Comparison Between First Pulse and Last Pulse Laser Scanner Data in the Automatic Detection of Buildings

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Abstract

A comparison between first pulse and last pulse laser scanner data in building detection was carried out. The automatic building detection method included region-based segmentation of a laser scanner derived digital surface model and classification of the segments by using the laser scanner data and an aerial ortho-image. Visual and numerical quality evaluations showed that the correctness of the results improved when last pulse data were used instead of first pulse data. According to a pixel-based comparison with a building map, the improvement was about 8 percentage units. The number of classification errors in the surroundings of the buildings decreased as a result of less vegetation. The number of false detections also decreased. These improvements were clearly shown by a building-based quality evaluation, where the inner part and surrounding area of each reference building was investigated and the number of false detections was calculated. For many buildings, the last pulse data with smaller buildings also corresponded better to the reference map, which improved correctness. The completeness of the results decreased slightly (about 2 percentage units according to the pixel-based comparison). One reason for this was the smaller buildings in the last pulse data.

Introduction

Previous research has shown that automatic detection of buildings from laser scanner data, or laser scanner and aerial image data, is possible with relatively good accuracy (see, for example, Hug, 1997; Matikainen *et al.*, 2003 and 2004; Voegtle and Steinle, 2003; Tóvári and Vögtle, 2004a; Vosselman *et al.*, 2004; Rottensteiner *et al.*, 2005a and 2007; Forlani *et al.*, 2006; Zhang *et al.*, 2006). Detected buildings can be used in 3D building reconstruction (e.g., Brunn and Weidner, 1998; Morgan and Tempfli, 2000; Vögtle and Steinle, 2000; Voegtle and Steinle, 2003; Rottensteiner, 2003; Forlani *et al.*, 2006) or change detection (Matikainen *et al.*, 2003 and 2004; Vosselman *et al.*, 2004 and 2005; Vögtle and Steinle, 2004), and they thus provide valuable information for mapping, map updating, and 3D city modeling. To achieve the best possible accuracy in building detection, the selection of methods, datasets and parameters for processing needs further consideration.

A large number of different approaches for building detection using laser scanner data have been presented (e.g., Hug, 1997; Lemmens *et al.*, 1997; Brunn and Weidner, 1998; Axelsson, 1999; Haala and Brenner, 1999; Maas, 1999; Morgan and Tempfli, 2000; Oude Elberink and Maas, 2000; Vögtle and Steinle, 2000; Alharthy and Bethel, 2002; Hofmann *et al.*, 2002; Rottensteiner and Briese, 2002; Zhan *et al.*, 2002; Vu *et al.*, 2003; Dash *et al.*, 2004; Luzum *et al.*, 2004; Muller *et al.*, 2004; Tóvári and Vögtle, 2004a; Vosselman *et al.*, 2004; Ma, 2005; Rottensteiner *et al.*, 2005a; Forlani *et al.*, 2006; Tarsha-Kurdi *et al.*, 2006; Wang *et al.*, 2006; Zhang *et al.*, 2006; Sohn and Dowman, 2007). Most of the methods are based on stepwise classification of the data to distinguish buildings from other objects. The first step is usually to separate ground from elevated objects, i.e., mainly buildings and trees, by using a filtering algorithm. After this, the most important task is to distinguish buildings from trees, which can also be carried out in several steps. Different types of information have been used to separate buildings and vegetation, including, for example, height texture (Hug, 1997; Maas, 1999; Oude Elberink and Maas, 2000) or surface roughness (Brunn and Weidner, 1998), reflectance information from images (Haala and Brenner, 1999; Vögtle and Steinle, 2000) or laser scanning (Hug, 1997), and shape and size of objects (Tóvári and Vögtle, 2004a). The building detection methods often use digital surface models (DSMs) in raster format, but they can also be based on the classification of the original laser points (Axelsson, 1999; Vosselman *et al.*, 2004) or use the point data in addition to raster data (Hug, 1997; Tarsha-Kurdi *et al.*, 2006). A normalized DSM is often produced by extracting a digital terrain model (DTM) from the DSM (e.g., Brunn and Weidner, 1998). Some of the methods begin by segmenting the data into spatially continuous, homogeneous regions or surfaces that are then classified (e.g., Hofmann *et al.*, 2002; Tóvári and Vögtle, 2004a; Vosselman *et al.*, 2004). Others first apply classification to individual pixels and aim to form meaningful regions on the basis of the classification results.

Laser scanner datasets currently in use typically contain laser points acquired with first pulse and last pulse modes. First pulse and last pulse points represent the first and last returns of emitted laser pulses, respectively. For smooth surfaces, such as building roofs and bare ground, the first pulse and last pulse heights are nearly the same. In vegetated areas, on the other hand, there is a clear difference in the heights, which provides useful information on the

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existence of vegetation. This information has also been used in several building detection studies to distinguish buildings from trees (e.g., Oude Elberink and Maas, 2000; Alharthy and Bethel, 2002; Voegtle and Steinle, 2003; Tóvári and Vögtle, 2004a; Rottensteiner *et al.*, 2005a, 2005b, and 2007; Forlani *et al.*, 2006; Wang *et al.*, 2006). Other studies, on the other hand, have used either first pulse (e.g., Hofmann *et al.*, 2002; Tarsha-Kurdi *et al.*, 2006; Zhang *et al.*, 2006; Sohn and Dowman, 2007) or last pulse data (e.g., Zhang *et al.*, 2006) alone. Rottensteiner *et al.* (2005b and 2007) tested their building detection method with different combinations of input data derived from laser scanner and multispectral image data. Their results suggested that the use of both first pulse and last pulse laser scanner data will not automatically give a better result than the use of last pulse data (in part of the classifications, image data were also used).

Steinle and Vögtle (2000) discussed the effects of different laser scanning modes on the results of building recognition and reconstruction. They demonstrated how building models acquired from first pulse data are systematically larger and those acquired from last pulse data are systematically smaller than reference models. This is due to the fact that at the edges of buildings first pulse returns are obtained from the roof and last pulse returns from the ground surface. Similar results were obtained by Ahokas *et al.* (2004). Better positional accuracy for building models can be obtained by determining the mean outline of buildings from first pulse and last pulse data (Voegtle and Steinle, 2003). When analyzing first pulse and last pulse data separately, Steinle and Vögtle (2000) found that first pulse data agreed better with cadastral maps or manually measured models. The advantage of last pulse data, on the other hand, was less vegetation and fewer objects on the roofs to confuse the data. From other studies, there is also some evidence that the use of last pulse data is advantageous in building detection, at least in some of the processing steps (Voegtle and Steinle, 2003; Tóvári and Vögtle, 2004b; Rottensteiner *et al.*, 2005b and 2007; Zhang *et al.*, 2006). To our knowledge, however, a comparative study with a detailed quality analysis concerning the results of automatic building detection has not been carried out.

The goal of our research is to develop an automatic change detection method for updating building maps. The first step of the process is building detection, which includes region-based segmentation of laser scanner data and classification of the segments on the basis of their properties in the laser scanner and aerial image data (Matikainen *et al.*, 2004). The present study was carried out to compare the quality of building detection results obtained using first pulse or last pulse data. This gives basic information for the selection of datasets for further development and operational processing. If buildings can be detected reliably enough by using only first pulse or last pulse laser scanner data, it is advantageous for practical work. The laser scanner datasets are very large and in this case only half of the data needs to be processed. In particular, we were interested in finding out how the use of either first pulse or last pulse data in segmentation and subsequent classification of the segments affects the quality of building detection. The segmentation stage determines the basic geometry of the detected buildings and is therefore a critical step in the process. The use of last pulse data might be useful, for example, to avoid situations where vegetation growing beside buildings is included in the building segments. This has appeared to be a common source of error in building detection (see Matikainen *et al.*, 2004; Vosselman *et al.*, 2005). On the other hand, the use of last pulse data could also have some negative effects on the quality of building detection. One possible reason for this is the smaller size of buildings in last pulse data, and there could also be some other reasons. For example, glass-covered surfaces, such as skylight windows on the roofs, can cause erroneously low height values for buildings more easily in last pulse data. The laser pulse can penetrate glass and can also bounce several times before it reaches the sensor, which results in multipath reflections (Zhang *et al.*, 2006).

Study Area and Data

Study Area

The study area is located in the suburban area of Espoonlahti, Espoo, about 15 to 20 km west of Helsinki. The quality of the building detection results was evaluated by using test areas covering about 2.1 km^2. A separate training area of about 0.4 km^2 was used for developing classification rules. The test areas can be roughly divided into an industrial area, a high-rise residential area, and a low-rise residential area. They contain a large variety of buildings of different sizes, different types, materials, and colors of roofs. There are small hills and ample vegetation in the study area. Forests and individual coniferous and deciduous trees, as well as lower vegetation, grow between the buildings.

Data and Preprocessing

The laser scanner data were acquired simultaneously in first pulse and last pulse modes using the TopoSys FALCON II system on 14 May 2003. At the time of acquisition, some deciduous trees were without leaves, while others had small leaves, which ensured the maximal elimination of vegetation points from the last pulse data (see Liang *et al.*, 2007). The flying altitude was 400 m above ground level, and the resulting point density was about 10 points per m^2. Due to an overlap between adjacent strips, the average point density in the datasets is about 17 points per m^2. Two digital surface models (DSM) in raster format were created by using the TerraScan software (Soininen, 2005; Terrasolid, 2007). The first pulse DSM was created from the first pulse data and the last pulse DSM from the last pulse data. The highest (first pulse DSM) or lowest (last pulse DSM) value within the pixel was assigned to each pixel, and interpolation was used to determine values for pixels without laser points. The original first pulse and last pulse laser points were also classified in TerraScan to detect points located 2.5 m above ground level. Ground points were first detected by a routine that iteratively builds a triangulated surface model. This routine is based on a filtering algorithm developed by Axelsson (1999 and 2000). Other points were then classified by another classification routine that compared them with a temporary surface model that was based on the ground points. The results of the point classification were used for distinguishing buildings and trees from the ground surface. An intensity image was also created from the laser scanner data, but it was not used for building detection in the study.

In addition to the laser scanner data, an aerial color ortho-image with red, green, and blue channels from 26 June 2003 was used in the study. The aerial imagery on a scale of 1:5 300 was acquired and scanned by FM-Kartta Oy. The ortho-image was then created with Z/I Imaging ImageStation® Base Rectifier (currently, Intergraph, 2008) using the laser derived first pulse DSM. Comparison of the rectified image with reference data shows that buildings are accurately located in the image. It must be noted, however, that areas behind buildings or trees in the original images are not correctly presented. They are still covered with the building roof or tree canopy, which reduces the usefulness of the ortho-image for building detection. These distortions, however, did not cause a major problem in our study because the basic geometry of the buildings, trees, and ground segments was determined on the basis of the laser derived DSM in the segmentation stage. The image was used as an additional data source in classification to distinguish building segments from tree segments.

A 2003 building map obtained from the City of Espoo was used as reference data for developing classification rules and evaluating the quality of the results. Compared with some ground measurements in the study area, the positional accuracy of buildings on the map is 0.5 m or better. The map data were converted from vector to raster format. In the original vector map, each building can consist of several polygons. Before the vector to raster conversion, the neighboring polygons were merged to obtain one polygon for each building. Polygons smaller than 20 m^2 were eliminated to exclude very small buildings and other constructions from the analysis. The raster maps used for rule development and quality evaluation were slightly different versions. Small polygons were eliminated from the map used for rule development before merging the neighboring polygons. Some small parts of larger buildings were thus also eliminated in the process and were missing from the training data. For quality evaluation, an improved version of the map was created by performing the merging operation before the elimination.

From the practical point of view, the building map provides an interesting and realistic reference data source because it is a real map of the study area. On the other hand, there are many differences in the appearance of the buildings on the map and in the laser scanner and aerial image data. First of all, the building outlines on the map represent the ground plans of the buildings instead of roof edges, which can cause a considerable error source for buildings with wide eaves. There are also some balconies or verandas that are not presented on the map but are visible in the laser scanner and image data. In some cases, on the other hand, constructions such as low stairways can be presented on the map but become classified as ground. These differences must be taken into account when investigating our accuracy estimates, especially the absolute numerical values. We expect, however, that comparisons with the building map can provide useful information on the relative quality of first pulse and last pulse laser scanner results because the same map was used in both cases.

In addition to the building map, a forest map obtained from FM-Kartta Oy was used in the development of the classification rules. The DSMs, aerial image and map data were all processed into raster format with 30 cm × 30 cm pixels.

Methods

Method for Building Detection

The building detection method used in the study was described in Matikainen *et al.* (2004). It is a relatively simple and straightforward method mainly using commercial software packages. The method is based on the following steps:

1. Segmentation of the DSM into homogeneous regions.
2. Classification of the segments into the classes "ground" and "building or tree" on the basis of the pre-classified laser points (see the Study Area and Data Section).
3. Classification of "building or tree" segments into buildings and trees using height texture, the aerial image, and the shape of the segments.
4. Improvement of the classification results by using the size of the segments and neighborhood information in addition to the three attributes above. The goal is to correct small, misclassified segments.
5. Classification-based segmentation to merge neighboring building segments. After this, each building segment represents one entire building.
6. Classification of the new segments based on the previous classification result and the attributes of Step 3.

Segmentation and classification, excluding Step 2, were performed using the eCognition® software (Definiens Imaging, 2003; Definiens, 2007). The segmentation method is based on bottom-up region merging and a local optimization process minimizing the growth of a given heterogeneity criterion (Baatz and Schäpe, 2000; Definiens Imaging, 2003). A heterogeneity criterion based completely on color information, which in this case corresponded to height in the DSM, was used. The heterogeneity values were thus calculated from the standard deviations of the height values, weighted by segment sizes. The resulting segments were regions with homogeneous height values.

The segments were first classified into the classes "ground" and "building or tree" using the laser points classified in TerraScan and segments exported from eCognition®. This was conducted in Matlab (The Math Works, 2007) by calculating the number of points over and under 2.5 m above ground level within each segment. Within each pixel, only the highest (first pulse DSM) or lowest (last pulse DSM) point was considered (the same points that were used when forming the DSM). The segment was classified as "building or tree" if more than 50 percent of the points within it had a height value of 2.5 m or over, otherwise as "ground." The classification result was then imported into eCognition® as an additional image layer and used to classify the segments into "ground" and "building or tree."

In the classification of buildings and trees, fuzzy membership functions (Definiens Imaging, 2003) were used. Attributes for distinguishing buildings and trees were selected and the membership functions were defined manually after investigating the histograms of known building and tree segments in the training area. Some classification tests were also carried out. The histogram analysis was conducted using Matlab. A segment was used as a training segment for building or tree if over 80 percent of it belonged to building or forest in the map data (some forest areas on the map were excluded because they included a considerable area covered by roads). Attributes studied included mean values and standard deviations of height, intensity and aerial image channels, size, various shape attributes, and various texture attributes. The attributes were exported from eCognition® for the analysis. Three attributes were finally selected for classification: (a) Grey Level Co-occurrence Matrix (GLCM) homogeneity of height (texture measure), (b) mean value of the segment in the red channel of the aerial image, and (c) standard deviation of length of edges in a "shape polygon" created from the segment (for a description and formulas of the attributes, see Definiens Imaging, 2003). The GLCM homogeneity is one of the texture measures presented by Haralick *et al.* (1973). These texture measures are calculated from a matrix commonly called a GLCM, and they can take into account gray-level variations between neighboring pixels in different directions. The "all directions" option was used in our study. In classification, the three membership values for each segment in the classes building and tree were combined by calculating their mean value.

The first classification results were improved by using the size of the segments and contextual information on the classes of neighboring segments. The goal of this classification step was to correct small, misclassified segments. For example, some small segments classified as buildings but mainly surrounded by trees or ground were classified as trees. To accomplish this, two additional membership functions were defined for the classes building and tree, one based on the area of the segment and the other based on the relative border length to neighboring building segments (the ratio of the border length shared with building segments to the total border length of the segment). In the classification, the two new membership values were first combined with each other by taking their minimum value (the fuzzy and operator). The final membership value for the segment in the class in question was either this value or the mean value of the three previously described attributes, depending on which was higher (the fuzzy or operator).

After the first segmentation step, each building typically consisted of several segments corresponding to different height levels. For example, flat-roofed buildings mainly consisted of large segments and gabled-roofed buildings of narrow segments. To obtain one segment for each building, neighboring segments classified as buildings were merged using a classification-based segmentation operation (Definiens Imaging, 2003). The new segments were then classified on the basis of the previous results but also using the three attributes of Step 3 for buildings and trees. A membership value in the class building, calculated on the basis of the three attributes, was in this way obtained for each building segment.

It should be noted that the classification rules were originally defined for first pulse laser scanner data. It is thus possible that they are not optimal for classifying last pulse data. The rules, however, are such that they can also be expected to provide feasible results for last pulse data. The same rules were used because this allowed a straightforward comparison between the classification results.

Methods for Quality Evaluation

Pixel-based Accuracy Estimates

Several different accuracy measures have been presented and used in remote sensing and building extraction literature (see, for example, Helldén, 1980; Henricsson and Baltsavias, 1997; Congalton and Green, 1999; Shufelt, 1999; Song and Haithcoat, 2005; Zhan *et al.*, 2005). Our study used completeness, which corresponds to interpretation accuracy (Helldén, 1980) or producer's accuracy (Congalton and Green, 1999), and correctness, which corresponds to object accuracy or user's accuracy. These measures (with varying terms) are commonly used to evaluate the classification accuracy of remotely sensed data. They have been used to evaluate the results of building detection by, for example, Rottensteiner *et al.* (2005a and 2005b) and Zhan *et al.* (2005). In addition to completeness and correctness, the mean accuracy (Helldén, 1980), which is a combined measure of completeness and correctness, was calculated. The accuracy measures were calculated by comparing the building detection results with the reference map pixel by pixel:

- $$\text{Completeness} = \frac{n_{CB\,\&\,MB}}{n_{MB}} 100\%, \quad (1)$$
- $$\text{Correctness} = \frac{n_{CB\,\&\,MB}}{n_{CB}} 100\%, \quad (2)$$
- $$\text{Mean accuracy} = \frac{2n_{CB\,\&\,MB}}{n_{MB} + n_{CB}} 100\%, \quad (3)$$

where $n_{CB\,\&\,MB}$ is the number of pixels labeled as buildings both in the classification result and on the map, n_{MB} is the total number of pixels labeled as buildings on the map, and n_{CB} is the total number of pixels labeled as buildings in the classification result.

Building-based Quality Evaluation

In addition to calculating the pixel-based accuracy estimates, the quality of the results was evaluated by comparing individual buildings on the map with corresponding buildings in the building detection results. This type of object-based evaluation is considered an essential part of the quality analysis of building extraction results (e.g., Zhan *et al.*, 2005; Pfeifer *et al.*, 2007). Determining whether a building is correctly detected is not a straightforward task because some criteria for correct detection have to be defined. Earlier studies have used, for example, overlap percentages between detected buildings and reference buildings (Matikainen *et al.*, 2003 and 2004; Rottensteiner *et al.*, 2005a and 2005b). In the present study, a different approach was selected to acquire more detailed information on the quality of the results and the nature of classification errors. The idea was to examine the inner part and surrounding area of each building presented in the reference map (see Plate 1a).

If a building on the reference map is correctly detected, the corresponding area in the building detection results should be labeled as a building (i.e., completeness). However, the detected building should not extend outside the area of the reference building (i.e., correctness). To allow small differences in the appearance of the buildings in the building detection results and on the map, buffer zones were created inside and outside the boundary of each reference building. This was carried out by Matlab using morphological operations dilation and erosion to extend and diminish the size of buildings, respectively. In earlier building extraction research, morphological processing of buildings has been used, for example, in change detection (Vosselman et al., 2004).

The area between the diminished and extended building, consisting of inner and outer buffer zones, was not taken into account in the quality evaluation. The diminished building formed the inner part of the building for evaluation. The surrounding area was the area outside the extended building. After an examination of the inner part and the surrounding area, each reference building was placed in one of six categories:

1. Inside and outside correct: The inner part is completely labeled as a building in the building detection results and the same building does not extend to the surrounding area.
2. Inside correct, outside incorrect: The inner part is completely labeled as a building but the same building extends to the surrounding area.
3. Inside incorrect, outside correct: The inner part is partly labeled as a building, partly as ground and/or tree. The building in the inner part does not extend to the surrounding area.
4. Inside and outside incorrect: The inner part is partly labeled as a building, partly as ground and/or tree. The building in the inner part extends to the surrounding area.
5. More than one building inside: Two or more separate buildings were detected in the inner part. The surrounding area was not examined.
6. No buildings inside: No buildings were detected in the inner part. The surrounding area was not examined.

To avoid unrealistically strict criteria, the comparisons were also made by allowing a negligible number of misclassified pixels. In this case, the same evaluation rules were used, but the inner part was considered correct if more than 99 percent of it was labeled as belonging to one building. The rest could be classified as ground and/or tree. The same number of misclassified pixels was also allowed in the surrounding area. The outside of the building was thus considered correct if pixels belonging to the building covered an area that was less than 1 percent of the area of the inner part of the building. Even these evaluation criteria were strict, taking into account that the building detection method was fully automatic. The

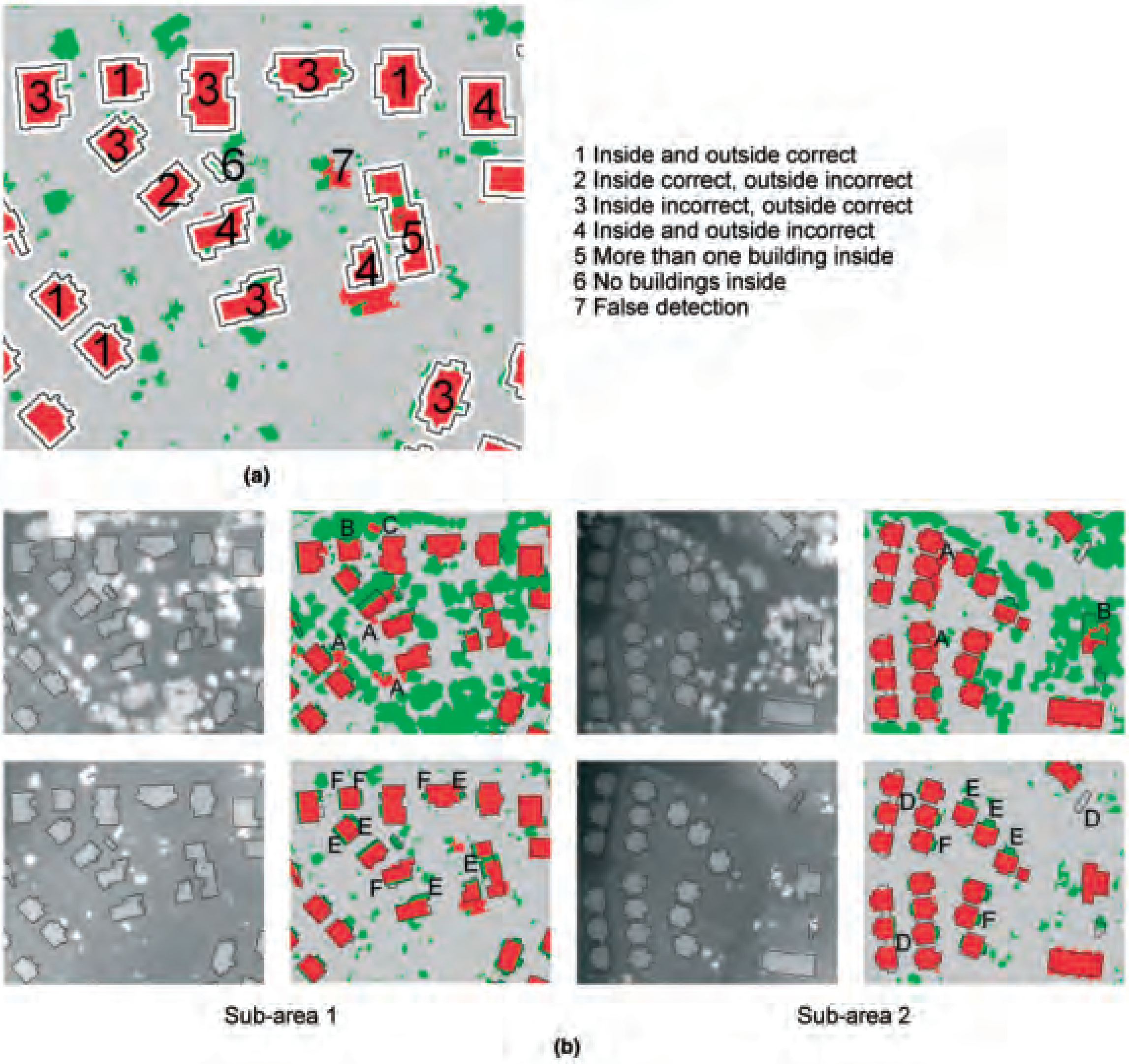


Plate 1. (a) Example of building-based quality evaluation. Buildings of the building detection result are shown in red, trees in green and ground surface in grey. Building vectors of the reference map are shown in black and the buffer zones in white; and (b) First pulse (upper row) and last pulse (lower row) DSMs and corresponding building detection results for two sub-areas of the low-rise residential area. The building map used in quality evaluation was overlaid on the DSMs and building detection results. Examples of typical problems encountered in classifications are shown with letters A to F (A: vegetation connected with a building, B: building partly under trees, C: tree classified as a building, D: low part of a building or other construction classified as ground, E: part of a building originally misclassified as tree, F: part of a building misclassified as tree as a result of using size and context information) (original map data © City of Espoo).

threshold value of 99 percent, however, was selected after some experiments because the use of the buffer zones and percentage thresholds can hide small classification errors, especially near the edges of buildings. If a lower threshold value had been used, more classification errors would have been hidden. Very small buildings were entirely covered by the buffer zone and could thus not be evaluated. An example of the quality evaluation is presented in Plate 1a.

A disk-shaped structuring element was used in the morphological operations to diminish and extend buildings. Two different radii were used: five pixels (corresponding to 1.5 m) and six pixels (corresponding to 1.8 m). The widths of the inner and outer buffer zones around the building boundaries were thus 1.5 m or 1.8 m, resulting in a total buffer width of 3.0 m or 3.6 m. The values of 1.5 m and 1.8 m were selected after visual comparison of the DSMs and the reference map. These values should cover small and predictable differences between the data sources, especially those caused by the representation of either roof edges or ground plans of the buildings. Two different radii were selected because buildings in first pulse data are larger than in last pulse data. Ahokas *et al.* (2004) analyzed the lengths of roofs in vector-format building models derived from the same laser scanner dataset that was used in our study. They found that roofs derived from first pulse data were about 21 cm longer than roofs measured in the field. Roofs derived from last pulse data were about 25 cm shorter than roofs measured in the field. In the position of a roof edge, this

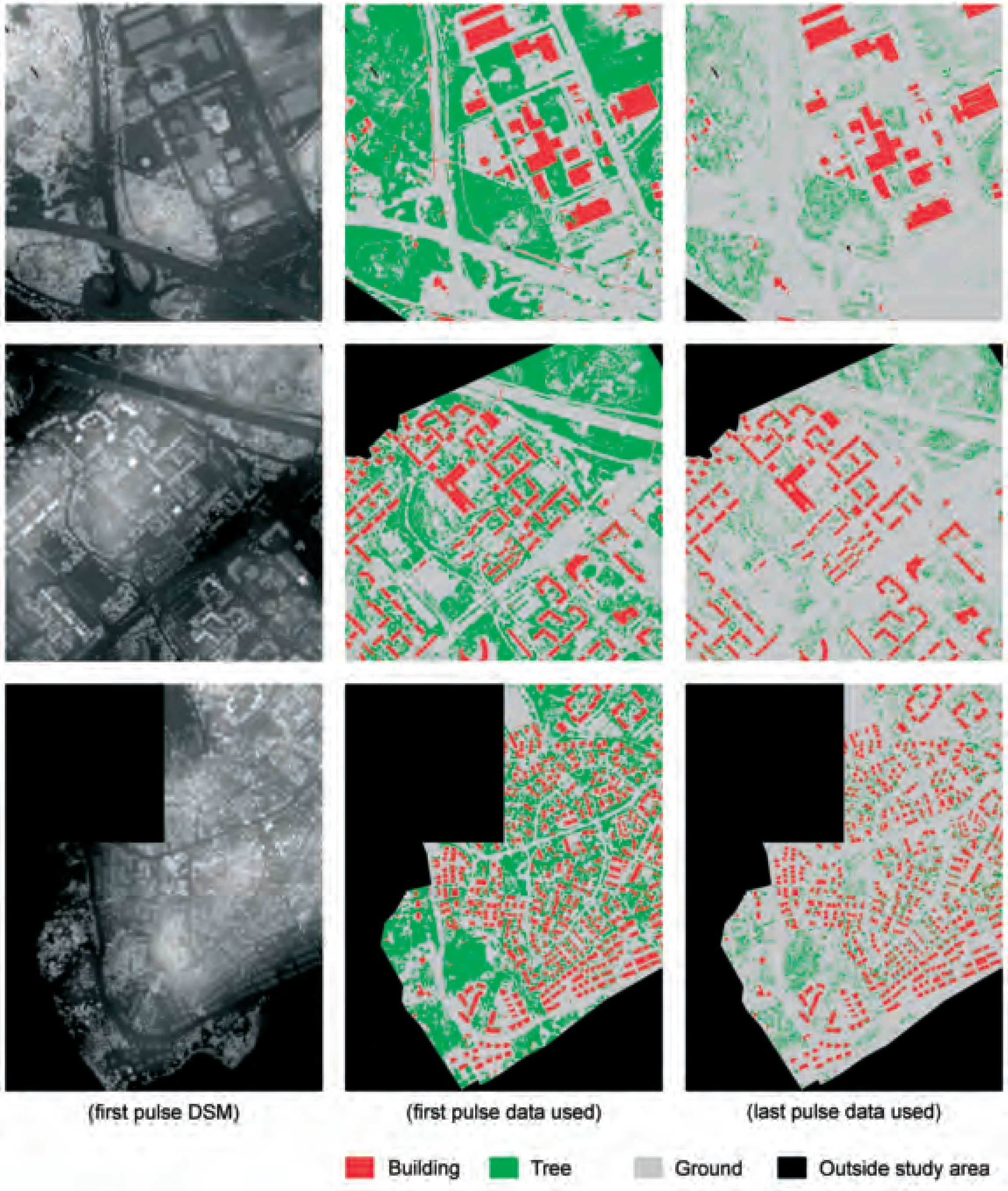


Plate 2. First pulse DSM and results of automatic building detection for the industrial area (upper row), high-rise residential area (middle row), and low-rise residential area (lower row). The results in the middle and right column of the plate were obtained by using the first pulse and last pulse DSM, respectively. In addition to the laser scanner data, an aerial ortho-image was used. The width of each area is 900 m.

difference between first pulse and last pulse data would mean a difference of about 23 cm. In our raster DSMs, the difference in the position of building edges can thus be approximated to be about one pixel (30 cm).

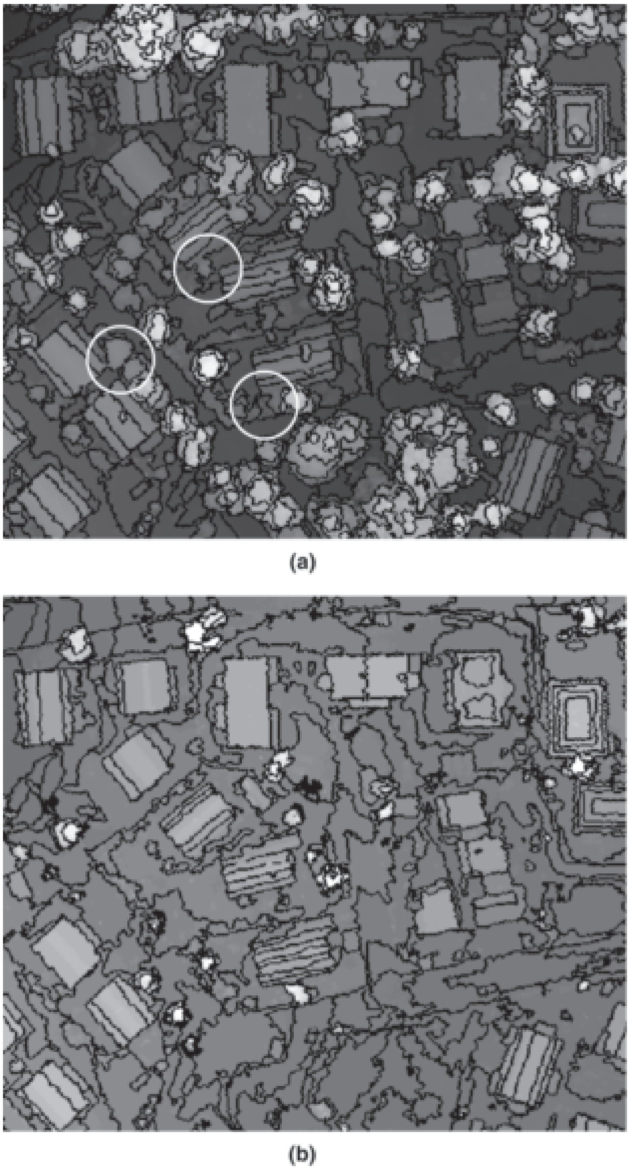
The buildings of the building detection results were also analyzed to find the number of false detections, i.e., objects classified as buildings but not presented as buildings on the map (i.e., correctness). A building was counted as a false detection if it did not have any overlap with buildings presented on the map. In this case, the original buildings of the raster map (without dilation or erosion) were used for the comparison.

Results and Discussion

Visual Evaluation

The first pulse DSM and building detection results for all test areas are presented in Plate 2. The results in the middle column of the plate were obtained using the first pulse DSM and aerial image, and the results in the right column were obtained using the last pulse DSM and aerial image. The general appearance of the results is satisfactory. The clearest difference between the first pulse and last pulse results is the proportion of the area classified as trees, which was considerably larger when the first pulse DSM was used.

Plate 1b shows two sub-areas of the low-rise residential area on a larger scale. The first pulse and last pulse DSMs and corresponding building detection results are shown for these sub-areas. The building map used in quality evaluation was overlaid on the DSMs and results (this version of the map was obtained by converting the raster map produced for quality evaluation into vector format). Segmentation results for one of the sub-areas are shown in Figure 1. It can be seen that the area covered by trees was clearly smaller in the last pulse DSM, which had positive effects on the segmentation and building detection results. Several typical errors can be seen in the first pulse results: vegetation connected into the same segments with buildings and thus classified as building (examples of this are shown by the letter A in Plate 1b and white circles in Figure 1), buildings that are partly under trees and thus not completely detected (B), and a tree segment classified as building (C). The number of such errors was smaller when the last pulse data were used.


(a)

(b)

Figure 1. Segmentation of (a) the first pulse, and (b) the last pulse DSM in Sub-area 1 of Plate 1b. Note the connection of vegetation into same segments with buildings in the first pulse DSM (examples of this are shown by white circles).

A closer look at the building detection results also revealed some other common errors. Some buildings, parts of buildings or other constructions presented on the reference map were lower than the threshold value of 2.5 m, and thus became classified as ground (D). Small protruding parts of buildings, such as balconies and verandas, were also often misclassified as tree (E, F). This can be partly related to the classification rules, which were created by using the reference map in which some small parts of buildings were missing. It is thus possible that the rules did not sufficiently take into account the characteristics of such small building segments, whose construction materials and shapes can be different from those of other typical building segments. The outer segments within a building can also include some vegetation. Partly the misclassification was a result of stage 4 in building detection, where the size and neighborhood of the segments were taken into account in order to correct small, misclassified segments. This improvement stage had positive effects on the results, but it also caused some new classification errors (F). Further development of the rules is thus needed to avoid erroneous corrections. The last pulse results could also be better if the rules were defined separately for last pulse data.

In Figure 2, the building detection results and map data are shown for a few individual buildings. In the high-rise area, flat roofs without eaves are typical. Building outlines determined from laser scanner data are close to those presented on the map, often slightly outside if using first pulse data and slightly inside if using last pulse data, which can also be seen in Figure 2. In the low-rise area, many building roofs have wide eaves and buildings detected from laser scanner data can be larger than the buildings on the map even when last pulse data are used.

Pixel-based Accuracy Estimates

When changing from first pulse to last pulse data, some changes in numerical accuracy estimates can be expected. As already discussed, buildings systematically appear too large in first pulse data and too small in last pulse data. A small decrease in completeness and a small increase in correctness of the results could thus be expected. The magnitude of these natural changes in our study, however, is difficult to estimate due to the differences between the map and remotely sensed data, which vary for different areas and buildings. Caution is thus needed when interpreting the accuracy estimates.

The pixel-based accuracy estimates for the results are shown in Table 1. The use of last pulse data instead of first pulse data led to a slight decrease in the completeness and a clearer increase in the correctness of the results. Taking into account all test areas, the completeness of the results decreased by about 2 percentage units (from 91.1 percent to 88.8 percent). The correctness increased by about 8 percentage units (from 84.0 percent to 92.3 percent). The mean accuracy was about 3 percentage units higher when last pulse data were used. Table 1 also shows the pixel-based accuracy estimates separately for the industrial area, high-rise residential area and low-rise residential area. The trends in each area were similar, except that both completeness

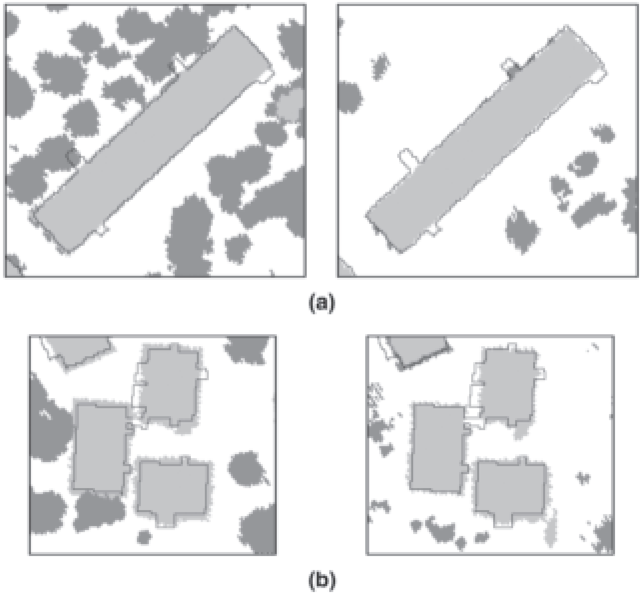


Figure 2. (a) A high-rise residential building, and (b) A low-rise residential buildings detected using the first pulse (left) or last pulse (right) DSM and aerial image. The building map used in quality evaluation was overlaid on the building detection results (original map data © City of Espoo).

Table 1. Accuracy of Building Detection Estimated Pixel by Pixel. Results Obtained Using the First Pulse (fp) or Last Pulse (lp) DSM and Aerial Image. (Ind. is Industrial Area, High res. is High-rise Residential Area, and Low res. is Low-rise Residential Area; see Plate 2)

	Area			
	Ind.	High res.	Low res.	All
Completeness	fp: 96.2% lp: 96.4%	fp: 91.6% lp: 88.4%	fp: 87.5% lp: 84.2%	fp: 91.1% lp: 88.8%
Correctness	fp: 84.8% lp: 93.4%	fp: 89.9% lp: 96.2%	fp: 78.8% lp: 88.3%	fp: 84.0% lp: 92.3%
Mean accuracy	fp: 90.1% lp: 94.8%	fp: 90.7% lp: 92.1%	fp: 82.9% lp: 86.2%	fp: 87.4% lp: 90.5%
Buildings classified as trees	fp: 2.0% lp: 1.5%	fp: 4.5% lp: 4.8%	fp: 8.5% lp: 9.6%	fp: 5.5% lp: 5.9%
Buildings classified as ground	fp: 1.8% lp: 2.1%	fp: 3.9% lp: 6.8%	fp: 4.0% lp: 6.2%	fp: 3.4% lp: 5.4%

and correctness improved in the industrial area when last pulse data were used (can be related to one large building, which was partly misclassified as ground when first pulse data were used). Factors leading to the slight decrease in completeness included the shrinking of buildings in last pulse data and a slight increase in the number of small protruding building parts misclassified as trees (see the discussion in the previous section). Glass surfaces on roofs also caused some errors when last pulse data were used, but due to their small total area, their effect on the accuracy estimates must have been small. The increase in the correctness of the results was more noticeable, and it is probable that the effect of the reduced amount of vegetation, especially deciduous vegetation, can be seen in the accuracy estimates, in addition to the small natural improvement due to smaller building sizes. The increase in correctness was highest in the low-rise residential area. The disturbance of vegetation is largest in this area and the benefits of using last pulse data are thus also larger. However, the type of roofs can also affect the accuracy estimates. For many buildings in the low-rise area, the last pulse data corresponded better to the map, which improved correctness.

Building-based Quality Evaluation

Table 2 shows the results of the building-based quality evaluation. The analysis was made in parts (one for the industrial area, one for the high-rise residential area and two for the low-rise residential area). If a building was located on the boundary of the parts, it became considered as two (or more) separate buildings.

Generally, the inner parts of the buildings were better detected when first pulse data were used. The difference in the total number of correct detections (inside correct, total number) was about 3 to 6 percentage units, depending on the width of the buffer zone and possible use of the threshold value to allow some misclassifications. The number of errors in the surroundings of the buildings, however, was clearly larger when first pulse data were used. In this case (outside correct, total number), the difference was about 20 to 23 percentage units. These comparisons are based on results where the width of the buffer zone was the same for both first pulse and last pulse results.

Many buildings are clearly smaller on the map than in the laser scanner data, and the use of the same buffer width for first pulse and last pulse results in the analysis

Table 2. Results of Building-based Quality Evaluation. Buildings from all Test Areas were Included

	All test areas, Buffer width 1.5 m, No misclassified pixels allowed	All test areas, Buffer width 1.8 m, No misclassified pixels allowed	All test areas, Buffer width 1.5 m, <1% misclassified pixels allowed *)	All test areas, Buffer width 1.8 m, <1% misclassified pixels allowed *)
Number of buildings on the map	745	723	745	723
Inside and outside correct	fp: 88 (11.8%) lp: 156 (20.9%)	fp: 151 (20.9%) lp: 226 (31.3%)	fp: 214 (28.7%) lp: 298 (40.0%)	fp: 248 (34.3%) lp: 352 (48.7%)
Inside correct, outside incorrect	fp: 260 (34.9%) lp: 144 (19.3%)	fp: 251 (34.7%) lp: 130 (18.0%)	fp: 251 (33.7%) lp: 135 (18.1%)	fp: 248 (34.3%) lp: 126 (17.4%)
Inside incorrect, outside correct	fp: 141 (18.9%) lp: 243 (32.6%)	fp: 126 (17.4%) lp: 210 (29.0%)	fp: 101 (13.6%) lp: 169 (22.7%)	fp: 88 (12.2%) lp: 131 (18.1%)
Inside and outside incorrect	fp: 157 (21.1%) lp: 92 (12.3%)	fp: 113 (15.6%) lp: 66 (9.1%)	fp: 80 (10.7%) lp: 33 (4.4%)	fp: 57 (7.9%) lp: 23 (3.2%)
More than one building inside	fp: 29 (3.9%) lp: 32 (4.3%)	fp: 29 (4.0%) lp: 32 (4.4%)	fp: 29 (3.9%) lp: 32 (4.3%)	fp: 29 (4.0%) lp: 32 (4.4%)
No buildings inside	fp: 70 (9.4%) lp: 78 (10.5%)	fp: 53 (7.3%) lp: 59 (8.2%)	fp: 70 (9.4%) lp: 78 (10.5%)	fp: 53 (7.3%) lp: 59 (8.2%)
Inside correct, total number	fp: 348 (46.7%) lp: 300 (40.3%)	fp: 402 (55.6%) lp: 356 (49.2%)	fp: 465 (62.4%) lp: 433 (58.1%)	fp: 496 (68.6%) lp: 478 (66.1%)
Outside correct, total number	fp: 229 (30.7%) lp: 399 (53.6%)	fp: 277 (38.3%) lp: 436 (60.3%)	fp: 315 (42.3%) lp: 467 (62.7%)	fp: 336 (46.5%) lp: 483 (66.8%)

*) Calculated separately for the inside and outside of the building as the percentage of the area of the inner part.

of the surrounding areas of the buildings may therefore favor the last pulse results, where buildings are smaller. If the evaluation results obtained by using the buffer width of 1.8 m for first pulse results and the buffer width of 1.5 m for last pulse results are compared, the percentage of correct detections (outside correct, total number) was 15 to 16 percentage units higher for the last pulse results. For the inner parts of the buildings, comparisons with the same buffer width may favor first pulse results. However, buildings are seldom clearly larger on the map than in the laser scanner data, and therefore the buffer width is not so critical for the analysis of the inner parts.

Table 3 shows the results of the building-based quality evaluation separately for the high-rise and low-rise residential areas. If the outsides of the buildings in the low-rise area are considered and first pulse results with a buffer width of 1.8 m are compared with last pulse results with a buffer width of 1.5 m, the percentage of correct detections

Table 3. Results of Building-based Quality Evaluation for the High-rise and Low-rise Residential Areas

	High-rise res., Buffer width 1.5 m, No misclassified pixels allowed	High-rise res., Buffer width 1.8 m, No misclassified pixels allowed	Low-rise res., Buffer width 1.5 m, No misclassified pixels allowed	Low-rise res., Buffer width 1.8 m, No misclassified pixels allowed
Number of buildings on the map	150	140	545	536
Inside and outside correct	fp: 22 (14.7%) lp: 22 (14.7%)	fp: 37 (26.4%) lp: 38 (27.1%)	fp: 59 (10.8%) lp: 120 (22.0%)	fp: 102 (19.0%) lp: 173 (32.3%)
Inside correct, outside incorrect	fp: 23 (15.3%) lp: 15 (10.0%)	fp: 24 (17.1%) lp: 11 (7.9%)	fp: 217 (39.8%) lp: 116 (21.3%)	fp: 208 (38.8%) lp: 105 (19.6%)
Inside incorrect, outside correct	fp: 47 (31.3%) lp: 57 (38.0%)	fp: 36 (25.7%) lp: 52 (37.1%)	fp: 88 (16.1%) lp: 175 (32.1%)	fp: 84 (15.7%) lp: 147 (27.4%)
Inside and outside incorrect	fp: 29 (19.3%) lp: 24 (16.0%)	fp: 24 (17.1%) lp: 17 (12.1%)	fp: 118 (21.7%) lp: 62 (11.4%)	fp: 84 (15.7%) lp: 46 (8.6%)
More than one building inside	fp: 7 (4.7%) lp: 9 (6.0%)	fp: 7 (5.0%) lp: 9 (6.4%)	fp: 21 (3.9%) lp: 23 (4.2%)	fp: 21 (3.9%) lp: 23 (4.3%)
No buildings inside	fp: 22 (14.7%) lp: 23 (15.3%)	fp: 12 (8.6%) lp: 13 (9.3%)	fp: 42 (7.7%) lp: 49 (9.0%)	fp: 37 (6.9%) lp: 42 (7.8%)
Inside correct total number	fp: 45 (30.0%) lp: 37 (24.7%)	fp: 61 (43.6%) lp: 49 (35.0%)	fp: 276 (50.6%) lp: 236 (43.3%)	fp: 310 (57.8%) lp: 278 (51.9%)
Outside correct, total number	fp: 69 (46.0%) lp: 79 (52.7%)	fp: 73 (52.1%) lp: 90 (64.3%)	fp: 147 (27.0%) lp: 295 (54.1%)	fp: 186 (34.7%) lp: 320 (59.7%)

was about 19 percentage units higher for the last pulse results. In the high-rise area, this difference was lower than 1 percentage unit (Here, it should be noted that the number of reference buildings was different for the buffer widths of 1.5 m and 1.8 m because the wider buffer covered more small buildings completely. If the same buildings were investigated, the last pulse results would be a little better.). One natural reason for the different behavior in the low-rise and high-rise areas is more vegetation in the low-rise area to confuse the data. In both areas, the use of first pulse data led to more complete detection of the inner parts of the buildings. An important reason for classification errors inside buildings was the misclassification of small protruding parts of buildings as trees.

The first pulse and last pulse results were also compared with each other building by building to obtain further information on relative quality. Table 4 shows the results of this comparison when all test areas were included. Table 5 shows the results for the high-rise and low-rise residential areas. The tables list the number of buildings that were correct in the first pulse results, last pulse results, both first pulse results and last pulse results, only first pulse results and only last pulse results. These comparisons confirm that the inner parts of the buildings were more completely detected from first pulse data and that there were fewer errors in the surroundings of the buildings when last pulse data were used.

There was a clear difference in the results for the surroundings of the buildings in the low-rise residential area in particular. When a buffer width of 1.8 m was used in the quality evaluation, the outsides of 22 buildings were correct only in the first pulse results and the outsides of 156 buildings were correct only in the last pulse results. For simplicity, this comparison was made by using the same buffer width for first pulse and last pulse results, and it is thus likely that it favors last pulse results. It was also noticed that the correspondence between the map and remotely-sensed data in the cases under analysis was not always good. For example, some buildings that were very near each other were detected as one building when first pulse data were used because there was no clear space between them in the data. The difference in the quality of the results, however, is clear enough to show that the last pulse results were better for the outsides of the buildings.

TABLE 4. COMPARISON OF THE BUILDING-BASED QUALITY EVALUATIONS FOR THE FIRST PULSE AND LAST PULSE RESULTS. BUILDINGS FROM ALL TEST AREAS WERE INCLUDED

	Number of cases			
	All test areas, Buffer width 1.5 m, No misclassified pixels allowed	All test areas, Buffer width 1.8 m, No misclassified pixels allowed	All test areas, Buffer width 1.5 m, <1% misclassified pixels allowed *)	All test areas, Buffer width 1.8 m, <1% misclassified pixels allowed *)
Inside and outside correct				
In fp results	88	151	214	248
In lp results	156	226	298	352
In fp results and lp results	53	99	164	204
Only in fp results	35	52	50	44
Only in lp results	103	127	134	148
Inside correct, total number				
In fp results	348	402	465	496
In lp results	300	356	433	478
In fp results and lp results	247	308	379	426
Only in fp results	101	94	86	70
Only in lp results	53	48	54	52
Outside correct, total number				
In fp results	229	277	315	336
In lp results	399	436	467	483
In fp results and lp results	197	244	287	311
Only in fp results	32	33	28	25
Only in lp results	202	192	180	172

*) Calculated separately for the inside and outside of the building as the percentage of the area of the inner part.

Table 5. Comparison of the Building-based Quality Evaluations for the First Pulse and Last Pulse Results in the High-rise and Low-rise Residential Areas

	Number of cases			
	High-rise res., Buffer width 1.5 m, No misclassified pixels allowed	High-rise res., Buffer width 1.8 m, No misclassified pixels allowed	Low-rise res., Buffer width 1.5 m, No misclassified pixels allowed	Low-rise res., Buffer width 1.8 m, No misclassified pixels allowed
Inside and outside correct				
In fp results	22	37	59	102
In lp results	22	38	120	173
In fp results and lp results	12	24	36	66
Only in fp results	10	13	23	36
Only in lp results	10	14	84	107
Inside correct, total number				
In fp results	45	61	276	310
In lp results	37	49	236	278
In fp results and lp results	27	43	199	240
Only in fp results	18	18	77	70
Only in lp results	10	6	37	38
Outside correct, total number				
In fp results	69	73	147	186
In lp results	79	90	295	320
In fp results and lp results	57	64	128	164
Only in fp results	12	9	19	22
Only in lp results	22	26	167	156

Taking into account both the inside and outside of the building (inside and outside correct), the last pulse results were clearly better in the low-rise area. In the high-rise area, the results were equally good. One could also argue that the best results would be obtained by using both first pulse and last pulse data because some buildings were detected better from first pulse data and some from last pulse data. This is possible but would require further research. For individual buildings in an automatic detection process, it is difficult to know which of the datasets gives a better result.

Table 6 provides information on the number of false detections, i.e., objects classified as buildings but not presented on the reference map. The number of false detections was larger when first pulse data were used. Taking into account all test areas, the percentage of false detections was about 16 percent in the first pulse results and about 5 percent in the last pulse results. In the industrial area, the number of false detections was large. Some power lines and trees were classified as buildings when first pulse data were used. There were also some buildings or building-like constructions that were not presented on the map. When last pulse data were used, the false detections mainly resulted from these. The number of real buildings in the industrial area was also relatively low, which increased the percentage of false detections. In the high-rise and low-rise residential areas, the number of false detections was smaller, but the reasons for the false detections were similar to those in the industrial area.

Other Observations

The laser scanner dataset, which was acquired in almost leaf-off conditions, provided a good basis for building detection. It is likely that the difference between first pulse and last pulse results would be smaller if trees were in full leaf. An ideal time to acquire laser scanner data for practical building mapping in Finland and other similar areas would thus be in spring when the snow has melted, but deciduous trees are still without leaves. This coincides with the time period normally used for acquiring aerial photos for mapping. Naturally, the data (e.g., point density), their preprocessing (e.g., pixel size, the selection of the minimum/maximum values for the DSMs) and the building detection method also have an impact on the results, and it is possible that different results would be obtained in other studies. However, the need to discriminate

TABLE 6. TOTAL NUMBER OF BUILDINGS IN THE BUILDING DETECTION RESULTS, AND THE NUMBER AND PERCENTAGE OF FALSE DETECTIONS (BUILDINGS THAT WERE NOT PRESENTED IN THE REFERENCE MAP)

	Industrial area	High-rise res.	Low-rise res.	All test areas
Number of detected buildings	fp: 122 lp: 61	fp: 160 lp: 150	fp: 501 lp: 508	fp: 783 lp: 719
Number and percentage of false detections	fp: 77 (63.1%) lp: 17 (27.9%)	fp: 25 (15.6%) lp: 13 (8.7%)	fp: 26 (5.2%) lp: 7 (1.4%)	fp: 128 (16.3%) lp: 37 (5.1%)

between buildings and vegetation is common to all methods, and the smaller amount of vegetation in last pulse data can facilitate this task, as shown by the results above.

Conclusions and Further Development

The results of the study confirm the expectation that the use of last pulse instead of first pulse laser scanner data can improve the results of automatic building detection. The building detection method included region-based segmentation of a laser scanner derived digital surface model and classification of the segments by using the laser scanner data and an aerial ortho-image. According to a pixel-based comparison with a building map, the completeness, correctness, and mean accuracy of the building detection results were about 89 percent, 92 percent, and 91 percent, respectively, when last pulse data were used. The correctness improved by about 8 percentage units and the mean accuracy by about 3 percentage units, compared with the results obtained using first pulse data. The completeness of the results decreased by about 2 percentage units. These accuracy estimates show the quality of the results compared with a real building map of the area. The different appearance of many buildings on the map and remotely sensed data, however, affect the numerical values. They cannot thus be directly compared or generalized with other studies.

The changes in accuracy between first pulse and last pulse results are partly related to the natural differences in the size of the buildings between the datasets. The smaller size of buildings in the last pulse data improved the correctness of the results. For many buildings, the last pulse data corresponded better to the map, which represented the ground plans of the buildings. On the other hand, the smaller size of buildings in the last pulse data decreased the completeness of the results. Visual evaluation and numerical building-based quality evaluation confirmed, however, that there were also other types of changes in the results. Due to the fact that there was less vegetation in the last pulse data, there were fewer cases where vegetation was included in the same segments as buildings, causing classification errors in the surroundings of the buildings. In addition, the number of false detections (non-building objects classified as buildings) decreased when last pulse data were used. The laser scanner data used in the study were acquired in almost leaf-off conditions, which is an ideal time for building mapping. It is likely that the differences between first pulse and last pulse results would be smaller when trees are in full leaf.

The results of the automatic building detection can be used as a basis for automatic building reconstruction and change detection. The detected building footprints surrounded with buffer zones could be used as search areas for determining the exact positions and 3D models for the buildings. The last pulse results with fewer misclassifications outside the actual building footprints are likely to provide a more reliable basis for the reconstruction. In change detection, the smaller number of erroneous buildings is likely to reduce the number of false alarms.

Some improvements to the classification results might still be achieved, for example, by adjusting the classification rules for last pulse data. Further development is also needed to diminish the number of small, protruding building parts classified as trees. Multispectral aerial images with visible and infrared channels and the difference between first pulse and last pulse laser scanner data could provide useful information for distinguishing buildings from trees. Trees in these datasets, however, can obscure buildings. If there is a tree canopy above a building, this part of the building will be classified as tree when an aerial image or the height difference is used. If there are lots of trees in the area, it might thus be better to rely on last pulse laser scanner data as much as possible. Compared with the other data sources, last pulse data have the unique advantage of "seeing" under trees. The use of last pulse data on its own would also be useful from the practical point of view. The laser scanner datasets are very large, and it is advantageous if the processing of data from one scanning mode is sufficient.

Overall, basic research on the selection of datasets and methods for building detection is still needed. Although a large number of different methods have been presented, comparative studies are rare (for examples of comparative studies, see Rottensteiner *et al.*, 2005b and 2007; Pfeifer *et al.*, 2007). Each study has typically used its own methods, datasets and study areas, which makes comparisons of results between different studies difficult. To meet the requirements of operational data processing, for example, in the context of countrywide laser scanning (Hyyppä *et al.*, 2007), optimal methods and datasets have to be found. The methods should be as automatic and reliable as possible, but they should also be relatively simple, fast, and general enough for operational countrywide processing.

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