APPROACHES TO THE FILTERING OF LASER SCANNER DATA

Peter Lohmann, Andreas KOCH, Michael SCHAEFFER
University of Hanover, Germany
Institute of Photogrammetry and Engineering Surveys (IPI)
Lohmann@ipi.uni-hannover.de
koch@ipi.uni-hannover.de
mschaeff@gmx.net

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ABSTRACT

Recently several papers have been published on the precision of Digital Terrain Models (DTM) which were produced by airborne laser-scanning. This precision is influenced by several factors, like navigation accuracy, quality of reference data but also by the way the "raw" laser scanner data is filtered. For the latter task mathematical models as well as algorithms can be used.

A specific problem in quantifying the accuracy is the typical asymmetric error distribution of laser measurements when compared to reference data. The data show only small negative deviations to the terrain-surface (below the terrain-surface), however, relatively large positive deviations due to vegetation or buildings (above the terrain-surface). This general problem must be taken into account.

Two different approaches for the filtering of laser-scanner data are presented in this paper, namely the use of linear prediction and the use of dual rank filters. Both methods are presented and their results are compared. If linear prediction is used as filtering method, it must be applied iteratively, because otherwise the results are strongly influenced by height points lying far above the mid-terrain-level. The use of linear prediction shows satisfactory results in forest areas, whereas other areas with steep terrain show problems which makes it necessary to locally adapt the method to the shape of the terrain.

Using the above approach of dual rank filtering some pre-knowledge of the area of concern is required and very often the process of filtering is influenced by interactive procedures like restricting the filter process to special areas of interest, to avoid a smoothing of the "natural" terrain. Dual rank filters show very promising results especially when filtering artificial objects like buildings but require interactive control and some pre-knowledge in order to properly set the necessary parameters.

1   INTRODUCTION

Since more than a decade the use of airborne laser scanner systems leads to height-models (Digital Surface Models, DSM), which describe the surface (vegetation-horizon, roof-heights of the houses, etc) very precisely . While there are application areas, in which the height of surface itself plays a major role, (urban planning, radio or mobile phone network-planning, etc), in many cases a description of the true topography (the terrain) is required (forest-stands, traffic line-planning, terrain-supervision, Geographic Information systems, for example ATKIS, the Authorative Topographic Cartographic Information System of the German surveying administration).

In the course of processing, higher vegetation-horizons and also buildings are removed, in order to generate a digital terrain-model (DTM). Removing of the height-values is called filtering. There are diverse methods and procedures for generating the DTM (Lohmann et al., 1997), like:

- Morphological Filters (Eckstein et al., 1995)
- Linear Prediction (Kraus et al., 1997)
- Spline-Approximation (Axelsson, 1998)
- General Digital Image Processing (Von Hansen et al., 1999)

Obviously, a fully automatic approach would be of advantage for reducing the DSM to a DTM. Different filter-algorithms have been reported upon (Fritsch et al. 1994, Kilian et al. 1996, Kraus et al.1998, Hug et al. 1997, Huising et al. 1998, Axelsson 1998 etc.), however nearly all of these methods still need improvement. In some cases the additional

use of intensity-images, which can be produced by some of the laser scanning systems, or the combined use of first- and last-pulse data and supporting GIS data or video was of help to improve the process of filtering.

This paper discusses the automatic derivation of the terrain-surfaces from Laser-DSM, without the use of additional information. Two filter approaches discussed in detail namely the frequently used method of "linear prediction" (Krauset al. 1997, Lohmann et al.1999) and of morphological image processing, in the form of the "Dual-Rank-Filter" (Eckstein et al. 1995, Schaeffer 1999).

2 DATA SET USED

Data acquisition for the experiment described in this paper was carried out by the company "TopoSys Topographische Systemdaten GmbH" in March as well as April 1998, using their laser-scanner-system (Lohr et al., 1995). The test-area is located in the west of Germany in the state North Rhine-Westphalia a few kilometers north of Recklinghausen. This is an area which is heavily influenced by coal mining and terrain subsidence. Under the responsibility of the "Deutsche Steinkohle AG" (DSK) the company TopoSys was contracted to perform a laser scanner survey. The TopoSys-Sensor works with help of a fiber glass bundle. The across-track resolution at a field of view of $\pm 7°$ is 127 points within each scan. This means, the spacing between two fibers amounts to $0,11°$, which corresponds to a point-spacing of 1,73 m at a cruising altitude of 900 m. In flight direction, a spacing between two scans ranges from 0,11 to 0,13 m at a speed of 70-80 m/s . A point density of 4 to 5 samples per m² is thus achieved .

3 LINEAR PREDICTION

The linear prediction is a statistical interpolation-method, being particularly suitable to the interpolation of digital terrain or surface models. The height-values to be filtered are available in irregular form or are arranged in a raster. A detailed description of the basics for this method can be found in (Kraus, 1997, Lohmann et al., 1999, Koch, 1999). In the following the implementation within the software DTMCOR at the Institute for Photogrammetry and Engineering Surveys at the University of Hanover is shortly described.

The linear prediction is based on the correlation of neighbouring points, expressed in the covariance function. In DTMCOR it has the form:

$$C(P_i P_k) = C(0) \cdot e^{-1,30103 \left(\frac{\overline{P_i P_k}}{B} \right)^2} \tag{1}$$

The covariance between two points P_i and P_k depends on their spacing $\overline{P_i P_k}$ (Figure 1). If the points are close to each other, the covariance is high. With growing distance, the covariance tends against zero. $C(0)$ is the vertex-value of the

Figure 1: covariance function

covariance function, the covariance for the spacing zero. In DTMCOR it is restricted to 0.99. B describes the distance, in which the effect of the covariance function is reduced to 25%. The value $-1,30103$ is a constant factor, $C(0)$ and B are parameters, that are defined in the dialogue between the software and the user.
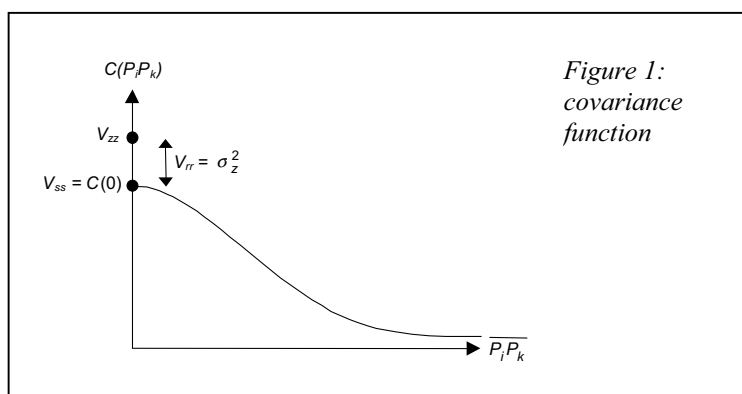
In order to perform linear prediction, it is neccessary to first separate a trend function. This can be done by means of a polynomial of very low degree or a moving plane. The result is the vector $\underline{z}$ which contains the centered points of measurements z_i. These values describe the deviations of the sample points from the trend function. Trend separation within DTMCOR is performed by the calculation of a moving plane, which is defined by three unknown coefficients a_0, a_1, a_2.

$$Z_i = a_0 + a_1 X_i + a_2 Y_i \tag{2}$$

In the linear prediction values u_i are estimated from the measurements $\underline{z}$ and the described covariance information contained in $\underline{C}$. The interpolated surface in point P_i is given by:

$$u_i = \underline{c}^T \, \underline{C}^{-1} \, \underline{z} \tag{3}$$

$$\underline{c}^T = [C(P_iP_1) \quad C(P_iP_2) \quad \cdots \quad C(P_iP_n)]$$

$$\underline{C} = \begin{bmatrix} \underline{V_{zz}} & C(P_1P_2) & \cdots & C(P_1P_n) \\ C(P_2P_1) & \underline{V_{zz}} & \cdots & C(P_2P_n) \\ \vdots & & \ddots & \vdots \\ C(P_nP_1) & C(P_nP_2) & \cdots & \underline{V_{zz}} \end{bmatrix}$$

$$\underline{z} = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix}$$

u_i	predicted value
$\underline{c}$	covariances between point to be interpolated and measurements
$\underline{C}$	covariance matrix
$\underline{z}$	vector of centered measurements

The vector $\underline{c}$ contains the covariances between the point P_i and the other measurements. The matrix $\underline{C}$ contains the covariances between the measurements, the main diagonal consist of the variance $V_{zz} = 1.0$ of the centered measurements. All measurements are regarded to be of equal accuracy. Since the vertex-value of the signal-covariance-function $C(0)$ is restricted to 0.99, interpolation and filtering is performed.

The area of investigation is devided into meshes of equal size. While processing the points of one mesh (processing unit = 1 mesh) the bordering meshes are also considered (8 surrounding meshes). The coefficients a_0, a_1, a_2 are computed by the measurements of the height-points P_j within the 9 meshes using a least-squares adjustment. This means the moving plane is adjusted to all points within the area of consideration ($j = 1,...,n$; n = number of points within the area of consideration).

Two tolerance factors are defined in the dialogue between DTMCOR and the user. First the user enters a tolerance-factor l_{tp} with respect to the moving plane. The height values whose deviations are above this tolerance are considered as outliers and are excluded. The trend-splitting is enforced iteratively, i.e. repeated several times, until no more height value is rejected. The height-outliers in the processing unit are deleted. The values as such recognized in the bordering meshes are available for computation of the next mesh again.

The second tolerance-factor l_{pre} checks the difference between centered measurement value z_i and value calculated by prediction u_i. If the residuals $\bar{z}_i$ are bigger than the predefined factor, these points are also eliminated.

$$\bar{z}_i = z_i - u_i \tag{4}$$

4.   DUAL RANK FILTERING

One method based on morphological filtering for the elimination of points above ground in a laser scanner data set has been implemented within a standard image processing software, the HALCON package, which offers a library of functions (operators) and a programming environment called Hdevelop (MVTec 1998).

Points above ground can be characterized by a large change of the height at the transition from the ground to the object and vice-versa (local discontinuity). This is quite obvious at buildings, where the outline of such height-alterations reflects the shape of the building. But also within vegetation such large height-alterations often appear.

The impementation is established by a series of modules in a processing chain within the HALCON environment. In order to detect the changes in height, a standard deviation filter is applied in a first step to the image. A small mask was used for the filter in order to obtain sharp edges. A size of 3x3 pixel was supposed to be sufficient. The filter generates a new image based on the value of the standard deviation within the mask (see Figure 2). Next a threshold is applied to the standard-deviation image in order to find the areas of large changes in height. The necessary threshold-value, however, can not be calculated precisely beforehand, because of the à priori unknown structure of the terrain. Therefore, in the beginning it is necessary, to determine this value on the basis of a test-window, which contains only true ground-

points. For an average flat terrain at a spacing of 1m per pixel, a threshold-value of approximately 1,8m has been shown to be appropriate and was used in the further processing. The detected and marked areas are stored as a region (Figure 2 Upper right).

Since this region represents just the height-discontinuities, it contains only the edges of interrelated areas like the walls of buildings. For this reason, the holes within the single areas are filled in the next step using a HALCON-Operator (Figure 2 Mid left). The interesting areas (region of interest, ROI) are now marked, like buildings and forest-areas in their outline. These ROI's, however, can not yet be removed in total, because clearings within forest-areas and inner courtyards of buildings are filled by this procedure. In order to avoid the unwanted elimination of true ground-points an additional step is necessary.

The total of the ROI's is split into its separate components that are examined sequentially in the following. An automatic procedure, which divides the observed ROI in sub-regions, is executed (Figure 2 Mid). In order to do so, the gray value-histogram for this ROI is smoothed using a Gaussian filter and the minima are subsequently determined. These minima serve as threshold-values for the subdivision into separate different height levels to be found within a ROI. The resulting sub-regions contain areas with homogeneous gray values. In the ideal case, this would be a single region, for example a building. Since frequently more than one sub-region is formed, for example by remaining ground-points, the sub-region of the darkest gray values is eliminated from the further procedure, as a candidate of a most likely ground-point region.
The largest of the remaining regions contains the object to be removed with best probability. A rectangle is fitted to this region (see Figure 2 Mid right). The length of the shorter side of the rectangle is used to size the mask of the now following dual-rank-filtering.

The dual-rank-filter (Eckstein et al., 1995)first sorts all gray values within a mask (a circular mask is used to achieve rotation invariance) in ascending order and chooses the value, that corresponds to a preset rank k.

Single rank: $\qquad R_k(\{I_1, I_2, ..., I_n\}) := I_k \qquad\qquad I$: image $\hfill (5)$

The value of k determines the gray-value to be selected at a position in percent above the lowest gray value in the sorted list. The process is repeated for a position from (100-k)%. This action is comparable to a morphological gray-opening or gray-closing, combining a gray-scale erosion and dilatation dependent on the used rank k.

Erosion: $\qquad (I \ominus_k m)(r,c) := R_k(\{I(r-i, c-j) \mid (i,j) \in m\}) \qquad$ *m:* filtering mask $\hfill (6)$

$\hfill$ *r,c:* row, column of image

Dilatation: $\qquad (I \oplus_k m)(r,c) := R_{n-k}(\{I(r-i, c-j) \mid (i,j) \in m\}) \hfill (7)$

Dual rank: $\qquad (I \circ m)_k := (I \ominus_k m) \oplus_k m \hfill (10)$

Within the dual rank the gray values within an object are replaced by values, which follow the surrounding topology and terrain. The resulting image is subtracted from the original. This results in an image which contains candidates for removal.

The resulting image is thresholded again, in order to mark only those points that show a minimum difference determined beforehand. This step is necessary to avoid a misclassification of points having only small height-differences, originating among others from ground unevenness. The threshold value to be determined is a function of the characteristics of the area of examination. A value smaller than approximately 0,5 m doesn't appear meaningful for a terrain with a spacing of 1m per pixel, since an unambiguous classification can hardly be guaranteed below this value.

The objects classified by this method can now be removed from the original height image. A method for filling the resulting gaps is to interpolate in two directions from the border points of the gaps. This simple type of interpolation fits to the surroundings quite well in a smooth terrain. At bigger gaps, however, the interpolation can generate an artificial crosswise pattern, which is produced by border points of varying heights. In order to smooth this effect, finally a mean value-filter is applied to the interpolation area in consideration of the border.
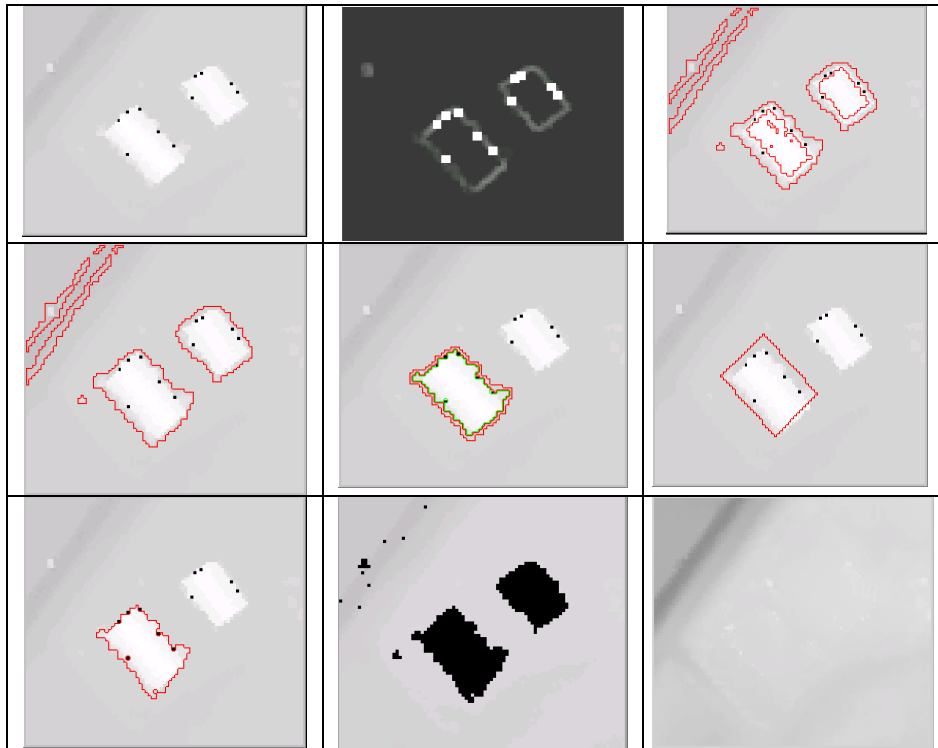
Figure 2: Processing chain
- Upper left: Window of DSM (Black points = Missing data)
- Upper mid: Standard Deviation Image
- Upper right: Marked regions
- Mid left: Filled regions
- Mid mid: Automatic threshold
- Mid right: Best fitting rectangle
- Lower left: Regions marked to cut
- Lower mid: Removed non-ground regions
- Lower right: Filtered and interpolated DTM

5. PRACTICAL RESULTS AND COMPARISON OF METHODS

This paper deals with data, which has a spacing of 1 meter in x- and y- direction. In forest areas the change in elevation can be up to 20 meters or more at a point distance of 1 meter. The effect of these rapid differences in elevation has been investigated. Previous work in this area has only been carried out using a 10 m grid (Koch, 1999, Lohmann et al., 1999).

The filtering of the DSM with help of DTMCOR (see chapter 3) is analysed on the basis of a test site. The area is partially covered with dense coniferous forest.

Figure 3 shows the color coded image of the DSM including two roads crossing the area. The peaks represent the treestands. In the middle and in the western part of the area most of the vegetation can be found. The size of the area is 1000 x 1000 meters. The minimum and maximum elevation in the DSM is 82,5 m and 139,6 m, respectively.

The following filter settings were used:

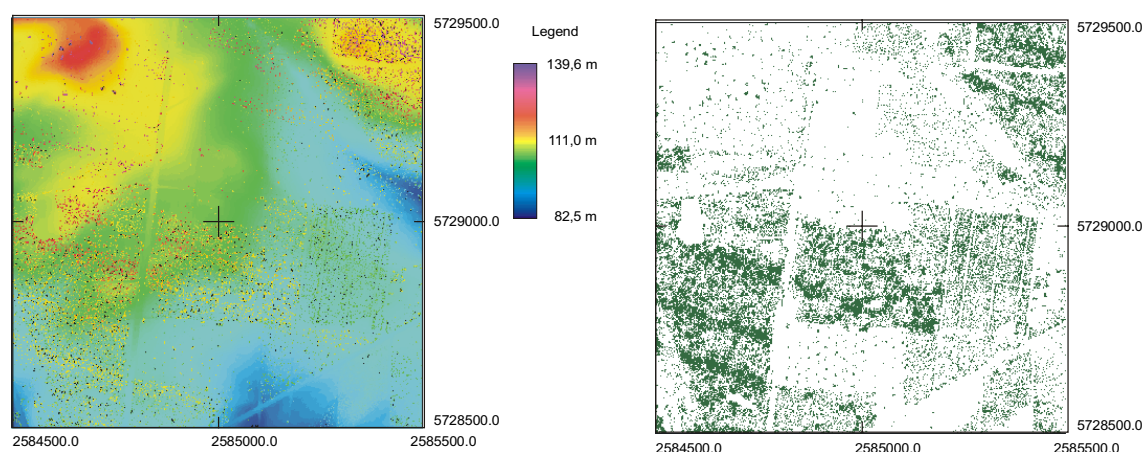|	
Tolerance factor l_{pre}	0,6 m
Tolerance factor l_{tp}	2,5 m
C(0) of covariance	0,7
Mesh size	7 m

Figure 3: Test area with (left: color coded heights; right: filtered points using DTMCOR)

The DSM is made up of 990.375 points with a grid width of 1m. About 10.000 points in the regular grid contain no height value, (black points) and are missing in the original data set. A total of 186.867 points or 18,9 % have been filtered by DTMCOR (Figure 3 right). By comparing the color coded image (Figure 3, left) with the filtered points (Figure 3, right) the structure and shape of the peaks also becomes visible. However, the number of filtered vegetation points is less than the number of the eliminated points. Relatively large areas of non-topographic points are detected by the filter algorithmn. This can cause problems in interpolating the openings. Therefore the adequate selection of the filter setttings is very important, especially the tolerance with respect to the moving plane, l_{tp}, and l_{pr} have a major influence the results. The higher the tolerance factors the less points will be eliminated. Consequently, this may cause that erroneous elevations resides in the final DTM.

5.1   LINEAR PREDICTION VERSUS DUAL RANK FILTER

A comparison between the results obtained by linear prediction and dual-rank-filtering has been carried within another test site. The area (see figure 4) is made up of a freeway, a high building and some forests. Large differences in elevation can be observed in a region close to the freeway. The size of the area is about 157.000 m². The DSM consists of 156.565 points, about 1.000 points of the grid have no elevation value. Especially one part of the building shows black areas without any elevation data.

The filtering of the test site with help of DTMCOR was done with the parameters mentionned above. 15.464 points (9,88 %) have been classified as vegetation or building points. 7715 points have been deleted by the trend removal and 7749 points (4,95 %) exceed the tolerance against the predicted surface. Figure 4 shows the results after filtering. It can be noticed that the forest areas have not been filtered completely. Especially in the region south of the freeway not all vegetation points have been detected. The freeway with ist ramp on both sides is still preserved. The breaklines and edges of the terrain are not eliminated, only in the neighborhood of the bridge a few points are classified as not belonging to the terrain due to big changes in height. However the mid column of figure 4 shows unsatisfactory results in the case of the big building which is not removed totally. The reason is that the choosen grid size of 7 meters is too small. Therefore the algorithmn has to be modified to locally adapt the grid size to the size of the buildings.

The results of dual rank filtering (Figure 4 right column) show very good results in case of the filtering of buildings and ramps. Forest areas are filtered very rigerously. The final interpolation sometimes yields a pattern like structure but in general this filter approach works quite well. Out of the 156.565 elevation values 13.225 (8,4%) have been detected as non-topographic points and are consequently removed and interpolated.

6.   CONCLUSION

The obtained results demonstrate very promising results for forested areas using the approach with linear prediction. However the parameter settings have to be investigated and tested beforehand. As could be shown the filtering of big buildings requires the use of rather large grid sizes, which on the other hand are not well suited in areas of undulated terrain, because it is smoothed too much. Therefore it is difficult to work with one set of parameters in areas of different topography. The most sensitive parameter is the size of the grid. A possible solution to this problem is the implementation of the technique of a progressive sizing determining the grid size locally as a function of the terrain curvature. A problem specific to forest areas, is the vast filtering of points, which in consequence results in problems with the interpolation of these gaps.
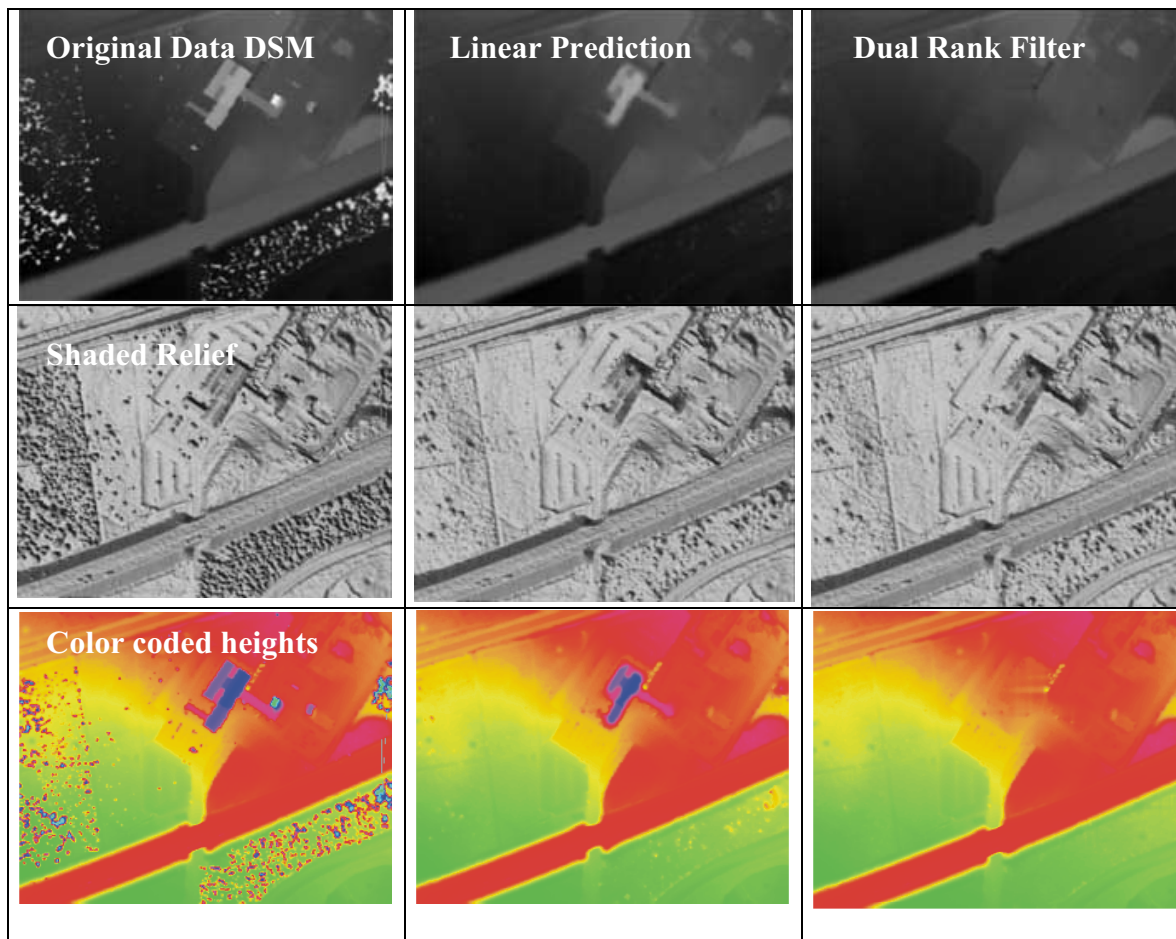
Figure 4: Results of Filtering (Left column: Original data; Mid: Linear prediction; Right: Dual Rank)

The result of morphological filtering shows a quite reliable recognition and removal of buildings and artificial structures, which are marked by a clear height-difference to their surroundings. These objects are separated very precisely on the basis of the implemented algorithm. Surfaces, which ascend or descend in nature diagonally and show a continuous slope, like dams or dikes, remain unconsidered in the first step of the algorithm, using the standard deviation filter. Consequently, these types of terrain features remain unchanged in principle. Break lines are first marked as edges, but do not form closed features. The resulting very narrow, long shape is excluded from further processing by analyzing the size and the form of a ROI, as a function of the biggest existing building. In case of filtering the vegetation one has to distinguish between single objects and extensive vegetation. Individual trees or bushes, exceeding the predefined height-difference to their surrounding, are recognized unequivocally and removed. Problems emerge with low vegetation which cannot be separated from ground points by examining their heights alone. In areas of dense vegetation, particularly in forests, the procedure of the laser-scanning leads to a wide scattering of height-values caused by the reflection at different vegetation-horizons. Therefore, ground-points and points of low vegetation are difficult to separate. For this reason, forest areas are removed nearly completely, leaving only few ground-points in comparison to the method of linear prediction.

The interpolation of the removed regions through bilinear interpolating sufficiently adapts to the surrounding terrain. The typical network pattern caused by this interpolation is minimized by averaging to an extent, that it is only perceptible at larger filled up regions. This is the case at big buildings like factories and also at extended woodlands.

Due to the fact, that this method leaves most of the topography unchanged (selective filtering), the accuracy is the same than that of the original measurements in non-filtered areas.

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