LEAST SQUARES MATCHING FOR AIRBORNE LASER SCANNER DATA

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ABSTRACT:

Finding corresponding spots in the overlap of two digital terrain models derived from airborne laserscanner data is required for two purposes: (i) *Strip adjustment:* Often the direct georeferencing (via GPS/IMU) of the individual laser strips is not perfect and the remaining (small) errors are to be removed by a strip adjustment. For this adjustment corresponding spots in the strips are required. (ii) *Quality control:* Often for a certain area several partly overlapping DTMs exist, which are generated from different data at different dates. In order to check the georeferencing of these DTMs the discrepancies between the DTMs in the common overlap should be computed. This again requires the identification of corresponding spots in two different DTMs. In this paper we present a method for deriving corresponding spots in two different overlapping point clouds with very high precision, by applying a robust version of the method of least squares area matching (LSM) on raster data interpolated from laser data (heights and intensity). The inclusion of laser intensity data is particularly useful in areas with little variation in height in order to derive the horizontal shifts between corresponding patches in the two data sets.

1. INTRODUCTION

Airborne Laser Scanner (ALS) works by sending a pulse to the earth surface and by receiving the returned signal, thereby determining the 3D coordinates of the measured ground point and also recording the intensity of the returned signal. This way a 3D point cloud is generated for (at least) the first and last echo.

In this paper we present a method for deriving corresponding spots in two different overlapping point clouds with very high precision. We assume the two point clouds are already approximately oriented with respect to a common system of coordinates. In this system the point cloud data is further assumed to be given in raster format; i.e. for each point cloud a dense raster is interpolated for the height of the first and last echo and also for the laser intensity values. The solution to this correspondence problem is required for the following applications:

- ALS strips have been directly georeferenced using GPS (Global Positioning System) and IMU (Inertial Measurement Unit). Afterwards the digital terrain model (DTM), the digital surface model (DSM) and the digital intensity model (DIM) were computed for each strip individually. For minimizing the GPS-IMU-errors and thus improving the georeferencing of the strips (e.g. [Friess 2006], [Kager 2004]), the (small) translations between the strips are required, which can be derived from corresponding spots in the overlapping ALS strips.

- For a certain area a DTM was derived from an ALS mission, which was undertaken at a certain date. At a later date for a nearby area another ALS mission is planned. For quality checking purposes, the new ALS mission will be planned so that both missions share a small overlap. In order to evaluate the quality of both DTMs the differences between both ALS-DTMs in their overlap have to be computed. This also requires corresponding spots in both ALS data sets.

The solution to the given correspondence problem can be solved using the least squares matching (LSM) technique known from digital Photogrammetry. In this approach two horizontal and one vertical shift are estimated between each pair of reference and target matrices. These matrices are manually identified in both data sets. This LSM approach can be applied on the DTM data directly – but also the DSM data offers additional information – and both data sets can be used together in a simultaneous adjustment. The addition of the DSM data is advantageous because it includes striking man-made object, but also high vegetation data. In order to remove the large height errors in the DSM caused by the high vegetation, the LSM-formulation for the DSM data has to be made robust.

The LSM approach can be extended to deal with the intensity data also. The DIM shares the same horizontal shifts as for the DTM and the DSM. For the third coordinate, however, the interpolated intensity is used instead of the height, thus the vertical shift can not be determined from the intensity data. The DIM for this approach should be derived from the intensity of the non-vegetation points [Attwenger and Kraus 2006]. This hybrid approach of including the DIM is particularly promising because it will yield the shift parameters also for areas with less height variation but high contrast in the laser intensity.

A further extension of this LSM approach would be the inclusion of terrain slope and curvature values. Their inclusion could be helpful in areas without striking objects, like man-made objects, and where also the near-infrared-based intensity spectrum is very poor.

In this paper the theory behind this approach is described in detail (section 3). Section 2 gives a literature overview on comparable approaches for solving the correspondence problem in the mentioned applications. In section 4 first experiences coming from practical examples are presented. In the end (section 5) we give a conclusion and an outlook for future work.

2. PREVIOUS WORK

For determining the discrepancies between overlapping laser strips and further for establishing correspondences between the strips in order to improve the orientation of the data, LSM was applied on airborne laser data in different ways in the past.

The approaches applied can be classified in the way the laser points are treated in the matching procedure:

a) LSM is applied on the original irregular ground points by utilizing a TIN structure; e.g. [Maas 2002], [Kilian et al. 1996].
b) before applying LSM, a regular raster is interpolated from the irregular points; e.g. [Burman 2000], [Behan 2000].

Although the approach of interpolating a regular raster before applying LSM is somewhat natural, as LSM was originally introduced for finding corresponding features in aerial images (which have a regular raster) [Grün 1985], this approach is reported to yield worse results compared with the TIN approach [Maas 2002].

The main drawback is due to height discontinuities (e.g. between buildings and ground), which cause occlusions. E.g. the wall of a building located near the border of the first strip is not seen in this strip, but is clearly visible in the second strip. If a regular raster is interpolated for the data of the first strip, then in this occluded region a tilted surface is interpolated, which connects the roof and the visible part of the ground. Consequently by matching the patch from the first and second strip of this respective building the shift parameters will be erroneous.

It should be noted, however, that occlusions also make problems in the TIN approach, where the roof and ground is connected by large and narrow triangles, but there such triangles can be removed from the data set by different strategies [Maas 2000].

It is interesting that height discontinuities (if not dealt with specifically) are not of benefit when performing LSM with heights (because of the occlusions). This is opposite to LSM with intensities in aerial images, where intensity discontinuities increase the precision of the results (as here the discontinuities do not cause occlusions).

LSM generally works on 2.5D data; i.e. for each ground position (X, Y) only one third coordinate is assigned. Consequently the LSM approaches can be classified further on what information is used as third coordinate during the matching procedure:

a) only the height is used as third coordinate [Kilian et al. 1996]
b) height and intensity of the return signal are used together as two separated – but co-registered – 2.5 D layers [Burman 2000], [Maas 2002].

Including the intensity of the return signal in the LSM is helpful in regions with low height variation. Provided the intensity shows high variation, the horizontal shifts between the patches in both strips can be determined with high precision. Because the height and intensity information are co-registered, i.e. they are measured in the same laser deflection direction, both data sets have the same horizontal shifts. The vertical shift of the height layer can be determined precisely and independently on the height variations, thus even for horizontal patches.

Recently [Akca and Grün 2005] revisited the LSM method and applied it also for terrestrial laser scanner data.

In this paper we revisit the approach of applying LSM on interpolated raster data. This is motivated by the fact that matching DEM-patches is a general problem worth investigating, and secondly by the fact, that often the irregular original laser points are not delivered by the flying company but an already interpolated regular raster of laser points.

With the knowledge of the previous work that is done in this field, we thus have to take care of possible occlusions, which may cause erroneous shift parameters. For this we follow two strategies: (i) perform the LSM in a robust way and (ii) omit patches with possible occlusions (mainly caused by buildings and vegetation). For (i) we apply the method of iteratively re-weighting the observations. For (ii) we first derive a DTM by hierarchical robust interpolation [Briese et al. 2002] for each laser strip. Due to the reduced height variation after this filtering, the planar shift parameters will be not very determinable in general. Therefore we expand the whole approach by simultaneously matching interpolated laser intensity information. Further we also have a look on how the inclusion of slope and curvature information derived from the DEM could be used during the LSM.

3. THEORY OF THE APPROACH

We start with two data sets, which are only slightly shifted horizontally and vertically. This is the prerequisite to apply LSM, during which a window of the first data set (template window) is shifted in X and Y with respect to a corresponding window (search window) in the second data set in order to minimize the squared sum of residuals.

Further we assume an interactive approach, i.e. a human operator manually selects suitable corresponding windows in both data sets. The strategy for applying LSM will be dependent on the properties of the surface in the area of these windows. The area can either be a smooth surface or a surface with vertical discontinuities.

3.1 Smooth Surfaces

A raster will represent a smooth surface either in open areas where no vegetation and buildings are present at all, or in areas where such non-terrain objects are removed during DTM-generation.

In case of smooth surfaces the observation equations for LSM of two corresponding windows (template *T* and search *S*) in the two data sets are the following:

$$v_Z = Z_X^S(X,Y)\cdot a + Z_Y^S(X,Y)\cdot b + c - (Z^T(X,Y) - Z^S(X,Y)) \quad (1)$$

With: $Z^S(X,Y)$ and $Z^T(X,Y)$are the heights of the search and template window respectively;
Z_X^S and Z_Y^S are the derivatives of the heights $Z^S(X,Y)$ of the template window in X and Y direction, which are derived from the differences at the Z-raster in these directions;

a and *b* are the unknown shifts in X- and Y-direction, respectively;
c is the unknown shift in Z-direction;
v_Z is the height residual.

The heights Z(X,Y) in both raster data sets must not be stored in 8-bit, as it is common in digital image processing, but rather as floating numbers.

The height variation in the Z-raster of a smooth surface is usually not very high. Consequently the unknown horizontal shifts *a* and *b* can not be determined very reliably (whereas the vertical shift *c* can be determined even for horizontal terrain, as the determinability of *c* increases with the number of corresponding cells in the two windows).

In order to increase the determinability of the horizontal shifts *a* and *b*, we also include the laser-intensity-raster (I-raster) in the matching process. Thus the system of observation equations (1) is expanded by the following equations:

$$v_I = I_X^S(X,Y) \cdot a + I_Y^S(X,Y) \cdot b + d - (I^T(X,Y) - I^S(X,Y)) \quad (2)$$

With: $I^S(X,Y)$ and $I^T(X,Y)$are the intensities of the template and search window respectively;
I_X^S and I_Y^S are the derivatives of the intensities $I^S(X,Y)$ of the search window in X and Y direction, which are derived from the differences at the I-raster in these directions;
a and *b* are the same unknown shifts in X- and Y-direction as in equation (1);
d an additional unknown shift in intensity (compensating different brightness in both windows)
v_I is the intensity residual.

Matching intensities (i.e. digital numbers or grey values) is the standard approach of LSM in digital (aerial) images, where also an unknown brightness parameter is introduced for each pair of corresponding windows in order to cope for changes in illumination – also a contrast parameter can be useful. Although laser scanning has an active light source (and therefore *no shadows* appear in the laser intensity data), the incidence angles on the ground are different for neighboring flight strips. This justifies the usage of these additional intensity-based unknowns.

Besides the laser-intensities other attributes coming from full-waveform laserscanning, like the backscatter cross-section [Wagner et al. 2006], can be included in the matching process in the very same manner.

Besides the mentioned data – in principle – also derived data from the heights, like the terrain slopes, can be used for the matching. For this purpose we determine the slopes (*K* and *L*) of the terrain in direction of X and Y. These values are the tangents of the respective slope angles. *K* and *L* are introduced in the whole adjustment by the following observation equations:

$$\begin{aligned} v_K &= K_X^S(X,Y) \cdot a + K_Y^S(X,Y) \cdot b - (K^T(X,Y) - K^S(X,Y)) \\ v_L &= L_X^S(X,Y) \cdot a + L_Y^S(X,Y) \cdot b - (L^T(X,Y) - L^S(X,Y)) \end{aligned} \quad (3)$$

With: $K^S(X,Y)$ and $K^T(X,Y)$are the slopes in X-direction of the search and template window respectively;
$L^S(X,Y)$ and $L^T(X,Y)$are the slopes in Y-direction of the search and template window respectively;
K_X^S, K_Y^S, L_X^S and L_Y^S are the derivatives of these slopes in X and Y direction, which are derived from the differences at the K- and L-raster in these directions;
a and *b* are the same unknown shifts in X- and Y-direction as in equations (1) and (2);
v_K and v_L are the residuals in the slope-values.

In a similar manner also the curvature values could be extracted from the Z-raster and used additionally in the adjustment. It should be kept in mind, however, that both the slope and the curvature are not original data but rather derived from the original data and are thus not independent from the heights. Furthermore the curvature is derived from the second differences of neighboring Z-values. Consequently random errors in these Z-values would be exaggerated in this way. We skip the listing of the respective equations for the curvature values.

In a simultaneous adjustment using all groups of equations (1), (2), (3) we also need to assign correct weights for the different groups. The slope equations (3) get a weight which is half of the weight of the height equations (1). Proper weights for the intensity equations (2) can be estimated from the a-posteriori accuracy of an adjustment, which uses only the equations (2). A further possibility for checking the weights of all three groups simultaneously is to perform a variance components analysis during the simultaneous adjustment of all groups of equations (1), (2), (3).

A note on break lines. In general the area around break lines in the terrain provides important variations for the matching process. In laser scanner data, however, break lines are not very well acquired due to the large beam divergence (or instantaneous field of view).

Therefore, in the Z-raster, which is the input to our approach, the break lines are not very well represented. They appear smoothed, mainly due to the filtering which is part of the DTM generation. Consequently the impact of break lines on the whole *area* based least squares matching is rather low.

On the other hand, break lines can be very well derived from the laser point data by intersecting tangent planes of the terrain [Briese 2004]. If this is done for two data sets, then corresponding 3D-lines, found in the overlap of the two data sets, can be used to perform *feature* based least squares matching. This, however, is not within the scope of this paper.

3.2 Surface with vertical discontinuities

Vertical discontinuities appear mainly on buildings and vegetation. First a few words about buildings. Figure 1 depicts the situation for a building from two neighboring laser strips before improving the georeferencing.

From figure 1 we see that the unknown translation (*a*, *b*, *c*) between the two windows can be derived from tilted planar surface patches, which are represented in the Z-raster. It must be noted, however, that for determining the three translations at least three planar patches having non-coplanar normal-vectors are required.

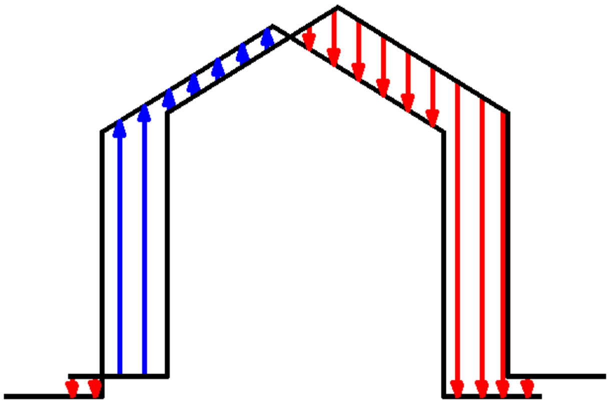


Figure 1 A building from two neighboring laser strips – before improving their georeferencing.

The edges at the border of the buildings are actually not required for the determination of the shifts. Furthermore the representation of the edges of buildings in the laser data is even worse than the representation of break lines in the terrain. This is due to the splitting of the laser cone that takes place when the laser beam hits the gutter. In the course of that multiple echoes will be recorded by the laser device: the first echo is returned from the gutter and the last one may be returned from the ground. Therefore, in case the original laser points are available, all raster cells coming from multiple echoes should be neglected for the matching. In this way also the raster cells falling into high vegetation areas are removed from the matching.

The vertical walls of building produce occlusions. Although, these occlusions are rather small due to the small field of view of airborne laser scanners, they are possible disturbances for the matching process. Further those vertical walls, which are visible to the scanner, contain laser points, which also have to be excluded from the matching process.

A general strategy to cope with the problems caused by edges, occlusions, points on vertical walls, vegetation and gross error points in general is to formulate the LSM in a robust way. A useful approach for robust adjustment, provided the number of gross errors is not too high, is to iteratively adapt the weights of the observations depending on the residuals *v* of the previous iteration. The adaptation of the weights can e.g. be done by the following formula (cf. [Briese et al. 2002]):

$$f(v_i) = \frac{1}{1+\left(\frac{1}{3}\cdot\left(\frac{|v_i - m|}{\sigma_i}\right)\right)^6} \quad (4)$$

Where: σ_i is the a-priori accuracy of the i-th observation;
v_i is the residual of the i-th observation from the previous iteration, m is the median of all v_i and p(i) := p(i)·f(v_i) is the weight of the i-th observation in the next iteration.

By means of this function f(v_i) the weights of observations with $v_i < 2\sigma_I$ are practically not affected at all, whereas observations with $v_i \geq 3\sigma_i$ is decreased by ≥ 50%; see figure 2. In this way the contribution of gross erroneous raster cells with to the matching result is reduced in an iterative manner.

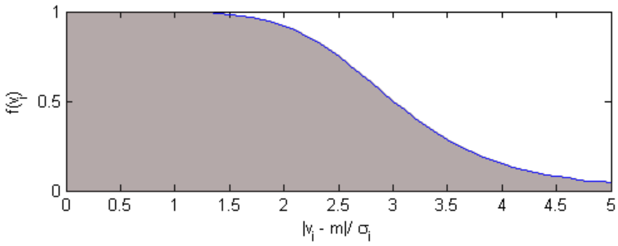


Figure 2 Graph of the weighting function f(v_i) in (4)

Another method for making the whole procedure more robust, is to adopt the accuracies of the filtering and interpolation of the raster as weights for the matching. The idea behind this is the following: if several original laser points in very different heights are used for the interpolation of one raster element (e.g. using the method of moving planes [Kraus 2000]) than this element should be treated with a lower weight during the matching process, where the weight decreases inversely to the amount of height variation used for the interpolation. [Maas 2002] applies similar ideas in the TIN data structure.

The result of this preprocessing step is, that only those raster cells are available for LSM, which lie on smooth surfaces or surface patches and that regions with discontinuities are labeled as "*do not use*". The observation equations (1), (2), (3) are then only set up for those raster cells, which lie in the template *and* the search window.

Finally another method to cope with the mentioned problems is to remove the responsible objects from the DSM by applying hierarchical robust interpolation which results in a DTM [Briese et al. 2002]. For this obtained smooth surface the findings of section 3.1 apply. However, by filtering a DSM to obtain a DTM, one has to be aware of the fact that certain parts, which are important for the LSM – like the plains of roofs – will also be removed.

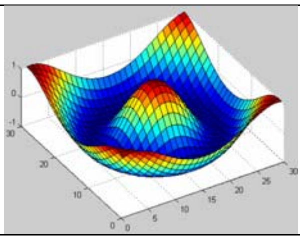
4. EXAMPLES

We conducted two different sorts of examples, one with synthetic data and one with real data.

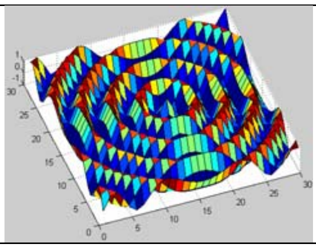
4.1 Synthetic data

The purpose of the synthetic example is to get first ideas on what the benefit of including slope observations during LSM could be. For this in the search and template windows (size 30x30m² and 20x20m², grid width 1m) a terrain using a cosine-based function with 1m amplitude was generated. Afterwards Gaussian noise is added to the heights in both windows. Then both windows are matched in two ways to find the horizontal shifts (*a*, *b*) and the vertical one: (i) using only the height information (equ. 1) and (ii) using height and the slope information (equ. 1 and 2).

Adding Gaussian noise to the error-free heights is repeated 100 times. Afterwards the differences of the resulting shifts from the matching are compared with the known true shifts and the standard deviations of these differences are analyzed. Also the estimated standard deviations (extracted from the a-posteriori covariance matrix of the shifts) are considered.



Noise	Height only		Height & Slope		Height only		Height & Slope	
[mm]	Sa	Sb	Sa	Sb	σa	σb	σa	σb
10	4.5	5.2	4.5	5.2	0.6	0.6	0.5	0.5
50	24.5	21.9	24.2	23.2	2.8	2.8	2.4	2.4
100	50.8	52.5	57.3	62.0	5.4	5.4	4.3	4.3
150	82.6	83.0	104.3	100.2	7.9	8.2	5.8	6.0



Noise	Height only		Height & Slope		Height only		Height & Slope	
[mm]	Sa	Sb	Sa	Sb	σa	σb	σa	σb
10	1.0	1.0	1.0	0.9	0.2	0.2	0.1	0.1
50	5.4	5.1	5.2	5.0	0.9	0.9	0.5	0.5
100	9.1	11.6	9.0	11.2	1.7	1.7	0.9	0.9
150	14.0	14.5	13.7	14.6	2.6	2.7	1.4	1.4

Figure 3 Two different synthetic terrain windows generated by a cosine-based function (amplitude 1m). Above: one wave. Below: five waves. Window size 30x30m² with grid width 1m. The table to the right of each figure shows the results of LSM computed using only the height information and using the combination of height and slope information in X and Y direction. The first column gives the standard deviation values of the applied Gaussian noise. The obtained accuracies of the unknown horizontal shifts between template and search window are given in two different ways: (Sa, Sb) are the standard deviations of the differences to the known true values and (σa, σb) are the standard deviations computed from the estimated covariance matrices. Observe that the estimates for (σa, σb) are much smaller than (Sa, Sb) and thus too optimistic. Actually those values should be very close together as only synthetic data is used. See text for the explanation why (σa, σb) are totally wrong estimates.

This process is repeated for different sizes of Gaussian noise (0.01m, 0.05m, 0.10m, 0.15m). Afterwards the whole process is repeated for a different generated terrain. All the terrains generated by the cosine-based function differ in the number of waves, two of which are shown in figure 3.

To the right of figure 3 are the standard deviations of the horizontal shifts (*a*, *b*) for these two synthetic terrains. From this listing of the standard deviations we get the following three important insights:

(i) The standard deviations get smaller with increasing number of waves (i.e. variation of the heights). This is easy to understand.
(ii) The standard deviations are more or less identical for LSM using only the height information and for LSM using both height information and slope information. Thus slope information (derived from the height data) does not contribute any gain in accuracy to the LSM using only heights.
(iii) The estimated standard deviations derived from the covariance matrices of LSM are way too optimistic. The reason for this is that the stochastic model used for LSM is simplified: The system matrix (the Jacobian matrix made up of the equations (1)-(3)) depends on stochastic quantities (the original observations) and the uncertainty of these observations is not correctly considered in the LSM approach – an observation which is also pointed out in [Maas 2002].

The latter fact has an important implication on practical tasks, since accuracy estimates can not be derived reliably from the resulting covariances of the LSM approach. Investigations on how to overcome this are part of future work.

4.2 Real data

In two examples with real data sets, the practical realization of LSM with height and intensity data from two ALS strips is demonstrated. The first example deals with an open surface (see figure 4) and the second one with a surface having vertical discontinuities (see figure 5).

Table 1 contains the obtained shift parameters (*a*,*b*,*c*) and the estimated accuracies of the height and intensity differences. For the intensity data besides the two horizontal shift parameters *a* and *b* also a brightness and a contrast parameter were used during LSM. Further the intensity data contain a few gross errors and 29 intensity values were eliminated during robust adjustment.

From the results of table 1 we see, quite expectedly, that the horizontal shift parameters *a* and *b* computed from the combination of both independent data types lies between the individually computed ones. The vertical shift *c* does not change much from height-only to the combined height+intensity version. This shows that both data types fit together and one can expect, that the horizontal shifts from the combined version to be more reliable than the ones from each individual version of LSM.

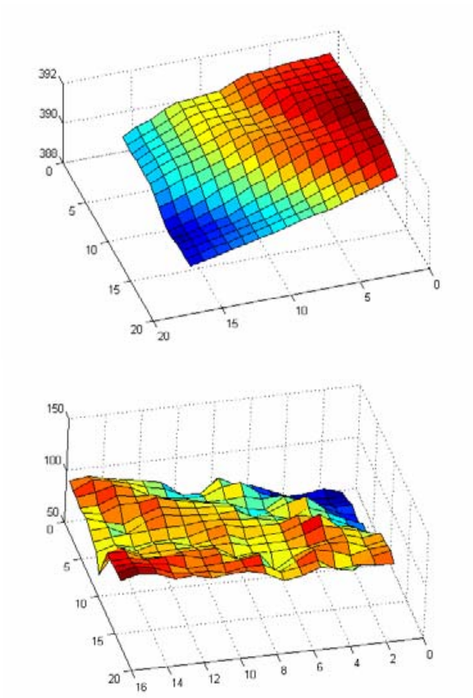


Figure 4 Real data example – open surface. Shown is the template window from one strip (size 15x15m², grid width 1m). Above: Height data of the template window (z-units: meter). Below: Intensity data of the same template window (z-units: digital numbers or grey-values). Observe the different slope-directions in height and intensity.

Used for LSM	sigma	a[m]	b[m]	c[m]
Height only	± 3.9cm	0.133	0.067	0.035
Intensity only	± 3.8 DN	-0.030	0.533	–
Height+Intensity	–	0.050	0.176	0.045

Table 1 The results for the real data example of an open surface. Sigma is the reference standard deviation obtained by the squared sum of residuals. For LSM using only the intensity data sigma is given in digital numbers DN.

The following table 2 contains the obtained shift parameters (*a*,*b*,*c*) and the estimated accuracies of the height and intensity differences. For the intensity data besides the two horizontal shift parameters *a* and *b* also a brightness and a contrast parameter were used during LSM. Due to the vertical discontinuities robust LSM is inevitable in order to get reliable results. The number of eliminated data is also mentioned in the caption of table 2. Figure 6 shows the distribution of the eliminated data.

Used for LSM	sigma	a[m]	b[m]	c[m]
Height only	± 5.0cm	0.105	0.225	0.046
Intensity only	± 3.6 DN	-0.129	0.157	–
Height+Intensity	–	0.092	0.239	0.047

Table 2 The results for the real data example of a surface with discontinuities. Sigma is the reference standard deviation obtained by the squared sum of residuals. For LSM using only the intensity data it is given in digital numbers DN. During robust LSM the following numbers of observations were eliminated: Height-only (272), Intensity-only (923), Height+Intensity (266+932).

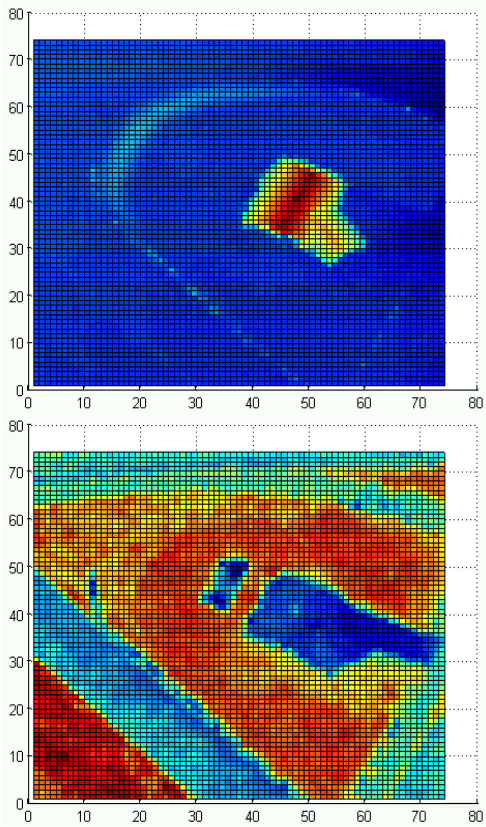


Figure 5 Real data example – surface with vertical discontinuities (in form of a building and vegetation on a line). Shown is the search window from one strip (size 74x74m², grid width 1m). Above: Height data of the search window. Below: Intensity data of the same search window. Observe the different texture information in height and intensity.

5. SUMMARY AND OUTLOOK

In this paper we presented a raster based approach for least squares matching in two different DEMs, which are derived from airborne laser data in overlapping strips. This approach uses simultaneously the heights and intensities from the laser data. Additionally slope information derived from the laser data can be used in the adjustment, however, in synthetic tests it was found that they do not contribute any gain in accuracy to the LSM using only the heights. This is because they are dependent from the heights. Only independent information like the laser intensity is beneficial for deriving the shift parameters. In this context also other independent parameters derived from full-waveform laserscanning could be useful.

When dealing with airborne laser data – especially in non-smooth areas – one has to take care of edges, occlusions, points on vertical walls, vegetation and gross error points in general during the matching process. Their disturbing influence on the matching result can be eliminated by robust approaches. Some of these have been presented (e.g. iterative re-weighting). Their principle success was demonstrated on a few examples. Since this, however, does not guarantee a general success in practice, in the future further empirical and more elaborated tests are to be conducted and also more sophisticated methods for dealing with the mentioned error sources should be investigated.

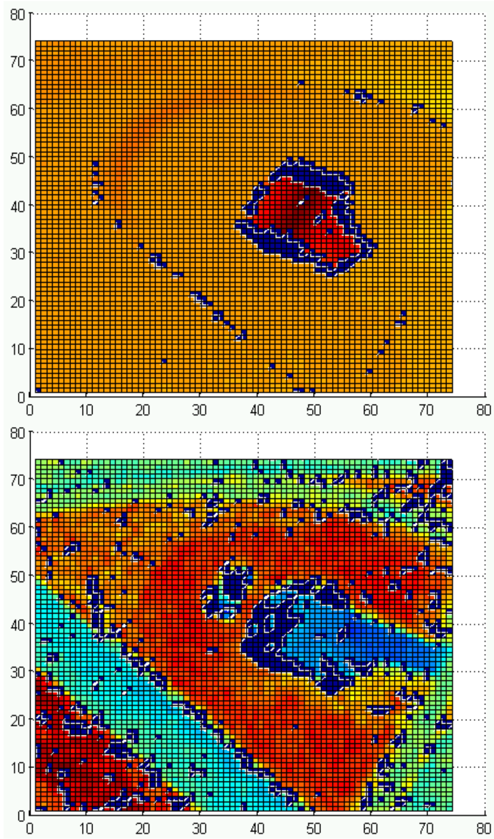


Figure 6 Distribution of the eliminated data in the real data example – surface with vertical discontinuities. Observe especially the massive elimination of both height and intensity data at the walls of the building and along the vegetation line.

In case the original unstructured laser points are given, the LSM can be performed using a TIN or a raster data structure. The mentioned error sources are a problem in both approaches and have to be dealt with specifically in both of them. Therefore it is interesting to compare their performance on different test data sets. Further, in both approaches interpolation of the original data is performed. In the raster approach, interpolation is done in both patches, whereas in the TIN approach interpolation is only done in the search-patch (however equations are build up twice for each pair of patches A-B; once patch A acts as search-patch and once patch B). Therefore it is worth investigating on how the results are affected by interpolation effects.

Finally, since accuracy estimates can not be derived reliably from the resulting covariances of the LSM approach, investigations on how to overcome this severe drawback are also part of future work.

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