Determination of deformation of high-capacity tank using terrestrial laser scanning

***Katarína Pukanská*[1], *Slavomír Labant*[1], *Karol Bartoš*[1], *Juraj Gašinec*[1] *and* *Jozef Zuzik*[2]**

The paper deals with the use of terrestrial laser scanning for the determination of a deformation extent of high-capacity tank resulting from a pressure equalisation of exterior and interior, i.e. an implosion. The methodology of survey and the interpretation method of the deformation extent is innovative in this field. The processing was realized using computer graphics software Microstation VX and Geomagic Raindrop 10. Not only the demonstration of position, extent of deformations and numerical expression of their direction and extent is the result of this survey, but also the analysis and proposal of repair works will be realized.

Key words: *high-capacity tank, terrestrial laser scanning, mathematical and graphical modelling*

Introduction

Steel tanks represents stationary devices that are designed for the storage of different types of media, for example liquid, gas or solid substances. These are objects that are mostly made out of steel. They may have a different geometric shape, but most frequently they are cylindrical or spherical objects. The production of such objects is based on a constructional design, into which all construction elements representing a single unit are integrated on the basis of intended use. The tank itself can be either above-ground, i.e. located on a supporting structure, or underground, i.e. placed in a socket and buried. The capacity of these objects tends to vary from small retention tanks to high-capacity objects with a capacity of several hundreds of thousands cubic meters. By purpose, they can be constructed as a single or double-walled objects. In the case of different tanks for the storage of hazardous materials, the legislation does not permit the production of tanks without a safety coating. Not only tanks for various petroleum derivatives but also tanks for fuel storage belong to such double-walled tanks.

The subject of survey

In the complex of Východoslovenská rafinéria, s.r.o., (distillation unit Senné) the survey of deformation extent was realized in June 2013. In order to change stored media, the tank (Tab. 1) was filled with hot water to a height of 2 metres in 2012. The main objective was the removal of sediments and residues of aromatics in the storage unit. After filling, the tank was hermetically sealed while there was a decrease of pressure due to condensation, leading to a collapse – the implosion of the tank caused by a violation of technological procedure. The tank was filled with water to a height of about 4 meters. The Fig. 1 shows the state of the tank after filling with water and places of water leak through cracks, incurred by the weakening of plastically deformed material, are clearly visible.

Fig. 1. The high-capacity tank in the Východoslovenská rafinéria, s.r.o.

Tab. 1. Basic technical information about the tank.

The owner	*Východoslovenská rafinéria,s.r.o., (distillation unit Senné)*
Type of the unit	*Tank for a production material*
The manufacturer	*NAFTA, a.s. GBELY manufactory ÚD*
Year of build	*1997*
Serial number	*1386*
Operating parameters	
Maximum operating pressure	*0,05 MPa*
Maximum test overpressure	*0,6379 MPa*
Maximum operating temperature	*40°C*
Capacity	*250 000 L*
Working substance	*AROMATY 60/90*

[1] *MSc. Katarína Pukanská, PhD., Assoc. prof. MSc. Slavomír Labant, PhD., MSc. Karol Bartoš, PhD., Assoc. prof. MSc. Juraj Gašinec, PhD.,* Technical University of Košice, BERG Faculty, Institute of Geodesy, Cartography and Geographic Information Systems, Letná 9, 040 01 Košice, Slovak Republic, katarina.pukanska@tuke.sk, slavomir.labant@tuke.sk, karol.bartos@tuke.sk, juraj.gasinec@tuke.sk

[2] *MSc. Jozef Zuzik, PhD.,* Institute of Business and Management, F BERG, Technical University of Košice, Letná 9, 042 00 Košice, Slovak Republic, jozef.zuzik@tuke.sk

By a subsequent control, also the anchorage of tank was documented and it was found that rips at three places were caused by the implosion. Material of the inner wall is damaged, but welded joints do not show damage. During the visual inspection of the tank in September 2012, the sample for metallographic study was taken and an ultrasonic thickness measurement was performed together with marking points of measurement. We have found the state of corrosion loss, which is not higher than 2 %.

Methodology

The survey of deformation extent of the steel tank for aromatics was realized in June 2013. After filling, the tank was hermetically sealed while there was a decrease of pressure due to condensation, leading to a collapse – the implosion of the tank caused by a violation of technological procedure [1], [12], [13]. The survey of tank deformation was realized in June 2013 by terrestrial laser scanning using the Leica ScanStation C10 instrument (Fig 2, Tab. 2). Since the deformation of tank had to be measured from its interior, the spatial position of points was determined in a local coordinate system, with the origin at the centre of the scanner at the first scanning station [6], [10]. For their calculation, the following equations (1) are used, where d is a slope distance, ω is a horizontal angle and ζ is a zenithal distance. It is a pulse full panoramic long-range scanner with the mean error of position determination 6 mm and distance measurement 4 mm.

Fig. 2 Terrestrial laser scanner Leica ScanStation C10

Tab. 2 Technical specification of Leica ScanStation C10

Accuracy of single measurement	
Position/Distance	6 mm/4 mm
Angle precision	
Horizontal/Vertical	12 " / 12 "
Modelled surface precision	2 mm
Range	300 m (18 % reflectivity) 134 m (90 % reflectivity)
Minimal step of scanning	1 mm
Scan rate	50 000 points/sec.
Laser class	3R, green (λ = 532 nm)
Spot size	0-50 m ≈ 4,5 mm
Field of view	
Vertical/Horizontal	270°/360°

Approximately 54,157 mil. points, which were used in processing, were obtained by field survey from two survey station inside the tank (Fig. 3). The object was scanned with a density 2x2 mm, in order to capture all deformations of the inner wall of tank to the maximum possible extent (Fig. 4).

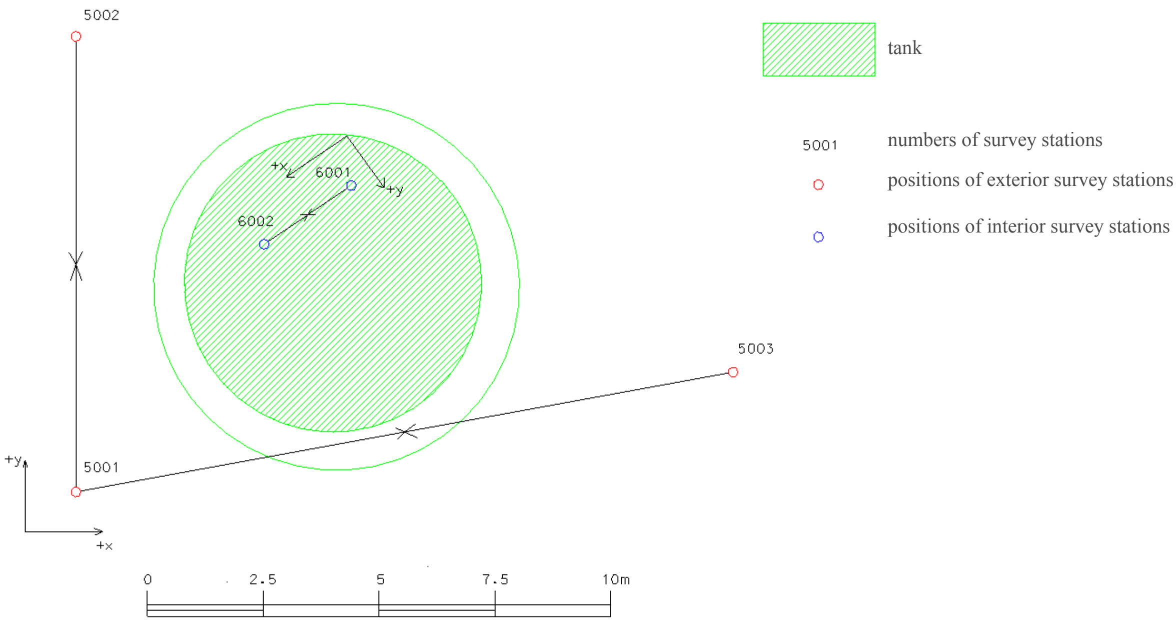

Fig. 3. Positions of survey stations.

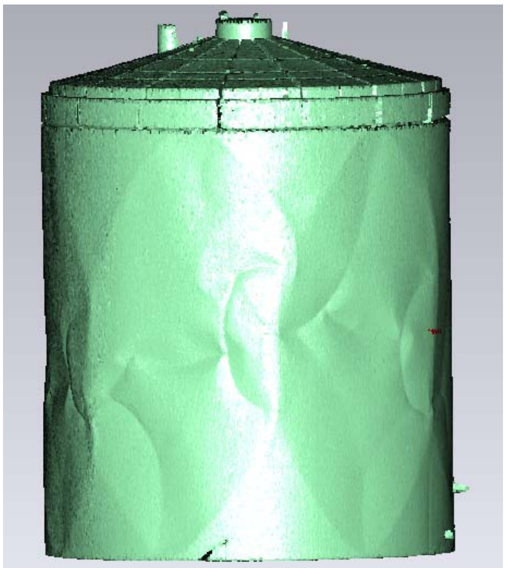

Fig. 4. The point cloud of the inner casing of the damaged tank. [Interactive 3D version of this figure](#).

Analysis results

Since manufacturing parameters of the damaged tank were not available, a cylinder surface, created by modelling based on measured data of the top and bottom centering, was selected as the reference object.

The approximation algorithm of empirically obtained data by a cylindrical body is based on the parametric representation of the cylinder, with n - measured points and k - determined parameters [3], [15]:

$$x = r \cdot \cos(\varphi) + x_0$$
$$y = r \cdot \sin(\varphi) + y_0, \qquad (1)$$
$$z = t + z_0$$

while the radius r and coordinates of the circle centre x_0, y_0 and z_0, are the unknown parameters that need to be determined. The number of unknown ($k = 4$), of which the vector of determined parameters h [m] was defined:

$$\underset{(4,1)}{h} = \begin{pmatrix} r \\ x_0 \\ y_0 \\ z_0 \end{pmatrix} [\mathrm{m}]. \qquad (2)$$

The cylinder height t is calculated as the difference of the z coordinates of the circle centres from the bottom $(j = 1)$ and top $(j = m)$ modelled centering:

$$t = z_{0n} - z_{01} \; [\mathrm{m}]. \qquad (3)$$

The Jacobian matrix of design A, which is composed of submatrices for each point of the j^{th} centering, is created for an adjustment by the LSM method [4], [16]:

$$\underset{(n,1)}{A} = \begin{pmatrix} A_{j1} \\ \vdots \\ A_{ji} \\ \vdots \\ A_{jn} \end{pmatrix}, \text{ where the submatrix for the } i^{th} \text{ point: } \underset{(3,4)}{A_{j,i}} = \begin{pmatrix} \cos(\varphi_{0i}) & 1 & 0 & 0 \\ \sin(\varphi_{0i}) & 0 & 1 & 0 \\ Z_{0j} & 0 & 0 & 1 \end{pmatrix}, \qquad (4)$$

where $i = 1,...,n$.

The vector of reduced measurements l_j was formed from measured points of selected centering:

$$\underset{(n,1)}{l_j} = \begin{pmatrix} l_{j1} \\ \vdots \\ l_{ji} \\ \vdots \\ l_{jn} \end{pmatrix}, \qquad (5)$$

where the vector for the i^{th} point: $$\underset{(3,1)}{l_{j,i}} = \begin{pmatrix} x_{ji} - (r_j^o \cdot \cos(\varphi_{0i}) + x_{0j}^o) \\ y_{ji} - (r_j^o \cdot \sin(\varphi_{0i}) + y_{0j}^o) \\ z_{ji} - z_{0j}^o \end{pmatrix} \text{[m]}, \quad (6)$$

after adding n-vectors to the vector of reduced measurements l_j will have a dimension of (3n,1), where r_j^o and x_{0j}^o, y_{0j}^o and z_{0j}^o are approximate values of unknown parameters chosen at the beginning of the calculation and φ_{0i} are bearing values of point x_{ji}, y_{ji}, z_{ji} from the circle centre x_{0j}, y_{0j}, z_{0j}. The vector of approximate values for the adjustment:

$$\underset{(4,1)}{h_{0,j}} = \begin{pmatrix} r_j^o \\ x_{0j}^o \\ y_{0j}^o \\ z_{0j}^o \end{pmatrix} \text{[m]}, \quad (7)$$

the approximate centre and radius of circles were obtained by an approximation of all points of the circle by graphical process using the Microstation V8 XM software. The calculation is realized by the LSM adjustment [5], [17]:

$$\underset{(4,1)}{dh_j} = (\underset{(4,3n)}{A^T} \cdot \underset{3n,4}{A})^{-1} \cdot \underset{(4,3n)}{A^T} \cdot \underset{(3n,1)}{l_j}, \quad (8)$$

where $$\underset{(4,1)}{\hat{h}_j} = \underset{(4,1)}{h_j^o} + \underset{(4,1)}{dh_j}, \quad (9)$$

where $\hat{h}_j$ is the vector of adjusted determined parameters for the j^{th} centering, where $\hat{h}_{j(t=1)} = h_{j(t=2)}$. The iteration is performed repeatedly, until increments of unknowns dh_j do not fall below a certain threshold or until the fulfilment of following equality:

$$|s_{oi} - s_{oi-1}| \langle \varepsilon, \quad (10)$$

where ε is a chosen constant, s_{oi} is the standard unit deviation after adjustment of the i^{th} iteration of r.

$$s_{0i} = \sqrt{\frac{v^T v}{r}}, \text{ with } r = 3n - 4. \quad (11)$$

After completion of iterations, the final $\underset{(3n,1)}{\underset{(n-1)}{L}} - \underset{(4,1)}{\underset{(k,1)}{C^o}}$ values for centerings are:

$$\text{for } j = 1,\ h_1 = \begin{pmatrix} r_1 \\ x_{01} \\ y_{01} \\ z_{01} \end{pmatrix} = \begin{pmatrix} 3.2394 \\ 98.695 \\ 101.192 \\ 105.335 \end{pmatrix} \text{[m]}, \quad (12)$$

$$\text{for } j = m \text{ we get } h_m = \begin{pmatrix} r_m \\ x_{0m} \\ y_{0m} \\ z_{0m} \end{pmatrix} = \begin{pmatrix} 3.2394 \\ 98.695 \\ 101.192 \\ 98.335 \end{pmatrix} \text{[m]}. \quad (13)$$

Coordinates of circle centres of bases and height of the cylinder were obtained from the algorithm for calculation of the approximated cylinder. Identified display of empirically obtained data and graphical model of reference object was created by graphical modelling in CAD software.

To solve the problem, we used a mathematical procedure for generating an approximate reference cylinder, based on the known coordinates of the centre of bases and height of the cylinder. By known mathematical equations, we created a simulated point cloud of the reference object. Coordinates of circle centres of bases were used as the input data:

$$\begin{aligned} x_s &= 98.695\ m, \\ y_s &= 101.192\ m, \\ r &= 3.239\ m. \end{aligned} \quad (14)$$

Individual points of the cylinder base were calculated on the basis of equations for calculating the position of point in a circle as follows [7], [8], [11]:

$$x_i = x_s + r \cdot \cos i \cdot \frac{\pi}{150},$$
$$y_i = y_s + r \cdot \sin i \cdot \frac{\pi}{150}, \quad (15)$$
$$i \in N \wedge i \in <1,300>.$$

The step of simulation was selected as π/150, equivalent to the length of circular arc (Fig. 5):

$$l = 2\pi r \cdot \frac{1}{300} = 6.78 \text{ [cm]}, \quad (16)$$

vertical shift of simulated points in a circle along the axis of cylinder was realized as:

$$z_i = z_s - i \cdot 0.1 \text{ [m]}. \quad (17)$$

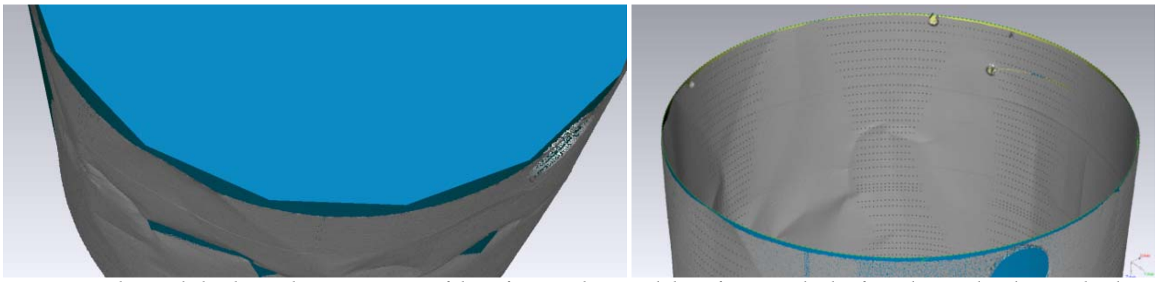

Fig. 5. The n-sided polygonal representation of the reference object and the reference cylinder from the simulated point cloud.

Selection of the spatial estimation method is to a great extent subjective and can greatly affect the accuracy of output values [2]. The final graphic interpretation to determine the extent of deformation due to the implosion was done in a graphical environment of the Raindrop Geomagic 10.0 software. The process of visualization is supported with tools implemented in a geographical information systems [9], [14]. Displayed deformation significantly exceeded the visible extent of deformation from the preliminary inspection and it is graphically and numerically shown on the Fig. 6 and in the Tab. 3.

Tab. 3 The numerical representation of the tank deformation

No.	Height from bottom [m]	Direction of the deformation	Graphically determined deviation in Microstation V8 MX [m]	Graphical deviation in Geomagic 10.0 [m]
1	2.50	-	0.145	<-0.136, -0.153>
2	2.20	+	0.096	< 0.082, 0.102>
3	3.03	-	0.162	<-0.153, -0.170>
4	3.25	+	0.070	< 0.068, 0.085>
5	3.50	-	0.131	< -0.119, -0.136>

The extreme deviation reached the value of 0.174 m, with the hypsometric separation into 22 parts with an interval of <0, 0.017> [m]. A negative direction of deformation represents the shift towards the inside of the tank and positive direction of deformation represents the bulge of the tank outwards from the reference object.

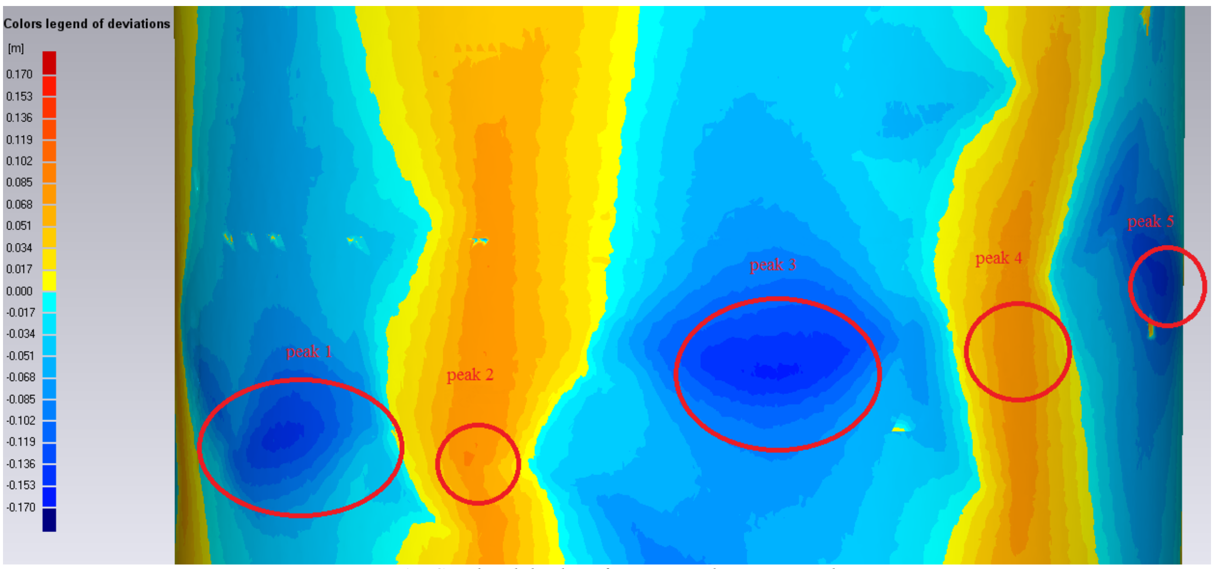

Fig. 6. Graphical display of positive and negative peaks.

Due to the significant difference in the pressure inside and outside of the tank, not only the displayed deformation occurred, but also gaps in the integrity of the inner casing, which was discovered only during the subsequent filling of the tank.

Conclusion

Use of the methodology of terrestrial laser scanning, in the case of determining deformations of tanks in mechanical engineering, is innovative, since previously the method of non-prism surveying using electronic total stations was widely used for this type of tasks. Not only the demonstration of position and extent of deformation, but also its numerical expression of shift or bulge of the steel casing represents an important contribution. In the case of massive gaps in the casing, the subsequent localization of the extent as well as identifying errors of welded joints is relatively easy.

References

[1] Černota, P., Staňková, H., Gašincová, S.: Indirect Distance Measuring as Applied upon both Connecting Surveys and Orientation One. *Acta Montanistica Slovaca. 16, 2011, 4, 270-275, ISSN 1335-1788*. Available at: http://actamont.tuke.sk/pdf/2011/n4/6cernota.pdf

[2] Gergeľová, M., Kuzevičová, Ž., Kuzevič, Š., Palková, J.: Comparison of interpolation methods for estimating climatological data. *SGEM 2013, 13th International Multidisciplinary Scientific GeoConference, Informatics, geoinformatics and remote sensing*: *conference proceedings, Albena, Bulgaria, 1, 2013, 677-683. ISSN 1314-2704, ISBN 978-954-91818-9-0.*

[3] Hampacher, M., Štroner, M.: Processing and analysis of measurements in engineering surveying. *Czech technical university in Prague, 2011, Prague, 312 p., ISBN 978-80-01-04900-6.*

[4] Jakub, V., Sabová, J., Weiss, G.: Local geodetic networks I. *1st edition. Košice, BERG Faculty, TU, 2008, 76 p., ISBN 978-80-553-0022-1.*

[5] Jakub, V., Weiss, G.: Breakdowns in the deformation monitoring and their control. *Acta Montanistica Slovaca. 12, 2007, 1, 1-7, ISSN 1335-1788.* Available at: http://actamont.tuke.sk/pdf/2007/n1/1jakub.pdf

[6] Kovanič, Ľ.: Possibilities of terrestrial laser scanning method in monitoring of shape deformation in mining plants. *Inżynieria Mineralna. 31, 2013, 1, 29-41, ISSN 1640-4920.* Available at: http://www.potopk.republika.pl/archiwum.html

[7] Luhmann, T., Robson, S., Kyle, S., Boehm, J.: Close-range photogrammetry and 3D imaging. *Walter de Guyter GmbH, 2014, Berlin, 684 p., ISBN 978-3-11-030269-1.*

[8] Luhmann, T., Robson, S., Kyle, S., Harley, I.: Close range photogrammetry: principles, methods and applications. *Whittles Publishing, 2006, Caithness, 510 p., ISBN 0-470-10633-6.*

[9] Mihalová, L., Kuzevič, Š., Kuzevičová, Ž.: Application of GIS in hydrogeology and engineering geology. *Acta Montanistica Slovaca. 12, 2007, 3, 454-457, ISSN 1335-1788*. Available at: http://actamont.tuke.sk/pdf/2007/s3/23mihalovakuzevicovci.pdf

[10] Pavelka, K., Hodač, J.: Photogrammetry 3: Digital methods and laser scanning. *1st edition, Czech technical university in Prague, 2008, Prague, 187 p., ISBN 978-80-01-03978-6.*

[11] Rákay, Š., jr., Rákay, Š., Weiss, R., Zuzik, J.: Adjusting wheel alignment on machinery equipment. *Acta Montanistica Slovaca. 17, 2012, 4, 348-353, ISSN 1335-1788.* Available at: http://actamont.tuke.sk/pdf/2012/n4/17rakay.pdf

[12] Sabová, J., Jakub, V.: Geodetic deformation analysis. *1st edition, Košice, BERG Faculty, TU, 2007, 128 p., ISBN 978-80-8073-788-7.*

[13] Sabová, J., Sabo, J.: Confidence ellipsoids in deformation analysis. *SGEM 2013, 13th international multidisciplinary scientific geoconference. Informatics, geoinformatics and remote sensing, conference proceedings, volume 2. 16-22 June, 2013, Albena, Bulgaria. Albena, STEF92 Technology Ltd., 2013, p. 79-86, ISSN 1314-2704, ISBN 978-619-7105-01-8.*

[14] Šimčák, M., Kuzevičová, Ž., Kuzevič, Š.: Three dimensional visualization choosen part of Košice city. *Acta Montanistica Slovaca. 12, 2007, 3, 563-566, ISSN 1335-1788.* Available at: http://actamont.tuke.sk/pdf/2007/s3/40simcak.pdf

[15] Štroner, M., Pospíšil, J.: Terrestrial scanning systems. *Czech technical university in Prague, 2008, 185 p., ISBN 978-80-01-04141-3.*

[16] Weiss, G., Jakub, V., Weiss, E.: Compatibility of geodetic points and its verification. *1st edition, Košice, TU, 2004, 139 p., ISBN 80-8073-149-7.*

[17] Weiss, G., Jakub, V.: The test verification of 3D geodetic points and their changes. *Acta Montanistica Slovaca. 12, 2007, special issue 3, 612-616, ISSN 1335-1788.* Available at: http://actamont.tuke.sk/pdf/2007/s3/46weiss.pdf