Analysis of error sources in Terrestrial Laser Scanning

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Abstract: *Although in the market, terrestrial laser scanners of several companies are available, a direct comparison between laser scanners is difficult because of their specific construction and defining parameters. Terrestrial laser scanning is being used more and more for a variety of applications. In order to see which laser scanning system is suitable for each application, it is essential to analyze the accuracy and behavior of these systems. Several researchers have already published in their papers methods and results regarding accuracy examination with laser scanners. The practice demonstrates that even the laser scanner producers publish in technical specifications the accuracies to point up the benefits of their product, sometimes these should not be accept as trued because of the fact that the accuracy differ from device to device and depends on the individual calibration and the care that has been taken in the use of the device. To be able to scientifically explain error sources for laser scanning, these are separated into four classes:* ***instrumental****,* ***object-related****,* ***environmental*** *and* ***methodological errors****.*

Keywords: *Terrestrial Laser Scanning, instrumental, object-related, environmental and methodological errors*

1. Introduction

Terrestrial **L**aser **S**canning is a new geodetic technique, through which can be measure fully automatically (more or less) with high accuracy and high speed a geometry, without the aid of a reflective environment. The measurement result is represented by a considerable amount of points known in literature as **point cloud**.

In the documentation of the existing construction and facilities and restoration of the historical monuments, the most important part is to know the geometry of the object. Today, the complex documentation of a construction is usually held in a GIS, a spatial representation of the object based on a limited number of basic modeling forms, such as *lines, polygons* and *frames.* Through them are represented edges, corners, patches and volume items of the real object. Depending on the purpose, the result should correspond within certain accuracy with the real object.

Starting from the many activities fields, where terrestrial laser scanning proves its usefulness, it can be made several observations regarding the accuracy. In some areas this parameter is not always a predominant requirement.

Each point cloud delivered by a laser scanner contains a number of points that are affected by large errors. If the final result is represented by the point cloud, the measurements precision can not be guarantee with the same level like a measurement done with a conventional topographic instrument.

A standard deviation for a few millimeters for a point contained by the scanned area is not leaving so much in evidence if this point is a part of an element which by processing operation has a regular geometry (patch, cylinder, etc) and if this point is used only to find parameters that are describing this item to a CAD representation. If we have to model irregular surfaces (usual through polygonal networks - grid or mesh) or point clouds affected by *noise* we may have difficulties in processing, especially with the finishing of the edges.

2. Classification of error sources

Until now, the research institutes have realized some tests using different models of laser scanners. From these analyses resulted a description of the error sources which may affect the terrestrial laser scanning measurements. These error sources may be separated in four classes:

- **instrumental errors;**
- **errors related to the form and the nature of the scanned object;**
- **errors caused by the environmental in which is performed the scanning;**
- **methodological errors.**

Practical experience has shown that reducing or eliminating the effect of these errors depends on the individual calibration of each type of instrument and the care that has been taken in the use of the instrument.

Taking into account the size of the object and the distance at which it is situated the conclusion would be that ***the scan procedures should be performed with an adequate scanner.***

While most specialists tend to consider the accuracy parameters as the predominant considerations in the comparison of measurements equipment, for practical uses are numerous other features which may be decisive in delivering a project.

2.1 Instrumental errors

Instrumental error may be categorized into ***systematic*** and ***random*** error and may be appropriate type of scanner. Random errors affect mainly the precision of the distance and angle measurements in the case of instruments that use *time of flight* principle. Systematic errors can be generated by the non-linearity of the time or temperature measuring system, which can strongly influence the electronic distance measurements.

2.1.1 Laser Beam width

One of the important properties of a scanner which strongly influences both the point cloud resolution and positional uncertainty is the laser beam width. Laser beam width increases once with the distance travelled. According to Weichel (1990) a laser beam width can be expressed as:

$$r(\rho_r) = r_0 \sqrt{1 + \left(\frac{\lambda \rho_r}{\pi r_0^2} \right)^2} \quad (1)$$

where:

- ρ_r is range relative to the beam waist location;
- ***r*** is the radius of the laser beam;
- r_0 is the minimum radius of the laser beam called the beam waist

The expansion of the laser beam is linear for long ranges, so divergence is often specified in term of initial diameter plus a linear expansion factor. Though several diameter definitions exist the most common definition is e^{-2} which encircles 86% of the total beam power within the Gaussian **irradiance**[1] distribution (Marshall, 1985).

Basically, the beam divergence has an effect on the angle measurements. The apparent location of the observation is along the centerline of the emitted beam. According to the practical experience the uncertainty of the position of the apparent location of the observation is equal with ¼ of the beam diameter.

2.1.2 Boundaries effect

One of the most important consequences of the laser beam is the boundaries effect. Since the laser beam is not a geometrical point, but an ellipse, when it hits a boundary of an occlusion, it is divided in two parts. A part of the beam will be reflected there and the rest may be reflected from the adjacent surface, a different surface behind the occlusion boundary. Hence, the reflected flux (irradiance) at this point will be a weighted average of the irradiance reflected by both surfaces.

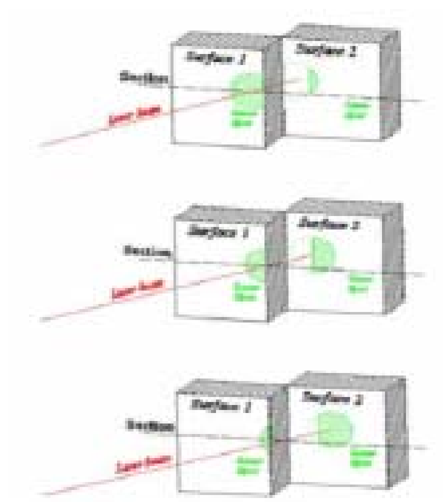

Figure 1. Erroneous measurements at the boundary of an occlusion (S. Sotoodeh, 2006)

2.1.3 Range accuracy

In terrestrial laser scanning ranging is carried out either by triangulation or by measuring time of flight of the laser signal. Another possibility to determinate the traveling time of the signal is realized by measuring phase difference between transmitted and received signal.

The range resolution for the triangulation scanners can be expressed by:

$$\delta_z \approx \frac{Z^2}{f \cdot D}\delta_p \qquad (2)$$

where:

- ***f*** is the effective position of the laser spot (effective focal length);
- ***D*** is the length of the triangulation baseline;

[1] ***„Irradiance" is the radiometry term for power of electromagnetic radiation at a surface, per unit area. Irradiance is used when the electromagnetic radiation is incident on the surface. Radiant emittance is used when the radiation is emerging from the surface. The SI unit for these quantities is watt/m²***.

- δ_p is the resolutions in laser position - it depends on the type of the laser sensor, peak detector algorithm, signal-to-noise ratio and the image laser spot shape;
- ***Z*** is the distance to the scanned surface.

For the time of flight scanners, it is known that the range accuracy depends on the time interval counter. In this case the range accuracy is represented by:

$$\delta_z \approx \frac{c \cdot T_t}{2\sqrt{SNR}} \tag{3}$$

where:

- T_t is the pulse rise time;
- ***SNR*** is *signal-to-noise ratio*;
- ***c*** is the speed of light.

In continuous wave laser ranging the laser intensity is modulated with a well defined function, e.g. a sinusoidal or a square wave signal. The range accuracy depends only on the modulated wavelength (λ_m) and the *signal-to-noise ratio* and can be described by:

$$\delta_z \approx \frac{\lambda_m}{4\pi \cdot \sqrt{SNR}} \tag{4}$$

2.1.4 Angular accuracy

Most laser scanner use small rotating device (mirror, prism) to deflect the laser pulse in a certain direction. Any small angular difference depends on the distance from the instrument to the investigated object and it may generate considerable errors in the coordinates of the points.

Angular accuracy depends on the positioning errors of the rotating device and the accuracy of the angular measurements device.

> ***The practical experiments show that the influence of these errors can be detected by measuring small horizontal angles and spatial distances between objects (e.g. spheres) which are located at the same distance from the scanner and comparing those with measurement results obtained with classical surveying instruments.***

2.1.5 Axis errors

Unfortunately, the mechanical design of laser scanners is different to total stations. Most investigations used for calibration of total stations cannot be applied to laser scanners. The measurements in two faces as well as the repetition of single point measurements are impossible.

From the development of the laser scanner calibration procedures result a geometric model which imposes to take into account the following axis:

- **Vertical axis** (principal axis): allows to the system to move the laser beam horizontally. Depending on the type of the scanner, panoramic or camera-scanner, this is the rotation axis of the scanning unit or is the axis which is orthogonal to the axis of the two rotating mirrors;

- **Collimation axis**: is defined by the center of the scanning mirror and the center of the laser spot deflected on the scanned object;
- **Horizontal axis** (secondary axis): defined by the rotation axis of the deflecting mirrors.

> ***Due to the tolerances indicated by the producers, these axis are not perfectly aligned and – consequently – exist the possibilities to meet the effect of the errors known from the classical measurement instruments: the collimation error and the non-horizontality of the secondary axis error.***

2.2 Errors related to the form and the nature of the scanned object

2.2.1 Surface reflectance

Starting from the assumption that laser scanners measure the laser beam reflections from the surface of an object, we have to deal with the physical laws of reflection and optical properties of materials of the investigated object. The surface reflection of monochromatic light shows reflected beams in many directions (Figure 2).

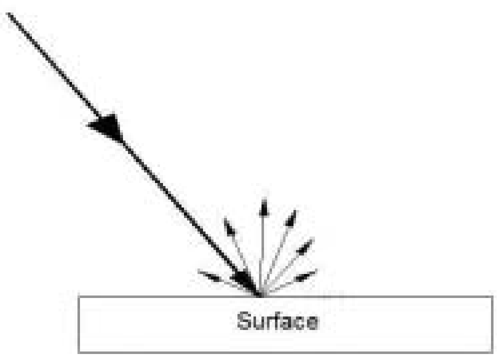

Figure 2. Diffuse (isotropic) reflection

This type of diffuse (isotropic) reflection can be described by Lambert's *cosine* law:

$$I_{refl.}(\lambda) = I_i(\lambda) \cdot k_d(\lambda) \cdot \cos(\theta) \tag{5}$$

where:

- $I_i(\lambda)$ is the incident light intensity as a function of wavelength (color);
- $k_d(\lambda)$ is the diffuse reflection coefficient which is also a function of wavelength;
- θ is the angle between the incident light and normal vector to the surface.

This formula shows us that the strength of the returning signal is influenced (among other facts such as distance, atmospheric conditions, incident angle) by the reflective abilities of the surface (*albedo*).

This means that for very dark surfaces (*black*) which absorb most of the visible spectrum, the reflected signal will be very weak. Thus the point accuracy obtain from the measurements will be affected by errors (*noises*). High reflective surfaces (e.g. *white* surfaces) yield strong reflections. However, if the object reflectivity is too high (shiny surface are not easy to record), the laser beam is totally reflected in mirroring direction and will hit another surface or will spread or dispersed. When the laser beam is dispersed on an irregular surface, the deflection results yields a random model known as ***speckle noise***.

It has been observed that recording surfaces of different reflectivity leads to systematic errors in distance measurements. Sometimes these errors can be greater than the standard deviation of a single distance determination.

In the same way the reflectance properties and color properties affect the accuracy of point determination. From practical experience it was found that there is a significant systematic range discrepancy, which can be – generally - correlated with different color of each surface with respect to the wavelength of the laser used.

2.2.2. Multipath reflection

Besides the reflectance effect, there are situations in which a number of materials have a translucent coating that allows the laser beam to refract and reflect on the surface of material itself (Figure 3).

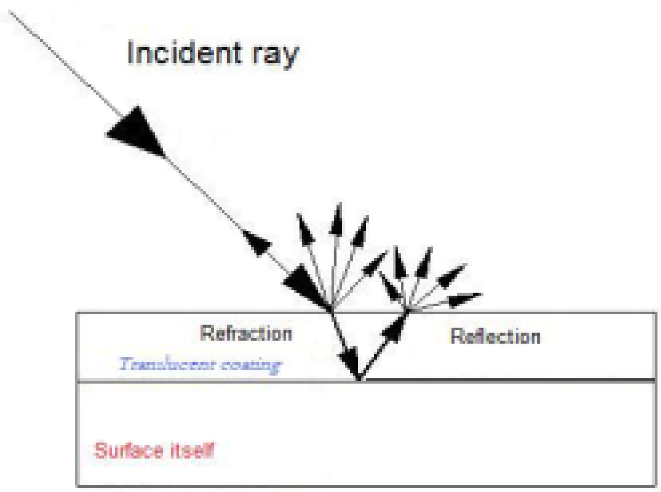

Figure 3. Refraction and reflection effect in translucent materials

This effect leads to an additional constant to the distance measurements which has to be taken into account in computation.

2.3 Errors caused by the environmental in which is performed the scanning

2.3.1 Temperature

It is necessary to be noted that temperature inside the scanner may be higher than the temperature of the surrounding atmosphere, due to internal heating of the components and external influences (e. g. sunlight). External radiations may influence one side of the tripod or scanner, which - by dilatation – can easily lead to distortion of the scan data.

Besides equipment temperature, an important factor of disturbance is represented by the scanned surface temperature. When scanning a hot object, the reflected radiations of the scanned environmental reduce the signal-to-noise ratio and the default precision of the distance measurements.

2.3.2 Atmosphere

Laser scanners operate properly when they are used in an environmental scanning which has a constant temperature along the measured distances. The accuracy of the measured distances will be affected when in the field of measuring emerge temperature differences.

Similar to all cases of distance measuring using laser technique, the environmental errors are caused by the atmospheric variations in temperature, pressure and humidity, all these affecting the value of the index of refraction and the length of the electromagnetic wave. This means that the speed of laser light is strongly dependent on the air density.

Most software components which guide and lead the scanning operations enable the possibility of setting atmospheric parameters in order to reduce the effect of the errors caused by atmospheric propagation.

In general, laser scanners are preset with values for atmospheric parameters (**ISO** standard): 15^{o}C and 1013.25 hPa. When working in different weather conditions than standard atmosphere it is necessary to readjust these parameters.

> ***A difference in temperature of 10^{o}C or in air pressure of 35 hPa may leads to a scanned distance error of 1 mm/100m.***

In terrestrial laser scanning this effect does not have a great influence on the results for small and medium scan distances.

When we are speaking about long distances or high precision scans, it is necessary to apply the correct atmospheric parameters.

> ***When working, for example, in mountain regions, can be estimated that the temperature decrease with 0.65^{o} C/100 m and air pressure decrease with 10 hPa/100 m. For a scan station situated at 2000 m the influence of the atmospheric parameters on the error of measured distances may lead to values up to 8 mm / 100 m.***

2.3.3 Interfering radiations

When laser scanners operate in very close frequency bands, the precision of distance measurements may be influenced by external radiation (e.g. sunlight, lamp). In this case, in the reception unit can be applied special optical interference filters which allow to the receiver to reach the correct frequencies.

2.3.4 Distortions from motions

Most laser scanners have a scan rate of 2000 to 500000 points per second. Although this rate is very high, scanning with a high resolution can take 20 – 30 minutes for the scanners that use *time - of - light* principle or 10 minutes for the scanners based on *phase difference* principle. During this time, the scanner is susceptible to vibration which may cause small displacements known as distortions from motions.

As each point is taken at different time, any motion of the scanned object or scanner will distort the collected data. For this reason, it is necessary that the scanner to be mounted on a stable platform to minimize the vibration phenomena.

Also, the scanned object must be fixed. Scanning object in motion is very difficult.

In a previous paragraph it was mentioned that the scanners can support movements (small displacement, distortions) due to the temperature changes, the best known case being the influence of solar heat on the tripod legs.

On the latest laser scanner systems (so-called ***scan-stations***) the compensation of any movements during the scan process is realized through a dual axis compensator.

Figura 4. Terrestrial laser systems

Scanner / Criterion		**Trimble GX**	**Leica ScanStation 1**	**Leica ScanStation 2**	**Riegl LMS-Z420i**	**FARO LS 880 HE**	**Z+F IMAGER 5006**
Scan Method		*Time-of-flight*	*Time-of-flight*	*Time-of-flight*	*Time-offlight*	*Phase difference*	*Phase difference*
Field of view [°]		360 x 60	360 x 270	360 x 270	360 x 80	360 x 320	360 x 310
Scan distance [m]		350	300	300	1000	< 76	< 79
Scanning speed [pts/sec]		≤ 5000	≤ 4000	≤ 50000	≤ 11000	120000	≤ 500000
Angular Resolution [°]	V	0,0018	0,0023	0,0023	0,0020	0,00900	0,0018
	H	0,0018	0,0023	0,0023	0,0025	0,00076	0,0018
3D scan precision		**12mm /100m**	**6mm / 50m**	**6mm / 50m**	**10mm /50m**	**3mm /25m**	**10mm /50m**
Camera		integrated	integrated	integrated	add on option	add on option	add on option
Inclination sensor		compen-sator	compensator	compensator	compensator	yes	yes

Table 1. Technical specifications of the terrestrial laser scanner systems regarding the scanning accuracy (K. Mechelke, T. Kersten, M. Lindstaedt, 2008)

2.4 Methodological errors

These errors are due to the chosen measurement method or the user experience which is not too familiar with this technology. For instance, if the user sets the *grid density* (resolution) higher than the laser scanner point accuracy, the signal reception process will have a higher frequency than the doubled bandwidth of the maximum frequency (the scan will be oversampled. In this case, there are generated *extra noises* and the scanning process time will increase substantially.

Another possible error sources could be the wrong choice of the terrestrial laser scanner. Choosing an inadequate scanner with a maximum distance that is near the maximum distance of the object scanned will lead to an inaccurate scan product.

Other possible errors may occur during the registration process. These errors depend on the method used to register the multiple point clouds.

3. Conclusions

Laser scanners are optical measuring systems based on a transmission of laser beam by moving (sweeping or rotating) mirrors on object surfaces. The object is lighted point by point and then the reflected laser beam is detected. In opposite to measurements on reflectors, the accuracy of distance measurements depends on the intensity of the reflected laser beam. Physical laws describe the functionality between accuracy and intensity (Gerthsen 1993). Main parameters in these functions are the distance, the angle of incidence, and surface properties (Ingensand et al. 2003).

Several practical investigation concerning the accuracy characteristics were achieved using the geodetic class scanning systems: GX Trimble, Leica ScanStation 1, Leica ScanStation 2, RIEGL LMS-Z420i, Faro LS 880, Imager 5006 - Zoller & Fröhlich and Leica HDS 6000 (Figure 4). The results are presented in the above table (Table 1).

4. Bibliography

1. *Boehler, Wolfgang; Marbs, Andreas* — ***3D Scanning Instruments.*** *Institute for Spatial Information and Surveying Technology, FH Mainz, University of Applied Science, Holzstrasse 36, 55116 Mainz, Germany.*
2. *Boehler, W.; Heinz, G.; Marbs, A.* — ***The potential of non-contact close range laser scanners for cultural heritage recording.*** *Institute for Spatial Information and Surveying Technology, FH Mainz, University of Applied Science, Holzstrasse 36, 55116 Mainz, Germany.*
3. *Coşarcă, Constantin* — ***Sisteme de Măsurare în Industrie.*** *Curs anul VI – Studii aprofundate, Bucureşti, 2009.*
4. *Heunecke, O.* — ***Laser Scanning – recent developments of a new geodetic technique.*** *Prelegeri Facultatea de Geodezie a Universității Tehnice de Construcții Bucureşti, 2004.*
5. *Ingesand, H.; Ryf, A.; Schulz, T.* — ***Performances and Experiences in Terrestrial Laserscanning.*** *Institute of Geodesy and Photogrammetry, ETH Zurich*
6 *Ingesand, H.; Schulz, T.* — ***Terrestrial Laser Scanning - Investigations and Applications for High Precision Scanning*** *Institute of Geodesy and Photogrammetry, ETH Zurich*
7. *Jocea, Andreea* — ***Terrestrial 3D Laser Scanning Application in Civil Engineering Projects.*** *Proiect de Diplomă, 2005.*
8. *Kersten, Th.; Mechelke, K.; Lindstaedt, M.; Sternberg, H.* — ***Geometric Accuracy Investigation of the Latest Terrestrial Laser Scanning Systems.*** *TS 2D – Calibration of Instruments, Integrating Generation FIG Working Week 2008, Stockholm, Sweden, 14 – 19 June, 2008.*
9. *Kutterer, H.* — ***Industrial Surveying.*** *Prelegeri Facultatea de Geodezie a Universității Tehnice de Construcții Bucureşti, 2007.*

10. *Lichti, Derek, Gordon, Stuart* — ***Error Propagation in Directly Georeferenced Terrestrial Laser Scanner. Point Clouds for Cultural Heritage Recording.*** *WSA2 Modelling and Visualization. FIG Working Week 2004. Athens, Greece, May 22-27, 2004.*

11. *Staiger, Rudolf* — ***Terrestrial Laser Scanning – Technology, Systems and Applications.*** *TS12 Positioning and Measurement Technologies and Practices. 2nd FIG Regional Conference Marrakech, Morocco, December 2-5, 2003.*

12. *Sotoodeh, S.* — ***Outlier Detection in Laser Scanner Point Cloud.*** *Institute of Geodesy and Photogrammetry, ETH Zurich*

13. ***** — ***Theory and practice on Terrestrial Laser Scanning.*** *Trening material based on practical application. Prepared in the framework of the project: „Learning tools for advanced three-dimensional surveying in the risk awareness project (3DRiskMapping)". Version 3.6, June 2008 – Theory. (European Leonardo Da Vinci programme).*