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TPS AND TLS LASER SCANNING FOR MEASURING THE INCLINATION OF TALL CHIMNEYS

TPS I TLS LASERSKO SKENIRANJE ZA ODREĐIVANJE VERTIKALNOSTI VISOKIH DIMNJAKA

Aleš Marjetič

ABSTRACT

The verticality of tall chimneys needs to be accurately monitored. Vertical plumbing, the classic geodetic procedure for detecting the inclination has certain drawbacks and can be replaced by modern technology if necessary. It was proposed a more general and rigorous procedure. For the researching it was used laser scanning methods which result in point clouds. Data acquired with two types of laser scanners were fit to a cylinder using the least squares adjustment. The aim of the paper was also to point out the differences between the used technologies, the differences between the results as well as influences on the computed inclination of the chimney and its practical explanations.

Keywords: chimney, TPS, TLS, scanning, modelling.

SAŽETAK

Geodetski monitoring visoke tačnosti nužan je pri ispitivanju vertikalnosti visokih dimnjaka. Ispitivanje vertikalnosti vertikalnim koncem končanice, klasičnim geodetskim postupkom za određivanje nagiba vertikalnih objekata, ima određenih nedostataka i ukoliko je potrebno može se zamijenjeniti modernim tehnologijama. Ovdje su predloženi općnitiji i strožiji postupci. Za istraživanje je korištena metoda laserskog skeniranja koja rezultira oblakom tačaka. Podaci dobiveni sa dvije vrste laserskih skenera su bili prikladni za cilindrični oblik dimnjaka uz primjenu izravnanja po metodi najmanjih kvadrata. Cilj članka je bio takođe ukazati na razlike korištenih tehnologija, razlike između rezultata kao i uticaje na izračunati nagib dimnjaka i njegovo praktično tumačenje.

Ključne riječi: dimnjak, TPS, TLS, skeniranje, modeliranje.

1 INTRODUCTION

European EUROCODE standards prescribe the maximum permitted horizontal offset Δ of the steel circumference of a standalone chimney with the height H_d (CEN, 2006):

$$\Delta[\mathrm{m}] = \frac{H_d[\mathrm{m}]}{1000}\sqrt{1+\frac{50}{H_d[\mathrm{m}]}}. \tag{1}$$

The horizontal offset on the top of the chimney is an outcome of the chimney's inclination which can lead to a permanent deformation of the chimney's construction. In classical engineering surveying the inclination of the chimney can be measured by vertical plumbing which has its certain drawbacks mostly due to many obstacles on chimney's surface. As an alternative our approach is based on the modelling of the object using measured points directly on its surface. Modern surveying instruments can perform the measurements in the so-called automatic scanning mode. We used two different terrestrial surveying measuring systems: the terrestrial positioning system (TPS) – total station Leica TS30 and the terrestrial laser scanner (TLS) – Riegl VZ-400. Point clouds on the object's surface can be geometrically modelled in a predetermined coordinate system. From the computed model the inclination of the chimney's central axis can be computed.

In the following sequel we are focusing on the deformation monitoring of an object using laser scanning methods. The scanning principles and applications for deformation monitoring of natural and manmade objects were the topics of many researchers in the past (Wujanz, 2016; Erdélyi et al., 2016 and Eling, 2009). Our consideration is slightly different. We are not trying to acquire the relative differences in point cloud geometry measured in two different time epochs but an absolute position of the model of chimney in 3D space. This information allows us to define its inclination according to orientation of third axis (vertical) in the time of measurements.

As the terrestrial geodetic measurements may be affected by random errors, systematic errors, which have a source in atmospheric influences, in influence of impact angles of laser beam etc, and outer forces on chimney's structure (sun heating, wind etc.) special attention is given to analysis of these influences on the computed inclinaton in the final section of this paper.

2 METHODOLOGY

It was decided to use the terrestrial laser scanning of chimney's surface. Points on the surface using laser scanning method are measured with three polar coordinates (Lichti and Skaloud, 2010; Vezočnik, 2011; Kregar et all, 2015): horizontal direction, zenith angle and slope distance (Figure 1).

In order to obtain the Cartesian coordinates of all measured points from different stations the position and orientation of the measuring device must be known and the distances appropriately reduced for the meteorological and geometrical corrections. The problem of setting the origin and orientation of the TPS instrument can be easily solved with the centring and levelling on the known station point (with known coordinates) and with the measured orientation direction to at least one known point. On the other hand, precise georeferencing of the considered TLS instrument (Wujanz, 2016; Lichti and Skaloud, 2010) and consequently measured point clouds must be made indirectly using additional measurements on the special targets. These targets must have known positons in order to provide appropriate accuracy and precision of the transformation parameters between the scanner's own inner coordinate system and the outer coordinate system, materialized by geodetic network of known points.

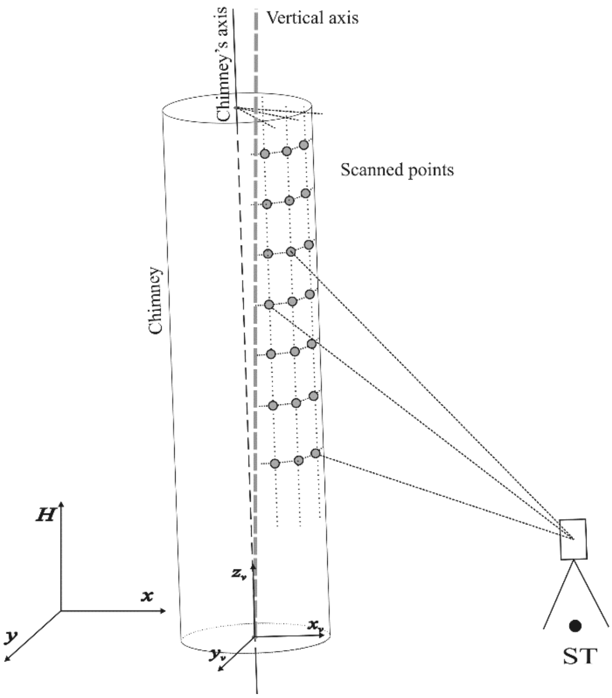

Figure 1. Method of scanning points on chimney's surface.

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Various errors can occur during the measuring process with random or systematic behaviour and influence on computed coordinates of points. Systematic errors must be removed by certified instrumentation and appropriate reductions of measurements (e.g. collimation error, index error for vertical angles, meteorological and geometrical corrections of slope distances etc.). With appropriately defined points and taking into account that the data acquisition in the scanning mode is fully automated it is possible that some points do not belong to the object's surface due to different obstacles on the chimney's surface (Figure 5). Such points would represent gross errors in the following process of modelling and need to be removed or filtered from the point cloud. When dealing with a small set of points (few hundreds) this filtration can be performed manually by graphically deleting point or set of points not belonging to the object's surface. But for a large point clouds (few millions), measured with TLS, numerical methods of filtering such as RANSAC algorithm (Fischler and Bolles, 1981; Vezočnik, 2011) can be much more appropriate. RANSAC algorithm was used in our case and is very effective.

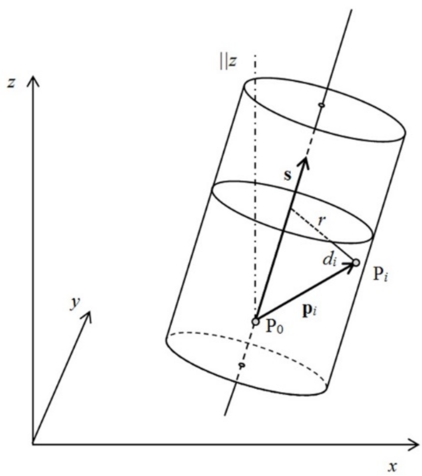


Figure 2. Inclination of the chimney's axis – cylinder parameters.

Point coordinates represent the measured values in the procedure of determining the parameters of the chimney's geometrical model. Knowing that the chimney was designed to have cylindrical shape our task is concentrated on finding the parameters of best fitting cylinder to the set of scaned points on its surface with the use of least square adjustment. We have to set the mathematical model connecting measurements (points) and unknown parameters of the cylinder. For that we used the orthogonal distance r_i (Figure 2) from the central axis for each measured point on the chimney's surface by using the property of the cross product (Luhmann et al., 2006; Vezočnik, 2011) which has to be equal to the radius of the cylinder:

$$\mathrm{F}\left(a,b,c,r,x_0,y_0,z_0,x_i,y_i,z_i\right):\ r_i=\frac{\left|\mathbf{p}_i\times\mathbf{s}\right|}{\left|\mathbf{s}\right|}=\frac{\sqrt{u_i^2+v_i^2+w_i^2}}{\sqrt{a^2+b^2+c^2}},\ r_i=r, \tag{2}$$

where: $u_i=c\left(y_i-y_0\right)-b\left(z_i-z_0\right),\ v_i=a\left(z_i-z_0\right)-c\left(x_i-x_0\right),\ w_i=b\left(x_i-x_0\right)-a\left(y_i-y_0\right),$

P_i (x_i, y_i, z_i) – measured point on the chimney's surface, P_0 (x_0, y_0, z_0) – point on the central axis, **s** = [a, b, c] – directional vector of the central axis, $\mathbf{p}_i = [x_i - x_0, y_i - y_0, z_i - z_0]$ – vector between points P_0 and P_i, r –radius (Figure 2).

In the Eq. 2 we treat a, b, c, r, x_0, y_0, z_0 as unknowns and x_i, y_i, z_i as measurements or measured points. From the Eq. 2 the mathematical model which connects measurements and unknowns is obviously nonlinear. If we assume that the measurements are affected by only normally distributed random errors the solution for the unknown cylinder parameters (unknowns) a, b, c and r can be computed using the least square adjustment technique. The linearized form of the Eq. 2 can be written for each measured point and then rewritten in the matrix form of the Gauss-Markov model $\mathbf{Al} = -\mathbf{Bx}$ (Teunissen, 2003; Kuang, 1996), connecting the observations **l** with unknowns in vector **x**. Here **B** is the matrix of derivatives of function F (Eq. 2) by unknowns ($\partial \mathrm{F}/\partial(a,b,c,r,x_0,y_0,z_0)$) and matrix **A** the values of derivatives of function F by measurements ($\partial \mathrm{F}/\partial(x,y,z)$) all computed in approximate values of unknowns and measured values of point coordinates. The solution for unknowns can be computed with the standard equations of least square adjustment procedure (Teunissen, 2003; Kuang, 1996; Kregar et all, 2015) as seen from Eq. 3 (including also additional computation of precision through covariance matrices (Teunissen, 2003):

$$\Delta = \left[a,b,c,r,x_0,y_0,z_0\right]^{\mathrm{T}} = \left(\mathbf{B}^{\mathrm{T}}\left(\mathbf{AQ}_{ll}\mathbf{A}^{\mathrm{T}}\right)^{-1}\mathbf{B}\right)^{-1}\mathbf{B}^{\mathrm{T}}\left(\mathbf{AQ}_{ll}\mathbf{A}^{\mathrm{T}}\right)^{-1}\left(-\mathbf{Al}-\mathbf{Bx}^{0}\right), \quad (3)$$

where $\mathbf{Q}_{ll}$ represents kovariance matrix of measurements, **l** vector of measured point coordinates and $\mathbf{x}^0$ vector of approximate values of unknowns.

The computed parameters for the directional vector of central axis (a, b, c) of the mathematical model allow us to compute the position and orientation of the chimney's central axis. The computed directional vector of the cylinder's central axis **s** = [a, b, c] and the unit vector in the direction of the z-axis **e** = [0, 0, 1] can be used for defining the inclination angle:

$$\mathbf{s}\cdot\mathbf{e} = \left|\mathbf{s}\right|\cdot\cos\varphi,\ \varphi = \arccos\frac{c}{\sqrt{a^2+b^2+c^2}}. \quad (4)$$

The offset of the chimney's top from the vertical axis can be calculated from the known height H_d of the chimney:

$$offset \approx H_d \cdot \varphi \quad (5)$$

The precision of inclination and offset can be computed using law of error propagation.

3 PRACTICAL EXAMPLE

The method is described and practically tested on two chimneys (approx. 65 m tall) in Brestanica (Slovenia) Thermal power plant (Figure 3).

Figure 3. Chimneys of the Thermal power plant Brestanica, Slovenia.

The scanning was for the purpose of comparison performed with a total station Leica Geosystems TS30 R1000 (Leica Geosystems, 2009) and a terrestrial laser scanner Riegl VZ-400 (Riegl, 2017). As reflectorless measurements can be problematic on reflective metal surfaces, mainly because of the low intensity of the measuring signal at greater impact angle (Kogoj, 2001) we tried to avoid measuring points on the chimney's visible edges.

Both instruments measure polar coordinates of each point. One of the important difference between these two technologies is the measuring speed. TS30 rotates the telescope around vertical and horizontal axis with the direct drives based on Piezo technology (Leica Geosystems, 2009) while the laser scanner Riegl VZ-400 uses a combination of rotating multi-face mirror and head rotation around vertical axis (Riegl, 2017) which is much faster. Compared to the terrestrial laser scanner the TS30's scanning procedure is considerably time consuming.

For the georeferencing of point clouds the coordinate system was provided through the pre-established geodetic network of nine points (O1 – O5 stabilized with concrete pillars and S1 – S4 temporarily stabilized with tripods). The geodetic network was measured with the sets of angles method for all three measuring values – horizontal directions, zenith angles and slope distances. Average values for horizontal directions, zenith angles and reduced slope distances were used in least squares adjustment of free network separately for horizontal and vertical components. The result were adjusted horizontal coordinates and heights of all network points with the precision much better than 1 mm (Figure 4) and of course with more than appropriate precision for scanning task.

TPS measurements were performed from three stations (S1, S2 and O2 in Figure 4) distributed around chimneys. Three setups of the TLS were close to the TPS setups and was georeferenced using additional measurements on special targets (Wujanz, 2016), positioned on the surrounding points of geodetic network.

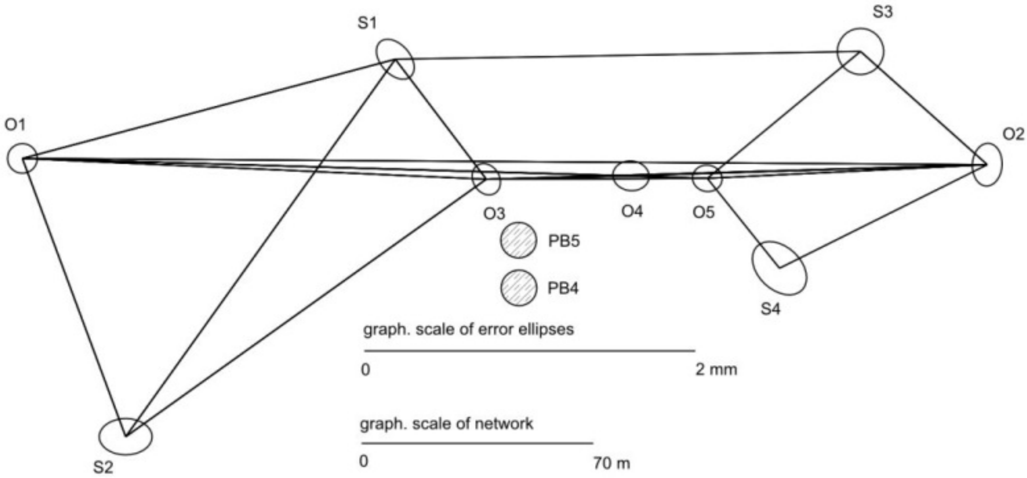


Figure 4. Geodetic network.

3.1 Measured points – point clouds

The graphical presentation of the point clouds (Figure 5) shows above mentioned difference between the two used technologies. With the TLS we can measure a higher number of points in a very short period of time including extra measuremnts on special target for point cloud registration (Lichti and Skaloud, 2010). On the other hand the TPS measuring process is extremely time consuming. It lasted about 1,5 hours for all three setups (including instrument setup and transportation between station points) and provided about 300 points per chimney. TLS resulted in a point cloud with several million points per chimney in approximately half an hour.

Acoording to the chimney’s shape (Figure 5) only approx. 35 m section of uniform cylindrical shape was used for computation of parameters (Table 1) and inclination angle. The offset (Table 1) was then extrapolated for the entire height of 65 m from foundation to the top.

In the sense of numerical computations the high number of points measured by TLS can be quite problematic. A high number of points (raster density of 1 cm) in the adjustment procedure results in large matrices which demands a lot of memory space and processing power.

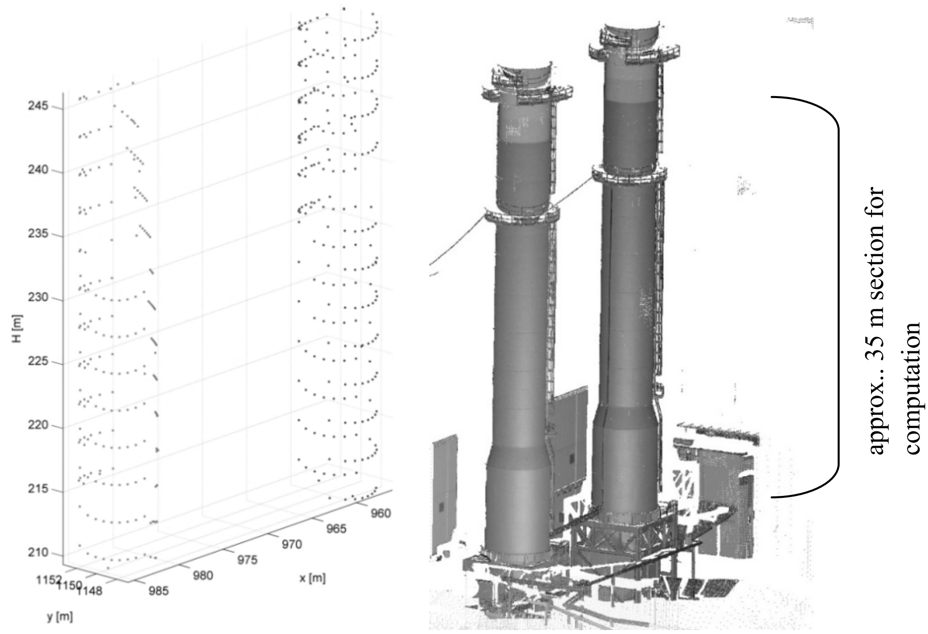


Figure 5. Point clouds achieved by Leica Geosystems TS30 R1000 (left) and Riegl VZ-400 (right, with marked section for computation).

The high number of points in the point cloud also leads to an overrated parameter's accuracy estimation. Therefore, we performed an analysis on how the offset of the chimney's top from the vertical axis depends on the different sample size of the scanned points. Therefore sample of some size was randomly selected ten times from the entire point cloud and the calculations were made for each selection (grey dots on Figure 4). After that the average value of ten repetitions was computed and this was repeated for each sample size to sample of size 12 000 points. Average values acoording to different sample sizes are shown with red line in Figure 4. Figure 4 also shows that the calculated offset from the chosen sample size varies by approximately 1 cm for small samples (few hundred points) and decreases to a value of approximately 2 mm when the sample size reaches the value of about 10 000 points. After this the variation cannot be reduced by increasing the sample size, which can be explained by the increase of the correlation between adjacent points. We can conclude that the sample of 10 000 scanned points for the computation of the model parameters and inclination is large enough and on the other hand we have to provide at least several thousands of scanned points to avoid too large dispersion of computed results as seen from graph in Figure 6. Here the TPS can be quite problematic with only few hundreds of measured points.

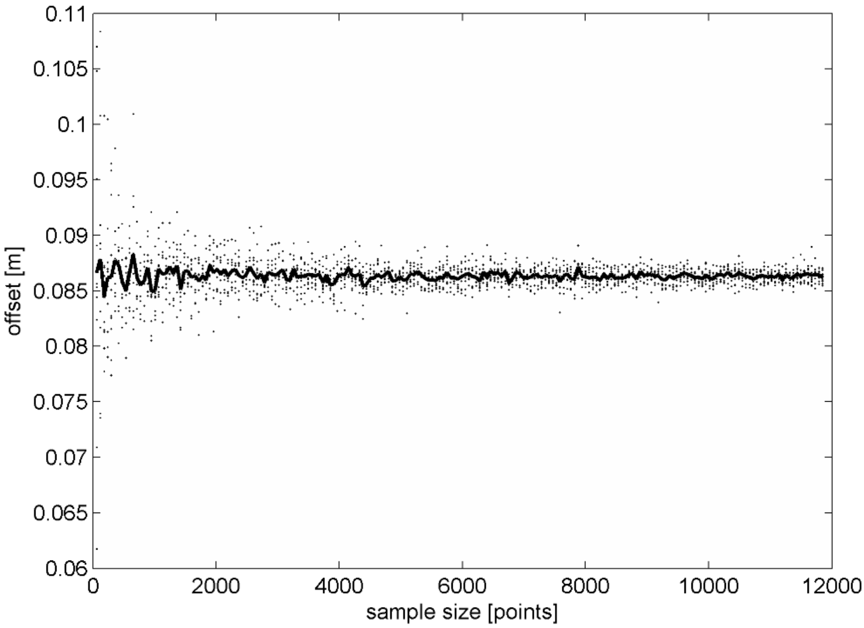


Figure 6. Dispersion of computed offset on the top of the chimney according to the used sample size.

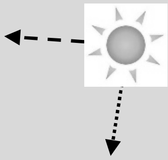
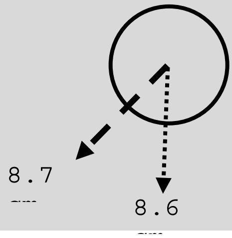
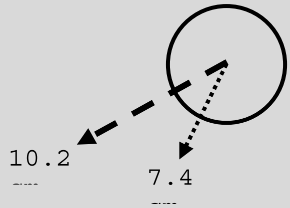
3.2 Numerical results – chimney's inclination

The calculations were performed in Matlab® software. The results from both instruments are shown numerically and graphically in Table 1.

Offsets in Table 1 represent the deviation of the top of the chimney from the vertical axis and are according to the computed precision significant for both chimneys.

Based on the results (Table 1) we can get the impression that a higher amount of points gathered with TLS will provide better results in sense of precision. Is this true? As far as the precision of the numerical results is concerned we would like to estimate the real precision of TLS measurements. The value of the standard deviation for each TLS parameter is up to ten times lower than for TPS. This is mainly due to the large sample size of the measured points (approx. 10 000 for TLS). The precision of the computed parameter depends on the number of observations and is graphically presented in Figure 7 – up to approx. 120 000 per sample. But from Figure 6, which represents the spread of the calculated chimney's offset for a selected number of scanned points, we can conclude that according to spread of approximately 2 mm for the randomly selected sample of 10 000 points the real precision must be represented by the maximum of that value and in our opinion no less than 1 mm. The decision for a sample of approximately 10 000 points is thus appropriate.

Table 1.
Numerical results

Chimney		**PB4**		**PB5**	
approx. sun direction in time of measurements (see Figure 10) 					
TPS		$\sigma_{a-prio} = 5.0$ mm $\sigma_{a-post} = 4.9$ mm		$\sigma_{a-prio} = 5.0$ mm $\sigma_{a-post} = 5.2$ mm	
number of used scanned points		324		321	
radius	r ; σ_r [m]	2.9113	0.0008	2.9095	0.0006
inclin. angle	φ ; σ_φ [″]	**268**	**23**	**369**	**22**
offset	$offset$; σ_{off} [m]	**0.0870**	**0.0050**	**0.1023**	**0.0046**
direction	ν [°]	**228**		**248**	
TLS		$\sigma_{a-prio} = 5.0$ mm $\sigma_{a-post} = 6.1$ mm		$\sigma_{a-prio} = 5.0$ mm $\sigma_{a-post} = 5.6$ mm	
number of used scanned points		11850		12533	
radius	r ; σ_r [m]	2.9115	0.0001	2.9133	0.0001
inclin. angle	φ ; σ_φ [″]	**275**	**4**	**235**	**4**
offset	$offset$; σ_{off} [m]	**0.0864**	**0.0008**	**0.0738**	**0.0007**
direction	ν [°]	**183**		**205**	

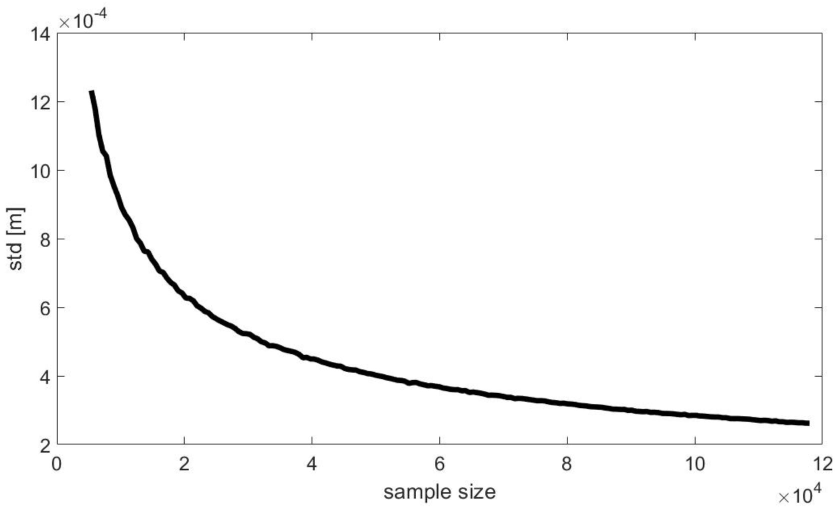


Figure 7. Dependency of the inclination precision (std – standard deviation) according to the sample size.

3.3 Compliance with international standards

For a 65 m of height the allowed horizontal offset defined by international standards (Eq. 1) on the top of considered chimney is 8.7 cm. For the chimney PB4 the offset does not exceed the maximum permitted both for TPS and TLS measurements. The horizontal direction of the inclination is slightly different. For chimney PB5 the value acquired with TPS measurements is nearly 2 cm higher and exceeds the maximum permitted value according to the EUROCODE 3 standards. Such differences in the values and their precision (Table 1) force us to consider which results (TPS or TLS) are more reliable and what causes the deviations.

3.4 The influences on the results

One of the aspects for comparing two used technologies is the dispersion of the measured points. Since we measured points on the chimney's surface, we have analysed the deviations of the point positions from their fitted surface. It is known that the precision of the point coordinates measured in the reflectorless mode is mostly affected by the angle of incidence of the laser beam, surface material as well as from the diameter of the laser beam. We know that due to its reflectivity smooth metal surfaces are not very appropriate for distance measurements in reflectorless mode.

As shown in Figure 8 representing the deviations of the actual shape from its geometrical regular model the dispersion of points is within – 3 to + 3 cm from the computed radius of the cylinder, same for TLS and TPS measurements. Practically the same dispersions of points for both technologies does not allow us to conclude that one technology is superior.

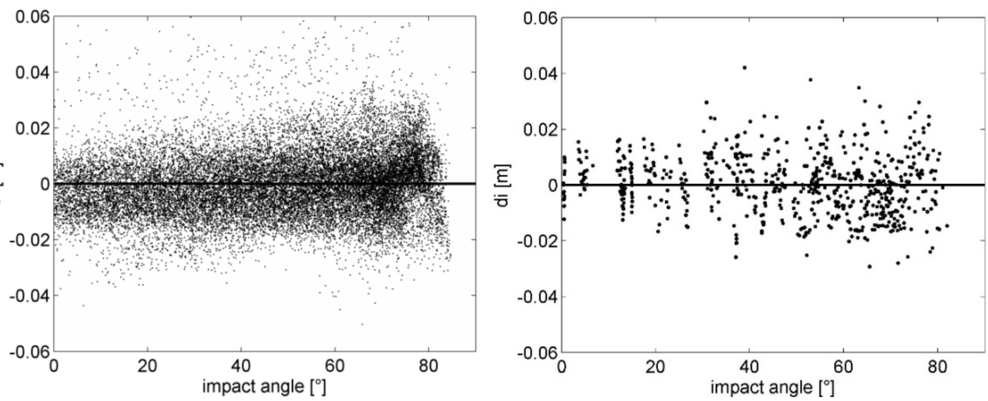


Figure 8. Dispersion of points on the chimney's surface (left – TLS, right – TPS).

Measurements with TLS were made early in the morning in stable, cloudy conditions and TPS later in longer time interval with strong and direct sun radiation and with temperature about 10°C higher according to TLS measurements (Figure 9). We can assume that the affect of the temperature (nonhomogenous distribution on surface) is significant and in combination with wind may affect inclination. From this aspect it can be said that TLS results are more reliable mostly beacuse of shorter time interval needed for measurements.

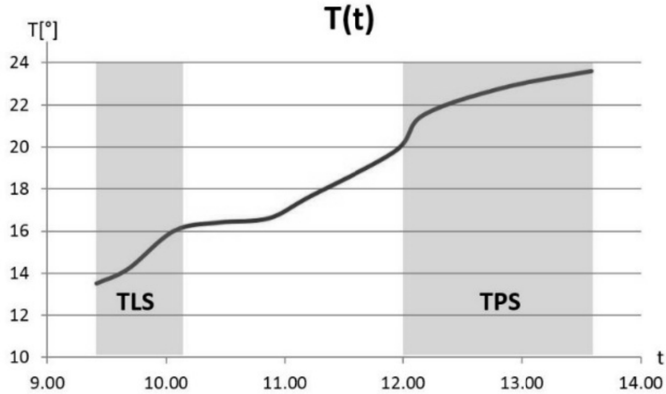


Figure 9. Changes in air temperature during measurements.

The differences in computed inclinations for TPS and TLS taking into account different weather conditions led us to perform separate, quite simple test. With the automated TPS we were continously monitoring the position of the point P1 signalized by the circular Leica prism [14] on the top of chimney PB5. The measurements were performed in similar weather conditions as they were in time of scanning with the TPS and TLS and through most of the day period. The monitoring was performed using the combinatons of different measuring sensors – tachymeter for measuring polar coordinates of points and atmospheric sensors for measuring pressure, temperature and humidity for atmospheric corrections. The stability of the instrument and orientation was ensured with placing the tachymeter and an extra orientation prism on the concrete pillar.

Our intention was to periodically measure the position of P1 taking into account that our presence in the field is not possible/allowed through the whole day period. So, for this purpose we developed the platform for combining different measuring sensors, which were joined through the Raspberry Pi computer. The two-way communication with the tachymeter and simultaneous measurements of atmospheric data were made remotely from the different location using the modem and appropriate data transfers protocols (GeoCOM, TCP/IP, SST). All measured data was then appropriately corrected and used for the computation of the positions of point P1 in different epochs as shown in Figure 10.

The results for the position of P1 in different epochs, seen from Figure 10, confirmed our assumptions. Obviously the sun radiation heats the chimney's metal surface and causes the chimney to deviate away from the sun consequently. These changes in positions are in the rank of several centimeters and thus differences in Table 1 are explainable. We can conclude that there is a need to measure or scan such object as quickly as possible and also in different weather conditions to get information of extreme inclination. Other thing is that with these results from Figure 8 many other possibilities of research and testing arose, such as testing the influence of temperature distribution on chimney's surface and influence of wind on inclination.

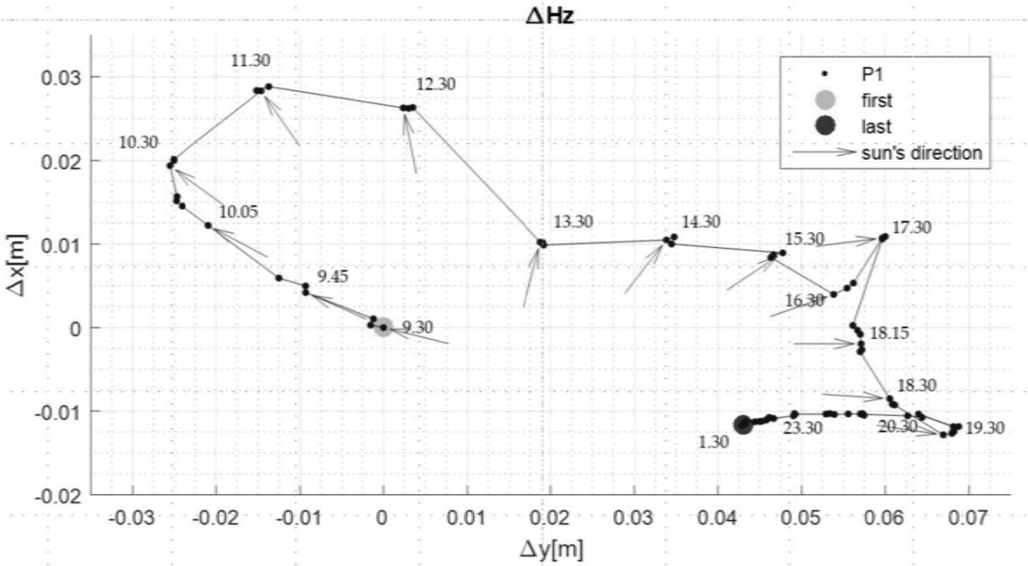


Figure 10. Influence of changing sun direction during measurements.

4 DISCUSSION AND CONCLUSION

The task of determining the inclination of tall chimneys is shown through practical example where we used modern total stations (TPS) and terrestrial laser scanners (TLS) for measuring point cloud on the chimney’s surface. The presumed geometrical shape of cylinder was fitted to the measured point cloud using least square adjustment. The cylinder parameters were used to compute the model’s central axis and its inclination. The described scanning method is more general and can also works with complicated axis symmetrical shapes.

Unlike the method of vertical plumbing the scanning method needs an appropriate definition of geodetic datum in order to realize the registration of point clouds from different instrument setups. Such geodetic datum provided by a geodetic network demands a lot of field work and computations. On the other hand the benefit of establishing a geodetic network is besides higher precision in process of georeferencing of the point clouds also the possibility to repeat the measurements from the same setups to exclude the influence of changing geometry of setup points.

Our research also assumes that the chimney acts like a rigid body which is not entirely true treatment. The chimney’s body is due to external forces actually bending but approximation with the rigid body of cylinder gives us an average value of an inclination through the whole length of the chimney and also compensates the extreme values of offsets on the top which may be caused also by errors in measurements. In our opinion the possible mistake of our assumption is negligible.

As far as two compared technologies are concerned it is not easy to define which approach proves better. TLS is according to TPS faster and provides large amount of data resulting mainly in a high level of redundancy in computation. Besides expensive instrument, registration of point clouds and filtering process is a bit more complex with TLS. On the basis of different TPS and TLS results for the same chimney some further questions arose. Some analysis and practical test in this research proved that the changing weather conditions during the measurements affect the results and therefore there is a need for fast measurements which only TLS can provide. Other thing that we have learned is that the laser scanning should be always joined together with other measurements. In the case of measuring chimney's inclination there is need for simultaneous measurements with the scanner, meteorological sensors and additional geodetic measurements on the prism set on the top of the chimney. With the improved set of sensors in the future, especially for the temperature of the surface and the wind speed we would be able to compensate changes due to changing weather conditions and to define the exact inclination of the chimney.

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LITERATURE AND REFERENCES

CEN (2006). *EN 1993: Eurocode 3: Design of steel structures – Part 3-2: Towers, masts and chimneys – Chimneys*. Brussels: European Comitee for Standardization.

Eling, D. (2009). *Terrestrisches Laserscanning für die Bauwerksüberwachung* (PhD thesis). München: Deutsche Geodätische Kommission.

Erdélyi, J., Kopáčik, A., Lipták, I., Kyrinovič, P. (2016). Automation of point cloud processing to increase the deformation monitoring accuracy. *Applied Geomatics*, *9*(2), 105-113.

Fischler, M. A., Bolles, R. C. (1981). *Random sample consensus: A paradigm for model fitting with applications to image analysis and automated cartography*, Commun. of the ACM, 24, 381-395, DOI: 10.1145/358669.358692.

Kogoj, D. (2001). Fähigkeiten elektronischer Distanzmesser bei reflektorloser Distanzmessung, *AVN. Allg. Vermess.-Nachr,* 5, 186-190.

Kregar, K., Ambrožič, T., Kogoj, D., Vezočnik, R., Marjetič, A. (2015). Determing the inclination of tall chimneys using the TPS and TLS approach, *Measurement* 75, 354-363, DOI:10.1016/j.measurement.2015.08.006

Kuang, S. (1996). *Geodetic network analysis and optimal design: Concepts and applications*, Ann Arbor Press, Chelsea, MI, USA, 1996,97-120.

Leica Geosystems (2009). *Leica TS30 White Paper*. Heerbrugg, Switzerland: Leica Geosystems AG.

Lichti , D. D., Skaloud, J. (2010). *Registration and calibration. In airborne and terrestrial laser scanning*, 1st ed.; Vosselman, G.; Maas, H-G.; Whittles Publishing: Dunbeath, Scotland UK, 109-118

Lichti, D. D. (2006). Error modelling, calibration and analysis of an AM-CW terrestrial laser scanner system, *ISPRS Journal of Photogrammetry and Remote Sensing*, 61, 307-324, DOI: 10.1016/j.isprsjprs.2006.10.004

Luhmann, T., Robson, S., Kyle, S., Harley, I. (2006). *Close range photogrammetry. Principles, methods and applications*, Whittles Publishing, Dunbeath, Scotland, 87–88.

Riegl (2017). *RIEGL VZ-400* [Brochure]. Horn, Austria: Riegl Laser Measurement Systems GmbH. Retrieved from:
http://www.riegl.com/uploads/tx_pxpriegldownloads/10_DataSheet_VZ-400_2017-06-14.pdf

Teunissen, P. J. G. (2003). *Adjustment theory – an introduction*, Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Mathematical Geodesy and Positioning, Delft, The Netherlands.

Vezočnik, R. (2011). *Analysis of terrestrial laser scanning technology for structural deformation monitoring* (PhD thesis), University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana.

Wujanz, D. (2016). *Terrestrial Laser Scanning for Geodetic Deformation Monitoring* (PhD thesis). Berlin: TU Berlin.

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