POSITIONAL UNCERTAINTY USING TERRESTRIAL LASER SCANNING TECHNOLOGY

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ABSTRACT:

Ben Kacyra was declaring at TED Conference in 2008 that Terrestrial Laser Scanning technology was designed for non-contact, faster, cheaper and precise measurements. He and Jerry Dimsdale developed and patented the technology in 1998 and since then it has been in constant improvement. The capabilities of the current Terrestrial Laser Scanning technology allow their use in various fields, including industrial metrology where the uncertainty and its estimation method must be as transparent as possible. For users of Terrestrial Laser Scanning equipment is imperative to distinguish between parameters that assess the quality of the measurement process and its outcomes, in this case the point cloud and its quality. This paper aims to outline the basic types of measurement process and the uncertainties related to 3D point cloud.

1. INTRODUCTION

1.1. Basic Concept

Considering that a measurement is a process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity (VIM, 2012), the qualitative evaluation of measuring process and the measurement result is realised using parameters such as (VIM, 2012):

- Measurement accuracy - closeness of agreement between a measured quantity value and a true quantity value of a measure;
- Measurement trueness - closeness of agreement between the averages of an infinite number of replicate measured quantity values and a reference quantity value;
- Measurement precision - closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions;
- Measurement uncertainty - non-negative parameter characterizing the dispersion of the quantity values being attributed to a measured, based on the information used.

For evaluation of uncertainties in measurements when there is used geodetic equipment there are accepted fields procedures for testing geodetic and survey instruments known as international standard ISO 17123. It consists of eight parts covering all surveying equipment, less Terrestrial Laser Scanning:

- ISO 17123-1:2014 1: Theory
- ISO 17123-2:2001 2: Levels
- ISO 17123-3:2001 3: Theodolites
- ISO 17123-4:2012 4: Electro-optical distance meters (EDM measurements to reflectors)
- ISO 17123-5:2012 5: Total stations
- ISO 17123-6:2012 6: Rotating lasers
- ISO 17123-7:2005 7: Optical plumbing instruments
- ISO 17123-8:2007 8: GNSS field measurement systems in real-time kinematic (RTK)

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According ISO 17123, the standard can be used when determining and evaluating the uncertainty of measurement results obtained by geodetic instruments and their ancillary equipment, when used in building and surveying measuring tasks. Primarily, these tests are intended to be field verifications of suitability of a particular instrument for the immediate task. They are not proposed as tests for acceptance or performance evaluations that are more comprehensive in nature.

ISO 17123 provides not only a means of evaluating the precision (experimental standard deviation) of an instrument, but also a tool for defining an uncertainty budget, which allows for the summation of all uncertainty components, whether they are random or systematic, to a representative measure of accuracy, i.e. the combined standard uncertainty.

Therefore, ISO 17123 provides, for defining each instrument investigated by the procedures, a proposal for additional, typical influence quantities, which can be expected during practical use. The customer can estimate, for a specific application, the relevant standard uncertainty components in order to derive and state the uncertainty of the measuring result.

For Terrestrial Laser Scanning equipment, in 2008 Reinhard Gottwald made a proposal for the 9th part of ISO 17123 – “field procedures for testing Terrestrial Laser Scanners” at “FIG Working Week 2008” which was not adopted yet.

Therefore, for the determination of uncertainties in measurements using Terrestrial Laser Scanners, the Guide to the Expression of Uncertainty in Measurement (GUM) is internationally accepted as standard (Paffenholz, 2012).

1.2. Terrestrial Laser Scanning Technology

Terrestrial Laser Scanning is a measurement technology which is based on the use of a light source for determining the position of the objects and interest areas in a 3D system. The measuring principle consist in a laser beam deflection through a mirror (by swapping or rotating) on an object surface, the reflection of the laser beam from the measured object surface and the receiving of the reflected beam (Jocea et al., 2013). Compared to measure distances using a reflective environment, the accuracy of measurement in this case depends on the intensity of the reflected laser beam.

Taking into account the measuring principle, Terrestrial Laser Scanning technology can be divided in three categories:

- Time of Flight Terrestrial Laser Scanners
- Continuous Wave Terrestrial Laser Scanners
- Triangulation Laser Scanners

The first two are used mainly for equipment with a range measuring interval that exceeds 3 meters, while scanners using triangulation method are used mainly to determine distances in laboratory and are known as “hand held laser scanners”.

The mirrors used to deflect the laser beam are grouped as follows (Reshetyuk, 2004):

- oscillating mirrors
- rotating polygonal mirrors
- “monogon” (flat) rotating mirrors

An important aspect of using laser scanners is that often the interest object is large and in order to achieve an exact digital copy are required multiple measurements from different positions, each measurement being materialized through a point cloud.

The union process of these point clouds it is called registration. If the connection of point clouds is made using points with known coordinated in a defined system, the process is called georeferencing.

For some applications (dimensional - control, measurements of deviations from the vertical) registration process is sufficient, but when we want to use the obtained data with other geospatial data is needed to perform georeferencing.

To achieve a compact point cloud it is necessary that the independent scans to be connected using various methods and processing programs. To connection of point clouds requires the existence of points and/or common areas between scans.
Depending on the project accuracy requirements the georeferencing process can be realized in several ways. The most accurate method is that is uses targets whose position has been determined in advance.

In order to use connection points is necessary to be accomplished one condition: the positional uncertainty of the points to be superior to that obtained by measuring equipment – laser scanner.

1.3 Measurements

To achieve a point cloud, Terrestrial Laser Scanning equipment performs two types of measurements: distances and angles (horizontal and vertical).

Distances

To measure the distance between device and object, the laser scanners are using light, thus assuring the traceability to the International System of Units because “meter is the length of the path travelled by light in vacuum during 1/299792458 of a second”.

If in vacuum the light has a constant speed, considered fundamental constant, in Earth’s atmosphere the light can be affected by various parameters. The speed of light is a function of temperature, atmospheric pressure, water vapour pressure (humidity) and wavelength:

$$ \text{Light} = f(T, P, e, \lambda) $$

where:
- $T$ = temperature
- $P$ = atmospheric pressure
- $e$ = water vapour pressure (humidity)
- $\lambda$ = wavelength

When using light to determine the distances device-object, the light is influenced, also, by the nature of object (colour, reflectance, material nature) as follows:

$$ \text{Roundtrip Light} = f(T, P, e, \lambda, \text{material reflectance}) $$

In 2004, Bruce R. Harvey from the University of New South Wales used a Cyrax laser scanner type with a wavelength of 532 nm. For a measuring range of 100 m he found the following: “an increase in atmospheric pressure leads to a decrease in the correction (3.6 mm over the range from 960 hPa to 1050 hPa), and an increase in temperature leads to an increase in the correction (4.3 mm over a range from 0°C to 45°C), but a change in the partial water vapour pressure (humidity) has no significant effect on the distance measurement (less than 0.005 of a millimetre)”.

As for determining the distance, the laser scanners are using light, or to be more exactly the amount of the reflected light from the object surface and returned to the equipment, the material reflectance has a great influence on the uncertainty of distance measurement. To define the influence caused by the reflectance are used targets whose reflectance is known on BaO₄ densities.

<table>
<thead>
<tr>
<th>Prod.</th>
<th>Faro</th>
<th>Leica</th>
<th>Riegl</th>
<th>Topcon</th>
<th>Trimble</th>
<th>Z+F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>X330</td>
<td>P15</td>
<td>VZ-1000</td>
<td>GLS-2000</td>
<td>TX8</td>
<td>5010C</td>
</tr>
<tr>
<td>Range</td>
<td>min/ max [m]</td>
<td>0.6/ 330</td>
<td>0.4/ 40</td>
<td>2.5/ 1400</td>
<td>1/ 350</td>
<td>0.6/ 120</td>
</tr>
</tbody>
</table>

Table 1. Measurement range of current laser scanners

Angles

For angular measurement, a laser scanner uses two pairs of coders for vertical and horizontal movement.

The Field Of View (FOV) of the laser scanners varies depending of the manufacturer and model. If the first devices were having small field angles, the current equipment reached maximum values of 400 degrees for horizontal angle and maximum of 320 degrees for vertical angle.

<table>
<thead>
<tr>
<th>Prod.</th>
<th>Faro</th>
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<td>GLS-2000</td>
<td>TX8</td>
<td>5010C</td>
<td></td>
</tr>
<tr>
<td>FOV Horiz. [°]</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>FOV Vert. [°]</td>
<td>305</td>
<td>270</td>
<td>100</td>
<td>270</td>
<td>317</td>
<td>320</td>
</tr>
</tbody>
</table>

Table 2. The field of view of current laser scanners

The angular uncertainty is depending on: used coders, the axes eccentricity and orthogonally.
Angle = f (coders, axes \perp, exaxes) \hspace{1cm} (3)

Usually Terrestrial Laser Scanning equipment are using coders of different accuracies for two directions: horizontal and vertical.

2. UNCERTAINTIES IN MEASUREMENTS

2.1. Uncertainty notion

As we know the error of measurement is obtained a difference between the measuring value and a true value of a measure. Often for various reasons, the measurement error is not, or cannot be known, it can be only appreciated.

The range in which can be appreciate, with a given probability, the true value of the measuring is called measurement uncertainty.

Measurement uncertainty is therefore an estimate of the limits of the probable measurement errors. If after a measurement (or a series of measurements) is attributed to the measuring a probable value, V, the uncertainty is expressed quantitatively by U, so the measurement result is shown by the expression: V ± U. Specified uncertainty includes all possible errors of a measurement, whatever their sources, nature etc. (Milea, 1985).

Measurement uncertainty is an assessment, a range of values (p “ignorance range”) of which we can estimate deviations boundaries but not the sign. Uncertainty cannot be eliminated or corrected (by applying corrections). Measurement uncertainty is a probabilistic concept, because its definition appeals to the notion of probability (in the mathematical sense).

The probability that statement that the true value of the measuring is within the range of uncertainty (within ± U) is called confidence interval (Milea, 1985).

In the Terrestrial Laser Scanning filed as in any other field in order to estimate a “correct” uncertainty it needs to be appreciated the uncertainty introduced by each source of possible errors. For that purpose, it must be taken into account four main sources of errors:

- Object of measurement
- The measuring instrument
- Object – instrument interaction
- The outdoor environment

For each possible source, the uncertainty introduced must be estimated taking into account the practical conditions of the experiment. It is necessary to know all the parameters of the object under measurement, which can influence the measurement.

To estimate the measurement uncertainty of the laser scanning equipment, it is taking as its basis the maximum permissible error as technical documentation is figuring.

Object-scanner interaction is evaluated by analyzing practical scheme of the whole measurement. The assessment of external influences requires that the correlations between the influence sizes and measurement process to be known based on observations made during other previous experiments and theoretical considerations applied judiciously. Correlation between the error and the factor set which produces requires a systematic program of experiments which can be applied only if there are controllable factors (Milea, 1985).

Based on practical experiments is intended to identify the contribution of each element which affects the measurement process.

Between mean square error \( \sigma \) and the partial mean square errors \( \sigma_i \) it can be write the equation:

\[
\sigma = \sum_{i} \sigma^2_i = \sum_{i=1}^{n} \sigma_i^2
\]

where: \( r_{ij} \) is the correlation coefficient between variables characterized by parameters \( \sigma_i \) and \( \sigma_j \). \( r_{ij} \) has a value between 0 and 1. When \( r_{ij} = 0 \) - an uncorrelated variables, the factors which generate errors \( \sigma_i \) and \( \sigma_j \) are completely independent from it, and when \( r_{ij} = 1 \), the variables are correlated total between them.

In case of Terrestrial Laser Scanning, the correlation coefficient is intermediate \( 0 < | r_{ij} | < 1 \). Since each laser scanning device type is different, different concepts, different method of determining the distance, the light with a different wavelength the correlation coefficient is unique.
To estimate the measurement uncertainty of a point in the point cloud using a Terrestrial Laser Scanning are needed practical experiments to study the behavior of the equipment with respect to repeatability, reproducibility and equipment confidence.

As mentioned, at this time there is no standard for testing a laser scanner, but there is a specialized literature with various items that refers to different types of experiments that highlight the influence of the factors regarding the measuring process.

One of the most comprehensive and feasible experiment is proposed by Leica, Hans Heister method, which involves the use of four targets arranged in two orthogonal planes whose position is determined from two scanning stations (Leica, 2008).

![Figure 4. Field layout (©Leica, 2008)](image)

From practical experiments result the uncertainty values for distance and angles (horizontal and vertical) measurements (Leica, 2008):

- **The distance**
  Scan from SC1: \((1-2)_{SC1} = (1-2) + 2c\)
  Scan from SC2: \((1-2)_{SC2} = (1-2)\)
  Results:

- **Horizontal angle**
  Scan from SC1: \((2-3)_{SC1} = (2-3) + 2c\)
  Scan from SC2: \((2-3)_{SC2} = (2-3) + c\tan (27.5) + Hz_{error-influence}\)
  Results: \(Hz_{error-influence} = (2-3)_{SC2} - (2-3)_{SC1} + 0.54c\)

- **Vertical angle**
  Scan from SC1: \((2-4)_{SC1} = (2-4) + c\)
  Scan from SC2: \((2-4)_{SC2} = (2-4) + c\tan (27.5) + V_{error-influence}\)
  Results: \(V_{error-influence} = (2-4)_{SC2} - (2-4)_{SC1} + 0.54c\)

As a result of estimation of random errors by repeating the measurement is reached to an uncertainty determination which can be called uncertainty of type \(A\), \(\sigma_A\), representing the mean square error which is estimated as a characteristic of uncertainty of type \(A\), for a given measurement process - \(\sigma_A\) - *experimental mean square error*. Another category of errors are estimated based on information that does not come from repeat measurements. They are estimated by assessments based on this information to determine another uncertainty, which can be called uncertainty of type \(B\), \(\sigma_B\) – *appreciated mean square error* (Fernandez Pareja et al., 2013).

For each equipment is necessary to prepare a personalized list of errors and their size that affect the measurement process.

<table>
<thead>
<tr>
<th>Input quantity</th>
<th>Uncertainty</th>
<th>Type of evaluation</th>
<th>Source of uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>(u_D)</td>
<td>A</td>
<td>Repetition and reproducibility, estimation of standard deviation</td>
</tr>
<tr>
<td>Hz</td>
<td>(u_\theta)</td>
<td>A</td>
<td>Repetition and reproducibility, estimation of standard deviation</td>
</tr>
<tr>
<td>Vt</td>
<td>(u_\phi)</td>
<td>A</td>
<td>Repetition and reproducibility, estimation of standard deviation</td>
</tr>
<tr>
<td>atmospheric temperature</td>
<td>(u_T)</td>
<td>B</td>
<td>General knowledge of the behavior</td>
</tr>
<tr>
<td>atmospheric pressure</td>
<td>(u_P)</td>
<td>B</td>
<td>General knowledge of the behavior</td>
</tr>
<tr>
<td>water vapour pressure</td>
<td>(u_w)</td>
<td>B</td>
<td>General knowledge of the behavior</td>
</tr>
<tr>
<td>pressure (humidity)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wavelength</td>
<td>(u_\lambda)</td>
<td>B</td>
<td>General knowledge of the behavior</td>
</tr>
<tr>
<td>Material reflectance</td>
<td>(u_{ref})</td>
<td>B</td>
<td>General knowledge of the behavior</td>
</tr>
<tr>
<td>Codificatores</td>
<td>(u_{cod})</td>
<td>A</td>
<td>Repetition and reproducibility, estimation of standard deviation</td>
</tr>
<tr>
<td>(\perp) axes</td>
<td>(u_\perp)</td>
<td>A</td>
<td>Centering eccentricity and estimation of standard deviation</td>
</tr>
<tr>
<td>Excentricity of axex</td>
<td>(u_{ex})</td>
<td>A</td>
<td>Centering eccentricity and estimation of standard deviation</td>
</tr>
</tbody>
</table>

Table 3. Uncertainty budget (Fernandez Pareja et al., 2013)

The two uncertainties of type \(A\) and type \(B\) are the two components of the measurement uncertainty, and they are different depending on the way that they were determined.

As each mean square errors \(\sigma_A\) and \(\sigma_B\) are characterizing statistically the measurement result, depending on a group variables which are acting...
simultaneously, according to the probability theory, the resulting mean square error of the measurement process is:

\[ \sigma^2 = \sigma_A^2 + \sigma_B^2 + \sigma_C^2 \]

The resulting mean square error \( \sigma \) is called in the international recommendations composed uncertainty or 1σ uncertainty by admitting the fact that the type A uncertainty is characterized by \( \sigma_A = S_0 \) and the type B uncertainty is characterized by \( \sigma_B = \sigma_C \).

**Stochastic components**

The observables of which the users have access are the coordinates \( X, Y, Z \) of the point cloud. These coordinates can be computed using (Cristea et al., 2013):

\[
\begin{align*}
X &= D \cos \theta \cos \varphi \\
Y &= D \sin \theta \cos \varphi \\
Z &= D \sin \varphi
\end{align*}
\]

where \( \theta \) = horizontal angle  
\( \varphi \) = vertical angle  
\( D \) = distance device - object

The spatial position of a point is defined taking into account the positioning uncertainties in 3D space.

**X direction**

For X direction uncertainty is derived partial the relationship \( X = D \cos \theta \cos \varphi \) depending on the components: \( D, \theta, \varphi \).

\[
\sigma_X^2 = (\cos \theta \cdot \cos \varphi)^2 \cdot \sigma_D^2 + (\cos \theta \cdot \cos \varphi)^2 \cdot \sigma_\theta^2 + 
+ (\cos \theta \cdot \cos \varphi)^2 \cdot \sigma_\varphi^2 + 2 \cdot \cos \theta \cdot \cos \varphi \cdot (-D \cdot \cos \theta \cdot \cos \varphi) \cdot \sigma_D \cdot \sigma_\theta + 
+ 2 \cdot \cos \theta \cdot \cos \varphi \cdot (-D \cdot \cos \theta \cdot \cos \varphi) \cdot \sigma_D \cdot \sigma_\varphi
\]

where: \( D \) is in meter and \( \theta \) and \( \varphi \) are in radians.

**Y Direction**

For Y direction uncertainty is derived partial the relationship \( Y = f(D, \theta, \varphi) \) depending on the components: \( D, \theta, \varphi \).

\[
\sigma_Y^2 = \sin \theta \cdot \cos \varphi \cdot \sigma_D^2 + \sin \varphi \cdot \sigma_D^2 \]

where: \( D \) is in meter and \( \theta \) and \( \varphi \) are in radians.

**Z Direction**

For Z direction uncertainty is derived partial the relationship \( Z = D \sin \varphi \) depending on the components: \( D, \varphi \).

\[
\sigma_Z^2 = \sin^2 \varphi \cdot \sigma_D^2 + \sigma_D^2 + 2 \cdot \sin \varphi \cdot (\sin \varphi \cdot \sigma_D \cdot \sigma_\varphi)
\]

where: \( D \) is in meter and \( \theta \) and \( \varphi \) are in radians.

**2.2. Positional uncertainty**

The uncertainty of a point in 3D space from a scan is given by the composition of the three directions for different values of horizontal and vertical angles.

\[
u_{1D} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}
\]

As mentioned, the maximum and minimum uncertainty in the three directions varies depending on the values of angles. If the angle is known, its origin is unknown and is specific to each manufacturer of scanning device. This should be taken into account when we want to determine the uncertainty of a point in 3D space.
3. CONCLUSION

The composed uncertainty $U$ is a synthetic characteristic of the measurement result in terms of the errors that affect it, is an indicator of a measurement uncertainty expressed in the simplest form.

To classify a point cloud, from qualitative point of view, is necessary to refer to the uncertainty of a point determination from a point cloud gathered from a single scan and to the uncertainty of a point determination from a registered point cloud. The quality of a point cloud is tied to the accuracy of the equipment, the quality of georeferencing and verification method.

In a laser scanning pyramid the point cloud forms the basis of this, the quality of georeferencing being of great importance because it affects all subsequent stages. To make an accurate georeferencing will be used points whose positional uncertainty will be better than the positional uncertainty a 3D point determined by the scanner.

4. REFERENCES


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1. ranging error – is defined as a systematic measurement error at around 10m and 25m, one sigma.
2. accuracy is the degree of conformity of a measured quantity to its actual (true) value, one sigma @100m range under RIEGL test conditions
3. distance between 1 and 150 m one sigma
4. range systematic error
5. 0.4 mm rms @ 10 m, black 14%, one sigma
6. 1.6 mm@100 m white 80%, one sigma


