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CRITERIA FOR CHOOSING TEST OBJECTS TYPE FOR TERRESTRIAL LASER SCANNERS CALIBRATION

Calibration of terrestrial laser scanners allows increasing the accuracy of the obtained data in order to comply with regulatory requirements for engineering geodesy works. Two types of test objects (TCO) are used for calibration: point-based and plane-based. The aim of this work is to evaluate, summarize and classify the criteria for selecting the type and subtype of test objects for terrestrial laser scanners calibration. The arrangement of the calibration polygon is performed by taking into account the minimization of possible errors, the ability to capture the maximum field of view and range of distances, and so on. Therefore, the selection criteria are considered, systematized, and recommendations for choosing the type of TCO for practical use are developed being based on its analysis. The main criteria influencing the metric quality of calibration data are determined. The criterion of the presence of planar elements or the possibility of installing point elements is set as secondary, which is considered after evaluating all other criteria and determining the necessary conditions. The main criteria are independence from the geometric quality of surfaces; independence on the laser beam angle of incidence; arrangement of overlapping scans; the ability to calibrate both the angular and rangefinder scanner unit; the ability to link to an external coordinate system. All these criteria are considered and their impact on the calibration results are analyzed. For a more accurate assessment of the criteria, it is recommended to use Student's t-test to determine the components of systematic error that most affect the calibration data. A promising area of research has been identified - the exact spherical planar TCO centroid's coordinates determination, which will allow one to take full advantage of both point-based and planar-based calibration objects. The scientific novelty of the study is to systematize the criteria for selecting test objects for calibration of terrestrial laser scanners and preliminary assessment of their impact on the calibration results. The obtained results allow taking into account the initial data and the existing conditions when evaluating the criteria for selecting the type of TCO for calibration in order to optimize the calibration process and further obtained data metric quality improvement.

Key words: terrestrial laser scanning, calibration, test calibration objects (TCO), point-based TCO, plane-based TCO, planar TCO, spherical TCO, cylindrical TCO, TCO type choosing.

Introduction

An increased accuracy is being a significant feature of engineering geodetic works in construction support. Existing technologies allow to meet these requirements in various ways, one of which is terrestrial laser scanning (TLS). However, despite the many advantages of TLS, the accuracy of the equipment in most cases does not meet regulatory requirements. Therefore, the task to improve the accuracy of the data obtained by the method of terrestrial laser scanning arises. Today, such a method of increasing accuracy is calibration. Calibration of terrestrial laser scanners is studied abroad at the universities of Calgary (Canada), Stuttgart, Hannover (Germany), Stockholm (Sweden), Zurich (Switzerland), Sydney (Australia), and in Ukraine – at the Kyiv National University of Construction and Architecture and National University “Lviv Polytechnic”.

To perform the calibration, a calibrating polygon with calibration test objects (TCO) is arranged. There are two types of TCO – point-based and plane-based. They are described by different mathematical and geometric models and are therefore used separately from each other.

Calibration studies on point-based test objects started in the early 2000s [Lichti et al., 2000] and have been active for a decade [Reshetyuk, 2009]. In [Rietdorf et al., 2004] the possibility of using planes for calibration was investigated, which was later developed in the works of other researchers [e.g. Lichti & Licht, 2006; Lichti, 2007; Bae & Lichti, 2007]. In the early 2010s, studies began on the use of cylindrical surfaces for calibration [Chan &

Lichti, 2012], and studies continued to compare calibration data obtained for different types of objects [e.g. Chow et. al., 2013].

Today, scientists usually study one type or subtype of test objects. In a number of works, such as [Chow et. al., 2011] the characteristics of accuracy and correlation of parameters of two types are comparing, or [Sossa, 2018] the minimum dimensions of planar TCO are substantiating, or [Schultz, 2012] the required accuracy of the reference device for measuring the coordinates of point-based TCO is determining. However, there are no criteria for selecting the type of TCO for calibration of TLS depending on the existing conditions and the expected result.

Purpose

The purpose of this work is to evaluate, summarize and classify the criteria for choosing the type of test objects for terrestrial laser scanners calibration.

Research methodology

The type of TCO choosing does not depend on the type of polygon used, but on the possibility / availability of different types of TCO, possible errors minimization, the ability to capture the maximum field of view and range of distances, and so on.

The author developed a model of preliminary assessment of the systematic error biases impact in the context of the universal device's error model and considered the impact of these biases on the coordinates by a priori simulation modeling of the results with systematic error (data before calibration) and its absence (data after calibration). This model allows estimating both the influence of individual biases and their total impact on the accuracy of the obtained coordinates for the subsequent analysis of the criteria for selecting the TCO type and the calibration accuracy.

Thus, it is necessary to consider the selection criteria, systematize them, and based on the analysis to develop recommendations for choosing the TCO type for practical use.

Research results

The fundamental difference between point-based and plane-based TCO is that when using point-based TCO, the coordinates of the target center are determined, while using plane-based TCO, the points defining the plane (flat, spherical or cylindrical) are determined. In addition, when calibrating with point-based TCO, it is necessary to additionally determine the coordinates of the targets with a reference device with an accuracy of at least three times better than the declared accuracy of the TLS being calibrated [Schultz, 2012]. Existing or specially prepared planes are used as plane-based test objects: structural elements indoors or outdoors, special spherical targets, etc.

As mentioned above, the mathematical models of calibration test objects differ.

The position of the point-based targets according to [Chow et. al., 2011; Lichti, 2007] is defined in spherical coordinate system:

$$\rho_{ij} = \sqrt{x_{ij}^2 + y_{ij}^2 + z_{ij}^2} + \Delta\rho,$$
$$\varphi_{ij} = \arctan\left(\frac{y_{ij}}{x_{ij}}\right) + \Delta\varphi, \quad (1)$$
$$\alpha_{ij} = \arctan\left(\frac{z_{ij}}{\sqrt{x_{ij}^2 + y_{ij}^2}}\right) + \Delta\alpha,$$

where ρ_{ij}, φ_{ij}, α_{ij} are range, horizontal angle, and vertical angle respectively of point i in scanner space j; x_{ij}, y_{ij}, z_{ij} are the Cartesian coordinates of point i in scanner space j; $\Delta\rho$, $\Delta\varphi$, $\Delta\alpha$ are the additional systematic correction parameters for range, horizontal angle, and vertical angle, respectively.

When using planes as targets in the TLS self-calibration the observations from the scanner are constrained to lie on each plane through the point-on-plane-condition equation (ibid). Using the well-known Gauss-Helmert model (also known as combined model), the plane parameters, exterior orientation parameters (EOPs), and calibration parameters are solved simultaneously in a least-squares adjustment:

$$n_k^T \left(M_j^T p_{ij} + P_{cj} \right) - d_k = 0, \quad (2)$$

where n_k is the normal vector of plane k; M_j is the 3D rotation matrix defining the orientation of scanner j as a function of the Cardan angle sequence; p_{ij} is a vector that consists of $x_{ij} y_{ij} z_{ij}$; P_{cj} defines the 3D position of scanner j; d_k is the orthogonal distance from the origin to plane k.

This model is widely used in photogrammetry and described in detail in [Föerstner, 2004].

One of the disadvantages of using planes as TCO is the possible lack of geometrically correct surfaces. For example, surfaces in the room (walls, floor, and ceiling) often have "patches" like vents, lighting devices and more. In addition, poor construction and installation work can lead to uneven surfaces, making it impossible to calibrate with them. Similarly, non-indoor surfaces used for calibration are affected by environmental conditions, and undergo temperature, and other deformations. In this case, we can consider alternative surface shapes, such as cylindrical.

In addition to the fact that cylindrical surfaces are also quite common – pipes, pylons (indoors), poles, supports, signs (outdoors), their advantages are that they are usually factory-made and maintain the geometric accuracy of the cylindrical surface quite accurately.

The principle of calibration on cylindrical targets is the same as on planar ones, only the geometric model of the plane differs. This allows the least squares method to be used to simultaneously estimate exterior orientation parameters, cylinder model parameters, and additional system parameters. First, the point cloud from the TLS is transformed into the coordinate system of the object by means of a strict transformation. Then the coordinates in this system are checked for maximum correspondence to the coordinates of the cylindrical surface by the method of least squares.

This expression allows us to convert coordinates from the coordinate system of the scanner $(X\ Y\ Z)^T$ into object's coordinates system $(x\ y\ z)^T$:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \left[R_3(\kappa_k) R_2(\varphi_k) R_1(\omega_k) \right]^T \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} X_{sk} \\ Y_{sk} \\ Z_{sk} \end{pmatrix} \quad (3)$$

where ω_k, φ_k, κ_k, X_{sk}, Y_{sk} та Z_{sk} are exterior orientation parameters of scanner position k.

While planar marks, regardless of how they are oriented in space, require one geometric model, vertical and horizontal cylindrical objects require three geometric models, denoted as f_V, f_{Hx} and f_{Hy} [Chan & Lichti, 2012]. Depending on the existing cylindrical surfaces orientation on the polygon, it is possible to align one, two or three models simultaneously.

The biases of systematic error are described [Bae, & Lichti, 2007; Chan,& Lichti, 2012; Chow, et al., 2011; Chow, et al., 2013; Lichti, & Licht, 2006; Lichti, 2007], based on a universal device's errors model.

The bias for the rangefinder offset is defined, depending on the conditions, or as a constant:

$$\Delta\rho = a_0 \quad (4.1)$$

or using the constant and the scale factor:

$$\Delta\rho = a_0 + s_\rho \rho_{measured}. \quad (4.2)$$

Vertical circle index error, as well as in classic geodetic instruments, is determined by a constant:

$$\Delta\alpha = c_0\ . \quad (5)$$

Trunnion axis bias similar to the telescope horizontal axis tilt is determined by the tangent of the vertical angle:

$$\Delta\varphi = \boldsymbol{b}_2 \tan(\alpha) \quad (6)$$

The collimation axis bias is determined by the secant of the vertical angle:

$$\Delta\varphi = \boldsymbol{b}_1 \sec\alpha \quad (7)$$

It is possible to generalize the above expressions on calibration subtypes: (4.1), (4.2) are used for calibration of the scanner rangefinder unit, and 5, 6, 7 – for calibration of the scanner angular unit.

Consider the criteria for selecting certain currents for calibration.

1. The presence of planar elements or the possibility of its installation to ensure the overlap of the maximum possible range of the scanner. The presence of possibility to set point marks to ensure the overlap of the maximum possible range of the scanner's field of view.
2. Dependence / independence from the geometric quality of surfaces.
3. Influence of the laser beam's incidence angle on the results of determining the coordinates of points.
4. Possibility / impossibility of scanning from another station (arrangement of overlapping scans).
5. Possibility / impossibility to calibrate both angular and rangefinder scanner units.
6. Possibility / impossibility of linking to the external coordinate system.

There is no calibration accuracy criterion in this list. Still in [Lichti, 2006; Lichti & Licht, 2010] suggested that similar results are obtained when calibrating point-based and plane-based targets. Data from further research confirm this. If one compare the results of the use of point-based and plane-based targets in modeling and carrying out real surveys [Chow et. al., 2011], it is seen that despite the different mathematical models, the data are approximately the same. All significant biases of the error show the same trends in calibration using both point-based and plane-based targets, and this applies to both panoramic and hybrid scanners. The exception is the bias of collimation error in hybrid scanners, which differs from the general trends in the use of plane-based targets (ibid.). In fact, the distribution of collimation error in hybrid scanners has long been a known problem and has not yet been resolved. However, plane-based targets have one advantage – they are easy to calibrate with at low scan point densities, unlike point-based targets. Although, given the speed of data collection by modern TLS (on average, 500.000 dots per second), this advantage does not look convincing. Therefore, this criterion is not considered in this paper.

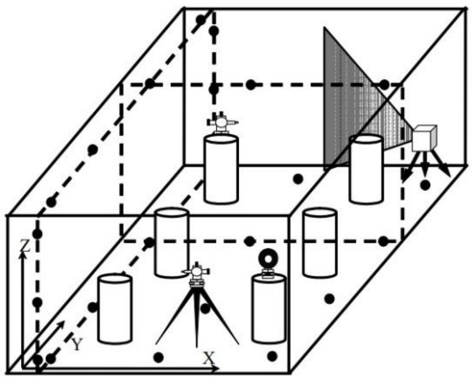

Fig. 1. Indoor polygon with point-based TCO [Reshetyuk, 2009]

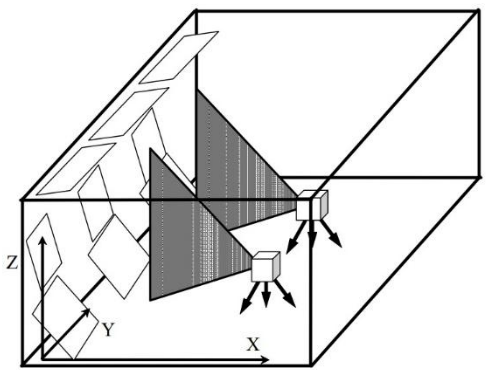

Fig. 2. Indoor polygon with plane-based TCO [Bae & Lichti, 2007]

For the analysis of the first criterion, first, it is necessary to proceed from the available conditions and possibilities for the calibration polygon arrangement. The polygon's type can be indoor or field one. The advantages of the indoor polygon are the ability to maintain stable temperatures, humidity and pressure to minimize the impact of environmental factors on the measurement results, as well as the ability to place test objects around the scanner, which in most modern models is 360° horizontally and up to 330° vertically. Examples of classical chamber polygons are shown in Fig. 1–2.

However, the disadvantage of indoor polygons is the limited space and, accordingly, the impossibility of calibration at all ranges of distances, which are 200–400 meters in modern models. In addition, there are models with the ability to measure distances up to 4000–6000 meters, which clearly indicates the impossibility of calibrating them indoors. Thus, there is a need to arrange a field polygon. The principles of its arrangement are similar, except for the obvious limitations on the location of the TCO for scanning at large angles. An example of such a polygon is shown in Fig. 3. Numbers indicate distances in meters.

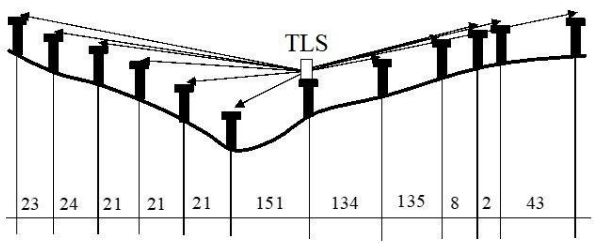

Fig. 3. Long-range field polygon [Lichti et al., 2000]

As can be seen from the figure, both point-based and plane-based TCO can be used on such a polygon. It should also be noted that in the standard conditions of urban development there is a large number of geometrically even planes. Therefore, with a good choice of station (elevated location, the presence of multi-storey buildings, etc.), it is possible to carry out calibration over sufficiently long distances and at sufficiently large angles of inclination. A necessary condition is the stability of weather conditions throughout the measurement process and the absence of wind.

According to the author, this criterion is secondary and depends on the desired calibration result. Therefore, the planning of the calibration polygon should be carried out after evaluating all other criteria and determining the necessary conditions.

When analyzing criterion No. 2, it should be noted that the dependence on surface evenness is valid only for plane-based test objects. For example, a painted metal column can no longer be used for calibration, like a cylindrical TCO, due to uneven application of paint. The same applies to other plane-based objects, both flat and spherical. Studies by Italian scientists [Alba et al., 2008] found an increase in the error of plane determination (so-called noise) with distance, even for factory-made plane-based TCO.

In Fig. 4, there is a sample of a spherical target with a diameter of 200 mm, which is used for scan registration, but can also be used for calibration.

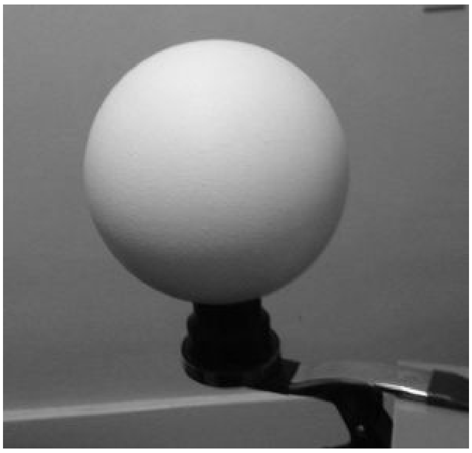

Fig. 4. A sample of spherical plane-based target

In the classical calibration approach, criterion № 3 applies to point-based targets. Despite the name, such objects are similar to flat planes, with one difference: due to the alternation of areas with different albedo, using such a target (see Fig. 5) one can determine its center with high accuracy.

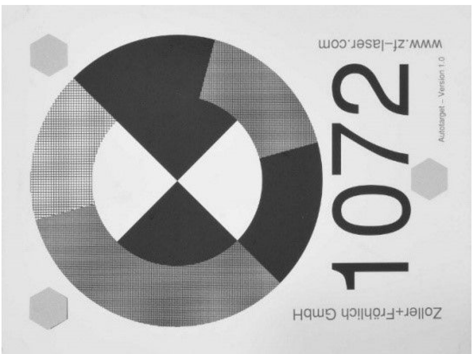

Fig. 5. A sample of point-based target

In addition, most modern devices have a function of automatic target's center determination, which is much more accurate than manual determination of coordinates from a point cloud [Sossa, 2015]. However, when re-scanning from another station, the angle of incidence of the laser beam can change significantly, thus forming the so-called TCO inclination. Data from studies [Miri & Varshosaz, 2011] of point-based targets show that the accuracy of determining the coordinates using TLS depends not only on the distance to the point, but also on the TCO inclination.

Therefore, it follows that the accuracy of determining the coordinates of points on the plane will decrease with increasing angle. As can be seen from Fig. 2, flat planes can be placed so as to minimize the effect of tilt. However, when using planes with curvature, one will also have to face the problem of tilt, because even on a spherical surface there is only one point, normal to the field of view.

The fourth, fifth and sixth criteria can be conditionally combined, as they relate to the calibration of the rangefinder unit. This calibration can be performed using plane-based targets in which the centroid coordinate can be calculated, by re-scanning it from another station. It follows that for flat plane-based TCO the arrangement of the floor is not a prerequisite.

It should also be noted that when calibrating over short distances, primarily for indoor polygons, it is possible to estimate or calibrate the rangefinder unit only approximately [Schultz, 2011]. Thus, to analyze this group of criteria, it is necessary to determine the degree of influence of the error of the rangefinder on the results of the obtained data. This once again leads to the classic problem of calibration polygons: the ability to place test objects over the entire range of distances and angles. In order to partially solve this problem, it is proposed to limit the distance of work to the maximum distance at which the calibration was performed. Additionally, there is a problem of TCOs density, namely, the angular size of the zone into which the field of view of the scanner is divided. After all, the very principle of system calibration, where the scanner is considered as a "black box" [Schultz & Sossa, 2015], assumes that the exact calibration parameters are determined only for the TCO, and only approximately between them, for example, by interpolation. With a very complex errors distribution that can occur in TLS systems, it is desirable to use automated calculation to compute the parameters of the transformation of all scans and modeling errors, for example, using neural networks [Schultz, 2012].

The author proposes to determine the main criterion for determining the condition under which, after correcting the measured values for reference points, the accuracy of determining their coordinates is sufficient for the necessary geodetic work, as well as when the approximation for a specific field of view of the scanner. In this case, the calibration results are considered as acceptable.

It is also worth noting that due to the reference to the external coordinate system and the presence of sufficiently large distances, it is possible to calculate the scale factor, which will increase the accuracy of calibration of the rangefinder. This criterion applies to point-based TCO only.

A separate issue is the exact determination of the centroids of spherical plane-based targets coordinates. Even in [Schultz, 2007] the question of such a determination was raised, but no tangible development has been obtained. According to the author, the solution of this issue will allow to make full use of all the benefits of calibration for both point-based and plane-based TCO.

Summarizing the above, the criteria for selecting the type of TCO are summarized in Table 1.

Table 1.

Correspondence of types and subtypes of TCO by criteria of their choice

Criteria / TCO type	Point-based	Plane-based		
		Flat	Spherical	Cylindrical
Independence on surfaces' evenness	+	-	-	-
Independence on laser incidence angle	-	+	-	-
No need to re-scan (overlapping)	-	+/-	-	-
Ability to calibrate rangefinder unit	+	-	+	+
Ability of linking to the external coordinate system	+	-	-	-

Using the mentioned criteria, it is impossible to unambiguously prefer any one type. Therefore, as mentioned above, based on the analysis of the criteria listed in Table 1, it is necessary to determine the necessary conditions, and based on the compliance of the criteria with these conditions to design and arrange a calibration polygon. It is advisable to use [Abbas et. al., 2014] t-test to assess the impact of systematic error biases, which are calculated to determine additional systematic corrections in distance, horizontal and vertical angle.

The obtained results allow taking into account the initial data and the existing conditions when evaluating the criteria for selecting the type of TCO for calibration in order to optimize the calibration process and further improving the metric quality of the obtained data. The proposed systematization of criteria avoids uncertainty and reduces the risk of unsuccessful attempts in the design and construction of polygons for terrestrial laser scanners calibration.

Scientific novelty and practical significance

The scientific novelty of the study is to systematize the criteria for choosing test calibration objects of terrestrial laser scanners and preliminary assessment of their impact on the calibration results. Thanks to the developed model of estimating the impact of both systematic error biases and their total impact, it is possible to use the t-test of individual biases and assess the accuracy of calibration.

Conclusion

The main criteria for choosing the TCO type during the terrestrial laser scanners system calibration are generalized and systematized. The influence of the specified criteria on direct measurements carrying out and on final result quality is investigated. It is determined that the design of the calibration polygon should be carried out after a comprehensive assessment of the criteria. In addition, it is recommended to conduct a preliminary analysis of the biases of systematic error that have the greatest impact on the data accuracy. It is established that a promising area of research is a combination of two types of TCO with the ability to accurately determine the coordinates of the centroid of a plane-based (spherical) object and correctly determine the biases of the systematic scanning error.

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КРИТЕРІЇ ВИБОРУ ТИПУ ТЕСТОВИХ ОБ’ЄКТІВ ДЛЯ ПРОВЕДЕННЯ КАЛІБРУВАННЯ НАЗЕМНИХ ЛАЗЕРНИХ СКАНЕРІВ

Калібрування наземних лазерних сканерів дозволяє підвищити точність отриманих даних з ціллю дотримання нормативних вимог для проведення інженерно-геодезичних робіт. При калібруванні використовують два типи тестових об’єктів: точкові та площинні. Метою цієї роботи є оцінка, узагальнення та класифікація критеріїв вибору типу та підтипу тестових об’єктів для проведення калібрування (ТОК) наземних лазерних сканерів. Влаштування калібрувального полігону виконується з урахуванням мінімізації можливих похибок, можливості захоплення максимального поля зору і діапазону відстаней тощо. Тому розглянуто критерії вибору, систематизовано їх, та на основі проведеного аналізу розроблено рекомендації по вибору типу ТОК для практичного використання. Визначено основні критерії, що впливають на метричну якість даних калібрування. Критерій наявності площинних елементів або можливості встановлення точкових прийнято як другорядний, що розглядається після оцінки всіх інших критеріїв і визначення необхідних умов. Основними критеріями визначено незалежність від геометричної рівності поверхонь; незалежність від кута падіння лазерного променю; влаштування перекриття сканів; можливість калібрування як кутомірного, так і віддалемірного блоку сканера; можливість прив’язки до зовнішньої системи координат. Розглянуто усі зазначені критерії та проаналізовано їх вплив на результати калібрування. Для більш коректної оцінки критеріїв рекомендовано використовувати t-критерій Стьюдента для визначення складових систематичної похибки, що найбільше впливають на дані калібрування. Визначено перспективний напрям досліджень – точне обчислення координат центроїду сферичного площинного ТОК, що дозволить в повній мірі скористатися перевагами як точкового, так і площинного об’єкта калібрування. Наукова новизна проведеного дослідження полягає у систематизації критеріїв вибору тестових об’єктів калібрування наземних лазерних сканерів та попередній оцінці їх впливу на результати калібрування. Отримані результати дозволяють попередньо врахувати вихідні дані та наявні умови при оцінці критеріїв вибору типу ТОК для калібрування з метою оптимізації процесу калібрування і наступним покращенням метричної якості отриманих даних.

Ключові слова: наземне лазерне сканування, калібрування, тестові об’єкти калібрування (ТОК), точкові ТОК, площинні ТОК, плоскі ТОК, сферичні ТОК, циліндричні ТОК, вибір ТОК для калібрування.

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