

Evaluation of LiDAR Point Clouds Density in the Interpolation of Digital Terrain Models for Power Line Planning in Northeast Brazil

Avaliação da Densidade de Nuvens de Pontos LiDAR na Interpolação de Modelos Digitais de Terreno para Planejamento de Linhas Elétricas no Nordeste do Brasil

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Abstract

Mapping activities for the implementation of basic and executive projects for electric power transmission lines systematically involves topographic surveys. This study presents the results of a comparative study on the influence of the density of aerial survey points, LiDAR (Light Detection and Ranging), for the calculation of digital terrain models (DTMs) in typical areas of the northeastern region of Brazil, in the context of modeling ground for planning electricity transmission lines. The study area is the region covered by the 230 kV Ibiçara/Brumado transmission line, located in the state of Bahia/Brazil. In part of this region, elevations of the mountains of the Western Edge of Chapada Diamantina predominate. Therefore, points with varying densities were used to interpolate DTMs in different environments. Point cloud classification (Airborne LiDAR) was performed using the TerraScan program using semi-automatic classification methods, followed by manual refinements. To evaluate the terrain models obtained with different point densities, four areas were selected under transmission line: Area 1 (24.4/m²), Area 2 (46.0/m²), Area 3 (33.7/m²) e Area 4 (29.7/m²). The Airborne LiDAR survey was performed with an Optech ALTM Pegasus HD500 sensor, calibrated to obtain a density of 15 points/m². The results showed that, depending on the nature of the vegetation cover, less dense laser surveys do not offer enough quality to generate DTMs. However, in some cases, when the vegetation is denser and the terrain is not flat, the quality of the DTM decreases as the density of the points decreases. The study shows that the survey density must be suitable for the region to be analyzed. An important guideline would be to repeat this study in other areas with different coverage and relief variations, in order to create specifications to serve as a basis for planning LiDAR surveys on other transmission lines.

Keywords: DTM; Airborne laser; Transmission lines

Resumo

As atividades de mapeamento para implantação de projetos básicos e executivos de linhas de transmissão de energia elétrica envolvem sistematicamente levantamentos topográficos. Este estudo apresenta os resultados de um estudo comparativo sobre a influência da densidade de pontos de levantamento aéreo, LiDAR (Light Detection and Ranging), para o cálculo de modelos digitais de terreno (DTMs) em áreas típicas da região nordeste do Brasil, no contexto de modelagem de terreno para planejamento de linhas de transmissão de energia elétrica. A área de estudo é a região de abrangência da linha de transmissão de 230 kV Ibiçara/Brumado, localizada no estado da Bahia/Brasil. Em parte desta região predominam as elevações das serras do Extremo Oeste da Chapada Diamantina. Portanto, pontos com densidades variadas foram usados para interpolar DTMs em diferentes ambientes. A classificação de nuvens de pontos (Laser Aerotransportado) foi realizada usando o programa TerraScan usando métodos de classificação semiautomática, seguida de refinamentos manuais. Para avaliar os modelos de terreno, obtidos com diferentes densidades de pontos, foram selecionadas quatro áreas sob a linha de transmissão: Área 1 (24,4/m²), Área 2 (46,0/m²), Área 3 (33,7/m²) e Área 4 (29,7/m²). O levantamento (Laser Aerotransportado) foi realizado com um sensor Optech ALTM Pegasus HD500, calibrado para obter uma densidade de 15 pontos/m². Os resultados mostraram que, dependendo da natureza da cobertura vegetal, levantamentos a laser menos densos não oferecem qualidade suficiente para gerar DTMs. No entanto, em alguns casos, quando a vegetação é mais densa e o terreno não é plano, a qualidade do DTM diminui à medida que a densidade dos pontos diminui. O estudo mostra que a densidade do levantamento deve ser adequada para a região a ser analisada. Uma diretriz importante seria repetir este estudo em outras áreas com diferentes coberturas e variações de relevo, a fim de criar especificações para servir de base para o planejamento de levantamentos LiDAR em outras linhas de transmissão.

Palavras-chave: DTM; Laser aerotransportado; Linhas de transmissão

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1 Introduction

In Brazil, almost all of the electricity generated comes from hydroelectric and thermoelectric plants (ONS 2017). This energy is transported through a system that interconnects the plants and consumer centers through energy transmission lines that, in most cases, are overhead, with cables supported on supports (towers or poles), and, in some specific situations, underground, with cables that are placed inside pipelines (ONS 2017). According to CBIE (2020), Brazil has more than 141,000 km of electric power transmission lines. The National System Operator (ONS) projects that the extension of the power grid will reach approximately 185,500 km of transmission lines in 2023 (CBIE 2020). Power transmission lines (LT) can be classified, depending on their capacity, into: transmission lines (high voltage/69 - 765 kV); sub-transmission (medium voltage/34.5 - 69 kV); and distribution (low voltage/7 - 13 kV) (Jwa, Sohn & Kim 2009).

The construction of transmission lines, whether for national interconnection or just to meet specific demands, is a service that requires many studies of both technical and economic feasibility and aims to make better use of energy (Azevedo 2011; ONS 2017; Tolmasquim 2015). The preparation of basic documents for the implementation of a transmission line dispenses with a thorough field survey, in order to provide knowledge of the physical, biotic and anthropic environment that the study corridor crosses (Azevedo 2011; ONS 2017). According to Azevedo (2011), the basic design of a transmission line requires guidelines and criteria that must be followed by the topography teams for the execution of the flat-altimetric survey services of the LT axis and strip, as well as of the services of cadastral survey of properties and forest surveys. It is also essential to gather meteorological, geotechnical and historical data for the region in order to define the best alternative. Some basic premises are fundamental for choosing the best route. The main one is the definition of the smallest possible total extension, thus reducing the quantity. Furthermore, strong deflections should be avoided, as the sharper the angles between two structures, the greater the efforts on the towers and foundations, thus requiring the installation of more robust and expensive anchors (ABNT 1985; Azevedo 2011; ONS 2017). According to Kim and Sohn (2010), geospatial information is essential for establishing activities related to the construction, control and inventory of a transmission line. The exact location of the physical structures of a transmission line, such as cables, towers and technical equipment, requires high precision and accuracy. There are several ways to obtain this information, for example, through topographic, photogrammetric and/or geodetic surveys. These activities

become slow and costly when carried out by conventional techniques and manual processes (Kim & Sohn 2010).

According to ABNT (1985), topography is a fundamental parameter in the preparation of basic and executive projects for Electric Power Transmission Lines, given that the project cost depends essentially on the profile of the land along this line. In a power generation company, the perspective is that topographic data can generate products that provide subsidies for a detailed study of alternative transmission line routes. Foreseeing technical and environmental issues, as well as the generation of planialtimetric maps and profiles that they are indispensable products in the referred projects for the creation of a transmission line (ABNT 1985; Azevedo 2011). From the environmental aspect, the distance from Permanent Protection Areas (APPs) and regions with fragments of native vegetation (IBAMA 2005). According to ABNT (1985), the space on the ground occupied by these elements and surroundings must be respected in view of the different forms of occupation. This protected area is called Servitude Strip (ABNT 1985). The easement strip needs to be at least 10 km away from indigenous reserves and quilombola villages (IBAMA 2005). Topographic data of interest to the type of project are analyzed only in the easement strip. The area considered as a right of way, has a coverage determined by the tension of the cables. For 138 kV high voltage towers, it is determined that the easement strip is 15 meters along the entire stretch to both sides from the center of the tower, totaling a corridor of 30 meters (ABNT 1985). Higher voltages, such as 230 and 500 kV, require, respectively, 50 and 65 meters of restrictive corridor, expanding the protection area (ABNT 1985). The layout is delimited by observing, beforehand, aspects that do not pose risks to the system. At this stage, preference is also given to areas close to regions with expansion possibilities in order to meet future network installations (Bubniak 2002). According to Law No. 6.938/81, which establishes the National Environmental Policy (PNMA), environmental licensing has become an integral part of national policy (MMA 1981). This act aims to make economic and social development compatible with the preservation of the quality of the environment and ecological balance, essential to life. Therefore, all activities and undertakings that use environmental resources and that may cause actual or potential risks of impacts to the environment must obtain the proper licenses from the competent environmental agency. Thus, the installation, expansion, modification or operation of any project, which in any way interferes with the environment, requires authorization (MMA 1981).

Airborne LiDAR (Light Detection and Ranging) is currently presented as an efficient technology in terms of precision for mapping surface information. Moreover,

weather conditions have no influence on this technique when gathering point clouds (Vosselman & Maas 2010). Thus, airborne LiDAR has been widely used in many areas, such as digital terrain model (DTM) extraction (Özcan & Ünsalan 2017) and three-dimensional model generation (Véga et al. 2016).

In order to improve their services, electricity transmission companies have been looking for new technologies that make the task of control easier, especially in transmission line networks. One of the options for mapping the land surface in the region where a transmission line will be implemented is the Airborne LiDAR (Light Detection and Ranging). LiDAR enables digital mapping and MDT generation. MDT facilitates the management of transmission networks, enabling the planning, location of the project execution area, construction and maintenance of the network (Valente 2015).

Laser scanning via LiDAR is a powerful technique to collect data necessary for the generation of the Digital Terrain Model (DTM), even in densely forested areas. DTM only contemplates the Earth's surface, without the objects that are on its surface (Salleh, Ismail & Rahman 2015). LiDAR observations located at the ground level can be separated from the initial point cloud and used as input for the generation of a Digital Terrain Model (DTM) via interpolation (Căteanu & Ciubotaru 2021).

One promising feature of LiDAR point clouds is the high-density with a large amount of data points. However, this imposes a great challenge on most traditional interpolation methods for the construction of high-resolution and high-quality DTMs (Chen & Li 2019). To develop algorithms for many other applications, a key step is to extract DTM information from point clouds that contain both terrestrial and non-terrestrial points. This process is often referred to as filtering. Point cloud filtering is a prerequisite for almost all LiDAR-based applications. However, it is challenging to select a suitable filtering algorithm to deal with high-density point clouds over complex landscapes (Chen et al. 2021).

Digital terrain model (DTM) generation is the fundamental application of airborne LiDAR data. In past decades, a large body of studies has been conducted to present and experiment a variety of DTM generation methods. Although great progress has been made, DTM generation, especially DTM generation in specific terrain situations, remains challenging (Chen, Gao & Devereux 2017). According to these authors, despite different categories of filtering strategies, these DTM generation methods present similar difficulties when implemented in sharply changing terrain, areas with dense non-ground features and complicated landscapes.

According to Xiang (2014), Filtering is also commonly done to reduce the file size of the deliverable point cloud since the full dataset can require intense computational power and data storage. Usually, the filtering is considered as the extraction of the DTM from the DSM, and the classification is regarded as distinguishing different objects such as vegetation, buildings, roads, power-lines, etc. from the laser point cloud data. Besides the determination of terrain, the extraction of buildings, vegetation and other important features above the ground are also worth considering.

Aiming at realizing filtering effectively, lots of algorithms have been put forward in the past twenty years (Hui et al. 2019). These filtering algorithms can be categorized into four classes: slope-based, morphology-based, surface-based, and segmentation-based (Sithole & Vosselman 2004; Meng, Currit & Zhao 2010). Currently, there are many algorithms available to filter ground returns from airborne LiDAR data. Some of them can be found in Montealegre, Lamelas and De la Riva (2015), Julge, Ellmann and Gruno (2014), and Chen, Xiang and Moriya (2020).

In this context, this article aims to present the results of a comparative study on the influence of LiDAR aerial survey point density for the calculation of digital terrain models (DTMs) in typical areas of the Northeast region of Brazil to support executive projects of electric power transmission lines.

2 Airborne LiDAR: Evolution and a Brief Discussion on the Technique

According to Ackermann (1999), the use of LiDAR technology started in the 1960s and was perfected in the following decades. This technology consists of scanning the terrain by projecting laser pulses from, for example, an airplane flying over the study area, to determine the elevation of the location where the pulse reaches the terrain. In the 1990s, LiDAR technology started to be disseminated with greater precision and consistency in the acquisition of data from aerial platforms, due to the evolution and integration of GPS (Global Positioning System) and IMU (Inertial Measurement Unit) Systems (Ackermann 1999; Diaz 2011; Diaz et al. 2014). Airborne LiDAR is an active remote sensing technology that provides accurate, high-resolution measurements of the topography, vegetation and buildings on the Earth's surface (Shan & Toth 2018). According to these authors Li et al. (2017), LiDAR pulses can partially penetrate the tree canopy and are unaffected by shadow and surrounding light conditions. LiDAR is an active sensor and can collect data during the day and night (Contreras, Sickert & Denzler 2020).

One of the main advantages of airborne LiDAR is the ease of obtaining a large number of points on the ground, even in areas covered by vegetation (Ferraz et al. 2016). The increase in point density drives new applications, such as reconnaissance and delimitation of towers and transmission lines, as well as buildings along the high range (Yu et al. 2015; Chen et al. 2018). This has benefits in determining a digital terrain model in areas covered by dense vegetation. According to Zhu and Hyypä (2014), the technological advancement of LiDAR sensors has allowed an increase in density from a few points to tens (55 points) per square meter. According to Căteanu and Ciubotaru (2021), the increase in the sampling density of LiDAR data is obtained by decreasing the sensor platform's flight altitude, reducing the scanning angle.

According to Shan and Toth (2018), the result of a LiDAR airborne survey is a dense set of three-dimensional XYZ coordinates, also called a point cloud. This cloud also includes points that hit objects other than terrain, such as the tops of trees. Thus, direct interpolation of a surface of this cloud does not generate a digital terrain model, but rather a visible digital surface model (DSM) (Shan & Toth 2018). According to these authors: a) DEM (Digital Elevation Model) it is a model of a "bare" land surface, which is supposedly free of trees, buildings, or other "non-underground" objects. b) DSM (Digital Surface Model) is an elevation model that includes the tops of everything including buildings, treetops and terrain where there is nothing else on top of it. c) DTM (Digital Terrain Model) is a more generic term that refers to a DEM (Digital Elevation Model) with one or more types of terrain information such as morphological terrain characteristics, drainage patterns and soil properties.

The difference between DSM and DTM provides a third model: the DEM (Digital Elevation Model), which represents only the height of objects above the terrain (Dong & Chen 2018; Shan & Toth 2018). Figure 1 illustrates the DTM and DSM models.

The generation of a DTM requires the classification of points into two groups: those that hit the ground and those that hit other objects. This problem has been the subject of several researches and different technical proposals aimed at finding solutions (Pacheco et al. 2011; Matikaine et al. 2016; Vosselman & Maas 2010). After removing points that do not correspond to the terrain, the point cloud has gaps where the emitted laser pulses cannot pass through the leaves and reach the ground, or when points that reach a building are removed. These gaps are usually filled by the application of interpolation methods (Chen et al. 2016; Shimalesky, Mitishita & Chaves Neto 2009). According to Chen, Gao and Devereux (2017), the generation of the DTM with Airborne LiDAR must be adapted to each region, depending on its characteristics, such as relief, vegetation cover and the occurrence of other objects in the scene. Merging multiple sources and integrating different methods can be an effective way to optimize DTM generation (Chen, Gao & Devereux 2017).

Applications of Airborne LiDAR technology related to surface representations, with studies aimed at the generation of large-scale TMD and high-precision mappings, were advocated in the late 1990s (Vosselman 1999). These studies continued with several studies in the 2000 (Chen et al. 2007; Schuffert 2013; Sithole & Vosselman 2004; Vögtle & Steinle 2005; Vosselman 2000). The main reference for comparing several methods of obtaining Digital Terrain Models from laser scanner data filtering is the work of Sithole and Vosselman (2004). Sithole and Vosselman (2004) compared the performance of eight filtering algorithms on the International Society of Photogrammetry and Remote Sensing reference dataset ISPRS) and found that adaptive triangulated irregular network (ATIN) also referred to as progressive TIN densification, PTD) outperformed others, as it used more context (Chen et al. 2021). In this study, the methods are grouped into the following categories (Table 1).

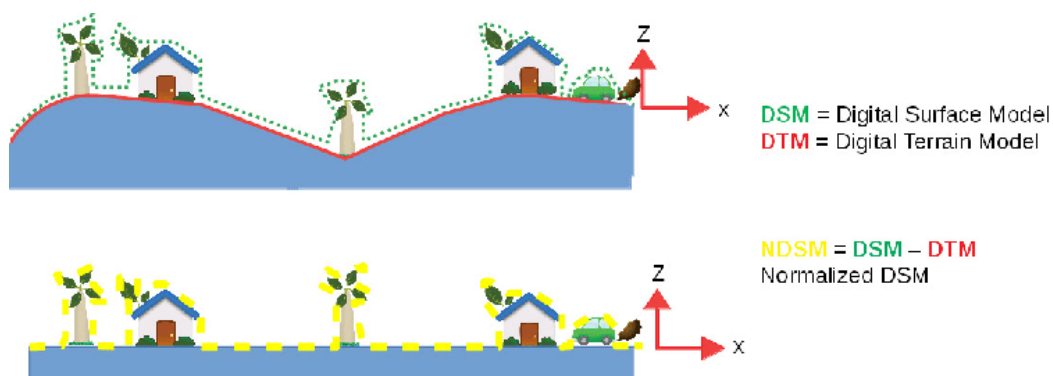


Figure 1 Illustration of DTM and DSM Models. DSM represents earth's surface and includes all objects on it. In contrast, DTM is a representation of a terrain's surface without any objects (Contreras, Sickert & Denzler 2020).

Table 1 Categories of methods for generating DTM (Sithole & Vosselman 2004).

Categories	Description
Declivity	In this method, it is assumed that the relief is smooth, therefore, when detecting sudden variations in the digital surface model, it is admitted that these variations are caused by the presence of objects existing above the terrain, such as trees and buildings. To locate these points, the difference between the elevation of the point in question and the elevation of its closest neighbors is analyzed. When this relationship results in slopes greater than the local slope of the terrain, the point is classified as not being of the terrain.
Surface	The method considers that at least a small number of points reach the terrain and that they can be used as a first estimate of the terrain. Thus, local minimums should be identified and used to build an initial model (surface) of the land. Next, the rest of the points are analyzed. If the point is close to this surface, it is added to the set, improving the initial approximation. Thus, the iterative method improves the model by adding points.
Segmentation	The data set is segmented and the resulting segments are classified considering the average height of the segment.
Minimum Block	The method defines a region around each pixel, where the local minimum is identified. The other points in the region are analyzed below, comparing their heights with the minimum height. If this difference is lower than a pre-established threshold, the point is considered to be from the ground. If not, it is eliminated.

Numerous studies have compared the relative performance of interpolation algorithms for DTM generation. While some studies are concerned with establishing theoretical models for DTM accuracy, most articles are empirical in nature (Căteanu & Ciubotaru 2021). In these cases, real world elevation data is collected in one or more test areas and a series of interpolation algorithms are tested, comparing interpolated DTMs with reference elevation data. In some cases, mathematically generated surfaces are tested instead of natural ones (Căteanu & Ciubotaru 2021; Chen & Li 2019).

Slope-based approaches always assume that the gradients between non-ground points and ground points are greater than those between ground points. Thus, if the slope or height difference between two points is greater than a pre-defined limit, the point with the highest elevation will be considered a non-terrain point (Hui et al. 2019). Vosselman (1999) proposed a pioneering slope-based algorithm. This method is closely related to the erosion operator used for grayscale mathematical morphology. Filter functions are derived that preserve important terrain features or minimize the number of classification errors. Filter performance deteriorates as dot density decreases. Zhang and Men (2010) complement this study by analyzing the advantages and disadvantages of point classification algorithms for the generation of a terrain model and recommend three aspects that should be taken into account: the use of adaptive thresholds, as different regions require different treatments; the combination of different methods; the integrated use of data from multiple sources when possible. Liu (2008) also recommends using additional information, when available, in order to better approximate the terrain variation. Several subsequent studies have been adapted for harsh environments. The results in general showed that slope-based approaches cannot achieve satisfactory accuracy (Chen et al. 2016; Hui et al. 2019; Lin & Zhang 2014).

In forested areas, the results point to a greater discrepancy between filters as the terrain becomes steep and as the undergrowth increases (Silva et al. 2018; Sterenczak et al. 2016). This fact is common in other benchmarks, which shows the greatest difference between filter efficiencies as terrain complexity increases (Korzeniowska et al. 2014; White et al. 2015). As presented by Montealegre, Lamelas and De la Riva (2015), steep slopes affect how filters recognize the returns belonging to vegetation from those from the ground, causing excessive removal of returns and reducing the details of the ground surfaces. Another source of errors in the filtering process is caused by the edge effect, which is the incorrect classification of returns at the boundary of the dataset due to the lack of returns outside the frontier (Korzeniowska et al. 2014).

Hui et al. (2016) improved the progressive morphological filter by combining it with a multilevel interpolation filtering method. Preliminary and promising results have been achieved in rough terrain environments. Mongus and Žalik (2014) proposed a DTM generation method involving multi-scale comparison, segmentation and operator morphology with high computational precision. This method has been frequently used not only because it is free from strategic parameters, but also because of its general suitability for various terrains (Chen, Gao & Devereux 2017). Hui et al. (2019) proposed a limitless filtering algorithm based on expectation maximization (EM). The filter was developed based on the assumption that point clouds are seen as a mixture of Gaussian models: EM is applied to perform the separation, which calculates the maximum likelihood estimates of the mixture parameters (Hui et al. 2019).

Cosenza et al. (2020) evaluated the impact of four popular filtering algorithms on the quality of the DTM and the estimation of forest attributes using the area-based approach. Chen et al. (2021) comparatively evaluated the

performance of five representative filtering algorithms in six study sites with different terrain characteristics, where three plots were located in urban areas and three in forest areas. Montealegre, Lamelas and De la Riva (2015) showed that Type II errors increase as the stitch density increases. Yilmaz and Gungor (2018) indicated that with increasing point density, the performance of the filtering algorithm decreases. Klápš̃t' e et al. (2020) compared six filtering algorithms in a study site with sparsely distributed vegetation and found that no universal method can outperform the others. Căteanu and Ciubotaru (2020), for example, presented a comparative analysis of the interpolation accuracy for nine algorithms, which are used to generate digital terrain models from airborne LiDAR, in mountainous terrain covered by dense forest vegetation. For most algorithms, they achieved similar performance in terms of overall accuracy, with RMSE values between 0.11 and 0.28 m (when the model resolution is set to 0.5 m). Additional information on the state of the art of DTM generation using LiDAR data can be obtained from Chen, Gao and Devereux (2017), Hui et al. (2019), Klápš̃t' e et al. (2020), Yilmaz and Gungor (2018) and Sterenczak et al. (2016).

3 Materials and Methods

3.1 Study Area

The study area is the region covered by the 230 kV Ibicoara/Brumado transmission line, located in the state of Bahia (Figure 2). This transmission line belongs to CHESF - *Companhia Hidroelétrica do São Francisco* - and is approximately 94 km long, in addition to having reference data from conventional topographic surveys.

Important factors for the choice of this transmission line are the geomorphological characteristics and the land cover and use of the relief of the region used as a security area of the enterprise. The main uses and occupations of the land along this transmission line are *capoeiras*, APP - Permanent Preservation Area, vegetation, riparian forest, pastures and the energy substations of the São Francisco Hydroelectric Company (CHESF) located, respectively, in Ibicoara and Bruma. The altimetric variation along the line guideline is greater than 800 meters.

3.2 Evaluation of Digital Model

To evaluate the terrain models obtained with different point densities, four areas were selected along the aforementioned transmission line. Airborne LiDAR planialtimetric data was used, with different point densities, provided by CHESF. The Airborne LiDAR survey was

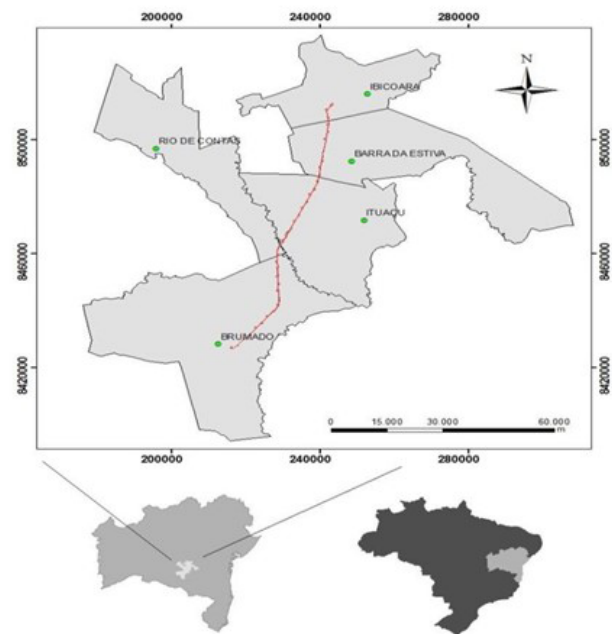


Figure 2 Location of the 230KV LT Ibicoara/Brumado/BA state. Adapted from RIMA (2009).

performed with an Optech ALTM Pegasus HD500 sensor, calibrated to obtain a density of 15 points/m². O voo foi realizado na altura média de 870m, ao longo de toda linha de transmissão, em 14 de dezembro de 2014. This system provides accuracy, reduced survey time and subsidies for the preventive maintenance of LT. Being equipped with the following components: INS (Inertial Navigation System), GPS (Global Positioning System), ALS (Airborne Laser Scanning) and Data storage units. In addition to obtaining georeferenced point clouds, the system allows the separation of the pulses emitted, determining the top of the objects and the level of the terrain, called, respectively, first pulse (last pulse) and last pulse (last pulse).

The classification of the point cloud was performed by the TerraScan program using semiautomatic classification methods, followed by manual refinements. Due to the large area, four cutouts were used in this study, from test areas with different types of land use and relief (Figure 3).

The first area comprises a flat region with little vegetation. The transmission lines and a small construction stand out. The second region is characterized by a strong slope, which can be divided into two parts. In the low part there is dense vegetation and, in the highest part, the vegetation is low and only the transmission line stands out from the land. The third test region is completely covered by dense vegetation, also having a slightly inclined relief. The fourth region is the most complex, as it contains a valley with the presence of a river. In the region close to

the river, the presence of dense vegetation is more visible and the slope of the terrain is larger. The size of each area, the total points present in these areas and the density of points per square meter, are described in Table 2.

3.3 Obtaining a Digital Terrain Model

As the flight does not necessarily follow the northern/southern or eastern/western directions, a rotation was applied to the points to approximate the contours of the raised region to the northern/eastern axes and thus reduce the white spaces in the digital terrain model in a raster format.

The point density of the survey is relatively high, between 24 to 46 points per square meter. Along with the intention of verifying if less dense surveys allow to represent the terrain with sufficient quality, less dense sets were generated from these original clouds. The intention was to determine the minimum density, for each form of relief, that allows to obtain a satisfactory DTM. To do so, new sets with lower density were generated from the original set of points, that is, fewer points. The density

was changed by varying the rate of collection of points along the swept line. The number of points per line (N) is a function of the sampling rate (f in kHz), that is, the pulse repetition rate, and the scan frequency (r, in Hz) which is equivalent to the number of lines scanned per second, according to Equation 1.

$$X = \frac{f}{2r}$$

The number of points per line was artificially decreased, selecting one point for each “n” points, that is, skipping “n” points. Thus, the points were sampled following constant steps. The first set contains all the survey points and was used as a reference. To form the second set, only half of the points were selected, that is, one point was collected and the other was skipped over the original file. In the third set, one point was selected from every 4 points of the original file. Finally, in the fourth set, the reduction was more severe, storing just one point in eight of the original series.

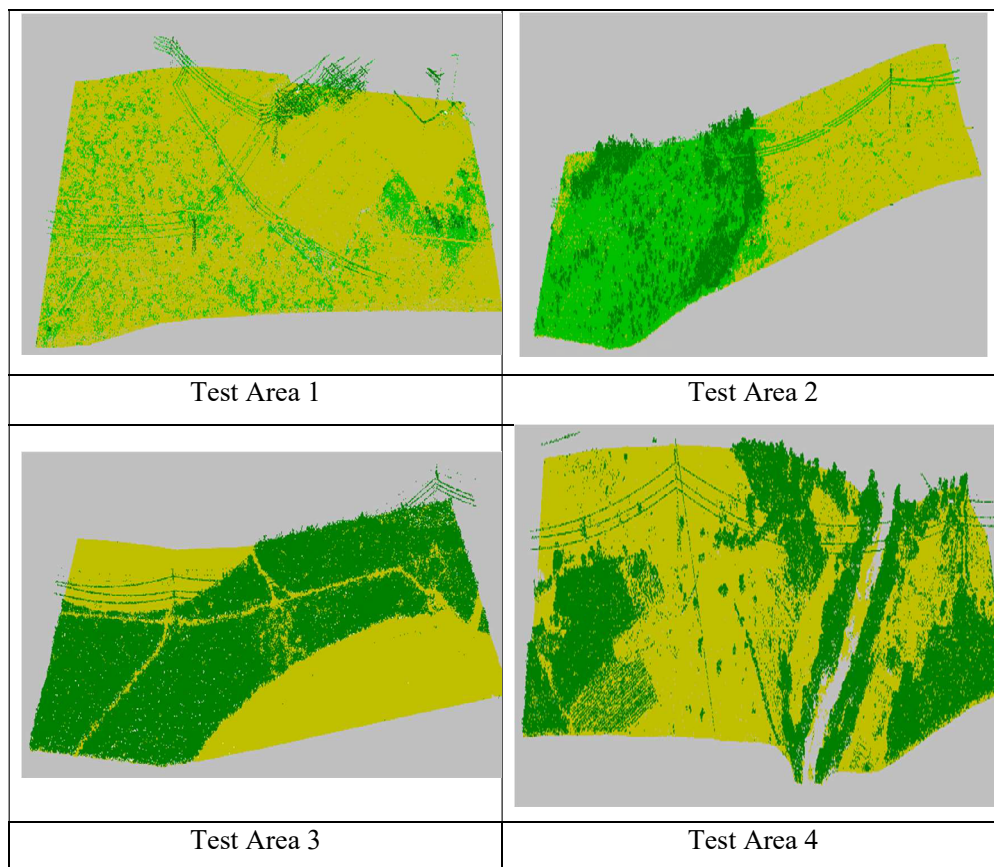


Figure 3 Four test areas used in this study with different types of land use and relief.

Table 2 Dimensions and total points in each region studied.

Area	Size (m ²)	Total Points	Density
Test Area 1	207030.00	5063883	24.4
Test Area 2	241914.00	11140185	46.0
Test Area 3	270847.00	9135149	33.7
Test Area 4	245350.00	7277291	29.7

For each set of points, the ones corresponding to the land surface were classified using the tools of the LasTools library, award-winning software for rapid LiDAR processing. The process is based on the progressive densification of the digital terrain model, as described in Axelsson (2000).

The classification of points separates the set of points into two classes: “terrain” and “others”. Initially, a rough approximation of the terrain is produced, selecting the lowest points within a sub-region of the study area. Analyzing a small region within the study area, it is assumed that at least one point has fallen on the ground then the minimum in this sub-region corresponds to a location on the ground. The size of the search area depends a lot on the relief. In flatter areas, the search region may be smaller,

as in areas densely occupied by buildings, for example, this region must be increased to ensure that at least one point of the land has been detected. This set of points (red dots in Figure 4) can give rise to an initial grid (Figure 4, right) that represents the terrain in a rough way, stored in the form of a triangulation.

This initial grid can be progressively densified, including new points that can also be considered from the terrain, from which the method name derives. For this, all the remaining points are analyzed. First, it is determined within which triangle of the TIN mesh the point falls. Then two parameters are analyzed, as shown in Figure 4: the first is the distance from the point to the vertices of the triangle and the second is associated with the angles formed by the plane of the corresponding triangle and the lines that join the point and the vertices. Based on these parameters, it is determined if the point is close to the surface of the digital model or if it is too far away. If it is far away, it is considered a peak associated with an object above the ground and this point is discarded. If it is considered close, it is included in the set of “terrain” points and after the iteration a new terrain model is produced. The process is stopped when there are no more points to be added to the “terrain” set.

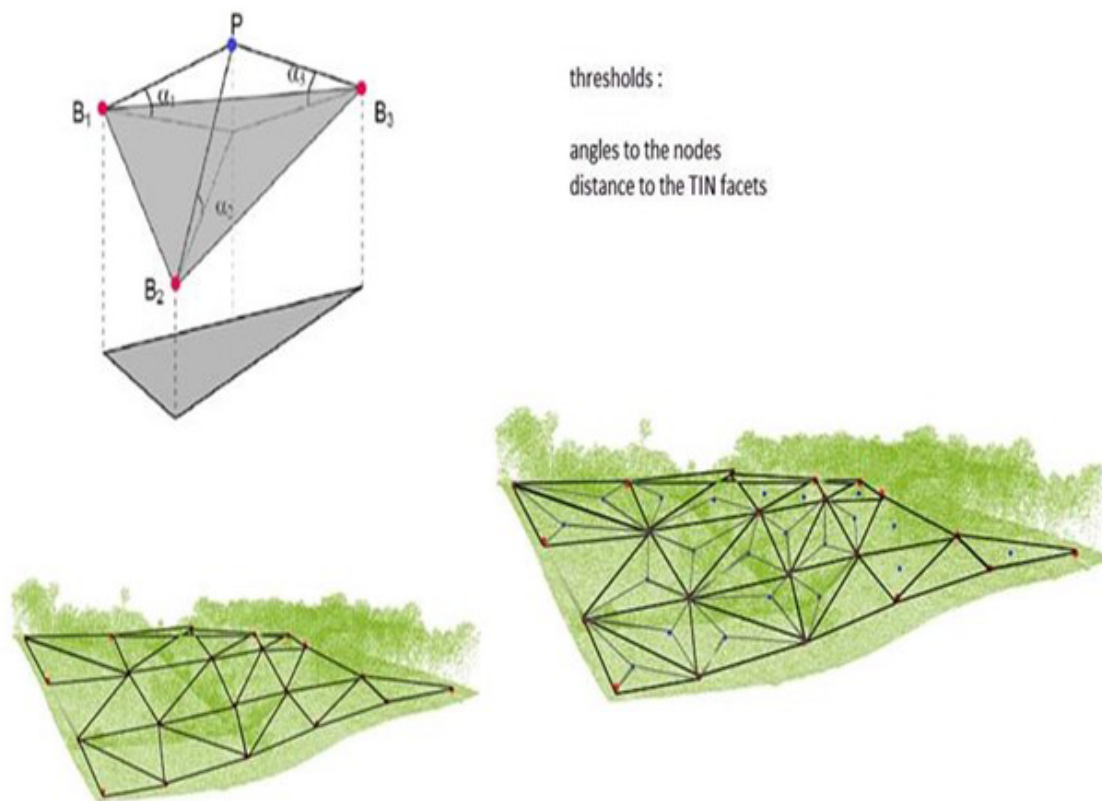


Figure 4 Production of the initial grid in the point classification method. Source: LBI ArchPro (2020).

Using each set of terrain points, raster models of the terrain were generated, where the faults caused by the removal of the points associated with objects above the terrain were filled by the linear interpolation method. With this, a set of 16 regular grids (raster) was obtained, four of which correspond to the group used as reference (original data), which are those related to the use of the maximum available density of points, that is, without removing points from the original set.

The analysis of the digital model of the terrain derived from the sets of points with lower density was performed by comparing the grid obtained with the respective reference grid. Thus, the difference between the grids was calculated according to Equation 2.

$$DIFF_{(R,i)} = MDT_{(i)} - MDT_{(R)}$$

Were:

$MDT_{(i)}$ = grid resulting from the decreased density;

$MDT_{(R)}$ = reference grid.

Zhang and Lin (2013), for example, proposed a method to optimize progressive TIN densification (PTD) to filter clouds of airborne LiDAR points. Experimental results compared with PTD, showed that the proposed method can preserve landscape discontinuities and reduce omission errors and total errors by about 10% and 6% respectively, which would decrease the advance of the operation manual necessary to correct the result post-processing.

The second Decree No. 89,817, dated June 20, 1984 (Brasil 1984), will be used to support the discussion, as this is the official Brazilian document for the evaluation of cartographic products. In its art. 8, the Decree establishes that the terms Standard Deviation (SD), Standard Error (EP) and Average Square Error (NDE) must be considered as

synonyms. The term Cartographic Accuracy (EC) is used as a reference in the assessment of accuracy, as shown in Table 3, or the accuracy of a cartographic product, with standard deviation (SD) being one of its components. The PEC-PCD establishes categories to assess quality in altimetric terms, of altimetric quoted points and digital models, as shown in Table 3, using the equidistance of the level curves (EC) as a reference. The equidistance of the level curves depends on the scale of the chart, with values of 1 m being adopted for the 1: 1000 and 1: 2000 scale, 2 m for 1: 5000 and 5 m for the 1:10 000 scale.

The discussion of the geometric quality of a letter was traditionally based on Decree # 89.817, of June 20th, 1984, Brazil. However, with the emergence of new methods of cartographic collection and representation, this decree was revised, and today it is common to follow the specifications of ETADGV, which establishes a new Standard of Cartographic Accuracy designed to meet Digital Cartographic Products (PEC-PCD) (DSG 2011). For the classification of a product in one of the PEC-PCD classes, statistics of 90% of the points collected in the cartographic product are considered in relation to the coordinates of the homologous points collected in the “most accurate source”. The altimetric and planimetric quality specifications, in terms of PEC-PCD, are shown in Table 3. The discrepancies between the coordinates of the homologous points must be equal to or less than the maximum error (EM) and standard error (EP) predicted for each scale. Additional information regarding the LIDAR point classification algorithms can be obtained from Schimdt, Rotteensteiner and Sörgel (2012) and Kim and Sohn (2011).

4 Results and Discussion

In each study region, the density of the set of points was progressively reduced, as shown in Table 4. The value of the density in each reduced set depends on the density of the original set.

Table 3 PEC-PCD categories for Digital Elevation Models and Altimetric Counted Points, according to DSG (2011), considering the maximum error (EM) and the standard error (EP).

Type	PEC	1:1.000		1:2.000		1:5.000		1:10.000	
		EM (m)	EP (m)	EM (m)	EP (m)	EM (m)	EP (m)	EM (m)	EP (m)
Planimetry	A	0.50	0.30	1.00	0.60	2.50	1.50	5.00	3.00
	B	0.80	0.50	1.60	1.00	4.00	2.50	8.00	5.00
	C	1.00	0.60	2.00	1.20	5.00	3.00	10.00	6.00
Altimetry	A	0.50	0.33	0.50	0.33	1.00	0.67	2.50	1.67
	B	0.60	0.40	0.60	0.40	1.20	0.80	3.00	2.00
	C	0.75	0.50	0.75	0.50	1.50	1.00	3.75	2.50

The density reduction in the four regions makes it possible to obtain 16 sets of points, four of which are the original ones, considered as references. Together with these separate sets, the points that reached the land and those that reached other objects, such as vegetation, buildings or transmission lines, were classified. The percentage of points that were identified as ‘terrain’, in this process, is shown in Table 4.

Table 4 Density of sets of points used in the tests in the different study regions and percentage of points that reached the terrain, according to the classification process.

Set	Region	Step	Density p/m ²	% of points in the terrain
11	1	1	24.5	87.79
12	1	2	12.2	88.09
13	1	4	6.1	88.53
14	1	8	3.1	89.18
21	2	1	46.1	57.67
22	2	2	23.0	58.25
23	2	4	11.5	59.03
24	2	8	5.8	60.21
31	3	1	33.7	51.45
32	3	2	16.9	52.04
33	3	4	8.4	52.85
34	3	8	4.2	53.79
41	4	1	29.7	65.32
42	4	2	14.8	65.77
43	4	4	7.4	65.96
44	4	8	3.7	66.22

After performing the interpolation of the DTM models, the analysis of the loss of information was performed by comparing each of the grids with the reference grid, as described in the methodology. Table 5 shows the result of this comparison.

The comparison reveals that the differences, on average, are very small, with the values of the average differences being very low, that is, the values, even after the reduction in density, are, on average, very close. It is noteworthy the fact that the extreme values of the difference between the grids are considerably larger, close to one meter, showing that the models may have greater dispersion in relation to the reference. However, the standard deviation of the differences between grids is small, showing that a large part of this difference is concentrated close to the average, that is, close to the null value.

Analyzing the standard deviations, it appears that they grow as the density is decreased. This was expected,

but it is noted that the decrease is not the same for all the study areas, as seen in Figure 5. The highest value corresponds to study region two. This region is covered by dense vegetation, which makes it difficult to detect points on the ground when using a lower density of points. For areas with dense vegetation cover, most of the profiled points refer to the canopy, with few points reaching the ground (Jensen 2009). On the other hand, minor differences are found in the first set of points, as it is a flat region and without many obstacles. Due to the characteristics of the region, the vegetation, although large, is sparsely distributed, leaving spaces with the presence of bare soil, as can be seen in the data set. So, the points classification algorithm works efficiently. Simpson, Smith and Wooster (2017), for example, highlights the need of ground control points to extract DTM from clouds of Airborne LiDAR points in forest areas, especially in areas where undergrowth or ground cover is predominant.

Table 5 Difference between the DTM produced after the reduction of points and the DTM produced with all available points

Set	Density p/m ²	Min (m)	Max (m)	Mean (m)	d.p.(m)
1-2	12.2	-0.71	0.95	-0.01	0.04
1-3	6.1	-0.80	0.96	0.003	0.05
1-4	3.1	-1.01	1.66	0.005	0.07
2-2	23.0	-1.23	1.53	0.03	0.13
2-3	11.5	-1.42	1.89	0.01	0.13
2-4	5.8	-1.31	1.61	0.03	0.15
3-2	16.9	-0.88	0.90	0.00	0.08
3-3	8.4	-0.93	1.00	-0.01	0.09
3-4	4.2	-1.05	1.00	0.00	0.09
4-2	14.8	-1.86	2.76	0.00	0.07
4-3	7.4	-1.84	1.93	0.00	0.08
4-4	3.7	-2.63	2.44	0.01	0.10

The 75% reduction in the initial density does not cause much difference in the first study area in relation to the difference obtained with 50% of the points. This is also seen, to a lesser extent, in areas three and two. The biggest problem occurs when the density of points is drastically reduced, in this case in the 1:8 ratio. In all of these regions, the standard deviation increases significantly, especially in region one. Special attention should be given to region three, as it is a particular case because it contains a region occupied by water. As water causes the loss of pulses due to specular reflection and greater absorption capacity, the presence of water at the bottom of the valley results in a region without points and, consequently, a decrease in standard deviation is observed.

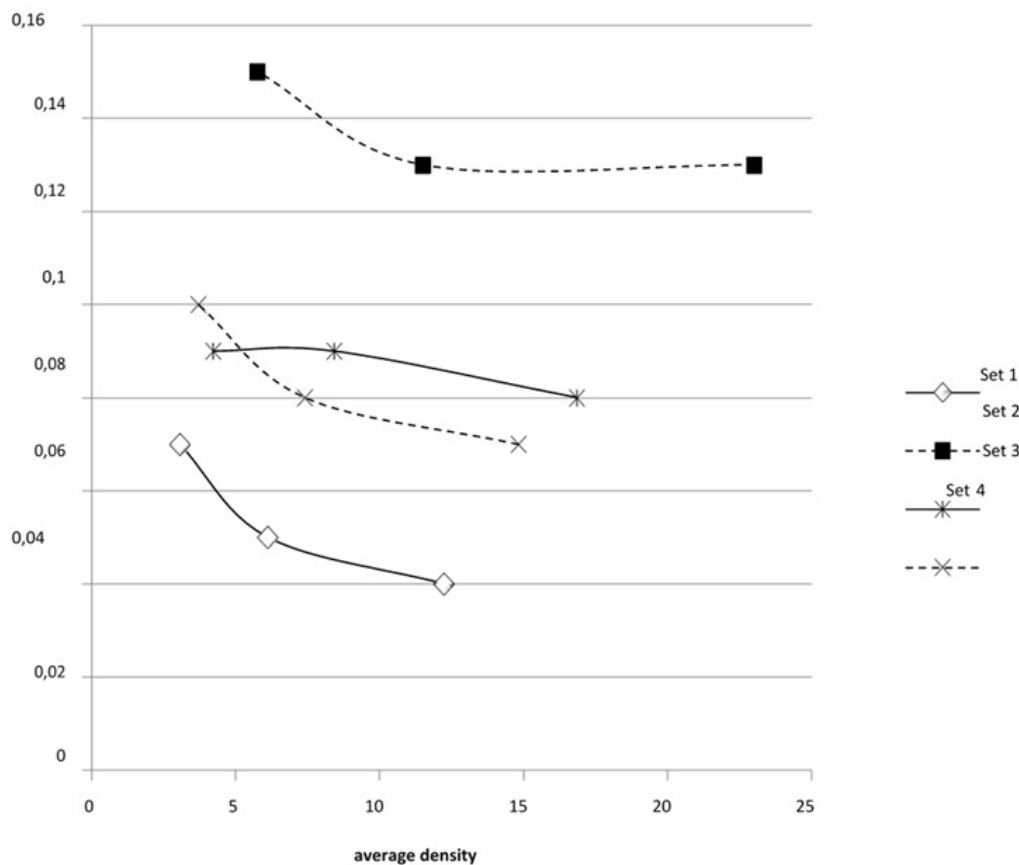


Figure 5 Standard deviation as a function of density.

By comparing the mean error values obtained, using the densest survey as a reference, and comparing these values with those shown in Table 3, the products can be classified in class A on the 1:1000 scale, even for the most severe reductions in density points. The big difference between the products is seen in the calculated standard deviation values. In regions covered by dense vegetation, the altimetric quality drops a lot and approaches the class A limit on this scale. Therefore, it is recommended to use high density of points in regions covered by dense vegetation. In regions with a lower vegetation density, even if they are rugged, low densities have produced results acceptable to national standards.

Salleh, Ismail and Rahman (2015) observed high density of vegetation has an impact on the accuracy of the DTM generated from airborne LiDAR data. According to these authors, this indicates the significant effect of the canopy density on the accuracy of the DTM derived from LiDAR: the results of this study showed the variation in the error of derivatives of LiDAR DTM by different slopes and canopy coverage. Root Mean Squared Error (RMSE) increases with the slope of the terrain (Salleh et al. 2015).

In the case of dense forest cover, the penetration rate of laser pulses is impaired, resulting in a lower density of ground-level observations (Maguya, Junntila & Kauranne 2013). The information from the literature mentioned above corroborates the results obtained in this work.

5 Conclusions

The methodological approach presented in this work, which involved the comparative analysis of DTMs, produced with different densities of Airborne LiDAR points, proved to be effective in the study of terrain modeling in safety bands of electric power transmission lines, given that the products were classified in a cadastral scale of 1: 1000.

The analysis of the digital terrain model in raster format, derived from sets of points with different densities, was carried out by comparing the grid obtained with the maximum available density with the produced grids, reducing the density by systematic suppression of points in the original point cloud. The results showed that less dense surveys produce greater errors. These errors depend a lot on the characteristics of the place, mainly due to the

presence of water and the density of vegetation and its distribution throughout the study area.

The results showed in a general way that, depending on the nature of the vegetation cover, the less dense laser surveys do not offer enough quality to generate DTM for the proposed purpose (transmission lines safety bands). However, in some cases, especially when the vegetation is denser and the terrain is undulating, the quality of the DTM decreases as the density of points decreases.

From the point of view of the current legislation, the decrease in the density of points, along the transmission line shown in this article, does not affect the cartographic quality of the DTM, except in regions covered by dense vegetation, where a survey with 5 points per square meter produces results that border the lower limit of class A.

The study shows that the survey density must be suitable for the region to be analyzed/studied. An important guideline would be to repeat this study in other areas with different coverage and relief variations, in order to create specifications to serve as a basis for planning Airborne LiDAR surveys in other electricity transmission lines.

The generation of DTM in power line corridors has been less common than the mapping of its components. In particular, automated extraction of transmission line (LT) conductors has achieved much attention in the literature. The studies linked and directed to the generation of DTM in LT are preliminary. This segment has been supported in an auxiliary way by optical images from satellites and by synthetic aperture radar (SAR). The Airborne LiDAR and SAR data (synthetic aperture radar) at the level of manned and unmanned aerial vehicles (UAV) appears as the most modern, effective and precise alternative for the implementation of basic and executive projects for electric power transmission lines.

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Conflict of interest

The authors declare no potential conflict of interest.

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