Methods for Measuring Height and Planimetry Discrepancies in Airborne Laserscanner Data

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Abstract

Airborne laserscanning (or lidar) has become a very important technique for the acquisition of digital terrain model data. Beyond this, the technique is increasingly being used for the acquisition of point clouds for 3D modeling of a wide range of objects, such as buildings, vegetation, or electrical power lines. As an active technique, airborne laserscanning offers a high reliability even over terrain with poor image contrast. The precision of the technique is often specified to be on the order of one to two decimeters. By reason of its primary use in digital terrain modeling, examinations of the precision potential of airborne laserscanning have so far been concentrated on the height precision. With the use of the technique for general 3D reconstruction tasks and the increasing resolution of laserscanner systems, the planimetric precision of laserscanner point clouds becomes an important issue.

In addition to errors in the laser distance meter and the deflecting mirror system, the error budget of airborne laserscanning instruments is strongly influenced by the GPS/INS systems used for sensor pose (position and orientation) determination. Errors of these systems often lead to the deformation of laserscanner data strips and may become evident as discrepancies in the overlap region between neighboring strips in a block of laserscanner data. The paper presents least-squares matching implemented on a TIN structure as a general tool for the determination of laserscanner strip discrepancies in all three coordinate directions, using both height and reflectance data. Practical problems of applying matching techniques to 2.5D laserscanner point clouds are discussed and solved, and the success of the technique is shown on the basis of several datasets. Applying least-squares matching techniques to dense laserscanner data in a TIN structure, strip discrepancies can be determined with centimeter precision for the height coordinate and decimeter precision for the planimetric coordinates.

Introduction

Airborne laserscanning—often also referred to as "lidar"—is an active technique to capture point clouds describing the terrain surface from an airborne platform. The technique is based on laser distance measurement (usually by time-of-flight measurement techniques), combined with a scanning mirror mechanism. Position and orientation parameters of the sensor system are mostly determined by an integrated GPS/INS system. While early systems typically produced datasets with a point density on the order of one point per ten square meters, recent high-resolution systems are capable of producing densities of one point per square meter or better. The flying height of laserscanner systems is limited by the laser power and receiver sensitivity. Together with a narrow opening angle for minimizing occlusions, this results in laserscanner datasets consisting of many parallel strips with a width of several hundred meters in most cases.

Over the last few years, airborne laserscanning has gained a lot of attention and has become a leading technique for the acquisition of digital terrain model data. Its advantages are its fast and efficient manner of data acquisition as well as its high reliability and precision potential. Since the early nineties, airborne laserscanning has been used for special tasks such as, for example, beach erosion monitoring. Meanwhile, it is replacing conventional stereo-imaging-based photogrammetric techniques and is accepted as a general tool for digital terrain model data acquisition. The Netherlands were the first country to generate a nationwide digital terrain model purely based on laserscanner data (e.g., Wouters and Bollweg, 1998).

While early systems offered data rates on the order of 2 to 7 kHz (i.e., 2000 to 7000 3D surface points per second), modern systems come with data rates of 25 up to 83 kHz. This gain in temporal resolution has not only increased the efficiency of data acquisition, but has also opened a whole range of new application fields to airborne laserscanning. It broadens the scope of the technique beyond the pure acquisition of digital terrain models to a more general tool for the acquisition of point clouds for 3D modeling of a wide range of objects. High resolution laserscanner data have proven to be a valuable source for the automatic generation of 3D building models (Haala and Brenner, 1997; Maas and Vosselman, 1999). Further examples of new application fields are the determination of forest stand parameters and corridor mapping.

The precision potential of the technique is often specified as 1 to 2 decimeters. Due to the primary application field in the generation of digital terrain models, research on the accuracy of airborne laserscanner data has so far been focused on the height component of the point clouds. Detailed examinations of the height accuracy potential of airborne laserscanning, identifying a number of systematic errors, have been published by Huising and Gomes Pereira (1999). With the recent development of the technique towards a general tool for 3D object model data acquisition, however, the accuracy of the planimetric coordinates becomes just as important.

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Generally, the accuracy potential of airborne laserscanning is mainly influenced by the following components:

- The precision of slant distance measurement is primarily determined by the precision of time-of-flight measurement. In addition, distance measurement may be influenced by the type of local ground coverage and the terrain slope (Kraus and Rieger, 1999). With most systems operating at narrow opening angles, errors in distance measurement propagate mainly into the height coordinate.
- The error budget of the scanning mirror is described by the angular resolution and may also be influenced by mechanical problems such as vibrations or oscillations. These errors will mainly propagate into the across-track planimetric coordinate.
- The position of the aircraft and the sensor is determined by differential GPS techniques at 1 to 2 Hz. Depending on the GPS satellite configuration, the error of the height coordinate will usually be larger than the error of the planimetric coordinates.
- An INS system integrated with the GPS system is used to interpolate and possibly smooth the 3D trajectory and to determine the aircraft pose parameters. Drifts of the INS system will primarily lead to errors in the roll, pitch, and yaw angles, which mainly influence the planimetric coordinates.
- Alignment errors between laserscanner instrument, aircraft body and GPS/INS system components will cause systematic offset and tilt effects in data strips.

While errors introduced by the time-of-flight measurement will be of a primarily stochastic nature, errors introduced by the GPS/INS system cause systematic deformations of laserscanner data strips. These effects may be of a local nature, but may also cause shifts, tilts, or torsions of whole strips (Crombaghs *et al.*, 2000). Strip errors will often become evident as discrepancies in the overlap area between neighboring data strips. The quality of digital terrain models generated from airborne laserscanner data in regions with limited terrain slope is primarily defined by the accuracy of the height coordinate of the data points, whereas general 3D object modeling tasks also pose high requirements to the planimetric accuracy potential.

In Crombaghs *et al.* (2000), height discrepancies between neighboring strips and with respect to ground control points have been determined by interactively selecting local groups of points in flat areas. Ground control point differences are determined by comparing the average height of a group of points on flat terrain with GPS height measurements; strip discrepancies are determined by the average height difference between two groups of points in the overlap region of parallel or crossing strips. Their results show systematic effects, which are characterized as offset, tilt, and bending of strips.

If airborne laserscanning is extended towards a technique for modeling general 3D objects such as buildings, more sophisticated techniques are required to examine the accuracy of the planimetric and height coordinates of laserscanner data. In the following, the application of a least-squares matching method, adapted to irregularly distributed 2.5D point clouds in a TIN structure, will be discussed as a tool for the determination of both horizontal and vertical local discrepancies between neighboring laserscanner data strips (Figure 1). Results of the application of the technique to two test datasets will be shown. Such discrepancies, together with control point measurements, may be used as an input to laserscanner block adjustment (Vosselman and Maas, 2001).

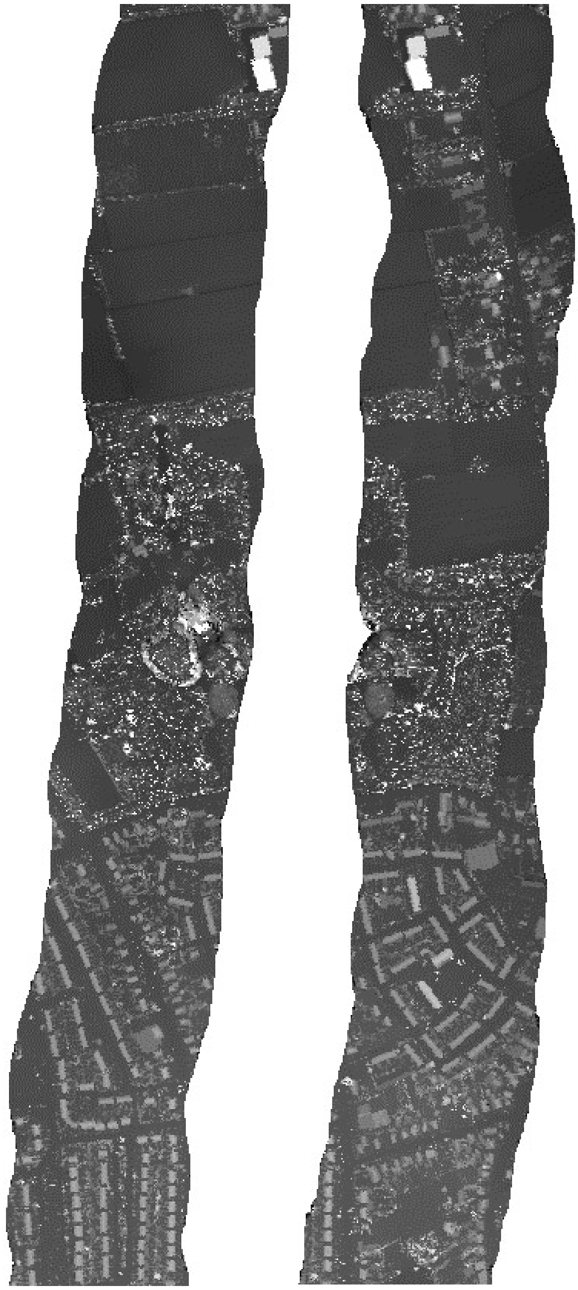

Figure 1. Two overlapping neighboring laserscanner data strips (height images).

Least-Squares Matching on a TIN Structure

Least-squares matching (LSM) is being used in many applications of photogrammetry, for example, for the establishment of correspondences between images of a scene taken from different viewing directions or between subsequent images of an image sequence. Formulated for two-dimensional grayscale images, it determines the parameters of an affine and radiometric transformation between corresponding patches of two or more images (Förstner, 1984; Grün, 1985). Typical application fields of LSM in aerial photogrammetry are the determination of homologous points between consecutive images for relative orientation and for photogrammetric digital terrain model generation, or matching between image strips of linear array cameras.

In contrast to digital image data, airborne laserscanner data consists of irregularly distributed 2.5D point clouds. Existing implementations of least-squares matching might be applied to these data after interpolating the data to a regular grid and scaling the height to a height image (Kilian, 1994). Such a procedure is often not adequate for the characteristics and quality of airborne laserscanner data: The reduction of laserscanner height data to 8 bits, as required by most standard LSM implementations, is not sufficient for the precision potential of laserscanner instruments. Moreover, the interpolation to a regular grid may introduce severe systematic errors by creating non-existing points in case of partial occlusions. A straightforward solution to this disadvantages is the formulation of LSM for the determination of 3D shifts between two clouds of irregularly distributed 2.5D points. This technique is discussed in detail in Maas (2000); it forms the basis for the examinations and results shown later and will only very briefly be outlined in the following.

Basic Algorithm

For the determination of shifts between neighboring or crossing laserscanner data strips, patches containing at least 20 to 30 points are cut out of the overlap region from both strips. The shape of these patches may be arbitrary, but will mostly be circular or rectangular. The 2.5D data in these two patches are shifted in all three coordinate directions in a way that the sum of the squares of height differences reaches a minimum. Because the point sets of the two patches are not identical or arranged on a regular grid, matching is performed between discrete points in one patch and points interpolated in the corresponding mesh of a TIN (triangulated irregular network) structure in the other patch (Figure 2). One observation equation is written for every original data point of both patches. The input into the observation vector for a data point is determined by the difference of the height of a point and the height at the same location in the other patch, computed by linear interpolation in the corresponding mesh of the TIN structure of the other data strip. The gradients for the construction of the design matrix are given by the surface normal of that TIN mesh.

The actual shift parameters are determined by a least-squares adjustment. Provided that there are good approximate values and sufficient height contrast within the patch, the solution will converge after a few iterations. The requirement for good approximate values forms no limitation to the application of the technique, because the errors observed in the laserscanner data will usually not exceed a few decimeters, while the diameter of the patches will typically be in the order of a few meters.

The requirement for sufficient height contrast can be formulated by the prerequisite that the patches to be matched must show surface normals in three non-coplanar directions to allow for the determination of all three shift parameters by LSM. As already discussed, determinability of the height shift is mainly given by flat terrain. In many cases, buildings or parts of buildings will depict suitable objects for the determination of the planimetric shift components in regions with limited terrain steepness, provided that they show roof faces in two non-opposite directions.

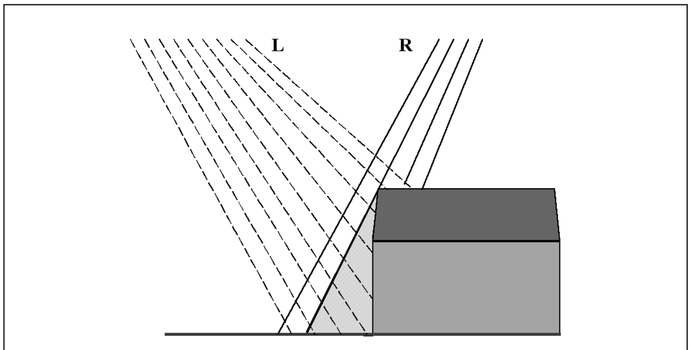

Figure 3. Occlusion in one strip at a building. Terrain points of strip "L" must not be matched with interpolated points in the gap in strip "R."

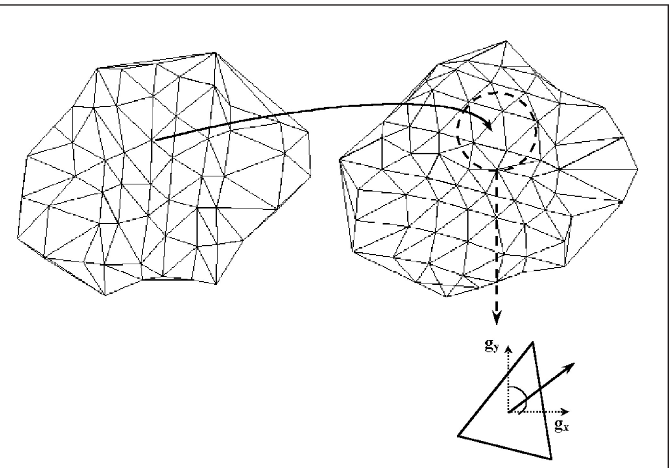

Figure 2. TINs of patches in two laserscanner data strips.

Refinement of the Algorithm

A severe problem when applying LSM to patches containing roofs is caused by occlusions typically occurring at one side of a building in one strip as a consequence of the quasi central perspective geometry of laserscanning in the across-flight direction (Figure 3). These occlusions become visible as gaps in one of the patches. Due to the composition of laserscanner data blocks of parallel strips, these occlusions will often occur in only one of the patches to be matched. As a consequence of this fact and of the minimization of the sum of height differences between the original data points of both patches and their interpolated corresponding values, the solution of LSM will suffer from significant systematic errors, which can roughly be characterized as a shift towards the occlusion zone.

To avoid these effects, points falling into occlusion zones, which are characterized by TIN-meshes with irregular shape and size, have to be excluded from the matching process. To fulfill the requirement of LSM for a bandwidth-limited signal, a further thorough analysis of the patch has to be performed in order to avoid degrading effects from points close to discontinuities such as roof edges (Maas, 2000). These extensions, which are crucial for the successful application of matching techniques to laserscanner data, can only be formulated if matching is applied to the original data points rather than to an interpolated height image containing artificial observations in occlusion zones.

As a consequence of the characteristics of laser pulse penetration as well as sampling pattern and viewing direction, data points on vegetation or other objects with an irregular shape may show rather different heights in neighboring strips, leading to unpredictable outliers in matching. These outliers will deteriorate the quality of the match and may falsify the result of matching. Obviously, the technique is better applied to last-pulse data with a larger chance of obtaining reflections from the ground. Remaining vegetation effects have to be removed by robust estimation techniques integrated into the LSM routine.

A general problem of LSM is the fact that the covariance matrix is generated from observations with stochastic properties. This fact originates from the noise of the laserscanner data points themselves, which can be estimated on the order of 3 to 5 cm (see Results section), plus some model noise caused by the fine structure within the patches, the laser spot size, and insufficient sampling. This noise propagates into the gradients of the

TIN meshes, which determine the design matrix and the covariance matrix used for parameter estimation in LSM. As a consequence, the estimated standard deviations of the shift components will generally be too optimistic, and correlations between parameters, indicating singularities caused by insufficient patch-gradients, will often not be detected. Techniques to yet derive realistic precision estimates are discussed in the Results section. To allow for a thorough analysis of the determinability of all three shift parameters in an automated matching strategy, a procedure for a detailed analysis of the design matrix, based on an examination of the significance and directional distribution of patch gradients, has been defined (Maas, 2000).

Constrained Versions

Constraints may be introduced into the matching process in situations with insufficient patch contrast, limiting the solution to the determination of a subset of the three shift parameters. By the definition of constraints, the technique can be limited to pure height or planimetry matching. In particular, the use of planimetry constraints, leading to the determination of only height discrepancies between patches, is valuable in flat regions with insufficient height texture, or in low-density datasets used for pure DTM applications over terrain with limited steepness.

Matching on Reflectance Data

Several airborne laserscanner systems deliver a reflectance signal derived from the intensity of the backscattered pulse-echo in addition to the actual height measurement. This reflectance value is sometimes being used for visualization purposes or in segmentation tasks (e.g., Oude Elberink and Maas, 2000). In high-density datasets, the reflectance signal provides a rather detailed image of the scene (Figure 4). Because the reflectance value is inherently perfectly referenced with the height data points, the contrast in the reflectance image may also be used for the determination of planimetric shifts between neighboring laserscanner data strips. Using the reflectance as observation in matching forms an analogy to standard grey-value-based photogrammetric matching techniques, again with the difference that matching is performed on irregularly distributed intensity values in an orthogonal projection.

This option of simultaneous matching in height and reflectance data is especially relevant in flat areas, where the patch contrast situation in height data allows only for the determination of the vertical shift parameter. In such situations, existing contrast in the reflectance image may substitute well for the determination of the two planimetric shift parameters. Figure 4 shows an example of a road crossing with white markings, where the height data allows only for the determination of the vertical shift parameter, while the reflectance data allows for the determination of the two planimetric shift parameters.

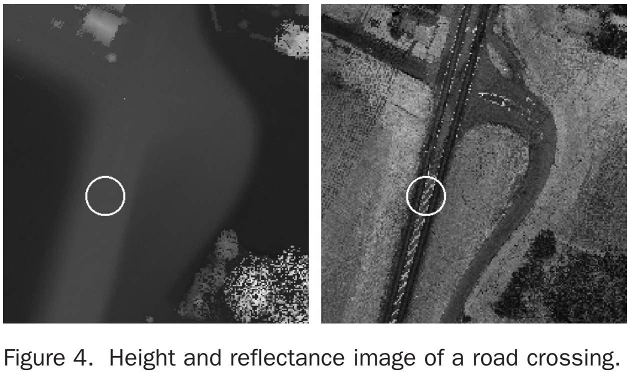

Figure 4. Height and reflectance image of a road crossing.

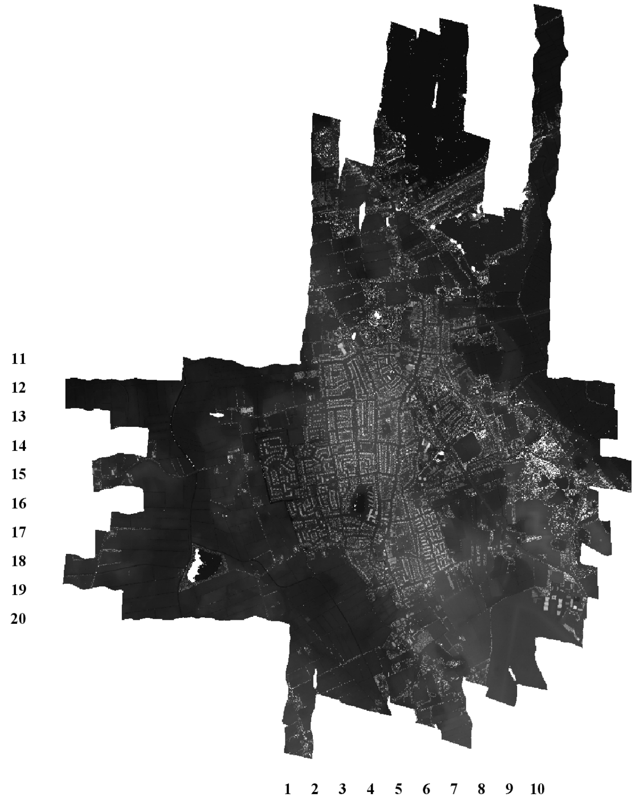

Figure 5. Laserscanning test block “Eelde” (The Netherlands) with totally 20 strips.

Results

The technique with the extensions as discussed earlier was applied to a part of the laserscanning test block “Eelde” in The Netherlands. This dataset was flown with a 10-kHz Optech system at a flying height of 500 m with a strip width of 250 m and a point density of about 0.3 points per square meter, corresponding to an average point spacing of 1.8 meter. It consists of ten strips flown in a north-south direction and ten strips flown in an east-west direction, covering an area of approximately 5 by 5 km^2 (Figure 5). Both first- and last-pulse echoes were recorded; only the last-pulse data were used for LSM in order to reduce effects caused by vegetation.

Matching with Planimetry Constraints

The planimetry-constrained version, allowing for the determination of only height discrepancies, was tested between a number of neighboring strips of the dataset. Flat areas such as meadows, fields, roads, or parking places were used for matching; outliers caused by vegetation within the patches were excluded by the use of robust estimation techniques. A patch radius of 7 meters was chosen, yielding an average of 50 points per patch.

The results of the analysis of a total of six strip-overlap regions are summarized in Table 1 and Figure 6. Figure 6 shows the trend of the height discrepancies over the full length of the overlap regions of the strips. The average distance between the analysis points is 100 m. Gaps are explained by regions where no suitable patches could be found in the strip overlap area because of insufficient strip overlap, or due to the presence of

Table 1. Results of LSM Constrained to Height Shift Determination, Applied to Dataset "Eelde" (see Figure 6)

Strips	2/3	3/4	4/5	5/6	18/19	19/20
Number of patches	51	50	60	64	79	91
LSM results over length of strip overlap [mm]:						
Average height difference	92	43	57	47	−27	7
Max. height difference	158	123	143	171	90	92
Min. height difference	1	−61	−33	−53	−83	−108
RMS of height differences	42	36	39	45	32	38
LSM internal parameters [mm]:						
Avg. st. dev. of unit weight	50	61	60	54	53	54
Avg. st. dev. of height shift	6	7	7	7	6	6

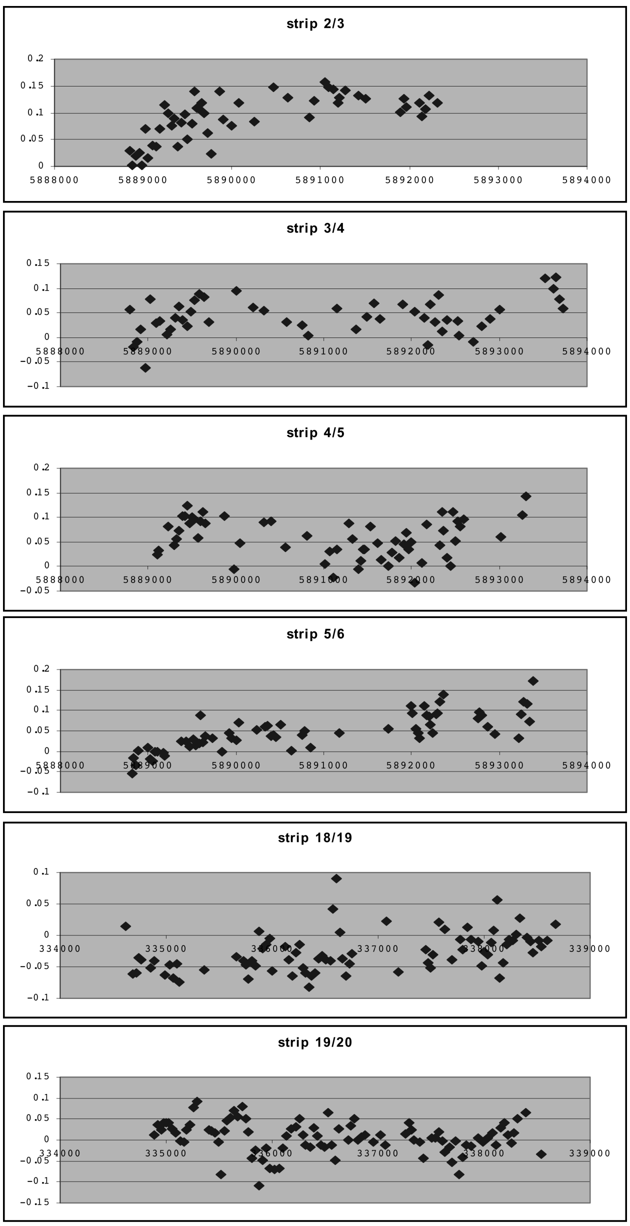

Figure 6. Height discrepancies [m] in strip overlap regions of the data block "Eelde" (Figure 5).

vegetation, buildings, or water. In all cases, the amplitude of the height discrepancies over the strip length of 5 km is on the order of 20 cm. Some of the strip-height discrepancy graphics indicate significant offsets; in two cases an (unexpected) non-linear trend of the height difference over the strip length can be recognized. The average standard deviation of unit weight obtained from LSM in the individual patches is 55 mm. Due to the stochastic properties in both patches, this leads to an estimate of about 40 mm for the precision of the individual laserscanner point heights, unaffected by systematic effects of the GPS/INS pose determination. Taking into consideration that the matching result is also influenced by effects of not-excluded vegetation remainders, terrain roughness, and undersampling, the precision of the individual laserscanner point height is even better than this. Due to the redundancy provided by the number of data points per patch, the precision of the patch difference measurement is in the millimeter range. Figure 7 (upper part) shows the trend of the height discrepancies over the length of the overlap region of two strips. A 450-m section of this dataset was examined in more detail with one height discrepancy analysis point every 5 m. In addition to an offset, a significant trend can barely be recognized here. Figure 8 shows a dense analysis of height discrepancies of the 450-m strip section with its left and right neighbors. Neither a trend nor a correlation between the two curves is recognizable here. These two figures may lead to the conclusion that the height difference pattern is mainly determined by the height precision of the kinematic GPS measurements at an aircraft speed on the order of 50 m/s, and that the role of INS in the GPS-INS integration is limited to orientation determination and the interpolation on the GPS trajectory. Further analysis on more datasets should be performed to prove this statement, which limits the benefits of efforts to create laserscanner block adjustment schemes.

The detected discrepancies between neighboring strips are within the accuracy requirements specified for most laserscanning projects. Nevertheless, a comparison between these errors and the precision of a single laser distance measurement indicates that the accuracy potential of airborne laserscanning might be significantly improved if a better DGPS height accuracy could be achieved. As shown in Vosselman and Maas (2001), the non-linearity of the observed trends in height discrepancies over the length of a strip—which partly stands in contradiction to the assumptions of Crombaghs *et al.*, (2000)—will however limit the accuracy improvement which can be achieved by laserscanner block adjustment techniques based on simple strip deformation models.

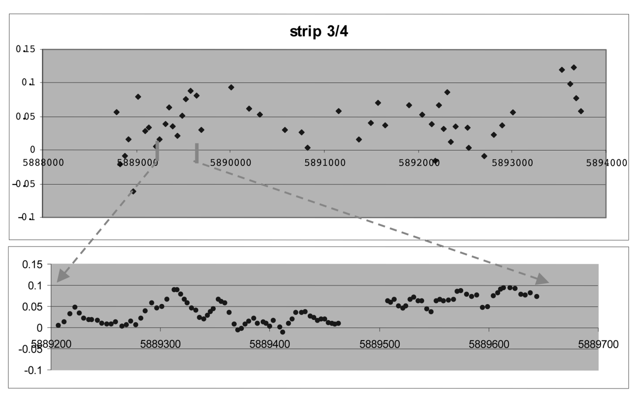

Figure 7. Height discrepancies between neighboring strips in [m]. Section of 5 km (top) section of 450 m (bottom).

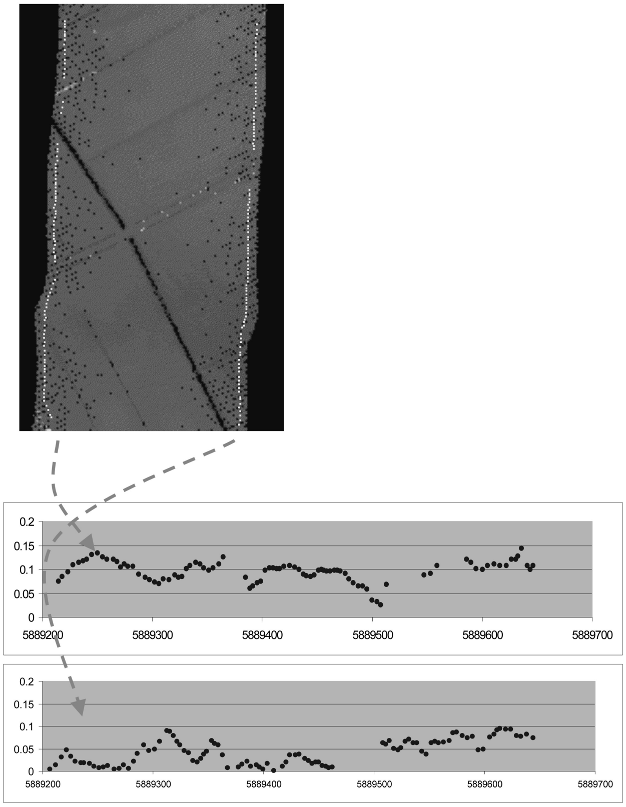

Figure 8. Height discrepancies in [m] between three neighboring strips.

Planimetry and Height Matching

In the unconstrained version of the algorithm, planimetry and height shifts between patches are determined simultaneously. The technique was applied to the common area of two crossing strips of the dataset shown in Figure 5. Due to the lack of an automatic point selection strategy, LSM was applied to a number of manually selected locations. The patch radius was chosen to be 12 meters, yielding an average 130 points per patch. The results are shown in Table 2 and Figure 9. Planimetric strip discrepancies of up to 70 cm were detected, while the height discrepancies are on the same order of magnitude as observed earlier. The standard deviation of the planimetric shift parameters, derived from the covariance matrix, is only 2 to 3 cm.

TABLE 2. RESULTS OF LSM APPLIED TO 60 PATCHES IN THE CROSSING SECTION BETWEEN TWO STRIPS (SEE FIGURE 9)

LSM results over test area:	*X*	*Y*	*Z*
Average shift	134	334	22
Maximum shift	570	690	49
Minimum shift	−280	−160	−60
LSM internal parameters [mm]:			
Avg. st. dev. of. unit weight		171	
Avg. st. dev. of shift parameter	27	26	8
Max. st. dev. of shift parameter	40	30	13
Result of regression analysis [mm]:			
Regression over X	153	133	22
Regression over Y	153	156	19

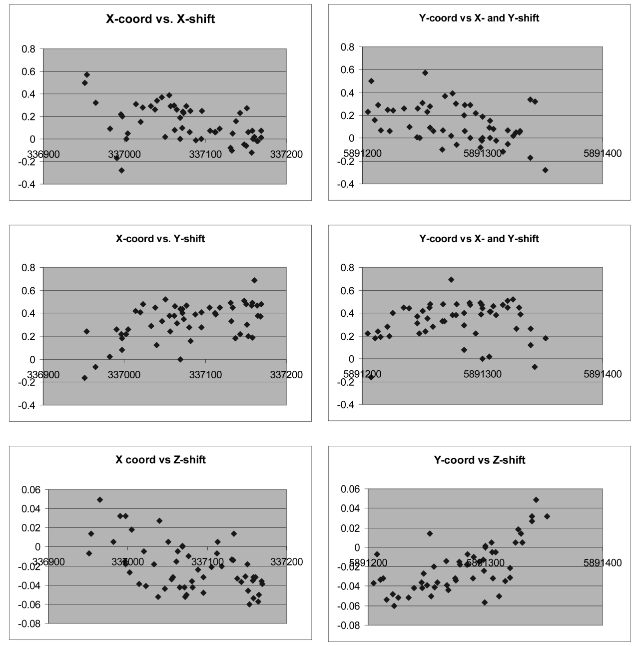

Figure 9. Trend of planimetry and height shift components between two crossing strips in Figure 5 over a section of 200 m (in [m]).

Expressed as relative precision in analogy to the subpixel precision as often used in raster image matching, this corresponds to about $^1/_{70}$ of the average point spacing. As discussed earlier, these precision figures are too optimistic. Assuming the complete absence of high-frequency effects in the discrepancies between the two data strips over the 200-m section, a more realistic precision figure can be derived from an analysis of the variance of the shift parameters over the test region after linear regression. This analysis indicates a precision of the shift parameters determined by LSM on the order of 15/15/2 cm in *X*/*Y*/*Z*. Similar results were obtained from other datasets. As one can see from Figure 9 and from the results shown earlier; however, the assumption of a linear behavior over a 200-m strip section does not hold. Therefore, the above precision measure can be considered too pessimistic. A realistic value for the planimetric precision potential of LSM applied to the dataset at hand is about one decimeter. A thorough analysis based on extensive ground control has to be performed to better quantify this value.

Examining the height texture of the dataset shown in Figure 5, it is obvious that many regions do not allow for a determination of all three shift parameters. In these cases, LSM can automatically be switched to planimetry-constrained matching, delivering only a height shift component. This lack of sufficient height texture over wide areas is obviously unfavorable for laserscanner data block adjustment. However, a suitable parameterization of the block adjustment may at least warrant an improvement of the planimetric quality of the data in regions where full 3D object information is needed.

The determinability of the shift parameters depends also on the point density: While the height shift will be determinable in almost any laserscanner dataset, the significant determination of the planimetric shift parameters is limited to datasets with suitable height texture and a point spacing of less than two meters. Because datasets with lower densities are only relevant for the determination of digital elevation models, but not for the extraction of general 3D objects, this fact does not depict a severe restriction.

Planimetric Shifts from Reflectance Data

The combined height and reflectance data matching technique as described in earlier was applied to a laserscanning dataset acquired by the FLI-MAP system. FLI-MAP I (Fugro N.V.; see, e.g., Pottle (1998)) is a helicopter-based laserscanning system with an 8-kHz sampling rate, which is mainly used for corridor mapping. It acquires 40 profiles per second with 200 points per profile. Range measurement is limited to first-pulse capture at a 20- to 200-meter slant distance, thus providing a maximum strip width of 200 m at a scan angle of 60°. Due to these system parameters, the point density is usually rather large. In the dataset used for the work presented here, the point density was on the order of five points per square meter. In addition to the laser range measurements, the FLI-MAP system is capable of delivering 6-bit intensity data.

A test area of three strips containing a road crossing with white street markings, which are clearly visible in a reflectance image (Figure 10), was selected from a large FLI-MAP project. Due to the lack of height contrast, the height data along the road allows only for the determination of a vertical shift between the strips. The reflectance image can be considered complementary to the height image and seems well suited for the determination of horizontal shift parameters. Matching was applied to a total of 25 tie points between the strips, choosing circular patches with a radius of three meters.

The results of the application of the technique to the three overlapping strips shown in Figure 10 are listed in Table 3. The amplitude of height discrepancies is on the order of 10 to 15 cm, while the planimetric discrepancies are up to 40 cm. Again, the estimated standard deviation for the planimetric shift parameters is too optimistic as a consequence of the stochastic properties in the covariance matrix. As already discussed earlier, variance measures in a local linear regression analysis were used to obtain more realistic precision figures. Due to the non-linear behavior of the discrepancies along a strip unveiled earlier, the latter measure will again be too pessimistic. Roughly, the precision of the shift parameters obtained from reflectance data can again be estimated on the order of 10 cm, compared to an average point spacing of 40 to 50 cm in the dataset at hand.

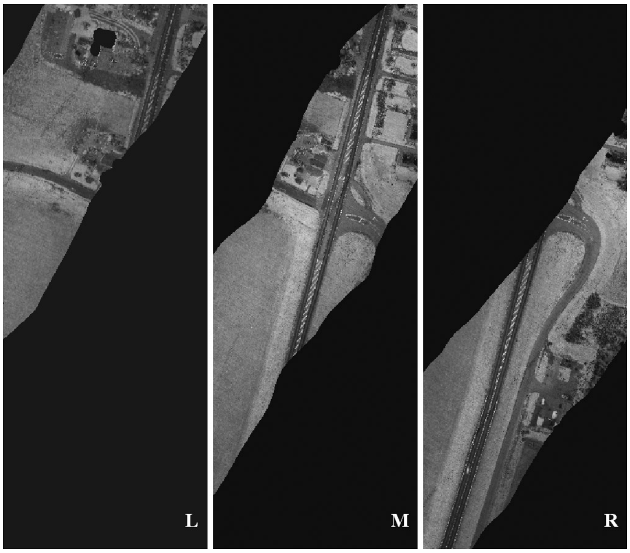

Figure 10. Reflectance image of a crossing in three neighboring strips.

TABLE 3. RESULTS OF HEIGHT AND REFLECTANCE MATCHING FROM 20 PATCHES IN THE SECTION SHOWN IN FIGURE 10

Shift parameters [mm]	Planimetry (from reflectance) X	Y	Height Z
strip M - L	−190 … +140	−460 … −100	−93 … −6
strip M - R	−180 … +220	−210 … +80	−46 … +91
Average standard deviation of shift parameters [mm]			
strip M - L	23	33	4
strip M - R	10	10	4
RMS from regression analysis of shift parameters [mm]			
strip M - L	123	136	36
strip M - R	70	80	33

Conclusion

Least-squares matching applied to laserscanner data in a TIN structure can be used to unveil both horizontal and vertical discrepancies between neighboring laserscanner data strips. Effects caused by height discontinuities in the data have to be handled very carefully to avoid systematic errors in the results. A thorough analysis of patch gradients and local correlation has to be performed to examine the determinability of shift parameters and to derive realistic precision figures. In this context, the application of matching to the original data points, rather than to an interpolated height image, is crucial.

In practical tests of the method, vertical discrepancies of less than 20 cm and horizontal discrepancies of up to 70 cm could be detected between neighboring or crossing laserscanner data strips. The precision potential for the planimetric shift parameters reaches decimeter-level and can be estimated to be on the order of $^1/_{10}$ to $^1/_{20}$ of the average point spacing. This precision is high enough to determine these shifts significantly. Local height shifts between neighboring laserscanner data strips can even be measured with a precision of a few millimeters when suitable patches in flat areas are found. The height precision of the individual laserscanner data point, unaffected by effects of the GPS/INS system, is estimated on the order of 3 to 4 cm. Reflectance data, acquired simultaneously with the actual height data by several laserscanner systems, may provide a useful signal for the determination of horizontal strip discrepancies in regions with poor height contrast but good image contrast.

Although the detected discrepancies are in reasonable accordance with the accuracy specifications of most systems, some systematic behavior can be recognized in the discrepancy images. Although these systematic effects are non-linear in most cases, they justify further work on the adjustment of laserscanner blocks with the goal of an overall improvement of the geometric quality of airborne laserscanner data, both in planimetry and height. The local effects of DGPS height precision on laserscanner data quality demand further improvement of DGPS and GPS/INS integration. Obviously, the statements about the precision of the pose parameters determined by the GPS/INS system apply to all other airborne sensors based on such a system, such as linear array cameras, multi- or hyperspectral scanners, or SAR systems. In contrast to imaging systems, however, airborne laserscanning offers a better precision in the height coordinate direction than in the planimetry coordinates. Therefore, it is more sensitive to the worse height precision of GPS; at the same time, it depicts a rather powerful tool to verify the height accuracy of kinematic GPS onboard an aircraft.

The method as presented in the paper depicts only a tool for the discovery of laserscanner strip discrepancies. It may be used for quantitative quality assessment of datasets. For an actual improvement of datasets, the results may be used as input into a laserscanner strip adjustment procedure. For this purpose, suitable interest operators have to be developed, detecting appropriate tie points. In addition to the presented application, the method described in the paper can also be adapted to be used as a general tool for matching 2.5D point clouds, for example, for fitting building models to laserscanner data or vice versa.

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