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A multi-directional ground filtering algorithm for airborne LIDAR

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ABSTRACT

Automatic ground filtering for Light Detection And Ranging (LIDAR) data is a critical process for Digital Terrain Model (DTM) and three-dimensional urban model generation. Although researchers have developed many methods to separate bare ground from other urban features, the problem has not been fully solved due to the similar characteristics possessed by ground and non-ground objects, especially on abrupt surfaces. Current methods can be grouped into two major categories: neighborhood-based approaches and directional filtering. In this study, following the direction of the second branch, we propose a new Multi-directional Ground Filtering (MGF) algorithm to incorporate a two-dimensional neighborhood in the directional scanning so as to prevent the errors introduced by the sensitivity to directions. Besides this, the MGF algorithm explores the utility of identifying pattern varieties in different directions across an image. The authors conducted a comprehensive test of the performance on fifteen study sites and compared our results to eight other publicized methods based on the Kappa coefficients calculated from the error matrices reported by ISPRS. Overall, the MGF filter produces a promising performance in both urban and forest areas. The size and shape of non-ground objects do not pose significant influence on the performance of the MGF algorithm. The fact that MGF algorithm is robust to two commonly required parameters, slope and elevation difference thresholds, has added practical merits to be adopted in different landscapes.

1. Introduction

An airborne LIDAR system acquires dense point measurements using three-dimensional coordinates more directly than traditional surveying and mapping systems, e.g., photogrammetric systems (Shan and Sampath, 2005). Value-added LIDAR products, like DTMs, hydrologic models, three-dimensional urban visualization models, and transportation network models, increasingly demand accurate LIDAR surveys (Hill et al., 2000). Currently, LIDAR has two major advantages over photogrammetric systems: (1) the acquisition of vertical information over a large area is more cost-effective; and (2) there are fewer requirements for data preprocessing. In terms of DTM creation, LIDAR has taken the place of traditional photogrammetric methods and become the primary technique for producing regional or national DTMs in some countries, especially in Europe (Vosselman, 2000; Schickler and Thorpe, 2001; Elmqvist et al., 2001).

In raw LIDAR data, both bare-ground and non-ground objects, such as trees, buildings, vehicles, and electrical wires, generate backscatter. Non-ground points need to be identified and eliminated from LIDAR measurements before constructing value-added products like DTMs (Zhang et al., 2003; Vosselman, 2000). Likewise, ground points need to be removed to accurately identify non-ground objects, such as buildings and trees. In either case, an efficient and accurate ground filtering is required. Existing algorithms have achieved some success, but usually have difficulty along steep slopes or ridges. To this end, our goal is to develop a better ground filtering algorithm to facilitate DTM creation.

Ground filtering algorithms operate on either raw LIDAR point clouds or gridded elevation values (Sithole and Vosselman, 2004), which are derived by interpolation of raw data. Interpolation techniques include fitting a linear function (Passini and Jacobsen, 2002), a surface function (Kraus and Pfeifer, 2001; Okagawa, 2001; Haugerud and Harding, 2001), a morphology function such as smoothness (Kilian et al., 1996) or a local mean or minimum value. Merits and drawbacks for the algorithms using either type of input data have been reported (Zhang et al., 2003). Algorithms that work on raw LIDAR data (Zhang and Whitman, 2005; Elmqvist, 2002) require less preprocessing, and avoid

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errors introduced by interpolation. But searching for neighbors in an irregularly distributed point cloud can be time-consuming and troublesome, especially when users apply the algorithms to broader areas. Interpolating points into a regularly distributed grid can resolve this problem more effectively. In this paper, we have developed a multi-directional ground filtering algorithm using gridded elevation values that economizes the search for neighbors in multiple directions.

Most ground filters are based on the assumption that natural terrain variations are gradual, rather than abrupt. Therefore, ground elevation and slope should vary smoothly when moving from one ground point to another neighboring ground point. In contrast, the boundary between ground and non-ground points should exhibit an abrupt change in elevation and slope. The joint use of slopes, elevation differences, and local elevations can discriminate ground points from non-ground points (Zhang and Whitman, 2005; Vosselman, 2000).

Existing ground filtering algorithms calculate elevation differences and slopes based on pixels within a roving, two-dimensional window or along a scan line in a specified direction. Generally, neighborhood-based filters preserve the shape of non-ground objects but are insensitive to small-scale elevation changes on ground, like shrubs, low walls, and vehicles. Directional scanning approaches may effectively detect small objects through referencing to its intermediate neighbors but sometimes may generate artificial lines across the ground or objects.

The two-dimensional roving window technique compares the center point value to the mean or minimum value of its neighbors, or to a value estimated from its neighbors. If the center point value is above a predetermined threshold, the point is labeled as non-ground. The size of the neighborhood is critical for the performance of neighborhood-based filters (Kilian et al., 1996; Zhang et al., 2003). If the neighborhood size is smaller than the size of non-ground objects, points lying near the center of the objects will be wrongly labeled as ground points since their predicted values will not deviate much from the elevation of the center of the objects.

Whitman et al. (2003) develop an expanding window technique by gradually increasing the window size to remove non-ground objects of different sizes and avoid mislabeling ground pixels. Zhang and Whitman (2005), Zhang et al. (2003), and Vosselman (2000) report similar techniques and results. Other approaches such as the weighted window (Kraus and Pfeifer, 2001), multi-resolution or changing mesh size (Silván-Cárdenas and Wang, 2006; Zhang and Whitman, 2005; Kampa and Slatton, 2004) are alternative strategies for this problem.

The scan line technique creates an elevation or slope profile for each scan line, and identifies ground points based on the information along the profile. Sithole and Vosselman (2005) segment the profile into ground and non-ground points based on elevation differences along scan lines. Sithole (2001) proposes an adaptive filter to identify ground points based on the slope threshold of a profile. Brovelli et al. (2002) filter non-ground points by comparing the elevation of the points with the estimated value in a bilinear spline surface. The major drawback of most scan line approaches is that they are limited by the choice of filtering directions. Most existing directional scanning methods suffer dramatically when the ground surfaces present unique patterns in different directions along a scan line profile. To remedy this shortcoming Shan and Sampath (2005) develop a one-dimensional and bi-directional labeling (OBL) filter combining elevation and slope changes. Nevertheless, a bi-directional filtering algorithm only considers one-dimensional neighbors (i.e., those along a scan line) and does not take full advantage of neighborhood information.

In this study, we present an algorithm that combines the advantages of the directional and neighborhood-based scanning. Development of this algorithm explores the utility of identifying a variety of patterns in different directions across an image. Specifically, our MGF algorithm considers the slopes for neighboring pixels in up to four directions (i.e., parallel and perpendicular to a scan line), and the elevation difference between a pixel and the local minimum elevation within a two-dimensional neighborhood and the nearest ground pixel. A practical advantage of the MGF algorithm is that the object size and shape have no significant influence on the performance of the algorithm, which is especially critical for urban applications. Additionally, the MGF algorithm is robust to parameter selection based on experiments with and without an optimization process.

2. Data

The International Society for Photogrammetry and Remote Sensing (ISPRS) Commission III/WG3 provides LIDAR data for eight study sites with both first and last returns in urban and rural environments. ISPRS collected the raw LIDAR data using an Optech ALTM scanner and manually generated fifteen reference sites from sites 1–7 (www.commission3.isprs.org/wg3/). The authors selected these fifteen sites to test the performance of the MGF algorithm and compare the algorithm with other methods evaluated by ISPRS. Table 1 describes the characteristics of the study sites modified from Sithole and Vosselman (2004). Site 8 is not included due to lack of reference data.

Two preprocessing steps are necessary prior to applying the MGF algorithm: outlier removal and grid interpolation. Outlier elevation values, including random errors caused by birds, airplanes, or sensor noises, can be removed using a histogram examination and the Delaunay triangulation technique (Silván-Cárdenas and Wang, 2006). The elevation histogram distribution reveals the elevation range of ground and above-ground features, and points with elevations out of the range are usually outliers. The remaining outliers are removed if the elevations fall out of the range of their neighbors as defined by Delaunay triangulation. In this research, the threshold for high outliers is twice as high as the one for low outliers because many above-ground pixels from trees are much higher than their triangulation neighbors. For example, if the threshold is five meters, the range is from five meters below the local minimum to ten meters above the local maximum elevation. The last preprocessing step is to interpolate the irregularly distributed point clouds into grid pixels by assigning the elevation of the nearest point found within a specified distance to the output pixel. When no point is within the specified distance a no-data value is assigned to the pixel.

3. The multi-directional ground filtering (MGF) algorithm

The MGF algorithm filters ground points based on three criteria: (1) the slope measured in various scanning directions; (2) the elevation difference between each point and the nearest ground point; and (3) the elevation difference between each point and the minimum elevation in a local neighborhood. Slope is calculated between each point and the previous point in a particular scanning direction. Elevation differences are simple arithmetic differences. We examine various neighborhood sizes to test their influence on the performance of the MGF algorithm. We believe that using these three criteria will produce a robust ground filtering algorithm.

The first step in running this algorithm is to select a ground pixel near the first scan line. Our algorithm automatically selects the lowest pixel within a local neighborhood since ground is usually the lowest feature in the local environment. To avoid selecting an outlier pixel instead of a true ground pixel we remove all outliers prior to analysis and alter the size and location of the searching area.

After finding the ground seed, the MGF filter iterates repeatedly through the following steps to label points as ground, non-ground, or uncertain. We scan each line in the two, three or four of the four possible directions: (1) left to right, (2) right to left, (3) top to bottom, and (4) bottom to top.

Table 1
Study site features after Sithole and Vosselman (2003)

Site	Pixel size (m)	Ref. data	Special features
City site 1	1	samp11	Steep slopes, mixture of vegetation and buildings on hillside, buildings on hillside, data gaps.
	1	samp12	
City site 2	1	samp21	Large buildings, irregularly shaped buildings, road with bridge and small tunnel, data gaps.
	1	samp22	
	1	samp23	
	1	samp24	
City site 3	1	samp31	Densely packed buildings with vegetation in between, buildings with eccentric roofs, open space with mixture of low and high features, data gaps.
City site 4	1	samp41	Railway station with trains (low density of terrain points), data gaps.
	1	samp42	
Forest site 5	2	samp51	Steep slopes with vegetation, quarry, vegetation on river bank, data gaps.
	2	samp52	
	2	samp53	
	2	samp54	
Forest site 6	2	samp61	Large buildings, roads with embankments, data gaps.
Forest site 7	2	samp71	Bridge, underpass, roads with embankments, data gaps.

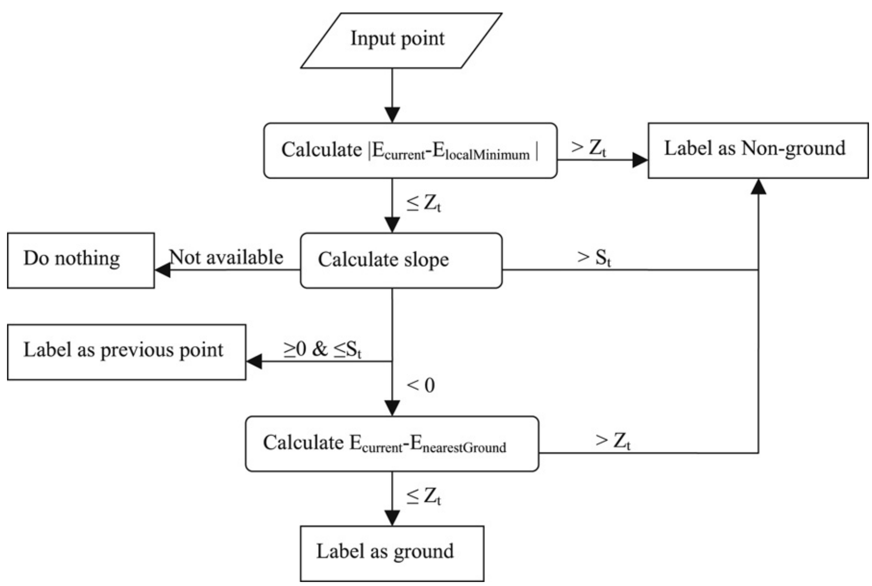

Fig. 1. Flow chart of labeling process of the MGF algorithm.

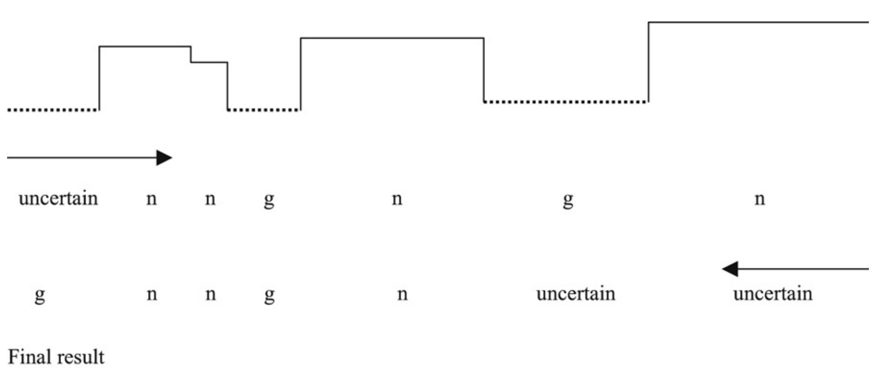

Fig. 2. The labeling process of the MGF filter given scanning directions from left to right and then from right to left. The dotted lines represent ground, and the others mean non-ground.

For each pixel, we illustrate the labeling process as shown in Fig. 1 and an example as shown in Fig. 2:

(1) Calculate the elevation difference between this point and its lowest local elevation.

a. If the elevation difference is greater than the elevation threshold, label this point as a non-ground point.

b. Proceed to the next step if the elevation difference is equal or smaller than the elevation threshold.

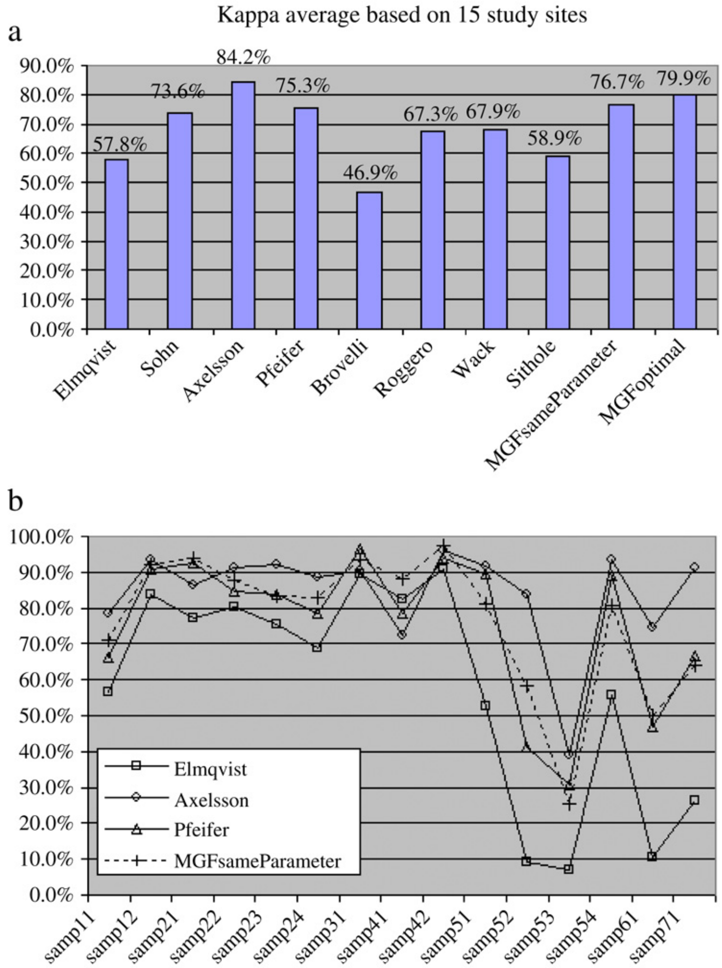

Fig. 3. Kappa averages on fifteen sites for nine filters (a) and Kappa values by sample sites for the MGF algorithm and three filters involved in the best performance (b).

Table 2
Parameters and kappa coefficients of the MGF algorithm

Site	Pixel size	Slope	Elevation	Kappa
samp11	1	30	1.0	70.96
samp12	1	30	1.0	92.28
samp21	1	30	1.0	93.79
samp22	1	30	1.0	87.83
samp23	1	30	1.0	83.35
samp24	1	30	1.0	82.83
samp31	1	30	1.0	93.31
samp41	1	30	1.0	88.27
samp42	1	30	1.0	97.18
samp51	2	60	2.0	81.18
samp52	2	60	2.0	58.43
samp53	2	60	2.0	25.60
samp54	2	60	2.0	80.61
samp61	2	60	2.0	50.16
samp71	2	60	2.0	64.11

Table 3
Optimized parameters and Kappa coefficient for the MGF algorithm

Site	Pixel size	Slope	Elevation difference	Kappa
samp11	1	60	1.0	70.96
samp12	1	30	0.8	93.12
samp21	1	45	0.9	95.40
samp22	1	45	0.9	88.75
samp23	1	30	1.6	87.56
samp24	1	30	0.8	83.39
samp31	1	30	0.5	97.45
samp41	1	15	1.3	88.58
samp42	1	30	1.1	97.25
samp51	2	15	1.8	87.20
samp52	2	30	2.7	65.57
samp53	2	60	2.9	31.25
samp54	2	30	0.9	92.71
samp61	2	60	2.2	52.43
samp71	2	45	1.3	67.36

(2) Calculate the slope between the previous point in the scan line and this point.
   a. If the slope is greater than the slope threshold, label this point as a non-ground point.
   b. If the slope is positive and equal or less than the threshold, label this point with the same label as the previous point.
   c. If the slope is not available when there is no previous point, do nothing.
   d. If the slope is negative, proceed to the next step.

(3) Calculate the elevation difference between this point and its nearest ground point.

Table 4
Kappa coefficients of the MGF algorithm on samp31 based on different window sizes

Window size	Kappa coefficient
3	97.45
5	96.45
7	95.01
9	93.83

   a. If the elevation difference to the nearest ground point is greater than the elevation threshold, label this point as a non-ground point.

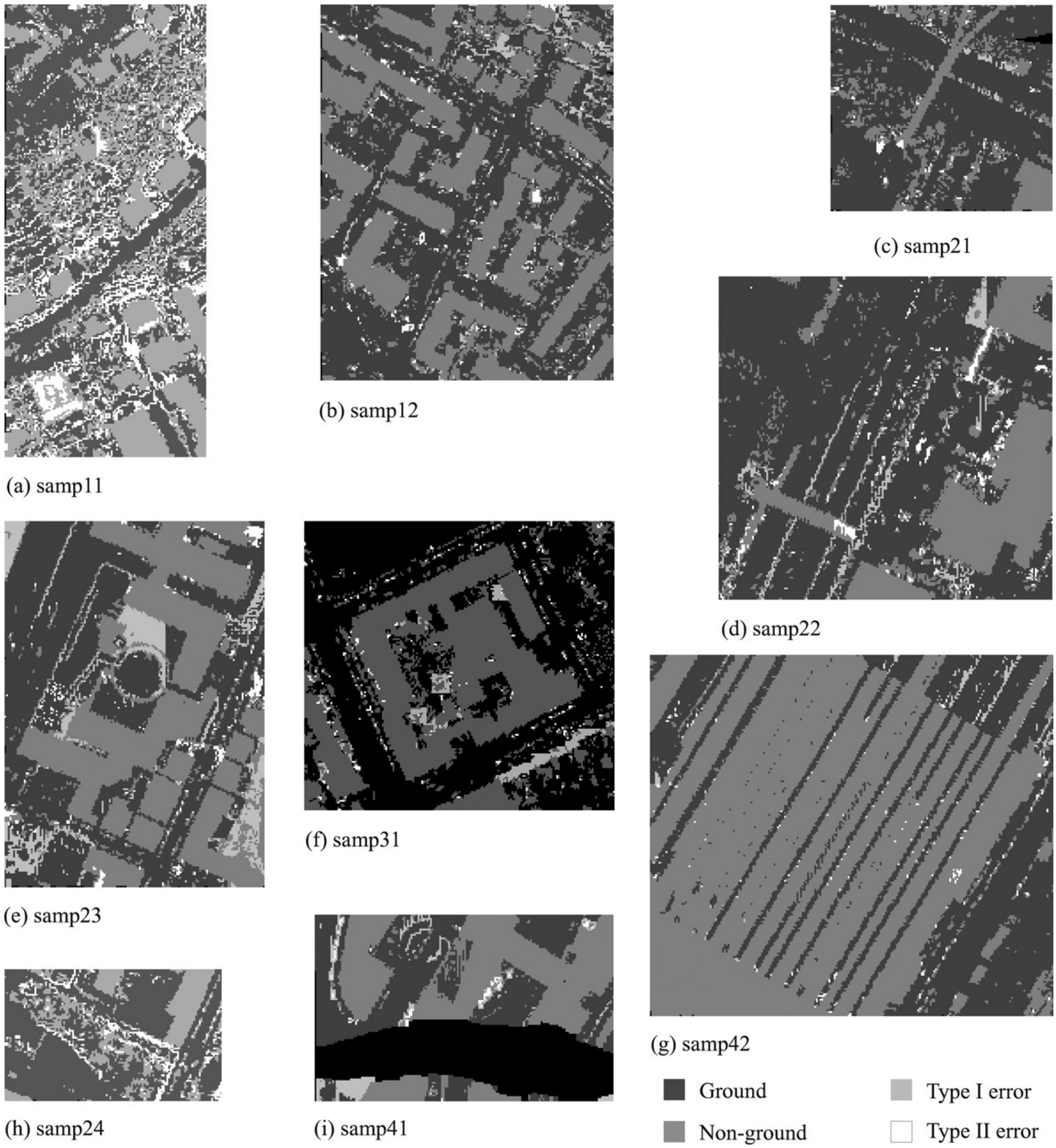

Fig. 4. Error distribution for city sites 1–4. Each image is displayed at a unique scale.

b. Otherwise, label this point as a non-ground point.

(4) Repeat steps 1–3 for each pixel in each scanning direction.

It is important to clarify that a previously ground-labeled point can change to non-ground if the slope or elevation difference along the current direction is larger than the threshold. Experiments prove that allowing status change generates higher performance. When searching for the nearest ground points, we target the smallest window that contains a ground point and then locate the nearest point to expedite the process.

4. Results and discussion

We apply the MGF algorithm to the fifteen urban and forest study sites provided by ISPRS and calculate the ground filtering accuracy using the Kappa Index of Agreement (Jensen, 2005). In the first section, we use identical slope and elevation threshold parameters for all urban sites and for all forest sites. We compare our results with eight other published ground filtering methods that were tested by ISPRS on the same datasets. In the second section, we test the sensitivity of our algorithm to the selection of slope and elevation thresholds by using an optimization process that incorporates ground truth data to determine the optimal thresholds for each site. The optimization demonstrates shows the potential performance of the MGF algorithm given well selected thresholds.

4.1. Comparative algorithm performance

The fifteen study sites are subsets from two larger sites provided by ISPRS to generate ground truth for ground filtering algorithms. The nine urban sites (samp11 to samp42) are relatively flat with few steep slopes. We use 30° and 1 m for the slope and

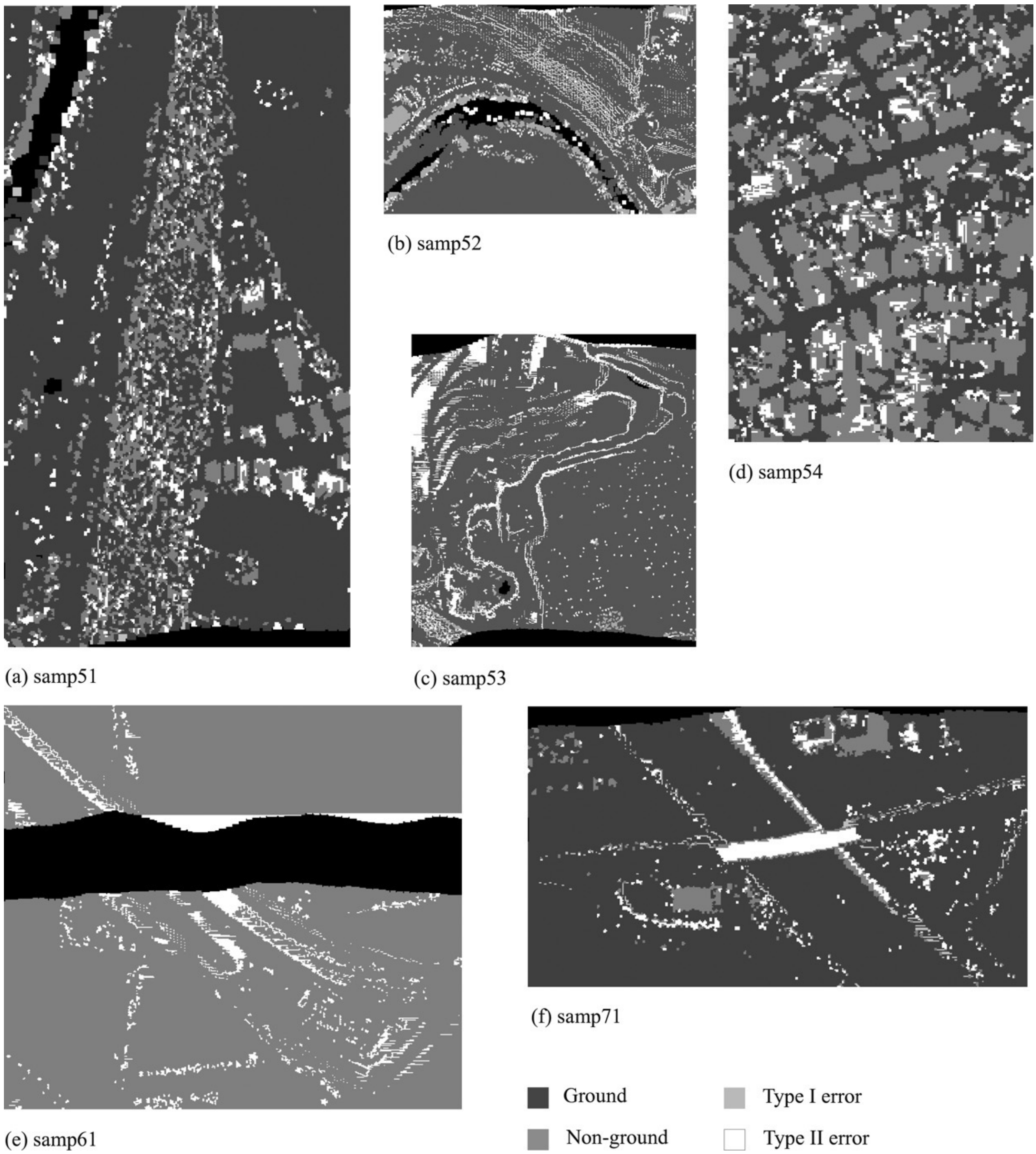

Fig. 5. Error distribution for forest sites 5–7. Each image is displayed at a unique scale.

elevation difference thresholds, respectively, at all urban study sites (Table 2). The forest sites (samp51 to samp71) contain more dramatic ground surface change. We use 60° and 2 m for the slope and elevation difference thresholds respectively at all forest sites. The window size for the local elevation search is three-by-three. The average Kappa coefficient of the MGF algorithm is 76.7%. The three best filters are selected for comparison with the MGF algorithm (Fig. 3). Compared to the performance of eight other algorithms, the MGF algorithm generates promising results — it is second best overall and thrice the best performing algorithm.

Figs. 4 and 5 show the spatial distribution of error for the MGF algorithm on each site. Sharp ridges on the ground surface are a major problem for ground filtering, which causes a dramatic drop in Kappa values for samp52 and samp53 as shown in Fig. 3. The errors are distributed mainly in thin zones along edges as shown in Fig. 5(b) and (c). Missing ground pixels on edges may smooth the edges on DEM products, but the MGF algorithm is capable of capturing the main ground terrain. Vegetation and buildings along steep slopes are another major challenge for ground filtering, as shown in samp11, samp24, samp51, and samp52. The challenge is that pixels are misidentified because the characteristic differences for ground and non-ground objects on steep surfaces are dramatically different than flat surfaces.

Gradual elevation changes, like those found on elevated highway bridges, are usually difficult to identify as shown in Fig. 4(c), (d), and Fig. 5(f). The MGF algorithm can identify most bridges except when the bridges are parallel to the last scanning direction as shown in Fig. 5(f). Large and irregularly shaped buildings or buildings with eccentric roofs are successfully captured as shown in Fig. 4(e), (f), and (i). These results indicate that the size and shape of non-ground objects have no significant influence on the performance of the MGF algorithm, even at the

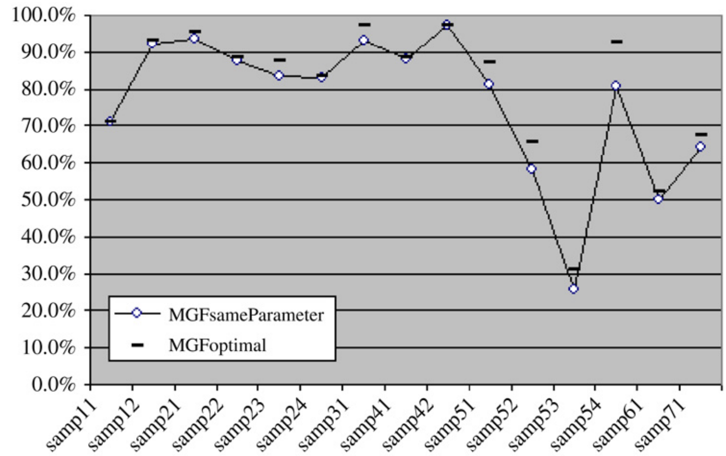

Fig. 6. The MGF performance with the same slope and elevation parameters for urban or forest sites and the performance with the optimized slope and elevation parameters.

smallest window size for the local minimum elevation search. In addition, misidentified lines or parts across the ground and non-ground objects are often present in the results of other filters as demonstrated by Sithole and Vosselman (2004). In contrast, the MGF algorithm preserves the shapes of ground and non-ground objects by distributing errors mainly on the edges of objects.

4.2. Sensitivity analysis

In theory, optimal slope and elevation difference thresholds should be the maximum ground slope and ground elevation difference of a particular study site. These thresholds are usually not available prior to analysis since ground points are not yet identified. For the ISPRS study sites, however, the ground points are already identified and available for assessing accuracy. We use the ground reference data to optimize our selection of slope and elevation difference thresholds and test the sensitivity of our algorithms to changes in thresholds.

We employ a back-calibration optimization process based on the ground reference data provided by ISPRS to find optimal slope and elevation thresholds. We test the slope threshold at 15, 30, 45, 60, and 75 degrees. We test the elevation difference threshold with 0.1 m increments from 0.3 m to 3 m. We also alter our neighborhood search size and scan line directions. Then, we compare Kappa coefficients for approximately 20 combinations of slope, elevation difference, neighborhood search size and scan line direction for each of the fifteen study sites. The result with the highest accuracy for each site identifies the "optimal" slope and elevation difference thresholds (Table 3).

The average kappa coefficient for the optimized results is 79.9% as shown in Fig. 3(a). This result is 3.3% higher than the result obtained using the identical thresholds for all urban or forest sites. The differences in slopes are up to 45°, the elevation difference is up to 1.5 m, and the average elevation parameter difference is 0.43 m. In relative flat urban or forest sites with small ground slope such as samp12, samp21, samp22, samp23, samp31, samp42, samp61, and samp71, the Kappa accuracies without optimization are rather close to the optimized results (Fig. 6). It appears the MGF algorithm generates similar results using approximate thresholds. The fact that the MGF algorithm is robust to slope and elevation difference thresholds demonstrates the wide applicability of this algorithm to additional landscape, especially those areas without steep slope and cliff.

Many methods referencing the local elevations require changing window sizes to capture objects of different size (Whitman et al., 2003). In this research, three-by-three, five-by-five, seven-by-seven, and nine-by-nine window sizes are applied to each study site to examine the influence of window size on the local minimum elevation search. For fourteen sites, the MGF filter generates the best performance with the smallest window size, and the accuracy decreases as the window size increases as shown in the example in Table 4. The single exception to this case is samp21, where the Kappa coefficient for the five-by-five window is slightly higher (0.32%) than the one for the three-by-three window. These results show that using the smallest window size significantly improves accuracy, and it is therefore reasonable to recommend the three-by-three window size for use in the MGF algorithm.

Overall, the MGF algorithm provides competitive performance according to the average Kappa coefficients based on fifteen study sites, below Axelsson's method (Axelsson, 1999) but above the other seven methods. Axelsson's method adaptively adjusts thresholds during iterations, and has a strong ability to handle surfaces with discontinuities as reported by Sithole and Vosselman (2004). Yet the MGF filter performs well even on static thresholds, especially in relative flat areas without steep slopes or cliffs.

5. Conclusions

Ground filtering is an important issue in LIDAR applications for both automatic DTM generation and feature identification. Researchers have developed many methods to tackle the difficulties of separating bare ground from other features (Sithole and Vosselman, 2004). However, the problem has not been fully solved, especially for a ground surface with abrupt changes. Directional filtering approaches provide a promising alternative by referring to the immediate neighbors instead of estimated values within a neighborhood. This enables directional scanning to identify more subtle surface change in the local environment. We present a multi-directional ground filtering (MGF) algorithm to incorporate two-dimensional neighborhoods in directional scanning and to explore the ability of a multi-directional approach to utilize the pattern variability along different directions.

We test the MGF algorithm on fifteen study sites both with and without optimization, and compare the results to eight other filtering algorithms using Kappa coefficients (Silván-Cárdenas and Wang, 2006) calculated from the error matrices reported by Sithole and Vosselman (2004). The results reveal several significant advantages of the MGF method. First, the MGF algorithm allows multi-directional filtering to detect the subtle elevation changes in different directions. Second, the MGF algorithm combines the advantages of neighborhood-based and directional scanning approaches. Third, the sensitivity of some directional scanning methods to steep slopes has been solved because of the multi-directional strategy and the combination of the local elevation search and the one-dimensional directional filtering. Even with the presence of ridges, the MGF algorithm is capable of capturing the major terrain features. Fourth, although building size and shape is a major challenge for many other neighborhood-based algorithms, they do not significantly hinder the MGF algorithm. Fifth, the fact that the MGF algorithm is robust to two commonly required parameters, slope and elevation difference thresholds, has the practical advantage of allowing it to be adopted in different landscape settings. Overall, the MGF algorithm provides promising performance based on the experiments on the fifteen study sites.

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