Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2017, 4(6):148-156**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Analysis of determining the heights with different surveying methods

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Abstract Height determination is one of the most important geodetic works in building construction. Most often it is used for the altitude presentation of the terrain to determine displacements, the height of buildings and for various precise laboratory and scientific research. The expected values in determining displacements and deformations can be confirmed with these results. A lot of methods can be used for determination of height differences; the choice of a method depends on the complexity of the project. Lately, one of the most frequently used methods is GNSS (Global navigations satellite system), which gives us fairly reliable 2D positional results while the altitude component does not give us such reliable outcomes. The obtained results for testing the GNSS measurements were compared by a robotic total station accuracy of 0.5. Before the experiment was conducted, temporal analysis of GNSS data was captured by individual axes and the different ways of processing information. The focus is on planning GNSS measurements needed for complex measurements. In order to improve the determination of the height, the component was increased in GNSS method of data collection from 10 Hz to 100 Hz, which is a partially improved end-Drag to change size.

Keywords civil engineering, surveying, precision, GNSS, robotic total stations, height

1. Introduction

In the last 20 years, technological development had a tremendous impact on the field of geodesy [1]. This development results in very advanced instruments which can perform really complex tasks. As a consequence, many fields are nowadays using GNSS techniques. A simple alternative method is developed to solve the GPS navigation equations directly without linearization and iteration to improve position accuracy [2]. Only technologically excellent equipment and measurement results such as GNSS instruments and robotic total stations give an insight into structure reaction during exploitation and if its behaviour is in accordance with design solutions. In such way we can assess the real situation and the security of the structure. However, structural analysis also requires reliable results by individual axes. The obtained results can determine whether the response of the structure is in accordance with the theoretical model and if the measured values can cause deformations on the structure on the long run. So we focus on geodetic measurements, which give us the absolute results in space. The temporal noise characteristics of GNSS time series is well described as a combination of white noise and power law noise [3]. Linear trend, offsets and potential periodicities can be well explained by deterministic models, while there are still unmodeled effects in continuous GNSS time series [4].

Nowadays, the 3D position of points can be determined in absolute terms by increasing the number of readings per second with GNSS instruments and robotic total stations. As a result, we are no longer limited to monitoring only static response but also the dynamic analysis of structures. Now we can also define the dynamic parameters of built structures such as natural frequency, damped oscillations and their own forms of oscillations. These dynamic parameters are functions of the global stiffness and are the best indicator of the real state of the structure. Any serious change that occurs in the structure could be the cause of the change in the dynamic parameter values.

There are a lot of studies on the accuracy of determination of position with GNSS equipment. Coloured noise was researched by Zhang et al. 1997 & Williams et al. 2004 [5-6]. Ionospheric delay, tropospheric delay, and loading of solid tide, pole tide, and ocean tidal were studied by Zumberge et al. 1997, King et al. 2001, Herring et al. 2010a, Herring et al. 2010b, Bertiger et al. 2010. El-Naggar (2011b) was also trying to enhance the accuracy of GNSS point positioning by converting the single frequency data to dual frequency data [7-11].

Our study used an experimental analysis of time of data acquisition to measure the dynamic response. In this way a confirmation of reliability of data can be obtained in real time versus result of varying lengths of data capture: 1h, 2h, 6h, 12h and 24h. After this test, a comparative analysis of GNSS receiver data versus automatic total station measurements was performed in terms of height. The height of the receiver was changed every minute for about 5cm and that change was measured with both instruments.

In general, the GNSS methods can be divided into absolute and relative. To accurately determine the position of the receiver in practice, the relative measurement method is mainly used. The method allows up to a few centimetres accuracy; therefore, we need at least two receivers, one of which is located at a point with known coordinates, and the other at the new point (virtual reference system VRS). Relative GNSS surveying methods are static, rapid static, kinematic and RTK.

A fast static method was used in the experiment. This surveying method is almost identical to the static method with the exception that duration of observations is shorter. The accuracy of this method is from 1 ppm to 10 ppm. Observations should last 5 to 20 minutes.

2. Measurement and analysis of GNSS results in different periods of time

The satellite signal point on the roof of the Faculty of Civil Engineering, Transport Engineering and Architecture (FGPA) in Maribor was chosen for the implementation of GNSS surveying reference and to avoid potential interference. We used a static method, which is the basic method for determining the relative position, in time intervals of 1 h, 2 h, 6 h, 12 h and 24 h with three different receivers.

For the purposes of the experiment, we used three different GNSS-receivers, which are shown in Fig. 1a, 1b and 1c.

1a 1b 1c

Figure 1: Topcon HiperPro (a), Topcon Hiper V (b), Leica SR9500 (c)

The final ephemeris was included in the data processing. Five permanent stations of Slovenian GNSS network signal (SIGNAL), two Austrian permanent stations network APOS (AUT) and seven IGS-points were also used in the data processing procedure.

Coordinates of the points were determined as the arithmetic average of the coordinates. Standard deviation and standard error were calculated using Eq. 1 and 2.

2.1. Standard deviation

The standard deviation (σ) is a very important statistical parameter whichprovides the value of statistical sign from the average. In other words, the standard deviation is a measure of the distribution dispersion of values.

$$\sigma_x = \pm\sqrt{\frac{\sum_{i=1}^{N}[v\cdot v]}{(n-1)}} \qquad (1)$$

where:

σ … standard deviation

v … deviation from arithmetic mean value

2.2. Standard error of arithmetic mean value

The standard error of the arithmetic mean is the standard deviation of the sampling distribution of arithmetic means and measures the accuracy of sample estimation of arithmetic mean. That tells us the range of movement of the arithmetic mean of the population. We can say that with a certain (usually 95%) confidence intervals.

$$\sigma_{\bar{x}} = \pm\sqrt{\frac{\sum_{i=1}^{N}[v\cdot v]}{n\cdot(n-1)}} \qquad (2)$$

where:

$\sigma_{\bar{x}}$ … standard error

An example of calculation of standard errors and the accuracy for the HyperPro measurements of the height are shown in Table 1.

Table 1: Standard error of arithmetic mean by the observation length for point height

		***h*[m]**	**Deviation from arithmetic mean**		**squares of deviations**	
h_1	1 h	285,413	v_1=h'-h_1	-0,0212	v_1*v_1	0,00044944
h_2	2 h	285,202	v_2=h'-h_2	0,1898	v_2*v_2	0,03602404
h_3	6 h	285,447	v_3=h'-h_3	-0,0552	v_3*v_3	0,00304704
h_4	12 h	285,456	v_4=h'-h_4	-0,0642	v_4*v_4	0,00412164
h_5	24 h	285,441	v_5=h'-h_5	-0,0492	v_5*v_5	0,00242064
	∑	**1426,959**			∑v*v	**0,0460628**

Number of measurement	n	**5**
Arithmetic mean	h'	**285,3918**
Standard deviation of individual measurement	σ_{hi}	**0,107**
Standard error of arithmetic mean	$\sigma_{\overline{hi}}$	**0,048**

2.3. Determination of the height according to the antenna type

The first comparison of the height determination refers to the receiver type. Standard errors of arithmetic mean of height by antenna type can be seen in Table 2. As expected, the determination of height using an old Leica receiver is the worst.

Table 2: Standard errors of arithmetic mean of height by antenna type

1	**H-pro**	**H-V**	**Leica**
y[m]	0,032	0,020	0,087
x[m]	0,133	0,062	0,334
h [m]	0,048	0,016	0,255

Fig. 2 shows the standard deviation by antenna type in the case of height measurement. It is obvious that the Topcon Hiper V antenna is the best, because the standard error of arithmetic means is the lowest.

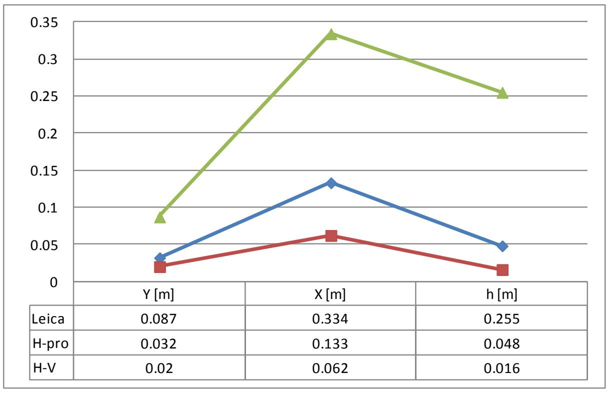

Figure 2: Standard error of arithmetic mean by antenna type

DOP (Dilution of precision) factors for one of the receivers at 24h observation period can be seen in Fig 3. Obviously, DOP factor varies during the day, so proper GNSS observation planning is needed. If we performed our observation only between 21h-3h a.m., that would result in the worst DOP factors and poor measurements result. Thus, we gain better average DOP and more accurate position determination by increasing the length of the observation.

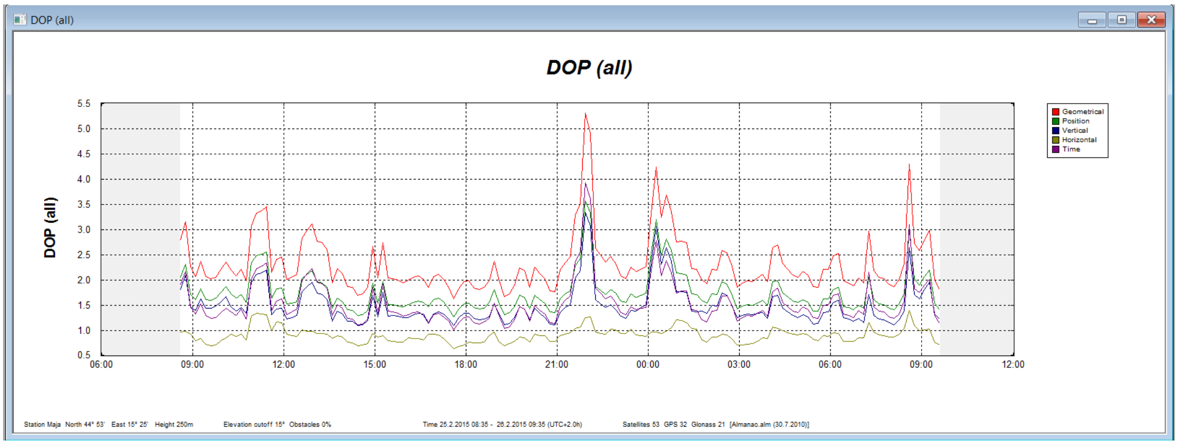

Figure 3: DOP factors for one of the receivers at 24h observation

DOP factors affect the accuracy of the determined position of the receiver. DOP depends on the constellation of satellites and it should be as small as possible. PDOP (position dilution of precision) factor at the receiver Hyper Pro ranged between 2.55 and 2.99, at the receiver Hyper V between 2.37 and 3.66 and at the receiver Leica between 4.46 and 9.29. Some DOP factors for Hiper Pro, Hiper V and Leica are shown in Table 3, 4 and 5 and Fig. 4.

Table 3: Number of tracked satellites and DOP factors for Hiper Pro

Hiper Pro	GPS	GLONASS	Sum	PDOP	HDOP	VDOP
1 h	11	5	16	2,639	1,388	2,243
2 h	12	7	19	2,764	1,564	2,266
6 h	18	12	30	2,757	1,551	2,273
12 h	27	16	43	2,996	1,577	2,547
24 h	31	19	50	2,551	1,340	2,171

Table 4: Number of tracked satellites and DOP factors for Hiper V

Hiper V	GPS	GLONASS	Skupaj	PDOP	HDOP	VDOP
1 h	10	8	18	2,379	1,279	2,006
2 h	12	8	20	2,608	1,327	2,245
6 h	16	13	29	2,992	1,424	2,632
12 h	24	17	41	3,237	1,693	2,757
24 h	30	18	48	3,662	1,976	3,075

Table 5: Number of tracked satellites and DOP factors for Leica

Leica	GPS	GLONASS	Skupaj	PDOP	HDOP	VDOP
1 h	7	0	7	9,296	6,616	6,522
2 h	8	0	8	4,460	2,609	3,616
6 h	11	0	11	6,223	3,859	4,881
12 h	22	0	22	8,300	4,924	6,665
24 h	30	0	30	9,063	4,837	7,651

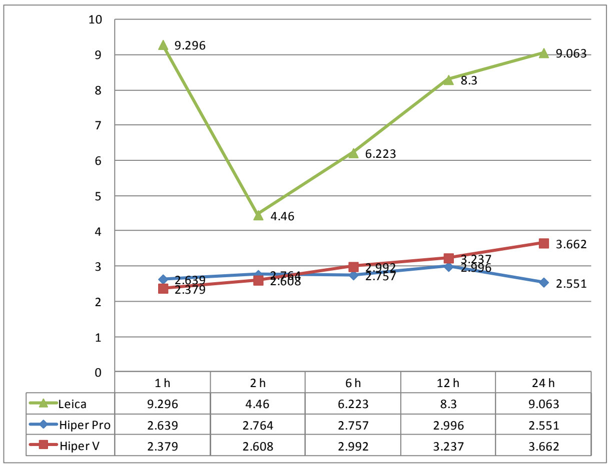

Figure 4: PDOP factors for 24h observation by antenna type

If the accuracy of the positioning of all three receivers is compared, quite a big difference between the Topcon Hiper V and Leica SR9500 can be noticed. Table 4 clearly shows that the results obtained with Hyper Vare most accurate. Hiper Vuses 226 GNSS channels and is one of the latest antennas in the market. Leica SR9500 is, on the other hand, the oldest and not so accurate anymore because it follows GPS satellites only. It tracksmerelyup to 30 satellites. In this experiment, we will hereafter focus only on h coordinate, especially because the emphasis is on determining the height component for dynamic and static structural analysis.

2.4. Determination of the height according to length of observation

All three above mentioned receivers enable different length observations to see the influence of different time period on the accuracy of determination of vertical component of the point. For that purpose, 1h, 2h, 6h, 12h and 24h observations were performed using Topcon Hiper Pro, Topcon Hiper V and Leica SR9500. Results from Tables 6-10 show acquisition of the point height in all cases and calculation ofarithmetic mean of the height, deviation from arithmetic mean, square of deviation, standard deviation of individual measurement and standard error of arithmetic mean.

Table 6: Precision analysis for 1h measurement

1h measurements		h [m]	Deviation from arithmetic mean		squares of deviations	
Topcon Hiper Pro	$h1$	285,4130	v_1=h'-h_1	0,450333333	v_1*v_1	0,202800111
Topcon Hiper V	$h2$	285,4240	v_2=h'-h_2	0,439333333	v_2*v_2	0,193013778
Leica	$h3$	286,753	v_3=h'-h_3	-0,889666667	v_3*v_3	0,791506778
	$\sum$	857,59	$\sum v$	-1,13687E-13	$\sum v*v$	1,187320667
Number of measurement					n	3
Arithmetic mean					h'	285,863
Standard deviation of individual measurement					σ_{hi}	0,770
Standard error of arithmetic mean					$\sigma_{\overline{hi}}$	0,445

Table 7: Precision analysis for 2h measurement

2h measurements		h[m]	Deviation from arithmetic mean		squares of deviations	
Topcon Hiper Pro	$h1$	285,2020	v_1=h'-h_1	0,202666667	v_1*v_1	0,041073778
Topcon Hiper V	$h2$	285,5220	v_2=h'-h_2	-0,117333333	v_2*v_2	0,013767111
Leica	$h3$	285,490	v_3=h'-h_3	-0,085333333	v_3*v_3	0,007281778
	$\sum$	856,2140	$\sum v$	-1,13687E-13	$\sum v*v$	0,062122667
Number of measurement					n	3
Arithmetic mean					h'	285,404
Standard deviation of individual measurement					σ_{hi}	0,176
Standard error of arithmetic mean					$\sigma_{\overline{hi}}$	0,102

Table 8: Precision analysis for 6h measurement

6h measurements		***h*[m]**	**Deviation from arithmetic mean**		**squares of deviations**	
Topcon Hiper Pro	*h*1	285,4470	v_1=*h*'-h_1	0,034	v_1*v_1	0,001156
Topcon Hiper V	*h*2	285,4890	v_2=*h*'-h_2	-0,008	v_2*v_2	6,4E-05
Leica	*h*3	285,507	v_3=*h*'-h_3	-0,026	v_3*v_3	0,000676
	∑	856,443	∑*v*	0	∑*v***v*	0,001896
Number of measurement					*n*	3
Arithmetic mean					*h*'	285,481
Standard deviation of individual measurement					σ_{hi}	0,031
Standard error of arithmetic mean					$\sigma_{\overline{hi}}$	0,018

Table 9: Precision analysis for 12h measurement

12h measurements		***h*[m]**	**Deviation from arithmetic mean**		**squares of deviations**	
Topcon Hiper Pro	*h*1	285,4560	v_1=*h*'-h_1	-0,0237	v_1*v_1	0,000560111
Topcon Hiper V	*h*2	285,4800	v_2=*h*'-h_2	-0,0477	v_2*v_2	0,002272111
Leica	*h*3	285,361	v_3=*h*'-h_3	0,0713	v_3*v_3	0,005088444
	∑	856,297	∑*v*	5,68434E-14	∑*v***v*	0,007920667
Number of measurement					*n*	3
Arithmetic mean					*h*'	285,432
Standard deviation of individual measurement					σ_{hi}	0,063
Standard error of arithmetic mean					$\sigma_{\overline{hi}}$	0,036

Table 10: Precision analysis for 24h measurement

24h measurements		***h*[m]**	**Deviation from arithmetic mean**		**squares of deviations**	
Topcon Hiper Pro	24 h	285,4410	v_1=*h*'-h_1	0,0700	v_1*v_1	0,0049
Topcon Hiper V	24 h	285,4850	v_2=*h*'-h_2	0,0260	v_2*v_2	0,000676
Leica	24 h	285,607	v_3=*h*'-h_3	-0,0960	v_3*v_3	0,009216
	∑	856,5330	∑*v*	-1,13687E-13	∑*v***v*	0,014792
Number of measurement					*n*	3
Arithmetic mean					*h*'	285,511
Standard deviation of individual measurement					σ_{hi}	0,086
Standard error of arithmetic mean					$\sigma_{\overline{hi}}$	0,050

Table 11 shows all standard error of the arithmetic mean for y, x and h. Standard error of arithmetic mean improves by increasing the observation time.

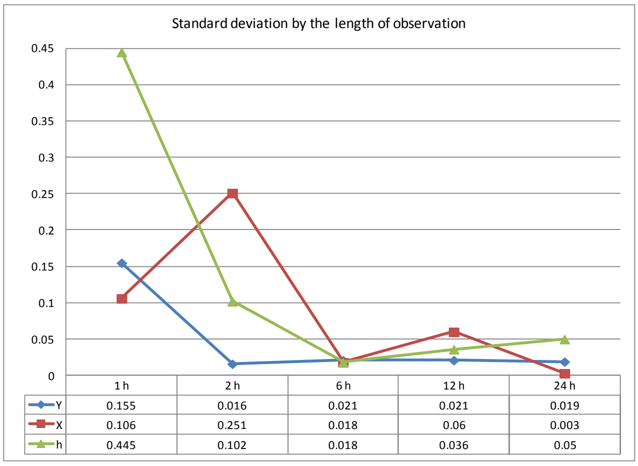

Figure 5: Standard deviation by the length of the observation

Table 11: Standard error of the arithmetic mean for *y*, *x* and *h*

	***y*[m]**	***x*[m]**	***h*[m]**
1 h	0,155	0,106	0,445
2 h	0,016	0,251	0,102
6 h	0,021	0,018	0,018
12 h	0,021	0,060	0,036
24 h	0,019	0,003	0,050

As expected, the trend shows improvement of accuracy by prolonging the observation time. From the average deviates only the determination of the point height. The accuracy is better and better till 6h observation, then it deteriorates because the height component does not depend on the length of the observation. In general, we can get better results with longer periods. In conclusion, monitoring of a height does not necessary need 24h monitoring, 6h are enough if other conditions are appropriate.
An experiment for comparison of height component with robotic total station Leica TS50 and Topcon Hiper V GNSS receiver was conducted in order to further improve the height component. The experiment was carried out in the open field, so that potential signal interference was eliminated and prior planning of the measurements could be done due to the good distribution of satellites.

3. The comparison of height determination

The analysis is based on the variation in the level of the receiver once every 60 seconds for about 5 cm. Both instruments were placed on the tripod with possibility of height changes (Fig. 6). During this period measurements with TS50on a precise prism GPH1P and Topcon Hiper V GNSS receiver were performed. At this time 5379 measurements were obtained in a local coordinate system and then compared.

Figure 6: Hiper V and GPH1P prism on a tripod

11 changes in the tripod were made, as shown in the Fig. 7.

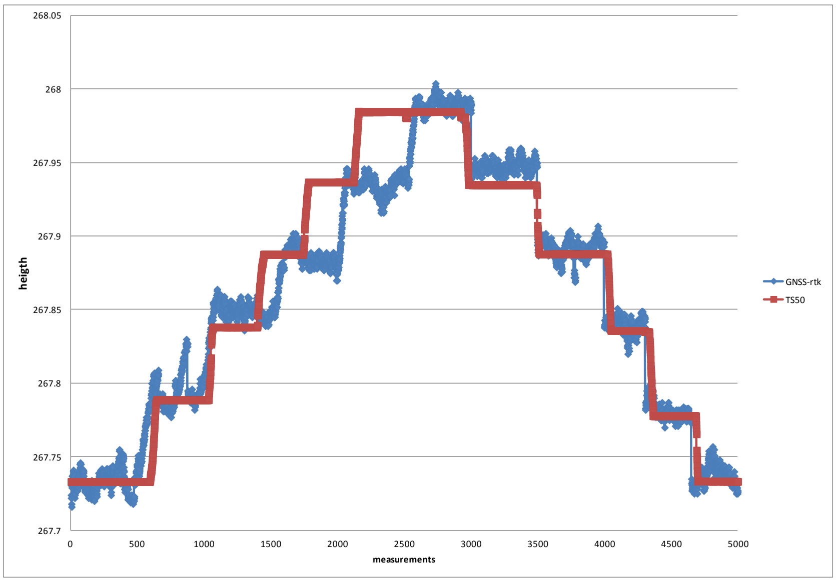

Figure 7: Different height measurements with GNSS and Leica TS50

Analyses were made for each different height position of the tripod. Standard deviation and standard error were calculated and Leica TS measurements were taken as a reference value. Fig. 8 and 9 show measurements of the first height position on Leica TS50 and Topcon Hiper V. As we can see, measurements with TS50 are far more accurate than with Hiper V, as expected. Standard deviation of measurements with Leica TS50 was 0.0026 mm and standard deviation of measurements with Topcon Hiper V was 0.1920 mm.

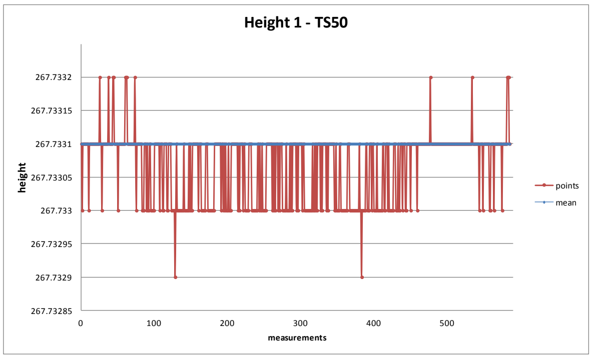

Figure 8: Measurements with Leica TS50

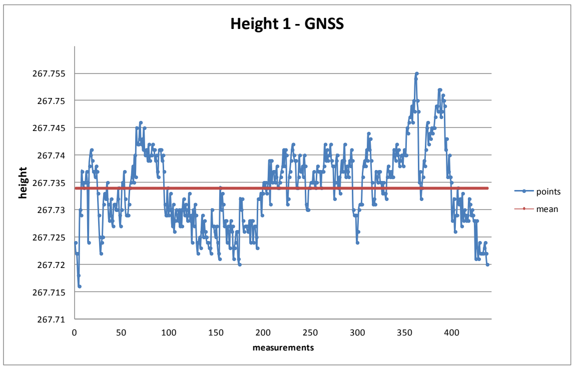

Figure 9: Measurements with Topcon Hiper V

Final results of comparison for all 11 height positions are shown in table 12. A mean of all standard deviation was also calculated. As we can see, GNSS measurements deviates from the mean height determined by TS50 for 5.1 mm.

Table 12: Comparison of height determination accuracy for all 11 positions

	TS50		GNSS		
	Average height [m]	Standard deviation of each measurements [mm]	Average height [m]	Standard deviation of each measurements [mm]	Deviation fromreference value in column 2[mm]
1	2	3	4	5	6
height1	267.7331	0.0022	267.7340	0.3328	0.9
height2	267.7887	0.0027	267.7948	0.7298	6.1
height3	267.8381	0.0032	267.8497	0.2339	11.6
height4	267.8877	0.0034	267.8856	0.3135	2.1
height5	267.9396	0.0033	267.9353	0.2706	1.6
height6	267.9846	0.0171	267.9896	0.2172	5.0
height7	267.9350	0.0026	267.9478	0.1920	12.8
height8	267.8880	0.0026	267.8920	0.2874	4.0
height9	267.8359	0.0032	267.8398	0.3205	3.9
height10	267.7778	0.0029	267.7816	0.2984	3.8
height11	267.7333	0.0028	267.7378	0.3570	4.5
Mean value	267.8493	0.0042	267.8535	0.3230	5.1

4. Conclusion

Today's technology development has also touched the field of geodesy. Thus, we are faced with instruments and equipment, which are highly sensitive and precise to perform most challenging tasks. In the construction industry, especially in the area of structure testing, movements, vibration and static responses can be monitored with high reliability and accuracy. This rapid development encroached on the area of construction and now we

can build different structures on such terrain where decades ago we did not even think of. The extreme terrain demands testing equipment, which does not depend on the height, inaccessibility and distance from reference points. GNSS equipment was tested in two independent experiments. In the first case, a time analysis of data acquisition was performed. It can be concluded that 24h monitoring is not obligatory for the purpose of height monitoring; nevertheless, standard error of arithmetic mean improves by increasing the observation time.
Since the emphasis was on height analysis, a second experiment was conducted which compared the variation in the height determined by the robotic total station and GNSS antenna. The results can be compared because of the numerous measurements redundant observations but GNSS measurements are still not precise enough to determine the displacements in the vertical direction. GNSS method can be used for monitoring in the examples where the vertical displacement is several centimetres. Our testing shows that the receiver should collect data at least 6 hours.

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