Monitoring of High-rise Building

Anna HOSTINOVÁ and Alojz KOPÁČIK, Slovakia

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SUMMARY

For engineering geodesy weren't technologies of global navigation satellite system (GNSS) interesting for long time, because they didn't sufficed for high accuracy requirements and for specific measurement conditions. Gradually also here last barriers in using GNSS technologies are falling and solution of traditional engineering geodesy problems obtains new dimension

.
In this situation comes to scene the Slovak permanent observation service (*SK*POS©). This service brings not only new possibilities of using technologies GNSS, but also many questions. One of them is, if and in which range can *SK*POS© find application also in engineering geodesy.

Although *SK*POS© was inaugurated to its practical life not long ago, it remarked many positive responses. Land surveyors quickly take fancy to it, especially in works for real estate register, where this service substituted unpractical using own reference station in real time kinematical method. One possible application in engineering geodesy can be the monitoring of movements and displacements of dynamical effortful constructions. This paper brings results of practical experiment oriented to monitoring of movements of high-rise building.

On the ground of these results we can say, that *SK*POS© is with certain restrictions exploitable in the field of dynamical monitoring of constructions and even also brings some advantages compared to present GNSS technology exploitation. The paper presents results of the experiment and data analysis made by the authors. Some parts of the experiment were compared with results of total station measurement.

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1. INTRODUCTION

The administrative high-rise building of the Faculty of Civil Engineering (SvF) of the Slovak university of technology (SUT) in Bratislava is one (block C) from the complex of three buildings, in which resides the SvF SUT. The building is situated on Radlinského Street in urban district Old Town of Bratislava. The aim of the monitoring of high-rise buildings isn't generally only determination of building movement in time, but also aspiration to find-out and identify natural frequency of the oscillation of the building structure.

2. DESCRIPTION OF THE EXPERIMENT

Description of the Measured Structure

The building has 24 above ground floors and its structure is created from ferro concreted walls and jambs completed with brick stall. Entire high of building is 76,42 m. High-rise building is vibrated with specific frequencies because of external forces. Most of these forces affects irregular, but if the frequency of actuating factor is closing to the own frequency of the structure, resonance is rising and amplitudes of this vibrations are a fortiori expressive. Values of calculated own frequencies of the building are presented in table 1.

Table 1 Own frequencies of the high-rise building of SvF SUT

f_{1x}	f_{2x}	f_{3x}	f_{1y}	f_{2y}	f_{3y}	$f_{1\theta}$	$f_{2\theta}$	$f_{3\theta}$
0,876 Hz	2,688 Hz	4,808 Hz	0,680 Hz	3,311 Hz	5,555 Hz	0,714 Hz	3,448 Hz	5,882 Hz

where f_x – frequency in first own form (axis x),
f_y - frequency in first own form (axis y),
f_θ – torsion frequency in warping.

1.2 Basic Description of the Experiment

The experiment was realized on 2 and 3 March 2007. It was oriented to monitoring of movements and deformations of the bloc C of the SvF SUT in Bratislava. The monitoring system consists of following devices and instruments:

- GNSS receiver and antenna Trimble R8,
- Robotic universal measuring station (UMS) Leica TCA 1101 with special prism,
- Two inclinometers Libela 2800 with I/O devices AE 2 DN,
- Measuring amplifier HBM Spider 8,
- Digital thermometers GREISINGER GFTH 200 and GPB 1300,
- Personal computer (PC).

Measurements were realized by both technologies in the same time from 3:30 pm local time (CET) 2. 3. 2007 to 3:30 pm CET 3. 3. 2007. Scope of the measuring was to monitor and determine the movements of the building for 24 hours. Experiment had to allow comparison of results from both concepts of measuring. That's way was monitored the same point on the top of the building by both methods. This enables the special reflected prism used, which allowed the centric fixation of the GNSS antenna on the same point (Fig. 2).

1.3 Monitoring by UMS Leica TCA 1101

By the UMS was measured the position of the reflected prism, which was localized on the top of the block C SvF SUT. The UMS Leica TCA 1101 (Fig. 1) was located on concrete pillar with metallic base for forcible centralization on the roof of the block A. To monitor the possible inclination of the pillar were also caught two inclinometers on fibreglass laminate plate fixed between the UMS and the metallic base. Periodically were together measured the actual temperature, atmospheric pressure and the humidity of the atmosphere. UMS was managed and controlled by software DocWork (Angermeier, Germany) installed on the PC.

Fig. 1 Robotic UMS Leica TCA 1101 with inclinometers

1.4 Monitoring by GNSS receiver Trimble R8

The aim of the experiment was to monitor relatively small movements of the high-rise building. Also there was required high measuring accuracy, determination of the actual position in mm range, made by maximum possible measuring frequency. Also the GNSS relative kinematical method was of used. The receiver located on the roof of the monitored building (Fig. 2) performed the function of the rover. Two variants of reference station were proposed. The first variant planed the exploitation of the new permanent GNSS network of Slovakia – *SK*POS©. The reference station will be defined as the VRS (virtual reference station) generated in specific distance from the point of measuring.

Fig. 2 GNSS antenna and receiver Trimble R8 with prism

In the second variant reference station will be the second GNSS receiver located permanently on the roof of the block A, which data are permanently registered and processed by the

Department of Theoretical Geodesy of the SvF SUT in Bratislava. Only signals from NAVSTAR GPS satellite were received, with the 1 s frequency.

System GNSS Trimble R8 comprises 72-channel multi frequency GNSS receiver, antenna and wireless technologies Bluetooth and GSM/GPRS. It can receive signals from NAVSTAR GPS (L1/L2/L2C/L5) and GLONASS (L1/L2). Frequency of the actualisation of the antenna position is 1, 2, 5 and 10 Hz. Input and output support formats: CMR+, RTCM 2.1, RTCM 2.3, RTCM 3.0 [2].

Table 2 System Trimble R8 accuracy (according to [5])

Method	*Horizontal accuracy*	*Vertical accuracy*
DGNSS	±0,25 m + 1 ppm	±0,50 m + 1 ppm
Static a Fast Static	±5 mm + 0,5 ppm	±5 mm + 1 ppm
Kinematical	±10 mm + 1 ppm	±20 mm + 1 ppm

2. MATHEMATICAL MODEL OF DATA PROCESSING

This paper brings results from the monitoring of building by GNSS technology only and their comparison with UMS data. Data registered by the receiver Trimble R8 located on the roof of the block C of SvF SUT in Bratislava were processed by post-processing method. Two main variants of processing were selected. The first variant exploited the service *SK*POS©, which generate VRS in specific distance from the point of measuring, and considering to this VRS we get corrections (for improving measurements) from the provider the Geodetic and Cartographic Institute (GCI). VRS sub-serves role of reference station and receiver on the roof of the building the role of rover. The second variant went out from data supplied from the Department of Theoretical Geodesy SvF SUT, their GNSS receiver was during the experiment located on concrete pillar (PIL1) on the roof of the block A. The distance between PIL1 and the UMS (pillar TOTS) is cca 45 meters. The receiver on point PIL1 represents in this case the reference station and the receiver on the block C (point named SVFC) the rover.

The recording frequency was 1 Hz. After slashing time series to 10 minutes segments and after their averaging we got another file of data with time separation of 10 minutes (Table 3).

Table 3 Analysed time series

Variant	**Recording frequency**	**Beginning of time series**	**End of time series**
Variant N.1	10 min	15:30:00 2.3.2007	15:30:00 3.3.2007
	1 s	17:00:00 2.3.2007	18:00:00 2.3.2007
	1 s	6:00:00 3.3.2007	7:00:00 3.3.2007
Variant N.2	10 min	15:30:00 2.3.2007	15:30:00 3.3.2007
	1 s	17:00:00 2.3.2007	18:00:00 2.3.2007
	1 s	6:00:00 3.3.2007	7:00:00 3.3.2007

These data were used for comparison the results with data from UMS, which during 24-hours experiment worked with interval of 10 minutes. During the time of sunset (17:00 h – 18:00 h CET) and sunrise (6:00 h – 7:00 h CET) was the UMS measurement set to maximum frequency and time series of 1 Hz frequency were from measured data calculated.

2.1 Data Processing

Variant N.1: reference station VRS

The aim of variant N.1 application was to verify the possibilities of using service *SK*POS© in for deformation measurement. For realization of this variant there was necessary to obtain corrections from *SK*POS© to measured data. The corrections were "produced" by the provider of the *SK*POS© the GCI through internet portal www.skpos.gku.sk for the chosen VRS. VRS was in this case defined in distance 159,92 m from the rover (point SVFC) which is approximately equal to distance between points PIL1 and SVFC in the variant N.2. The geodetic coordinates of VRS are B = 48° 09′ 09′′, L = 17° 06′ 50′′, H = 220 m.

Data processing was done in program LEICA Geo Office. The results, geocentric coordinates of SVFC from 24-hours measurement made with 1 Hz frequency, were given in ETRS 89 (parallel in WGS 84).

Transformation from the geodetic Cartesian system to local topocentric system
Because of next processing and comparing of results with results from UMS it was necessary to transform ETRS coordinates to local topocentric system with the system centre in VRS. Result of this step were the coordinates n, e, and v of SVFC and the approximately coordinates n, e, v of TOTS in the defined local topocentric system.

Transformation of the local topocentric coordinates n, e to coordinates x, y
The aim of the experiment was the monitoring of 2-D movement of the structure only, also the coordinate v was not processed. The shift of the coordinate system centres to TOTS (coordinates n', e') and rotation of all system to line TOTS-SVFC was made in next step. Result of this transformation was coordinates x and y of SVFC in local topocentric coordinate system with centre and orientation of axis which is identical with the centre and orientation of the coordinate system the UMS.

Variant N.2: reference station PIL1

The second variant was prepared to compare results from the first variant. Philosophy of data processing was similar to the variant N.1. Difference was only in the reference station, which is chosen in this case its sub served station on point PIL1.

2.2 Mathematical Model for Measurement Analysis – Time Series

Files of measured and further processed data verified condition of solid time step between values, and so they can be called time series. According to definition the time series is a sequence of data points, measured typically at successive times, spaced at (often uniform) time intervals. Time is the argument, from depends values of time series. Spirit of the time series analysis is creation of the model, which equally truly describes basic properties of the time series and permits to understand the mechanism of generation of values of the time series. First step is the graphic representation of values in dependency to the time. Already from this representation is sometimes possible to see expressive trend or periodic character of the stochastic process [1].

The target of time series analysis is first of all the decomposition of the time series to some elements, which are essentially more easily and clearly interpretable. Generally is time series decomposed to the trend, the periodical components and the stochastic component [3].

Trend is mostly the most important element of time series. For finding trend are usually used these methods [1]:
- Regression analysis,
- Method of moving averages,
- Non-linear (exponential) adjustment.

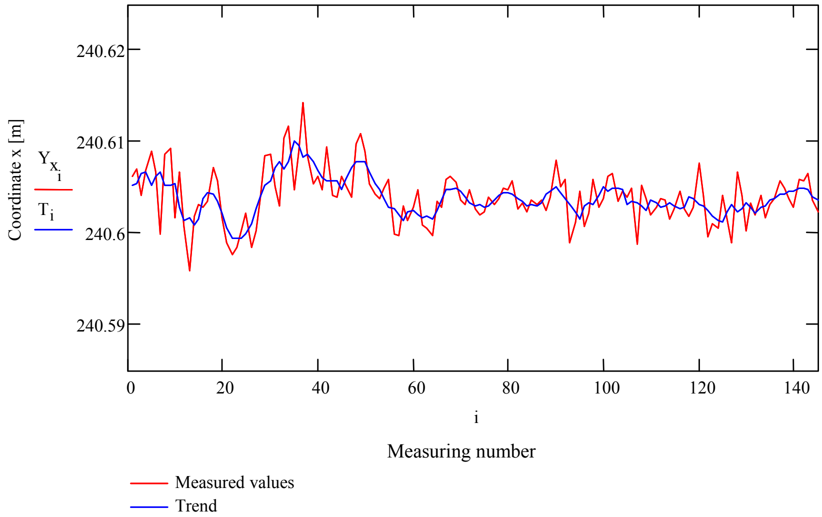

Fig.3 Trend calculated for variant N.1 - axis x

For the examined time series appeared method of moving averages was the best solution for trend analysis. This method belongs to the adaptive progresses of trend elimination, which are competent automatically respond to potential changes in the character of the trend. Length of moving average is necessary to choose in way, when the characteristic features of the trend are visible [4].

3. INTERPRETATION OF TEST RESULTS

First step to understanding of measuring results, in this case time series is the graphical representation of results. Already in this phase is possible to designate in many cases the basic characteristics of the series. Next are described few reflections obtained from the analysis of the individual series and from comparison of results of both variants.

3.1 Trend Analysis of Time Series

24 hours measurement: 15:30, 2. 3. 2007 – 15:30, 3. 3. 2007

Coordinates x:
The range of the time series values in variant N.1, using *SK*POS©, is bigger (about 20 mm) then in variant N.2 (about 10 mm). The shapes of both curves aren't in generally similar, although in some sectors (about first 2 hours) they are proximate not only with shape, but also with values. Big differences in values are noticeable in first half of the experiment; in second part of the experiment they are similar with dispersion (Fig. 4).

Coordinates y:
The time series of variant N.1 is more dispersed (about 20 mm) then the series of the variant N.2 (average about 12 mm), although the variant N.2 includes some values (outliers), which are out from the general trend almost 20 mm (Fig. 4).

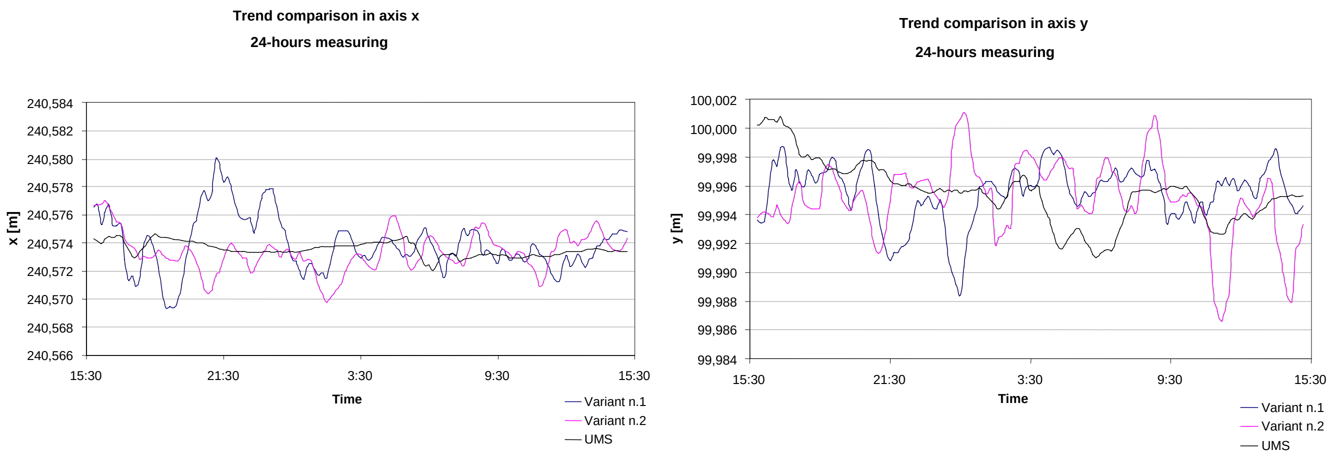

Fig. 4 Graphical comparison of trends of the time series in variants N.1, N.2 and UMS

3.2 Analysis of the periodic components

For analysis was applied mathematical model, which includes also time series decomposition to components and the spectral analysis. After elimination of the trend by moving averages method was made the spectral analysis. The question is first of all, if this residual time series (Fig. 5) contain still any significant periods, or it is flat random noise.

It is problematical to substantiate existence of periodical effect with presented period. One of the possibilities is, that there are so called false frequencies (respective periods), which weren't in fact in measuring occurred. Definitely there aren't among them frequencies of proper oscillations of building, which are from 0,68 Hz to 5,88 Hz (with periods 1,47 s to 0,17 s). To their identification it will be needed to justify receiver to higher assay frequency, at least 10 Hz. Application of service *SK*POS© will be a problem, because today it affords corrections with maximal frequency 1 Hz. Another possibility, how to explain some values of determined frequencies, is influence of outer forces on building. Into reflection there come raids of wind, which affect only specific time with same frequency and in same setting or other unknown effects.

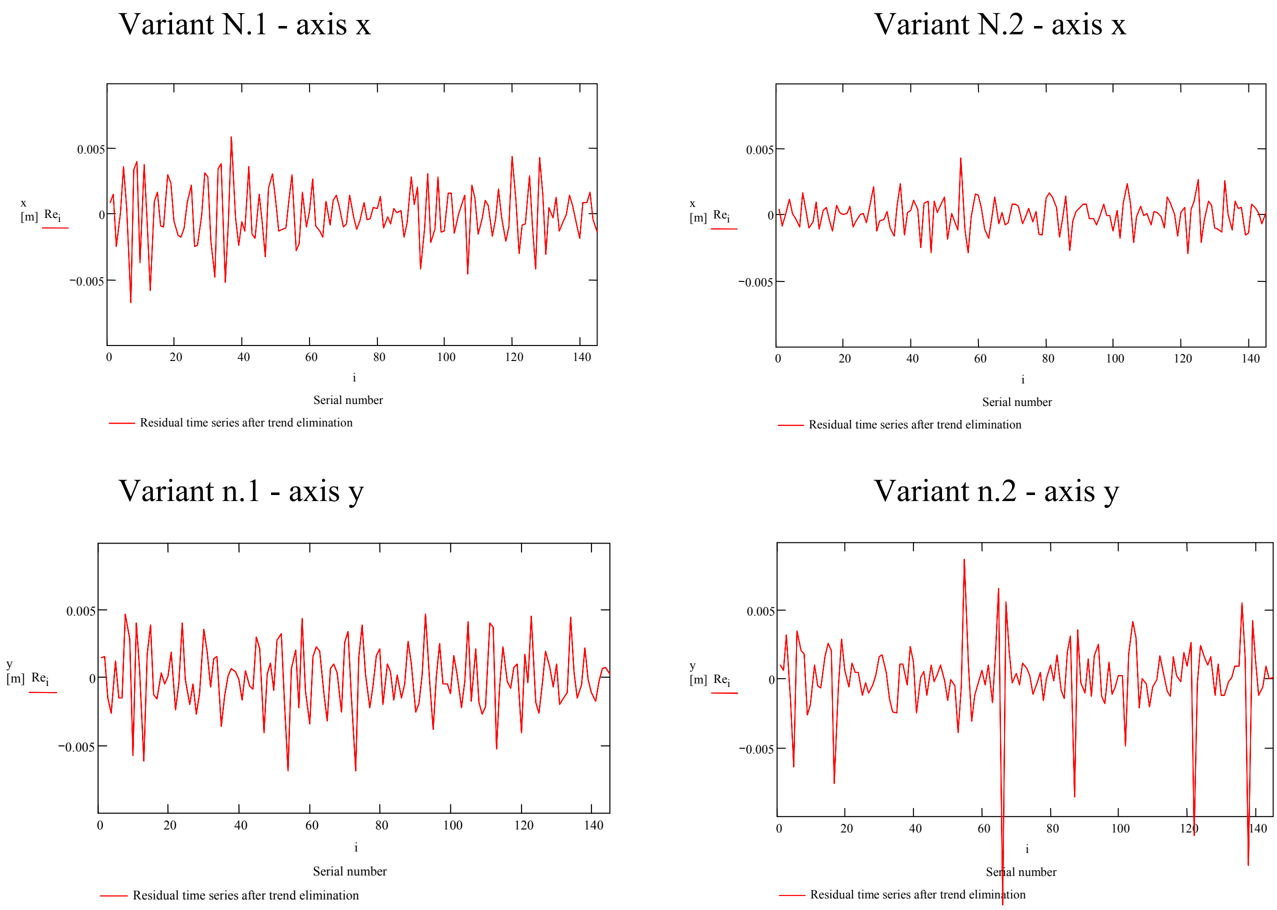

Fig. 5 Graphical representation of residual time series after trend elimination (24-hours measuring, interval of data registration 10 minutes)

For significant period identification was used the Fisher test, which enables the investigation of periods in periodogram, respective in graph of spectral density. The biggest value from each graph of spectral density was tested on significance level $\alpha = 0{,}01$ and comprised with critical value. Results of comparison are in table 4. In time series, where zero hypothesis were refused, continued the data processing to modelling and determinate the cyclical component of the series. After this, precision of estimated values in the time series can be recognised and largeness of flat random noise in residual time series can be designated.

Table 4 Fisher test

Variant	Time interval	Length of time series	Coordinate	Superior standard deviation **s [mm]**			Appeared the most significant period	Fisher test (for α=0,01)		
				Time series						
				Initial	After trend elimination	After cyclical element elimination	**T**	Test. statistics **W**	Critical value g_F	Zero hypothesis $Y_t=\varepsilon_t$
N.1	10 min	24 h	x	2,9	2,2	-	36 min	0,092	0,123	dont´t refused
			y	3,1	2,4	30.10^{-6}	37 min	0,132	0,123	refused
	1 s	1 h (6:00 - 7:00)	x	3,5	0,1	1.10^{-6}	47 s	0,009	0,007	refused
			y	4,0	1,8	1.10^{-6}	56 s	0,009	0,007	refused
	1 s	1 h (17:00 - 18:00)	x	4,8	1,9	1.10^{-6}	59 s	0,012	0,007	refused
			y	5,3	2,3	1.10^{-6}	54 s	0,012	0,007	refused
N.2	10 min	24 h	x	2,0	1,2	-	40 min	0,095	0,123	dont´t refused
			y	4,2	3,0	-	40 min	0,106	0,123	dont´t refused
	1 s	1 h (6:00 - 7:00)	x	2,0	1,3	1.10^{-6}	29 s	0,010	0,007	refused
			y	4,0	2,5	1.10^{-6}	24 s	0,017	0,007	refused
	1 s	1 h (17:00 - 18:00)	x	2,4	1,6	1.10^{-6}	36 s	0,009	0,007	refused
			y	3,4	2,0	1.10^{-6}	60 s	0,010	0,007	refused

The values of the standard deviation (in geodesy also called mean square error) of initial time series indicated that values of time series obtained from service *SK*POS© (variant N.1) are measured with smaller accuracy. Differences between values of the standard deviation of both variants in residual time series aren't so expressive. This effect can be caused because incorrect trend was used and potential less accurate results of variant N.1 were improved. Another explanation is, that variant N.1 accuracy indicated in residual time series is really close to variant N.2 accuracy and in initial time series of variant N.1 were only more expressive some forces, which in variant N.2 stayed drowned out. In residual component of time series are values of standard deviation in interval from 1 mm to 3 mm, and in each time series is lower value of the standard deviation in axis x. This information is logical, because axis x is in direction of longer side of rectangle ground plan. Building is in this direction more compact and values of time series are measured with higher accuracy. Interesting is, that in variant N.2 is difference between the standard deviation of axis x and y more notable then in variant N.1.

Experiment was realized and processed in way, which allows comparison of results from GNSS measuring and results from building monitoring with robotic UMS Leica TCA 1101 (Fig. 4). The UMS performed monitoring of building with much smaller measurement dispersion and with higher accuracy.

4. CONCLUSION

Results of the experiment showed, that measuring with service *SK*POS© account in very precise applications certain differences compared to measuring with reference station. Values of coordinates from variant N.1 (*SK*POS©) fluctuate in bigger interval then in variant N.2 (own reference station). The most precise were remarked building movements in parallel experiment with UMS and they were in axis x about 3 mm and in axis y about 10 mm. GNSS receiver, with usage reference station PIL1, recorded movements 7 mm in axis x and 14 mm in axis y, and with usage VRS from *SK*POS© 11 mm in axis x and 13 mm in axis y. It is interesting, that all types of measuring remarked bigger oscillations in axis y, what correspond with reality. After trend elimination was the dispersion and the standard deviation of both variants similar. It can mean two things: used incorrect trend, and so improving of otherwise less accurate results of variant with *SK*POS©, or really similar accuracy of both variants. The comparison of the series whit more accurate results from UMS indicates, that both variants can stay on approximate same level of accuracy.

Interesting fact is in which conditions was the experiment realized. From this point of view, it would be appropriate to measure in extreme (temperature and operation) conditions, when is building movement more expressive, because in usual conditions is the building movement inside the limits of the GNSS technology.

On the ground of results of experiment we can say, that *SK*POS© is with certain restrictions exploitable in the field of dynamical monitoring of structures and even also brings some advantages compared to present GNSS technology exploitation. When stable signal receiving in all parts of Slovakia will be guaranteed, the service *SK*POS© definitely strike also other parts of engineering geodesy.

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BIOGRAPHICAL NOTES

Anna Hostinová is PhD student at the Slovak University of Technology.
Study Geodesy and Cartography SUT Bratislava 2000-2005. Publication in various journals and conference proceedings.

Alojz Kopáčik is Professor at the Slovak University of Technology.
Study Geodesy and Cartography SUT Bratislava 1977-82. Doctor studies at the Department of Surveying the SUT Bratislava in 1982-85. Senior lecturer 1985-1998, 1998-2004 Assoc. Professor, since 2004 Professor at the Department of Surveying. Lecture from Geodesy for CE, the Underground and Mine Surveying and Engineering Surveying, Measurement systems in engineering surveying and Surveying for Civil Engineering (in English).

Chair of FIG C6, delegate national for the FIG C2 (Education). Member of the Slovak Chamber of Surveyors and Cartographers, Member of the board of Geodetski list (Croatia) and the WG's of FIG and IAG, which activity is oriented to implementation of laser technology in geodesy. Research in the filed of TLS applications, automated measuring systems, calibration. Chairman of the TC 89 - Geodesy and cartography (Slovakia), author of 4 ISO standard translations to the Slovak system of standards (STN).

CONTACTS

Ing. Anna Hostinová
Department of Surveying, SUT Bratislava
Radlinského 11
Bratislava
SLOVAKIA
Tel. +421 2 5927 4391
Fax + 421 2 5296 7027
Email: anna.hostinova@stuba.sk

Univ.-Prof. hab. Alojz Kopáčik, PhD**.**
Department of Surveying SUT Bratislava
Radlinského 11
813 68 Bratislava
SLOVAKIA
Tel. +421 2 5927 4559
Fax + 421 2 5296 7027
Email: alojz.kopacik@stuba sk
Web site: www.stuba.sk