

# COMPARISON OF FILTERING ALGORITHMS

George Sithole, George Vosselman  
Department of Geodesy, Faculty of Civil Engineering and Geosciences  
Delft University of Technology  
The Netherlands  
g.sithole@citg.tudelft.nl, M.G.Vosselman@geo.tudelft.nl

Commission III, Working Group 3

**KEY WORDS:** LIDAR, DEM/DTM, classification, filtering

## ABSTRACT

To determine the performance of filtering algorithms a study was conducted in which eight groups filtered data supplied to them. The study aimed to determine the general performance of filters, the influence of point resolution on filtering and future research directions. To meet the objectives the filtered data was compared against reference data that was generated manually. In general the filters performed well in landscapes of low complexity. However, complex landscapes as can be found in city areas and discontinuities in the bare earth still pose challenges. Comparison of filtering at lower resolutions confirms that amongst other factors the method of filtering also has an impact on the success of filtering and hence on the choice of scanning resolution. It is suggested that future research be directed at heuristic classification of point-clouds (based on external data), quality reporting, and improving the efficiency of filter strategies.

## 1 INTRODUCTION

While commercial Airborne Laser Scanning (ALS) systems have come a long way, the choice of appropriate data processing techniques for particular applications is still being researched. Data processing, here, is understood as being either semiautomatic or automatic, and includes such tasks as “modelling of systematic errors”, “filtering”, “feature extraction” and “thinning”. Of these tasks, manual classification (filtering) and quality control pose the greatest challenges, consuming an estimated 60 to 80% of processing time (Flood, 2001), and thus underlining the necessity for research in this area. Algorithms have been developed for semi automatically/automatically extracting the bare-earth from point-clouds obtained by airborne laser scanning and InSAR. While the mechanics of some of these algorithms have been published, those of others are not known because of proprietary restrictions. Some comparison of known filtering algorithms and difficulties have been mentioned in Huising and Gomes Pereira (1998), Haugerud and Harding (2001), Tao and Hu (2001). However, an experimental comparison was not available. Because of this it was felt that an evaluation of filters was required to assess the strengths and weaknesses of the different approaches based on available control data. In line with the framework of [ISPRS Commission III](#), the [Working Group III/3 "3D Reconstruction from Airborne Laser Scanner and InSAR Data"](#) initiated a study to compare the performance of various automatic filters developed to date, with the aim of:

1. Determining the comparative performance of existing filters.
2. Determining the performance of filtering algorithms under varying point densities.
3. Determining problems in the filtering of point-clouds that still require further attention

In line with these aims a web site was set up in which twelve sets of data were provided for testing. Individuals and groups wishing to participate in the study were kindly requested to process all twelve data sets if possible. A total of 8 data sets (results) were received. The algorithms used by participants come from a cross-section of the most common strategies (or variants) for extracting the bare-earth from ALS point-clouds. The report is broken into three main parts. Section 2 discusses common characteristics of filtering algorithms. Sections 3 and 4 describe the data used, and discuss the results of the comparisons. In section 5 the results from the study is discussed and conclusions are drawn in respect to the objectives setout.

## 2 FILTER CHARACTERISTICS

Filters are built from combinations of different elements. Therefore, to understand or predict the behavior and output of a filter the way in which elements are combined has to be understood. Seven elements have been identified:

### 2.1 Data Structure

The output of an ALS is a cloud of irregularly spaced 3D points. Some filters work with the raw point-cloud. However, to take advantage of image processing toolkits some filtering algorithms resample the ALS produced point-cloud into an image grid, before filtering.

### 2.2 Test neighborhood and the number of points filtered at a time

Filters always operate on a local neighborhood. In the classification operation (bare earth or object) two or more points are classified at a time. In regard to the neighborhood this classification can be done in three possible ways.

**Point-to-Point** - In these algorithms two points are compared at a time. The discriminant function is based on the positions of the two points. If the output of the discriminant function is above a certain threshold then one of the points is assumed to belong to an object. Only one point is classified at a time.

**Point-to-Points** - In these algorithms neighboring points (of a point of interest) are used to solve a discriminant function. Based on the output of the discriminant function the point of interest can then be classified. One point is classified at a time.

**Points-to-Points** - In these algorithms several points are used to solve a discriminant function. Based on the discriminant function the points can then be classified. More than one point is classified in such a formulation.

### 2.3 Measure of Discontinuity

Most algorithms classify based on some measure of discontinuity. Some of the measures of discontinuity used are, height difference, slope, shortest distance to TIN facets, and shortest distance to parameterized surfaces.

### 2.4 Filter concept

Every filter makes an assumption about the structure of bare earth points in a local neighborhood. This forms the concept of the filter (figure 2.1).

**Slope based** - In these algorithms the slope or height difference between two points is measured. If the slope exceeds a certain threshold then the highest point is assumed to belong to an object.

**Block-minimum** - Here the discriminant function is a horizontal plane with a corresponding buffer zone above it. The plane locates the buffer zone, and the buffer zone defines a region in 3D space where bare earth points are expected to reside.

**Surface base** - In this case the discriminant function is a parametric surface with a corresponding buffer zone above it. The surface locates the buffer zone, and as before the buffer zone defines a region in 3D space where ground points are expected to reside.

**Clustering/ Segmentation** - The rationale behind such algorithms is that any points that cluster must belong to an object if their cluster is above its neighborhood. It is important to note that for such a concept to work the clusters/ segments must delineate objects and not facets of objects.

### 2.5 Single step vs. iterative

Some filter algorithms classify points in a single pass while others iterate, and classify points in multiple passes. The advantage of a single step algorithm is computational speed. However, computational speed is traded for accuracy by iterating the solution, with the rationale that in each pass more

information is gathered about the neighborhood of a point and thus a much more reliable classification can be obtained.

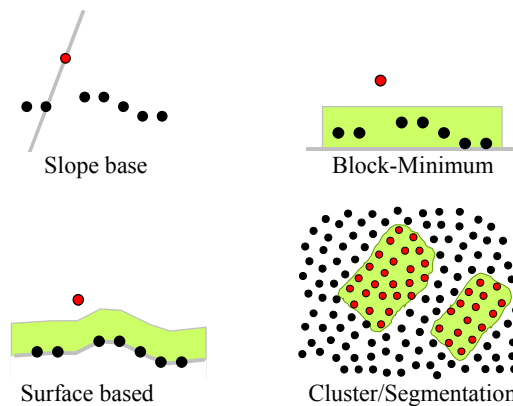


Figure 2.1 Filter concepts

### 2.6 Replacement vs. Culling

In culling a filtered point is removed from a point-cloud. Culling is typically found in algorithms that operate on irregularly spaced point-clouds. In a replacement, a filtered point is returned to the point-cloud with a different height (usually interpolated from its neighborhood). Replacement is typically found in algorithms that operate on regularly spaced (rasterized) point-clouds.

### 2.7 Using first pulse and reflectance data

Some scanners record multiple pulse returns. This feature is advantageous in forested areas, where the first pulse is usually off vegetation and subsequent pulses are from surfaces below the vegetation canopy. Additional to multiple pulse measurements the intensity of the returned pulses is also measured. Different surfaces in the landscape will absorb/reflect pulses differently and therefore it may be possible to use this information in classifying points.

## 3 TEST DATA AND ALGORITHMS

As part of the second phase of the [OEEPE project on laser scanning](#) (OEEPE 2000) companies were invited to fly over the Vaihingen/Enz test field and Stuttgart city center. These areas were chosen because of their diverse feature content. [Eight sites](#) were selected for the comparison of filtering algorithms. The landscape was scanned with an Optech ALTM scanner, and the data was produced by [FOTONOR AS](#). Both first and last pulse data were recorded. Eight test sites (four urban and four rural) were chosen. The urban sites were at a resolution of 1-1.5m. The rural sites were at a resolution of 2-3.5m. This data was offered to participants for processing. Some characteristics of the test-sites are listed below:

- (i) Steep slopes, (ii) Mixture of vegetation and buildings on hillside, (iii) Large buildings, (iv) Irregularly shaped buildings, (v) Densely packed buildings with vegetation between them, (vi) Building

with eccentric roofs, (vii) Open spaces with mixtures of low and high features, (viii) Railway station with trains (low density of terrain points), (ix) Bridge, (x) High bridge, (xi) Underpass, (xii) Ramps, (xiii) Road with embankments, (xiv) Road with bridge and small tunnel, (xv) Quarry (break-lines), (xvi) Vegetation on river bank, (xvii) Data gaps

Two sites were also provided at three different resolutions (1-1.5m, 2-3.5m, 4-6m for the urban and 2-3.5m, 4-5.5m, 7-10m for the rural) to test filter performance at three different point-cloud resolutions. To obtain the first reduced resolution the scan lines in the original point-clouds were detected and every second point in a scan line was dropped. Similarly, the second reduced point-cloud was produced from the first reduced point-cloud.

### 3.1 Reference data sets

The reference data was generated, by manually filtering the eight data sets. In the manual filtering, knowledge of the landscape and some aerial imagery where available. All points in the reference data sets were labelled “Bare Earth” or “Object”. From the eight data sets fifteen samples were abstracted. These fifteen samples were rechecked and it is these samples that are used in the quantitative analysis. The fifteen samples are representative of different environments (but are more focused in respect to the expected difficulties).

### 3.2 Filtered data sets

Corresponding samples to the fifteen reference samples were also extracted from the filtered data provided by the participants. The filtered data sets contain only the bare earth points.

### 3.3 Participants

Eight individuals/groups submitted results for the test. A brief breakdown of the participants and a description of their filters are given in Table 3.1.

Table 3.1 Participants

Developer(s)	Filter Description
M. Elmqvist - FOI (Swedish Defence Research Institute), Sweden	Active Contours - Elmqvist (2001)
G. Sohn - University College London (UCL)	Regularization Method - Sohn (2002)
M. Roggero - Politecnico di Torino	Modified Slope based filter - Roggero (2001)
M. Brovelli - Politecnico di Milano	Spline interpolation - Brovelli (2002)
R. Wack, A. Wimmer - Joanneum Research Institute of Digital Image Processing	Hierarchical Modified Block Minimum - Wack (2002)
P. Axelsson - DIGPRO	Progressive TIN densification - Axelsson (1999, 2000)
G. Sithole, G. Vosselman - TU Delft	Modified Slope based filter - Vosselman (2000), Sithole (2001)
N. Pfeifer, C. Briese - TU Vienna	Hierarchic robust interpolation - Pfeifer et. al. (1998), Briese et. al. (2001)

## 4 RESULTS/ COMPARISONS

### 4.1 Qualitative assessment

The fifteen samples were extracted with a view to examining and comparing how the different filters behave and to identify difficulties in filtering. Based on an examination of the eight data sets and the fifteen sample sets, each of the filters was assessed for difficulties.

#### 4.1.1 Filtering difficulties

The filtering difficulties identified from the qualitative comparison relate to Outliers, Object Complexity, Attached Objects, Vegetation, and Discontinuities in the Bare Earth. Each is briefly discussed below.

##### 4.1.1.1 Outliers

**High outliers** - These are points that normally do not belong to the landscape. They originate from hits off objects like birds, low flying aircraft, etc. Most filters handle such features easily, because they are so far elevated above neighboring points. Therefore it is included here for completeness only.

**Low outliers** - These are points that also normally do not belong to the landscape. They originate from multi-path errors and errors in the laser range finder. Most filters work on the assumption that the lowest points in a point-cloud must belong to the terrain. These points are naturally an exception to the rule. Many algorithms also work on the assumption that points neighboring a lower point must belong to an object. In practice this assumption usually holds. However, in cases where the lowest point is an outlier, the assumption fails completely, resulting in an erosion of points in the neighborhood of the low outlier.

##### 4.1.1.2 Object complexity

**Very large objects** - Because many of the filtering algorithms are localized, large objects may not be filtered if the size of objects exceeds that of the test neighborhood.

**Very small objects** (elongated objects, low point count) - Prominent examples of such objects are vehicles.

**Very low objects** (walls, cars, etc.) - The closer an object is to the bare earth, the more difficult it becomes for algorithms to differentiate between it and the bare earth. This problem is complicated even further by the need not to incorrectly filter off small but sharp variations in the terrain.

**Complex Shape/Configuration** - A major difficulty posed by urban environments is the variety and complexity of objects found in them. This complexity manifests itself in the shape, configuration, and lay of objects.

**Disconnected terrain** (courtyards, etc.) - In urban environments, it is common to find patches of bare earth

enclosed by objects. The decision of whether an enclosed patch is bare earth is not always clear-cut.

#### 4.1.1.3 Attached objects

**Building on slopes** - Such objects have roofs that are elevated above the bare earth on some sides and minimally or not at all on other sides. Because of this it becomes difficult to distinguish between such objects and the bare earth.

**Bridges** - Artificial structures spanning the gap (road, river, etc.,) between bare earth surfaces.

**Ramps** - Natural/Artificial structures spanning the gaps between bare earth surfaces; where one is lower than the other.

#### 4.1.1.4 Vegetation

**Vegetation on slopes** - Vegetation points can be filtered based on the premise that they are significantly higher than their neighborhoods. This assumption naturally falls away in steep terrain where terrain points may lie at the same height as vegetation points.

**Low vegetation** - Similar to the problem of low objects, except this time complicated by steep slopes.

#### 4.1.1.5 Discontinuity

**Preservation** (Steep slopes) - Generally objects are filtered because they are discontinuous to the terrain. Occasionally it also happens that the bare earth is piecewise continuous. At discontinuities some filters will operate as they would on objects. Therefore, discontinuities in the Bare Earth are lost.

**Sharp ridges** - The preservation of ridges is a similar but more drastic problem of retaining convex slopes as described by Huising and Pereira (Huising et. al. 1998).

#### 4.1.2 Assessment

The qualitative assessment was based on a visual examination and comparison of the filtered data sets. The Qualitative assessment of filters is summarized in Tables 4.1, 4.2. The main problems faced by the filter algorithms are in the reliable filtering of complex scenes, filtering of buildings on slopes, filtering of disconnected terrain (courtyards), and discontinuity preservation.

Table 4.1 Meaning of Good, Fair and Poor (used in Table 4.2)

Rating	Item filter rating	Influence rating
Good	Item filtered most of the time (> 90%)	No influence
Fair	Item not filtered a few times	Small influence on filtering of neighboring points
Poor	Item not filtered most of the time (< 50%)	Large influence on filtering of neighboring points

Table 4.2 Qualitative analysis

	Elmqvist	Sohn	Roggero	Brovelli	Wack	Axelsson	Sithole	Pfeifer
<b>Outliers</b>								
High points	G	G	G	G	G	G	G	G
High points influence	G	G	G	G	G	G	G	G
Low points	G	F	F	G	G	F	F	G
Low points influence	G	G	G	G	G	P	P	G
<b>Object complexity</b>								
Objects	G	G	G	G	G	G	G	G
Large objects	G	G	G	G	G	G	G	G
Small objects	F	F	F	F	F	F	F	F
Complex objs.	F	F	F	F	F	F	F	F
Low objects	P	P	G	G	G	F	F	F
Disconnected terrain	F	F	F	F	F	F	F	F
<b>Detached objects</b>								
Building on slopes	G	F	F	F	F	G	F	G
Bridges	G/R	G/R	G/R	G/R	G/R	F	G/R	G/R
Ramps	P	P	P	P	P	F	P	P
<b>Vegetation</b>								
Vegetation	G	G	G	G	G	G	G	G
Veg. on slopes	G	G	F	F	F	F	F	G
Low veg.	G	F	F	F	G	F	F	G
<b>Discontinuity</b>								
Preservation	P	P	P	P	F	F	P	F
Sharp ridges	P	P	P	P	F	P	P	P

G, Good; F, Fair; P, Poor; R, Removed

## 4.2 Quantitative assessment

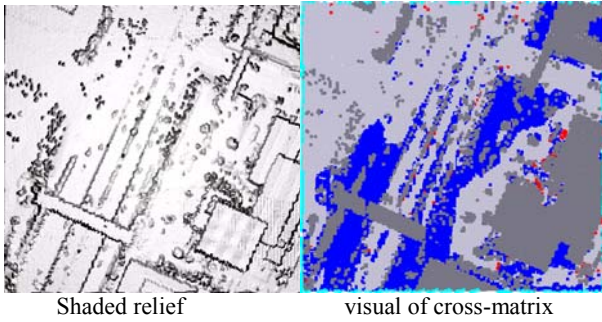
The quantitative assessment was done by generating cross-matrices and generating visual representations of the cross-matrices (figure 4.1). The cross-matrices were then used to evaluate Type I and Type II errors, and visual representation were then used to determine the relationship of Type I and Type II errors to features in the landscape. Furthermore the size of the error between the reference and filtered DEMs was computed and analyzed. The purpose of this was to determine the potential influence of the filtering algorithms on the resulting DEM, based on the predominant features in the data sets. It must be stressed that what is presented here covers the difficulties in filtering as observed in the data and in general all the filters worked quite well for most landscapes.

### 4.2.1 Type I vs Type II

All the filtering algorithms examined make a separation between Object and Bare Earth based on the assumption that certain structures are associated with the former and others with the latter. This assumption while often valid does sometimes fail. This failure is caused by the fact that filters are blind to the context of structures in relation to their neighborhoods. Because of this a trade off is involved between making Type I (reject Bare Earth points) and Type II errors (accept Object points).

Axelsson		Unused		121		
Ref	Filtered		BE	Obj		
	BE	Obj				
BE	21880	602	22482	68.99%		
Obj	588	9515	10103	31.01%		
	22468	10117	32585			
	68.95%	31.05%				
	ratio BE-Obj/ Obj-BE					1.02

Typical numerical results (including cross-matrix)



**Figure 4.1** Sample data for quantitative comparison and assessment

The output from some participant's filters is gridded or altered in position from the original. Because of this, DEMs were generated for the participant's filtered data and the height of the points in the reference data were compared against these DEMs. Using a predefined threshold (20 cm) and based on the height comparison, the points in the reference data were labelled as Correct Bare Earth, Type I error, Type II error or Correct Object. Therefore, the Type I and II errors have to be understood in the context of height comparison of the reference against the filtered DEMs. The computed errors ranged from 0-64%, 0-19%, 2-58% for Type I, Type II and the Total errors respectively. This shows that the tested filtering algorithms focus on minimizing Type II errors. It can be seen even more clearly from the graphical comparison that most filters focus on minimizing Type II errors, except the filters by Axelsson and Sohn. In other words filter parameters are chosen to remove as many object points, even if it is at the expense of removing valid terrain, suggesting that participants consider the cost of Type II errors to be much higher than that of Type I errors.

#### 4.2.2 Steep Slopes

The Axelsson filter generated the least total error (total number of points misclassified) on steep slopes. One explanation for this could lie in the Axelsson filter's (or parameterizations) bias towards Type II errors. In general there are fewer Object points than there are Bare Earth points, and if bias is on making Type II errors then it also means that the Type II misclassifications will be fewer than Type I misclassifications. Nonetheless, filtering in steep terrain still remains a problem especially at reduced resolutions.

#### 4.2.3 Discontinuities

The two slope based filters have the most difficulty with discontinuities in the Bare Earth. This is borne by the large

number of Type I errors. However, when the height difference at discontinuities increases the performance of the slope-based filters remains the same. This is not the case with some of the other filters, where a discontinuity can also influence filtering in the neighborhood of the discontinuity. Another interesting aspect of filtering at discontinuities is where the Type I errors occur. Some filters only cause Type I errors at the Top edge of discontinuities, whereas others cause errors at both the top and bottom edges. The potential for the latter case happening is relatively higher for surface based filters.

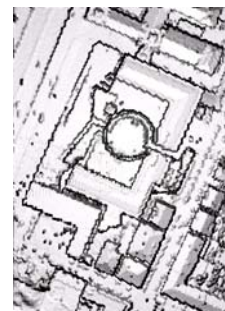
#### 4.2.4 Bridges

As already mentioned, structure based filters are blind. Because of this filters do not make a reasoned distinction between objects that stand clear of the Bare Earth and those that are attached to the Bare Earth (e.g. bridges). From the results it can be seen that the removal of bridges can be complete partial or not at all. All the algorithms for the exception of Axelsson's seem to remove bridges consistently. A possible reason for this could be the method of point seeding used in the algorithm.

Another problem with the filtering of bridges relates to the decision made about where a bridge begins and ends. This problem is detected by Type II errors at the beginning and end of bridges (Bridges in the test were treated as objects). This error though is generally not large. Similar to bridges are ramps. Ramps bear similarity to bridges in that they span gaps in the Bare Earth. However, they differ in that they do not allow movement below them. As such ramps were treated as Bare Earth in the reference data. All algorithms filtered off the ramps.

#### 4.2.5 Complex scenes

Shown in the scene (figure 4.2) is a plaza surrounded on three sides by a block of buildings. From the plaza it is possible to walk onto the road to the east and also descend via stairs to the road below (west). Further, complicating matters there is a sunken arcade in the center of the plaza. Defining what is and what is not Bare Earth in such a scenario is difficult. In this example the plaza and arcade were assumed to be Bare Earth based on the rationale that it is possible to walk without obstruction from the plaza to the roads on the west and east. However, this assumption is very subjective.



**Figure 4.2** Complex scene

#### 4.2.6 Outliers

The number of outliers (both high and low) are relatively small and therefore their contribution to Type I and Type II errors is small. However, their influence on filtering in their neighborhoods can be considerable. The filters by Axelsson and Sithole produce such Type I errors. While single outliers cause problems for a few filters numerous closely spaced outliers will cause problems for many filters. Even more, the influence of numerous outliers in their neighborhoods can be significant depending on the concept base of the filter.

#### 4.2.7 Vegetation on slopes

Most of the filters do well in identifying vegetation on slopes. However, some of this is done at the cost of increased Type I errors in the underlying slope, and in the case of the Elmqvist and Brovelli filters quite significantly.

#### 4.2.8 Low Bare Earth point count

Because filters depend on detecting structures, especially those that detect Bare Earth it is essential that there be enough sample Bare Earth points. Most of the filters do well in identifying Bare Earth points despite the low count of Bare Earth points.

#### 4.3 Effect of resolution

As the resolution of the data is lowered, the bare earth and objects begin to lose definition. Therefore, this comparison aims to determine how filters cope when the resolution of the bare earth and objects breakdown. To test this the filtered data at the different resolutions (for sites 1 and 8) were compared with reference data of corresponding resolution. A cross-matrix was generated for each comparison. The results are shown in the charts in figure 4.3. For some of the participants there was no data at some of the resolutions. Overall Type I and Type II errors increase with decreasing resolution. However, comparing site 1 and 8 it can be seen that there are variations and exceptions. Four possible reasons are offered.

Landscape characteristics – The size of Type I errors for site 1 are much larger than those for site 8. This is due to (i) more complex objects in site 1, (ii) buildings and vegetation on steep slopes in site 1.

Filter concept vs. Neighborhood size – In section 2.4 four different filter concepts were identified. The choice of neighborhood was also touched on in section 2.2. The combination of these factors is thought to be responsible for the variations in Type I errors. For site 1 both slope based filters (Roggero and Sithole) show decreasing Type I errors with decreasing resolution. As resolution is decreased there are fewer points against which a point is tested (fixed neighborhood), hence in steep slopes a drop in Type I errors is to be expected. Naturally Type II errors will also increase. For surface based and minimum-block filters (Pfeifer and Wack) the neighborhood has to be expanded to achieve a minimum

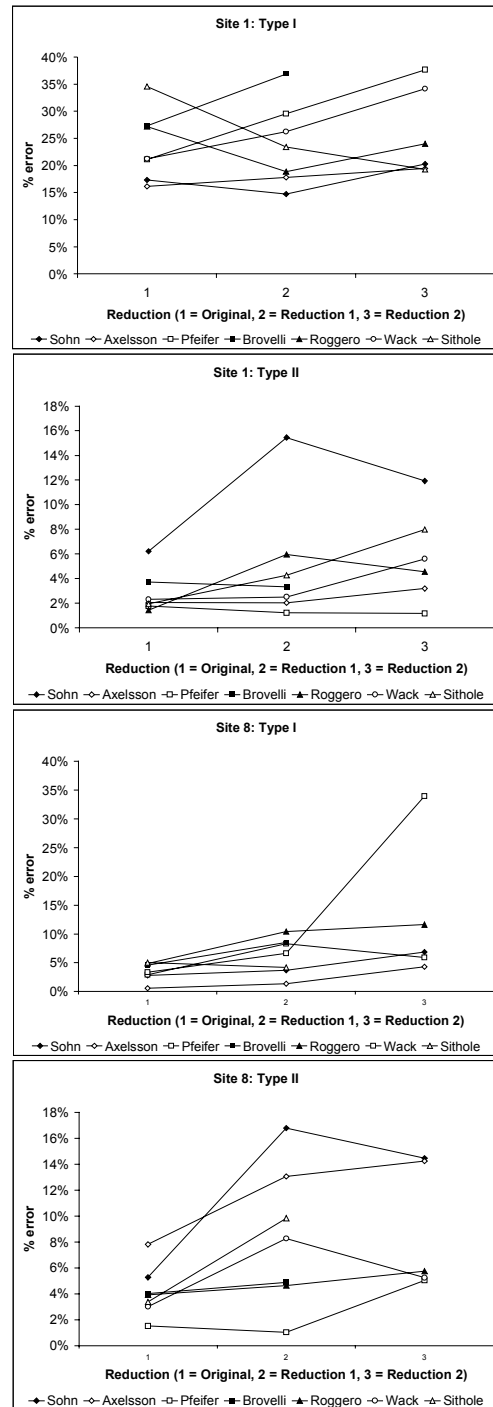


Figure 4.3 Type I and Type II errors vs. resolution. Site

sampling of a surface. Because of this the surface fit becomes more general and an increase in Type I errors can be expected.

Filter parameter optimality – Filter parameters have to be tweaked to obtain optimal results at different resolutions. However, it is not always guaranteed that the most optimal resolution will be obtained at different resolutions. The small decreases in Type I or Type II errors are believed to be due to this.

Edge effects – For filters that work on gridded data, artifacts can become pronounced along edges of the data (or where there are gaps), especially at the lower resolutions. The large increase in Type I error in Site 8 (10m resolution) for the Wack filter is due to this.

## 5 DISCUSSION

The objectives of the study were to, (1) determine the performance of filter algorithms, (2) determine how filtering is affected by point density and (3) establish future research issues. These objectives are treated individually in the sections below.

### 5.1 Performance

What has been presented are some of the striking difficulties in filtering as observed in the data. In general all the filters worked quite well in landscape of low complexity (characterized by gently sloped terrain, small buildings, sparse vegetation, high proportion of bare earth points).

**Main problems** - Problems that pose the greatest challenges appear to be complex cityscapes (multi-tier buildings, courtyards, stairways, plazas, etc.) and discontinuities in the bare earth. It is expected that tailoring algorithms specifically for these areas may improve results, albeit by a small amount.

**Strategy** - Overall surface based strategies appear to yield better results. This noted, it is the opinion of the authors that clustering and segmentation algorithms (or some hybrid based on these concepts) hold more promise.

**Which error should be reduced?** - A decision always has to be made between minimizing Type I and Type II errors. The question of which error to minimize depends on the cost of the error for the application that will use the filtered data. But from a practical point of view it will also depend very much on the time and cost of repairing the errors manually, which is often done during quality control. Experience with manual filtering of the data showed that it is far easier to fix Type II errors than Type I errors. Generally Type II errors are conspicuous. In contrast, Type I errors result in gaps in the landscape, and deciding whether a gap has been caused by a Type I error or from the removal of objects is not easy. There is also a third alternative, and that is to minimize the Total error. But reducing the total error is biased in favor of minimizing Type I errors because very often in a landscape there are relatively more bare earth points than there are object points.

### 5.2 Point density

More tests on decreasing resolution will need to be done, as the test sites chosen have proved inadequate to obtain a conclusive picture of the effects of resolution on filtering. The complexity of the sites has meant that even at the highest resolutions the filters have difficulties, which then masks the performance of the filters at lower resolutions. Nonetheless, in choosing the scan resolution the filter concept used becomes critical, especially in

landscapes with steep slopes. Additionally a large Type I error does not necessarily mean the resulting DEM will be poor. Importantly it depends on where Type I and Type II errors occur in the landscape.

### 5.3 Research Issues

It is recognized that full automation is not possible, nonetheless the difficulties observed in complex urban landscapes and bare earth characterized by discontinuities provide challenges that can potentially be overcome and thus improve the reliability of filtering.

#### **Classification using context knowledge and external information**

- As already indicated filtering of complex scenes is difficult and to obtain significant improvement will require: Firstly, algorithms that reason the classification of points based on the context of their neighborhoods. This opposed to current algorithms that classify solely based on structures (i.e., slopes, surfaces, etc.). This assertion is confirmed by the fact that in the comparisons surface-based filters performed better than point-based filters that examine less neighborhood context. Secondly, the use of additional information such as imagery to support the classification process, because even with more context, reliable results may not be realized because (a) the semantics of objects in a landscape change with the context (urban, rural, industrial, etc.) of the environment, (b) It is not possible to extract sufficient semantic information from the position of the points alone, (c) where there are insufficient or no bare earth points a classification of objects cannot be made, and (d) point-clouds will contain systematic errors (multi-path, etc.) and noise.

**Strategy** - Current filtering strategy only makes two distinctions between features in a landscape, bare earth or object. But from the results it is evident that this distinction is inadequate. A hierarchical approach to filtering will potentially yield more controlled results. In the hierarchical approach, points that are identified as object are further classified to search out objects (bridges, etc.) that have strong associations with the bare earth.

**Quality reporting, Error flagging and Self-diagnosis** - Here checking filtering quality has been possible because some reference data could be generated. The results have shown that filters are not foolproof and performance can vary from one type of environment to another. Therefore, while testing a filter against reference data is a good measure of gaining an appreciation of the filters performance, it is not a guarantee that a filter will always perform as expected. If the type of environment being filtered is untested then unpredictable results can be and should be expected. Therefore, it would be advantageous if filters could be designed to report on the anticipated quality of the filtering and/or flag where the filter may have encountered difficulties. There is also the matter of perception of reliability. This particularly relates to filters that output interpolated data. The existence of data after filtering creates the perception that it is accurate (i.e., it is the bare earth). However, the tests have shown that with interpolated data it is

arguable about what accurate is, since it depends very much on the threshold used in the comparison.

**Effort vs. Result** - At a certain point depending on the concept or implementation used better results will not be obtained by filtering based on positional information alone. Ascertaining when that limit has been reached is difficult, but it is important to be aware that it exists, especially when large volumes of data are processed. If the limit of each algorithm were known then a multi-algorithm approach could be used to increase the efficiency of filtering. In this way the most efficient filter (in terms of computing effort and algorithm complexity) could be used for specific regions in a data set. There is also the aspect of parameter selection. For any landscape filter, parameters are chosen with the most difficult situations in mind. For some filters, choosing parameters in such situations translates into more processing time. For such filters it would be more efficient to automatically gauge the landscape characteristics in an area and use the most optimal filter parameters.

## 6 CONCLUSION

The results from eight algorithms were compared against reference data sets. For typically non-complex landscapes most of the algorithms did well. However, for complex landscapes performance varied and surface based filters tended to do better.

The effect of lowered resolutions on the performance of filters was also tested. Comparison of the results at lower resolutions confirms that amongst other factors the method of filtering also has an impact on the success of filtering and hence on the choice of scanning resolution. However, more tests are required to form a clear impression of which filter characteristics have a significant impact on filtering at lower resolutions.

The filtering of complex urban landscapes still poses the greatest challenges. As has been suggested elsewhere, filtering using segmentation, and understanding of the context of the landscape being filtered and data fusion might be one ways in which this challenge could be overcome.

The full report of the test can be found at the following URL: <http://www.geo.tudelft.nl/frs/isprs/filtertest/>

## 7 ACKNOWLEDGEMENTS

This study would not have been possible without the help and co-operation of participants who took time from their schedules to filter the twelve data sets. The authors wish to extend their gratitude to P. Axelsson, C. Briese, M. Brovelli, M. Elmqvist, N. Pfeifer, M. Roggero, G. Sohn, R. Wack and A. Wimmer.

## REFERENCES

Axelsson P., 1999: "Processing of laser scanner data - algorithms and applications". ISPRS Journal of Photogrammetry & Remote Sensing, 54 (1999). pp. 138 -147.

Axelsson P., 2000: "DEM Generation from Laser Scanner Data

Using Adaptive TIN Models. In IAPRS. Vol. 33. part B4/1, pp. 110-117.

Briese C., Pfeifer N., 2001: "Airborne laser scanning and derivation of digital terrain models". Proceedings of the 5<sup>th</sup> conference on optical 3D measurement techniques, Vienna, Austria.

Brovelli M.A., Cannata M. and Longoni U.M., 2002: "Managing and processing LIDAR data within GRASS". Proceedings of the GRASS Users Conference 2002, Trento, 11-13 September 2002 (in print on Transaction in GIS).

Elmqvist M., 2001: "Ground Estimation of Laser Radar Data using Active Shape Models". Paper presented at the OEEPE workshop on airborne laserscanning and interferometric SAR for detailed digital elevation models 1-3 March 2001, paper 5 (8 pages). Royal Institute of Technology Department of Geodesy and Photogrammetry 100 Stockholm, Sweden.

Flood M., 2001: "LIDAR activities and research priorities in the commercial sector". IAPRS. WG IV/3., Vol XXXIV. Annapolis, MD, 22-24 Oct 2001. pp.678-684.

Haugerud R.A., Harding D.J., 2001: "Some algorithms for virtual deforestation (VDF) of LIDAR topographic survey data". IAPRS, Vol. XXXIV -3/W4 Annapolis, MD, 22-24 October 2001. pp. 211-218.

Huising E.J., Gomes Pereira L. M., 1998: "Errors and accuracy estimates of laser altimetry data acquired by various laser scanning systems for topographic applications". ISPRS JPRS, Vol. 53, no. 5. pp.245-261.

OEEPE: 2000 Working Group on laser data acquisition. ISPRS Congress 2000. [http://www.geomatics.kth.se/~fotogram/OEEPE/ISPRS\\_Amsterdam\\_OEEPE\\_presentation.pdf](http://www.geomatics.kth.se/~fotogram/OEEPE/ISPRS_Amsterdam_OEEPE_presentation.pdf)

Pfeifer N.; Kostli A., Kraus K., 1998: "Interpolation and filtering of laser scanner data - implementation and first results." International archives of photogrammetry and remote sensing, Vol XXXII, Columbus, part 3/1 Columbus, pp.153 - 159.

Roggero M., 2001: "Airborne Laser Scanning: Clustering in raw data". IAPRS, Vol XXXIV -3/W4 Annapolis, MD, 22-24 Oct, 2001. pp. 227-232.

Sithole G., 2001: "Filtering of laser altimetry data using a slope adaptive filter". IAPRS, Vol. XXXIV -3/W4 Annapolis, MD, 22-24 October 2001. pp. 203-210.

Sohn G., Dowman I., 2002: "Terrain Surface Reconstruction by the Use Of Tetrahedron Model With the MDL Criterion". IAPRS, Vol XXXIV Part 3A. ISPRS Commission III, Symposium. September 9 - 13, 2002, Graz, Austria. pp. 336-344.

Tao C. V., Hu Y., 2001: "A review of post-processing algorithms for airborne LIDAR Data". Proceedings ASPRS conference April 23-27, 2001. St. Louis Missouri. CD-ROM, 14 pages.

Vosselman G., 2000: "Slope based filtering of laser altimetry data". IAPRS, Vol XXXIII, Part B3, Amsterdam, The Netherlands. pp. 935-942.

Wack R., Wimmer A., 2002: "Digital Terrain Models From Airborne Laser Scanner Data - A Grid Based Approach". IAPRS, Vol XXXIV Part 3B. ISPRS Commission III, Symposium. September 9 - 13, 2002, Graz, Austria. pp. 293-296.