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Diploma Thesis

Determination, Filtering and Analysis of Digital Elevation Models

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diploma thesis for

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Determination, Filtering and Analysis of Digital Elevation Models

Digital elevation models (DEMs) are a basic component of any GIS. Not in all areas of the world DEMs with sufficient accuracy and resolution are available. The free of charge available SRTM height models have a limited accuracy of approximately 5m standard deviation and 3 arcsec point spacing. If this cannot be accepted, better height information has to be generated. The very high resolution space images are usually not available as stereo combinations, but with the Indian Cartosat-1 a stereo imaging system with 2.5m ground sampling distance can be used.

Digital surface models shall be generated from Cartosat-1 stereo scenes in the two test areas Warsaw and Mausanne. The optimal procedure for matching shall be analyzed and generated height models shall be compared with available reference data. By filtering it shall be tried to extract digital elevation models from the original determined digital surface models. The whole procedure has to be analyzed with the reference height model.

A quite more precise, but also expensive method is the airborne laser scanning. Even with the last pulse by laser scanning not all object points are located on the bare ground. With a data set from the Harz mountains, the filtering of a laser scanning data set to a DEM, containing only the height of the bare ground, shall be investigated.

TABLE OF CONTENT:

INTRODUCTION:

Digital Elevation Models and Digital Surface Models are basic contents of any GIS. Nowadays, the three dimensional data acquisition of large areas has to be made in short time with high accuracy. It can be acquired by high resolution satellite imagery, laser scanning or Interferometric Synthetic Aperture Radar.

Different applications require different accuracy of such products. In this thesis data from the stereo satellite CARTOSAT-1 and the laser scanner Optech ALTM have been used.

In the last few years, laser scanning is in the center of interest of research as quite new, modern and productive technology. Both CARTOSAT-1 can be classified as high and Optech ALTM as very high-resolution technique.

Depending upon the requirement, both techniques play an important role.

AIM OF THESIS:

The main aims of this work are investigations connected with analysis of Digital Elevation Models and Digital Surface Models, their generation from satellite images of CARTOSAT-1 and from laser scanning measurements.

One universal conception of data processing does not exist. Different requirements, terrain types, different environmental and weather conditions during measurements have to be threatened individually. Sometimes composition of available algorithms and methods is needed. Different parameters were taken into consideration to estimate the optimal combination. This is especially important for various types of terrain: flat, forestry or rolling areas.

The influence of matching, filtering and interpolation methods on model's accuracy and eventually proposals of results improvement are presented.

I. Data characteristics:

1.1. CARTOSAT-1 characteristics:

Satellite images used in the investigations were acquired from the Indian **Cartosat-1** satellite, known also as IRS-P6 satellite. Cartosat-1 has 2.5 m Ground Sampling Distance (GSD). The spacecraft has two panchromatic cameras looking at +26° and -5° nadir angle along the track. The whole spacecraft is steerable to provide wider coverage in a shorter period. The panchromatic band has a bandwidth of 500 nm to 850 nm with 10 bit radiometric resolution. The stereo model has a swath of 30 km and in the orbit direction 26.86 km. Each camera features a linear CCD detector array of 12 288 pixels with 7 x 7 microns size of one CCD-element. The overall size of each PAN camera is 150 cm x 850 cm x 100 cm with a mass of 200 kg.

The two pan-cameras cover a stereo model in the same pass.

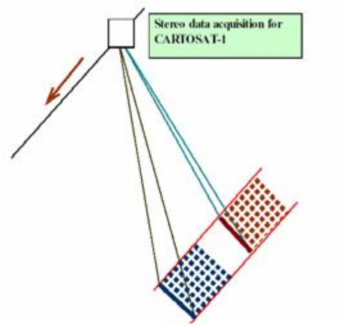


Fig. 1. configuration of Cartosat-1

Stereo model is taken by imaging with the CCD linear array with a small time difference (about 50 s) due to the forward and backward look angles of the two cameras.
One major change in imaging conditions during this time period is due to earth rotation. An algorithm for Earth rotation compensation is being used to eliminate the delayed observations of the two cameras.

Subject of research are the data sets of the Warsaw and Mausanne area. The images have been taken by Cartosat-1 in winter 2006. All investigations were made with the software developed by the Leibniz University Hannover. The ground coordinates of control points were determined by GPS.

1.2. Orientations and corrections:

Most modern sensors have the possibility of direct sensor orientation based on gyros, star sensors and GPS in the satellite (see chapter 1.3.b.). So that scene orientation is roughly known.

Mainly two types of image products are distributed:

Level 1A-type image improved by inner orientation, merging sub-lines and with radiometric corrections,

Geo-referenced level 1B-type image projected to a plane with constant object reference height.

In some cases whole orientation elements are given as rational polynomial coefficients.

All these images are not really original images. In fact they are free from some of geometric and radiometric errors.

1.3. Geometric aspects of satellite images:

Raw satellite data suffers from both geometric and radiometric distortions which have to be corrected. The various corrections should be applied as follows:

Radiometric Corrections: Each of Cartosat-1 satellite sensors consists of linear arrays of Charge Coupled Devices (CCD). The response of the different elements of any of the arrays will not be exactly identical. Radiometric correction is the process which normalizes these responses on the base of laboratory and in orbit radiometric calibration. Corrections contain: detector normalization, framing of required scene, failed/degraded detector correction and line loss correction.

Geometric Corrections: Improvement by the laboratory CCD-line correction and the combination of the CCD-lines. In addition some imaging problems can be respected like: distortion due to the relative motion of the satellite with respect to the earth , distortion due to earth curvature, panoramic distortion arising out of the tilt angles or satellite movement and orbit perturbations, variations of orbiting speed,

Corrections are needed for removing the above mentioned distortions and projection in the user specified map projection in the desired datum.

1.3.a. INNER ORIENTATION OF ORIGINAL IMAGES:

In case high resolution satellites there are different methods of acquiring images. Most traditional satellites had a fixed view direction in relation to the orbit. CARTOSAT-1 images with linear CCD lines. Modern satellites have possibility of changing the view direction to observe the interest-area. The satellites are equipped with reaction wheels or control moment gyros - rotating gyroscopes with changeable speed for the rotation of the whole satellite.

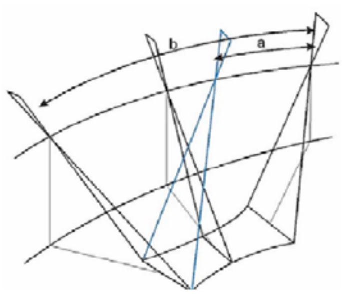


Fig.2: slow-down mode

The satellite speed is very high (6.87 km/sec footprint speed), so that the time of good image quality usually is too short. That’s why some of them are equipped with Transfer Delay and Integration sensors (TDI). Usually there is a small CCD arrays, and the energy from one element is shifted to the next one, according to the forward motion speed:

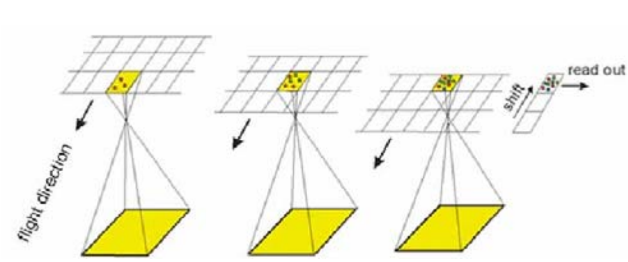


Fig.3 TDI sensor

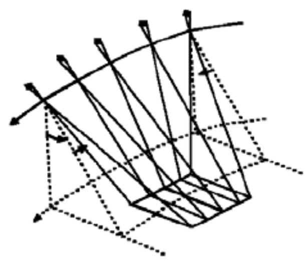


Fig 4. Constant changing of view direction

In case CARTOSAT-1 there is different solution of this problem. The satellite rotates during imaging with effect of orbit path extension (figures 2 and 4). It gives permanent change of view direction of taking images. This method characterise *slow down mode factor* of reduction angular speed: b/a. This factor depends on velocity of satellite and his altitude.

Another geometric aspect of space images is its physical acquiring (sensor geometry).

CARTOSAT-1 is equipped with 3 CCD-lines, their relative position and the orientation in relation to the satellite has to be known. This is described by the inner orientation.

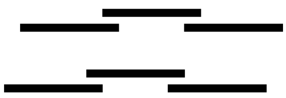


Fig. 5: Shifted sub-lines

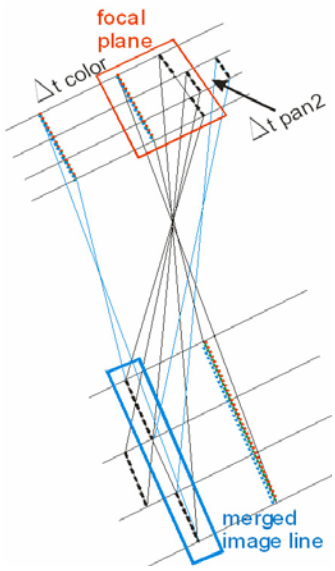


Fig. 6: situation also in case of multi spectral images.

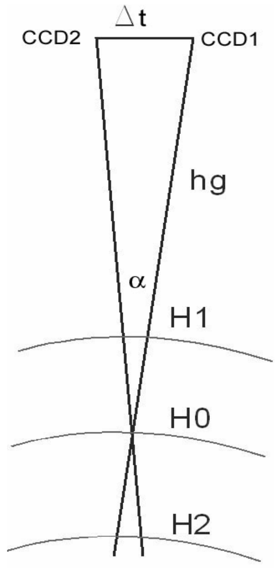


Fig. 7: shifted lines and reference height.

The high resolution satellites use such sub-CCD-lines, collecting the signal independently (fig. 6). Instead of one straight line there are three sub-lines, shifted to each other (fig. 5). During the preparation process these lines are merged to one homogenous line, so for the user this looks like a solid line.

Such conditions of different location of single sub-line may cause discrepancies depending upon the object height, as it is shown on figure 7. Depending upon the sensor, a mismatch in the order of 1 pixel appears with height differences from hundreds to thousands meters against the reference height. In most cases such differences are unimportant.

The geometry of the different image products is shown in figure 8:

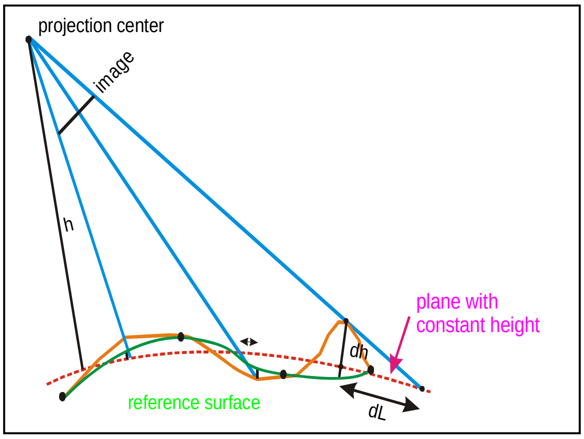


Fig. 8: Terrain relief correction.

The level 1B-type images are projected to a reference plane with constant height. This geo-referenced image product is not an orthoimage; the point position is depending upon the individual height.

A correction of the location with the individual height and the view direction is called *terrain relief* correction

1.3.b. DIRECT SENSOR ORIENTATION

Determination of image orientation without using control points is now available by using modern technologies. Today the imaging satellites are equipped with a positioning system like GPS, gyroscopes and star sensors to define attitudes and position of satellite sensor. Gyroscopes used as determination of satellite attitude are supported by star sensors. Star sensors are updating of gyros by the reference position of stars. GPS observations (ephemeris, orbit calculation are calculated by using celestial and terrestrial reference systems) are expressed in International Terrestrial Reference Frame and further relations with national systems can cause some errors. For the very high resolution satellites, the orientation accuracy without using control points is in the range of 8-12 m. But the accuracy can be improved by control points.

SCENE ORIENTATION:

1) **RECTIFICATION OF SENSOR LINES:**

The scene orientation describes the relation of the image position to the terrain coordinates. The relations between image coordinates and ground coordinates can be described by mathematic methods:

a) *Polynomial method:*

Creating a 2D and 3D model (with Z coordinate):

$$x = a_0 + a_1X + a_2Y + a_3XY + a_4X^2 + a_5Y^2 + \ldots$$
$$y = b_0 + b_1X + b_2Y + b_3XY + b_4X^2 + b_5Y^2 + \ldots \qquad (1)$$

This method is much less robust than others, and has disadvantages: it requires significant number of control points with good 3D-distribution, and is numerically unstable. Such method should be avoided.

b) *Rational Polynomial Coefficient (Rapid Positioning Capability)*

The sensor oriented rational polynomial method is based on the direct sensor orientation, it is more accurate in comparison to previous one. The purpose of a replacement model of camera is to provide a simple set of equations **to accurately represent the ground to image**

relationship of the physical camera. The RPC coefficients are used in the RPC equations to calculate an image (sample, line) coordinates from an object (longitude, latitude, height) coordinates. For this model, image vendors describe the location of image positions not directly using satellite position coordinates but as a function of the normalized object coordinates (longitude, latitude) by the ration of polynomials:

$$x_{ij} = \frac{P_i^1(\varphi,\lambda,H)_j}{P_i^2(\varphi,\lambda,H)_j} \qquad y_{ij} = \frac{P_i^3(\varphi,\lambda,H)_j}{P_i^4(\varphi,\lambda,H)_j} \qquad (2)$$

x, y – image coordinates
φ, λ, H are latitude, longitude, and height;
C- coefficients

where a polynomial has equation:

$$P(\varphi, \lambda, H) = C_1 + C_2\lambda + C_3\varphi + C_4H + C_5\lambda\varphi + C_6\lambda H + C_7\varphi H + C_8\lambda^2 + C_9\varphi^2 + C_{10}H^2 + C_{11}\varphi^2H + C_{12}\lambda^3 + C_{13}\lambda\varphi^2 + C_{14}\lambda H^2 + C_{15}\lambda^2\varphi + C_{16}\varphi + C_{17}\varphi H^2 + C_{18}\lambda^2H + C_{19}\varphi\lambda H + C_{20}H^3 \qquad (3)$$

This third-order rational function has 20-term polynomial. When we substitute *P* in (2) with the polynomials (3), we obtain 40 Rational Function (RF) coefficients in each equation (20 coefficients in the numerator and 20 in the denominator). RPC are usually calculated by providers of satellite images without using Ground Control Points. This relation has to be improved by (GCPs). This kind of solution is named as *bias corrected RPC* solution.

In this method particular components have no simple physical or geometric interpretation connected with parameters or distortion but this is a non-parametric model.

Usually the RPC method is used as a first step of geometric reconstruction process made by image user.

The **CARTOSAT-1 RPC** files are delivered in ASCII-format; the details are corresponding to the RPC-format of other satellites and described in a manual available in the WEB.

3) RECONSTRUCTION OF IMAGING GEOMETRY

To obtain projection centre on the orbit we can use known direction to scene centre or first line of image available from metadata. Using parameters of slow down factor and the earth rotation, location of equivalent projection centre on the orbit and its view direction can be reconstructed. As well every individual scene point and the view direction from every ground point can be calculated. If parameters of direct orientation are satisfactory, there is no need of using additional ground control points.

4) TERRAIN DEPENDENT RPC: Method consists in polynomial coefficients just based on ground control points, not using some information from direct sensor orientation. This method may cause large problems in flat area with one reference height level and in areas with not equal control points distribution. This method is very unstable and has low accuracy (residuals of control points have no control)– it never should be used.

5) 3D AFFINE TRANSFORMATION: this method also does not use sensor orientation. High resolution satellites have small view angle, and this allows the substitution of the CCD line perspective geometry by this transformation:

$$x_{ij} = a_1 + a_2 *X + a_3 *Y + a_4 * Z$$
$$y_{ij} = a_5 + a_6 *X + a_7 *Y + a_8 * Z \qquad (4)$$

This equation needs 4 ground control points (each GCPs give for 2 coordinates, summing we obtain 8 parameters). There is a possibility to extend the transformation in respect of slow down mode (different view direction fig. 4) to 12 parameters, or to 16 parameters according to not parallel boundaries of scene and its scale -fig 2.

6) DIRECT LINEAR TRANSFORMATION: this transformation is based on perspective projection, and just like previous method doesn't use any information from sensor characteristic:

$$u = \frac{L_1 x + L_2 y + L_3 z + L_4}{L_9 x + L_{10} y + L_{11} z + 1}$$
$$v = \frac{L_5 x + L_6 y + L_7 z + L_8}{L_9 x + L_{10} y + L_{11} z + 1} \qquad (5)$$

11 unknowns need 12 coordinates of 6 GCPs. This solution is more problematic than affine transformation and requires more well-distributed control points and is at lower accuracy level.

The geometric orientation of two types of raw images: level 1A and level 1B can be done similarly:

Level 1B images having some corrections (line rotation and reference height, described above), need only general orientation connected with datum. Firstly there is terrain relief correction introduced and than 2D transformation to control points. With the exception of IKONOS images, after terrain relief correction a two-dimensional affine transformation to the ground control points is necessary, requiring at least 3 control points.

Digital Elevation Model:

2.1. Digital Elevation Models and Digital Surface Models:

A Digital Elevation Model is the representation of the bare ground with usually uniformly spaced z-values as array of points (X,Y,Z) with interpolating algorithms enabling reproducing shape of particular area. This model is usually understood as earth surface without human artifacts such as buildings or bridges and without vegetation.

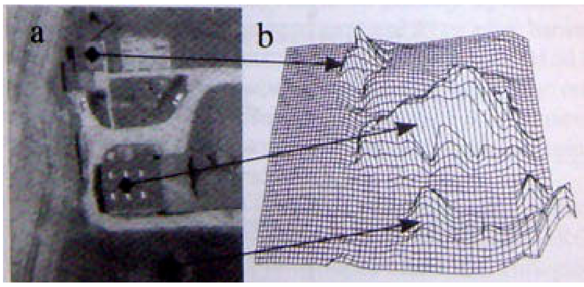


Fig. 9: transition of terrain from image to point net.

DSMs describe the surface in the sense of ``the first point of intersection by a projecting ray", so DSMs include points on buildings and vegetation as well as terrain points (include the highest elevation at each point).

DEM is a 2.5D geometric data base model, that contains the elevations of points with respect to a reference surface, without any restriction on what the object is like. Most terrain information systems model the terrain surface in 2.5D (with plane two-dimensional geometric base function additionally DEM).

From mathematical point of view, only surfaces which can be represented as $Z = Z(X,Y)$ can be modeled by these systems. As the earth surface cannot be described by one closed analytic function in a scale appropriate for topographic mapping, it has to be divided into small parts and sections and within them the surface presented by points can be approximated.

DTMs can be generated from distinct points having been measured in different ways:

-analytic plotters, immediate measurements, digitalizing, laser scanners or InSAR, **image matching techniques.**

2.2. MODELS OF DIGITAL SURFACE MODELS:

1) GRID

There are different methods of storing terrain data:

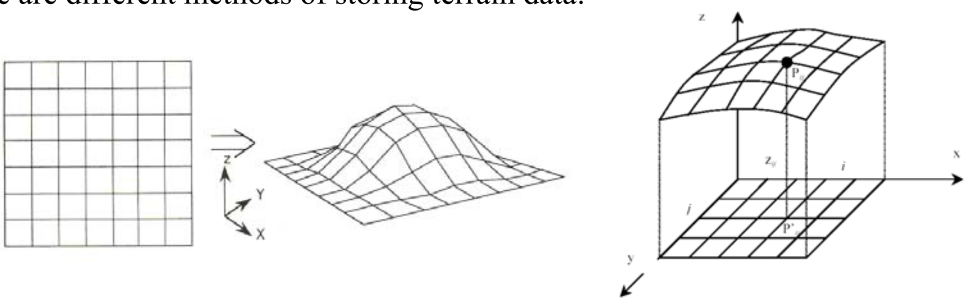


Fig. 10: GRID model. Representation of points in 2D and 3D space.

GRID model creates only the array of X,Y,Z points, but only the Z-value of nodes is recorded. X and Y coordinates are defined by their position in the array. But when we want to model the surface we should choose one interpolation algorithm. This is great advantage of GRID structure: searching proper points and quite fast interpolation. After DEM generation we can increase density of model points. There are different methods of interpolation, for example finite elements interpolation or linear prediction.

One of interpolation methods represent figure:

$$Zw = \frac{\sum Zi * \frac{1}{di^n}}{\sum \frac{1}{di^n}} \quad (6)$$

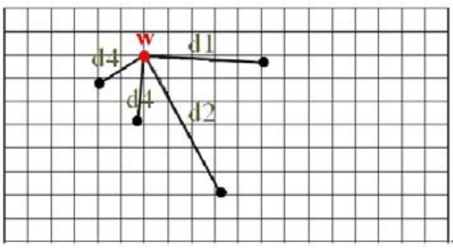


Fig. 11: interpolation by inversed distance.

In calculation the inversed distance is used. Therefore, on the final result of Z value calculations the largest influence have points, which are nearest to the searched node of the mesh. To consolidate of method action we use involutes of the distance. The main disadvantage is the fact, that Z value of mesh’s node will never exceed the height of points that were used in interpolation process. In this reason, some of geomorphologic structures are not modeled well, they can be deformed and the terrain surface is flattened.
To avoid such situation different types of terrain need different interpolation methods.

2) TIN

In this model points are being joined automatically in triangular irregular network. The facets of this grid osculate to the shape of surface.

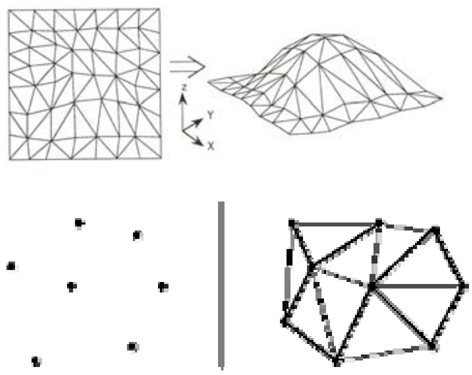


Fig. 12: TIN and point representation.

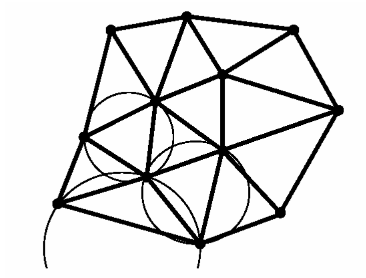


Fig. 13: Delauney's triangulation

The most popular method of creating triangular network is Dalaunay triangulation. Triangles are created in order that none of points that doesn't belong to this triangle wasn't placed inside circle circumscribed at triangle (fig. 13.). After creating Dalauney's network, we can interpolate height of point of terrain, which projection at plane surface is in a triangle:

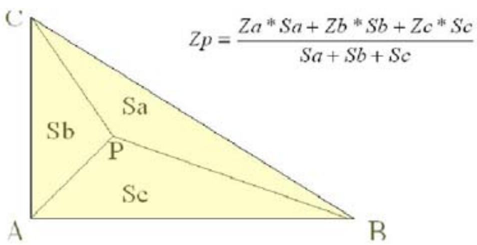


Fig. 14: TIN interpolation.

(7)

Z coordinate values are computed as a weighted mean from vertical coordinates. Value of weight is a field of triangles acquired from division primary's triangle by searched point P.

3) HYBRID MODEL

Sudden changes in topographic surface: cliffs, rivers or mountain picks are not presented in grid model of terrain. Discontinuity of surface slopes or drainage features require using *breaklines* to increase DEM accuracy.

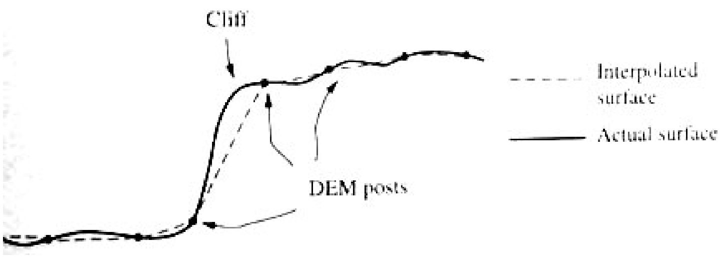


Fig. 15: example of break-line

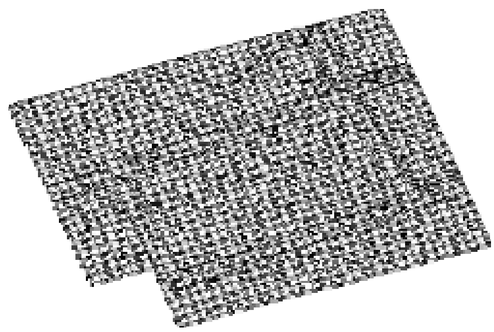


Fig. 16: model improved by road breaklines

The break-lines are introduced in the generation process in both models: along these lines, no smoothness assumptions are introduced, and the intersection points of the break lines with the grid lines have to be determined as additional unknowns. The break lines have to be added to the DTM data structure which will then no longer be a pure raster representation. Basic data base of model is completed by vector data describing position of measured points and characteristic lines and terrain forms.

2.3. DSM GENERATION

AUTOCORRELATION:

The first step in image matching is the automatic detection of corresponding points in the same area. This is needed in generating Digital Elevation Models (also Digital Surface Models).

Corresponding points:

More and more new attributes of sensors occurred causing new problems and forcing developing of matching algorithms. The satellite imagery is more demanding than aerial one, because of weather conditions or scale of image. In case of satellite imaging these parameters seldom can be changed. Illumination is dependent upon season and latitude (time of day is fixed by orbital parameters); base to height ratio is set by the satellite operator or is fixed by the satellite; the scale is fixed by sensor resolution, orbital height and look angle. All these conditions have an influence to quality of image matching.

There are several solutions of the matching problems. There are *area based, feature based* and *hybrid* matching methods. Each of them goes with similar way: definition of searching area, finding candidate pairs and comparison of their attributes.

The automatic image matching can be based on different methods:

1) **Area Based Matching** is based on signal analysis's algorithms, searching characteristic values or differences for example pixel density. There are two methods: *cross correlation* and *least square matching*.

Cross correlation is an algorithm for the location of corresponding image patches (sections of image) based on the similarity of gray levels. There are two images to relating: reference and search image. A reference point is given in the reference image, and its coordinates are searched for in the search image. For that purpose, the reference image is moved in the search image, and the position of maximum similarity of gray levels is searched for. At each position of the reference image in the search image, a similarity value, e.g. the cross correlation coefficient $k_{R,S}$ of the gray levels is calculated according to equation (8):

$$k_{R,S} = \frac{\sum g_R \cdot g_S - \sum g_R \cdot \sum g_S}{\sqrt{[\sum g_R^2 - (\sum g_R)^2] \cdot [\sum g_S^2 - (\sum g_S)^2]}} \tag{8}$$

The position of the point corresponding to the reference point is given by the position of the maximum of the similarity measure (in this case coefficient k_{RS}).

In this method template window is moving above searching window.

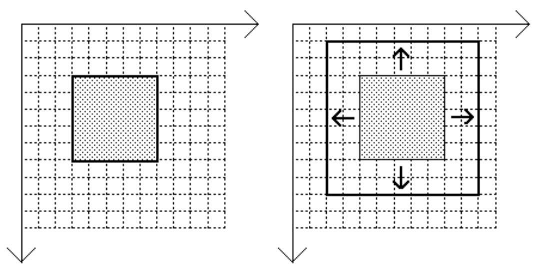


Fig. 17: cross correlation method of shifted windows.

With every shift of the template window the correlation coefficient for each pixel in these windows is computing (fig.17). The result of computation is accepted if it obtains at least threshold value. The threshold can be chosen and is bounded by -1 and 1. Thus the position of that point can be determined with a resolution of 1 pixel. In this method accuracy is dependent of differences in optic densities of the same pixels, shadows and covered areas or shifted, moving objects.

To improve correlation speed especially in case of aerial photography, process of searching is made along epipolar lines. Epipolar lines are defined by ***epipolar plane***. The perspective centers O_1, O_2 and observation, ground point P form epipolar plane. The two lines where plane intersects images are named ***epipolar lines.*** These lines are corresponding, so the point imaged in one photo on particular epipolar line will be also on the conjugate epipolar line in second image.

So that one-dimension matching can be made along the epipolar line.

Furthermore, these images don't have y-parallax, which can disturb in DEM generating.

If we accept base O_1, O_2 as x axis in model coordinate system, the epipolar lines are not parallel to it. Thus, the image has to be transformed into normalized image by resampling of images and affine transformation (known image coordinates and fiducial marks coordinates) into normalized image. Very helpful is also Over View images which are reduced original images. New pyramidal images have different size and resolution. They are needed for example in hierarchical method, where correlation begins in the last pyramidal image.

Next method is method used in program DPCOR:

Least squares matching is the most accurate method and usually used to refine the conjugate point coordinates to sub pixel accuracy (accuracy limit about 0.1 pixel);

6 affine and 2 radiometric transformation parameters between image chips of a stereo pair are estimated by iterative least squares adjustment; the convergence radius of this method is 1-2 pixels which demands for another method for pre-positioning of the window centers. LSM bases on minimizing gray values differences of two tested windows.

Extended form of Least Square Matching method is *adaptive LSM* used by Gruen. In this algorithm number, type of parameters and weighting observations depending on their importance can be chosen and accommodate to structure of match signal.

Main thesis of this algorithm is iteratively finding such position and size of window to fulfill condition: that the sum of differences of pixels gray levels between search and template window is minimal.

Program DPCOR based on adaptive least square matching method using region growing by Otto-Chau algorithm:

The pixel coordinate system is defined as: rows and columns with pixel coordinates in the center of element (or 0.5;0.5 for corner position):

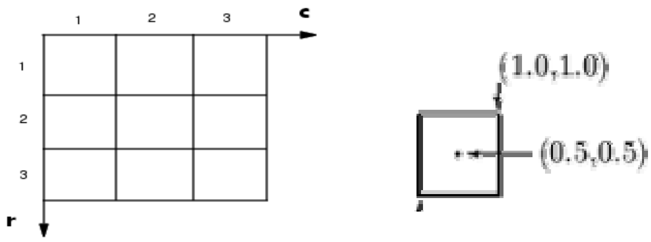


Fig. 18 a: pixel coordinate system.

If the sensor coordinate system and the image coordinate system are not identical, the relation between them can be described by a transformation.

In order to elimination of noise between two images the template and search window must be chosen, and generally we can say there are two images: first-‘reference’ image and the second one ‘searched’ image. The reference image is transformed to the search image.

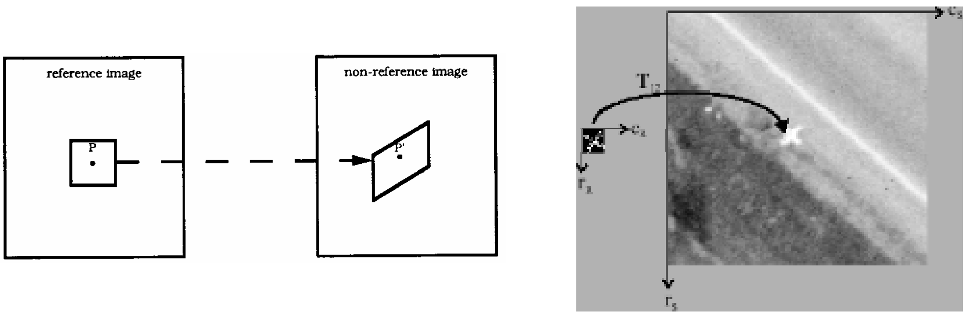


Fig.18 b: *search* and *reference* images with transformation.

Due to radiometric errors and unknown transformation parameters, there will be gray level differences between these two images. If the image patch is small and smoothed, relation between gray values of these two images can be expressed:

		g-gray values
$g_1(r,c)+e(r,c)=g_2(r,c)$	(9)	*e-noise vector caused by different radiometric and geometric effects in both images.*

During computation process the parameters of image transformation are estimated from these observed gray level differences by a least square adjustment, that the vector e is minimized. This adjustment has to be performed iteratively using the corrected transformation parameters of the previous adjustment as approximations for the next one (with every approximation results of parameters are better): The gray values of pixel in the second image are compared with gray values of points in the first one, and the correlation coefficient is computed. The point can be recognized as matched if it's within the chosen threshold. Program needs at least one pair of conjugated points to start analysis. Then these points become the center of searching window. The step of points searching can be defined before matching. The program will choose as the next matched points pair these pixels which have the highest correlation coefficient and move window to this pair. Iteratively whole image will be searched by this method. The center of transformed search image patch after last iteration is taken as corresponding point of template window. The main problem with this algorithm is that there must be good [within 2 pixels] initial estimates of correspondences. Then it is possible to improve results and provide a better estimate.

According to the great number of observations (one observation per pixel of the reference image) and the mathematical model respecting also terrain inclinations, LSM is the most accurate image matching technique. The transformation parameters can be estimated with an accuracy of up to 0.1 pixels. However, it is very sensitive with respect to the quality of the approximations. They have to be known already with an accuracy of few pixels. For that reason, Least Square Matching is often used to improve accuracy as a final step following the application of another matching technique, e.g. cross correlation, for establishing the approximations of transformation. Just as cross correlation, Least Square Matching will fail if the two image patches are not similar; it is especially confronted with problems if there are occlusions connected with surface discontinuities. It can be seen that pixels in homogeneous regions with gray level differences being close to zero do not deliver any information for the determination of the parameters. Some parameters cannot be determined if there are certain dependencies between the gray level differences. For instance, the rotations cannot be determined for circular targets. Least Square Matching can be expanded to more than two images.

2) **Feature Based Matching**- this method uses separated groups of pixels from each image and compares primitives (lines, edges, points). Having detected features in two or more images, correspondences between homologous features from different images have to be found.

Features can be local and global. Some of local features and their mutual relations can describe larger, global features. Relations can be geometric: for example distance or an angle between them, radiometric (i.e. gray value) or topologic. Each feature is characterized by attributes: image coordinates, optical density, orientation, gradient, length and curvature of lines. All these compared features are being correlated independently of image's geometry or density. Features should be distinct with respect to their neighborhood, invariant with respect to geometric and radiometric influences, stable with respect to noise, and seldom with respect to other features.

Point features:

In order to proper distinguishing such features as: spots, corners they should fulfill most important criteria: They ought to be the centers of highly variable areas, hence the variance should be high in all directions. After collecting all attributes of points, they are compared to the threshold, deciding whether accept a feature or not. Because of possibility of mismatching some points that are ambiguous, usually, algorithm use additional computing window to suppress non-maxima noise-neighboring pixels chosen. Within this window only the features with best attribute values are accepted. To detect point features are used some 'interest operators'. They should be clearcut, invariance to expecting geometric and radiometric distortions, be stable, rare, and easy to interpret.

We can distinguish some stages in finding corresponding points: calculating characteristic parameters (usually they depend on gray values, structure or texture within window) for each window in the image or its part, and comparison obtained results with chosen limits.

There are many interest operators, some of them are:

- Foerstner operator: usually is used to detect corners, centers of circularly symmetrical features. Firstly, the gray level gradients of the image by using operator (Sobel, Prewitt) is computed, than the normal matrix N is determinate and two criteria: weight (proportional to contrast), and roundness (error ellipse) are estimated. Also the non-maxima within window size are suppressed, and accurate point coordinates are calculated.

- Moravec operator: calculates corresponding points according to high variances of interested points (in low contrast area any point can be matched) in all directions: vertical, horizontal and diagonal in two directions.
- Hannah operator: similar to Foerstner: detects points with steep autocorrelation function in all directions.

Edges and lines: can be considered as a discontinuity in the function of gray level e.g. gray changes as a boundary of objects: fields, roofs, roads. Some problems appear when in different images the same surface or edge looks different. It can be caused by noise of image, different shape (projection distortion) or by existing more than one similar feature (ambiguity of feature). This problem can be solved that at each level of hierarchy correspondingly sized edge operator is used to searching features in original image. To detect images we can use Sobel, Prewitt or gradient mask working only in one e.g. horizontal direction. Sometimes an image has a noise, so that the very low sensitivity filter is needed. The most popular edge operator is Laplacesian of Gaussian smoothing operator. There are computing second derivates of intensity values. In convolved image an edge pixels corresponds to the zero value. Then the results of computing zero-crossing: contrast sign and angle of edge feature are stored. Matching is then made in the right image, searching for zero-crossings of the same sign, using a single zero-crossing from the left image. To reduce not proper matches a feature and to ensure that they are similar in each image, the neighborhoods of zero-crossings are checked.

The comparison of these methods should take into consideration: matching quality, dependence on image structure, image quality and processing-time of algorithm:

<table>
<tr><th rowspan="2"></th><th colspan="2">Area Based Matching</th><th rowspan="2">Feature Based Matching</th></tr>
<tr><th>Cross Correlation</th><th>Least Squares Matching</th></tr>
<tr><td>Accuracy</td><td>High accuracy</td><td>Most accurate</td><td>Low precision</td></tr>
<tr><td>Initial approximation</td><td>Necessary</td><td>Necessary</td><td>Medium</td></tr>
<tr><td>Multi image matching</td><td>Not possible</td><td>Possible</td><td>Possible</td></tr>
<tr><td>Sensitiveness due to radiometric noise, differences in optical densities.</td><td colspan="2">Very sensitive</td><td>Low sensitive</td></tr>
</table>

All described methods have its advantages and disadvantages. Generally, Area Based Matching is highly dependent on optical density condition of images, shadows, moved and shifted objects, or discontinuity of these objects. In case of Cross Correlation method raising the correlation coefficient threshold may be a solution of this problem, but it produce less matched points. As CC also LSM is very sensitive to initial approximation, but it is a very precise method (up to 0.1 pixel), usually used to improve results of other solutions. On the one hand Cross Correlation is based on a very simple algorithm, is fast but can have ambiguous, many solutions of point choosing especially in low contrast areas. Least Square Matching is low efficient when image texture is pure, and is more time consuming. Feature Base Matching methods give unique determination of primitives with high accuracy and higher tolerance to distortion or illumination problems. Furthermore FBM requires taking into consideration big region to extract features in the lower contrast image, so that it is more computation and time consuming than Area Based Matching methods, and results may contain gaps-in this areas, where there is no texture on the image. Usually the combination of methods is the best solution. Feature Based Matching can be used to detect seed points to improve approximation in Area Based Matching-Least Square Matching methods to obtain high accuracy of process.

2.4. DEM-DSM FILTERING:

Digital Elevation Models from both scenes of Cartosat-1 we can obtain only by filtering of generated DSM. Elimination of ground points located on the artificial or natural non-terrain-objects can be done in program RASCOR. There are several methods of data filtering: spline approximation, shift invariant filters, linear prediction, morphological filters and others. The filter methods always are based on the local neighborhood. Most filtering conception are based on investigations about objects discontinuity.

RASCOR enables the filtering of data with previous defined characteristic of terrain relief. Different algorithms are used in different areas.

Generally RASCOR investigate the terrain in X and Y direction or in a sub-area in relation to the neighborhood. Short or long profiles dependently of terrain characteristic are checked.

For example, for flat regions simple moving plane interpolation will be used. It is based on preliminary estimation of the terrain: the same type or various type. In the next step undulation of terrain:

-flat area will be interpolated by moving plane
-rolling by tilted plane
-mountainous by polynomial surface

RASCOR investigates, analyzes and creates their histograms of *height differences of neighboring points* in X and than Y direction, and estimates usable thresholds. This helps to establish which points have to be eliminated at first. Firstly, the height distribution is checked to confirm that area is homologous and to establish some data limits. The maximal differences in relation to neighbored points in both directions, shows this thresholds. After elimination of points beyond minimal or maximal height, the height differences of neighbored points in X and Y directions are computed. The lower point will be kept, the higher will be removed. Program will also analyze the height values against the mean value of 5,7,11,15,21,31 neighboring points in X, Y directions. It is useful in elimination of blunders, because in most cases the lower point will be kept and the highest point will be removed. This simultaneously will help in elimination of buildings. Investigations made also in Z values in both directions can detect a 5 time-overflow of height change limit multiplied with factor of distance between neighboring heights. If this change firstly goes up and then down this means that algorithm can recognize object as a building.
After this preliminary filtering, in case of undulated terrain, a moving plane by polynomial interpolation of second degree will be used. As required by the terrain, the profile investigations will be made on short and long distances. In case of rolling area tilted planes are used and for mountainous area a polynomial surface of second degree. For further investigations a sub-area may be chosen: buildings, trees. The last possible option is also prediction, also named least square interpolation.

2.5. DEM accuracy:

The accuracy of a DEM is subject to many factors such as the number of sampling points, the spatial distributions of the sampling points, the methods used for interpolating surface elevations, the propagated error from the source data, and other factors. DEM accuracy is presented as an RMSE of observation discrepancies, frequency distribution, accuracy as function of slope or accuracy of interpolation.
In this investigation the influence of interpolation and terrain relief will be studied.

RMSE of observations:

According to

$$\mathrm{RMSE} = \pm\sqrt{\frac{\sum_{i=1}^{n} DH^2}{n}} \qquad (11)$$

The root mean square error defines differences between values of Z-coordinates (H) and equivalent values of Z of reference points in n-observations.
It certificates about accuracy of interpolated DEM in relation to topographic surface and rate of fitting generated model into real terrain surface.

Accuracy is also a matter of terrain inclination, that we can express with formula:

$$SZ=A+B*\tan slope(\alpha) \qquad (12)$$

Where it is linear dependency with α as terrain inclination.
This dependency appears mainly in undulated and rolling areas.
Root Mean Square discrepancies against reference model are checked by the program DEMANAL and the results can be seen in the table 4.
By this software, characteristics of accuracy can be given. It is possible to define some special areas, for example forests, where height may be less accurate than in others. Analysis are derived by using reference model in raster (equal point spacing) form. All characteristic can be represented as diagram of accuracy as a function of terrain inclination or frequency distribution.

III. RESULTS:

Whole investigations were made in software created in University of Hannover DPLX and DPCOR for matching, DEMANAL to characterize DEM, and filtered with RASCOR.

3.1. MATCHING:

The first step of investigations was matching made in DPCOR program.

Matching was taken in three different parameters:

There were: the threshold for the correlation coefficient, size of search window and step of searching.

1) Distribution of correlation coefficient:

The influence of correlation coefficient value was investigated in both Warsaw and Mausanne scenes. Result is presented as statement of points distribution: numeric and graphic:

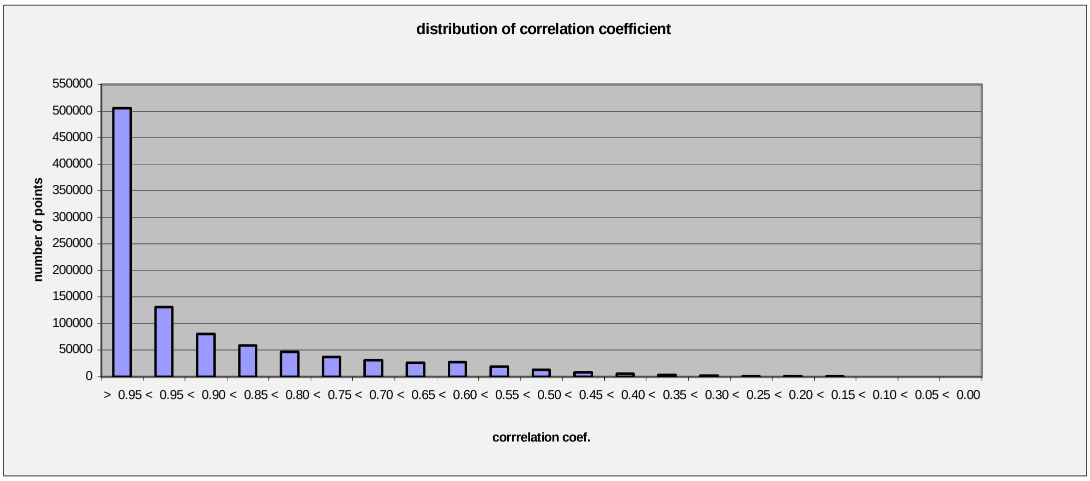


Fig.19a: Distribution of correlation coefficient (scene Warsaw) –correlation coefficient=0.6; searching window 10x10; step=3.

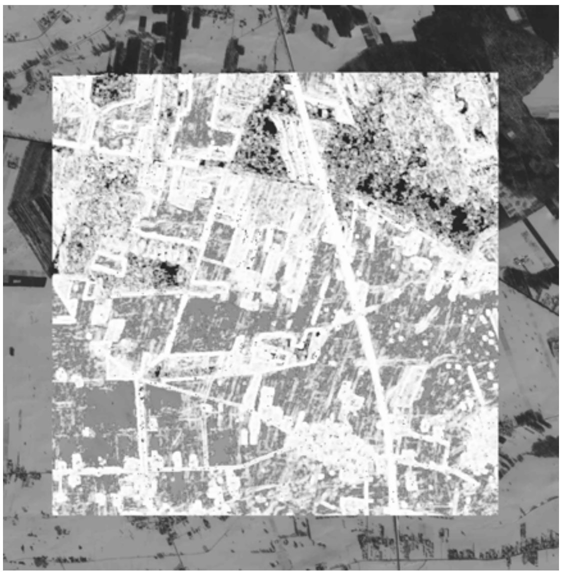


Fig.19b: Quality image: overlay of image and image points, representation of correlation coefficient as gray value(0-255)
mask of matching (white color-best results gray value 1=1.0 correlation coefficient)

Here are presented results from matching with a threshold of 0.6 for correlation coefficient value as a most optimal option. Figures 19b, 20b, 21b and 22b show image areas and conditions of matching. The gaps in a matching-results-mask present places, where correlation coefficient was below the limit, so that points weren't respected as conjugate. Such difficulties are connected with weakness of this method, namely contrast of image. Areas with low variance of gray value are most problematic. Forests and open areas (especially with snow cover) -low contrast of pixels brings the worst effects. The sane situation can be observed in shadow regions:

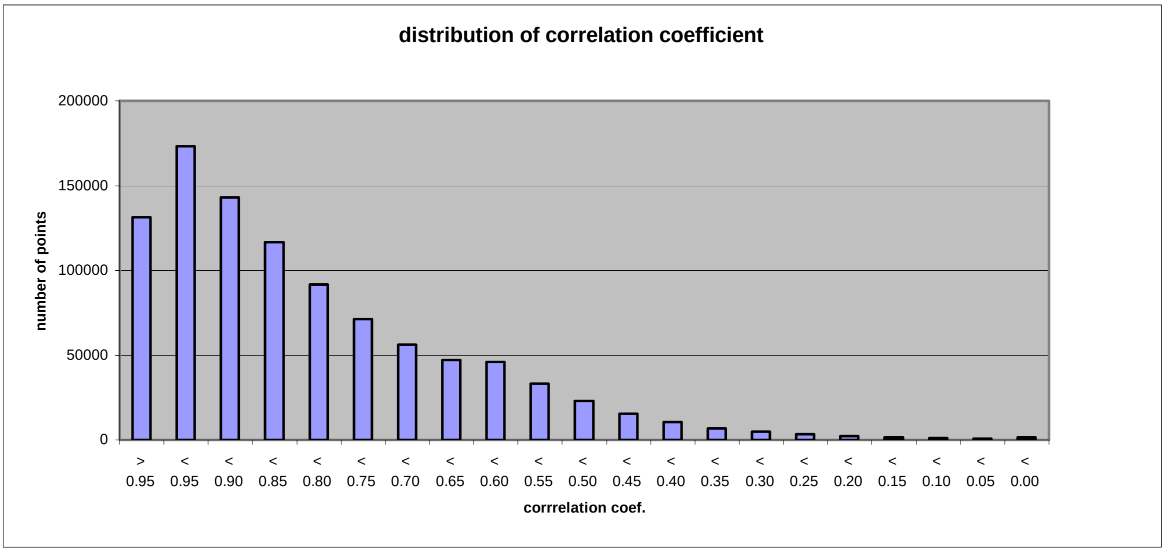


Fig 20a. Distribution of correlation coefficient of matched points in Mausanne scene mountain areas (correlation coefficient=0.6, search window 10x10, step=3).

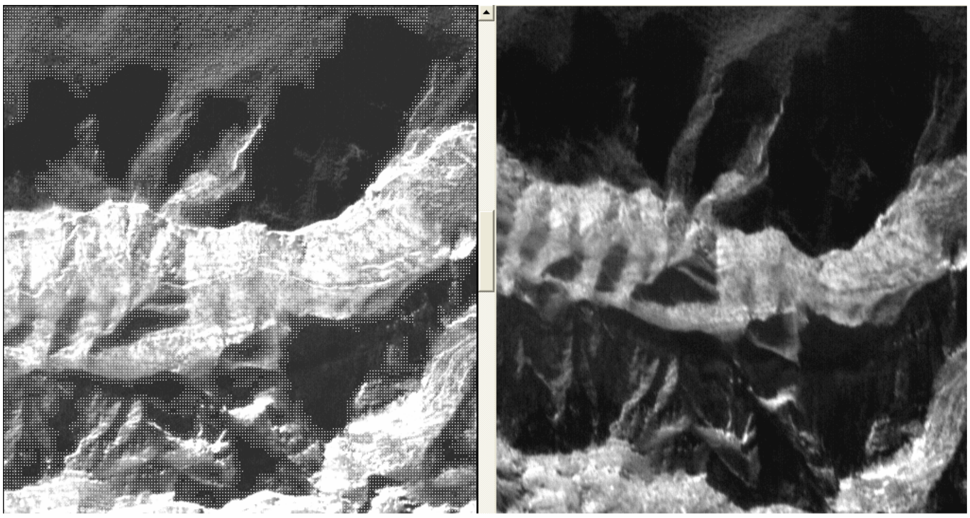


fig 20b. On the left: mask of matching. Area covered with mask represents values of correlation coefficient above threshold(0.6) and on the right original image to comparison. (Mausanne)

This is very visible in mountainous areas (figure 20 b.), where high slope caused shadows in lower terrain. Such dark parts of image cannot be recognized. Generally, though rolling terrain causes big problems in recognizing points, the well lightened scarps revealed many details, so that finally most of terrain was covered in well-matched pixels pairs. The least problems bring: fields boundaries, roads, build-up regions. They are matched well and most of points are classified in range of <1-0.95> correlation coefficient value, and that gives sure results. Different situation (just like previous data set) is in high variance contrast area:

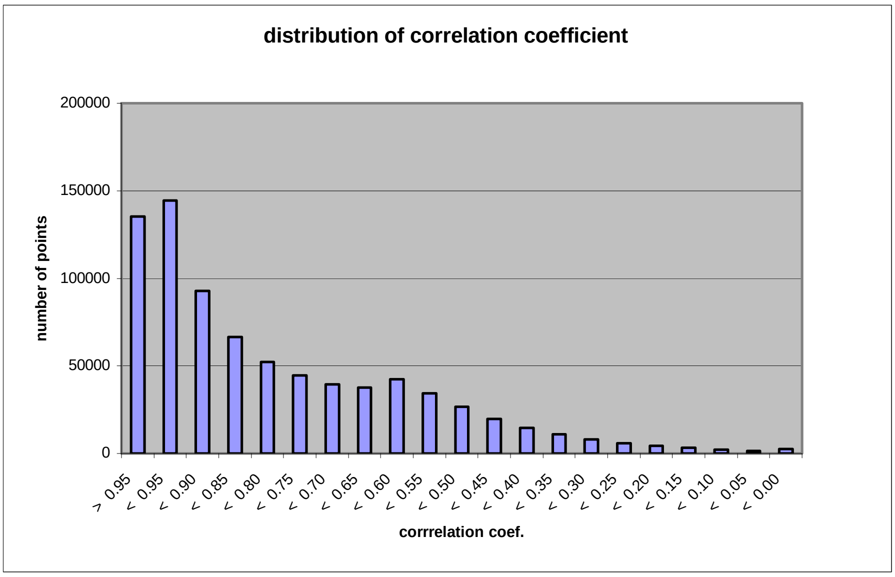


Fig. 21a: Distribution of correlation coefficient of matched points in Mausanne scene – flat area (correlation coefficient=0.6, search window=10x10).

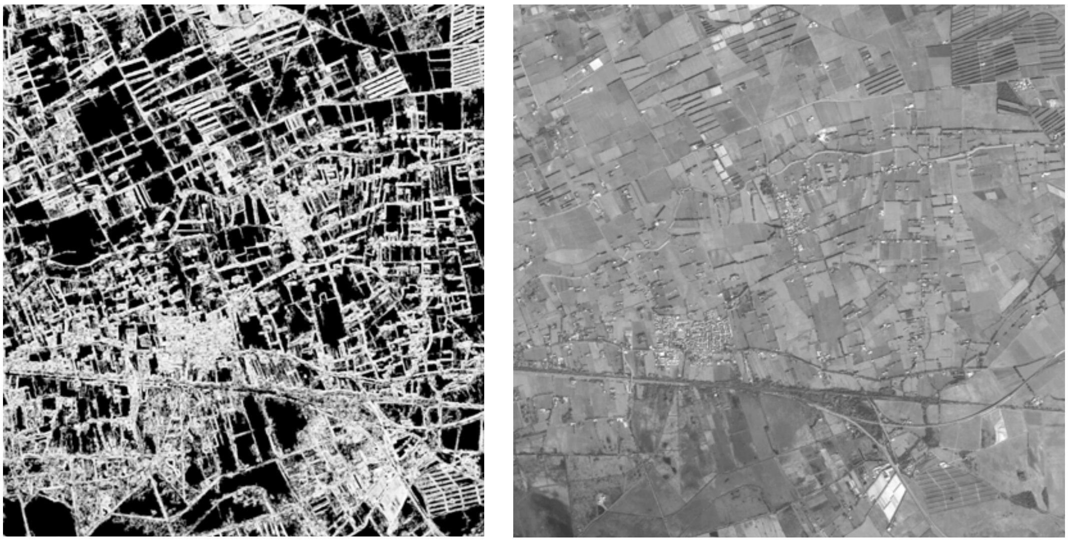


Fig. 21a: on the left: only a mask of quality image (white color best results gray value 1=1.0 correlation coefficient)	on the right side original image

In case second data set (Mausanne) most of points are ranged in <0.90-0.95> (fig.21a). and there is no problem with finding details.

Statistical results are compared in tables:

% matched points	R=0.45 Step=3 Window size 10x10	R =0.6 Step=3 Window size 10x10	R =0.8 Step=3 Window size 10x10	R=0.6 Step=1 Window size 10x10	R=0.6 Step=3 Window size 5x5
Open area	**93 %**	**86%**	**64 %**	**98 %**	**20 %**
Build up	**96 %**	**91 %**	**75 %**	**99 %**	**40 %**

Tab1. Results from Warsaw scene, percent of matched points in different matching parameters.

	R =0.6 Step=3 Window size 10x10	**R=0.45** Step=3 Window size 10x10
build up area and mountainous	**84 %**	**90 %**
open area	**70 %**	**75 %**

Tab 2. Mausanne scene percent of matched points in different matching parameters,

As we can see in table 1 and 2, the higher the threshold for correlation coefficient , the number of properly matched points is lower. Decreasing value of coefficient enlarges the number of matched points. Similar effects presents Mausanne scene. With growing tolerance we can expect better results with little decrease of accuracy.

2) Matching step width:

Second condition submitted to consideration was matching step width. This parameter is connected with area of searching correspondences. Step determinates how precise and how compute-consuming analysis are. The lower value of this parameter is, the higher number of studied points is.

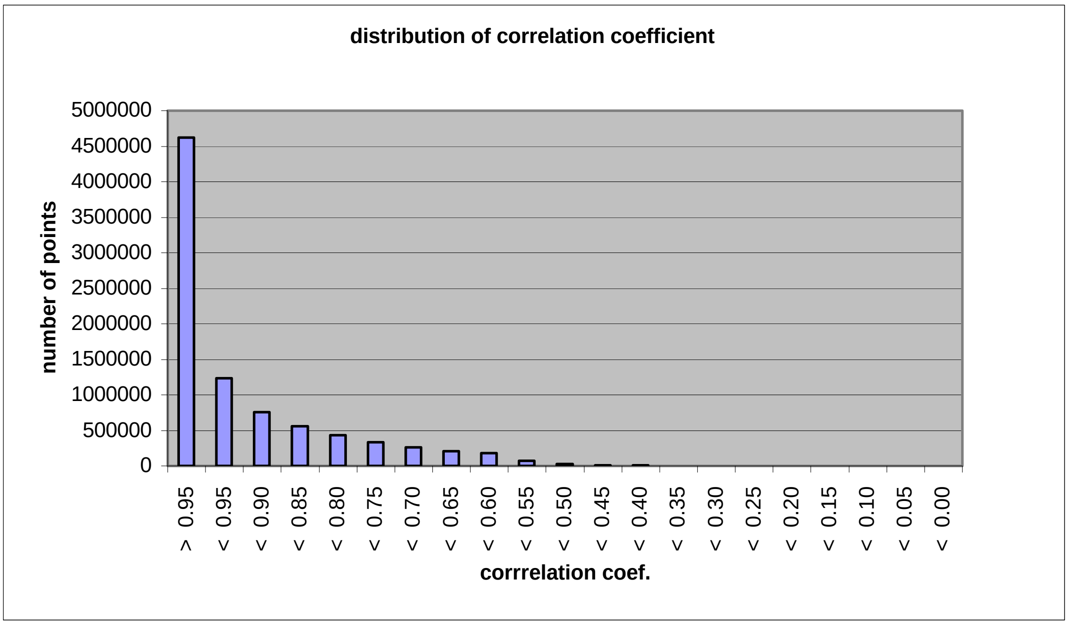


Fig. 22a: Distribution of points in one-step matching.

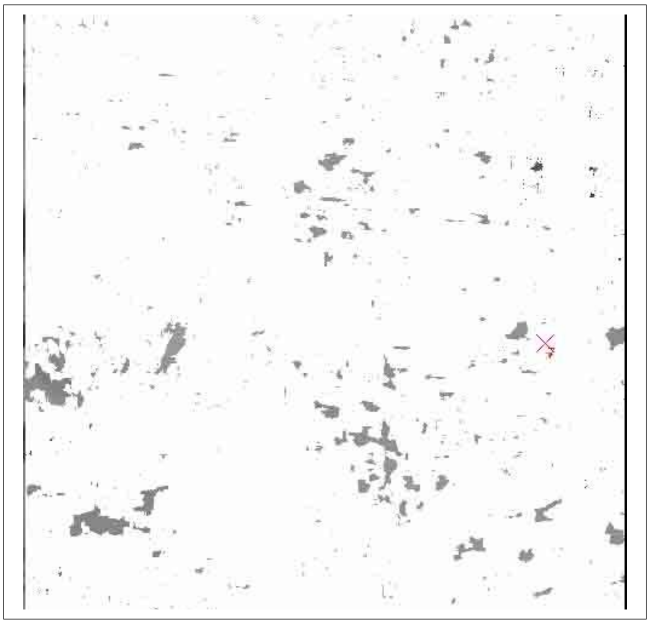


Fig. 22a:
Image quality mask of matched area; representation of correlation coefficient as gray value (0-255) mask of matching (white color best results gray value 1=1.0 correlation coefficient)
one step matching, correlation coefficient = 0.6.

In comparison, the 3-step matching we can see in the table 1 and the mask of matching in the figure 21.a. on the first side, the number of matched points is incomparable higher. But, decreasing of step value brings also satisfying results (about 90 % of points above correlation coefficient's limit). As it can be seen on figure 19.a., the highest percent of matched points with every 3 pixel step matching, is in the range <0.90-0.95> of coefficient distribution. Searching in every raw and column step (so every pixel) leads to most reliable results, but in fact also to similar accuracy of DEM, but is much more time and space consuming.

1) Searching window:

Searching window is an area in which conjugate points are being searched. Changing its size leads to enlarging or reducing search area. In regions with small contrast decreasing window size decreases also number of matched points. With larger window, in the build up areas percentage of matched points is much higher than in open ones. It follows from higher contrast of neighboring points. Smaller searching window (5x5) gave worse results.
The smaller size of window the smaller number of matched points. It is very visible in open areas, (fig 23a), where percentage of matched points is very low. It comes from problems with finding corresponding points in both images, where contrast was low and search area small. But there was no problem with corresponding points in case of objects with high contrast even with small search window (there is much more comparable details):

Fig. 23a: Image represents area with matching parameters: correlation coefficient r = 0.6; search window 5x5, step 3 (dotted regions shows conjugate points)	Fig.23b: Image represents area with matching parameters: correlation coefficient r = 0.6; search window 10x10, step 3 (dotted regions shows conjugate points)

Too small or too large areas for searching points do not give good results. In order to matching step and matching method, window size should allow to search sufficient gray variations of conjugate pixels pairs in different directions. Window 5 x 5 is too small for investigations for every third pixel.

DTM accuracy	R=0.6, WINDOW SIZE 10X10 STEP = 3	R=0.6, WINDOW SIZE 5X5 STEP =3	R=0.6, WINDOW SIZE 10X10 STEP = 1	R= 0.8, WINDOW SIZE 10X10 STEP = 3
Before filtering	**2.92 m**	**3.84 m**	**2.71 m**	**2.75 m**
after filtering	**2.22 m**	**3.34 m**	**2.17 m**	**2.20 m**

Table. 3: Presents DSM and DEM accuracy according to matching parameters in Warsaw scene.

Conclusions:

Matching processed by this method have even sub-pixel accuracy. Best results we can achieve using different matching parameters to different areas. The most optional results for build up areas are 0.6 coefficient 3 step matching and 10 x 10 search window.

Good results we can obtain using for open areas r = 0.45 though, this solution may not be efficient, because enlarging number of corresponding points, it doesn't increase accuracy. That can be dangerous and suspicious, as in fact we obtain more conjugate points which might not be unique.

Better effects of matching and accuracy are in the first data set from Warsaw. It can be caused different terrain conditions (flat area easy to interpolation (DEM accuracy), better matching results), image taking conditions (weather, season) or accuracy of Ground Control Points.

Negative influence on efficiency of this matching method have:

➢ Low image contrast connected with:

• terrain structure (fields, forests, buildings)

• season (snow coverage)

• repetitive structure

➢ Ambiguity of objects

➢ Terrain relief (high slopes, shadows)

➢ Method parameters:

• correlation coefficient threshold

• size of searching window

3.2. DSM & DEM ANALYSIS:

MAUSANNE AND WARSAW REGIONS:

3.2.a. Digital Surface Model:

Digital Surface Model is a product of image matching. Its accuracy can be presented by RMSE, bias value, inclination, or accuracy of rays intersection. Value of error is dependent on terrain type, accuracy of data and image matching.

Components of accuracy:

1) Root Mean Square Error and bias correction:

DSM accuracy corresponds to RMSE which certifies about accuracy of terrain surface projection in reference to known another terrain model. (see chapter 2.5.).

Warsaw scene:	**RMSE [m]**	**Bias [m]**	**RMSE without bias [m]**
Open and forest area	**4.09**	-1.00	3.97
Filtered open area	3.05	0.64	2.98
Build up area	2.63	-0.26	2.61
Filtered build up area	1.97	0.74	1.83
Filtered (second iteration)	3.84	2.26	3.10
Mausanne scene:			
Mountainous area	3.83	1.48	3.53
Filtered mountainous area	3.88	2.58	2.90
Whole area (Mausanne)	4.02	0.58	3.98
Filtered whole area	3.71	1.84	3.22

Table 4: Results of DSM and DEM accuracy from both Warsaw and Mausanne scenes according to root mean square error, residuals with control points and RMSE without bias.

Mausanne (mountainous area); Warsaw (build, up, open and forest area)

The root mean square error of DSM is lower for open area with very low buildings, fields and forests. It is caused by low contrast differences and almost unchanging pixel values, what in case Area Based Matching method is very crucial. Little better results we obtain in mountainous area, while there is more small shadows connected with undulated terrain relief giving more diversified texture. Best results are in build up area (Warsaw scene), where such objects as: roads, buildings, fences, human-made objects raise accuracy and distinction of surface features. Also bias correction (with control point's improvement) indicates on terrain characteristic: negative values appears in flat open-forest area and build up area in reference to template model. Sudden changes and protrusions above the ground objects are obstructions in interpolation. Bias correction is a result of comparison tested model with reference model, using coordinates of ground control points. Its sign indicates on type of correction. Negative presents objects above the ground.

2) Slope

Accuracy depends also from terrain inclination, connected with sometimes sudden, quite high changes in terrain elevation. This influence is most visible in Mausanne scene and can be presented as equation:

$SZ=A+B*\tan slope(\alpha)$ (12)

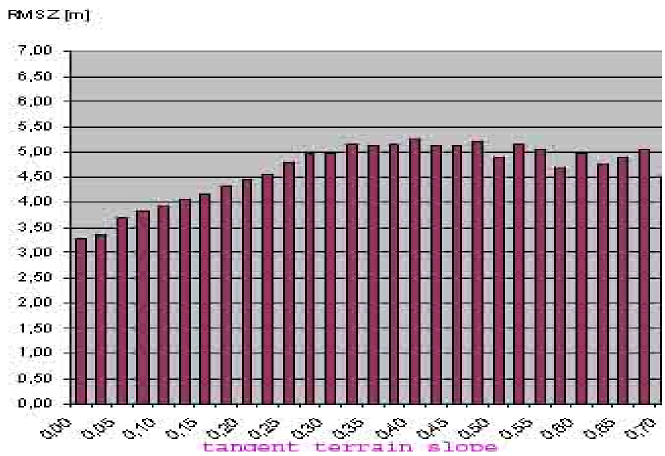


Fig. 24: Error of DEM as a function of terrain inclination (Mausanne area)

The average RMSE filtered data: 3.26 + 2.957. With growing terrain inclination error is bigger, but accuracy depends also from type of terrain:

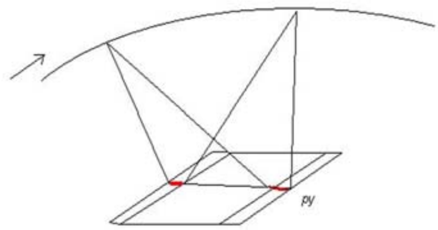
Warsaw:	**SZ as a function of terrain inclination [m]**
Open area (but also forests)	3.73 + 9.575 * tanα
Filtered open area	2.93 + 1.839 * tanα
Mausanne:	
Mountainous area	3.48 + 1.091 * tanα
Filtered mountainous area	3.09 + 4.051 * tanα
Whole area	4.04 – 0.516 * tanα
Filtered whole area	3.26 + 2.957 * tanα
Filtered whole area 2^{nd} iteration	3.35 + 3.142 * tan α

Table 5: Results of Models accuracy as a function of slope both of Warsaw and Mausanne scenes.

In the case of this dependency results are similar to RMS errors. As we can see in fig. 24 and table 5, terrain inclination brings some problems during filtering, especially areas with vegetation cover.

The DEM accuracy was almost linearly correlated with the terrain slope, with the larger errors in the steepest slopes. For the aspect, the best and worse results generally occurred in the fore-slopes and back-slopes. Finally, the more pronounced the relief, the higher the correlation between the elevation accuracy and the aspect is, the larger the variations of the elevation accuracy are.

3) PY limit:



Parallax limit conditions and accuracy of work. Ground coordinates of corresponding image points are computed by intersection of rays (fig. 25).

fig.25: Parallax p_y

Rays may not intersect exactly, that’s why there have to be chosen p_y limit. Thus, very important in generating model is value of toleration of parallax (p_y) :

Differences in DEM accuracy brings changing of py limit.

Py limit	DSM accuracy	RMSE py	% of not accepted points
3.00	2.96 m	1.13 m	10
1.50	2.77 m	0.71 m	30

Table 6: p_y limit and accuracy (Warsaw scene)

Root mean square errors of parallax –y, are presented in table 6. with the py limit corresponding 1,2 pixel in the image mean error equals about 1 meter. About 10 % of intersected points were not accepted because of exceeding tolerance threshold. Some of points were even 28 meters out of this limit. With smaller limit of passing rays py=1.5 m (corresponds 0.6 pixel) number of not accepted points is lower, and values of this discrepancies exceed even 40 m the tolerance.

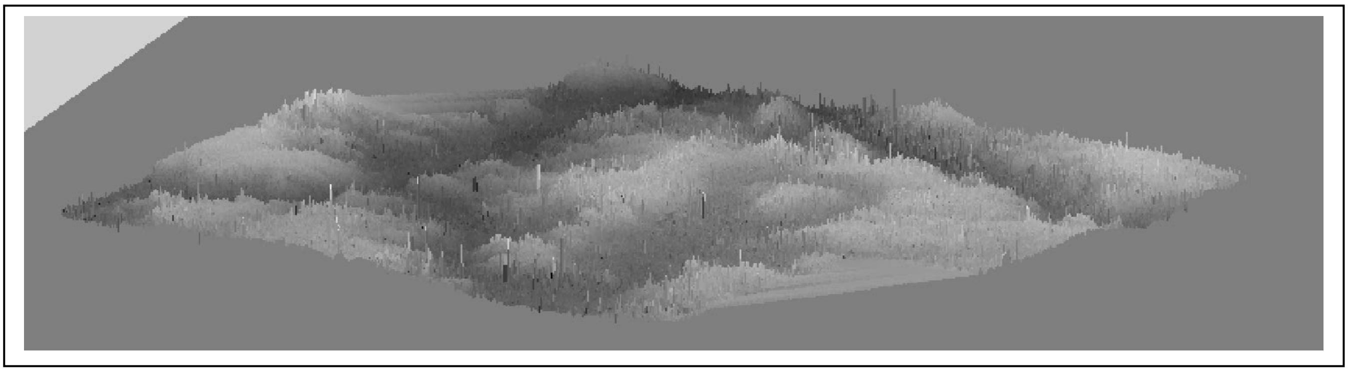


Fig. 26: DSM with p_y limit = 3.00, Warsaw scene.

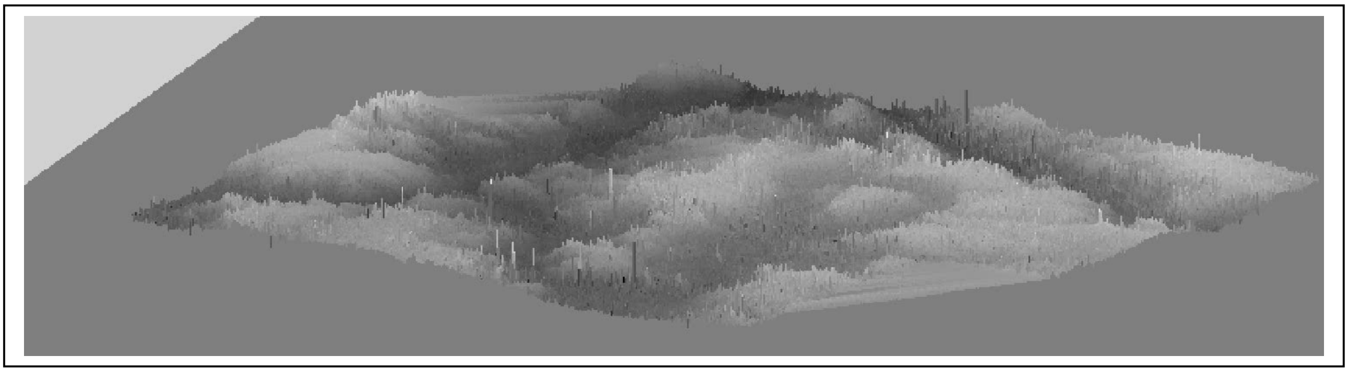


Fig. 27: DSM with p_y limit = 1.5, Warsaw scene.

With smaller p_y limit there is more detail data with higher accuracy of surface model. Obviously the percentage of not-accepted points is much lower with decreasing p_y tolerance. Decreasing this parameter allows on better representation of ground objects. Error of surface model according to reference model is lower with smaller tolerance, because ground points are determined more precisely. As well less undesirable elements are eliminated from model. Changes are visible, but they are small, seldom and have small influence on the final result.

3.2. b. Digital Elevation Model and filtering:

Filtering bases on the different surface interpolation methods, suitable for certain terrain characteristics. With program RASCOR filtering can be made according to terrain texture and undulation.

Table 7 shows results of filtering algorithm of program RASCOR.

Most of points are removed in the filtering process using polynomial fitting, which is most suitable for built areas.

% **WARSAW**:	Z DIFFERENCES NEIGHBORED POINTS	POLYNOMIAL FITTING	POLYNOMIAL SURFACE	NOT USED POINTS
Build up (low) area	13 %	30 %	1 %	63 %
Flat area(also some vegetation)	16 %	19 %	3 %	37 %
MAUSANNE:				
Mountainous area	13 %	17 %	3 %	34 %

Table 7: percent of eliminated points in different filtering steps: Mausanne and Warsaw.

Majority of points (63 %) was removed in build up areas where there was plenty of artificial or men-made objects on flat area. It is quite easy to detect non-ground objects. More problems occurred in unchangeable surface on long distance and in mountainous regions.
For flat areas, most of points were removed by analysis of height distribution and its limits. Then, in dependency of terrain relief, polynomial fitting and profiling is used. This algorithm was most crucial in built area.
Results of filtering is presented in the table 7, as well on frequency distribution diagram-figure 28.

The were investigating undependably two areas : Warsaw- flat terrain, and Mausanne- the rolling one.

WARSAW:

There were taken two things into consideration:

1) Number of iteration in filtering process:

	Before filtering	one iteration	two iterations	
			First	Second
DEM accuracy RMSE	**2.92 m**	**2.22 m**	2.32 m	**2.07 m**
% filtered points		57 %	72 %	

Table 8: Results of second iteration (Warsaw scene) presented as RMS error and percent of eliminated points.

2) Frequency distribution of dz as f(dz):

The influence of elements not belonging to the bare ground can be also shown by distribution of heights. Negative values are seen as point located on the objects above the ground.

This diagrams can be compared before and after filtering to see changes in distribution of model's points.

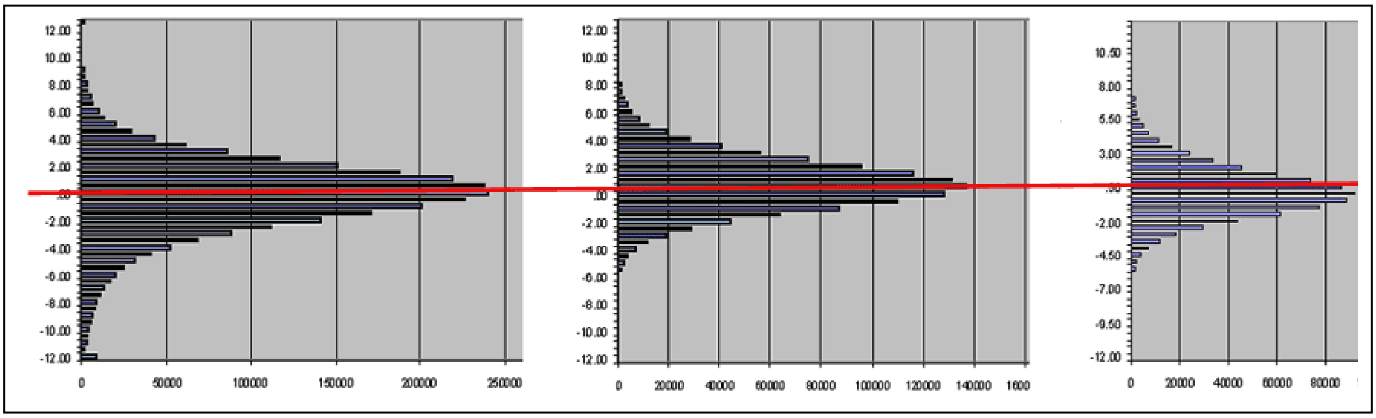


Fig. 28: Frequency of distribution of whole investigated Warsaw scene. From the left: DSM, DEM after first and second iteration.

First iteration removed about 60 % of points-mostly considerable objects, in the second iteration there were removed about 70 % of rest of points. Figure 28 represents frequency of distribution. It corresponds to influence of objects above bare ground. In the graph of not filtered area, the diagram of height differences function has some noise on the margins. Filtering improves results, removes not needed points and makes diagram more symmetric. Figures below shows models before, and after filtering of the Warsaw-flat, open area.

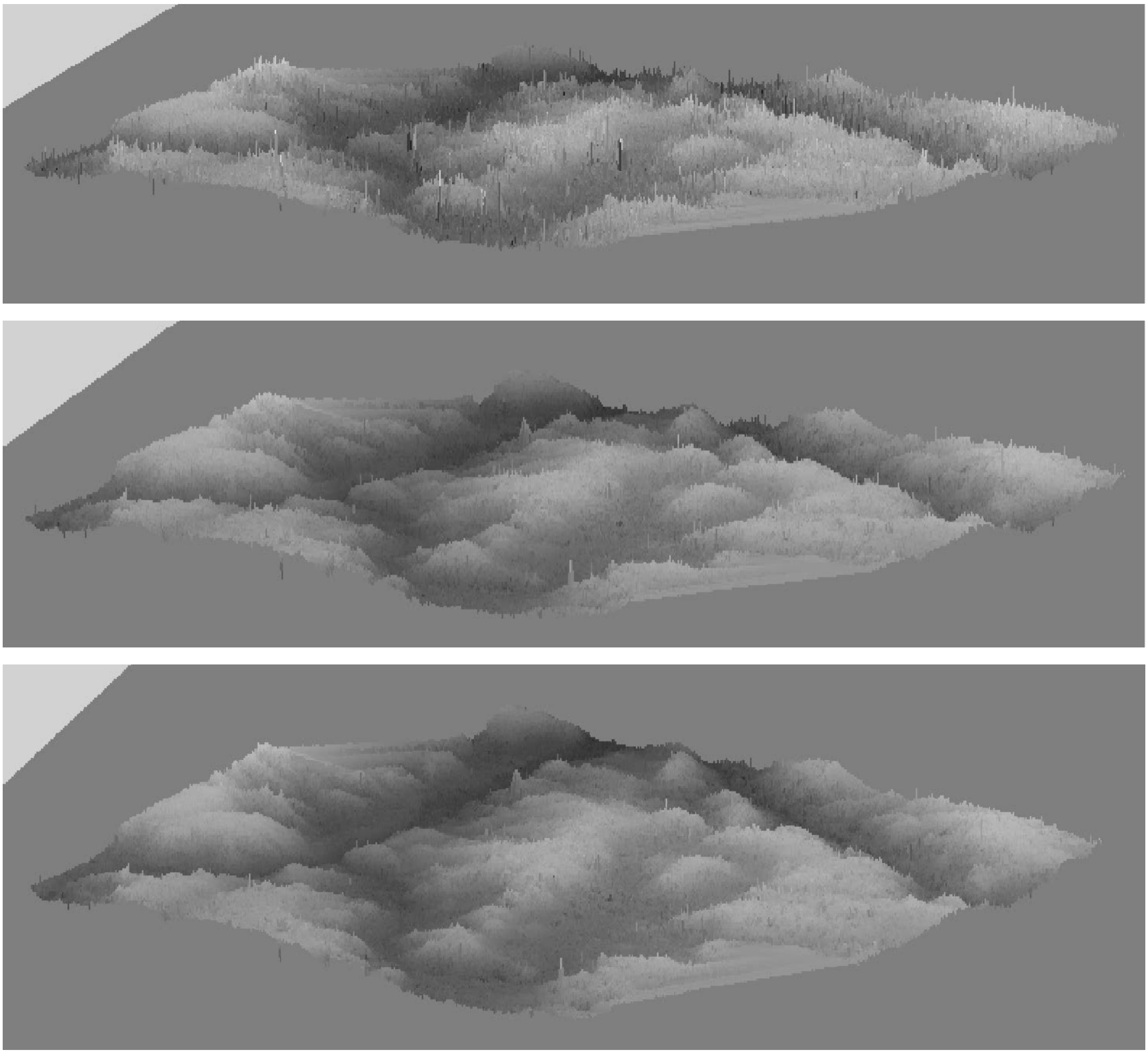


Fig. 29: From the top: DSM, DEM with the 1st iteration and with the 2nd iteration.
Area from Warsaw data set, open flat regions.

Differences between not filtered and filtered data are visible. The surface is more smooth and the ground's exposure is better. As it can be predicted, second iteration of removing terrain objects was not necessary. First iteration removed almost completely objects not belonging to the terrain, second filtering was not required. Single peaks and rest of small elements are removed. Table 8 presents accuracy and percent of this removed elements.
The accuracy of DEM is higher, but it follows from fewer number of points.

MAUSANNE:

Second area-Mausanne was investigated in respect of different terrain coverage: flat, almost bare ground with small objects and rolling regions with some forest coverage.

Figures below show distribution of frequency according to different surface types:

Mountain, forestry terrain:

Digital Surface Model Digital elevation Model

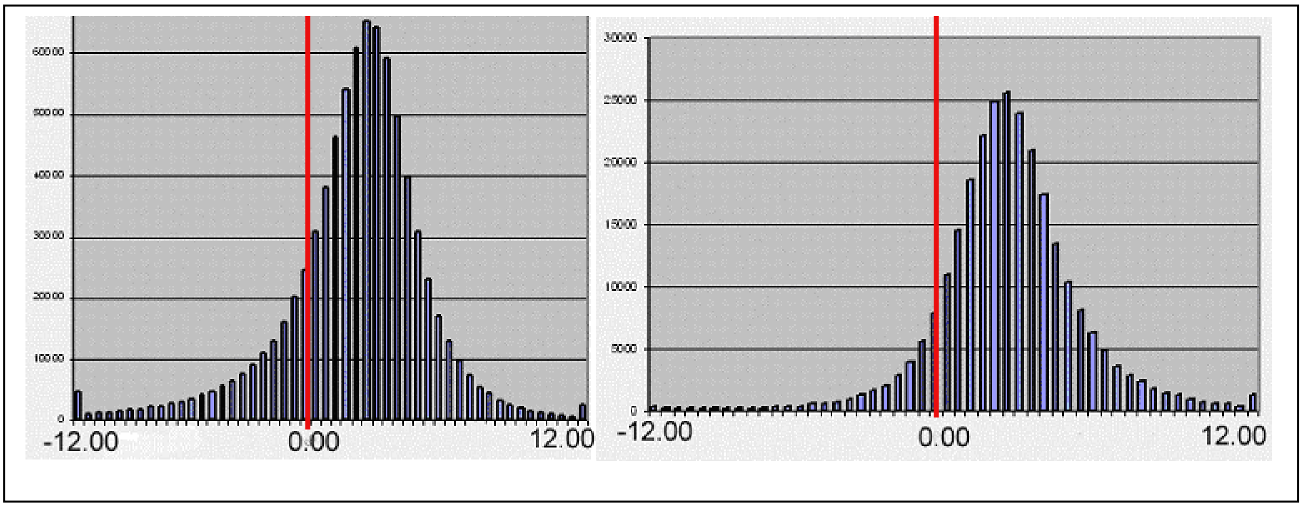


Fig. 30: on the left: distribution of frequency of DSM and on the right : DEM mountain terrain(Mausanne).

The diagram of frequency distribution of height differences of not filtered area represents discrepancies in respect to the reference file (left side of figure 30). Values on the right side of the red line indicates on some objects above the ground. After filtering in mountainous area there were problems with estimation and distinction of ground cover with height differences. Diagram is more symmetric, and the noise is removed. During filtering there were removed about 35 % of points.

Open area:

Filtering in open areas with low buildings was also needed. Results are better than before filtering. The frequency distribution is more asymmetric, but shows that big errors (figure 31 on the left) and discrepancies in comparison to reference model are removed. Also root mean square error is smaller.(see table 4 and 5).

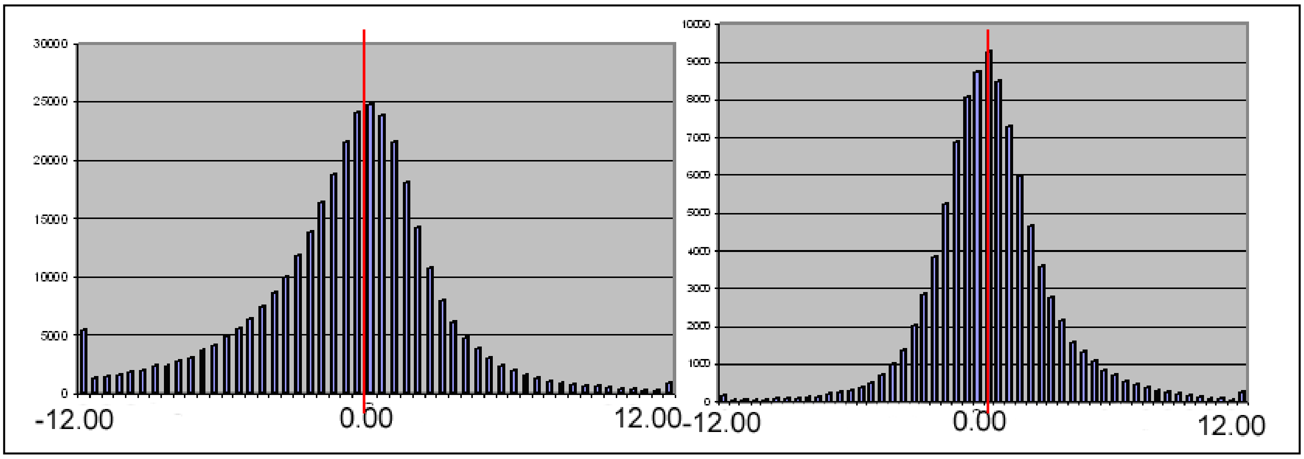


Fig. 31: distribution of frequency: DSM (left) and DEM (right) open area of Mausanne scene.

Results for whole area: Area before filtering, and after: There are visible changes in flat area, where there were removed most of points. This differences are quite small because of not so many above-ground objects.

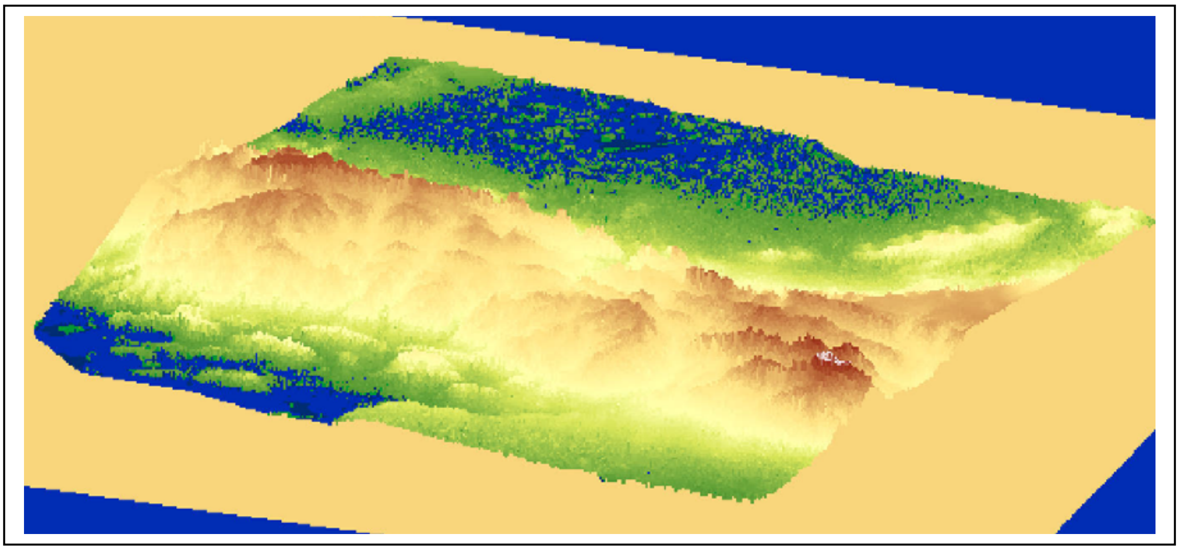


Fig. 32: Digital Surface Model of Mausanne area.

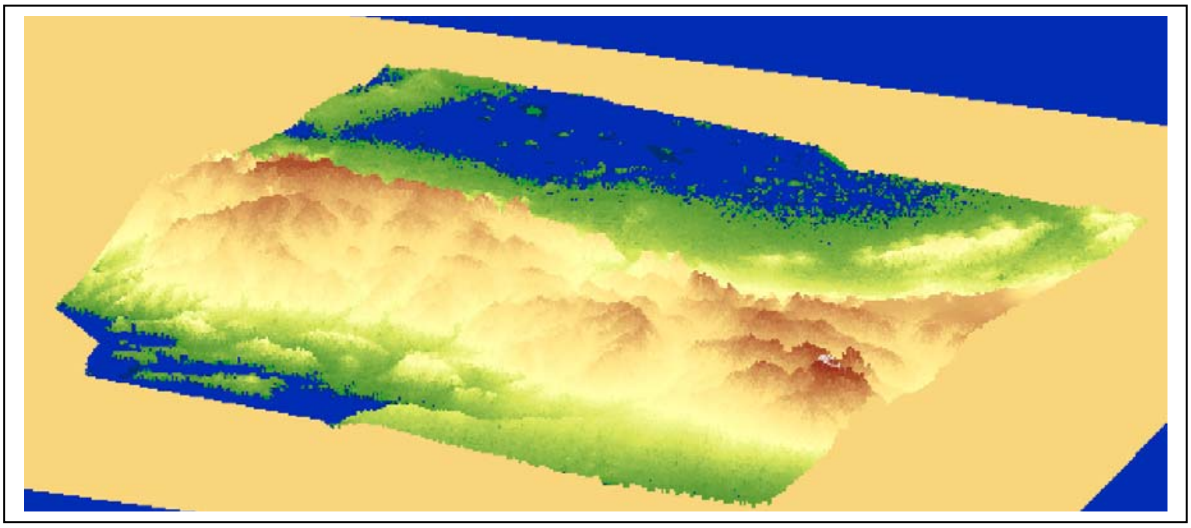


Figure 33: Digital Elevation Model of Mausanne area.

Very small part of objects was removed. Mostly there were pick value (left part of mountains) and some elements in left corner of image.

Generally filtering improves results. But very important is number of iterations and terrain relief. Filtering increased accuracy of whole investigated area about 0.8 m and gave mean value of RMS error for both area about 3.80 m in reference to template Digital Elevation Model.

Filtering of data was needed and didn't bring much problems. Usually one iteration was enough. After this process, the noise and random peaks were removed, giving more precise representation of terrain, heightens accuracy in response to reference files.

Different surface interpolation methods gives best results suitable for certain terrain characteristics. After filtering models were smoothened, ground exposure was better, noise and big errors were removed. Distributions of heights also were more symmetric. As it could have been predicted-second iteration in the flat area was not necessary. Most of points in flat area, with low building and some vegetation were removed by analysis of height distribution and its limits and by polynomial fitting.

In comparison to this investigations also data from laser scanning will be filtered.

FILTERING OF LASER SCANNER DATA.

Data acquired from laser scanning differ from space images. Random points clouds from vegetation area is very specific. The laser beam has a characteristic ability of penetration through existing gaps in plant cover and to register several reflections connected with single pulse. This makes it possible to establish basic vegetation parameters, such as trees' height, diameters of their crown, density of afforestation, estimation of biomass, determination of forest borders. Very often data from scanning is provided as preordered grid. This is based on interpolation of grid points supported by spread laser points. With such a "reduced" data, filtering it is possible to use simplified algorithms.

Filtering is especially difficult in forest areas, because of partial plant cover penetration. Not always laser pulse reaches the ground, and also trees may have different heights and density. Usually filtering with one iteration is not enough to remove all vegetation elements. Below results are presented showing the removing of terrain objects from the rolling area of Harz Mountains in north-centre of Germany. Filtering has been made with program RASCOR using a different number of iterations (fig. 34).

Two iterations are not enough in case forest area. In the first step program removed only the highest trees. Hummocks and glades were recognized properly and remained as terrain relief. Already after 7 and 8 iterations, even small terrain objects seem to be eliminated.

Obviously a small number of elements not belonging to the bare ground are remaining. It can be caused by not-compound distribution of trees in not the same heights and small "gaps" in forest cover. On the slopes, earlier covered by vegetation, bare ground after filtering is rough, because of difficulties in estimation real tree heights in densely covered areas. Small remaining discrepancies can be eliminated by using mean or median filters.

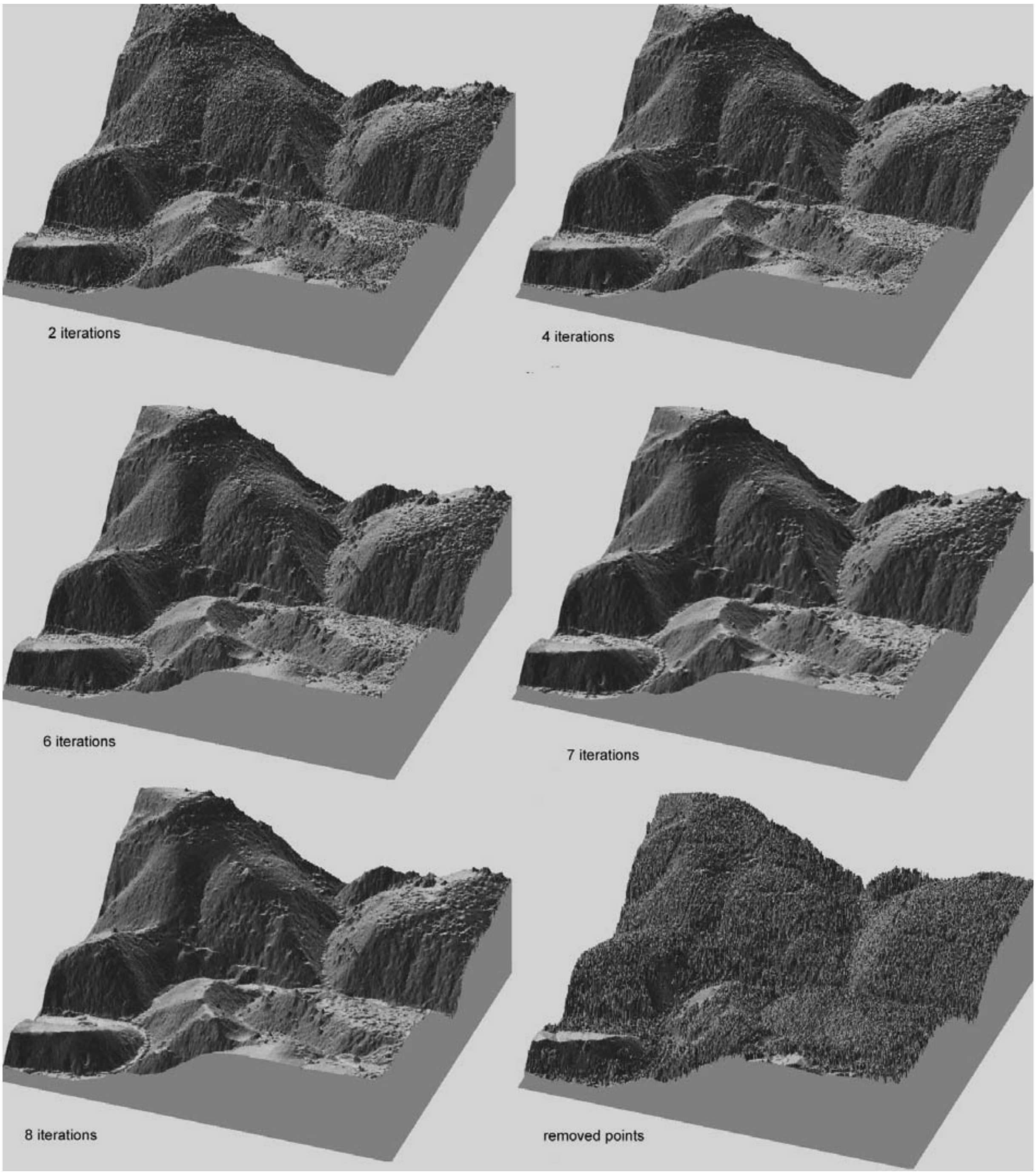


Fig 34: filtered models: from the upper left to lower right: filtering by 2/4/6/7/8 iterations, and removed object points.

Two files: with raw, not filtered data and bare ground model files were compared and are presented as differential model:

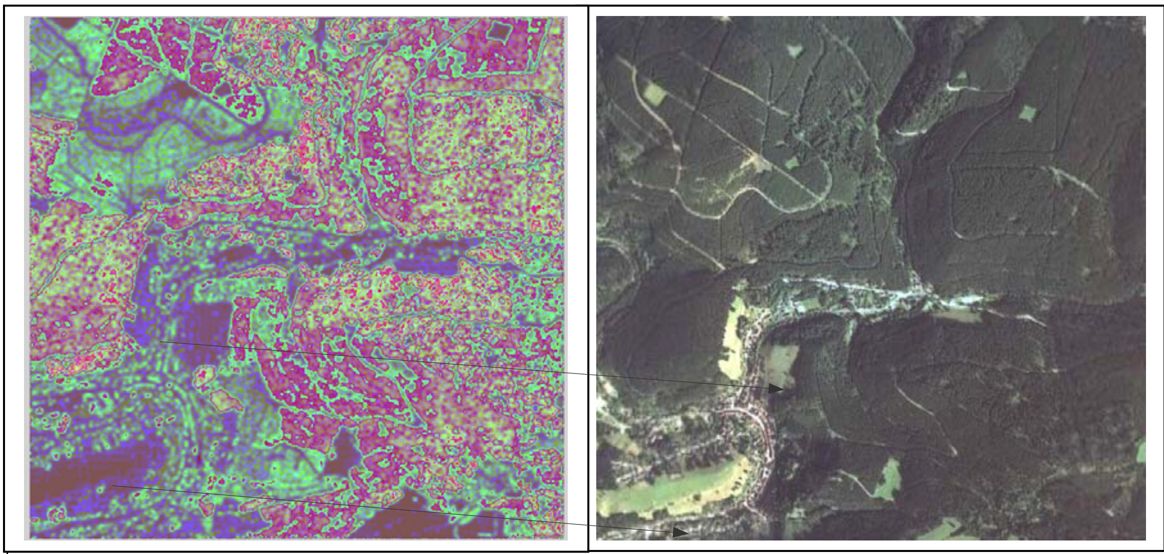
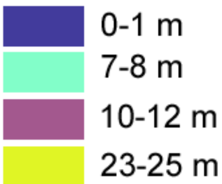


Figure 35: differential image of two files: DSM and DEM. Blue areas indicates on no differences between models (so not covered regions) and green, red, green present differences in objects heights. On the right side the same area but as satellite image.

The differential image between digital surface model and digital elevation models is presented in figure 35. Blue areas indicate very small differences between models. That means these regions were not covered by any objects. The color scale shows the size of differences between both height models. On the right side there is the same area but shown as satellite image. By comparing these two images we can find if the classification process of terrain objects was made properly.



As we can see, areas with bare earth are recognized as real terrain surface. Roads and glades are distinguished very well. Also buildings along the road are classified and removed. It is possible to check the approximate filtering accuracy (point classification). Differences between both models not exceed value of 25 meters. We can estimate that this is the mean height of terrain objects. This type of visualization checks and gives us also information about terrain cover characteristic.

Reassuming, in comparison to satellite imagery, filtering random distributed point clouds from laser scanner data is more difficult, and more computation time-consuming than satellite height models, but as well more efficient in areas with vegetation cover.

Interpolation:

By filtering the model accuracy can increase, but interpolation and creating continuous surface may cause some difficulties. Very important is the selection of parameters to obtain good representation of ground surface. Table 9 is a statement of different parameters combinations for the first Mausanne area:

	DSM	FILTERED DATA	INTERPOLATION	INTERPO-LATION	INTERPO-LATION	INTERPO-LATION
GRID size	30 m	30 m	30 m	30 m	*7.5 m*	***7.5 m***
Triangulation window size			75 m	25 m	*75 m*	***25 m***
RMSE	4.02 m	3.71 m	6.66 m	6.44 m	*6.44 m*	***6.42 m***
Bias	0.58 m	1.84 m	1.32 m	1.25 m	*1.54 m*	***1.52 m***
RMSZ	3.98 m	3.26+2.957 *tanα[m]	6.71-2.802 *tanα[m]	6.65-2.826 *tanα[m]	*6.66-2.559 *tanα[m]*	***6.65-2.601 *tanα[m]***

Table 9. Mausanne scene. Result of interpolation accuracy with different parameters.

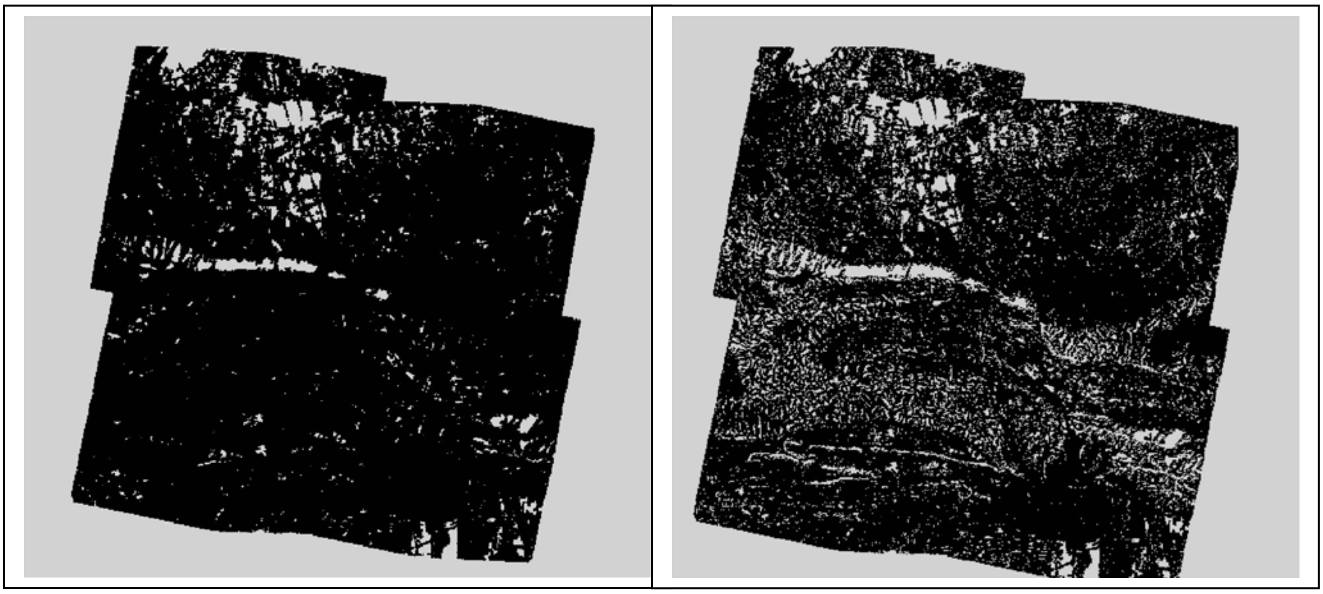


Figure 36. DSM as binary image; white spaces are gaps in model with 30 m grid size, on the right: image after filtering but without interpolation.

Figures 36 and 37 represent binary images of surface and elevation models. White values show gaps in both models, generated with 30 m GRID size. On the left side there is a DSM. Gaps in data appear in northern part of the height model in the flat area and also in the regions of very steep terrain (slope of mountain). On the right side there is the same area but filtered and before interpolation. It is noticeable that largest problems with interpolation may occur in flat and inclined regions (white spaces).

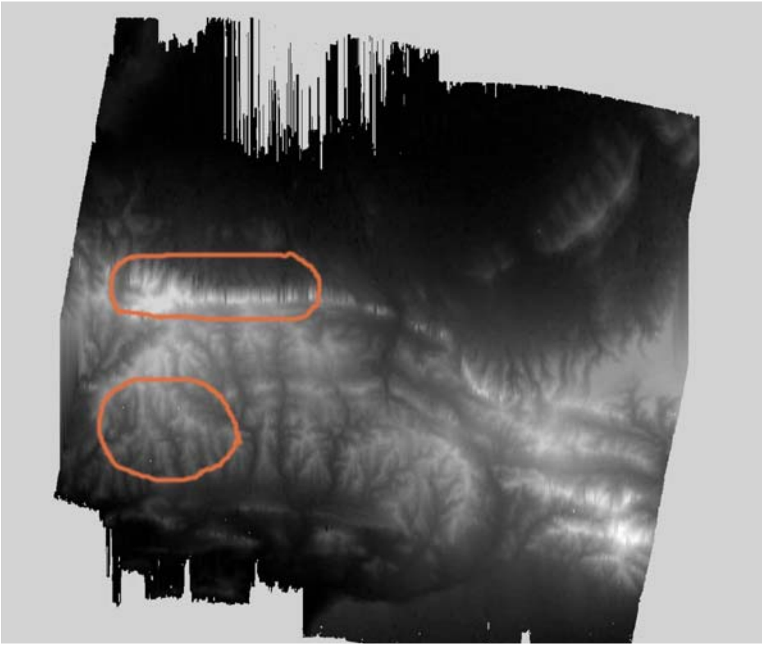


Figure 37: Problematic areas of interpolation with 30 m grid spacing and 25 m distance of interpolation.

In relation to interpolation distance and GRID of DEM spacing, following investigations have been made:

As we can see in table 9, the interpolation distance and size of grid spacing was successively changed:

Figure 37 presents the interpolated DEM. Circled areas are reveling areas where interpolation can be troublesome. In case of inclined terrain and mountain peaks, difficulties with interpolation may appear. The wide spacing of 30 m, in case inclined terrain and short distance (25 m) of interpolation, can be not accurate enough to estimate points heights.

Below there is a view on this area from northern-fore-hill side. Most difficulties occurred in inclined terrain and flat one, as it was mentioned earlier:

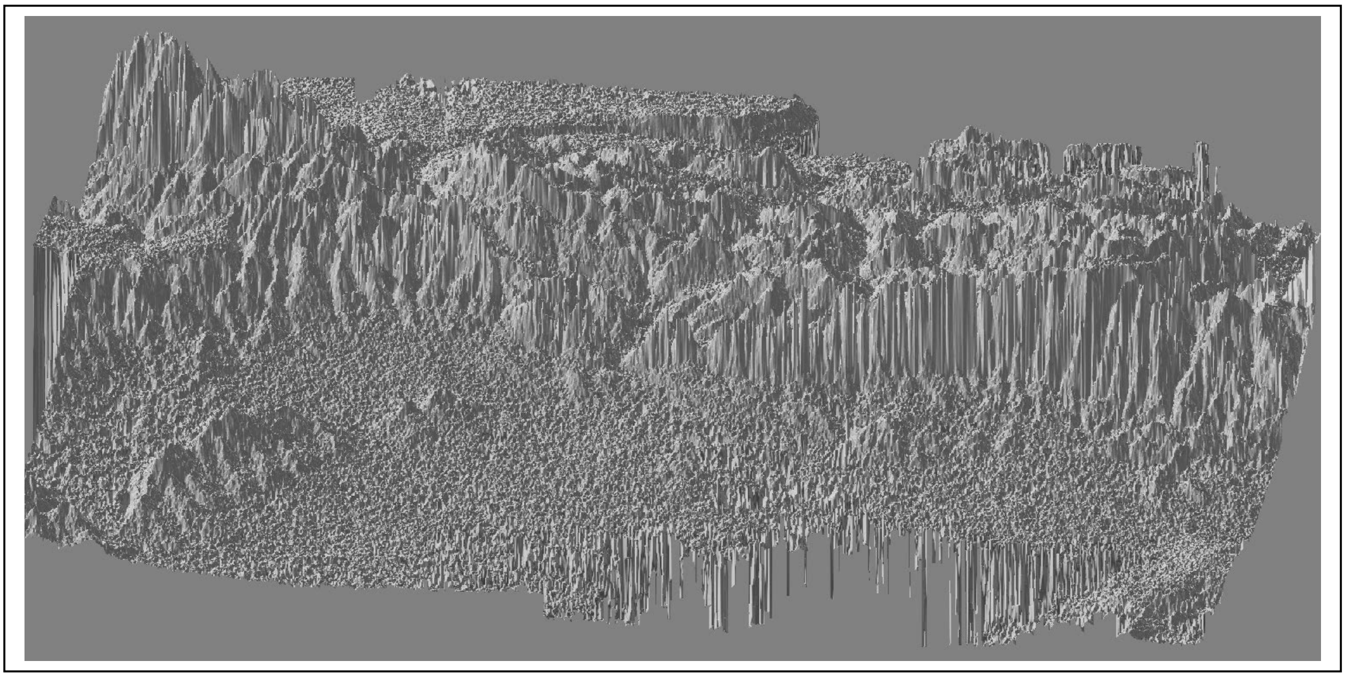


Fig. 38: Mausanne area: view on the slope, interpolated over 25 m spacing

Changing the grid size to multiple of three times pixel size, i.e. 7.5 m, increase the morphologic details about terrain.

Results of digital surface model with 7.5 m grid size:

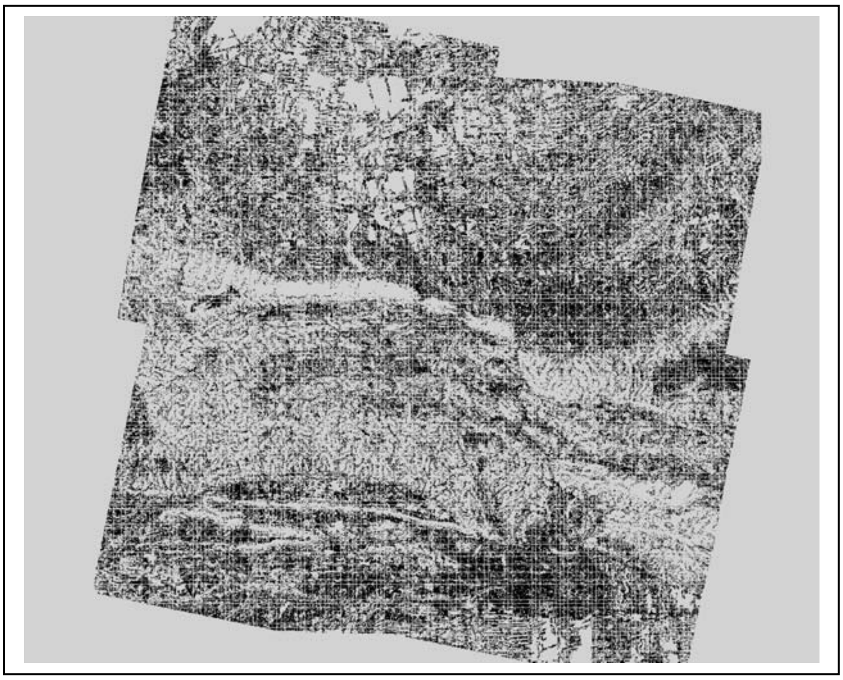


Figure 39: DEM: Mausanne area with 7.5 m grid size: binary image: white spaces: gaps in data set

In this type of terrain representation, dense mesh improves interpolation:

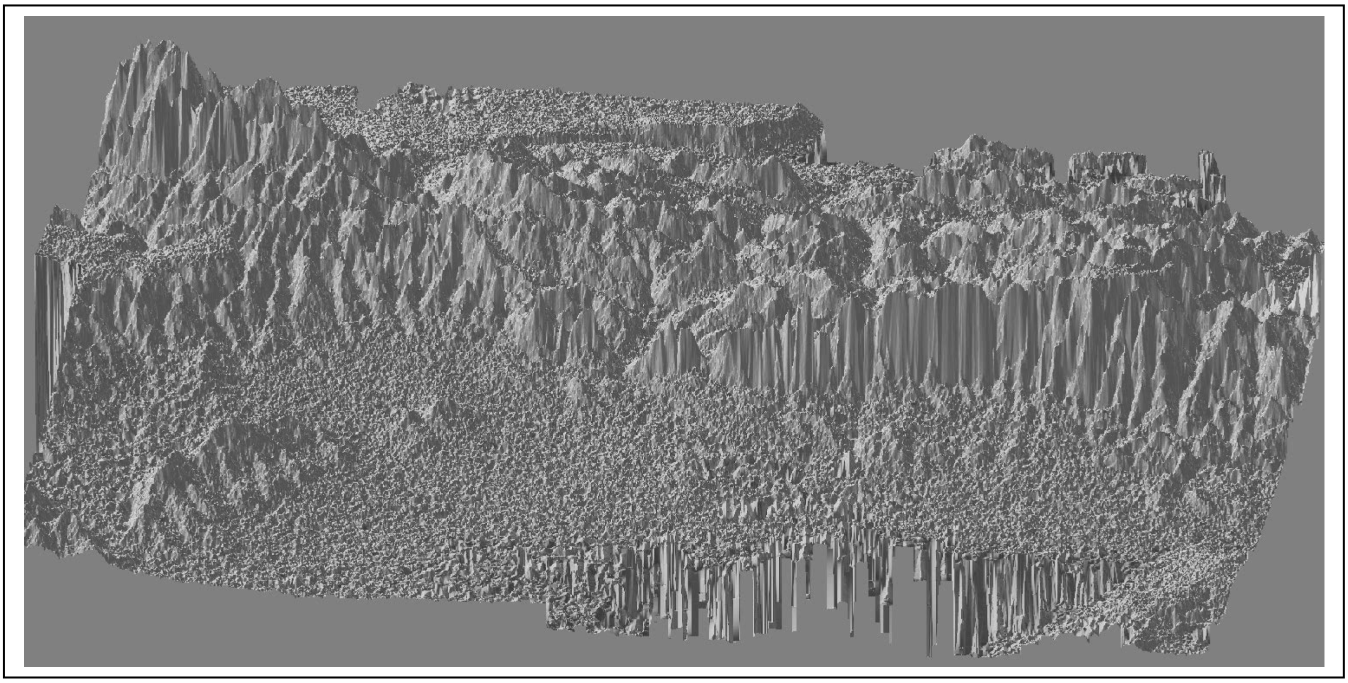


Figure 40: View on the fore-slope terrain of Mausanne data: grid size 7.5 m and interpolation distance 75 m.

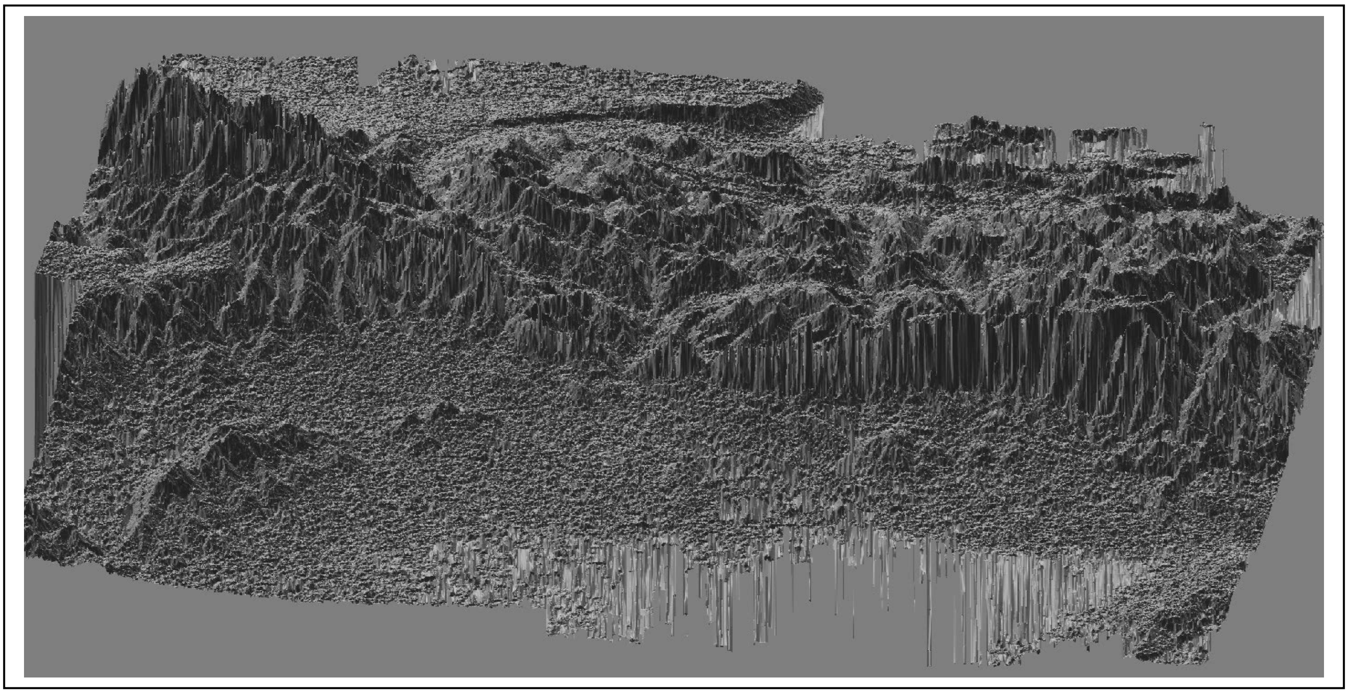


Figure 41: View on the fore-slope terrain of Mausanne data: grid size 7.5 m and interpolation distance 25m.

By densification of data mesh, decreasing interpolation distance brings better results, though the size of 75 m also seems to be enough. There are no visible gaps in both interpolated data sets. Noticeable are some problems with interpolation in steep areas and flat regions (figures 37 & 38). This is the reason for the conclusion, that in case of rolling areas, the grid could be densified to obtain more detailed height models.

Of course there will be large gaps in flat areas. Too small size of matching window cannot lead to satisfying matching. But differences in elevation are small enough to obtain properly interpolated points. With rolling terrain, gaps in data sets, and interpolation over long distance may lead to a loss of morphologic details. The resolution shown in figure 41 seems to be the best one (see also table 9).

In Warsaw scene, covering a flat area, the matching window of 25 m is too small. Algorithm cannot find enough neighboring data, causing gaps in data:

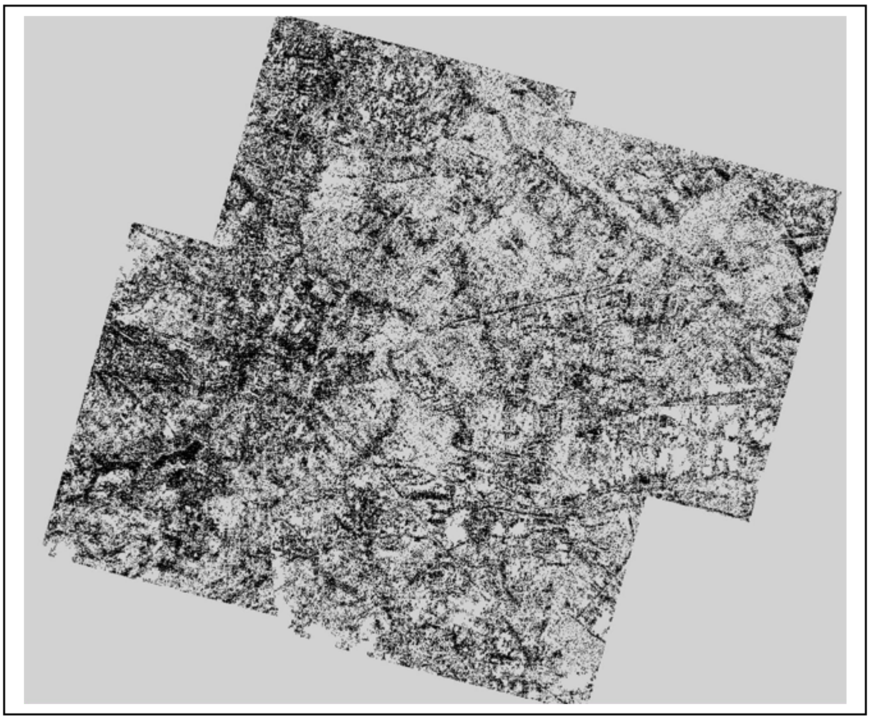


Figure 42: Binary image of Warsaw area with matching window of 25 m and interpolation distance-75 m, white = gaps in height model.

Below there is an image after calculating unknown height point values of flat area with 25 m interpolation distance:

Of course the largest problems with interpolation appear for large grid spacing and a matching window of 25 m is too small to find “template” points.

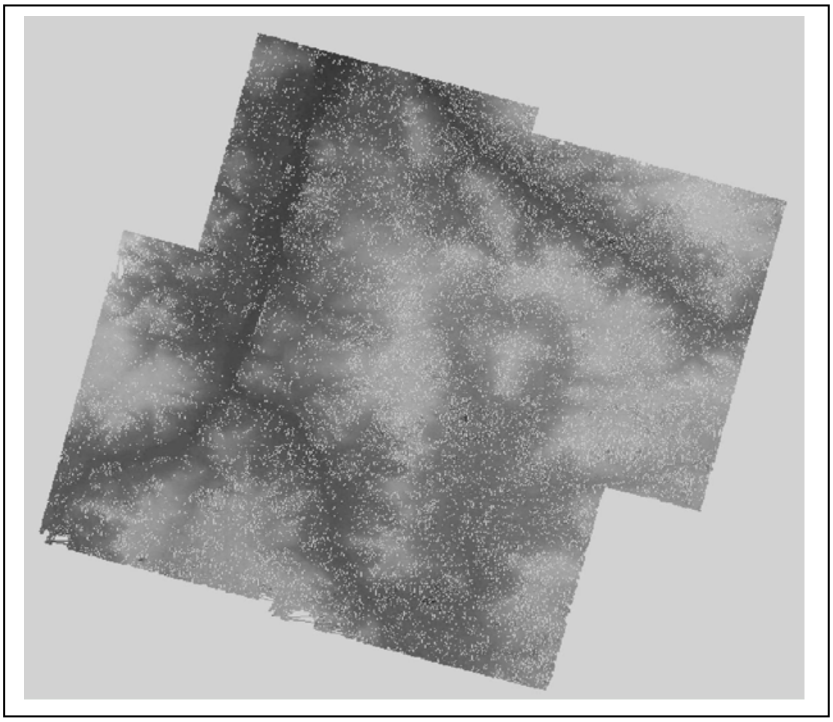


Figure 43: Image of interpolation over 25 m distance and grid size 25 m. white spaces-gaps in model.

The same region but denser mesh and longer distance:

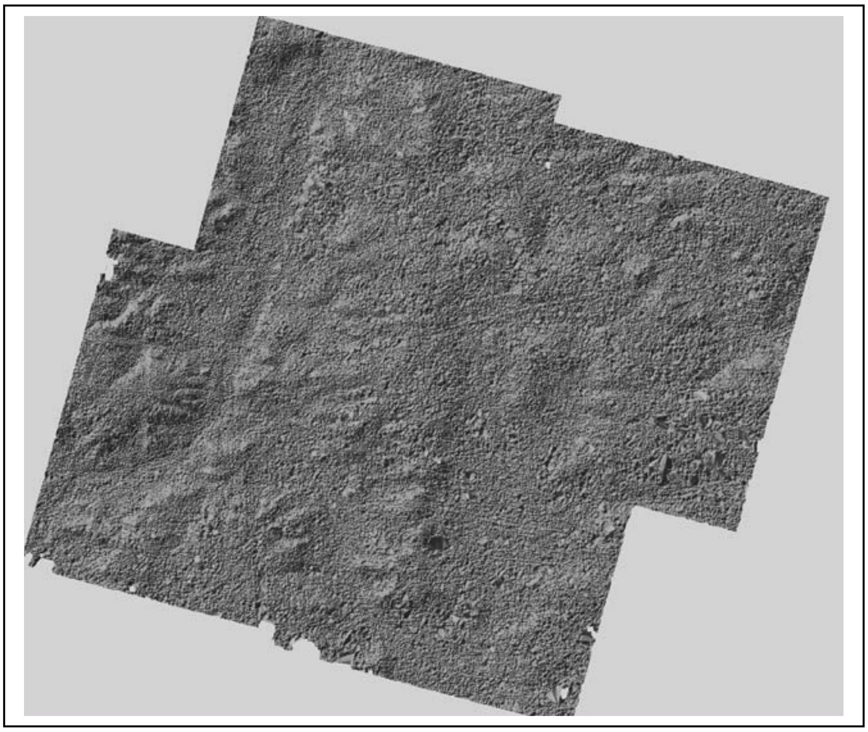


Figure 44: interpolation with distance 75 m and grid spacing of 7.5 m; Warsaw scene.

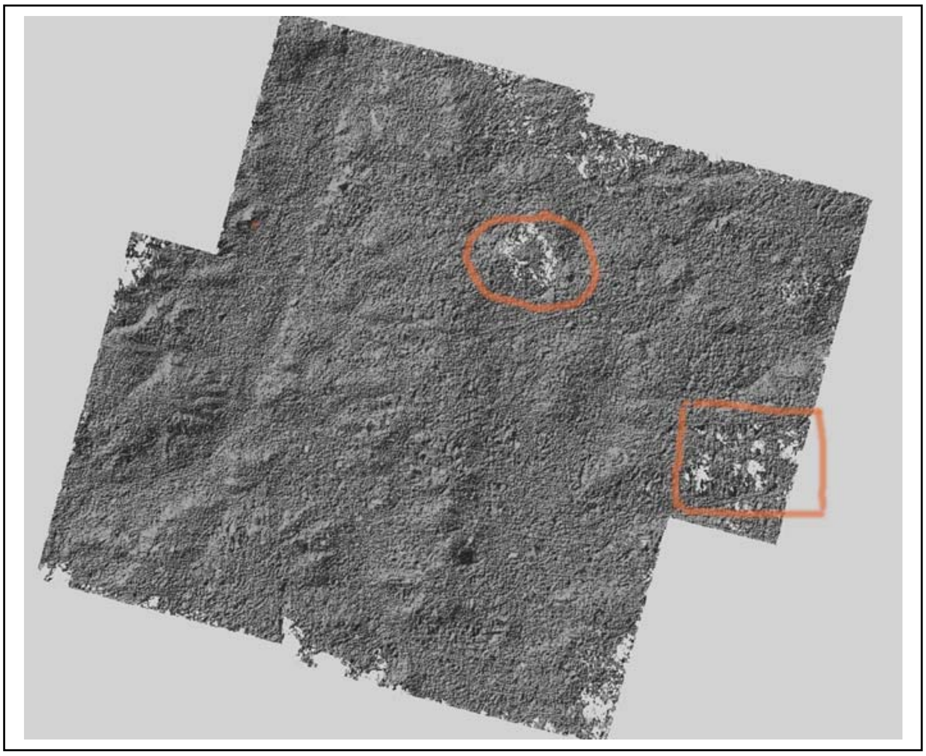


Fig. 45: Shaded relief, distance 25 grid,7.5 m grid spacing.

	DSM	FILTERED DATA	INTERPOLATION SZ=A+B*TAN α	INTERPO-LATION	INTERPO-LATION	INTERPO-LATION
GRID size	25 m	25 m	***25 m***	25 m	***7.5 m***	7.5 m
Triangulation window size			***75 m***	25 m	***75 m***	25 m
RMSE	2.92 m	2.22 m	***4.91 m***	4.98	***4.80 m***	4.71 m
Bias	-0.28 m	0.74 m	***2.54 m***	2.60	***2.33 m***	2.35 m
RMSZ	2.87+0.209 *tanα[m]	2.22_0.556 *tanα[m]	***5.14-20.679 *tanα [m]***	5.22-20.806 *tanα [m]	***5.05-23.349 *tanα***[m]	4.97-22.813 *tanα[m]

Table 10: Warsaw scene. Result of interpolation accuracy with different parameters.

Best solution for flat terrain seems to be 7.5 m grid size and interpolation over long distance.

Best results are obtained in small grid size and long distance interpolation (fig. 44). Small spacing of Digital Elevation Models leads to more accurate height values in case of flat areas. Comparable results have been achieved with larger grid size (25m), but as it is shown in figure 44, the quality of terrain representation is better.

CONCLUSIONS:

The main aim of this thesis has been investigations connected with the analysis of Digital Elevation Models, their generation from satellite images and from laser scanning measurements. The most important thing was to find the best solution in generating and processing different data sets.

Chosen image matching methods and parameters brought satisfying results to obtain correct digital elevation models. Decreasing the threshold of the coefficient enlarges the number of matched points. Matching with step width of just one pixel is very efficient-almost whole points were recognized as conjugate, but this solution is too time consuming and not justified by the results.

Independently from terrain type, the higher the correlation coefficient threshold, the number of properly matched points is lower. Additional snow cover gave worser results in Mausanne area than in the Warsaw data set. High contrast and good feature discrimination favour higher accuracy of digital elevation models.

Finally as the best results have been achieved with: 0.6 correlation coefficient threshold (for build up, 0.45 for open areas), width matching 3 pixels and 10 x 10 matching window.

Filtering of digital surface models has increased data accuracy. Different surface interpolation methods give best results, suitable for certain terrain characteristics. After filtering the height models were smoothened, ground exposure was better, noise and large errors were removed. Frequency distribution of heights was more asymmetric. As it was predicted, the second iteration in the flat area was not necessary. Most points in flat area, on low buildings and vegetation were removed by analysis of height distribution and its limits and by polynomial fitting. But in case of data from laser scanner even 7 iterations were indispensable.

Analyses of interpolation revealed that most visible gaps in data are in flat parts of terrain, and in the very steep terrain. Very important were also the strong influence of parameters such as interpolation distance, grid size and type of terrain.

Very important is the matching method. Its disadvantage in number of properly matched points leads to lower agreement with the reference data; especially in forest and rolling, shaded areas.

Reassuming, CARTOSAT-1 as a high resolution satellite fulfilled requirements connected with digital model determination and required accuracy, giving a product that can be widely used in different applications.

Results can be improved by

- using different matching parameters for different image structures and
- combination of matching methods (e.g. both cross correlation and LSM)
- filtering, especially filtering different terrain types separately
- using a higher number of iteration for filtering only when it is necessary to avoid a loss of morphologic details
- using proper data arrangement: in rolling and steep terrain a denser grid and shorter interpolation distance, and long interpolation distance in flat areas.

Biography:

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List of tables:

Figure listing:

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Diploma Thesis

Determination, Filtering and Analysis of Digital Elevation Models

Anna Fryśkowska,
Hannover, March 6, 2007