QUALITY CONTROL ISSUES OF AIRBORNE LASER RANGING DATA AND ACCURACY STUDY IN AN URBAN AREA

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ABSTRACT

The major factors affecting the accuracy of Airborne Laser Scanning (ALS) systems are the errors in ranging, in the position of the laser firing point, and in the attitude of the laser beam. Since the derivation of a precise theoretical accuracy model is rather complicated, accuracy estimates are mostly obtained by comparing Digital Elevation Models (DEMs) derived from laser scanning with reference DEMs. This technique works well on flat or gently sloping terrain, however it is not suitable for complex 3D terrain. For example, small displacements of the laser footprints can cause large elevation errors around tall buildings. Large range errors can occur when the elevation or brightness varies within the footprint, such as along the boundaries of buildings, or around trees. Moreover, other non-sensor related factors, such as the point distribution, the post-processing algorithms, and the extracted features also effect the accuracy. We first present a general quality control scheme, followed by analyzing the accuracy of ALS over urban terrain. The analysis is performed low altitude aerial photographs. First, a reference DEM was measured from the aerial photographs on the analytical plotter. To facilitate the visual comparison between the reference DEM and the surface points from ALS, both the reference DEM and the laser points were back-projected onto the aerial stereo photographs. The differences between the two surface descriptions were obtained in the classical way by comparing the laser points with the reference DEM. This standard approach is not suitable in areas of large elevation changes. A better way to compare the accuracy is to extract features and to compare them. We compare planar surface patches and 3-D lines obtained from intersecting planes.

1 Introduction

Airborne laser ranging, with its high accuracy potential and dense sampling, is a technology successfully used in an ever increasing range of applications. Originally employed for ice sheet monitoring, DEM derivation in forested areas, and biomass computations, new applications, for example in mapping urban areas are explored. The information that constitutes the result of an application, e.g. a DTM including breaklines, or buildings for a city model, is not explicitly available in the raw laser data set; rather, it must be extracted. The question of how well features can be extracted and how accurate they are is a quality control aspect.

There is no redundant information available when computing the 3-D positions of individual laser points. Hence, no explicit quality measure exists at the outset; we rely on the assumption (based on experience) that the points are good. Another characteristic of raw laser data is its random distribution with respect to object boundaries. It would be sheer coincidence if a laser shot had hit the boundary of an object to be mapped; even if it had we would not know because laser points carry no information about objects.

We present a third argument in support of developing a general quality control scheme for airborne laser ranging data and derived features. Imagine we have aerial imagery and laser ranging data of the same scene. Imagery is immediately accessible by our visual system for analysis and interpretation. However, this is not the case for the laser data for humans do not have a sensory system that would response to range data—we cannot directly interpret raw laser points and quickly decide if the data make sense. A transformation into a more suitable representation is required.

The next section elucidates quality control issues related to airborne laser ranging. It begins with an assessment of raw laser points. As the abstraction level increases, the quality of extracted features is increasingly influenced by the post-processing algorithms. Apart from the data, it is important to include the algorithms into the quality control.

We have performed several experiments in the Ocean City test site, established by ISPRS Working Group III/5 (*Csathó et al.* (1998)). Surfaces obtained from laser scanning systems are compared with photogrammetric measurements, carried out on analytical plotters and softcopy workstations. This paper describes the experiments, reports the results, presents an analysis and outlines future research.

2 Background

Raw laser data is hardly ever used as an end result. Usually, information is extracted during various post processing steps. Fig. 1 depicts the major processing steps (see also *Schenk* (1999a)).

Quality control should be conducted on every stage, beginning with an assessment of the raw laser points, including blunder detection, to an analysis of extracted features and derived surface properties. Such analysis may range from simple plausibility checks to thorough error studies. We distinguish between qualitative and quantitative methods.

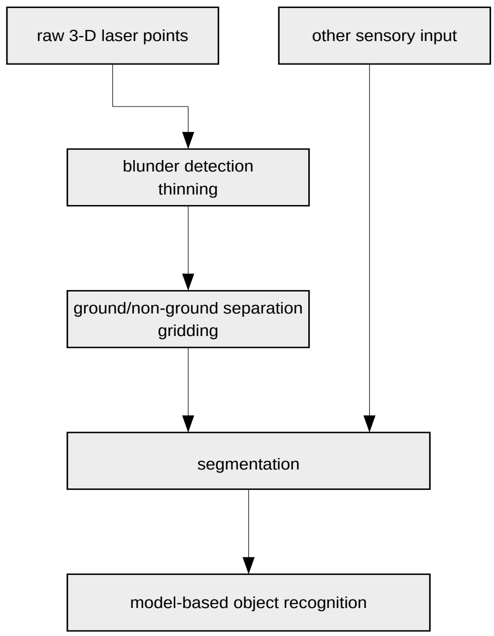


Figure 1: Major processing steps of raw laser data. A popular sequence is to interpolate the irregularly distributed laser points to a grid, followed by object modeling. A conceptually more pleasing sequence includes segmentation (preferably without gridding), before object modeling is attempted.

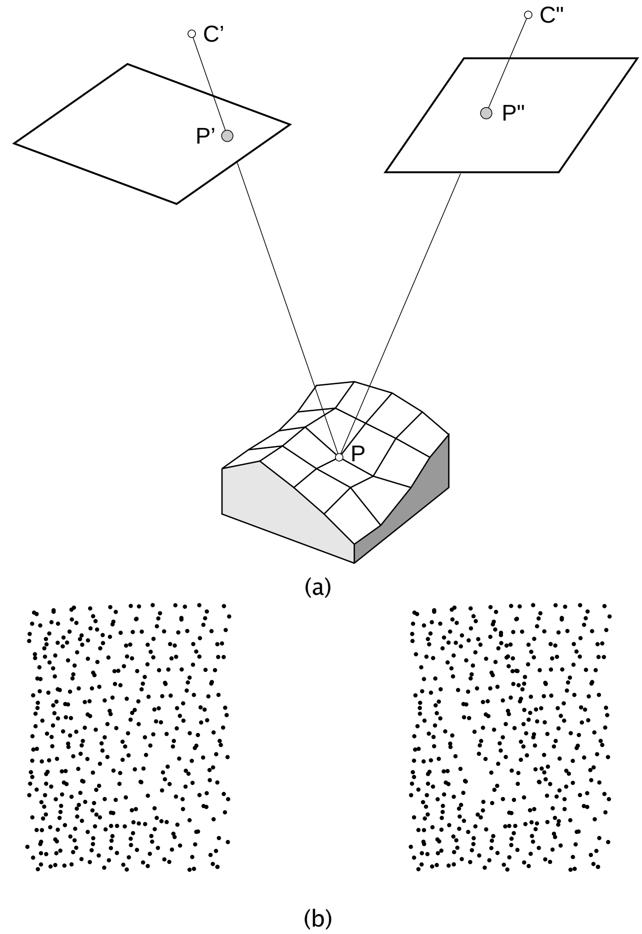


Figure 2: Figure (a) illustrates the principle of generating a stereogram from a raw laser data set. Based on an assumed exterior orientation, synthetic laser images are computed that can be viewed stereoscopically on stereoscopes, analytical plotters, or softcopy workstations. The latter possibility is appealing for it allows to browse through large data sets with the possibility to measure. In (b), a stereogram of laser points is generated. It contains the apartment building shown in Fig. 3. Viewed under a stereoscope, a vivid 3-D impression of the building and its surrounding appears.

2.1 Qualitative Analysis

The purpose of qualitative control is to quickly answer the question if the data makes sense, or if it contains obvious errors. Such tests are usually performed by representing the data in a manner suitable for analysis by humans. The human visual system is remarkably adept in analyzing pictorial information. Various visualization methods for laser ranging exist. A popular method is to interpolate the irregularly distributed points to a grid (gridding), followed by converting the interpolated elevations to gray levels. The resulting range image is a useful rendering of the laser surface. Other approaches include perspective views of the laser surface, for example by wire diagrams or TIN models. Such presentations give vivid impressions about the topography and objects.

A visualization method that allows true stereo viewing is based on computing a stereogram of the 3-D data set. Fig. 2(a) shows the principle of back projection. The exterior orientation of two images is assumed to be known; then image points of the laser data are computed by the collinearity equations. The resulting laser point images can be viewed stereoscopically, for example by photogrammetric equipment, including stereoscopes, analytical plotters, and softcopy workstations. This offers the possibility to perform measurements which, in turn, may lead to a quantitative analysis. Fig. 2(b) is an example of a stereogram, obtained with the laser scanning data over an apartment building.

2.2 Quantitative Analysis

Quality control by visualization is subjective in nature. To obtain objective quality criteria we need to measure and compare. Quality criteria refer to the raw laser surface as well as to derived properties, such as smooth surface patches, breaklines, and object boundaries. The geometric aspect of these properties is expressed by a suitable error quantity that depends on the nature of the error sources. Uncertainties in the semantic aspects of extracted features is hardly considered. The following discussion is restricted to geometric errors of points and extracted features.

Assessment of Raw Laser Points A simple but most effective way to assess the geometric accuracy of raw laser surfaces is to compare them with known surfaces. Since surfaces are rarely known, except perhaps for calibration test fields, we need other ways to assess the accuracy. Densely distributed laser footprints offer the possibility of local surface analysis. This internal analysis is based on the fact that physical surfaces are in general smooth. The error analysis is usually performed in conjunction with thinning (see, e.g. *Csathó et al.*

(1995)). Clearly, the errors derived in this manner are relative, reflecting the inner accuracy of the laser ranging system.

A better way to assess the geometric quality of a laser data set is to compare it with a description of the same surface but obtained from an independent source, for example with photogrammetry. Laser ranging generates an irregularly distributed set of surface points. It is very unlikely that the control surface is represented by the same points. Thus, the challenge is to compare two discrete surface descriptions that have no identical points. Converting both data sets to a regular grid is a popular method but the comparison of grid post elevations is now affected by interpolation errors. Another restriction is that both sets need to be in the same reference frame.

A better solution is to compare the differences between the two sets at their original point locations. This is possible except that a local surface patch must be generated for one of the two sets. Details of such an approach are discussed in *Habib and Schenk* (1999) and *Postolov et al.* (1999), for example.

Quality Control of Derived Surface Properties The error analysis of raw laser points yields important information but does not tell much about the accuracy of derived surface properties, such as breaklines and smooth surface patches. The error analysis of derived surface properties does not only depend on the inherent quality of surface points, obtained from laser ranging or photogrammetry, but also on the feature extraction methods. In fact, post-processing algorithms often have a larger impact on the quality of extracted features than the raw surface points. If the extracted features have known geometric aspects then a simple quality control measure is to determine the difference between extracted and known properties. Breaklines may be straight lines, for example; in addition they may be horizontal and have known lengths. Smooth surface patches may be planar, and have perhaps even known tilt angles. If no control information exists about extracted features then one can measure it photogrammetrically in order to check the feasibility of the extraction algorithm and the goodness (e.g. accuracy, distribution) of the surface points.

It is worth to consider an another aspect in the context of quality control; it is related to the quality of the problem statement, or to the question asked. Suppose the problem is to locate the boundaries of a building in a laser data set. To sketch a simple case assume the building has a flat roof and a flat, non-vegetated surrounding. Now, grouping the laser points into building top and ground is a piece of cake. But where exactly is the boundary? It can only be determined within an uncertainty range that mainly depends on the point spacing and the size of the building. Hence, the problem as stated is ill-posed. The fact that the boundary cannot be precisely located is not a quality problem of the laser points but a quality problem of the question asked.

In summary we conclude that the quality of derived surface properties depends on the problem stated, the algorithm used to solve it, and on the quality of the raw laser points, for example their point accuracy and spatial distribution. We elucidate some of the quality control issues in the next section with experiments on real data.

3 Comparison of Surfaces Obtained from Laser Ranging and Photogrammetry

The following experiments used data from the Ocean City test site. Before describing the experiments we briefly summarize the specifications of the test data.

3.1 Test Site Ocean City

A multisensor data set has been collected over Ocean City, Maryland, under the auspices of ISPRS WG III/5, the Geomatics Laboratory for Ice Dynamics of the Byrd Polar Research Center, and the Photogrammetry Laboratory of the Department of Civil and Environmental Engineering, OSU. The data set comprises aerial photography, laser scanning data, and multispectral and hyperspectral data. *Csathó et al.* (1998) provide a detailed description. Also, the WEB site http://wwwphoto.eng.ohio-state.edu informs about the current status.

For the experiments we use an aerial stereopair (original negatives and digital images, scanned with 28 μm pixel size) and laser scanning data. Large scale aerial photographs were flown by the National Geodetic Survey (NGS) at a flying height of 372 m (photo scale approx 1 : 2,435). One strip was triangulated in the classic way, using GPS ground control points. NASA Wallops made several laser data sets available, using the Airborne Topographic Mapper (ATM) laser system. The ATM is a conical scanner, developed by NASA for the purpose of measuring ice sheet surfaces. Recently, other applications have been pursued, for example beach mapping.

The exterior orientation of the photographs is in the same reference frame as the laser points. Consequently, features derived from both data sets can be compared directly.

The photogrammetry laboratory performed an aerial triangulation and several manual measurements. A skilled operator measured a dense DEM on the Zeiss C120 analytical plotter. The grid spacing of 2 m compares approximately to the average density of the laser points. In addition to the DEM, some building outlines and roof tops have been digitized for comparison with the extracted features from the laser points. Fig. 3 shows the study site. We focus on the apartment building in the left part of the figure and the residential area next to it.

Figure 3: The study site for the experiments reported in this paper is a small area of the Ocean City Test Site, established by ISPRS WGIII/5. The apartment complex (left) has a flat roof but a fairly complicated roof outline. A DEM with 2 m grid spacing was measured on and around the building. Similarly, a DEM was measured in the highlighted part of the residential area.

3.2 Direct Comparison of Laser Points and Photogrammetry

The first experiment is simple but very effective. Fig. 4 shows the laser points, projected back to the imagery. It is the same principle discussed in the previous section where a synthetic laser point stereogram was generated (Fig. 2).

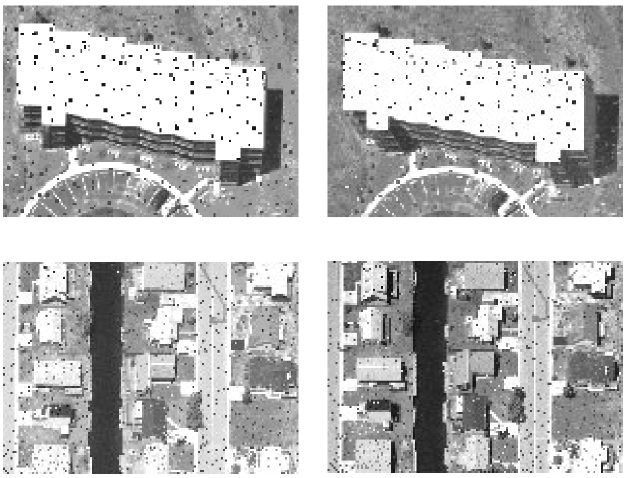


Figure 4: Illustration of projecting the laser points to a stereopair (backprojection). The stereopair can be viewed on an analytical plotter or on a softcopy workstation. If the laser points are not on the visible surface, defined by the stereo image, differences can be measured and analyzed. This technique is also very useful to examine "problematic" laser points, for example around buildings. It is also possible to perform the comparison automatically by image matching techniques (see text for details).

The 3-D laser points are projected to the stereopair with the exterior orientation established during the process of aerial triangulation. This basically mimics the image formation process—instead of recording light intensities from a point in the scene by a camera, the process is performed analytically. We have used this method extensively to check if photogrammetry and laser data are in the same reference system. Analytical plotters and softcopy workstations are particularly suited for this task because they position the measuring mark automatically on points entered as a file.

How valid is an analysis of recorded differences? Are differences due to laser errors or due to measuring errors? As a rule over the thumb we can expect the following elevation accuracy σ_z from photogrammetry

$$\sigma_z = (0.06 \div 0.08) \cdot H \tag{1}$$

If the flying height H is entered in meters then σ_z will be in millimeters. In our case, with $H \approx 370$m, the expected accuracy of a well defined point is better than 3 cm. Points on roofs, parking lots, streets, etc. are well defined and thus very suitable to check the accuracy of laser points. Examples of less well defined points include vegetated areas, ranging in uncertainty from grassy areas to crops, shrubs, and trees. Such points should be left out in an accuracy study.

Backprojection is also very useful for examining laser points in critical areas, for example around buildings. Having the possibility to analyze the surface within the footprint may offer new insight into the interaction of the laser beam with surfaces. Waveform analysis as a function of surface properties, such as material, roughness, topography surely would benefit greatly from this approach. We are currently analyzing surfaces around footprints of weak laser returns. This information is available for ATM laser data, processed by NASA Wallops, for example.

We should like to point out to an interesting modification of backprojection. Instead of letting a human measure the differences between laser points and surface, we use automatic image matching techniques. If the laser point is really on the visible surface then its backprojected position in the images is conjugate. We can check by comparing a small image patch around the conjugate points by area-based matching (*Schenk* (1999b)). The matching vectors of all the points checked in this fashion are a direct indication of how well laser points agree with the visible surface.

3.3 Detailed Study of a Tall Building

We have analyzed the laser data set over the building area shown in Fig. 3 in various aspects. First we briefly describe the comparison of the laser points with the data set obtained from photogrammetry. We then analyze extracted surface properties and present results.

Although the laser and photogrammetry data sets describe the same surface there are no identical points and the comparison is usually performed with interpolated points. Fig. 5 shows a perspective view of the model created from the two data sets. Since the building was manually measured, including breaklines, it is no surprise that its model, shown in Fig. 5(a) looks more realistic than the TIN model created from the irregularly distributed laser points (Fig. 5(b)).

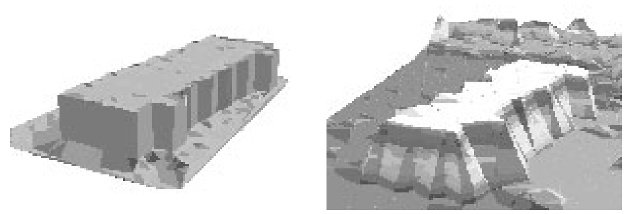


Figure 5: Perspective view of the building model. The left image shows the model created from photogrammetrically measured points. The right image is a TIN model of the laser points. The photogrammetric model is superior because twice as many points were measured. The building outline (breakline) was also measured.

The comparison between the two data sets was performed by computing the vertical differences between points in the photogrammetric model to the corresponding laser point surface. This includes interpolation and the result is influenced by interpolation errors. These errors are quite large, especially near breaklines. Not surprisingly, the resulting standard deviation of ± 1.08 m is an order of magnitude larger than what one would expect. The test clearly demonstrates the inability of this popular comparison method to express a meaningful point accuracy, except for smooth surfaces.

The second test with the same data was concerned with assessing the accuracy of derived features. Surface properties such as breaklines and smooth surface patches are obtained by segmentation (*Csathó et al.* (1999)). Segmenting the surface points in the building area should result in planar surfaces and breaklines. Our simple segmentation method proceeds in two steps; first, the points are grouped into potential surface patches, postulating a surface hypothesis. The second step is concerned with verifying the hypothesis by fitting a plane through the points. The deviations of the points to the plane serve as a validity measure for accepting or rejecting the plane hypothesis. The validity is not a fixed threshold value; domain knowledge about expected surface roughness (e.g. man-made objects vs. vegetated areas) and a priori error estimates of the surface points influence the acceptance criteria. The results of surface segmentation, together with other information, are further analyzed in an object recognition system.

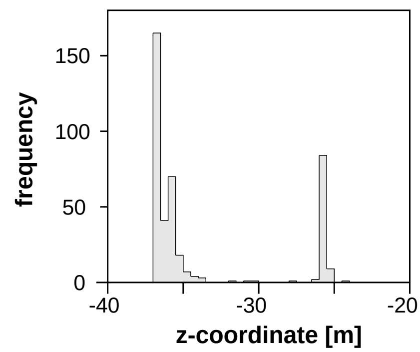
The final result of the grouping process in the building area divides the points into potential roof points and non-roof points. This is achieved by analyzing the elevations of points, similarly to histogram thresholding, except that the spatial distribution of roof point candidates is taken into account. This reduces the chance that points on trees or other objects of similar height may accidentally be labeled as roof points. Fig. 6(a) shows a histogram of the laser point elevations. All the points clustered within -35 m to -37 m satisfied the spatial extent criteria and subsequently entered the second phase. Fig. 6(b) depicts the spatial distribution of the labeled points; large dots symbolize roof points.

The roof points enter a planar surface adjustment. The three parameters a, b, c of the equation

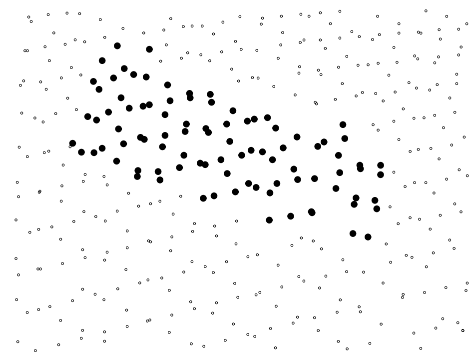
$$z = a \cdot x + b \cdot y + c \tag{2}$$

are determined in a least-squares adjustment which is based on the simplified error model that random errors occur only in z while x and y are considered as constants (*Schenk* (2000a)). The standard deviation of the adjustment is a good measure of how well the points lie on a plane. One out of 94 laser points was identified as a blunder and removed from the adjustment. An analysis of the blunder revealed that the point was on a chimney and not on the roof surface. The resulting standard deviation of the plane adjustment was $\sigma_z^L = \pm 5.7\,\text{cm}$. Considering the large redundancy, the error measure is quite reliable. It confirms the high (internal) accuracy of laser ranging. One may even argue that part of the standard deviation is due to the non-flatness of the roof.

We have repeated the same experiment with the manually measured DEM. Out of 265 roof points, the adjustment procedure eliminated six points as blunders. These points were measured on small objects on the roof, such as chimneys and vents. The resulting standard deviation $\sigma_z^H = \pm 6.2\,\text{cm}$ is nearly identical to the one obtained from the laser points. However, it is higher than the expected value of 3cm, obtained with Eq. 1.



(a)



(b)

Figure 6: The laser point elevations are represented as a histogram (a). The two peaks are related to roof points and ground points. An extended histogram thresholding (see text) leads to the grouping depicted in (b). Solid dots label roof points.

Again, the larger value may well be caused by the non-flatness of the roof.

3.4 Segmentation Experiments in Residential Area

The residential area, highlighted in the right part of Fig. 3, poses new problems for the segmentation. The procedure described in the previous section must be modified. Not only are the buildings much smaller but the roofs have a more complicated structure, consisting of several roof planes with surface normals pointing in different directions. Objects near buildings, such as shrubs and trees may have similar heights, challenging the separation of roof points by histogram thresholding. To cope with this situation, we have modified the segmentation approach that consists now of the following four major tasks:

hump detection is a rough analysis of the entire project area with the purpose of identifying local areas that contain objects of certain vertical dimension. We skip the details here and refer the interested reader to *Wang* (1999).

grouping generates hypotheses of roof points belonging to one roof plane. Grouping is a local process, confined to the regions identified by humps detection. Planes are found by a Hough transform technique.

plane fitting is performed by a robust adjustment, taking all the points the grouping process identified as candidates for planar surface patches.

plane analysis examines the planar surface patches, detects regularities, intersects roof planes and analyzes the resulting roof edges.

Fig. 7 shows a perspective view of the detected humps, obtained from the DEM. In the interest of brevity we concentrate on one hump only, located in the lower left corner of Fig. 7.

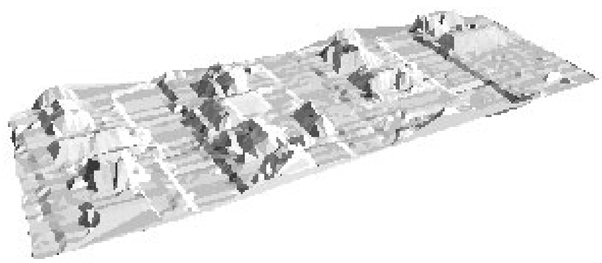


Figure 7: Perspective view of the residential area, indicating the humps detected. The segmentation results of the hump in the lower left corner are presented in this section.

In the case of non horizontal roofs, grouping by histogram thresholding does not work anymore. Since the roof points have all different elevations, no peak appears. Also the spatial context is lost in a histogram which makes it impossible to distinguish points that belong to different surfaces of similar elevation extent. In short, we need another approach.

We employ the Hough technique to find planar surface patches within the humps. As described in detail in *Schenk* (2000b), a parameter space with a, b, c, the three parameters of the plane equation Eq. 2, is generated. A closer examination of this equation reveals that switching from the original to the parameter representation simply changes the role of variables and parameters. Suppose a, b, c are now variables; then x, y, z become coefficients, but the equation is still defining a plane. Let us pick a point P in the spatial domain. A plane passing through $P = [x_p, y_p, z_p]^T$ is defined by its three parameters—hence it corresponds to the point $[x_p, y_p, z_p]^T$ in the parameter space. A second plane through P creates another point in the parameter space, and so on. Where are all the points, generated by all planes passing through P? They are related by Eq. 2, that is, they define a plane. We have identified the duality of point to plane relationship between spatial and parameter domain.

The following steps find planes that pass through surface points:

1. Pick a point P_i from the hump region.
2. Point P_i defines a plane in the parameter space. Increment all cells in the discrete parameter space (accumulator array) that are on this plane.
3. Repeat step 1 and 2 until all points are processed.
4. Analyze the accumulator array. Clusters identify planes; the total number of entries in one cluster corresponds to the number of points that lie on this particular plane. The spread of the cluster is a quality measure for how well the plane fits the points.

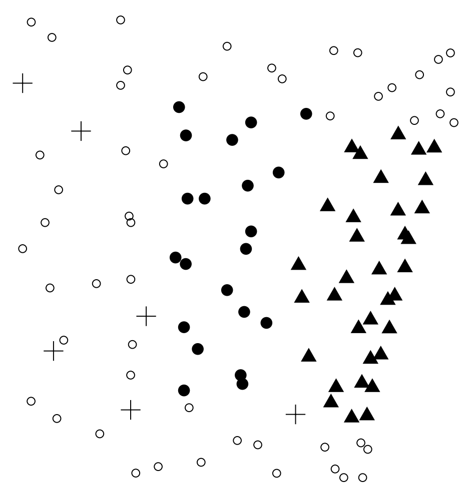


Figure 8: The laser point elevations are grouped into three planar surface patches. Solid circles and solid squares identify points that are likely to belong to a roof plane. The crosses are points on the ground that may lie on a horizontal surface. Grouping did not classify the points depicted as triangles.

Fig. 8 depicts the result of finding planes within the selected hump region. Solid circles and solid triangles label candidate points for two different roof planes; circles refer to ground points that are likely to be on a horizontal surface; crosses mark unclassified points. The final plane parameters are determined by a least-squares adjustment. Table 1 summarizes the results for the three planes, using the laser points and the DEM points. The standard deviation for the two roof planes is very similar to the result obtained from the building analyzed in the previous section. It confirms again the high ranging accuracy of the laser points. The standard deviation for the ground points is considerably higher simply because

Table 1: Results from roof plane analysis.

	roof 1	roof 2	ground
laser			
# pts.	21	34	32
σ[m]	0.035	0.052	0.195
photogrammetry			
# pts.	25	14	26
σ[m]	0.108	0.036	0.232

Table 2: Results from roof ridge analysis.

	laser	**DEM**	**direct**
azimuth [^{o}]	9.3	8.8	6.1
zenith [^{o}]	0.5	0.6	1.3
X	4.12	3.60	3.88
Y	1.13	1.13	1.13
Z	-30.86	-30.99	-30.95

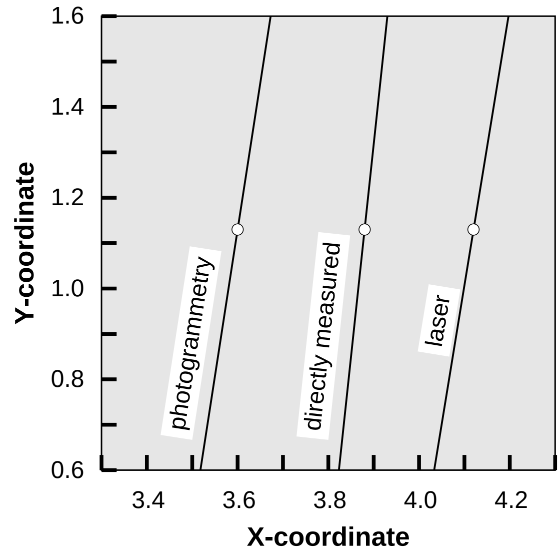


Figure 9: The roof ridge was computed by intersecting the two roof planes, obtained from laser roof points and from DEM measurements. The edge was also directly measured. The figure shows the three roof edges, together with the reference points whose values are listed in Table 2.

the physical surface is not exactly a plane and σ is more indicating the roughness than the ranging accuracy.

The relatively large standard deviations related to the surfaces computed with DEM points may surprise at first sight. Since the DEM was measured dynamically, the expected point accuracy is higher than Eq. 1 indicates. In fact, the values in Table 1 are within the range one can expect from this measuring mode.

The last quality control check performed in this experiment concerns the positional accuracy of the roof ridge, computed by intersecting the two roof planes. The roof ridge vector is directly obtained from the plane parameters. As shown in *Schenk* (2000b), the vector components can be used to specify the spatial direction of a 3-D line, for example by the two angles azimuth and zenith. The azimuth defines the line direction in the $x-, y-$ coordinate plane, while the zenith angle refers to either one of the other two coordinate planes.

The ridge was computed from the roof points of the laser data set and from the photogrammetric DEM measurements. The edge was also directly measured on the analytical plotter. Table 2 lists the results. When comparing the angles (azimuth and zenith) one should take the building size of 15 m into account. The small zenith angle resulting from intersecting the roof ridge indicates an almost horizontal roof ridge. To compare the positions of the three roof edges, a reference point on each edge was chosen with identical $Y-$ coordinates. Considering the small azimuth, the positional accuracy can be expressed by the $X-$ differences of the reference point (see Fig. 9).

The numbers in Table 2 reveal that the roof lines found by intersecting the corresponding roof planes are in fairly close agreement with the direct measurements. Note that a small difference in surface normals may cause a substantial displacement in the roof line. Moreover, the intersection of roof planes does not necessarily correspond to the physical roof edge.

4 Conclusions

We performed several experiments with airborne laser ranging data within an urban region of the ISPRS Commission III test site (Ocean City, Md). The analysis of raw laser points resulted in a point accuracy of approximately ± 6 cm, confirming the high accuracy potential of laser ranging. We used two different approaches for assessing the quality of raw laser points. The first method entailed a straightforward comparison between laser points and a DEM, derived from manual measurements on an analytical plotter. Since the point distribution between the two sets of surface points is different, no direct point to point comparison is possible—interpolation to identical x, y positions is inevitable. That is the pitfall of this method, particularly when regions with surface discontinuities are compared. A better approach is to segment the surface and to compare the segmentation parameters.

The distribution of laser points has no direct relationship with object boundaries; in this respect, the distribution is entirely arbitrary. If object boundaries are defined by intersection of physical surfaces then the boundaries can be computed if laser points on these surfaces are available. We have used this approach to compute roof ridges of buildings in a residential area. The comparison with independent measurements showed that the accuracy of derived surface properties depends not only on the laser point accuracy but also on how well a physical surface can be mathematically modeled. For example, how close is a real roof to a plane?

Our experiments also showed that the “problematic" laser points around buildings, often discarded by researchers, are actually very useful in the process of verifying hypotheses of objects. For example, points that do not seem to belong to a roof nor a ground surface may have been reflected from the side of a building. Clearly, this would be very useful evidence when we hypothesize about buildings and try to reconstruct its shape. We will intensify our research effort to detect these "problematic" points and to take advantage of them in the object recognition process. This will include an attempt to better understand the relationship of the laser's return signal and the surface it was reflected from.

5 Acknowledgement

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