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Research Article

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A-Priori Estimate of the Airborne and Mobile Laser Scanning Data Accuracy

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ABSTRACT

Relevance

For the increased demands of the global economy, it is necessary to obtain accurate three-dimensional data about the topography and terrain features for the collection of which the laser scanning is the effective method. However, the assessment of the data accuracy obtained by these methods is not sufficiently developed. In this context, the article provides a formula for estimating the accuracy of the data obtained by means of mobile and airborne laser scanners, depending on the errors in the definition of exterior orientation elements. This conclusion is based on the derivation of the transition equations from one coordinate system to the other. To make it easier to solve the problem, it is accepted that angular elements of the exterior orientation do not exceed the values by a few degrees. Additionally, when solving the task, it is taken into account that the calculation of the most probable trajectory is carried out based on the Kalman-Bucy filter.

Scientific value

The current demands of the world economy require accurate detailed spatial data in 3D. Laser scanning is the top requested one to meet these challenges. However, in order to use these tools, you must perform a priori assessment of the accuracy of the data obtained. One of the main components of the resulting accuracy is the error in determining the elements of the scans exterior orientation. Therefore, the topic of presented article is relevant and requested.

Scientific novelty

The proposed formula of a priori assessment of the accuracy of the products obtained makes it possible, in practice, to choose suitable technological tools when performing the manufacturing operations and thereby lead to the economic effect.

Keywords: mobile laser scanning, airborne laser scanning, accuracy, elements of exterior orientation, GNSS-equipment, inertial geodetic system.

INTRODUCTION

The current challenges of providing the country's defence, the production processes of high-tech enterprises and the systems of expert assessments are forcing to increase the spatial information requirements, namely to accuracy, detail level, and visualization. It should also be borne in mind that many of them require the availability of spatial information on-line or as soon as possible. These tasks can include [1-3, 8, 10, 15]:

- emergency recovery when removing ruins;
- operation of precision robotic systems during explosive device disposal;
- executive survey of marine oil platforms due to significant space limitations;

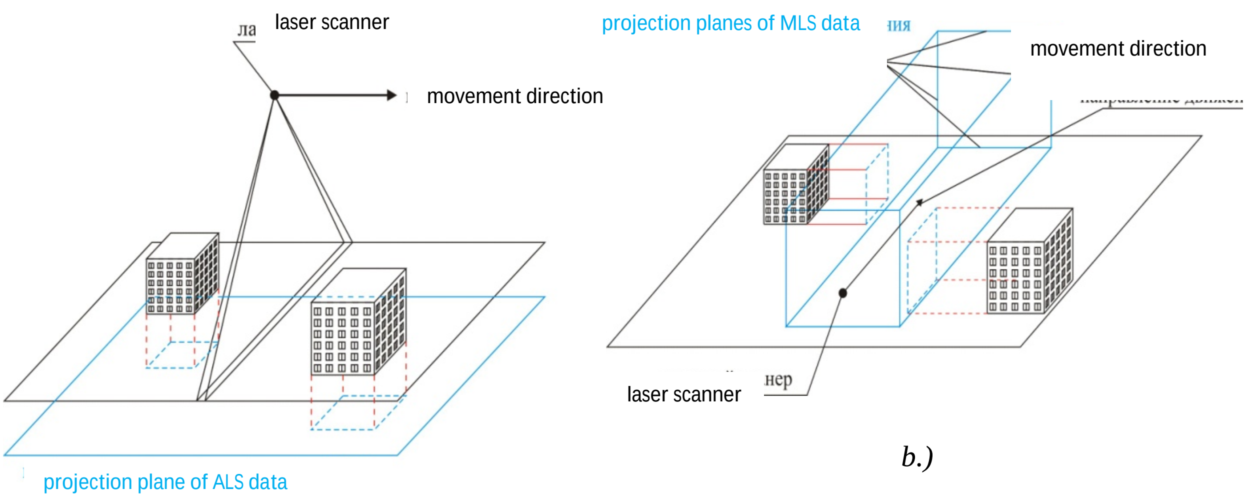
- control and alignment of the installation of technological equipment and complex engineering facilities;
- determination of the geometric parameters of complex dynamic processes (crash tests, projectile explosions, and so on) and other tasks.

The solution to thesedefense, the scientific and production tasks in the shortest time is possible using only laser scanning technologies. But in this case, the problem of a significant increase in data processing speed and accuracy assessment of the data obtained appears [10, 15].

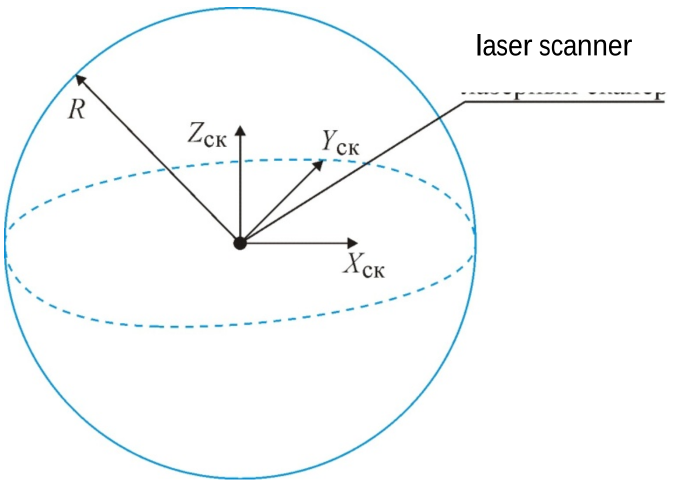
METHODOLOGICAL BASE.

To improve the performance of data processing algorithms, it is more reasonable to take into account the topology of their obtaining. Figure 1 shows the differences in the topology of terrestrial, airborne, and mobile laser scanning data obtaining.Figure 1*b* shows that the terrestrial laser scan topology is equivalent to a sphere. For the last, the topological properties are identical to the cube, tetrahedron, parallelepiped, and so on. From this it follows that the laser scan data topology is equivalent to all of the above-listed volumetric bodies. However, for airborne and mobile laser scanning, the topology of data acquisition is identical to the plane or set of planes. As a result, the difference in the topology of data acquisition by airborne, mobile, and terrestrial laser (Figure 1) scanning impose significant features on the development of processing algorithms and accuracy estimation. To improve the performance of data processing algorithms, it is necessary to take into account the topology of their acquisition.In addition, the distinctive feature of mobile and airborne laser scanning from terrestrial one is that the first two are in motion and the last one - in a stationary position. As a consequence, during mobile and airborne laser scanning, each element of the image has its own individual exterior orientation elements, while during terrestrial scanning they are united for the scanner station. Additionally, as a consequence of this difference, the additional errors occur, resulting in different (about 3-15 times) accuracy of the product being produced. For this reason, the terrestrial laser scanning data processing algorithms differ from the algorithms used for airborne and mobile laser scanning data. It concerns from the input laser pulse processing to the final result obtaining. The only thing that can combine processing algorithms is the idea or approach to processing. In addition, it should be borne in mind that the accuracy of the models under creating according to terrestrial laser scanning data is much higher than in the case of airborne and mobile scanning, so that these technologies will have a priory different principles for taking into account the factors influencing the accuracy of data acquisition and processing [1-9].

Based on the evidence presented, it can be concluded that the developments for airborne and mobile laser scanning should be carried out jointly.



b.)



c)

Figure 1- Differences in the topology of laser scanning data acquisition:
a) Airborne; *b)* Mobile; *c)* Terrestrial

The accuracy and density of the data obtained from mobile laser scanning (MLS) and airborne laser scanning (ALS) depends on several factors [1-9]:

- Carrier's speed;
- Accuracy of measurements by scanner, GNSS-receivers, Inertial Geodetic System (IGS);
- Carrier's motion trajectory;
- Time of continuous operation since initialization;
- Constellations of satellites during the system operation.

One of the important stages in the technology of laser scanning is the scans exterior orientation. The accuracy of the implementation of this process determines the final accuracy of building a digital model of the situation and terrain [1, 2], the quality of the point model interpretation and the ability to automate the process of constructing the digital surface model (DSM).The studies objective is to deduce formulas for estimating the accuracy of mobile and airborne laser scanning data acquisition, depending on the error in definition of the exterior orientation elements.The MLS and ALS systems consist of GNSS-receivers, Inertial Geodetic System (IGS) and laser scanner. The result of the MLS and ALS systems operation is the exteriorly-oriented dots array. With this, data adjustment received by GNSS-receiver and IGS are carried out jointly. Thus, the exterrior orientation elements (EOE) are defined regardless of the scanning results. In this case, the total root-mean-square error (RMS error) of the terrain or object point coordinates acquisition can be represented as follows [10]

$$m_K^2 = m_{\text{ОР}}^2 + m_{\text{ИЗМ}}^2 , \qquad (1)$$

where$m_{\text{ОР}}$– RMS error is due to errors of the scans exterior orientation;

$m_{\text{ИЗМ}}$– RMS of the model points coordinates setting caused by the effects of the scanner instrumental errors, external environment and metrological properties of the scan target calculated by formulas [10.11]:

$$m_R^{\text{ед.из.}} = \sqrt{m_{F[f_{\text{вх}}(t)]}^2 + m_{R(T,P,E)}^2 + m_{R_{\text{вибр}}}^2 + \frac{\left(m_{R_{\text{метрол}}}^2 - m_{\sigma R_{\text{инстр}}}^2\right)}{\sqrt{n}} + m_{\delta_R}^2} , \qquad (2)$$

$$m_\varphi^{\text{ед.из.}} = \sqrt{m_{\delta\varphi(T,p,E)}^2 + m_{\varphi_{\text{вибр}}}^2 + \frac{\left(m_{\varphi_{\text{метрол}}}^2 - m_{\sigma\varphi}^2\right)}{\sqrt{n}} + m_{\delta_\varphi}^2} , \qquad (3)$$

where $m_{F[f_{\text{вх}}(t)]}$ is the root-mean-square errors caused by the change in the input signal function during measuring distances.

$m_{R(T,P,E)}$, $m_{\varphi(T,P,E)}$ is the root-mean-square errors in measuring distances and angle caused by the residual effect of the systematic errors;

$m_{R_{вибр}}$, $m_{\varphi_{вибр}}$ is the root-mean-square errors in measuring distances and angle caused by vibrations of MLS or ALS;

$m_{R_{метрол}}$ - $m_{\varphi_{метрол}}$ is the errors of a single measurement of distance and angle resulting from metrological inspection of the instrument;

$m_{\sigma R}$, $m_{\sigma\varphi}$ - values of systematic instrumental errors. The error data can be excluded according to metrological inspection. The ways of systematic errors exclusion are identified in scientific studies presented in the papers [8, 9];

m_{δ_R}, m_{δ_φ} is the root-mean-square errors caused by accidental changes in vibration settings, changes in wind velocity and direction, heterogeneity of the metrological properties of the target, etc.;

n is the number of ways.

For exterior orientation of laser scanning data, the expression is used

$$\begin{bmatrix} X_{вн} \\ Y_{вн} \\ Z_{вн} \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} + A \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \tag{4}$$

where $X_{вн}$, $Y_{вн}$, $Z_{вн}$ - coordinates of the scan points in the world coordinate system, that can be geodetic or set conditionally depending on the task to be solved;

X, *Y*, *Z* - coordinates of the scan points in the scanner coordinate system

X_0, Y_0, Z_0 - coordinates of the geodetic datum *OXYZ* of the scan in the world system of $OX_{вн}Y_{вн}Z_{вн}$;

A – matrix of directing cosines defining the orientation of the *OXYZ* coordinate system relative to $OX_{вн}Y_{вн}Z_{вн}$, which in general has the following form

$$A = \begin{bmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{bmatrix}, \tag{5}$$

wherea_1, a_2, a_3,…, c_3 – directing cosines which are functions of Euler angles ε, η, ξ.

m_{OP} error in the *X*, *Y* и *Z* coordinates can be calculated after differentiating the expression (4) according to the elements of the exterior orientation. Then RMS of the defining coordinates $X_{вн}$ of the object points will be expressed by the formula [12-15]

$$\begin{aligned} m^2_{X_{вн}} &= m^2_{X_0} + \left[\left(\frac{\partial a_1}{\partial \varepsilon}\right)^2 m^2_\varepsilon + \left(\frac{\partial a_1}{\partial \eta}\right)^2 m^2_\eta + \left(\frac{\partial a_1}{\partial \xi}\right)^2 m^2_\xi\right] X^2 + \\ &+ \left[\left(\frac{\partial a_2}{\partial \varepsilon}\right)^2 m^2_\varepsilon + \left(\frac{\partial a_2}{\partial \eta}\right)^2 m^2_\eta + \left(\frac{\partial a_2}{\partial \xi}\right)^2 m^2_\xi\right] Y^2 + \\ &+ \left[\left(\frac{\partial a_3}{\partial \varepsilon}\right)^2 m^2_\varepsilon + \left(\frac{\partial a_3}{\partial \eta}\right)^2 m^2_\eta + \left(\frac{\partial a_3}{\partial \xi}\right)^2 \cdot m^2_\xi\right] Z^2, \end{aligned} \tag{6}$$

Where $\left(\frac{\partial a_1}{\partial \varepsilon}\right), \left(\frac{\partial a_1}{\partial \eta}\right), \left(\frac{\partial a_1}{\partial \xi}\right), \ldots, \left(\frac{\partial a_3}{\partial \xi}\right)$ – partial derivatives from the directing cosines of expression (5) according to the elements of the exterior orientation of the scan ε, η, ξ.□.

Similarly, the formulas expressing RMS $m_{Y_{вн}}$ and $m_{Z_{вн}}$ can be received. Since the angular elements of the exterior orientation of the scan ε and η are small, to simplify the analysis of the equations, we assume that cosε≈cosη≈ 1, sin ε≈ε и sin η≈η. Taking into account the assumptions made, after some conversions of the dependence formula, the definition errors of model point coordinates from the accuracy of the scan exterior orientation will take the form

$$\left.\begin{aligned} m_{X_{вн}}^2 &= m_{X_0}^2 + m_\xi^2 \cdot Y^2 + m_\varepsilon^2 \cdot Z^2 \\ m_{Y_{вн}}^2 &= m_{Y_0}^2 + m_\xi^2 \cdot X^2 + m_\eta^2 \cdot Z^2 \\ m_{Z_{вн}}^2 &= m_{Z_0}^2 + m_\varepsilon^2 \cdot X^2 + m_\eta^2 \cdot Y^2 \end{aligned}\right\}. \tag{7}$$

By substituting the errors values of exterior orientation in expressions (8), you can get errors in the coordinates of a particular point.

During the joint adjustment of GNSS measurements and data obtained from IGS, using the Kalman-Bucy filter, change of the exterior orientation of elements along each axis can be represented as a linear equation, for example for the X axis [16, 17]

$$x_k = \begin{vmatrix} x \\ \dot{x} \end{vmatrix}, \tag{8}$$

where $\dot{x}$ is the speed of the carrier movement which is the first derivative of the movement.

With this, during adjustment by means of the Kalman-Busy filter it is considered that $(k-1)$ and the k position change of the carrier, the movement occurs with the constant acceleration of a_k. In this case, the position equation at the moment of time k is recorded as follows [16, 17]

$$x_k = F x_{k-1} + G a_k, \tag{9}$$

where $F = \begin{vmatrix} 1 & \Delta t \\ 0 & 1 \end{vmatrix}$

$$G = \begin{vmatrix} \frac{\Delta t^2}{2} \\ \Delta t \end{vmatrix}$$

In this case, the covariance matrix of impacts will take the form [16, 17]

$$Q = \sigma_a G G^T = \begin{vmatrix} \frac{\Delta t^4}{4} & \frac{\Delta t^3}{2} \\ \frac{\Delta t^3}{2} & \Delta t^2 \end{vmatrix} \delta_a^2, \tag{10}$$

where δ_a is the root-mean-square error of the acceleration definition that can be presented as

$$\delta_a^2 = \frac{4}{\Delta t^4}\delta_x^2, \qquad (11)$$

whereδ_x is the root-mean-square error of the position definition.

RESULTS.

Thus, based on equations (11) and (12), it follows that the determination accuracy of the exterior orientation elements using the Kalman-Bucy filter corresponds to the operation accuracy of GNSS-equipment and IGS.The operation accuracy of GNSS- equipment in pure kinematics mode is (50 mm ± 10 mm/km) [16-19]. The errors of the IGS operation is 5-10" [20-22]. By providing these values in expressions (6), you can obtain the coordinates definition errors of the point array, which is due to the accuracy of the measurement of the EOE as shown in Table 1.

Table 1 - SPC for determining the coordinates of the object's points, depending on the errors of the exterior orientation elements of the scan

Method of Laser Scanning	m_X, m	m_Y, m	$m_{план}$, m	m_Z, m
1	2	3	4	5
Mobile Laser Scanning $\delta_{X_0} = \delta_{Y_0} = \delta_{Z_0} = 50$ mm $m_\varepsilon = m_\eta = m_\xi = 5''$	*X* = 50 m, *Y* = 0 m, *Z* = 0 m			
	0.050	0.051	0.071	0.051
	X = 0 m, *Y* = 50 m, *Z* = 0 m			
	0.051	0.050	0.071	0.051
	X = 35.355 m, *Y* = 35.355 m, *Z* = 0 m			
	0.050	0.050	0.071	0.051
	X = 20 m, *Y* = 20 m, *Z* = 41.23 m			
	0.051	0.051	0.071	0.050
	X = 0 m, *Y* = 0 m, *Z* = 50 m			
	0.051	0.051	0.071	0.050
Airborne Laser Scanning $\delta_{X_0} = \delta_{Y_0} = \delta_{Z_0} = 50$ mm $m_\varepsilon = m_\eta = m_\xi = 10''$	*X* = 0 m, *Y* = 0 m, *Z* = 1500 m			
	0.088	0.088	0.125	0.050
	X = 600 m, *Y* = 600 m, *Z* = 1237 m			
	0.083	0.083	0.118	0.065
	X = 600 m, *Y* = 0 m, *Z* = 1375 m			
	0.083	0.088	0.121	0.058
	X = 0 m, *Y* = 600 m, *Z* = 1375 m			
	0.088	0.083	0.121	0.058

The provided values of the coordinate determination errors of the laser reflection points correspond to the ideal case:

- no failure of GNSS signal;
-
- PDOP does not exceed 3;
- no abrupt changes in the carrier position;
- no radio interference.

DISCUSSIONS.

Based on the theoretical studies carried out and practical experience, the following recommendations can be made for the exterior orientation of mobile and airborne laser scanning data:

- to improve the reliability and accuracy of the exterior orientation elements definition, you should place the reference points;
- the overlapping between adjacent routes improves the reliability of the exterior orientation elements definition with little impact on the accuracy of their adjustment;
- the accuracy of the mobile laser scanning data obtained is greatly affected by the errors in the operation of GNSS- equipment;
- theaccuracy of the airborne laser scanning data obtained is greatly affected by the errors in the operation of GNSS- equipment and IGS.

The authors of the works [1-10] were involved in the assessment of the data acquisition accuracy of mobile and airborne laser scanning or individual systems. But in most of these works the conclusions were made about operation of certain blocks. The difference of the presented researches is the comprehensive solution of the a priori estimates of the data accuracy obtained by mobile and airborne laser scanners.

CONCLUSION.

The presented formulas (1) and (7) of the accuracy a priori estimates are useful for pre-calculating the accuracy of airborne and mobile laser scanning data. In this case, it is necessary to use the methods of preliminary calculations for measurement errors made by GNSS-equipment as set out in works [23-25].Thus, the article introduces formulas that allow you to make preliminary calculation of the a priori accuracy of the data obtained during the works design stage.

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