Advanced LiDAR

http://publish.mersin.edu.tr/index.php/lidar/index

e-ISSN 2791-8572

ADVANCED LIDAR

Enhancing Ground Point Extraction in Airborne LiDAR Point Cloud Data Using the CSF Filter Algorithm

Berkan Sarıtaş[1], Gordana Kaplan[*2]

[1]Eskisehir Technical University, Graduate School of Science, 26555, Eskisehir, Türkiye; (berkansrts@gmail.com)
[2]Eskisehir Technical University, Institute of Earth and Space Sciences Institute, 26555, Eskisehir, Türkiye; (kaplangorde@gmail.com)

Keywords

Remote Sensing,
CSF Filter,
Point Cloud,
SAM,
LIDAR.

Research Article

Received : 03.07.2023
Revised : 22.08.2023
Accepted : 14.09.2023
Published : 30.09.2023

* **Corresponding Author**
kaplangorde@gmail.com

Abstract

Airborne laser scanning (ALS) is a remote sensing method widely recognized for its efficiency in acquiring data quickly and delivering accurate results. To ensure the reliability of ALS data, effective decontamination is crucial. This study aims to enhance the data quality of three distinct LIDAR datasets representing urban, rural, and forest environments by applying the CSF Filter algorithm in the CloudCompare software, an open-source tool widely used in point cloud processing. The impact of various data characteristics and input parameters on the filtering results was assessed through a series of comprehensive tests. The results of our analysis revealed a notable relationship between the selected parameters and the quality of the filtered data. Specifically, when the cover value within the CSF Filter parameters was increased, a corresponding increase in data loss was observed, leading to significantly flawed outcomes. These findings emphasize the importance of carefully selecting and fine-tuning the input parameters to avoid undesirable consequences. The findings underscore the importance of combining automated filtering algorithms with manual cleaning to achieve high-quality and reliable point cloud data for various geospatial analyses and applications.

1. INTRODUCTION

LIDAR is a remote sensing technology, which stands for Light Detection And Ranging (Erişir, 2015). The measurements carried out using LIDAR technology enable the collection of raw data on non-man-made objects and objects that are man-made, that is, all the properties found on the earth's surface (Kostrikov, 2019). 3D digital terrain model (DTM) is a very important resource for determining the details of the earth's surface and preparing projects. The outstanding feature of LIDAR technology as the biggest advantage is revealed when compared with traditional methods of creating numerical models of the earth's surface. These advantages in question are the values of labor, time and accuracy (Karasaka & Keleş, 2020). LIDAR data as point cloud is named. This is due to the fact that the targets have changed and the aircraft being scanned it is due to the irregularity of the scan data as a result of their movements (Lu et al., 2011).

When we look at the areas of use of LIDAR technology, there are two different types of LIDAR: Terrestrial LIDAR and Aerial LIDAR (Çelik et al., 2014).

When LIDAR systems are examined, low cost as well as high point density allows obtaining high and high accuracy reference numerical altitude data, less land studies compared to classical ground measurements and numerical aerial photogrammetry can be shown as advantages of the system (Çelik et al., 2014; Ekercin & Üstün, 2004).

Cite this;

Sarıtaş, B. & Kaplan, G. (2023). Enhancing Ground Point Extraction in Airborne LiDAR Point Cloud Data Using the CSF Filter Algorithm. Advanced LiDAR, 3(2), 53-61.

When the spectral characteristics of the lasers in LIDAR systems are examined, they are located in very wide spectra such as 50-30000 nm from visible and near infrared. The lasers involved in LIDAR systems are limited to the near infrared spectral region. The reason fort his is to reach the data day and night, in the shade or among the clouds (Çelik et al., 2014; Wehr & Lohr, 1999).

Terrestrial Laser Scanning: Terrestrial Laser Scanning (TLS) technology enables the execution of 3D coordinates precisely and automatically (Cömert et al., 2012; Yuriy Reshetyuk, 2009). When examined, it is applied in areas such as registration operations of cultural heritage and engineering projects (Cömert et al., 2012; Lichti & Gordon, 2004).

Aerial Laser Scanning: Modern remote sensing technologies have revolutionized the way we monitor and map large-scale regions, gradually replacing traditional measurement methods. Aerial laser scanning, a prominent laser scanning technology, has emerged as one of the most effective remote sensing methods (Uray 2022). This technique involves transmitting lasers from scanning devices mounted on aircraft or helicopters, which reflect off objects. The distance between the scanning device and the scanned object is then calculated based on the pulse's return time. Aerial LIDAR systems typically comprise three components: GPS, IMU, and a scanner. The scanner records the reflection values, GPS captures location information of the point cloud, and the IMU-derived orientation parameters of the aircraft assist in calibrating the point cloud (Civelekoğlu, 2015).

Remote sensing methods, such as LIDAR, facilitate the creation of numerical elevation models that encompass comprehensive elevation information of the Earth's surface. Models containing three-dimensional information about various structures on the Earth's surface are known as numerical elevation models, while those representing only the bare land surface are referred to as numerical terrain models (Uray, 2022).

LIDAR technology enables the collection of raw data on both natural and man-made objects present on the Earth's surface (Kostrikov, 2019). It allows for rapid and precise acquisition of physical data in a non-contact manner, facilitating the creation of accurate 3D models (Fidan & Fidan, 2021).

The formats of the point cloud data obtained using aerial LIDAR technology may vary, as well as the format often obtained ".las" is an extension structure. When looking at the formats used other than this format, ASCII, .point cloud data can also be obtained in the form of xyz text, fast binary, scan binary and grass sites formats and data processing studies can be performed (Civelekoğlu, 2015; Habib & Rens, 2017).

Point clouds, which are obtained using airborne laser scanning technology, allow us to obtain more information about the terrain than many other sources of data acquisition. Recently, LIDAR point clouds created as a result of obtaining data by airborne (airplane, helicopter) laser scanning are the main data source in order to produce a high-resolution digital surface model (DSM) or digital terrain model (DTM) (Podobnikar & Vrečko, 2012).

This study aims to investigate the performance of different filtering algorithms, specifically focusing on the CSF filter algorithm, in determining ground points for classification in point clouds obtained using LIDAR technology. The research examines various point clouds with distinct properties and compares the accuracy rates of different classification and filtering algorithms. The objective is to determine which algorithm delivers more successful filtering results for specific feature-bearing point clouds.

Previous studies in the literature have employed the CSF filtering algorithm for filtering ground points, such as the study titled "Performance Analysis of the CSF Algorithm for Filtering Ground Points." This research focused on an area characterized by challenging terrain with steep slopes and dense forest cover. Orthophotos obtained simultaneously with the LIDAR data served as reference data for the study. Point cloud data were processed using the CloudCompare software, with specific parameter values selected for filtering operations. The study employed a classification threshold value of 0.5, a repetition time of 1000, and varied grid resolutions of 0.2, 0.3, 0.4, 0.5, 1, and 2. The results demonstrated distortions in the surface model with increasing grid resolution values, resulting in a reduced number of ground-class points. Consequently, manual filtering was deemed necessary to eliminate non-ground points.

By conducting an in-depth analysis of different filtering algorithms, this study contributes to the field of current research topics in LIDAR technology. The findings offer insights into the most effective filtering algorithms for specific types of feature-bearing point clouds, facilitating accurate data analysis and interpretation for various applications (Karasaka & Keleş, 2020).

Looking at another study in the literature, "Assessment of the performance of eight filtering algorithms by using full-waveform LiDAR data of unmanaged eucalypt forest" provides filtering of ground points obtained using the Axelsson filtering algorithm contained in the Terrascan commercial software and seven different filtering algorithms contained in the open-source Aldpat software. The mean value, standard deviation and Roor Mean Squared Error (RMSE) metric values were used to evaluate the weaknesses and strengths of the filtering algorithms. This research focuses on circular plots consisting of brushwood and unmanageable acalyptus forests with different characteristics, where the tree frequency falls by 1600 trees per hectare. In order to evaluate the SAM data generated as a result of the study, a reference SAM surface is created with the help of GNSS receivers. As a result, it is seen that the Axelsson filtering algorithm and the Polynomial Two-Surface Fitting filtering algorithm obtain the highest quality value in terms of RMSE value (Gonçalves & Pereira, 2010).

2. Method

2.1. Point Cloud

In order to be scanned with LIDAR systems, the surface of the objects of the handled area is obtained in 3D. The scanning process is performed systematically, quickly and automatically, and x, y, z coordinate information for many points can be accessed per second. The set of points obtained by scanning is usually collected as a point cloud during scanning (Gümüş & Erkaya, 2007).

In addition to providing metric and visual or thematic information about an object, a point cloud is the sum of the x, y, z coordinates in the general reference system of objects. If these properties are to be examined, the spatial relationship of the objects between each other and the geometry of the objects, the properties used to Decipher the qualities of the object surface, where metric properties, density or RGB values are found, are called visual or thematic properties (Fröhlich et al., 2000).

2.2. Point Cloud Filtering

The raw LIDAR point cloud contains reflections of all man-made or non-man-made points on the earth's surface (Doğruluk et al., 2018). In order to create a SAM with LIDAR, the points belonging to the ground class must be cleared of objects that do not belong to the ground class, such as trees and buildings. This process in question is called filtering (Soycan et al., 2011b). In order to obtain a high quality surface, it is very important to filter the point cloud in a precise and effective way (Liu, 2008).

When the physical properties of the ground points are taken into consideration, they are grouped in four different ways (Süleymanoğlu & Soycan, 2017; Meng et al., 2010):

- **The lowest height:** Ground points at additional high height in available LIDAR data are the points.
- **The steepness of the floor surface:** When looking at the Declivity between the ground and points that do not belong to the ground, it is steeper than the Declivity between neighboring ground points.
- **The height difference between the decking points:** The high elevation differences of the points between each other indicate the points belonging to objects such as buildings and trees, while the low elevation differences indicate that it is the declivity point.
- **Homogeneity of the floor surface:** The points belonging to the ground are partly smoother and more continuous than the points belonging to other objects.

In the process of creating numerical models consisting of irregular point clouds, processing LIDAR data is an important process. An important stage in the process in question is the filtering of raw LIDAR data. There are many free, open source and many commercial software available for determining the points belonging to the ground class using the filtering algorithms of the LIDAR point cloud. When looking at the literature, it is seen that the strengths and weaknesses of each filtering algorithm stand out for different land surfaces (Karasaka & Keleş, 2020).

Many of the filtering methods use geometric relationships between neighboring points to determine whether the points are on the decking or not. Information such as the pulse width from the exact waveform of the obtained signal, which gives more effective results in areas covered with low vegetation, can improve the desired result (Vosselman & Maas, 2010). The properties of an object that creates a normalized digital surface model (nDSM) and the land surface greatly improve the quality of filtering. There are cases when almost all filtering methods eliminate points that are outside the ground class with difficulty or protect them properly so that DSMs can be created. Examples of these situations are larger buildings, dense vegetation, ramps, bridges, steep slopes, hydrological bodies and different geomorphological edges, i.e. cliffs and riverbanks (Podobnikar & Vrečko, 2012).

A lot of algorithms have been developed for filtering 3D point cloud data. Filtering algorithms are divided into 4 separate groups as Morphological Filtering Algorithms, Gradual Tightening Algorithms, Surface-based Filtering Algorithms and Segmentation-based Filtering Algorithms (Süleymanoğlu, 2016; Briese, 2010).

2.2.1. Morphological filtering algorithms

The filtering algorithms in this group are based on mathematical morphology and are interested in the shapes or shape measurements of objects (Haralick & Shapiro, 1992; Uray, 2016). Various experiments conducted on LIDAR data using morphological filters show that these filters have the ability to distinguish objects outside the ground (Kobler et al., 2007; Uray, 2016). The morphological operators used in the digital image processing are the basic alarm operation, and the operators in question are erosion, expansion, opening and closing. Of these four operators, the wear and expansion operators form the basis of mathematical morphology (Süleymanoğlu, 2016; Haralick & Shapiro, 1992).

2.2.2. Stepwise classification filtering algorithms

It classifies the point cloud data in an iterative manner by starting the filtering process using a small number of point cloud data (Süleymanoğlu, 2016; Briese, 2010). These are algorithms developed based on the principle of smoothness of the floor surface. The points where sudden changes and deviations occur in the point cloud data are considered to be non-ground points. A surface is created using the TIN method from the point cloud data to detect areas where local deviations and sudden changes occur, and thus changes in the surface geometry can be observed accurately (Süleymanoğlu, 2016; Haugerud & Harding, 2001; Meng et al., 2010).

2.2.3. Surface-based filtering algorithms

It uses DSMs created by using the entire dataset for the purpose of filtering point cloud data. In this aspect, it is similar to gradual classification algorithms, but unlike the gradual classification algorithms of surface-based filtering algorithms, instead of adding point data to the ground class step by step, surface-based filtering algorithms initially accept all points as ground points and create temporary DSM using these points. In the next step, the contribution of all points to this surface is reduced, deleted or increased (Süleymanoğlu, 2016; Briese, 2010).

2.2.4. Segmentation and clustering based filtering algorithms

It is based on the approach of classifying point groups by filtering in a collective format instead of classifying points by filtering them one by one (Süleymanoğlu, 2016; Briese, 2010). Points with similarity are included in the same cluster. The classification of the clusters is based on topological relations (Süleymanoğlu & Soycan, 2017; Sithole & Vosselman, 2005).

2.3. Digital Surface Model (DSM)

The numerical surface model can be specified as a model expressed in the 3D coordinate system of XYZ values. DSM is a model formed as a result of showing all man-made and man-made objects that are located on the earth in order to digitally express the earth's descriptive surface. As indicated by the SYMS as a numerical image containing a height value in each pixel, the XYZ values, which are independent of each other and randomly distributed, can also be expressed as a set of triangles that do not intersect each other at known points. With these models, surface areas, volume calculations, slopes and isohips can be used to create (Uray, 2016).

2.4. Digital Terrain Model (DTM)

The term numerical terrain model is defined by the Massacusetts Institute of Technology as a simplified statistical representation of a continuous surface with many points with known XYZ coordinates .(Maliqi et al., 2017; Pedersen, 2022). Models that are used in the same sense as DSM, but are not in vegetation together with all objects that are man-made, are called numerical terrain models. DTM consists of points with high values that better show the true shape of the earth. The material curves obtained using DTM, produced with DSM, show the true shape of the earth in a superior way. DTM is the synonym of DSM for the simple land surface (Maune, 2011; Uray, 2016).

If we look at the areas of use of DTM; There are many areas such as urban planning, forest management, topographic map, transportation, flood hazard and risk maps (Hill et al., 2000; Uray, 2016).

It is possible to produce a numerical terrain model with different interpolation algorithms. The purpose of use and production of the numerical terrain model determines which interpolation algorithm should be used when creating a numerical terrain model. Numerical terrain models produced for geodetic and engineering purposes are commonly represented by a regular grid of points that reproduce the surface heights (GRID), an irregular grid (TIN) and vector lines of the numerical terrain model (Maliqi et al., 2017; Pedersen, 2022). One of them is the slope relief caused by a mathematical operation in the Numerical terrain model raster (Pedersen, 2022; Vosselman & Maas, 2010).

Grid: It is a raster representation of the numerical terrain model on a normal grid. The land surface is represented as a set of elevation values that are related to uniformly distributed X and Y coordinates (Maliqi et al., 2017; Pedersen, 2022)

TIN: It is a numerical terrain model adapted bby multi-GIS software and automatic mapping software (Bjørke, 2010; Pedersen, 2022). TIN models consist of points connected by lines forming triangles, and all triangles form continuous surfaces within them. The surfaces formed are defined by the heights of the three corner points of the triangles (Maliqi et al., 2017; Pedersen, 2022).

Slope relief: It is a visualization method of the height model. These show local elevation changes more clearly than an elevation grid (Pedersen, 2022; Vosselman & Maas, 2010).

2.5. Application

In this study, we investigate the effectiveness of the CSF Filter algorithm, implemented in the CloudCompare software, for filtering LIDAR point cloud data with urban, rural, and forest characteristics. By varying the input parameter values, we aim to determine which parameter values yield more accurate ground point classification. The study involves the creation of Surface Models (SAM) for each parameter value applied in the filtering algorithm, followed by an accuracy analysis of the resulting SAMs.

During the acquisition of LIDAR point clouds, atmospheric conditions like fog or rain can lead to the formation of noise points. Manual cleaning methods using the CloudCompare software are employed to remove these noise points. Subsequently, the CSF Filter algorithm, available in CloudCompare, is utilized for ground point classification. The cover value parameter is assessed using different combinations to determine its impact on the filtering results.

Through this research, we aim to identify the most effective parameter values for accurate ground point classification in LIDAR point cloud data. The findings will contribute to enhancing the data quality and reliability of LIDAR-based applications in urban, rural, and forest environments. Additionally, the study highlights the importance of pre-processing steps, such as manual noise removal, and provides insights into the optimization of the CSF Filter algorithm for improved point cloud filtering.

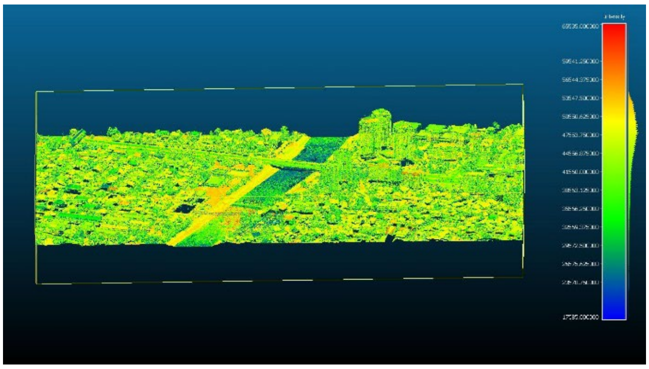

Figure 1. Display of urban area LIDAR data in CloudCompare software

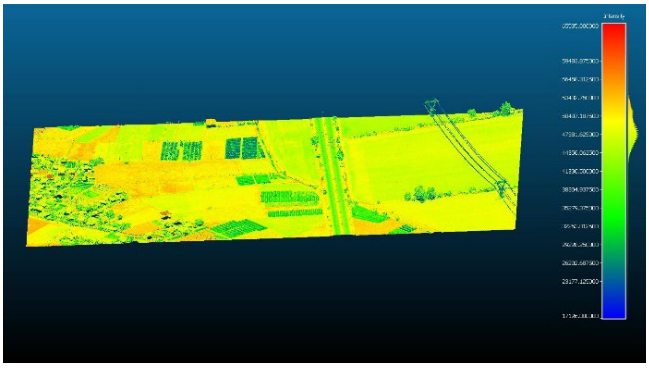

Figure 2. Displaying rural area LIDAR data in CloudCompare software

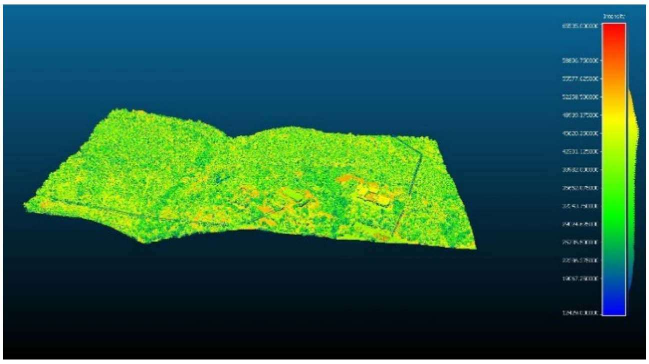

Figure 3. Displaying forest area LIDAR data in CloudCompare software

2.5.1. Filtering of LIDAR data – urban area

The urban area (300 ha) is comprised of an urban area with a total of 312 buildings in the west part of the city of Skopje, the capital of North Macedonia (Figure 1). The study area is divided into two parts, with the Vardar river with a width of approximately 60 m. The left part of the study area contains dense and low residential grid-like buildings with a maximum of 10 m height, while on the right side, there are higher residential and commercial buildings with a maximum height of 70 m. The urban area is generally flat, and the surface elevation of the study area varies from 250–327, while the terrain elevation is from 250–325. Besides buildings, the study area contains many trees, three bridges, and a riverbank of 20 m in width from both sides (Kaplan et al. 2022).

The study area is located in a high-risk seismic zone with a history of destructive earthquakes. Thus, a shallow, magnitude 6.1 earthquake with an intensity rating of IX (Mercalli scale) hit the city in 1963, when the disaster caused significant loss of life and property. More than 1,000 people have been killed, 4,000 injured and more than 200,000 displaced (Kaplan et al., 2022).

Almost %80 of the city was destroyed, and many public buildings, schools, hospitals and historical sites were seriously damaged. More recently, in 2016, a powerful, magnitude ML5.3 earthquake struck the capital (Kaplan et al., 2022; Sinadinovski et al., 2022).

The LIDAR data were obtained from the Cadastre Department of North Macedonia. Data collection was carried out with an aerial platform, Cessna 402B and Riegl VQ-780i sensor system. The data collection was carried out on May 3, 2019 under a clear sky and an air temperature of 11 ° C. The soil sampling distance of LIDAR data is 5 points / m2 (Kaplan et al., 2022).

Figure 5. The study area in city of Skopje, used for the analyses (Adjiski et al., 2023)

Table 1. Number of LIDAR point cloud points in the urban area

Cloth Resolution	Number of LIDAR Points
Original Data	4,537,424
0.1	2,878,720
0.5	2,373,512
1	2,174,743
2	1,896,947
5	1,557,410

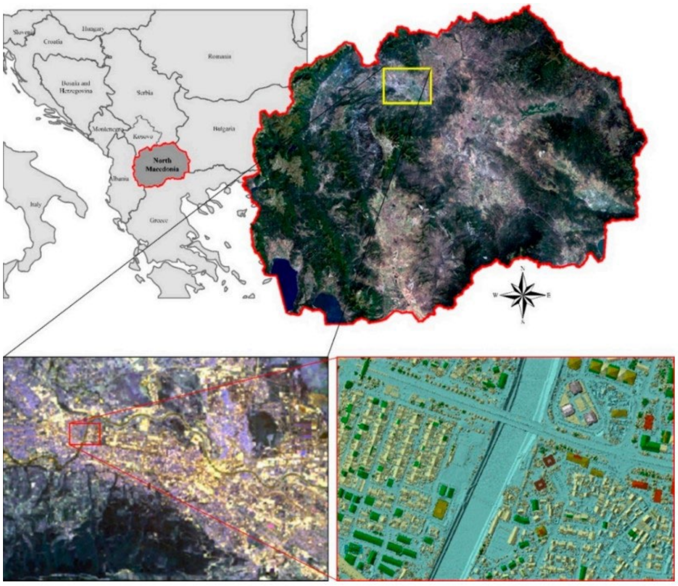

Figure 4. The urban area (Kaplan et al., 2022)

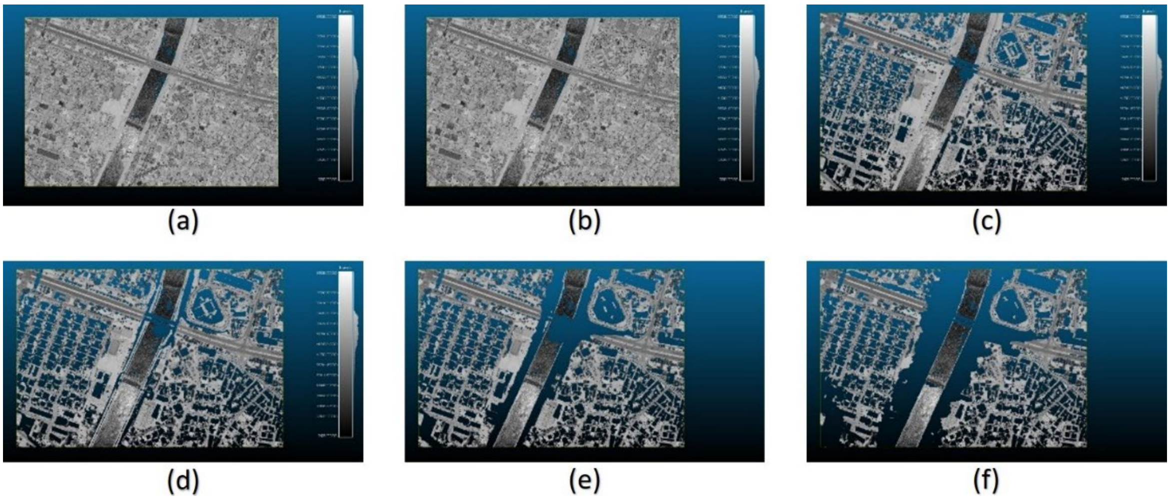

Figure 6. For an urban LIDAR point cloud; (a) The Original Point Cloud, (b) Data Obtained As a Result of Entering the CSF Filter Algorithm Cover Value as 0.1, (c) Data Obtained as a Result of Entering the CSF Filter Algorithm Cover Value as 0.5, (d) Data Obtained As a Result of Entering the CSF Filter Algorithm Cover Value as 1, (e) Data Obtained as a Result of Entering the CSF Filter Algorithm Cover Value as 2, (f) Data Obtained as a Result of Entering the CSF Filter Algorithm Cover Value as 5.

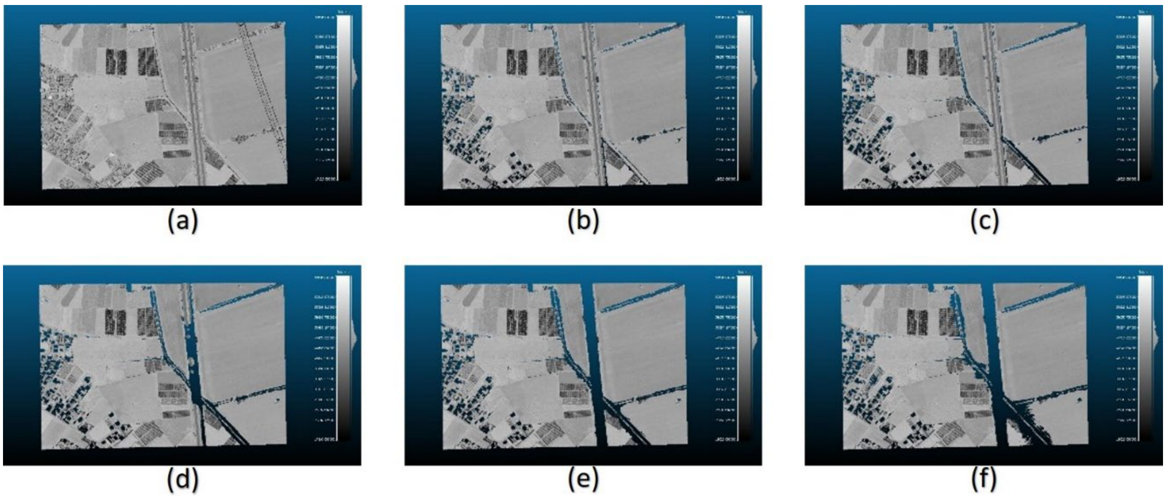

Figure 7. For rural LIDAR point cloud; (a)The Original Point Cloud, (b)The Data Obtained As a Result of Entering the CSF Filter Algorithm Cover Value as 0.1, (c) The Data Obtained as a Result of Entering the CSF Filter Algorithm Cover Value as 0.5, (d) The Data Obtained as a Result of Entering the CSF Filter Algorithm Cover Value as 1, (e) The Data Obtained as a Result of Entering the CSF Filter Algorithm Cover Value as 2, (f)The Data Obtained as a Result of Entering the CSF Filter Algorithm Cover Value as 5.

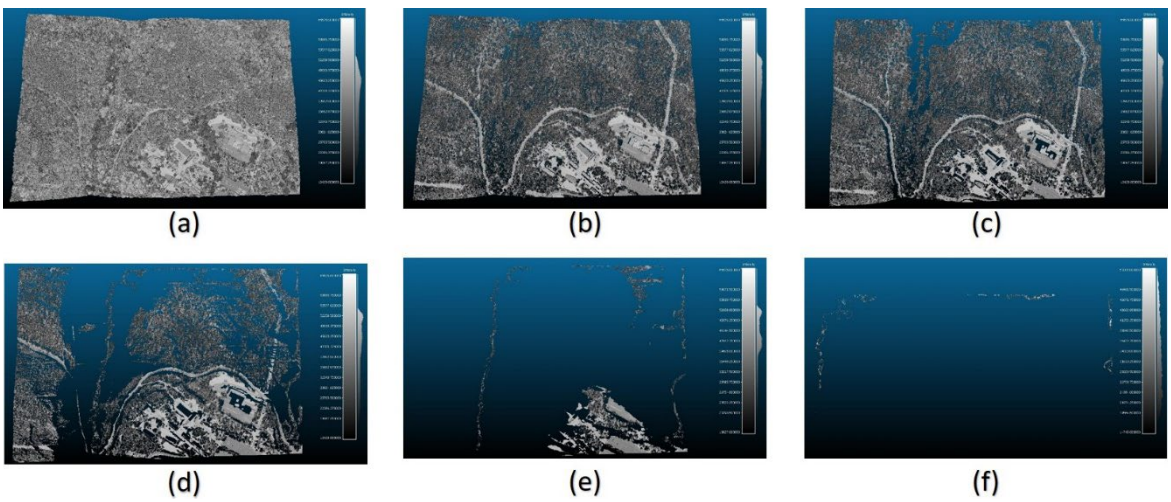

Figure 8. For Forest LIDAR point cloud; (a)The Original Point Cloud, (b)The Data Obtained As a Result of Entering the CSF Filter Algorithm Cover Value as 0.1, (c) The Data Obtained as a Result of Entering the CSF Filter Algorithm Cover Value as 0.5, (d) The Data Obtained as a Result of Entering the CSF Filter Algorithm Cover Value as 1, (e) The Data Obtained as a Result of Entering the CSF Filter Algorithm Cover Value as 2, (f) The Data Obtained as a Result of Entering the CSF Filter Algorithm Cover Value as 5.

2.5.2. Filtering of LIDAR data – rural area

The agricultural study area is flat and consists of corp fields, divided with a road. The main part of the crops are empty, while smaller part of the area consist of green crop lands.

Table 2. Number of LIDAR points cloud points in the rural area

Cloth Resolution	Number of LIDAR Points
Original Data	4,277,552
0.1	3,874,365
0.5	3,823,732
1	3,688,195
2	3,555,055
5	3,453,315

2.5.3. Filtering of LIDAR data – forest area

The forest area is characterized by its abundant growth of dense and towering trees, which create a captivating and enchanting environment. The natural landscape is further enhanced by the presence of rugged mountains.

The terrain within the forest area is undulating, with varying altitudes and steep slopes that add a sense of adventure and challenge to exploring the region.

Table 3. Number of LIDAR points cloud points in the forest ares

Cloth Resolution	Number of LIDAR Points
Original Data	13,952,936
0.1	3,350,703
0.5	2,859,832
1	1,782,871
2	306,483
5	8,293

3. Results

When examining the ground points classified by the CSF Filter algorithm, it becomes evident that there is a loss of data in the ground points as the cover value increases, leading to noticeably incorrect classifications. While it was initially assumed that the decrease in the cover value would accurately determine the actual ground points, it is observed that planar areas such as building roofs are mistakenly classified as ground points.

In assessing the urban, rural, and forest characteristics of the data, it becomes apparent that the most successful results are achieved in rural areas. However, this assessment has been primarily based on visual analysis. In future studies, it is crucial to perform a statistical accuracy assessment to obtain more reliable and objective results. By conducting such an assessment, the outcomes can be quantitatively compared and analyzed to validate the algorithm's performance across different landscapes.

This statistical accuracy assessment would involve rigorous data analysis and comparison of ground truth data with the algorithm's classifications. Furthermore, the assessment should consider factors like the complexity of urban and forest environments, as they pose additional challenges for accurate ground point classification.

By conducting a thorough statistical accuracy assessment, it will be possible to gain a deeper understanding of the algorithm's limitations and strengths across various landscape types. This assessment will provide more robust evidence to evaluate the algorithm's effectiveness and guide future improvements and optimizations.

In conclusion, while the CSF Filter algorithm exhibits data loss and incorrect classifications in ground points with increasing cover values, a more comprehensive and statistically rigorous accuracy assessment is required to assess its performance accurately. By conducting such an assessment and comparing the results across different urban, rural, and forest landscapes, a clearer understanding of the algorithm's performance can be obtained, leading to further improvements and advancements in the future.

4. Discussion

In the process of removing ground points, which is being performed using the CSF Filter algorithm, manual cleaning operation is required in the remaining parts due to the fact that planar areas are considered as ground. In this way, the process of obtaining ground points will reach a more accurate result.

5. Conclusion

In order for the accuracy analysis to be performed with more precise results, reference SAM data are needed. As a result of comparing the obtained data with the reference data, the accuracy rates of the parameters will be determined more accurately.

Acknowledgement

This study is adapted from Berkan Saritas's master's thesis.

Author contributions

Conceptualization and design: Berkan Sarıtaş, Gordana Kaplan
Data collection: Gordana Kaplan
Analysis of data and interpretation of results: Berkan Sarıtaş
Writing the first draft of the manuscript: Berkan Sarıtaş, Gordana Kaplan
Review and editing: Gordana Kaplan

Conflicts of interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

Research and publication ethics were complied with in the study.

References

Adjiski, V., Kaplan, G. & Mijalkovski, S. (2023). Assessment of the solar energy potential of rooftops using LIDAR datasets and GIS based approach. *International Journal of Engineering and Geosciences*, 8(2), 188-199.

Bjørke, J. T. (2010). Digitale terrengmodeller universitetet for miljø og biovitenskap.

Briese, C. (2010). Extraction of digital terrain models. *Airborne and Terrestrial Laser Scanning*, 135-167. https://repositum.tuwien.at/handle/20.500.12708/26779

Çelik, H., Baş, N. & Coşkun, H. G. (2014). Taşkın modelleme ve risk anaizinde LİDAR verisiyle sayısal yükseklik modeli üretimi. *Gümüşhane Üniversitesi Fen Bilimleri Enstirüsü Dergisi*, 4(1), 117. https://doi.org/10.17714/GUFBED.2014.04.009

Civelekoğlu, B. (2015). Hava LİDAR verilerinin sınıflandırılması ve orman ağaçlarına ait öznitelik değerlendirilmesi İstanbul Belgrad Orman Örneği. Master's Thesis, Yildiz Techinical University, Istanbul (in Turkish).

Cömert, R., Avdan, U., Tün, M. & Ersoy, M. (2012). Mimari belgelemede yersel lazer tarama yönteminin uuygulanması (Seyitgazi Askerlik Şubesi Örneği). *Harita Teknolojileri Elektronik Dergisi*, 4(1), 1-18.

Doğruluk, M., Coşkun Aydin, C. & Yanalak, M. (2018). Kırsal alanlarda SYM üretiminde filtreleme yöntemlerinin performans analizi: Hava LİDAR uygulaması; İstanbul Örneği. *Geomatik Dergisi*, 3(3), 242-253. https://doi.org/10.29128/geomatik.414412

Ekercin, S. & Üstün, B. (2004). Uzaktan algılamada yeni bir teknoloji: LİDAR. *HKM Jeodezi Jeoinformasyon Arazi Yönetimi Dergisi*, 0(91), 34-38. https://search/yayin/detay/59216

Erişir, Z. (2015). Nokta tabanlı sınıflandırma yöntemleri ile LİDAR verilerinin sınıflandırılması. Master's Thesis, Yildiz Techinical University, Istanbul (in Turkish).

Fidan, D. & Fidan, Ş. (2021). Yersel lazer tarama teknolojileriyle oluşturulan 3B modellerin akıllı kent uygulamalarında kullanımı: Mersin Süslü Çeşme Örneği. *Türkiye LİDAR Dergisi*, 3(2), 48-57. https://doi.orrg/10.51946/melid.1021819

Fröhlich, C., Mettenleiiter, M., Härtl, F., Dalton, G. & Hines, D. (2000). Imaging laser radar for 3D modelling of real World environments. *Sensor review*, 20(4), 273-282. https://doi.org/10.1108/02602280010351019

Gonçalves, G. R. & Pereira, I. G. (2010). Assessment of the performance of eight filtering algorithms by using full-waveform LİDAR data of unmanaged eucalypt forest. Silvilaser, 187-196. https:/www.researchgate.net/publication/353307644

Gümüş, K. & Erkaya, H. (2007). Mühendislik uygulamalarında kullanılan yersel lazer tarayıcı sistemler. *TMMMOB Harita ve Kadastro Mühendisleri Odası 11.Türkiye Harita Bilimsel ve Teknik Kurultayı* 2-6 Nisan.

Habib, A. & Rens, J. V. (2017). Quality assurance and quality control of LİDAR systems and derived data. Advanced LİDAR Workshop, University of Northern Iowa, 10, 269-294. https://doi.org/10.1201/9781420051438.CH9

Haralick, R. M. & Shapiro, L. G. (1992). Computer and robot vision. In addison wesley: Reading. Longman Publishing Co. Inc. https://scholar.google.com.tr/citations?hl=tr&user=X8NqGhsAAAAJ&view_op=list_works&sortby=pubdate

Haugerud, R. A. & Harding, D. J. (2001). Some algorithms for virtual deforestation (VDF) of LİDAR topographic survey data. *International Archives of Photogrammetry and Remote Sensing*, 211-217. http://pugetsoundLIDAR.org

Hill, J., Graham, L., Henry, R., Cotter, D. & Young, D. (2000). Wide-area topographic mapping and applications using airbone light detection and ranging (LIDAR) technology. *Photogrammetric Engineering and Remote Sensing*, 66, 908-914.

Kaplan, G., Comert, R., Kaplan, O., Matci, D. K. & Avdan, U. (2022). Using machine learning to extract building inventory information based on LİDAR data. *ISPRS International Journal of Geo-Information*, 11(10). https:doi.org/10.3390/IJGI111005117

Karasaka, L. & Keleş, H. (2000). CSF (Cloth simulation filtering) algoritmasının zemin noktalarını filtrelemedki performans analizi. *Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi*, 267-275. https://doi.org/10.35414/akufemubid.660828

Kobler, A., Preifer, N., Ogrinc, P., Todorovski, L., Oštir, K. & Džeroski, S. (2007). Repetitive interpolation: A robust algorithm for DTM generation from Aerial Laser Scanner Data in forested terrain. *Remote Sensing of Environment*, 108(1), 9-23. https://doi.org/10.1016/J.RSE.2006.10.013

Kostrikov, S. (2019). Urban remote sensing wiith LIDAR fort he Smarth City Concept implementation. Visnyk of V. N. Karazin Kharkiv National University, Series 'Geology, Geography, Ecology', 50. https://doi.org/10.26565/2410-7360-2019-50-08

Lichti, D. D. & Gordon, S. J. (2004). Error Propagation in directly georeferenced terrestrial laser scanner point clouds for cultural heritage recording. FIG Working Week.

Liu, X. (2008). Airbone LİDAR for DEM generation: some critical issues. http://Dx.Doi.Org/10.1177/0309133308089496, 32(1), 31-49. https://doi.org/10.1177/0309133308089496

Lu, Y., Wang, X., Zhou, K. & Yang, J. (2011). MATLAB tools for LIDAR data conversion, visualization and processing. In X. He, J. Xu & V.G. Ferreira (Eds), International Symposium on LIDAR and Radar Mapping 2011: Technologies and Applications. https://doir.org/10.2228/12.912529

Maliqi, E., Penev, P. & Kelmendi, F. (2017). Creating and analysing the digital terrain model of the slivovo area using QGIS Sofware. *Geodesy and Cartography*, 43(3), 111-117. https://doi.org/10.3846/20296991.2017137645

Maune, D. (2011). Digital elevaion model (DTM) whiepaper NRCS high resolution elevation data. USDA Natural Resources Conversation Service National Geospatial Management Center.

Meng, X., Currit, N. & Zhao, K. (2010). Ground filtering algorithms for airbone LIDAR data: A review of critical issues. *Remote Sensing*, 2010, 2(3), 833-860. http://doi.org/10.3390/RS2030833

Pedersen, V. F. (2022). Filtering av LIDAR-punktsky for opprettelse av nøyaktig DTM: en prestasjonsanalyse av to punktskybehandlingssystem, Master's Thesis, miljø- og biovitenskapelige universitet.

Podobnikar, T. & Vrečko, A. (2012). Digital elevation model from the best results of different filtering of a LIDAR point cloud. *Transaction in GIS*, 16(5), 603-617. https://doi.org/10.1111/J.1467-9671.2012.01335.X

Reshetyuk, Y. (2009). Self-calibration and direct georeferencing in terrestrial laser scanning. Doctoral Thesis, Royal Institute of Technology (KTH), Department of Transport and Economics Division of Geodesy.

Sinadinovski, C., Markušić, S., Stanko, D., McCue, K. F. & Pekevski, L. (2022). Seismic analysis of moderate size earthquakes recorded on stations at close epicentral distances. *Applied Sciences*, 12(1), 470. https://doi.org/10.3390/APP12010470

Sithole, G. & Vosselman, G. (2005). Filtering of airbone laser scanner data based on segmented point clouds. *Interational Institute for Geo-Information Science and Earth Obseervation*, 66-71. https://research.utwente.nl/en/publications/filteringof-airborne-laser-scanner-data-based-on-segmented-point

Soycan, M., Tunalıoğlu Öcalan, T., Soycan, A. & Gümüş, K. (2011b). Three dimensional modeling of a forested area using aan airbone light detection and ranging method. *Arabian Journal for Science and Engineering*, 36(4), 581-595. https://doi.org/10.1007/S13369-011-0054-8/METRICS

Süleymanoğlu, B. & Soycan, M. (2017). Hava LİDAR verilerinde kullanılan filtreleme algoritmalarının incelenmesi.

Uray, F. (2016). Hava LİDAR nokta bulutu verileri filtreleme algoritmalarının geliştirilmesi ve performanslarının karşılaştırılması. Master's Thesis, Necmettin Erbakan Universiyt, Konya (in Turkey).

Uray, F. (2022). Derin öğrenme tekniklerini kullanarak hava LİDAR nokta bulutlarının sınıflandırılması. Doctoral Thesis, Necmettin Erbakan University, Konya (in Turkey).

Vosselman, G. & Maas, H. G. (2010). Airbone and terrestrial laser scanning. Whittles Publishing. https://www.whittlespublishing.com/Airborne_and_Terrestrial_Laser_Scanning

Wehr, A. & Lohr, U. (1999). Airbone laser scanning – An introduction and overview. ISPRS Journal of Photogrammetry and Remote Sensing, 54(2-3), 68-82. https://doi.org/10.1016/S0924-2716(99)00011-8