

Airborne Laser Scanning and Derivation of Digital Terrain Models¹

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Abstract: Airborne laser scanning is widely used for the derivation of terrain information in wooded or open areas but also for the production of building models in cities. For this, the generation of a digital terrain model (DTM) is also required. In this paper laser scanning, and the filtering and classification of laser scanner data with a specific algorithm are described. The results for test data sets are presented.

Key words: DTM, laser scanning, filtering, classification

1 Introduction

Airborne laser scanning has become a widely used technique for the derivation of topographic data. The term Lidar (light detection and ranging) is used, too. The high degree of automation in both, capturing the data and processing the data, contributed to its fast spread. The scanner is mounted on an aircraft or helicopter, which usually flies over the terrain in a strip-wise manner. The laser (near IR) measures with a high frequency (1-83kHz) distances to the ground (most scanners with the run-time-principle) with an accuracy of a few cm. The beam is deflected with different methods (rotating or oscillating mirrors) in the scanner. On the ground points are sampled randomly, the laser beam is remitted in all directions, a small portion traveling back the same way through the atmosphere. If the laser is reflected on a still water surface or absorbed (dark asphalt) no point can be measured. The exterior orientation of the platform is determined with GPS (1-10Hz) and INS (1kHz and more). Due to errors in the exterior orientation of the platform adjacent laser strips usually do not coincide exactly (10cm or more).

Currently, the main application for laser scanner data is the production of digital terrain models (DTM), whereas the fully automatic derivation of building models ([2], [3], [4]) is not as operational yet. The automatic derivation of tree height and extraction of other forest stand parameters is investigated [5], as well as the automatic derivation of break lines in the laser data ([6], [7]).

This paper will focus on the filtering of laser scanner data for obtaining elevation information in wooded as well as in built-up areas. The DTM is necessary for all the applications described in the previous paragraph. In the next section a short presentation of the algorithm

¹ This article is a shortend but also extended version of [1] with emphasis on the methodology of laser scanning and the characteristics of laser scanner data.

developed at the Institute of Photogrammetry and Remote Sensing of the Vienna University of Technology (I.P.F.) will be given, especially the extension to the hierarchical approach will be treated. Data of an OEEPE test data are investigated in section 3.

2 Algorithm for Classification of Lidar Data

There are different filter algorithms for the processing of laser data. On the one hand it can be seen as the filtering of gross errors (off-terrain points, above and less often below it), on the other hand it can be seen as classifying the given points in terrain points and others (possibly more than one class). Vosselman [8] based an algorithm on mathematical morphology. This requires a triangulation, but only for topology (finding the neighbors), but not for surface representation. A different approach is to generate a very coarse description of the surface first (e.g. the lower part of the convex hull of the point set as in [9]), and continually add points to this surface [10]. The new points must fulfill certain criteria (e.g. distance to the momentary surface (the triangulation) smaller than ...). Other algorithms require a gridding (rasterization) of the data first. Then digital image processes can be applied to filter the data, which are very fast because the topology of the surface is very well known in this data structure. Mostly, the filtering is designed to give optimal results under certain conditions (e.g. in wood, [11]). The term *to filter* can have two meanings: the filtering (smoothing) of random measurement errors, and the filtering (elimination) of gross errors, which is also a classification. Unless stated otherwise we will always use the term in its second meaning.

The algorithm of the I.P.F., was originally designed for laser data in wooded areas. Altering the values of some parameters and the application of a hierarchical approach, made it possible to apply it also to city areas. In order to describe these extensions completely, a brief review of the algorithm will be given first. For a comprehensive description see [1] and [12].

In our algorithm - the iterative robust interpolation - a rough approximation of the surface is computed first. Next, the residuals, i.e. the oriented distances from the surface to the measured points, are computed. Each (z-)measurement is given a weight according to its distance value, which is the parameter of a *weight function*. The surface is then recomputed under the consideration of the weights. A point with a high weight will attract the surface, resulting in a small residual at this point, whereas a point that has been assigned a low weight will have little influence on the run of the surface. During these iterations a classification is preformed, too. If an oriented distance is above or below certain values, the point is classified as off-terrain point and eliminated completely from this surface interpolation. This process of weight iteration is repeated until all gross errors are eliminated (a stable situation) or a maximum number of iterations is reached.

2.1 Hierarchical approach

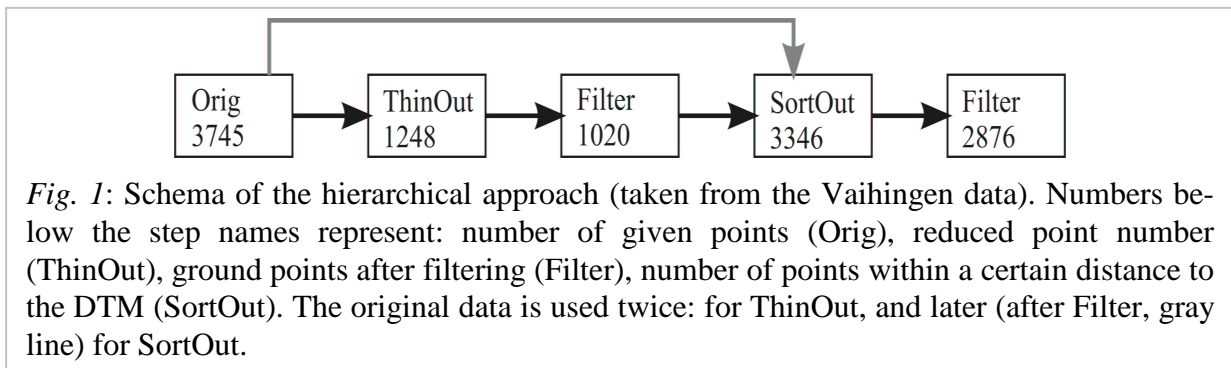
The process of weight iteration has been embedded in a hierarchical setup. It is comparable to a hierarchical setup using image pyramids, in our case data pyramids. Typically two or three levels are sufficient. However, in comparison to image analysis, the reduction function operates on point data, not on pixels. (If the laser data is provided as a digital geo-coded image where the grey values represent the terrain heights, the pyramids would be image pyramids.) The method proceeds:

1. Create the data sets with the lower resolutions,
2. filter the data and generate a DTM (starting with the coarsest level),
3. compare the DTM to the data of higher resolution and take points within a certain interval.

This process (steps 2 and 3) is repeated for each level, schematically it is shown in fig. 1 for two levels (level 0 and 1). Though this procedure can be applied to any laser data set, or other data with gross errors, its advantages become important for dense data sets (0.5 point/m² or more). The method speeds up the filter process, enforces the elimination of houses and dense vegetation and makes the process more robust.

Generating a data set with lower resolution (*thin out*) (e.g. mean / lowest / next-to-center point in each cell of a regular grid) has two advantages: 1. The regular structure of laser scanner data in built up areas (long sequences of points on the ground, on the roof, resp.) is broken apart. 2. The classification and filtering is accelerated, because a smaller data set is handled.

With the coarser data set a filtering is performed and a DTM is generated. Of course, embankments, break lines and other features are represented less distinctively than in the original data, but this is due to the coarser data, not to the filtering. Therefore, for performing the filtering on the next lower level, the original point data (or the data of the corresponding pyramid level) and the DTM of the coarser level have to be combined to generate the data for the lower (finer) level. The original points and their distances to the DTM at the current resolution are analyzed. If they are within a certain interval they are accepted, otherwise they are rejected (sorted out). This step is called *sort out*. For laser scanner data the lower bound of this interval is negative (e.g. -1m) and the upper bound is positive (e.g. 2m). With this data set the next filter step can be performed. The choice of the interval is not as critical as one might expect first, which is due to the filter step that is performed afterwards. Some vegetation points are included in the data set because they are relatively close to the ground, but they can be filtered in the next step.



3 Examples

Two areas (Vaihingen and Stuttgart) were flown by Fotonor and were available within an OEEPE test. First and last pulse and the intensities have been recorded simultaneously with an Optech laser scanner.

The data sets have been processed with the hierarchical approach of the filter algorithm described above. Default values have been used for the parameters of the filter and no manual editing was performed, the filter results will be presented. The vertical accuracy is determined with ground points for Vaihingen. Small studies and preliminary results on the first-and-last pulse data and the intensities will be presented.

3.1 Vaihingen

First, only the last pulse data was used, because our aim was to filter the vegetation and houses and obtain a ground model. Under our present working conditions we process data sets of up to 5 mio. points as one unit. As it can be seen in the left part of fig. 2 (a small part of the whole area) there are houses, vegetation and negative gross errors (50m below the ground) which have to be eliminated from the data set. The average point density is 0.23 points/m², the area is 50km².

In fig. 2 a comparison between the original data and the filtered data after the last iteration step can be seen. No manual intervention was performed during the iterations, the parameters used are default parameters and have not been adapted to this special data set, no manual deletion or inclusion of points was performed.

Result of Filtering: The vegetation has been eliminated completely. Also the houses were eliminated, but a kind of ridge remains east of the middle. This appears to be a large but low building which could not be eliminated completely. The embankments have been preserved, though they lost some of their sharpness. The remaining building could have been removed with a different set of parameters, but this would have eliminated more of the embankments.

Accuracy determination: For the area of Vaihingen the Institut for Photogrammetry at Stuttgart University measured ground points with a GPS System using a reference and a rover station. All together 4 areas with different terrain characteristics have been measured. Together with the accuracy of the laser data they are in the following table.

area	r.m.s.	mean	max	point num.	characteristics
Grassland	0.11	+0.08	0.73	1368	different slope, smooth
Sport ground Vaihingen	0.08	+0.06	0.30	77	flat
Sport ground Illingen	0.08	+0.07	0.17	102	flat
Railway station	0.48	+0.39	1.46	210	railway ramp

The vertical accuracies have been determined by means of an elevation model. The vertical distances from the check points to the elevation models were computed. The elevation model was computed without filtering for these areas. The vertical accuracies (root mean square, mean, and maximum error, under the assumption of error free check points) are shown in the table above in meter. For the first 3 areas there is still a systematic shift of about 7cm. This shows that the accuracy of a single laser measurement is even higher, but uncertainties in the determination of the transformation parameters and the modelling of the flight path will always remain. The errors for the railway ramp are higher. This is a consequence of the low point density in the lidar data, the check points lie on a break line. However, visual inspection of the co-ordinate values of the laser points and the check points showed, that the accuracies are similar to those of the other three examples.

First and last pulse data: The question arises, whether the first and last pulse data can be used to simplify or improve the filter process in wooded areas. Therefore, 6 rectangular areas of the Vaihingen data set were selected, all lying completely in wooded areas. The areas all together have an extension of 0.6km². It is notable that the point density of 0.20 points/m² over the wooded areas is smaller than the average point density (0.23 points/m²).

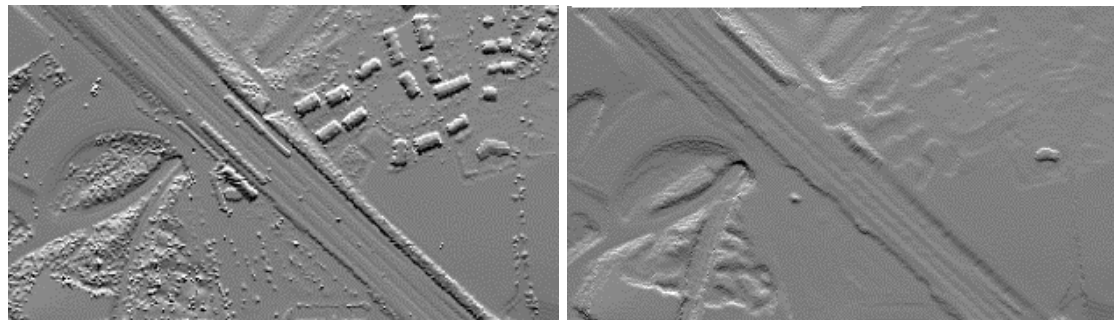


Fig. 2: Vaihingen, original vs. filtered data in a shading, area about 0.3km².

First, the distances between the first and the last reflected pulse for each measurement were computed. When we speak of measurement we mean the position and intensity of the first and the last pulse (8 values). A histogram of the distribution of these distances can be seen in fig. 3, left side. For 19.7% the distances are smaller than 1m. These points are not necessarily ground points. It is also possible that the laser beam is reflected twice in the canopy or in medium layers of the trees. As it can be seen, the pulses are either very close to each other (within 1m), or more than 4m apart. The first-last distances go up to 40m, which also includes a few gross errors. The points were separated in two groups, the ones where first and last pulse are close to each other and the ones which have a higher distance (threshold 2m). These 2 groups have been compared to the ground model which was derived previously. For the time being, we assumed that the filtering worked 100% correct. Additionally, it can be assumed that if the filtering is not completely correct, the errors occur only locally, for specific positions like peaks or steep descents. Thus, the errors - if any - induced by filtering errors are small in number.

The distances from the last pulse points to the ground model can be seen in the right part of fig. 3. The last pulse points range from 5m below the terrain to 36m above the terrain. For the measurements where the first and the last pulse are close to each other, 62.8% of the last pulse points lie within ± 1 m terrain distance, whereas for the points which have a higher difference between first and last pulse this number is 81.0%. Furthermore, 16% of the last pulse points lie between 10m and 30m above the terrain.

The penetration rate for this data set is about 77% (points within ± 1 m terrain distance). The chances that a last pulse point is a ground point are higher, if the distance between the first and the last pulse point is large, than if the distance is small. However, the differences are not too big. Furthermore, no strong correlation between the intensities over the forested areas and the distance from the last pulse to the filtered terrain could be proven. The first intensity is usually low (dark), whereas the second is larger (bright).

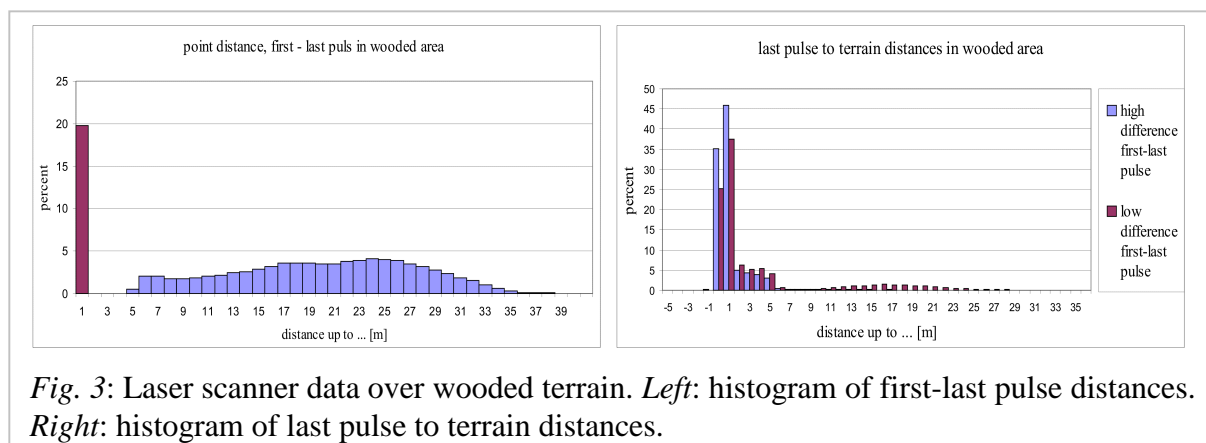


Fig. 3: Laser scanner data over wooded terrain. *Left*: histogram of first-last pulse distances. *Right*: histogram of last pulse to terrain distances.

3.2 Stuttgart

As mentioned above, this data is from an Optech scanner, too. The point density for this data is 0.81 points/m^2 . A part of the original data can be seen in the left part of fig. 4. The project area is about $2.5 \times 2.5 \text{ km}^2$. Fig. 4 shows the original data vs. the filtered data. Almost all houses were eliminated, only the biggest ones (the train station) remained. A few artifacts remained, also because not all negative blunders were eliminated correctly. With minimal human intervention these errors can be corrected.

First and last pulse and intensities: Like in Vaihingen, a histogram was computed which shows the distances between the first and the last pulse points. For 84.7% the distance is smaller than 25cm. The remaining distances are between 5m and 35m (at edges of houses, in trees, ...). There is a strong decline in the frequency from 5m to 25m. To record two distinctive echoes they must originate from surfaces which have a certain distance, which is at least half of the length of the wave package (pulse duration \times speed of light). A small number of points show distances larger than 35m, originating in gross measurement errors. This is either a first pulse point which is much too high or a last pulse point which is below the terrain level (e.g. from multipath effects). Both situations occur in the Stuttgart data set.

Furthermore, different methods have been performed to compute an ortho image with the recorded intensities which can be seen in fig. 5. The intensities from 0 to 250 have been assigned to the identical grey values, larger intensities were set to gray value 255. The images on the left hand side were generated using a $2 \times 2 \text{ m}^2$ raster. The intensities of all points falling in such a cell (which is determined with the x and y co-ordinate of the point) are averaged. The upper image shows this for the first intensities, the lower one for the last intensities. The choice of the cell size is critical. If it is too small, too many cells (pixels) obtain no value and the visual impression is unappealing. In the upper left image for 0.2% of the pixels no intensity value could be computed. If the cell size is too big, then image detail is lost. Therefore, the cell size has to be in the order of the average point distance. This problem can be avoided by interpolating a functional model (like an elevation model) with the intensity values as the observed function values and the x and y co-ordinates as the locations in the parameter domain (upper right image). This avoids the question of the cell size, only the grid

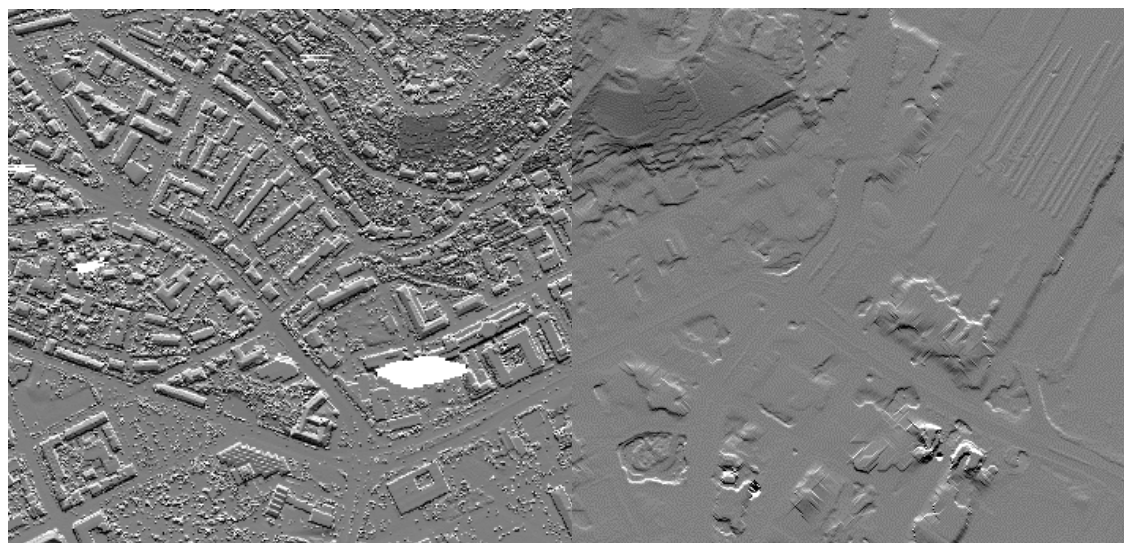


Fig. 4: Northern part of Stuttgart, original data vs. ground model. A small number of buildings (e.g. the train station) were not eliminated.

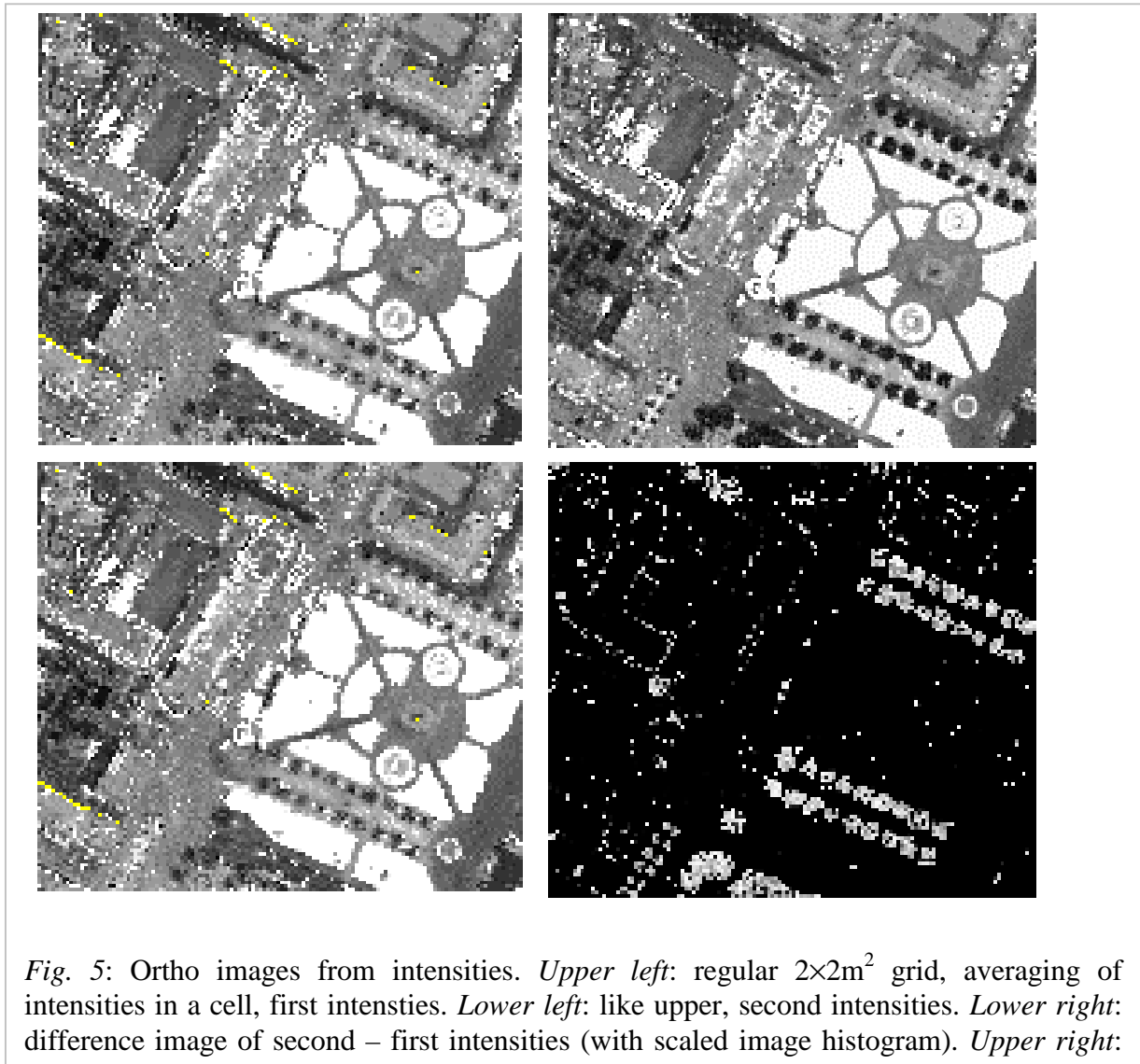


Fig. 5: Ortho images from intensities. Upper left: regular $2 \times 2\text{m}^2$ grid, averaging of intensities in a cell, first intensities. Lower left: like upper, second intensities. Lower right: difference image of second – first intensities (with scaled image histogram). Upper right:

size has to be chosen, which is a lot less critical. If it is too small, the processing time may increase, but no holes appear. For the upper right image a grid length of 1.5m was chosen, thus the image is sharper. Here, also the first intensities were used.

The lower right image of fig. 5 shows a difference image of the first and last pulse image on the left side. The palette has been linearly scaled to cover the whole range. Single trees can be detected: in the first pulse data they appear black, in the last pulse data they have higher intensities.

4 Conclusions

In this paper we presented the iterative robust interpolation (using linear prediction) which has been embedded in a hierarchical approach. This improves the filter result and speeds up the computation. The software used is SCOP++ of the I.P.F., a GUI-version of the laser scanner extension will be available, too. With the OEEPE test data sets the suitability of the algorithm has been demonstrated. The quality of laser scanner derived DTMs is very high. However, improvements can come from various sources. Especially the automatic detection of break lines in the laser data itself, or the utilization of extern data (e.g. digital maps) are important. As the penetration rate can vary strongly in laser scanner data sets, a laser scanner

DTM should be supplied together with a reliability and/or accuracy layer, indicating the quality of the model for a certain area. Furthermore, the purpose the DTM is used for, plays a role during the filter process. For our algorithm this corresponds to different sets of parameters during the filter steps. The simultaneous recording of first and last pulse and the intensities offers the possibility to obtain an ortho image. The interpolation of the intensities is a suitable method to generate such images. Trees appear darker in a first intensities image and brighter in a last intensities image. For the area of Stuttgart we observed that 85% of the first and last pulses are identical (no difference in position), whereas for the wooded areas of the Vaihingen example this is only valid for 20%. Although more information is available with first and last pulse and intensity data, filtering still remains an important task.

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