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Reducing redundancy of laser scanning data for building digital terrain models

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Abstract. The main subtle aspects of airborne laser scanning (ALS) involve a large level of density of laser reflection points (LRP) within a certain unit area. This results in the need to process a large amount of information while building digital terrain models (DTMs). Such processing is computationally intensive. For this reason, the main task which is solved during DTM building is to create an accurate description of terrain features required for geodetic works. At the same time, it is necessary to observe the minimum number of LRPs related to the characteristic landforms in the considered location to minimize the use of computing power. Currently available algorithms of information distribution for DTMs built on standard coordinate grids do not allow to successfully resolve data arrays while preserving the proper detalisation level of certain locations. New software, which is used in geodesy and makes it possible to create sparse data arrays during DTM building, is based on a closed code. The paper proposes an algorithm for finding unknown intermediate data obtained with laser scanning of terrain relief, which allows effective thinning of laser reflection points that are insignificant when describing the terrain relief. An automatic technique of DTM building is developed. An algorithm for searching unknown intermediate LRP arrays is formed. Displot is available for sloped areas as well. At the same time detailisation in the quality of structure lines and special points is preserved.

Keywords: digital terrain model (DTM), digital relief model (DRM), airborne laser scanning, quality assessment of digital terrain models, digital mine model.

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Снижение избыточности данных лазерного сканирования для построения цифровых моделей рельефа

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Резюме. К основным нюансам воздушного лазерного сканирования (ВЛС) следует отнести большой уровень плотности точек лазерных отражений (ТЛО), который присутствует в рамках определенной единицы площади. Это приводит к тому, что возникает потребность в обработке большого количества информации во время выстраивания цифровых моделей рельефа (ЦМР). Такая обработка требует больших затрат вычислительных ресурсов. По этой причине главной задачей, которая решается при выстраивании ЦМР, становится создание описания особенностей местности, требуемой для проведения геодезических работ точности. При этом нужно соблюдать минимальное число ТЛО, относящихся к характерным рельефным формам в рассматриваемой локации для минимизации использования вычислительных мощностей. Имеющиеся сейчас алгоритмы распределения информации для ЦМР, выстроенных на стандартных координатных сетках, не дают возможности успешно разрежать массивы информации при сбережении должного уровня детализации определенных локаций. Новое программное обеспечение (ПО), которое используется в геодезии и позволяет создавать разрежение массивов сведений во время выстраивания ЦМР, базируется на закрытом коде. В работе предложен алгоритм нахождения неизвестных промежуточных данных, полученных с лазерным сканированием рельефа местности, позволяющий эффективно осуществлять прореживание точек лазерного отражения, являющихся незначительными при описании рельефа местности. Создана автоматическая методика выстраивания ЦМР. Сформирован алгоритм поиска неизвестных промежуточных массивов ТЛО. Разрежение доступно и для участков под наклоном. При этом сохраняется детализация в качестве линий структуры и особых точек.

Ключевые слова: цифровая модель рельефа, цифровая модель местности, воздушное лазерное сканирование, оценка качества цифровых моделей рельефа, цифровая модель шахты.

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Introduction

The paper examines the methods for building digital terrain model (DTM) based on airborne laser scanning (ALS) information. Taking into account great interest shown by scientists to the subject of data array reduction for building the models under consideration, many problems in this area remain unsolved [1-3]. Currently available algorithms of information distribution for DTMs built on standard coordinate grids do not allow successful reduction of data arrays while preserving the proper detail level of certain locations [4-6]. Operational techniques for finding intermediate unknowns in laser airborne scanning need to be matched to the current techniques for finding intermediate unknowns. They can decrease the level of detail. It is also possible to choose to sparse the data arrays associated with coordinates. In this case, it takes more time or more powerful equipment has to be used.

In addition, it is necessary to note that the software, which is used in geodesy and makes it possible to create sparse data arrays during DTM building, is based on a closed code. Accordingly, they are a kind of "black box" for building algorithms for searching unknown points in the software. Here it is impossible to make certain changes or to conduct a study of efficiency, speed of operation [7-9].

Based on the results of ALS, it is possible to obtain LRP with such a level of density that is required for DTM. The stages of ALS information processing include the allocation of LRP classes. Standard classes include land surface, land model points, lost points, different types of vegetation (differ in height). The most significant class is the terrestrial points class. The land surface class forms the DTM and DRM.

Taking into account laser reflection points (LRP) extraction, which is performed automatically, non-significant points can be formed, which are located above or below the LRP base cloud [5]. The relative number of these points is not large enough. At the same time, even a small error can lead to terrain distortion. For this reason, it is mandatory to perform manual verification of the classes. For this purpose, it is necessary to look through plots, building of height-colored models, and horizontal constructions [1, 10-11].

Based on the fact that the number of points that are on the ground can be very high, up to 1 000 000 per 500 m2, the DTM alignment requires rarefaction [4, 12-13].

It is worth noting that the point density level of laser mappings, regardless of their class, reaches 10 points per 1 m2. At the same time, the density of LRPs, which belong to the class of the earth surface, reaches up to 3 points per 1 m2. In order to build topographic plans, such work would be unnecessary and decreases productivity [7, 14-15]. It is required to determine the LRP densities depending on the surface slope angle. They can have different terrain relief character. It is also necessary to determine the minimum number of LRPs required to build DTMs related to different terrain types. Development of an algorithm for rarefaction of large arrays of LRPs, which has low computational complexity and at the same time makes it possible to form an irregular coordinate grid, is a relevant scientific problem of practical importance.

Methods

Creation of a data interpolation algorithm. To solve the issue under consideration, a coordinate redundancy parameter was created. If it is possible to find 3 nearest points in different directions for an arbitrary point of the data array, then it should be considered redundant. This is relevant if the length of the normal from the original point plotted by the 3 closest ones is less than the allowable length [16-18].

To remove the unnecessarily high number of LRPs based on the above parameter, an algorithm for finding intermediate unknown points was developed. It was based on software that is created in Python. The step-by-step operation of the algorithm is described below.

The input information for the software is supplied as text with the coordinates of the LRP. This is done in "*XYZ*" format. Next, the translation of the text information and filling the array of coordinates of points A are carried out. Here all rows are corresponding to a certain point. The initial 3 columns correspond to the coordinates present within the 3D space [19-21]. Accordingly, the array A is a matrix of size [n×3]. Here n is the number of LRP points in the initial set of information.

The value of the minimum information granularity should be set. It is required to calculate the highest deviation of a point from the plane constructed by means of 3 neighboring points: ΔD [22-24]. Such actions are performed for each point of the array A. For this reason, for the following description of the algorithm, we should define an arbitrary point O. It contains coordinates ($x0$, $y0$, $z0$) from the array A.

A complete copy is created for the data array A, excluding the point *O* and forming the array B. Two columns are attached to the data array *B*, which have the information about the length l and the angle of rotation of the vector built from the points from the array B to the point O. These are in the XY system. The applicate Z is not taken into account here. For all points N from array B with coordinates x_n, y_n, z_n, the calculation of the length l to *O* is done as follows:

$$l = \sqrt{(x_n - x_0)^2 + (y_n - y_0)^2}.$$

The angle of rotation of the vector *ON* to *O* is calculated as:

$$\theta = atan2\left(\frac{y_n - y_0}{x_n - x_0}\right).$$

Here atan2 is an arctangent function that provides the return of the direction rotation angle by considering quadrants as opposed to the standard arctangent [25-27].

Computation of the parameters l and θ for all points in the array *B* requires dividing them according to the growth of the parameters l. Therefore, the closest points to the *O* coordinates will be at the very beginning. The results of this information structure are shown in Table 1.

It is necessary to distinguish 3 directions of finding the closest points. They can be labeled as: northeast, $\theta\epsilon[0;\frac{2\pi}{3})$; west, $\theta\epsilon[\frac{2\pi}{3};\pi) \cap [-\pi;-\frac{2\pi}{3})$; southeast, $\theta\epsilon[-\frac{2\pi}{3};0)$.

The algorithm goes through the rows of the array B after some time. As the result, everything is found by the nearest points (min l). Let us name the points A, B, C. If any of the close to N points is not found, then O stays in the original data array A. Another point is selected for lining up. This situation is typical if O resides on the boundary of LRP [28-30]. At the same time, the closest point to it is located in another data array of LRP. It can also happen that the information about a point will be missing.

If *A*, *B*, *C* are found, a plane called *ABC* is constructed based on them. Its equation in three-dimensional form looks like this:

$$ax + by + cz = d.$$

The coefficients a, b, c are the coordinates of the normal vector *N* to the plane *ABC*. They are calculated from the vector product of any 2 vectors related to *ABC*. For example: $N(a, b, c) = AB \times AC$. The coefficient d is calculated from the scalar product of the direction of normal *N* and the coordinates of point *B* or *C*: $d = N \cdot B$.

The absolute distance that is present within the three-dimensional space between *O* and *ABC* is then calculated as follows:

$$L_{xyz} = \frac{|ax_0 + by_0 + cz_0 - d|}{\sqrt{a^2 + b^2 + c^2}}.$$

If $L_{xyz} < \Delta L$, then O is not significant for terrain estimation. It can be disregarded in the initial array A. Next, we proceed to study another point. Here the dimensionality of the array A is reduced to $[n - 1 \times 3]$. Due to this, a sparse information is obtained. After studying each point of array A, the sparse information is stored in a new file. It is used for further in special software.

In order to eliminate too many LRPs, an algorithm to find unknown points is formed. It was developed in Python 3,6.

In the previous research on this topic, it was possible to determine the required point density for certain landforms. The data obtained is summarized as follows:

1. Plain with angles up to 2º regardless of the scanner passport error. The lowest allowable number of reflection points to form an electronic models considered to be 0,23 t/m^2. If we take into account the impact of the passport error of the scanning device, the value is 0,41 t/m^2.

2. Relief with angles up to 4º regardless of the scanner passport error. The smallest permissible number of reflection points for the formation of the electronic model is considered to be 0,48 t/m^2. If we take into account the impact of the scanning device passport error, the value is 0,67 t/m^2.

3. Intersected with angles up to 6º regardless of the scanner passport error. The lowest allowable number of reflection points for the formation of the electronic model is considered to be 0,93 t/m^2. If the impact of the scanning device passport error is taken into account, the value is 1,20 t/m^2.

4. Mountainous and foothill with angles more than 6º regardless of the scanner passport error. The lowest allowable number of reflection points for the formation of the electronic model is considered to be 1,59 t/m^2. If we take into account the impact of the scanning device passport error, the value is 1,93 t/m^2. In Figure 2, the coordinate axis is indicated as relief slope angles. The abscissa axis is shown by the deviation of the required LRP density, taking into account the error of the equipment and regardless of these data.

It was possible to form methods that allow automating the processing of the ALS data array, obtained from the moment of point extraction for the ground surface in the corresponding software. This is carried out according to the following parameters:

1. The density of LRP in the DTM is obliged to be the lowest possible, which increases the efficiency of the subsequent drafting stages.

2. The distance between points should not exceed 20 m, which depends on conditions for accuracy of topographic maps of 1:500, 1:1000 scales.

At the same time it is required to provide the specified parameters of DTM accuracy.

The set of parameters described above makes it possible to form at the output of the model the minimum requirement for resources for calculations during its processing and building. At the same time topographic maps, which are built on the considered DTMs, should meet the accuracy requirements.

The sparse LRP, which belongs to the class of the earth surface, is performed using the generated algorithm for finding unknown points. It was able to determine that the maximum distance ΔD from the point to be excluded to the plane created from 3 neighboring points creates the minimum accuracy of the model built from the sparse information.

We were able to deduce that the mean square distance from the points to be excluded from the ALS data set to the planes formed by 3 neighboring points is related to the calculated mean square deviations of the elevations of the DTM in ArcGIS environment, which is built from the two types of LRP array. Accordingly, searching for unknown points of the LRP array by the developed algorithm with a certain ΔD on creates a sparse LRP array at the output with $\delta_D \leq \Delta D$.

The value of ΔD is taken as a measure of the expected accuracy of the model built from the sparse array of information. The alignment is relative to the model built from the initial ALS information, and the parameter $\delta_D$represents the actual accuracy [11-15].

Automatic building a DTM of certain accuracy can be achieved by iteratively using an algorithm for finding unknown ALS points. The algorithm concerns the points with changing the value of ΔD in all iterations and calculating the actual accuracy of the DTM. The calculations are performed after all iterations. They are finished at the moment when they become close to the deviation target.

The step change of ΔD is carried out by means of the proportional integral control function. It is interrelated with δ_D, calculated at the previous step by the formula:

$$\Delta D = K_p(\delta_D - \delta_D^*) + K_I \int (\delta_D - \delta_D^*),$$

where δ_D^* is the limit parameter of deviation error according to the height indicators corresponding to the limit characteristics of the mean square error (MSE) during the terrain survey: 0,18 m; K_p, K_I , are the coefficients of integral and proportional change of ΔD value, they are chosen by experience. The iteration able to fulfill the equality specified below is the final sparse array of LRP. It does not fit into the specified precision δ_D^*:

$$|\delta_D - \delta_D^*| \leq \delta_y,$$

where δ_D is the setpoint of the largest deviation of the real accuracy from the assumed one.

The considered sequence of actions makes it possible to generate a DTM that meets the first and third criteria. To satisfy the second criterion, the LRP array should be distributed into sectors of 20x20 m area. The main points are placed in the corners of these sectors, which do not need to be found.

Results

A significant issue that concerns the evaluation of the search results for unknown LRP array data becomes the comparison of the accuracy of the original DTM and the DTM that were obtained from the sparse array.

The simplest method of evaluating the accuracy of the DTM that was obtained after searching for unknown LRP array data using the generated algorithm becomes the evaluation after each iteration. This is relevant for cases when for all excluded points the deviation D_{xyz} from the plane formed by three points standing next to each other will be noted. In this situation, it is required to enter the magnitude of the inaccuracy of the missing data search using the mean square deviation δ_D of each excluded point. This is done using the formula:

$$\delta_D = \sqrt{\frac{\sum_{N_{D-1}}^{N_D} D_{xyz}^2}{n_d}},$$

N_D – is the number of points excluded in the process under consideration. The accuracy estimation was validated on the basis with the MSE values, which were obtained in ArcGIS Spatial Analyst.

Table 1 shows the results of comparison of the accuracy of DTM obtained by searching for unknown intermediate values using this algorithm.

The exact error of the mean square deviation of DTM heights with interpolation calculated on the basis of indicators and with the help of ArcGIS becomes negligibly small and for the studied areas with the change of ΔD parameters within certain limits [0,1; 0,3] is not more than 0,008 m.

The parameters of the mean square deviation δ_D of the DTM in height, which was obtained during the computation of points in the exclusion process, were generated by the algorithm. For this purpose, the estimation of the accuracy of the DTM embedded over the LRP array from the original DTM was applied.

Table 1 – Comparison of DTM accuracy estimation during interpolation by the algorithm
Таблица 1 – Сравнение оценивания точности ЦМР при интерполяции алгоритмом

Indicator, m	ΔD	Plot Number			
		1	2	3	4
MSEArcGIS	0,1	0,072	0,074	0,075	0,085
δ_D		0,071	0,074	0,078	0,082
δ_{AO}		0,001	0,000	0,003	0,003
MSEArcGIS	0,2	0,142	0,178	0,181	0,182
δ_D		0,141	0,170	0,175	0,181
δ_{AO}		0,001	0,008	0,005	0,001
MSEArcGIS	0,3	0,144	0,210	0,223	0,241
δ_D		0,142	0,212	0,220	0,243
δ_{AO}		0,002	0,002	0,003	0,002

It should be noted that the indicators δ_D do not coincide with the initially set ΔD. This is due to the nuances of the relief formed by the considered LRP array. Based on Table 1 we can come to certain conclusions. For flat areas 1 parameter has a limited value (below ΔD).

By adding feedback on the parameter δ_D to the algorithm under consideration and changing ΔD based on it, it is possible to automatically obtain DTM with RMS (root-mean-square error) that does not exceed a specific value. The following conclusions can be drawn from the results of the search for unknown intermediate values. Taking into account the fact that the areas do not coincide in terms of relief features, the effectiveness of the algorithm used is mainly related to the given parameters of the RMS. This feature is related to the fact that even within the hilly terrain flat surfaces with slope are formed. They can be cut quite efficiently by applying the applied GRID algorithm. It obtains maximum parameters at small grid step values, decreasing with rising grid step of GRIDs.

The efficiency of the generated algorithm is compared with the closest equivalent. The software with the algorithm of the most important model points extraction serves as such analog. Comparison of the efficiency of search for unknown intermediate values using the generated algorithm and selection of mean square deviation (MSD) was carried out within as part of the steps indicated below. In order to select the MSD, the maximum deviation of 0,13 m was generated. From the moment the MSD was isolated from the original LRP array, the rarefaction of the original LRP array was performed iteratively. It was gradually increased in each new iteration by the parameter ΔD. This continued until there were no more points left in the LRP than there were in the MSD. Next, RMS scores were calculated in ArcGIS sparse using the 2 DTM algorithms relative to the DTM plotted against the original LRP cloud.

To study the performance of the sparse algorithms, 2 square plots were taken. Each had a side of 20 m:

The results of the rarefaction are shown in Table 2. The visualization of the DTM in 3D is indicated in Figure 1. Here, the models plotted against the original and thinned arrays are shown.

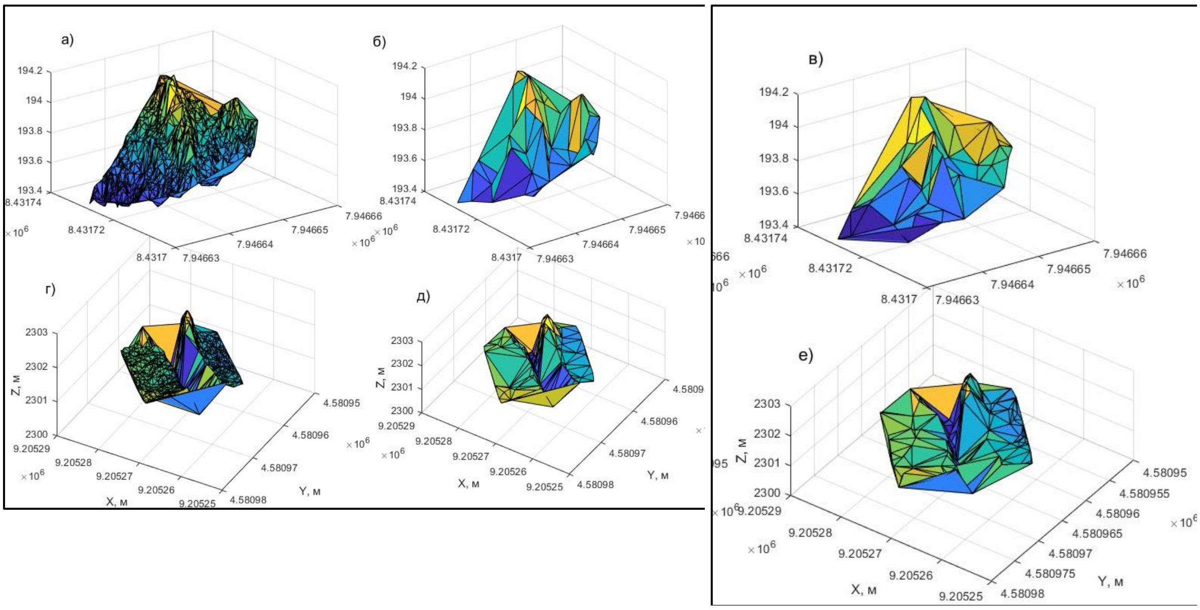

Figure 1 – Three-dimensional visualization of DTM:

а) by original LRP of plot 1; б) by original LRP of plot 2; в) by sparse in similar software LRP of plot 1; г) by sparse in similar software LRP of plot 2; д) by sparse with algorithm LRP of plot 1; е) by sparse with algorithm LRP of plot 2

Рисунок 1 – Трехмерная визуализация ЦМР:

а) по изначальным ТЛО участка 1; б) по изначальным ТЛО участка 2; в) по разреженным в аналогичном ПО ТЛО участка 1; г) по разреженным в аналогичном ПО ТЛО участка 2; д) по разреженным с алгоритмом ТЛО участка 1; е) по разреженным с алгоритмом ТЛО участка 2

To study the performance of sparse algorithms, 2 square plots are selected. The sides of each are 20 m:

1. Plot 1: flat terrain with slope. Elevations: 193,4-194,1 m.
2. Plott 2: mountainous terrain with a ravine. Altitudes: 2300-2302,3 m.

Table 2 – Comparison of the results of the LRP array interpolation by the developed algorithm and the algorithm of model fiducial pointsfixation (in similar software)
Таблица 2 – Сопоставление результатов интерполяции массива ТЛО разработанным алгоритмом и алгоритмом выделения КТМ (в аналогичном ПО)

	Plot1	**Plot2**
S, m^2	399,2	392,7
Initial Number of LRP	1266	841
Maximum Deviation of Applicate TerraScan, m	0,13	0,13
Maximum Deviation of Absolute Distancefor developing algorithm, m	0,045	0,052
LSR number, after interpolation	67	118
MSD, after interpolation in similar software product, m	0,102	0,084
MSD, after interpolation with developed algorithm, m	0,081	0,053

Discussion

Computation of structural lines is one of the most essential steps in DTM generation. The initial information for DTM building comes from distance sensing techniques. It includes a list of structural lines and elevations [31-33]. All this sets new constraints for the shape of the terrain. At the same time, the coordinates of elevations and nodes of some structural lines are specified with a high level of accuracy [34-36]. For this reason, it makes sense to apply an electronic model based on a triangular grid. Designated points act as its main nodes.

Structural lines define the areas of relief slope difference. Significant change of these parameters results in the fact that there is a significant deviation of the actual distance δ_{xyz} from the point to the plane formed by 3 points. In order to determine the structural lines, it is required to fix the points where $\delta_{xyz} \geq \Delta H$ into the corresponding array. Here ΔH acts as the specified minimum height difference. After this mark, a point should be considered as belonging to a structural line [16, 36-37].

Figure 2 shows the DTM plotted from the original ALS information of the rocky-type plot (Figure 2a) and the DTM plotted from the points found as structural lines (Figure 2b). Based on the indicated image, we can conclude that this grid makes it possible to carry the structure lines in a special layer. This layer will then be used when drawing the structure lines. This requires less information cost than determining structure lines without specialized tools.

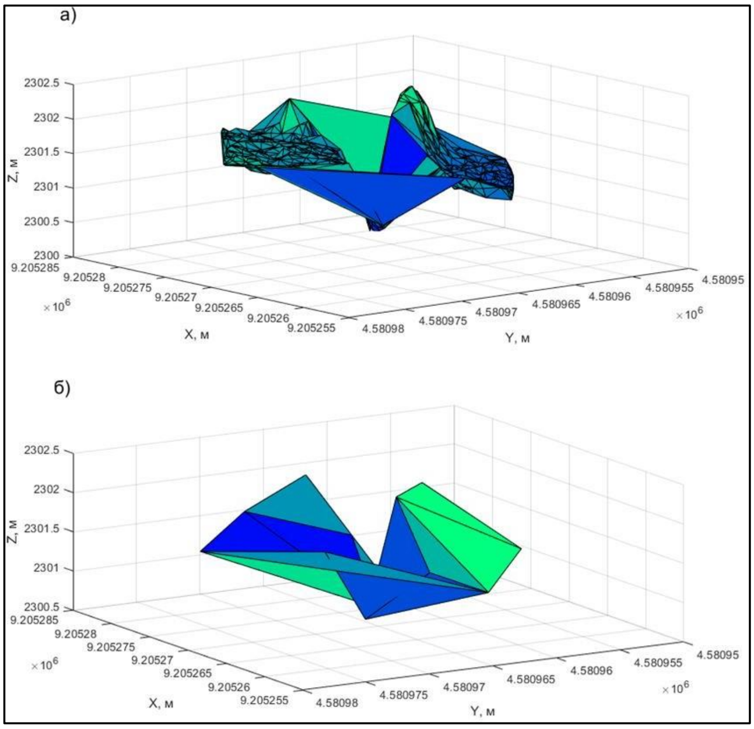

Figure 2 – а) DTM from the original ALS data of the rocky area; б) DTM from points recognized as structural lines
Рисунок 2 – а) ЦМР по исходным данным ВЛС скалистого участка; б) ЦМР по точкам, распознанным как структурные линии

Conclusion

An algorithm for unknown intermediate data acquired with laser terrain scanning is proposed, which allows efficient thinning of laser reflection points that are insignificant in terrain description. Data redundancy is determined by calculating the distance from a point to a plane including three neighboring points for it located in different directions. The proposed method of redundancy determination is implemented with the help of simple mathematical operations, due to which a lesser computational complexity of the algorithm is achieved in comparison with proprietary analogs. This makes it possible to increase the resolution efficiency of large-scale LRP arrays.

An automatic methodology for DTM construction is developed. It maintains the increase of engineering geodetic surveys efficiency during project preparation due to the use of modified electronic models adapted for a large number of software types.

An algorithm for the search of unknown intermediate LRP arrays is formed. The basic features of this algorithm include the ease of computation and the opportunity to successfully resolve points located on flat areas. The calculations do not use discretization of the plot into components, for example, based on the Delaunay algorithm. Discretization is also available for sloped plots. The detalisation in the quality of structure lines and special points is preserved.

A universal algorithm is developed, which is suitable for various fields of activity, including creation of digital models for mines and workings. The developed methodology also allows for allocating a separate layer with points that can be attributed to structure lines to ensure accurate reflection of relief features when creating a topographic map. Recently, unmanned aerial vehicles and aerial photography have become more and more widespread, so such topographic maps can be generated on the basis of various aerial images.

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