Determining the non-verticality of tall chimneys using the laser scanning approach

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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. We proposed a more general and rigorous procedure. We 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.

Key words: chimney, TPS – terrestrial positioning system, TLS – terrestrial laser scanner, scanning, verticality, modelling

1 INTRODUCTION

European standards prescribe the maximum permitted horizontal offset Δ of the steel circumference of a standalone chimney with the height H_d - EUROCODE 3: *Design of steel structures – Part 3-2: Towers, masts and chimneys – Chimneys* (EUROCODE 3):

$$\Delta[\mathrm{m}] = \frac{H_d[\mathrm{m}]}{1000}\sqrt{1+\frac{50}{H_d[\mathrm{m}]}} \qquad (1)$$

The horizontal offset is an outcome of the chimney's inclination which can lead to a permanent deformation of the chimney's construction. In classical surveying the inclination of the chimney can be measured by vertical plumbing which has its certain drawbacks (Kregar et al, 2015). 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.

2 METHODOLOGY

Points on the chimney's surface can be measured with three polar coordinates: horizontal direction, zenith angle and slope distance. In order to obtain the Cartesian coordinates of the measured points the position and orientation of the instrument must be known. 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 points. On the other hand, precise georeferencing of the considered TLS instrument (Lichti et al, 2010) and measured point clouds can be made indirectly using additional measurements on the special targets with known positons in order to provide appropriate accuracy and precision of the transformation parameters between the scanner's own and the outer coordinate system.

Various errors can occur during the measuring process. As 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 (Fig. 3). Such points would represent gross errors and need to be removed. When dealing with a small set of points this can be performed manually, but for a large point clouds, numerical methods such as RANSAC algorithm (Fischler and Bolles, 1981) can be more appropriate and was used in our case.

Point coordinates represent the measured values in the adjustment procedure for determining the parameters of the chimney's mathematical model. For the connection between measurements and unknown parameters we used the orthogonal distance r_i (Fig. 1) 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:

$$r_i = \frac{|\mathbf{p}_i \times \mathbf{s}|}{|\mathbf{s}|} = \frac{\sqrt{u_i^2 + v_i^2 + w_i^2}}{\sqrt{a^2 + b^2 + c^2}}, \; r_i = r \qquad (2)$$

where: $u_i = c(y_i - y_0) - b(z_i - z_0)$, $v_i = a(z_i - z_0) - c(x_i - x_0)$, $w_i = b(x_i - x_0) - a(y_i - y_0)$, 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, $\mathbf{s} = [a, b, c]$ – 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 (Fig. 1).

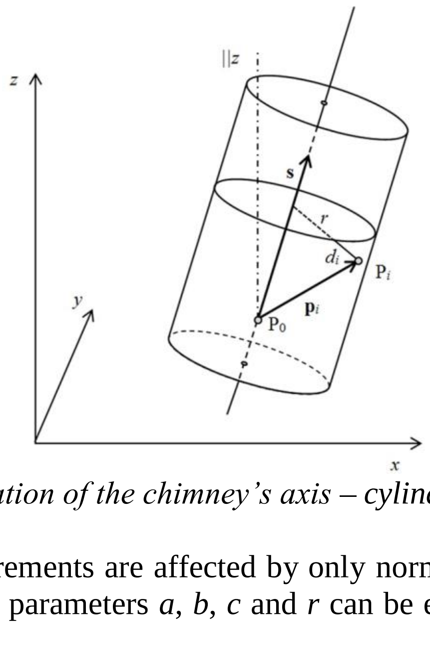


Fig. 1 Inclination of the chimney's axis – cylinder parameters.

If we assume that the measurements are affected by only normally distributed random errors the solution for the unknown parameters a, b, c and r can be easily 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 (Teunissen, 2003, Kuang, 1996) of the Gauss-Markov model $\mathbf{A}\hat{\mathbf{l}} = -\mathbf{B}\hat{\mathbf{x}}$, connecting the observations $\hat{\mathbf{l}}$ with unknowns in vector $\hat{\mathbf{x}}$. The whole solution can be seen in Kregar et al, 2015. The computed parameters 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 $\mathbf{s} = [a, b, c]$ and the unit vector in the direction of the z-axis $\mathbf{e} = [0, 0, 1]$ can be used for defining the inclination angle:

$$\mathbf{s} \cdot \mathbf{e} = |\mathbf{s}| \cdot \cos\varphi, \ \varphi = \arccos\frac{c}{\sqrt{a^2 + b^2 + c^2}} \tag{3}$$

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

$$offset \approx H_d \cdot \varphi \tag{4}$$

3 PRACTICAL EXAMPLE

The method is described and practically tested on two chimneys (approx. 65 m tall) in Brestanica (Slovenia) Thermal power plant where the scanning was performed with a total station Leica Geosystems TS30 R1000 and a terrestrial laser scanner Riegl VZ-400. As reflectorless measurements can be problematic on reflective 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. The greatest difference between these two technologies is the measuring speed. TS30 rotates the telescope with the use of piezo drives while the laser scanner Riegl VZ-400 uses rotating mirrors and is much faster. Compared to the terrestrial laser scanner the TS30's scanning procedure is considerably time consuming.
TPS measurements were performed from three stations (S1, S2 and O2 in Fig. 2) distributed around chimneys. These station points were included in pre-established geodetic network (Fig. 2). Three setups of the TLS were close to the TPS setups and was georeferenced using additional measurements on special targets, positioned on the points of geodetic network. Detailed explanation of measuring procedure can be found in Kregar et al, 2015.

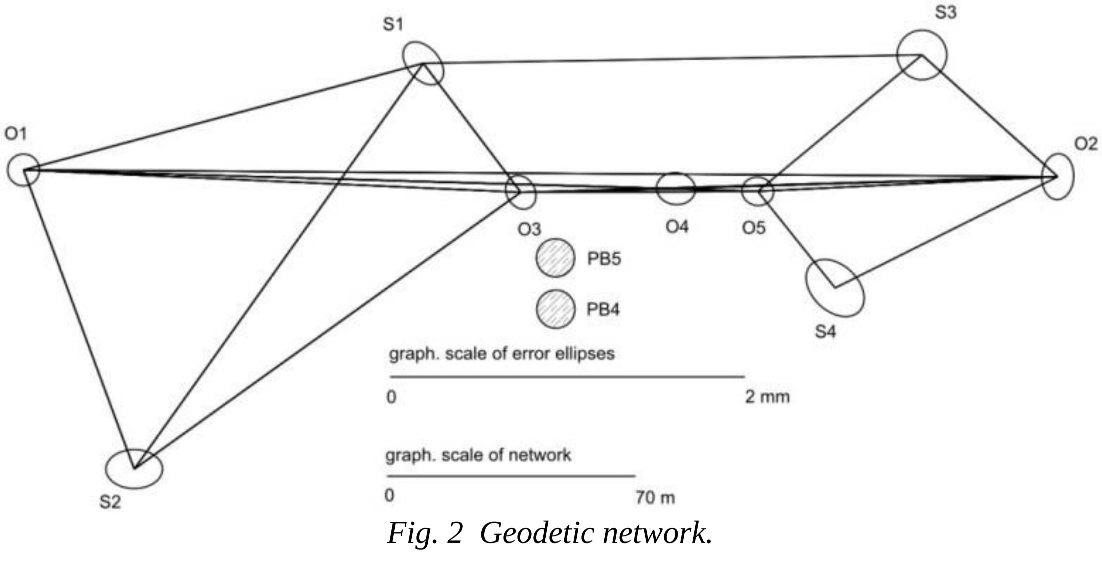


Fig. 2 Geodetic network.

3.1 RESULTS – TS30 R1000 vs. RIEGL VZ-400

3.1.1 Measured points – point clouds

The graphical presentation of the point clouds (Fig. 3) shows the main 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. 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 less than 500 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 (Fig. 3) only approx. 40 m section of uniform cylindrical shape was used for computation of parameters (Table 2) and inclination angle. The offset (Table 2) was then extrapolated for the entire height of 65 m from foundation to the top.

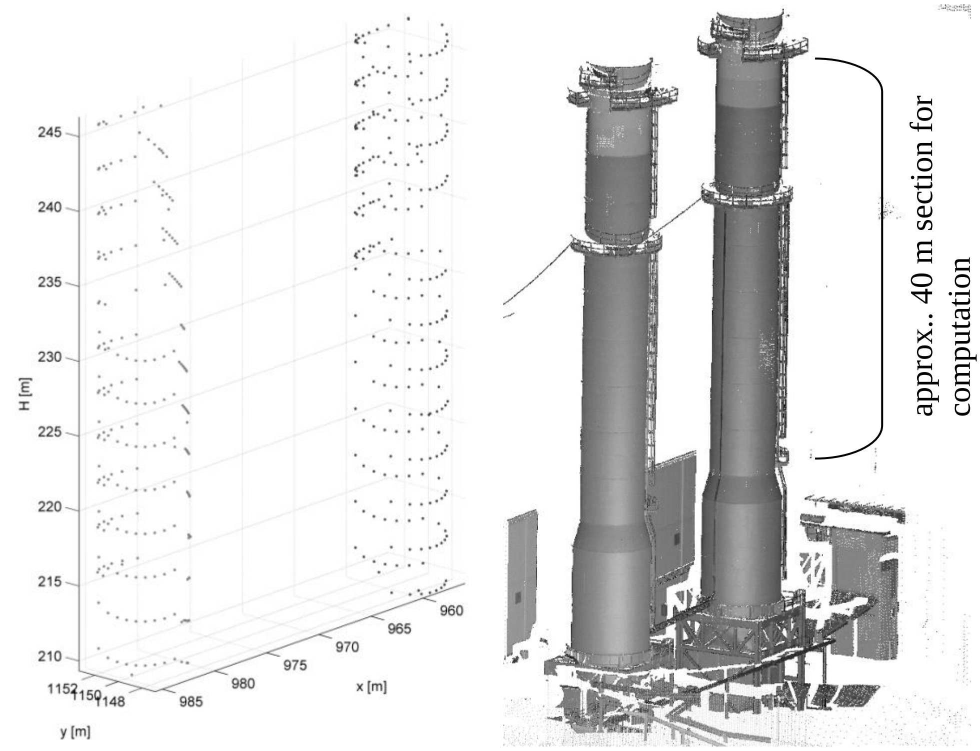


Fig. 3 Point clouds achieved by Leica Geosystems TS30 R1000 (left) and Riegl VZ-400 (right, with marked section for computation).

In the sense of numerical computations the high number of points measured by TLS can be 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. Optimization of the computation procedure should be used therefore (Kregar et al, 2015).

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 each sample size was randomly selected ten times from the entire point cloud and the calculations were made for each selection. Fig. 4 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 points. We can conclude that the sample of 10,000 scanned points for the computation of the model parameters is large enough.

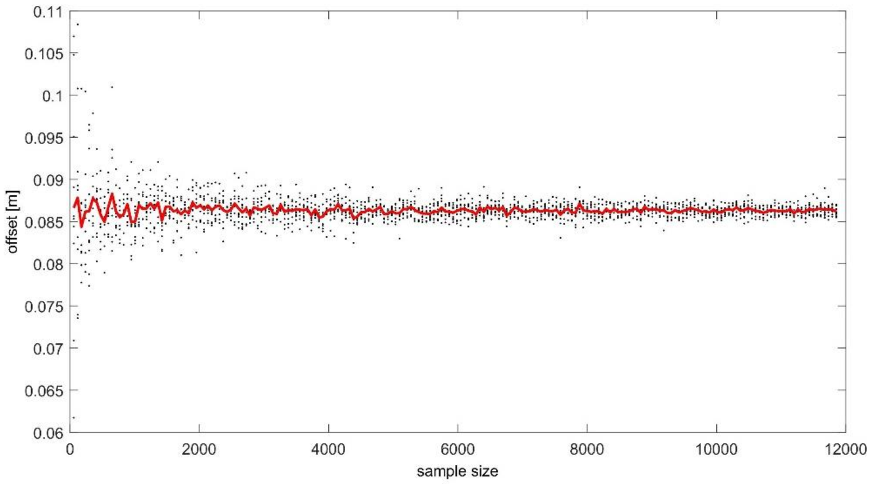
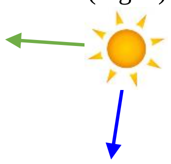
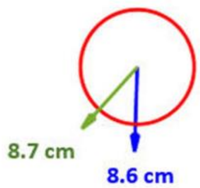
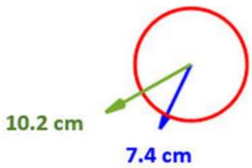


Fig. 4 Computed non-verticality according to the sample size.

3.1.2 Numerical results – chimney's inclination

The calculations were performed by Matlab® software package. The results from both instruments are shown numerically and graphically in Table 2.

Table 2. Results.

Chimney		**PB4**		**PB5**	
approx. sun direction in time of measurements (Fig. 7) 					
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* ; s_{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* ; s_{off} [m]	**0.0864**	**0.0008**	**0.0738**	**0.0007**
direction	ν [°]	**183**		**205**	

Offsets represent the deviation of the top of the chimney from the vertical axis and are according to the computed precision significant for both chimneys (Table 2).

Based on the results (Table 2) 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 (Table 2). 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 calculated parameter depends on the number of observations and is graphically presented in Fig. 5 – up to approx. 120.000 per sample. But from Fig. 4, 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.

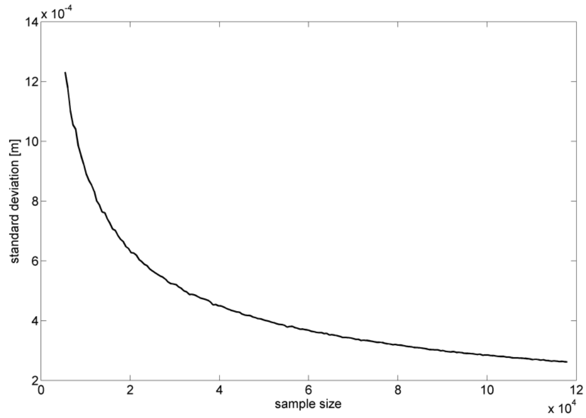


Fig. 5 Dependency of the inclination precision according to the sample size.

3.1.3 Compliance with international standards

For a 65 m of height the allowed horizontal offset defined by international standards (eq. (1)) at the top of the 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 2) force us to consider which results (TPS or TLS) are more reliable and what causes the deviations.

3.1.4 The influences on the results

One of the aspects for comparing these two technologies is the dispersion of the measured points. Since we measured points on the chimney's surface, we 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 Fig. 6 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.

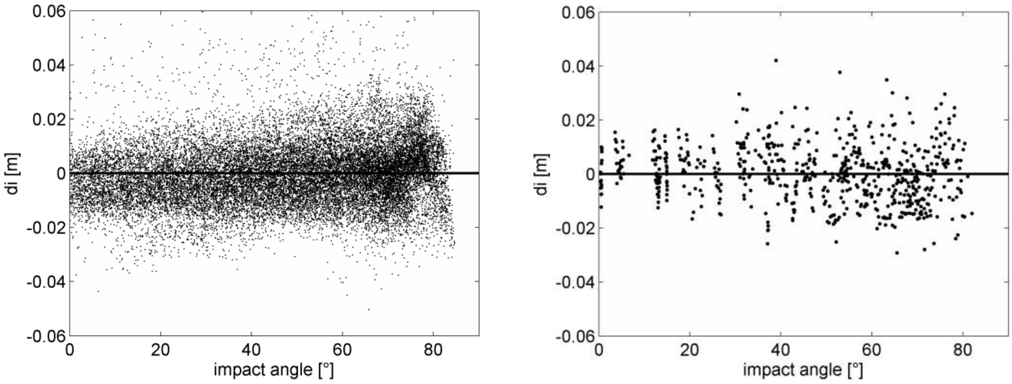


Fig 6 Dispersion of points on the chimneys surface (left – TLS, right – TPS).

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 (Fig. 7). 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.

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 prism on the top of one chimney. The measurements were performed in similar weather conditions through most of the day period. The results confirmed our assumptions. 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 2 are explainable.

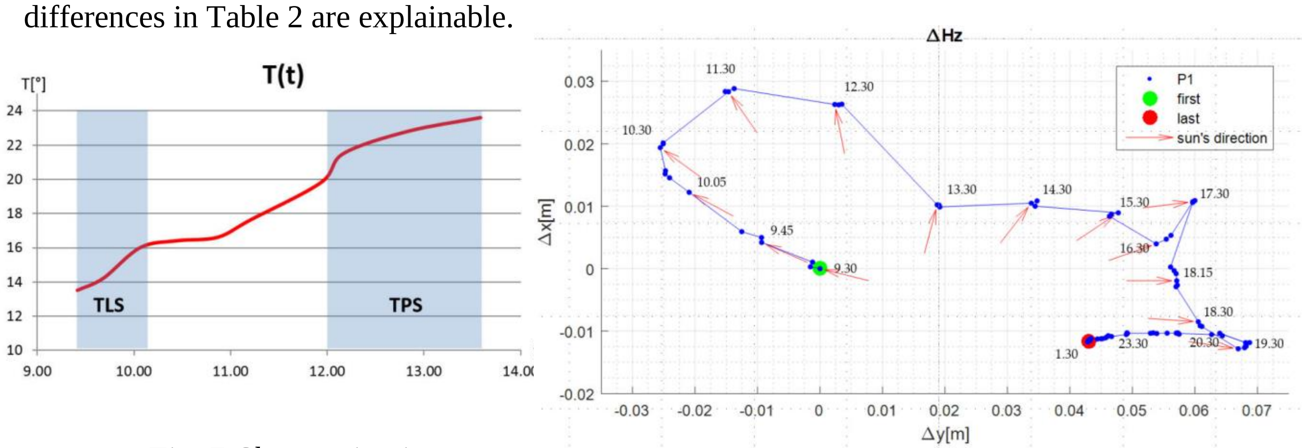


Fig. 7 Changes in air temperature and sun direction during measurements.

4 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 the point cloud on the chimney's surface. The geometrical shape of cylinder was fitted to this point cloud using least square adjustment. The cylinder parameters were used to compute the model's central axis and its inclination.

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 but also allows repetition of measurements. The described scanning method is more general and can works with complicated geometrical shapes.

As far as two compared technologies are concerned it is not easy to define which approach proves better. TLS approach 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 and filtering process is a bit more complex. On the basis of different TPS and TLS results for the same chimney some further questions arose. Some analysis and practical test 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.

REFERENCES

EN 1993 EUROCODE 3. Design of steel structures – Part 3-2: Towers, masts and chimneys – Chimneys

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(2015) 354-363, DOI:10.1016/j.measurement.2015.08.006

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, 2010, pp. 109-118

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(1981) 381-395, DOI: 10.1145/358669.358692.

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

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.

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, 2003.

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

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(2007) 307-324, DOI: 10.1016/j.isprsjprs.2006.10.004

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