, the DSM was generated only for the panchromatic stereopair due to its higher resolution. For evaluation purposes it was compared to very accurate lidar elevation data. The analysis revealed an overall vertical difference between the models of 8.2 m, where only one third of the differences are below 3 m. The results were worse in steep areas with high vegetation and regions with shadows caused by hills or clouds. Better results can be obtained with previous manual or automatic editing of the automatically extracted model. On the other side, orthoimages that were also produced are very accurate – the evaluation showed results with horizontal RMSE errors below 1.5 pixels for both stereopairs when compared to aerial orthophotos.

KEY WORDS

Ikonos stereo satellite images, digital surface model, stereoscopy, ortho-images, evaluation

IZVLEČEK

V članku je opisana izdelava digitalnega model površja (DMP) in ortopodob iz pankromatskega in multispektralnega stereopara posnetkov Ikonos. Pri tem se ugotavlja primernost posnetkov za kartiranje višine vegetacije večjega območja in uporabnost rezultatov za namene različnih prostorskih analiz. Koraki obdelave so vključevali izravnavo posnetkov s snopi z različnimi razporeditvami in številom oslonilnih točk, izdelavo digitalnega modela površja in ortopodob ter vrednotenje rezultatov. DMP je bil zaradi boljše ločljivosti posnetkov izdelan samo iz pankromatskega stereopara. Rezultati so bili vrednoteni s primerjavo z zelo natančnim modelom površja, izdelanim iz lidarskih podatkov. Analize so pokazale, da je povprečna višinska razlika med modeloma 8,2 metra, pri čemer je samo tretjina razlik manjših od 3 metrov. Rezultati so bili slabši na strmih pobočjih z visoko vegetacijo in območjih s sencami, ki so jih povzročili hribi in oblaki. Po drugi strani so bili rezultati vrednotenja ortopodob z ortofoto posnetki veliko boljši, saj so RMSE (koren povprečne kvadratne napake) položaja znašali pod 1,5 piksla za oba uporabljena stereopara.

KLJUČNE BESEDE

stereo satelitski posnetki Ikonos, digitalni model površja, stereoskopija, ortopodobe, vrednotenje

1 INTRODUCTION

Owing to their high spectral and spatial resolution, image size and frequent revisit time, high-resolution (HR) satellite images are becoming increasingly used as data source for topographic and thematic mapping. In the last years many new HR satellites have been launched in the orbit, with the aim to eventually replace the older successful satellites like QuickBird and Ikonos, which are still fully operational, although they have already exceeded their expected life expectancy. More information about the satellites can also be found on DigitalGlobe in GeoEye websites (http://www.digitalglobe.com; http://www.geoeye.com). Both satellites have the capability of acquiring stereopairs from which digital surface models (DSM) can be produced.

In the last decade a lot of research has been addressed to digital surface model extraction from high resolution airborne/spaceborne sensors. Different methods for elevation data extraction and DEM generation were tested before and after the Ikonos imagery was available and the first obtained results suggested a vertical accuracy of 2 m, but only if photogrammetric procedures were involved (Li, 1998). Extensive experiments on DEM generation from stereopairs were recently performed by Toutin (2004a) who achieved a linear error of 6.4 m with 68 percent level of confidence (LE68)[1] for the whole DEM using winter images. These results were not entirely satisfactory taking into account that the accuracy of the stereo bundle adjustment was 2 to 3 m and also in relation to the 1 m Ikonos pixel size and a B/H ratio of 1.

This paper will present the work done to generate orthoimages and digital surface models from an Ikonos stereopair with the tools available commercially in ERDAS Imagine and its module Leica Photogrammetry Suite. The main aim was to obtain reliable data about the vegetation height for the forest management units Slivnica and Menišija which cover an area of approximately 87 km^2. We will show that it is possible to easily generate DSMs and orthoimages of a large area using high resolution satellite imagery with a small number of ground control points. Additionally we tested the usefulness of the imagery and the methods for the production of the final results that were evaluated using very precise ground truth data. The evaluation addressed not only the production steps and the results, but also tried to assess the reliability of the geometric model and image matching method implemented in the used software. For this reason the obtained DSM was not additionally corrected before the evaluation.

2 IKONOS STEREO IMAGES

Ikonos satellite was launched on 24th of September 1999 and is known to be the world's first sub-meter commercial satellite. It has a panchromatic spatial resolution of 1 m (0.82 m at nadir), multispectral resolution of 4 m and a swath width of 11.3 km at nadir. Ikonos has a radiometric resolution of 11 bit/pixel and is capable of off-nadir imaging to the angle of up to 60 degrees in any direction. This off-nadir viewing capability is very important to shorten the revisit time and to produce stereopairs from neighbouring orbits (across-track) or from the same orbit (in-track). Stereopairs obtained from the same orbit have a base to height ratio (B/H) of 1, which is ideal

[1] LE68 is used to describe the vertical error associated with 68% of the DTM based on the 3D reference points used. For example, if LE68 is 6.4 m, 68 % of the DTM has an error of less than 6.4 m.

for stereoscopic photogrammetric processing. Beside this characteristic the in-track stereopairs have the advantage of time consistency, which means that variations (changes) in surface cover between the images in the pair are reduced to almost zero. These characteristics are essential for the extraction of digital surface models (DSM) from satellite stereoimages.

The Ikonos stereopair was acquired in the framework of the project "Methodology for the production of detailed digital maps of vegetation height and forest density" (Janža et al., 2008), which aimed at producing a map of forest height and density by using various remotely sensed data. The imaged region shown in Figure 1 is located in the south-central part of Slovenia, near Cerknica, and includes a hilly area with extensive forests, a town, villages and rivers. This region was chosen because it contains a large variety of tree types and forest patterns. The region name Slivnica was taken from the highest peak in the area.

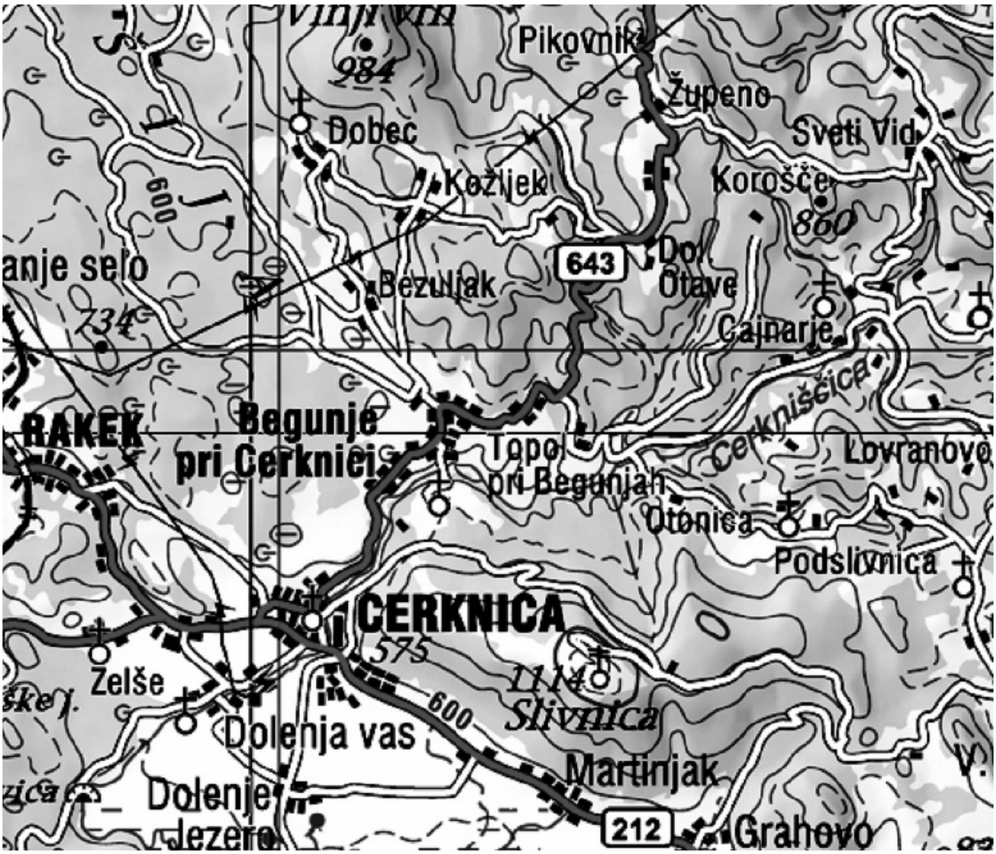

Figure 1: Area of interest for Ikonos stereopair acquisition (source: PK 250, August 2006, © Geodetska uprava Republike Slovenije).

The stereopair was ordered in winter 2006 and the acquisition was scheduled for April 2007, in the middle of the growing season. The area was imaged on 7th of April in stereo mode, resulting in two images of the same area taken from two different angles. The size of the images was 10 km by 10 km with scan angles of ±27°, which produces a B/H ratio of 1. Both images had multispectral and panchromatic bands. The properties of the images are summarized in Table 1 below.

	Multispectral images	**Panchromatic images**
Producer	Space Imaging	
Project Name	Slivnica	
File Type	TIFF	
Bands	green, blue, red, infrared	panchromatic
Bits/Pixel	11	
Number of Bands	4 x 1	1
Stereo Position	left, right	
Datum	WGS84	
Pixel Size X	4 m	1 m
Pixel Size Y	4 m	1 m
Product Order Map Units	meters	
Columns	3083 pixels	12332 pixels
Rows	3083 pixels	12332 pixels

Table 1: Properties of the acquired Ikonos for the Slivnica region.

Unfortunately both images contained around 20% of clouds that affected the final results in these areas. The left raw image of the panchromatic stereopair is presented in Figure 2. The clouds on the top and bottom part of the image can be clearly seen.

For the purpose of triangulation, orthorectification and accuracy assessment, additional spatial data were acquired during the project. Since precise spatial data (e.g. GPS measurements) were unavailable, digital elevation model DMV12.5 and orthophotos DOF5 were used for the collection of control and check point coordinates. Because of the nominal accuracy of the orthophotos (around ±1 m) and the random measurement errors, the estimated planimetric accuracy of the collected points should be better than 1.5 m. Digital elevation model with a 12.5 m grid and 3.2 m average elevation accuracy was used for height determination of the collected points and orthorectification. To better understand the terrain roughness and for the subsequent evaluation of the produced surface model it was also used for the computation of the digital terrain aspect and slope models of the usable (cloudless) test area. Figure 3 shows the histogram of the slopes on the DMV12.5 digital terrain model. The slopes range from 0° to 40° with the highest slopes represented mostly by the Slivnica hill. The average slope is 11.3°, indicating a quite rough terrain. Half of the area contains slopes below 10° and bins from 0° to 31° represent 99% of the total slopes.

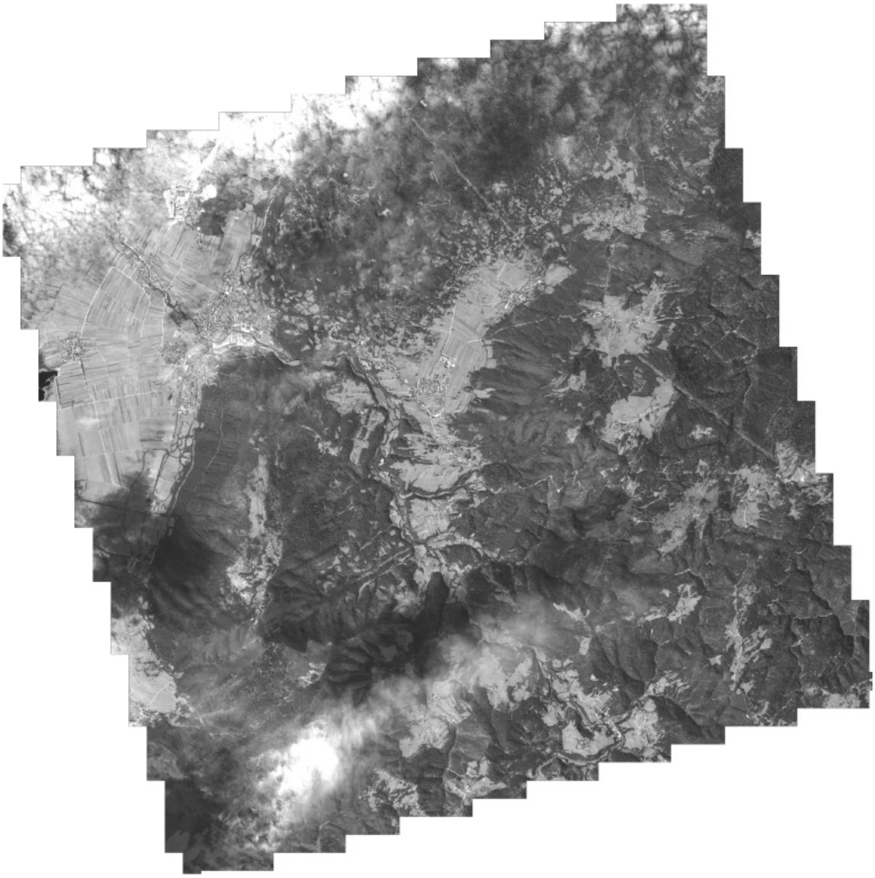

Figure 2: Left panchromatic Ikonos image.

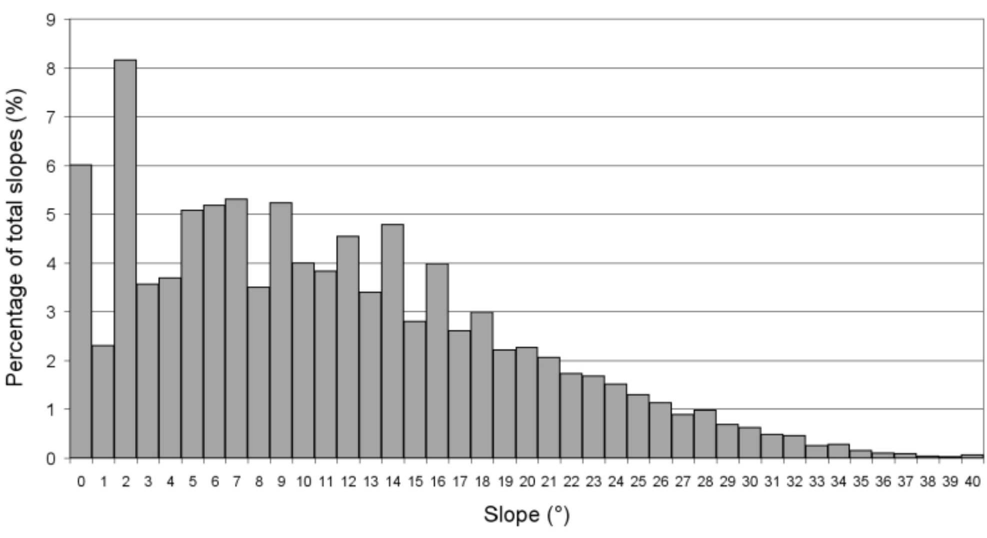

Figure 3: Histogram of the slopes derived from the digital elevation model with 1° bin.

For the assessment of the accuracy a very detailed raster digital terrain model derived from lidar data was used. The lidar data were acquired in the framework of the above mentioned project. The test area was scanned in the beginning of May 2007, producing a point cloud with a density of more than 5 points per square meter. The absolute planimetric and vertical accuracy of the data was better than 0.1 m. From the raw data two products were made: a digital elevation model (bare Earth model) and a normalized digital surface model (nDSM). nDSM can be seen as the difference between the digital surface model and the bare Earth model. The heights in the model are equal to the object heights (buildings, trees, etc.) above the Earth surface. From nDSM the height of the vegetation and man-mane structures can be easily determined using a histogram (Figure 4) or by other means of visualization. The acquired nDSM has an average altitude of 9 m and represents mainly forest vegetation.

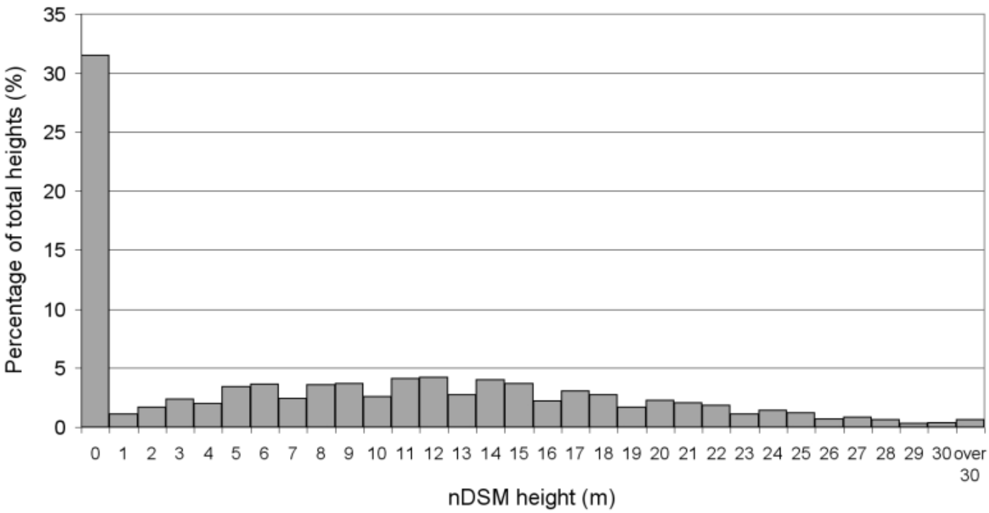

Figure 4: Histogram of the nDSM height model produced with laser scanning with 1 m bin.

Unfortunately the lidar DEM and nDSM were produced relatively late in the project and were not used in the generation of the Ikonos DSM and orthophotos.

3 SURFACE MODEL AND ORTHOIMAGE GENERATION

Orthoimages and DSM were generated in Leica Photogrammetry Suite, which is a module of the remote sensing software Erdas Imagine. The theory of the processing of satellite images is exhaustively presented in Marsetič (2005) and Marsetič et al. (2007) and will not be extensively described in this paper. On the other hand, the various processing steps for DSM and orthoimage production from the panchromatic and multispectral images with their results and evaluations are described in the following sections.

3.1 GCP collection and block adjustment results

On each of the two stereopairs 25 ground control points (GCPs) were collected with respective planimetric coordinates in the national coordinate system taken from DOF5, altitude from the DMV12.5 and image coordinates. The points were evenly distributed accross the images (mostly on crossroads) covering the lowest and the highest elevations to avoid extrapolations in planimetry and elevation (Toutin, 2004a). The pointing accuracy was estimated to be between one and two pixels (errors from the source and manual point measurement).

Block adjustment or triangulation starts with the determination of the interior and exterior orientation. The interior orientation gives the internal geometry of the sensor; on the other hand the parameters of the exterior orientation define the position and the orientation of the sensor at the time when the images were acquired. The interior geometry of the Ikonos sensor is very stable and can be assumed as constant throughout the acquisition. On the other hand, the exterior orientation of a scanned image is quite complex. To facilitate processing, the images are accompanied by respective rational polynomial coefficients (RPC) files where the data about the approximate position and orientation are stored. The rational function model from which the coefficients are derived is a replacement or numerical approximation of the physical model and is fully presented in Tao et al. (2001). Studies have also demonstrated that the rational model can achieve the same accuracy as the full physical camera model (Grodecki et al., 2003) which describes the relationship between the camera coordinate system and the physical environment in a mathematically rigorous way (usually with modified collinear equations) and is used for the restitution with all input and output parameters. A physical model can be generic or bound to a specific imaging system. The software uses the RPC coefficients and additional ground control and tie points to compute the external orientation of the images. The control and tie points additionally connect the stereopair and improve the orientation of the images.

According to Erdas (2008a) only a few points are enough to accurately define the exterior orientation parameters. Having this in mind, the block adjustment was done with various configurations of ground and check points to test the model. Some of the most significant tests are shown in the tables below. For every test a predefined number of ground control points was chosen, transforming the remaining to check points (CHK) for accuracy assessment. Within each test, the configuration of the control and check points was changed several times (e.g. ground control points became check points and vice versa) and the test result was obtained by averaging the results of all configurations.

Table 2 shows the RMSE (Root Mean Square Error) error of control and check points for the panchromatic stereopair. Ignoring Test #1 due to the lack of check information, the best result is achieved by using 20 evenly distributed ground control points. The results were expected, as in principle more GCPs lead to better accuracy. In Test #2 the check point RMSE was the smallest for all the coordinates, but it was slowly increasing with the reduction of the number of ground control points. The best results were obtained in the X direction.

Test:	GCP RMSE [m]			CHK RMSE [m]		
	X	Y	Z	X	Y	Z
#1: 25 GCP	1.51	1.84	1.63	/	/	/
#2: 20 GCP, 5 CHK	1.62	1.93	1.67	1.09	1.41	1.40
#3: 15 GCP, 10 CHK	1.62	1.72	1.59	1.51	2.19	1.79
#4: 10 GCP, 15 CHK	0.60	1.40	1.20	2.02	2.50	2.07
#5: 3 GCP, 22 CHK	0.17	0.17	0.10	3.36	3.98	3.79

Table 2: Block adjustment results for the panchromatic stereopair.

Table 3 shows the results for the multispectral stereopair. In this case we got slightly unexpected results because the best ones were obtained with 10 ground control points. The difference compared to the solutions using 15 and 20 GCPs is very small and the results are even better in the X direction. The relations would probably change if more configurations or check points were used. However, better solutions with fewer GCPs are not entirely impossible, as stated by some authors (Toutin, 2004a; Dowman, 2003).

Test:	GCP RMSE [m]			CHK RMSE [m]		
	X	Y	Z	X	Y	Z
#1: 25 GCP	1.89	2.32	3.15	/	/	/
#2: 20 GCP, 5 CHK	1.92	2.19	2.94	1.93	2.79	4.30
#3: 15 GCP, 10 CHK	1,73	2,18	3,09	2,43	2,65	3,95
#4: 10 GCP, 15 CHK	1.51	2.72	3.14	2.67	2.19	3.79
#5: 3 GCP, 22 CHK	0.09	0.20	0.15	3.93	6.95	6.42

Table 3: Block adjustment results for the multispectral stereopair.

On both stereopairs the model performed well and the RMSE of around 1.4 m for the panchromatic pair and around 3 m for the multispectral pair reflects mostly the input GCP errors. Other authors that used different algorithms achieved for panchromatic images a RMS error below 1 m, but they used blocks of images and precise GCPs (Fraser et al., 2006; Grodecki et al., 2003). The casual direction errors of the points seen in Figure 5 suggest that the points contain only random errors without systematic influence.

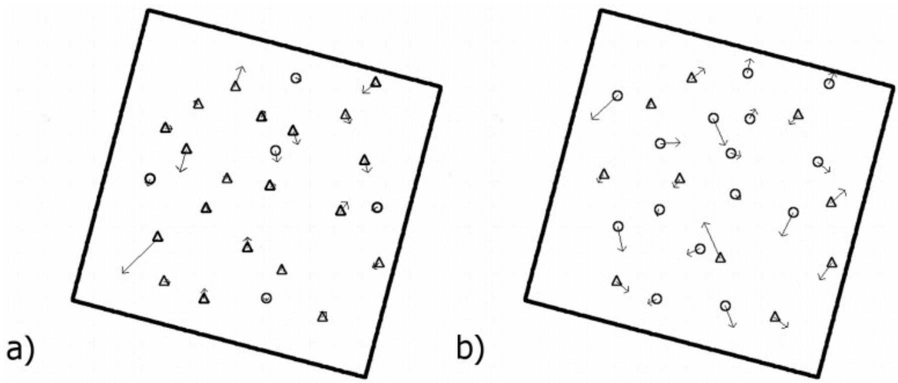

Figure 5: Horizontal residual vectors of the panchromatic a) and multispectral b) stereopairs, where the GCPs are represented with triangles and the CHKs with circles.

3.2 DSM generation results and evaluation

When the exterior orientation parameters for all images are known, we can proceed with the generation of digital surface models and orthoimages. Digital surface models, which represent the outer envelope of the surface or the tops of vegetation, buildings or terrain, are generated almost automatically using image matching. The image correlation or matching process refers to the automatic identification and measurement of the corresponding image points that represent the same surface feature on at least two overlapping images. The image matching is guided by strategy parameters that affect the outcome of the process and by exterior parameters that determine the quality and accuracy of the results. There are three strategy parameters: search window size, correlation window size (both expressed in pixels) and coefficient limit of the cross-correlation. The search window is a bigger rectangular area of pixels on the first image where the correlation with the correlation window from the second image is computed. The smaller correlation window matches the search window in all possible combinations computing correlation coefficients for all of them. Normally the biggest coefficient means that the area in the search window and the correlation window represent the same feature. The coefficient is then compared to a threshold which is defined by the coefficient limit parameter. If the computed coefficient is bigger than the threshold parameter, the match is accepted. The strategy parameters of the panchromatic stereopair that produced the best results and were used in the process of automatic digital surface model extraction are listed in Table 4. They were selected based on the shape of the surface and empirical testing. The size of the windows and the coefficient threshold are proposed by the program according to the selected terrain type, but the best results were obtained by further testing of different values that usually did not deviate much from the proposed ones.

Search window [pixel]	23 × 5
Correlation window [pixel]	5 × 5
Coefficient limit	0.7

Table 4: Image matching strategy parameters.

The matching process is the most important part of the DSM generation chain and considerably affects the result. When the same features in both images are identified, the elevation parallaxes are extracted and feature spatial coordinates are computed. From the obtained feature coordinates a regular DSM grid spacing is interpolated.

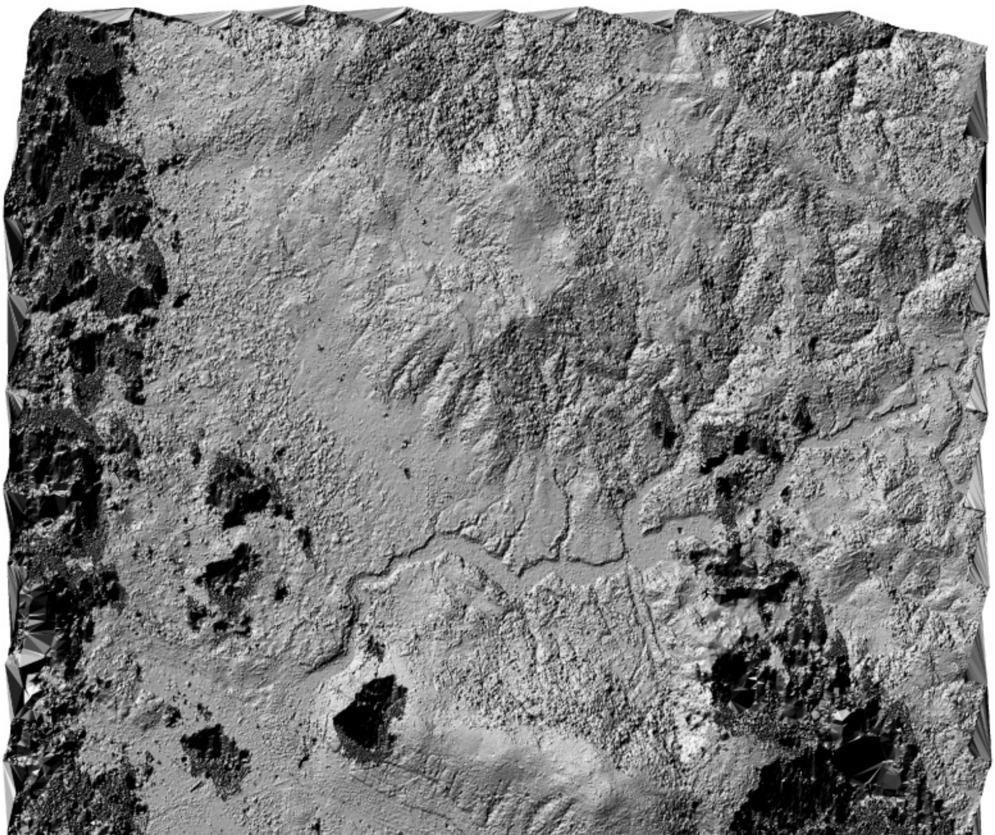

Figure 6: Shaded DSM with a 3 m resolution obtained from panchromatic images.

Because of limits in the used software the output resolution of the models is three times the input resolution of the images. Thus, the surface model derived from the panchromatic images has a resolution of 3 m and from the multispectral images a resolution of 12 m. Because of the coarser resolution of the multispectral images only the surface model made from panchromatic images was further evaluated. The shaded DSM obtained from panchromatic images can be seen in Figure 6.

On the shaded relief the mismatched areas caused by the clouds and cloud shadows can be clearly seen on the west and south-east part. Some artefacts are also present in the steep terrain, especially on the slope of the Slivnica hill. Good results are obtained on flat areas and in the river basin.

Before the evaluation of the DSM with regard to the surface model obtained with laser scanning, the quality of the matching was assessed through the computed coefficients. Regarding their quality the coefficients can be sorted in five classes. Table 5 gives the percentage of particular classes for the panchromatic stereopair. The percentage of suspicious matchings corresponds to the percentage of the area covered by clouds and shadows, where the image matching usually fails. The majority of matchings are good, but only 21.2% are excellent.

Class	Percentage [%]
Excellent (1 – 0.85)	21.2
Good (0.85 – 0.70)	56.8
Fair (0.70 – 0.50)	0.0
Isolated	0.0
Suspicious	22.0

Table 5: Percentages of quality classes for the panchromatic stereopair.

Because of the relatively high share of clouds and shadows in the images only a part of the test area can be compared to the detailed lidar digital surface model. Therefore, for accuracy estimation only the cloudless regions that overlap with the lidar model were used; they represent 55% of the whole imaged area. The lidar surface model was produced in a grid with 0.5 m spacing from filtered points and was later resampled to a 3 m grid to facilitate the comparison with the produced Ikonos DSM. For accuracy assessment a direct comparison with lidar points would produce more reliable results, but unfortunately at the moment of the computation they were not available.

Figure 7 graphically shows the computed elevation errors. The first results indicate that the average vertical difference between the Ikonos and the lidar model is approximately 8.2 m, where one third of the differences is below 3 m. Almost all the values fall in the interval ±50 m, where the limit values represent casual blunders and mismatchings. These are just medium results when compared to the block adjustment results and also in relation to the Ikonos 1 m pixel and the good viewing geometry and time of acquisition. Comparable results were obtained also by Toutin

(2004) with the 3D CCRS (Canada Centre for Remote Sensing) physical geometric model, but with not optimal winter images. Because of the different resolutions of the compared models and different time of acquisition (the lidar data were taken almost one month after the Ikonos data), the obtained height errors are presumably larger than when same-time data acquisition is performed or when comparing Ikonos DSM with only filtered lidar points.

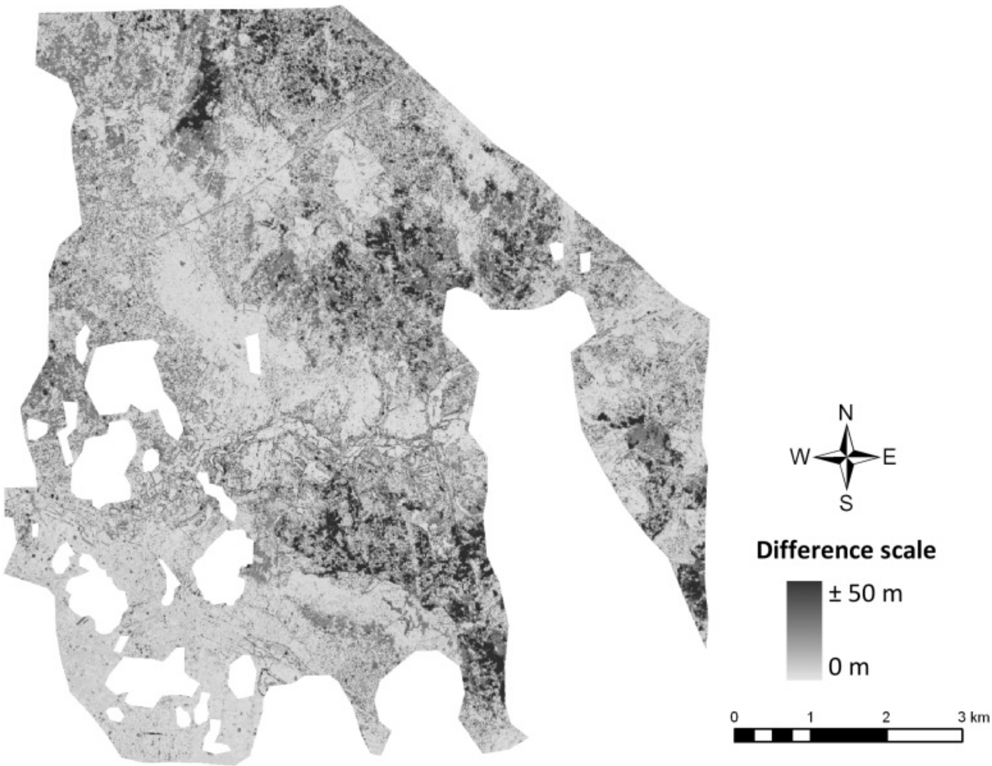

Figure 7: Difference between Ikonos and lidar surface models.

In order to locate large errors, the obtained DSM was then compared to orthoimages as well as slope and aspect layers produced from the DMV12.5 elevation model. Orthoimages can be used to identify shadows and objects that make image matching difficult. Because of the relatively low elevation (50°) and the south position of the Sun (azimuth of 160°) the shadows were long and pointed to the north and north-west. The largest errors were found in the slopes that are oriented to north and east. After detailed verification it turned out that the erroneous slopes were mainly those with shadows and very steep inclination. Some blunders were caused also by manmade objects and in regions with sudden height changes (borders between different landcovers, high trees etc.).

The quantitative evaluations were related to the terrain relief (slope) and vegetation height. Figures 8 and 9 show the statistical results with linear regression computed from the comparison of the elevations of the extracted DSM and lidar DSM. The first graph represents the comparison of both DSMs for every 5° slope bin. The error increases almost linearly through the bins, which indicates a strong linear correlation between elevation errors and slopes with $R^2 = 0.955$. The same conclusions apply when comparing elevation errors with the heights of the nDSM (normalized DSM) computed from the lidar data. The elevation errors and nDSM heights have even bigger linear correlation than the previous comparison with R2 = 0.994. These results indicate that the slope and the heights of the vegetation, buildings and other objects have a big influence on the accuracy of the stereo-extracted DSM.

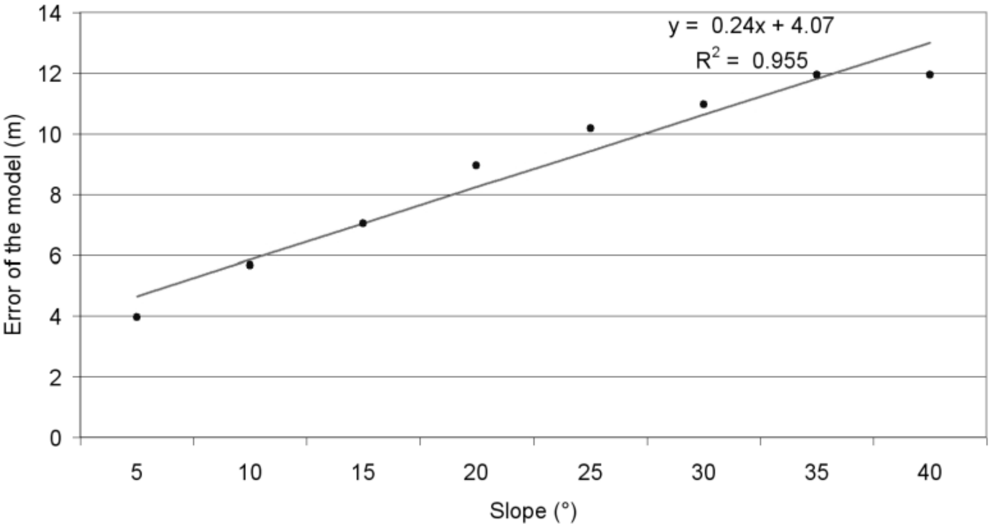

Figure 8: Graph of the statistical results with linear regression for 5° slope bin.

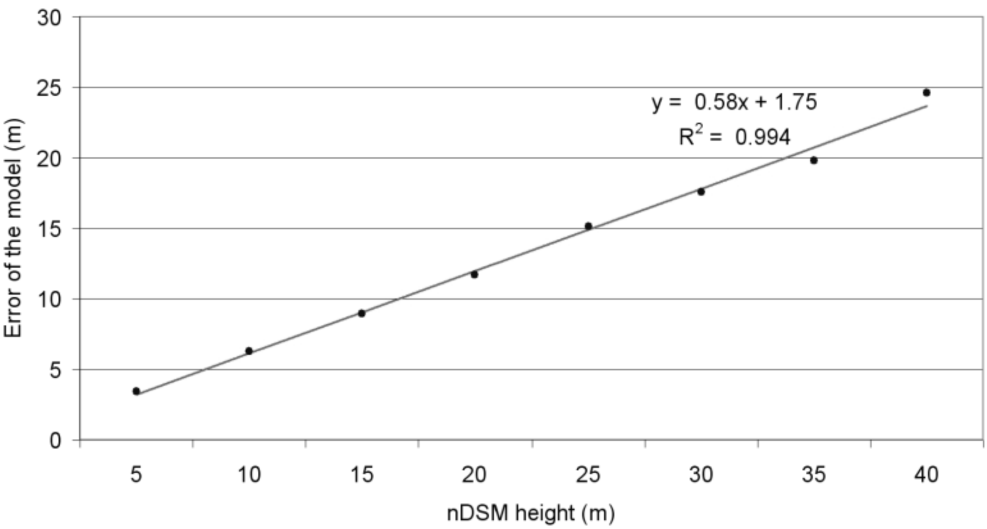

Figure 9: Graph of the statistical results with linear regression for 5 m nDSM height bin.

3.3 Orthoimage generation and evaluation

Orthoimages are created through orthorectification of the raw imagery. Orthorectification is the process of removing geometric errors inherent in the imagery and it generates images in the orthogonal projection that possess geometric fidelity. Measurements taken from orthorectified images correspond to the measurements taken on the Earth's surface (Erdas, 2008b). Thus, orthoimages can be used in the same way as already generally accepted aerial orthophotos and serve to various purposes. Besides the raw imagery the orthorectification process uses as input data also the orientation parameters and a digital terrain model which is very important in hilly regions. In our case a DEM with a resolution of 12.5 m was used. The resolution of the resulting orthoimages (Figure 10) was kept unchanged regarding the input images and their accuracy was tested using digital aerial orthophotos DOF5. The planimetric accuracy in the X and Y directions which was estimated using the RMSE is around one pixel for both the panchromatic

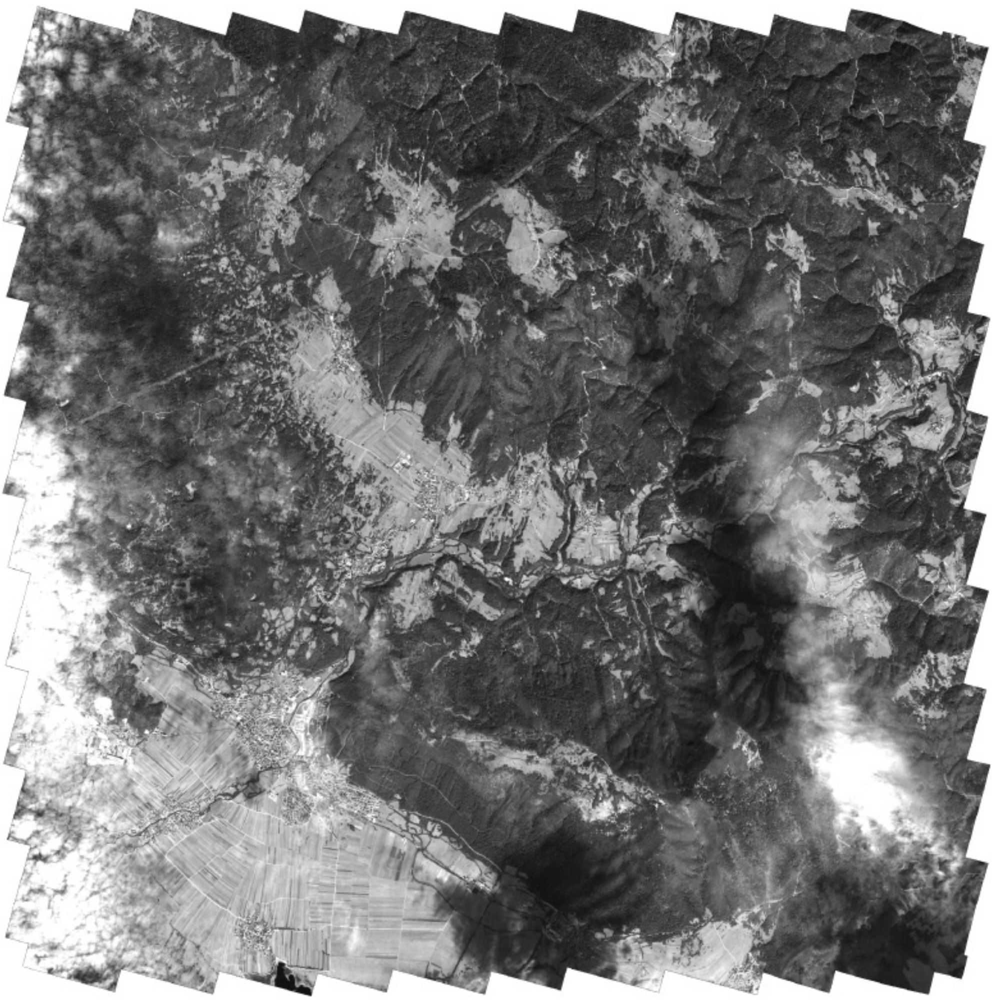

Figure 10: Orthorectified panchromatic image.

(1.4 m) and multispectral images (4.2 m). The accuracy is normally better in the X direction, mainly due to the viewing geometry of the sensor. As the check was made manually, the results also contain some random measurement errors that lowered the accuracy.

The results for the panchromatic and multispectral images are summarized in Table 6. The first column of the table shows the type of images, the second shows the estimated planimetric accuracy (RMSE) in meters and the third and fourth columns present the means of absolute residuals in the X and Y directions in meters.

Image	RMSE (XY) [m]	Residual abs(X) [m]	Residual abs(Y) [m]
PAN	1.43	0.66	0.96
MS	4.18	1.74	3.01

Table 6: Accuracy of the produced Ikonos orthoimages.

4 CONCLUSIONS

A digital surface model and orthoimages were generated from two stereopairs of Ikonos images acquired over the hilly region of Slivnica north of the Cerknica lake. The results were evaluated using aerial orthophotos taken in 2006 and a surface model produced from laser scanning data that were acquired nearly one month after the stereopairs. The orthoimages show a good positional accuracy in a range of less than 1.5 pixels. On the other hand, the results of the digital surface model (made from the panchromatic stereopair), when compared to accurate elevation lidar check data, are not adequate for most uses. The average difference between ground truth (lidar model) and the produced model is approximately 8 m with only one third of the differences below 3 m. The geometric model performed well in almost flat or uncovered land, but is almost unusable in very steep slopes and shady areas. It can be concluded that the main causes for the poor quality of the model can be found in the steep relief, vegetation cover and shades. These causes could be partially corrected with an improved algorithm for image matching.

When comparing the obtained results to the accuracy results of surface models extracted from various high-resolution sensors (Toutin, 2004b), similar findings can be clearly seen in almost all the cases. Although the studies are very alike, they cannot be directly compared because of different imaging modes and conditions. Despite that the results of this study show a higher degree of blunders in the model because of bad matchings. The big elevation errors and blunders are also a consequence of different resolutions of the compared surface models and different time of the acquisition of the datasets. In addition, the obtained surface model was tested without previous refinement and manual correction or stereo measurement which can provide much better results.

The Ikonos stereo images can be used to easily produce high resolution orthoimages and large area DSM with a small number of ground control points. The produced orthoimages can be used instead of orthophotos, where color images are not needed or where a 4 m spatial resolution is sufficient. For the purpose of vegetation height mapping the derived DSM is not good enough and would be conditionally applicable only in flat areas.

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