QUALITY CHECKING OF ALS PROJECTS USING STATISTICS OF STRIP DIFFERENCES

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ABSTRACT:

We present an automatic method for checking the geometric accuracy of ALS points. First for each strip a DEM is interpolated using the moving planes method. The accuracy of the interpolated height at each grid point and the distance between each grid point and the centre of gravity of the original ALS points used for interpolation are used to derive a smoothness mask for each strip. Afterwards for pairs of overlapping strips the difference of their DEMs is computed. Grid points, which are inside the smoothness mask of both strips, are compared with a given threshold for the height differences. The percentage of the grid points exceeding this threshold is a first quality measure for the given ALS data. If this percentage is larger than a given threshold, then we perform another analysis, which is based on LSM. LSM computes the 3D shift between both overlapping strips in many locations of a window which slides from one end of the strip overlap to the other. By comparing the X, Y, Z components of these shifts with predefined tolerances for the accuracy in planimetry and height the location and size of regions hurting these tolerances can be spotted.

1. INTRODUCTION

Over the last ten years airborne laser scanning (ALS) has established itself as the prime data acquisition method for digital canopy and digital terrain models (DTM). It is a technique based on direct georeferencing; i.e. position and attitude of the scanning system is determined by GNSS (Global Navigation Satellite System) and an IMU (Inertial Measurement Unit). Direct georeferencing does not perform a simultaneous adjustment of the measurements involved, but completely relies on the quality of the GNSS/IMU processing, the knowledge of the transformation from the GNSS/IMU sensors to the laser-sensor (misalignment and lever-arm), and the calibration of the laser-sensor. Errors in the mentioned parameters will propagate into errors in planimetry and height of the points on the ground.

Direct georeferencing is now considered as a well established industrial method [Skaloud 2007], however its reliability is still an open problem. The stability of the misalignment, the lever-arm and the calibration of the laser-sensor since their last determination can not be guaranteed. Even the synchronization between GNSS/IMU and laser sensor can have a small gap. Therefore the real reliability and accuracy of the resulting ALS point cloud can not be predicted.

Consequently, the *geometric accuracy* of the originally directly georeferenced ALS points should be checked before usage, whether a-priori defined quality figures are met. If the quality is sufficient, then further processing can continue e.g. DTM generation. If the quality is not sufficient, then suitable procedures (e.g. ALS strip adjustment [Kager 2004]) for improving the orientation of the strips (and the calibration of the ALS sensor) should be performed. Afterwards the quality of the ALS points due to the changed orientation and calibration must be checked again.

Because of the sampling characteristics of laser scanning the points themselves can not be compared – but interpolated surfaces can. When talking about quality in form of geometric accuracy one has to distinguish between relative and absolute accuracy. Whereas the absolute accuracy always requires some sort of external reference data (e.g. ground control points defining a control surface), the relative accuracy can be checked using only the data itself. There either the internal geometry can be exploited (e.g. points are known to lie on a mathematically defined surface e.g. a plane) or natural (mathematically not defined) surfaces measured independently in different flight strips are compared.

This second method of checking the relative accuracy can be applied to ALS data provided the strips were flown with sufficient side overlap, which usually has to be done in order to guarantee a gapless data collection. Then the surfaces in the overlap measured in different strips serve as check features. Because of the sampling distance of ALS points these surfaces need to have a certain smoothness otherwise the interpolated surfaces in the individual strips will be too different in shape for comparison.

This paper describes a simple method for checking the relative accuracy of ALS data using *interpolated* digital elevation models (DEM) for each strip. This interpolation provides valuable information which can be used to extract smooth surfaces. Only such surfaces are considered in this method. First only the height difference (dz) between two overlapping strips is computed. If too many grid points exceed a predefined threshold for dz, then an analysis using least squares matching

(LSM) follows which determines 3D shifts between corresponding windows in overlapping strips. An analysis of these shifts is particularly useful because dz is the summed effect of all errors from GNSS/IMU/laser. For this reason also the planar coordinates are affected and so dz is determined at non-corresponding gird points. Consequently dz does not reflect the actual Z accuracy. Therefore a differentiation of this total error into its parts in X, Y, Z gives better information about the planimetric and height accuracy.

This method so far only checks the relative accuracy but could be easily extended for absolute accuracy. Then the external surface information has to take the role of one strip.

The paper is structured as follows: Subsection 1.1 gives an overview on the present status of ALS quality checking, followed by an overview of the proposed method in subsection 1.2. Section 2 deals with the description of the method. In section 3 first results using real data are shown. Section 4 concludes the paper by giving an outlook on future work.

1.1 Previous Work on ALS Quality Checking

Different approaches for checking the ALS quality in height and planimetry were presented in the past. Most approaches are in some way based on LSM. Therefore it makes sense to distinguish between LSM-based and non LSM-based approaches.

1.1.1 LSM-based approaches: 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].

LSM was originally introduced for finding corresponding features in aerial images (which already have a regular raster structure) [Grün 1985]. Therefore it is somewhat natural to interpolate a regular raster before applying LSM. However 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 in the ALS data. E.g. the averted wall of a building located near the border of the first ALS strip is not seen in this strip, but is clearly visible in the second strip. If a regular grid 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].

On the other hand the heights of the regular raster interpolated from many surrounding original irregular points will have better accuracy, compared with the TIN approach where the interpolation is based only on three points.

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 in 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 variation of the surface normals. 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.

1.1.2 Non LSM-based Approaches: For checking the quality of the (relative) georeference of ALS data [Kager 2004] proposed colour-coded height differences between pairs of overlapping ALS strips. These strip differences are the effect of all errors coming from GNSS/IMU/laser. Therefore, by colour-coding these differences a simple visual inspection of the quality of the relative accuracy over larger areas is provided; see figure 1 (left). Differences over non-smooth areas (e.g. vegetation, walls, etc.) will be large in general, because there due to the different viewing directions in the overlapping strips the laser beam will hit points at very different heights. These non-smooth areas will appear very prominent in the colour-codings. However the human inspector quickly learns to mask out these areas and concentrate on the smooth areas while watching the colour-codings in a suitable zoom on screen (preferably 1cell:1pixel). The colour patterns in the smooth areas can give valuable indications on the error source (e.g. IMU misalignment).

[Schenk et al. 2001] project the ALS points into aerial images and use these image positions to start an LSM in the images. By comparing the spatially intersected points with the ALS points the height accuracy is assessed. Additionally the planimetric accuracy is assessed by comparing lines (as intersections of planes) from the ALS data with corresponding lines extracted from the aerial images.

[Huising and Pereira 1998] use various photogrammetrically determined external control data to inspect the planimetric and altimetric quality: roof outlines, height profiles, and DEMs.

Although the additional photogrammetric data – if available – can be a valuable source for checking, one has to observe that the accuracy provided by this data has to match (or even surpass) the accuracy potential of the ALS data. In general, however, the height accuracy of ALS is better than the planimetric one, whereas in Photogrammetry the height accuracy is usually worse than the planimetric one.

1.2 Outline of the Method

In this paper we first follow the approach of [Kager 2004] of colour-coded height differences in overlapping strips. Originally the colour-codings were designed for human usage, where the prominent colours in non-smooth areas do not disturb. However, for automating the quality control it is required to consider only the height differences in smooth areas. We solve this problem by a smoothness-mask. The latter is derived from the accuracy of the interpolated height at each grid point estimated during the interpolation of the DEM for each strip.

The height differences between both strips are easy to produce and may serve as a first automatic quality check by comparison with a given threshold; e.g. a suitable multiple of the height accuracy specified by the client who ordered that ALS flight. The colour-coded height differences without the non-smooth areas may serve then as quick visual quality documentation.

In case this first height check does not meet with the expected height threshold, a deeper analysis must be carried out. Because the height differences between pairs of overlapping strips show the summed effect of all errors from GNSS/IMU/laser, a differentiation of this total error into its parts in X,Y,Z could yield further information.

For this we revisit the approach of applying LSM on interpolated raster data. 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) omit occluded and non-smooth areas (mainly caused by buildings and vegetation) and (ii) perform the LSM in a robust way.

For (i) we use the mentioned smoothness mask derived for the height differences. Only DEM grid points which are labelled as smooth are used for the LSM. For (ii) we apply the method of iteratively re-weighting the observations.

2. DESCRIPTION OF THE METHOD

We assume the original (irregular) ALS points to be given strip by strip. If multi-echo data are given, then for creating a smooth surface it can be beneficial to extract only the single echoes (i.e. first = last echo). However up to now we do not perform this additional check and use only the last echoes.

2.1 Interpolating a DEM for Each Strip

First, the original ALS points are organized in a kd-tree (k-dimensional tree) allowing a quick multiple nearest neighbours search. Then a 2.5D DEM is computed for each strip. For the DEM we use a grid width smaller than but close to the point distance of the original ALS points; e.g. 1m. The DEM is derived using the so-called *moving planes interpolation* [Kraus 2000]. This interpolation method is advantageous at the early stage of quality control, since it combines high speed and moderate smoothing capabilities. At each grid point the n closest original ALS points are used to determine a local adjusting plane.

To avoid grid point extrapolation a constraint to the multiple nearest neighbours search can be applied forcing to have at least one point in each quadrant. Anyway, we do not use quadrant-based point selection in our approach since it is rather time consuming and we employ the extrapolation information for the derivation of the mask as described later. Additionally a maximum distance s_{max} between the grid point and each closest ALS point should be defined in order to exclude areas with no ALS point information from the subsequent analysis.

After estimating the plane parameters, the height at the location of the current grid point is determined. We use the parameterization z = ax + by + d and prior to computation we centre a local coordinate system in the location of the grid point. The height of the grid point results to be d. Additionally, the accuracy of the interpolated height turns into σ_d which is

$$\sigma_d{}^2 = \left((n-3)n\right)^{-1} \cdot \sum_{i=1}^{n} v_{z,i}^2$$

with $v_{z,i}$ being the residual of the i-th point.

Additionally, after computing the adjusting plane, the eccentricity ε at that grid point is determined. This is the distance between the 2D-location of the grid point and the centre of gravity of the points used for determining the plane.

The plane parameters (a,b), σ_d and ε are stored in separate layers.

2.2 Deriving a Mask for Covering the non-Smooth Areas

For analyzing the strip differences it is required to consider only height differences in smooth areas. For this we need a smoothness-mask. A simple way of creating such a mask is to use only those grid points, where σ_d is below a certain threshold σ_{d_max}, which depends on n and the accuracy of the original ALS points. σ_{d_max} will be in the order of a few cm. Under the assumption, that the height accuracy of the original ALS points is Gaussian, σ_d will be χ^2 distributed.

With σ_d we identify smooth areas, but we further have to deal with border areas (e.g. at the border of the strip) and occlusion areas (e.g. caused at the backside of buildings). Both are characterised by extrapolation. The eccentricity layer ε is particularly helpful for detecting such areas. A grid point located in a smooth area will be more or less in the centre of its n closest ALS points. There, ε will be close to zero. Grid points at the border of extrapolation or larger occlusion areas will have ALS points only on one side. There, ε will be significantly larger. Grid points in the middle of such extrapolation areas will hurt the maximum distance s_{max} and will be flagged as 'no data' right after the DEM interpolation. The selection of smooth cells which were not extrapolated is therefore derived by:

$$mask_{use} = (\sigma_d < \sigma_{d\_max}) \;\&\; (\varepsilon < \varepsilon_{max})$$

Such a mask is derived for each strip. After analysing σ_d and ε chances are that a few isolated grid cells will still remain in non-smooth areas; e.g. n vegetation points which accidentally lie close to one common plane. In order to remove such isolated cells the derived mask is filtered with a 3x3 median filter but only allowing cells to be turned off:

$$mask_{use,\,median} = medfilt2(mask_{use}, [3\ 3]) \;\&\; mask_{use}$$

2.3 Analyzing the strip differences

For each pair of overlapping strips the difference of their DEMs is computed. As already mentioned the colour-coded height differences can serve as first visual quality documentation; see figure 1 (left). However for being not distracted by the large differences in the non-smooth areas, it is advantageous to use the derived mask; see figure 1 (right).

Besides this qualitative documentation also a quantitative one can be derived by comparing the height difference dz of a pair of overlapping strips ($strip_1$ and $strip_2$) with a predefined threshold dz_{max}; e.g. specified by the client who ordered the ALS flight. The grid points whose height difference dz exceeds dz_{max} are found by the following logical operation:

$$mask_{dz} \;=\; mask_{use,\,median}(strip_1) \;\&\; mask_{use,\,median}(strip_2)$$
$$H = [abs(dz) > dz_{max}] \;\&\; mask_{dz}$$

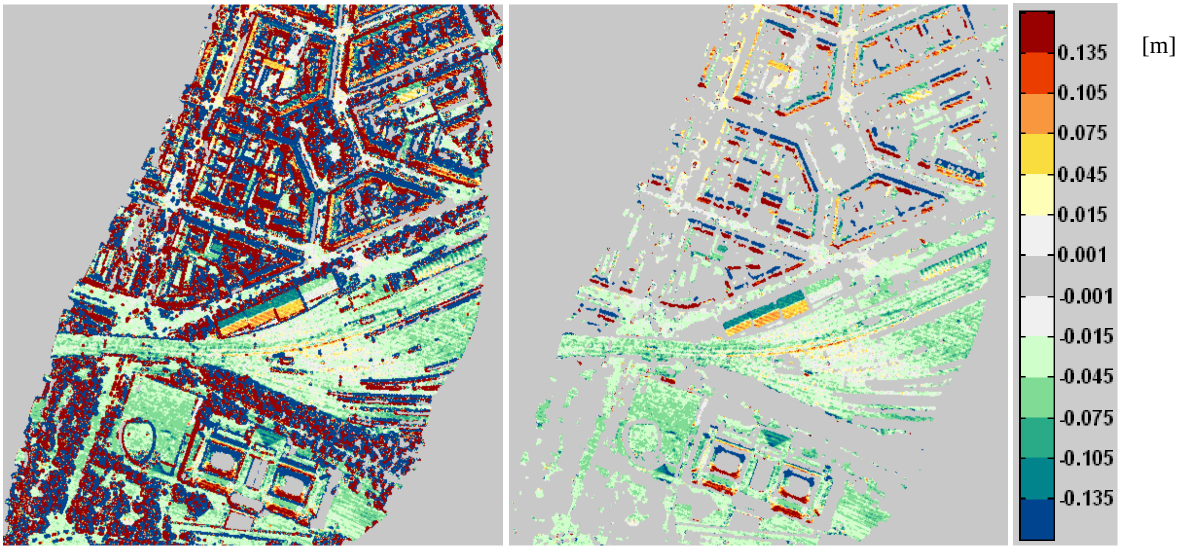

Figure 1: Color-coded height difference using the original georeference of the data in section 3 (strip 7 – strip 6; only a section is shown); left without mask, right with mask;

H is actually a logical array. Therefore the percentage of grid points used for the strip analysis exceeding the given threshold dz_{max} is given by:

$$h = sum(H)/sum(mask_{dz}) * 100$$

This percentage h can be compared with a given acceptance limit, e.g. 0.1%. If a certain strip pair does not fulfil this requirement a deeper analysis should be initiated; e.g. visual inspection of the masked colour strip difference and/or an LSM-based analysis of the planar and height shifts between both strips (see next section).

2.4 LSM-Based Analysis

The analysis of the masked strip differences gives a first quality indication. If these differences do not fulfil the expectations, a deeper analysis should be initiated. Unexpected large height errors in the overlap of two strips are caused by systematic errors of the georeferencing (GNNS/IMU) and/or the system calibration (e.g. misalignment, offset and scale of the laser range finder and the angle measurement unit). Because the height differences between pairs of overlapping strips show the summed effect of all errors from GNSS/IMU/laser, this total effect should be split into its parts in X, Y, Z.

A simple method capable of determining the (X, Y, Z)-shifts between two slightly shifted grids is LSM. There a window of the first data set (called template window) is shifted in X and Y with respect to the corresponding window in the second data set (called search window) in order to minimize the squared sum of Z-residuals. The basic equation for LSM is:

$$Z^S(X+a,Y+b) \;=\; Z^T(X,Y) + c, \qquad (1)$$

with:
$Z^S(X,Y)$ and $Z^T(X,Y)$ are the heights in the search and template window at grid-location (X, Y) respectively.
a,b,c are the shifts of the template window in X, Y, Z.
The corresponding observation equation for that linear least squares adjustment is given by:

$$v_Z \;=\; Z^S_X(X+a°,Y+b°)\cdot\Delta a + Z^S_Y(X+a°,Y+b°)\cdot\Delta b + \Delta c - (Z^S(X+a°,Y+b°) - Z^T(X,Y) - c°), \qquad (2)$$

with:
Z^S_X and Z^S_Y are the derivatives of the heights in the search window Z^S in the X and Y direction, respectively.
a°, b°, c° are the zero initialized approximate values of the shifts and Δa, Δb, Δc are their unknown corrections.
v_Z is the height residual.

Prerequisite for matching template and search window successfully is that the cells in both windows refer to the same object. Therefore parts covered by vegetation or parts occluded by buildings should be neglected. For this $mask_{use,\,median}$ of each strip is used to select only smooth cells for LSM; i.e. only cells at (X,Y) are used if: $mask^S_{use,\,median}(X+a°,Y+b°) = mask^T_{use,\,median}(X,Y) = 1$.

After each iteration Z^S and $mask^S_{use, median}$ need to be interpolated at the location (X+a°,Y+b°). For the heights a linear interpolation is usually sufficient. For the mask a nearest neighbor interpolation or a linear interpolation with subsequent thresholding can be used.

One can however not rely only on the mentioned masks, because cells where the objects do not correspond may still be present. For example: A few isolated cells and even small groups of connected cells in non-smooth areas may have survived the mask generation. Or a large car may have changed location between both strips. Such blunder cells would produce huge Z-residuals, which would result in unrealistic large LSM-shifts. Therefore the robustness of LSM has to be assured. A useful approach for robust adjustment is to iteratively adapt the weights of the observations depending on the residuals *v* of the previous iteration. This approach can be applied, provided the number of gross errors is not too high, which however should be guaranteed by the smoothness mask. The adaptation of the weights p_i can e.g. be done by:

$$\sqrt{p_i} = \frac{\sigma_0}{\sigma_i} \cdot \frac{1}{1 + \left(\frac{|v_i - m|}{h \cdot \sigma_i} \right)^{4h/s}} \qquad (3)$$

σ_0 is the reference variance a priori; 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. The parameter h determines which observation will get its √p halved. The parameter s defines the slope of the weighting curve at point (h/0.5). Figure 2 shows the weighting curve for h = 3 and s = 2.

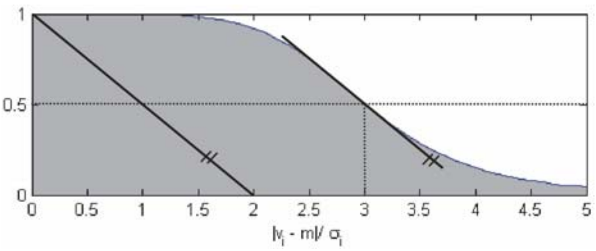

Figure 2 The weighting function in (3) for h = 3 and s = 2.

The determinability of the unknown horizontal shift parameters depends on the variation of the surface normals in the masked Z-raster of both ALS strips. In principle, the unknown shifts (*a*, *b*, *c*) between the two windows can be derived if the window consists of at least three tilted planar surface patches (with non-coplanar normal vectors).

Because of the masks, only cells from smooth areas are used within LSM. If the windows are selected too small, then the variation of the normal vectors is likely to too small to determine the unknown horizontal shifts reliably [1]. Only in urban parts enough different tilted roof planes may be available.

In order to increase the determinability of the horizontal shifts a and b, we use large windows, which cover (across track) the entire width of the overlap of two strips (W_{AC}). Along track the window is elongated sufficiently (W_{AL}) to make enough variation of the normal vectors probable; e.g. 50 cells. LSM for such large windows (of size W_{AC} x W_{AL}) will return an average over possible individual shifts inside that window. However this compromise between averaged shifts and determinability seems acceptable in view of a general quality check. If at certain spots a detailed analysis of the shifts is required, then smaller and specifically centred windows can be applied.

Another possibility for increasing the determinability of the horizontal shifts would be the inclusion of laser intensity grids; e.g. [Kraus et al. 2006].

The LSM window (of size W_{AC} x W_{IN}) is first placed at the beginning of the overlap of the two strips. After determining the shifts there, the window is shifted by $W_{IN}/3$ in flight direction. Using this technique of a sliding window the progress and variability of the shifts along the flight line is determined. By comparing these shifts with predefined tolerances for the accuracy in planimetry and height the location and size of regions hurting these tolerances can be spotted.

3. EXAMPLES

First examples were performed with real data coming from an ALS flight over Schönbrunn castle, Vienna, made with a Riegl LMS-Q560 scanner. The average flight height above ground is 500m, the average ground speed is 50m/sec. The mean point density is 1 pt/m². The swath width is ~400m and the strips overlap by ~60%. The area is covered by 11 strips. Two of them were used for the example (strips 6 and 7).

At first the difference between both strips was computed following sections 2.1 – 2.3. The grid width of the DEM for each strip was set to 1m and the moving planes interpolation used the closest 8 points (s_{max} = 2.1m, without forcing points to be in each quadrant as the point distribution was rather homogenous). The masks for each strip were derived using:
$mask_{use} = (\sigma_d < 10cm) \;\&\; (\varepsilon < 0.8m)$

Figure 3 (middle) shows the masked colour-coded height difference over the entire overlap and figure 1 (right) shows a section. The height difference over the entire overlap showed the following statistics:
Number of cells: 888501
Number of smooth cells (inside $mask_{use, median}$): 382878
Number of cells (inside $mask_{use, median}$ and hurting an assumed dz tolerance of 10cm): 16158

Thus 4.2% of the used cells of the strip hurt this tolerance. Therefore the LSM-based analysis described in section 2.4 was also carried out. The size W_{IN} of the sliding window was set to 50m. Figure 3 (top) shows the progress of the X,Y,Z-components of the LSM-shifts along flight trajectory. A few rapid changes especially in the Y-component are evident. The Y-component is almost parallel to the flight direction. The other two components have rather small values over the whole strip overlap. It is interesting to see that the Z-component is quite small (between -4 and +4cm), which shows that the accuracy in height is much better than in planimetry (with shifts ranging from -30 to +40cm).

The reliability of the determined LSM-shifts is not so easy to determine. One might look at the a-posteriori accuracies of the

[1] The vertical shift c can be determined even for horizontal terrain, as the determinability of c only depends on the number of corresponding cells in the two windows.

shifts. However, these estimated standard deviations derived from the covariance matrix 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 coefficients of equation (2)) 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].

Therefore in order to somehow validate these determined shifts, we applied two approaches: (i) Comparison of the differences before and after LSM. Figure 3 (bottom) shows that the median of all differences did decrease. Further see figures 5 and 6 which show the decrease of the height differences after applying the determined shift for the section shown in figure 1. (ii) Comparison of the progress and variability of the shifts with the progress and variability of the GPS/IMU observations. See figure 4, which shows the variability of the IMU (rotation) observations. There similar sudden changes at the same locations can be seen. These coincidences may indicate problems of the GPS/IMU/laser processing (e.g. a time offset between GPS/IMU and laser system). Both comparisons thus give good indications that the determined shifts are reasonable.

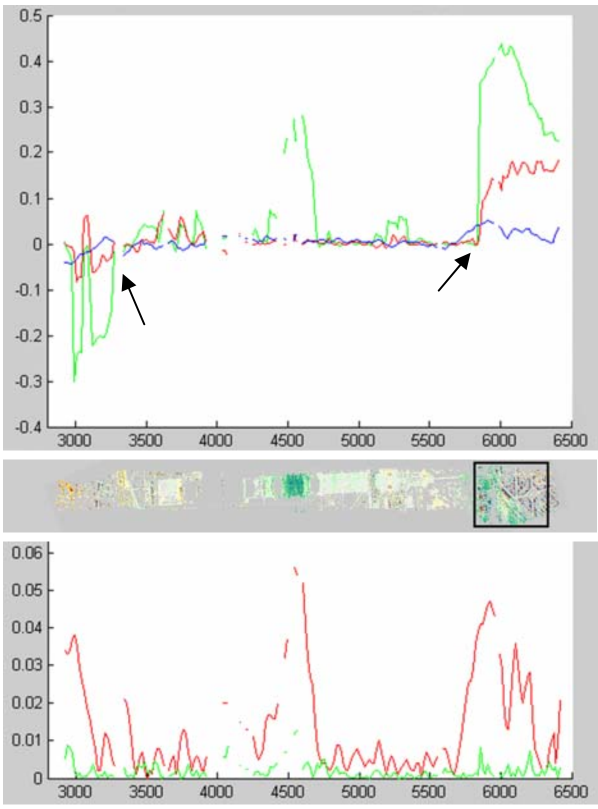

Figure 3: Progress and variability of the 3D-shift determined by LSM in sliding windows (window size W_{IN} 50m) over the entire overlap of strip 6 and 7.

top: red/green/blue = x/y/z-components of shift (units = [m]). Sudden changes at the beginning and end of the overlap of both strips are marked by arrows. These areas also show large height differences (compare with middle figure).

middle: masked color-coded strip difference of the entire overlap of both strips with length ca. 3.5km (rotated by 90° for better visualization and scaled to match the horizontal extent of the shift plot). Remark: the black box is the section shown in figures 1 & 5.

bottom: Absolute value of the median of the differences inside the sliding window between strip 6 and 7 (using $mask_{use,\ median}$ for each strip) before (red) and after LSM (green). The median is computed for each position of the sliding window.

4. CONCLUSIONS AND OUTLOOK

We showed how the quality of ALS strips can be checked using DEMs. First the difference of the DEMs of overlapping strips is computed. For the analysis of this difference only smooth areas should be considered and occluded parts (e.g. caused by buildings) should be neglected. This was solved by a mask which was derived from σ_d and ε; σ_d is the standard deviation of the DEM interpolation at each grid point and ε is the distance between each grid point and the CoG of the original laser points used for the interpolation.

The height differences between pairs of overlapping strips show the summed effect of all errors from GNSS/IMU/laser. If the analysis of height differences indicates that predefined accuracy measures are not met, then a second processing step based on LSM is performed. Here a 3D-shift is computed inside a relatively large window, which is sliding from one end of the overlap to the other. The determined 3D-shifts along the overlap give indications on the planimetric and height accuracy of the ALS data. In the example shown the planimetric accuracy turned out to be worse than the height accuracy – an observation also made by other authors e.g. [Mass 2002]. Consequently clients who order ALS flights should not only define tolerances for height but also for planimetry. If the geometric accuracy of the original ALS data does not fulfil the required quality measures, then an ALS strip adjustment [Kager 2004] should be computed.

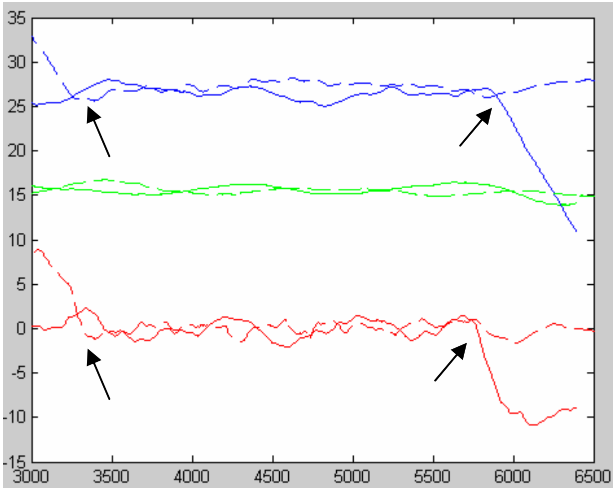

Figure 4: Progress and variability of IMU-rotations (red/green/blue = roll/pitch/yaw, solid line = strip 6, dashed line = strip 7); vertical units: [°]; horizontal units: [m]; angles where shifted vertically for better visualization. The locations of sudden changes in roll and pitch match those of the LSM-shift in figure 3 (top).

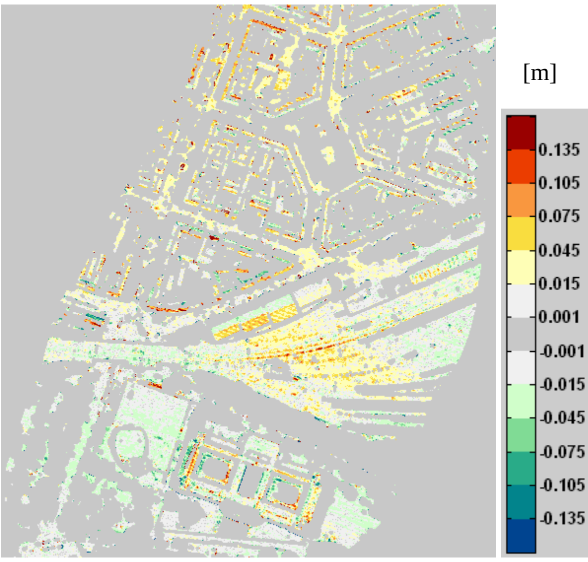

Figure 5: Color-coded height differences after applying 3D-shift determined by LSM for the section shown in figure 1 (shift value: 0.162 0.315 0.037); cf. also with figure 3 which shows that the shifts in this part of the overlap change dramatically. Therefore only one LSM-shift for this area is not sufficient.

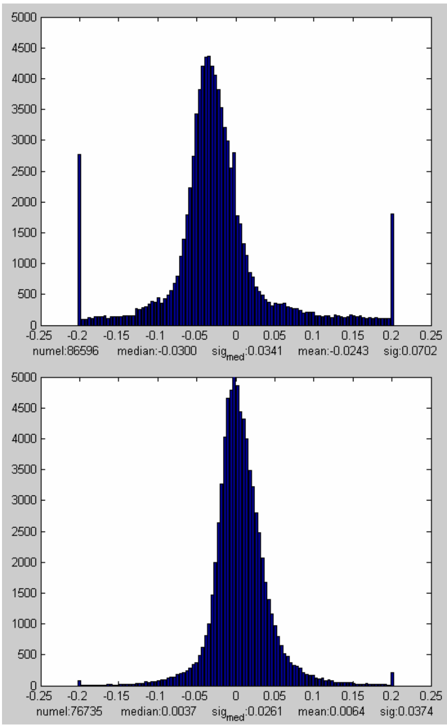

Figure 6: Histograms of the height differences in the section shown in figure 1; top: original georeference (cf. figure 1 (right)), bottom: after considering the 3D-shift of LSM (cf. figure 5); in both cases the smoothness mask is considered.

Future work will concentrate on the following issues:

- ALS block statistics: So far, the analysis provides only information about the *overlap* between two strips, but not about the individual strips themselves. Most strips overlap with two neighbor strips. The analysis of all overlaps should provide more information for each strip (e.g. clearly spot which individual strips in a larger block have wrong georeference or calibration), although a certain datum problem will always remain if only relative measures (i.e. the differences) are considered.
- Absolute accuracy: So far only the relative accuracy can be checked. By providing external information (e.g. terrestrially measured points on roofs or on curved smooth surface patches) small reference DEMs could be set up. If these DEMs contain enough different surface normals (e.g. neighboring roofs with different expositions clustered together), then using LSM these windows with their respective masks could be used to determine the absolute accuracy of the containing strips.
- Further empirical and more elaborated tests with different real data are required in order to investigate the controlling parameters (tolerances for height and planimetry, grid width, settings for deriving the smoothness masks, window sizes for LSM and controlling LSM in general).
- Some authors reported about benefits of using intensity data for determining the planar shifts especially in flat areas. This shall be included in future work.
- Some authors reported about worse results obtained by LSM based on rastered data compared with results obtained by LSM of the original unstructured laser points using a TIN data structure. Partly these errors were attributed to occlusions. With the smoothness and extrapolation masks derived in this paper it is interesting to compare the performance of LSM using the masked raster with LSM based on TIN.
- 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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