CODEN STJSAO
ZX470/1466

ISSN 0562-1887
UDK 528.73/.74:528.41/.42:681.51

# Applicability of Continuous Real-Time Monitoring Systems in Safety Assurance of Significant Structures

***Janez ROŠER[1], Ivica RISTOVIĆ[2]* and *Milivoj VULIĆ[1]***

1) Naravoslovnotehniška fakulteta, Univerza v Ljubljani (Faculty of Natural Sciences and Engineering, University of Ljubljana), Aškerčeva 12, 1000 Ljubljana, **Republic of Slovenia**

2) Rudarsko-geološki fakultet, Univerzitet u Beogradu (Faculty of Mining and Geology, University of Belgrade), Đušina 7, 11000 Beograd, **Republic od Serbia**

janez.roser@ntf.uni-lj.si

Original scientific paper

In recent years, there has been significant advancement in monitoring sciences, especially due to the continued development of measuring equipment. Consequently, continuous real-time monitoring of integrity of significant structures, like buildings, bridges, dams, as well as the movement of slopes, landslides and volcanoes has become possible. This paper presents the usefulness of continuous real-time monitoring system that is able to combine geodetic, geotechnical and meteorological sensors to match the needs of the monitoring project. At the experimental polygon, we have installed four points; one reference and three observation points, all based on global navigation satellite system (GNSS) sensors. For every point, we acquire location in sense of coordinate Y, X and H in the local coordinate system, which allows observing any movements and deformations on observation points. Moreover, the characteristics of experimental polygon correspond to observing structures and also any changes on the Earth's surface. The real-time visualization of acquired data enables us to decide on further measures in the shortest possible time, which reflects in major safety, as well as in the avoidance of severe damage. On the basis of 20 minutes of measurements, executed every 24 hours, we have calculated that it is possible to detect, with a 99.73% probability, all displacements larger than 1.2 mm and relative movements larger than 3 mm. The monitoring results and regression lines indicate that displacements for two points are no more than 1 mm, while on one we have obtained displacement of approximately 7 mm in a time period of only three months. The results obtained are significant and confirm the necessity of continuous real-time monitoring systems.

**Keywords**
*Deformations*
*Error analysis*
*GNSS-sensors*
*Monitoring system*
*Movements*

**Ključne riječi**
*Analiza pogrešaka*
*Deformacije*
*GNSS-senzori*
*Monitoring sustav*
*Pomicanje*

**Received (primljeno)**: 2009-11-27
**Accepted (prihvaćeno)**: 2010-05-30

## Primjenjivost kontinuiranog monitoring sustava u realnom vremenu za održavanje sigurnosti važnih objekata

Izvornoznanstveni članak

U posljednjih nekoliko godina, došlo je do velikog napretka u znanosti o nadzoru (monitoringu), posebice zbog kontinuiranog razvoja mjerne opreme. Prema tome, kontinuirani real-time nadzor integriteta značajnih objekata, kao što su zgrade, mostovi, brane, pomicanje padina, klizišta i vulkana, postao je moguć. Ovaj rad opisuje korist kontinuiranog monitoring sustava u realnom vremenu koji omogućava kombiniranje geodetskih, geotehničkih i meteoroloških senzora kako bi se odgovorilo potrebama monitoringa. Na eksperimentalnom poligonu su instalirana četiri mjerna mjesta; jedna referentna i tri promatrane točke, a sve se zasniva na globalnom navigacijskom satelitskom sustavu (GNSS). Za svaku točku može se odrediti položaj u lokalnom koordinatnom (Y, X, H) sustavu koji omogućuje praćenje pomicanja i deformacija na mjernim mjestima. Štoviše, karakteristike eksperimentalnog poligona odgovaraju opažanim strukturama kao i bilo kakvim promjenama na površini Zemlje. Real-time vizualizaciju prikupljenih podataka omogućuje odlučivanje o daljnjim mjerama u najkraćem mogućem roku, što se odražava boljom zaštitom radi sigurnosti, kao i izbjegavanjem ozbiljnih šteta. Na temelju 20 minutnih mjerenja, koje se vrši 24 sata na dan, izračunato je da je moguće s 99,73 % vjerojatnosti otkriti sva pomicanja veća od 1,2 mm, a relativna pomicanja veća od 3 mm. Rezultati monitoringa i regresijska analiza pokazuju da pomicanja dvaju mjernih mjesta nisu veća od 1 mm, a za jedno mjesto je dobiven pomak od oko 7 mm u vremenskom periodu od samo tri mjeseca. Dobiveni rezultati su značajni i potvrđuju nužnost kontinuiranih real-time monitoring sustava.

**Symbols/Oznake**

| | |
|---|---|
| $Y$ | - UTM coordinate in $Y$ direction<br>- UTM koordinata u $Y$ smjeru |
| $X$ | - UTM coordinate in $X$ direction<br>- UTM koordinata u $X$ smjeru |
| $H$ | - UTM coordinate in elevation direction<br>- UTM koordinata u smjeru visine |
| $\hat{Y}$ | - the most probable UTM coordinate in $Y$ direction<br>- najvjerojatnija UTM koordinata u $Y$ smjeru |
| $\hat{X}$ | - the most probable UTM coordinate in $X$ direction<br>- najvjerojatnija UTM koordinata u $X$ smjeru |
| $\hat{H}$ | - the most probable UTM coordinate in elevation direction<br>- najvjerojatnija UTM koordinata u smjeru visine |
| $r$ | - scale factor<br>- mjerilo |
| $h$ | - specific entalpy, kJ/kg<br>- specifična entalpija |
| $n$ | - number of observations/days<br>- broj opažanja/dana |
| $v$ | - residual<br>- pogreška |
| $\sigma$ | - standard deviation<br>- standardna devijacija |
| $\sigma^2$ | - variance<br>- varijanca |
| $CQ$ | - Coordinate Quality<br>- kakvoća koordinate |
| $Q$ | - diagonal elements of variance-covariance matrix<br>- dijagonalni elementi matrice varijance-kovarijance |
| $M_o = \sigma_o$ | - unit weight standard deviation<br>- srednja devijacija jedinice težine |
| $K_{total}$ | - total annualized HRSG cost<br>- ukupni godišnji trošak kotla utlizatora |

**Indices/Indeksi**

| | |
|---|---|
| day | - day<br>- dan |

## 1. Introduction

Human interference of any kind in the environment can affect the stress-strain relations governing in those areas, resulting in landslides and slope failures. Furthermore, the safety and vitality of significant structures have become important issues. Thus, measures for preventing structural collapses, slope failures and landslides are of great interest to engineers. However, the afore-mentioned disasters do not occur without warning. Due to the needfulness of relating information, continuous real-time monitoring is suitable for observation of variations in structures or land masses. Continuous monitoring is a very complex system, constituted from methodology, sensors, software and knowledge for data acquisition and processing. Monitoring as an activity does not have any influence on operational procedures and is non-destructive. Moreover, the cost of monitoring in comparison to the possible cost due to any disasters that can be prevented by it is negligible. Several recent deformation-monitoring studies have proven that this kind of control is suitable for the observation of variations in structures and their vicinity as well for mass movements [1]. Presented monitoring can be required for underground constructions and their influence on nearby structures (e.g. [2-3]), for monitoring deformations and deflections of bridges [4], water dams (e.g. [5-6]) and ground subsidence [7], as well as for monitoring slope stability and steep embankment in open pit-mines (e.g. [8-9]). Furthermore, monitoring is suitable for controlling the behaviour of landslides and volcanoes (e.g. [10-11]). A continuous real-time monitoring system can be used also for structural health-monitoring purposes instead of conventional monitoring using accelerometers. Çelebi has showed that monitoring based on GNSS provides sufficiently accurate measurements of relative displacements, so that dynamic characteristics of the vibrating systems can be accurately identified [12].

The motivations for this work were: 1. the determination and presentation of events; deformations, movements in real-time, 2. to assure safety, 3. post-processing in order to assess some correlations between movements and other effects on the site such as temperature, water saturation, wind, blasting, quakes etc., 4. creating virtual sensors to better understand what is happening. The data acquired may be used for further computation, deformation analysis, predictive maintenance and of course alarming. One of the monitoring attributes is also to support decision-making. The essence of a continuous real-time monitoring system is to respond as quickly as possible, meaning that we can take the necessary steps to prevent some harmful events before the accuracy analyses are completed. Those accuracy analyses take time, which would usually result in late decision-making. Thus, decision-makers have to choose between alternative procedures (Figure 1): a) to perform accuracy analysis and lose valuable time or b) to decide on further actions on the basis of a visual diagram comparison. We speak in favour of the second option, since the warning can be given in time to evacuate personnel and equipment. However, without experiences in accuracy analyses, decision-making on a visual basis

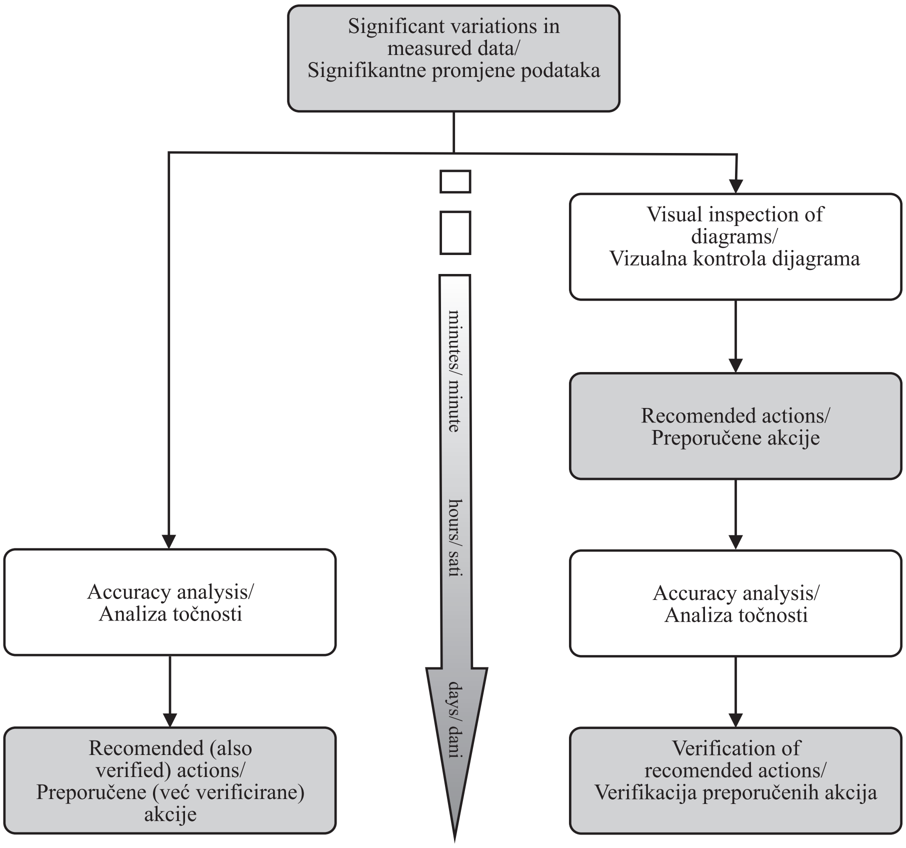

**Figure 1.** Decision procedures

**Slika 1.** Procedura odlučivanja

is delicate. Nevertheless post-festum analyses should be done to verify previous decisions, and for more accurate results.

## 2. Experimental monitoring system

The fundamental requirement of the continuous real-time GNSS based monitoring is that a permanent GNSS receiver must be located at each point so as to be monitored. The experimental continuous real-time monitoring system consists of four points; one stable/reference point, GRS1, and three observation object points, GMX1, GMX2 and GMX3 (Figure 2).

On the reference station, one dual frequency receiver and three single frequency receivers are installed on the observation points. In addition, the system is designed to enable the connection of various sensors. We have also included in the experimental monitoring system, two-axis inclinometers, along with the belonging thermometers, to follow the position of the tangential plane of the subsidence surface at measurement points. All points are also equipped with a battery power supply and a communication box for remote control and data delivery via the wireless communication network. The equipment installed and used is represented in Figure 3. We acquire coordinates $Y$, $X$ and $H$ in the local coordinate system for every point, and for three observation points, also their inclinations in two directions. The reference point is used as an origin of vectors to observation points, from which the coordinates of the observation points are defined. Any kinds of change in size and/or direction of vectors signify the movements of observation points.

The time interval of registered measurements depends on the scope of monitoring and, in our case, the measurement interval could be set from 10, 30 or 60 minutes to 3, 6, 12 or 24 hours. Extremely short intervals of 1 sec or less have also been planned to be carried out. It should be mentioned that measurements at some defined time interval mean that not only one measurement but many are acquired inside that time interval, and the most representative of the measurements is then selected. Referred time intervals correspond to requirements of monitoring for different purposes [13]. For example, if our aim is to detect changes above tunnels or on water dams, the required measurement interval should be 10, 30 or maximum 60 minutes. In case of monitoring important structures such as power plants, power or water lines, this period should vary from 1 to 12 hours. When we deal with projects that do not involve fast changes or we do not need data delivered over short periods of time, such as open pit mines, stone-pits, constructions, the measurement periods could be increased to 12 or

24 hours. Generally speaking, the frequency of data acquisition should be experimentally adapted to the best-suited of observed processes.

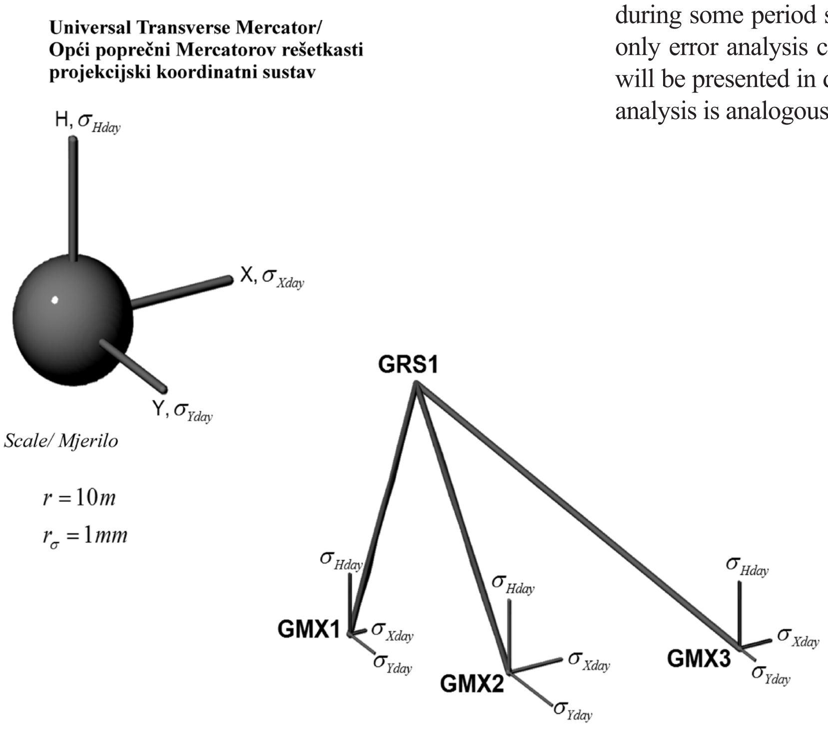

**Figure 2.** Scheme of the monitoring system

**Slika 2.** Shema monitoring sustava

## 3. Error analysis

A least squares adjustment is a well-known technique to process sets of redundant observations acquired with the GNSS. General results are the coordinates of measured points and their standard deviations. Any coordinate changes during some period signify point movement. In this paper, only error analysis calculations for 24 hour measurements will be presented in detail. For any other time intervals, the analysis is analogous.

### 3.1. Error analysis theory

In geodetic observations, the true position of any point is never known. The most probable point coordinates in case of redundant observations is simply the arithmetic mean [14]:

$$\hat{Y} = \frac{\sum_{day=1}^{n} Y_{day}}{n}, \tag{1}$$

$$\hat{X} = \frac{\sum_{day=1}^{n} X_{day}}{n}, \tag{2}$$

$$\hat{H} = \frac{\sum_{day=1}^{n} H_{day}}{n}, \tag{3}$$

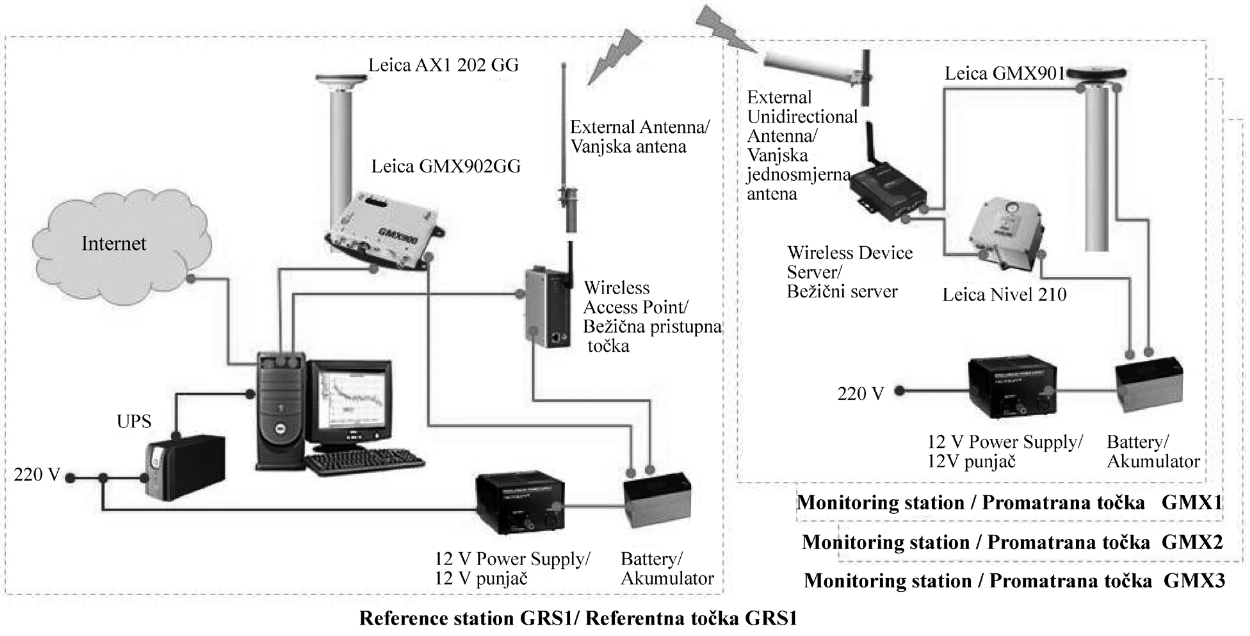

**Figure 3.** Equipment on reference and observation points (pictures from Leica catalogues)

**Slika 3.** Oprema na referentnoj i promatranoj točki (slike iz Leica kataloga) where $\hat{Y}$, $\hat{X}$, $\hat{H}$ are the most probable coordinates, $\sum_{day=1}^{n} Y_{day}$, $\sum_{day=1}^{n} X_{day}$, $\sum_{day=1}^{n} H_{day}$ the sum of the individual measurements $Y_{day}$, $X_{day}$, $H_{day}$, and the $n$ the total number of observations/days.

Furthermore, the residuals are calculated as:

$$v_{Yday} = Y_{day} - \hat{Y} , \tag{4}$$

$$v_{Xday} = X_{day} - \hat{X} , \tag{5}$$

$$v_{Hday} = H_{day} - \hat{H} , \tag{6}$$

and standard deviations as:

$$\sigma_{Yday} = \sqrt{\frac{\sum_{day=1}^{n} v_{Yday}^2}{n-1}} , \tag{7}$$

$$\sigma_{Xday} = \sqrt{\frac{\sum_{day=1}^{n} v_{Xday}^2}{n-1}} , \tag{8}$$

$$\sigma_{Hday} = \sqrt{\frac{\sum_{day=1}^{n} v_{Hday}^2}{n-1}} , \tag{9}$$

where $\sigma_{Yday}$, $\sigma_{Xday}$, $\sigma_{Hday}$ is the standard deviation of a group of observations of the same quantity (point coordinates $Y$, $X$ or $H$), $v_{Yday}$, $v_{Xday}$, $v_{Hday}$ the residual of an individual observation, $\sum_{day=1}^{n} v_{Yday}^2$, $\sum_{day=1}^{n} v_{Xday}^2$, $\sum_{day=1}^{n} v_{Hday}^2$ the sum of squares of the individual residuals, and $n$ the number of observations/days. Variances are equal to $\sigma_{Yday}^2$, $\sigma_{Xday}^2$, $\sigma_{Hday}^2$ the square of the standard deviations.

In practice, we often want to estimate unknown coordinates based on one or more series of observations. The sample mean $\hat{Y}$, $\hat{X}$, $\hat{H}$ are standard estimates of $v_{Yday}$, $v_{Xday}$, $v_{Hday}$ [15-16].

$$\sigma_{\hat{Y}} = \sqrt{\frac{\sigma_{Yday}^2}{n}} , \tag{10}$$

$$\sigma_{\hat{H}} = \sqrt{\frac{\sigma_{Hday}^2}{n}} , \tag{11}$$

$$\sigma_{\hat{H}} = \sqrt{\frac{\sigma_{Hday}^2}{n}} . \tag{12}$$

## 3.2. Error analysis results

For analysis, the positions refer to a local coordinate system. A transformation must be carried out to convert the positions delivered in the GNSS UTM frame into the local system (Figure 2). Here, the presented error analysis results are based on 10 minute and 24 hour measurement time intervals.

For observation points GMX1, GMX2 and GMX3, the results address a total period of 136, 119 and 151 days, respectively. The corresponding results for a 24 hour time interval are shown in Table 1.

**Table 1.** Error analysis results for a 24 hour time interval on observation points GMX1, GMX2 and GMX3

**Tablica 1.** Rezultat analize pogrešaka za interval od 24 sata na mjernim točkama GMX1, GMX2 i GMX3

| **Point / Točka** | **GMX1** | **GMX2** | **GMX3** |
|---|---|---|---|
| $n$ | 136 | 119 | 151 |
| $\sigma_{Xday}$, m | 0.0003 | 0.0010 | 0.0006 |
| $\sigma_{Yday}$, m | 0.0008 | 0.0014 | 0.0005 |
| $\sigma_{Hday}$, m | 0.0010 | 0.0012 | 0.0011 |
| $\sigma_{\hat{Y}}$, m | 0.0000 | 0.0001 | 0.0001 |
| $\sigma_{\hat{X}}$, m | 0.0001 | 0.0001 | 0.0000 |
| $\sigma_{\hat{H}}$, m | 0.0001 | 0.0001 | 0.0001 |
| $\hat{X}$, m | 3413.894 | 3427.574 | 3465.288 |
| $\hat{Y}$, m | 8834.659 | 8805.291 | 8793.635 |
| $\hat{H}$, m | 453.731 | 455.675 | 455.777 |

The analysis of a 10 minute interval measurements was performed as well. The results are shown in Table 2. Note that incomplete measurements were eliminated from the analysis. We considered only measurements that correspond to the criteria of 60 % of realised observations in a period of a day.

Among other parameters, Leica's instruments also yield the Coordinate Quality (*CQ*) parameter. The *CQ* parameter is based on the standard deviation, but additionally, empirical assumptions about environmental conditions are also taken into consideration. The *CQ* is derived so that there is at least two thirds of a probability that the computed position deviates from the true position by less than the *CQ* value [17], [18].

$$CQ = M_0 \sqrt{Q_{11} + Q_{22} + Q_{33}} \quad M_0 = \sigma_0 . \tag{13}$$

**Table 2.** Error analysis results for a 10 minute time interval on observation points GMX1, GMX2 and GMX3

**Tablica 2.** Rezultat analize pogrešaka za interval od 10 minuta na mjernim točkama GMX1, GMX2 i GMX3

| **Point / Točka** | **GMX1** | | **GMX2** | | **GMX3** | |
|---|---|---|---|---|---|---|
| | min | max | min | max | min | max |
| $\sigma_{Xi}$, m | 0.0012 | 0.0456 | 0.0011 | 0.0343 | 0.0027 | 0.0402 |
| $\sigma_{Yi}$, m | 0.0019 | 0.0125 | 0.0015 | 0.0111 | 0.0031 | 0.0162 |
| $\sigma_{Hi}$, m | 0.0031 | 0.0293 | 0.0026 | 0.0193 | 0.0057 | 0.0257 |
| $\sigma_{\hat{Y}}$, m | 0.0001 | 0.0038 | 0.0001 | 0.0022 | 0.0002 | 0.0034 |
| $\sigma_{\hat{X}}$, m | 0.0002 | 0.0011 | 0.0001 | 0.0009 | 0.0003 | 0.0013 |
| $\sigma_{\hat{H}}$, m | 0.0003 | 0.0024 | 0.0002 | 0.0012 | 0.0005 | 0.0023 |
| $\hat{X}$, m | 3413.886 | 3413.897 | 3427.564 | 3427.576 | 3464.781 | 3465.291 |
| $\hat{Y}$, m | 8834.636 | 8834.660 | 8805.243 | 8805.294 | 8793.623 | 8793.637 |
| $\hat{H}$, m | 453.728 | 453.735 | 455.672 | 455.677 | 455.677 | 455.778 |
| *n* # | 89 | 144 | 90 | 144 | 89 | 144 |

In Table 3, CQ values for observation points GMX1, GMX2 and GMX3 are depicted, which all correspond well with the mean standard deviations $\sigma_{\hat{X}}$, $\sigma_{\hat{Y}}$ and $\sigma_{\hat{H}}$ from Table 1.

**Table 3.** Coordinate Quality (*CQ*) values for GMX1, GMX2, and GMX3

**Tablica 3.** Vrijednosti kakovoće koordinata (CQ) za GMX1, GMX2, i GMX3

| **Point / Točka** | | **GMX1** | **GMX2** | **GMX3** |
|---|---|---|---|---|
| *CQ*, m | min | 0.0001 | 0.0001 | 0.0001 |
| | max | 0.0001 | 0.0001 | 0.0002 |

The presented error analysis deals with point coordinate estimations and their standard deviations. For long period measurements, the obtained accuracy is below 1 mm (Tables 1-3). Further calculations can include analyses of gross errors, data snooping, global test, all of which can be found in literature (for example [19]).

## 4. Visualisation as a quick method for decision making

Continuous real-time monitoring enables a rapid and proper response to time-critical emergencies, such as mass movements or a loss of structural integrity. As evident from Figure 1, a lot of valuable time can be preserved if we make a first decision on the basis of visual inspection and comparison of diagrams, which would be most welcome when potentially hazardous situations occur. For example, the diagrams on Figure 4 show the observation point coordinates variations in time from the experimental polygon for approximately three months, sampled with 24 hour intervals. With ellipse marks on diagrams, the simultaneous changes on all observation points at the same time are shown, which indicate that this event is due to an external influence, perhaps errors on the data-acquisition device during on-the-fly calculations, satellite constellations, meteorological conditions. If we compare the final displacement values (arrows on Figure 4) of points GMX1, GMX2 and GMX3, it is evident that point GMX2 (marked with darker arrows) is steadily shifting (consider the trend of coordinates change), which is evident through visual inspection only.

Regression analysis (accomplished by common software) is an effective method to quickly explore the relationships between point variations and potential point movements [20], [21]. In particular, the real-time visualisation of regression lines for the observation points data allows users to decide whether observing variations indicate movement points or not, and without executing error analysis. Regression lines that correspond to point GMX1, GMX2 and GMX3 variations are shown in Figures 5, 6 and 7. Figure 5 (above) shows point GMX1 displacement values in main coordinate directions (N – North, E – East, H – Height) and corresponding regression lines. It is evident that regression lines are within the accuracy of the monitoring system (variations less than 1 mm) and thus indicate that point GMX1 is stable. Furthermore, the latter is even more obvious when we look at the diagram and corresponding regression line of the total displacement of point GMX1 (Figure 5 (below)).

The diagrams of point GMX2 observation data indicate the point movement in a north-east direction, namely in north, east and height coordinate axes direction for approximately 4 mm, 5mm and 2 mm, respectively (Figure 6 (above)). According to the total displacement regression line of point GMX2, the point had moved by approximately 7 mm in the period of three months (Figure 6 (below)).

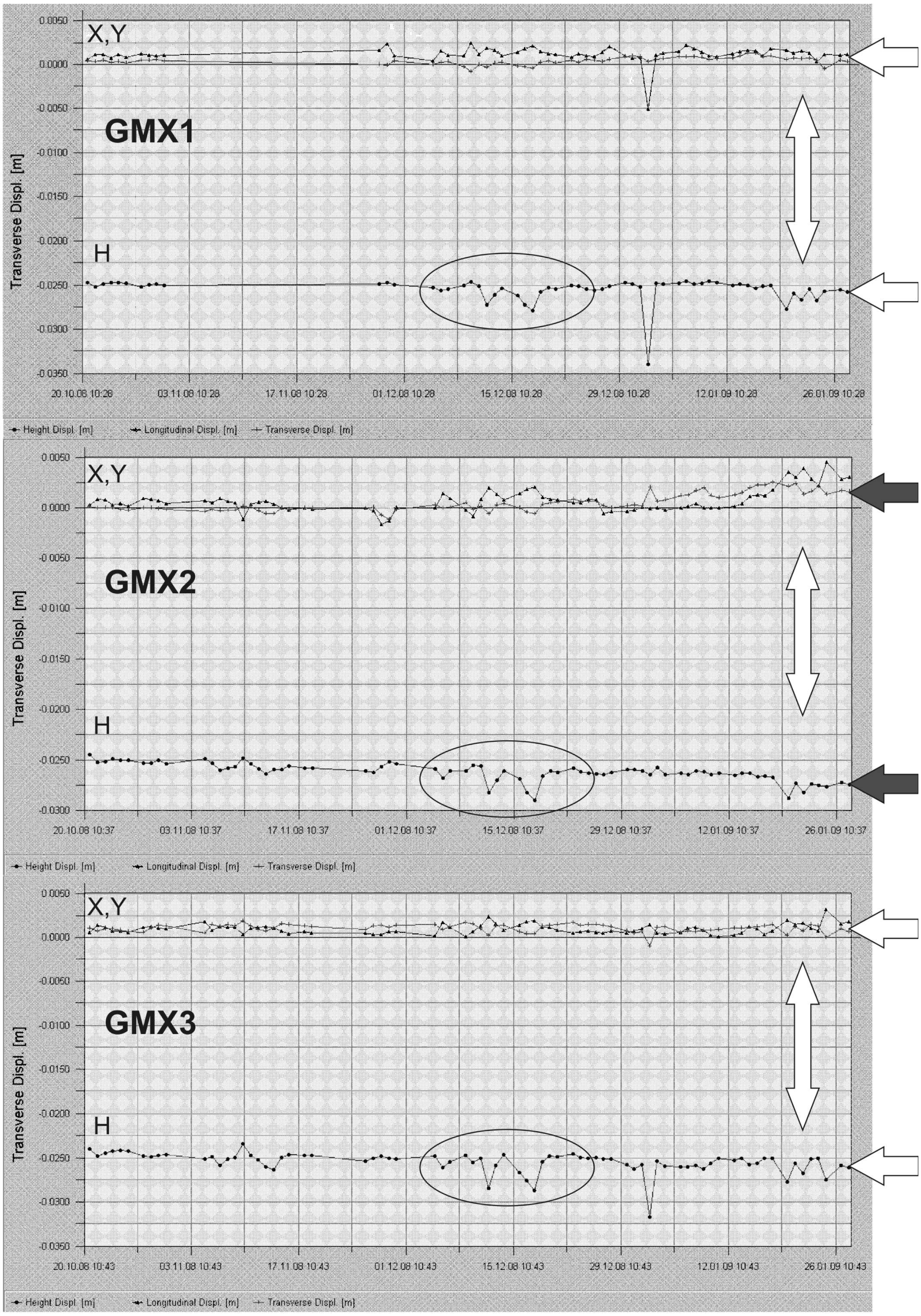

**Figure 4.** Point displacement real-time diagrams for observation points GMX1, GMX2 and GMX3

**Slika 4.** Real-time dijagram pomjeranja promatranih točaka GMX1, GMX2 i GMX3

Variations on observation point GMX3 are shown on Figure 7. Regression line values are within the monitoring system accuracy (variations less than 1 mm) and thus there is no indication of significant changes on point GMX3.

The trends of regression lines can be visually observed by users, but the quantitative values of the point movements need to be further examined by detailed error analyses to verify preliminary decisions based only on visual inspection. The calculated displacement of GMX2 is approximately 7 mm in 3 months, which is a significant change as to $\sigma_{day}$. For the remaining two points, calculated displacements are approximately 1 mm, and so far both points are determined as stable.

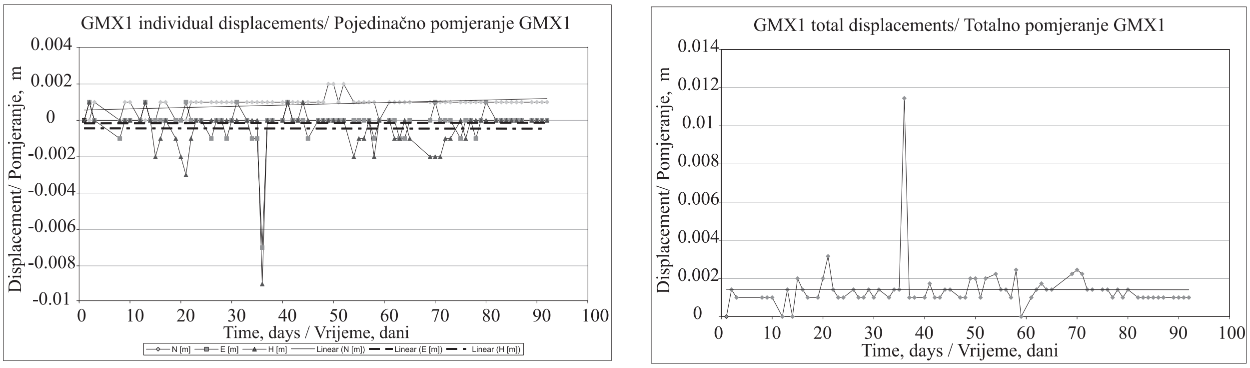

**Figure 5.** GMX1 point displacements and regression lines; Individual displacements according to coordinate axis directions and their regression lines (left), Total displacement and corresponding regression line (right)

**Slika 5.** Pomjeranja točke GMX1 i regresijski pravci; Pojedina pomjeranja u smjeru koordinatnih osi i odgovarajući regresijski pravci (lijevo), Totalni pomak i odgovarajući regresijski pravac (desno)

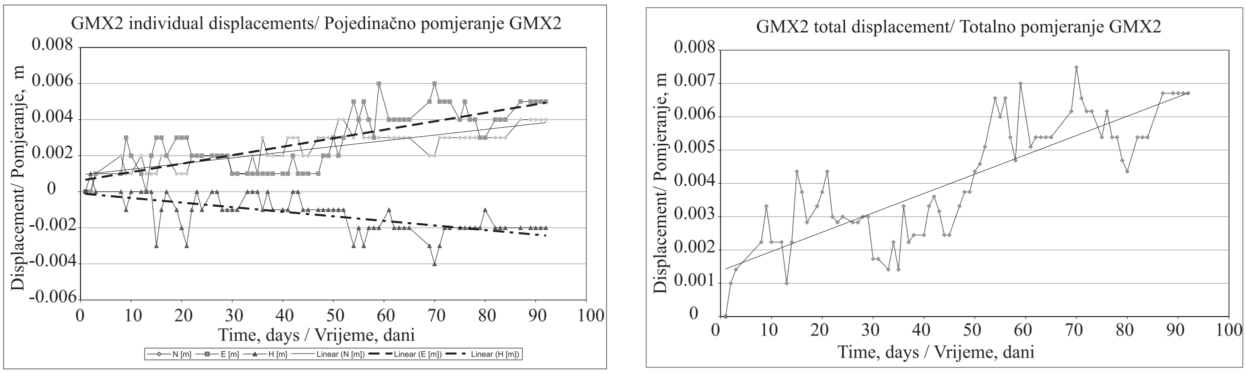

**Figure 6.** GMX2 point displacements and regression lines; Individual displacements according to coordinate axis directions and their regression lines (left), Total displacement and corresponding regression line (right)

**Slika 6.** Pomjeranja točke GMX2 i regresijski pravci; Pojedina pomjeranja u smjeru koordinatnih osi i odgovarajući regresijski pravci (lijevo), Totalni pomak i odgovarajući regresijski pravac (desno)

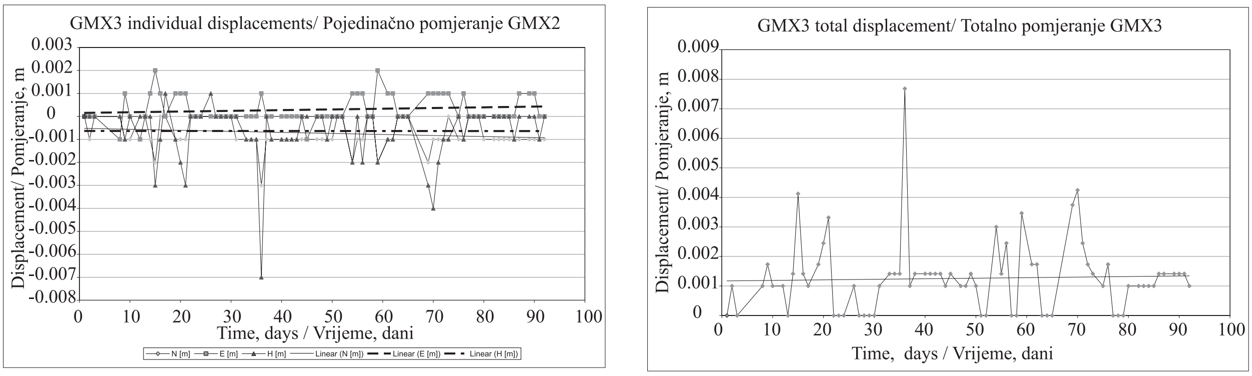

**Figure 7.** GMX3 point displacements and regression lines; Individual displacements according to coordinate axis directions and their regression lines (left), Total displacement and corresponding regression line (right)

**Slika 7.** Pomjeranja točke GMX3 i regresijski pravci; Pojedina pomjeranja u smjeru koordinatnih osi i odgovarajući regresijski pravci (lijevo), Totalni pomak i odgovarajući regresijski pravac (desno)

## 5. Conclusions

GNSS-based monitoring solutions are an important measuring tool to observe the movements and deformations of significant structures and the Earth's surface. The accuracy of such measurements depends on various factors, including sampling frequency, time intervals, satellite constellation, multipath. However, on the basis of 20 minutes of measurements on every 24 hours, we have calculated that the standard deviation of the monitoring system described in this paper is 0.1 to 0.5 mm and therefore allows us to detect displacements larger than 1.2 mm and relative movements larger than 3 mm, both with a 99.73 % probability. Obtained accuracy values are better than that provided by the manufacturer (Table 4). These findings refer only to the GNSS measurements. So as to achieve an even higher accuracy, the monitoring system can be spread out into a robotised total station and/or level (for example [22]).

Through comparison between standard deviations for 10 minute observations within a day ($\sigma_{\hat{X}}$, $\sigma_{\hat{Y}}$, $\sigma_{\hat{H}}$) and standard deviations for 24 hour observations ($\sigma_{Xday}$, $\sigma_{Yday}$, $\sigma_{Hday}$), it is clear that the values agree with one another well. The values range from 0.1 mm to 3.8 mm (Table 1 and Table 2) and are within the expected accuracy. Furthermore, this proves that observations conducted every 24 hours fulfil the monitoring requirements for projects that do not involve fast changes. For more delicate and critical projects, the observation interval should be shortened. If we compare Coordinate Quality (*CQ*) values for GMX1, GMX2, and GMX3 with standard deviations, it can be seen that *CQ* values are reliable for long period measurements. Observation points GMX1 and GMX3 are determined as stable, since the corresponding regression lines in the diagrams are almost horizontal (Figure 5 and 7). The calculated displacements for GMX1 and GMX3 are no more than 1 mm. Most significant displacement of approximately 7 mm were observed on point GMX2, which is evident through regression lines (Figure 6) and later on also supported by calculations.

**Table 4.** Leica GNSS sensor accuracy [23]

**Tablica 4.** Točnost Leica GNSS senzora [23]

| Sensor type / Vrsta senzora | Time interval / Vremenski interval | 2D accuracy / 2D preciznost (95 %) | Height accuracy / Visinska preciznost (95 %) |
|---|---|---|---|
| Dual-frequency (GMX902) | 10 min | 5.2 mm | 11.8 mm |
| | 1 h | 3.8 mm | 7.2 mm |
| | 24 h | 1.8 mm | 2.0 mm |
| Single-frequency (GMX901) | 10 min | 7.2 mm | 12.4 mm |
| | 1 h | 3.8 mm | 7.0 mm |
| | 24 h | 2.2 mm | 1.8 mm |

The continuous real-time monitoring system presented through this article has many benefits; we gain the greatest quantity of data per unit of time, employing the least of engaged resources, we obtain information in real-time and thus react immediately to solve potentially hazardous situations, the system allows a plug-in of a very large number of different types of sensors so as to adjust to the specific process characteristics, and it offers greater accuracy than other surveying techniques. Through real-time monitoring of important structures, abnormal behaviour can be detected and, therefore, it is possible to avoid severe damage or even save lives.

## Acknowledgements

The authors are indebted to Geoservis d.o.o. which donated and maintained the instruments and software throughout the experiment, and to Marmor Sežana, for their cooperation.

## REFERENCES

[1] JURIŠIĆ, M.; HENGL, T.; BUKVIĆ, Ž.; EMERT, R.: *Geoinformacijske tehnologije i gospodarenje okolišem*, Strojarstvo, 40 (1998), pp. 215-221, Zagreb, Croatia.

[2] GRINSTEIN, R.: P*lanning a Geodetic Monitoring System for the Metropolitan Tel-Aviv Light Rail Train Red Line Project*, FIG Working Week 2009, Surveyors Key Role in Accelerated Development - Proceedings, Eilat 2009.

[3] VULIĆ, A.; TODOROVIĆ, R.T.; VULIĆ, M.: *Monitoring System in Tunnelling, 9th International Symposium on Tunnel Construction and Underground Structures - Proceedings*, Ljubljana 2009.

[4] ROBERTS, G.; BROWN, C.; OGUNDIPE, O.: *The Use of GNSS to Monitor the Deflections of a Motorway Viaduct*, FIG Working Week 2009, Surveyors Key Role in Accelerated Development - Proceedings, Eilat 2009.

[5] HE, X.; YANG, G.; DING, X.; CHEN, Y.: *Application and evaluation of a GPS multi-antenna system for dam deformation monitoring,* Earth Planets Space (2004) Vol. 56, 1035-1039.

[6] LIMA, N.; CASACA, J.; HENRIQUES, M.J.: *Accuracy of Displacement Monitoring at Large Dams with GPS*, In: Sanso, F. and Gil, A.J. (editors) Geodetic Deformation Monitoring: From Geophysical to Engineering Roles, Springer Berlin, Heidelberg 2005, 239-243.

[7] GE, L.; RIZOS, C.; HAN, S.; ZEBKER, H.: *Mining subsidence monitoring using the combined INSAR and GPS approach*, The 10th FIG International Symposium on Deformation Measurements - Proceedings, Orange 2001.

[8] KIM, D.; LANGLEY, R.B.; BOND, J.; CHRZANOWSKI, A.: *Local deformation monitoring using GPS in an open pit mine: initial study,* GPS Solutions (2003) Vol. 7, 176-185.

[9] ROŠER, J.; KOS, A.; KORTNIK, J.; LAMOT, A.; VULIĆ, M.: *Monitoring – spremljanje pomikov in deformacij v realnem času*, Zbornik Strokovnega posvetovanja rudarjev in geotehnologov ob 41. Skoku čez kožo, Ljubljana 2009.

[10] RUTLEDGE, D.; GNIPP, J.; KRAMER, J.: *Advances in real-time GPS deformation monitoring for landslides, volcanoes, and structures*, The 10th FIG International Symposium on Deformation Measurements - Proceedings, Orange 2001.

[11] BERTACCHINI, E.; CAPITANI, A.; CAPRA, A.; CASTAGNETTI, C.; CORSINI, A.; DUBBINI, M.; RONCHETTI, F.: *Integrated Surveying System for Landslide Monitoring*, Valoria Landslide (Appennines of Modena, Italy), FIG Working Week 2009, Surveyors Key Role in Accelerated Development - Proceedings, Eilat 2009.

[12] ÇELEBI, M.: *GPS in dynamic monitoring of long-period structures,* Soil Dynamics and Earthquake Engineering (2000) Vol. 20, 477-483.

[13] BARŠIĆ, Z.; BARŠIĆ, G.: *Uncertainities of Out of Form and Position Measurements Results Obtained by Co-ordinate Measuring Machine*, Strojarstvo, 48 (2006) Number 1- 6, pp. 251-261, Zagreb, Croatia.

[14] WOLF, P. R.; GHILANI, C. D.: *Elementary Surveying, An Introduction to Geomatics,* 9th Edition, Pearson Prentice Hall, New Jersey 2002.

[15] STRANG, G.; BORE, K.: *Linear Algebra, Geodesy, and GPS*, Wellesley - Cambridge Press, Wellesley 1997.

[16] GODEC, Z.: *Zaokruživanje mjernog rezultata*, Strojarstvo, 37(1995), pp. 213-217, Zagreb, Croatia

[17] Leica Geosystems, GPS Newsletter – Sensor, A One Page Newsletter On System 500 GPS. Vol. 00, No. 17.

[18] Leica Geosystems, GPS Newsletter – SKI-Pro, A one page weekly newsletter on System 500 GPS, 00/16, August 28, 2000.

[19] KUANG, S.: G*eodetic Network Analysis and Optimal Design: Concepts and Applications,* Ann Arbor Press, Inc., Chelsea, Michigan 1996.

[20] MIHAILOVIĆ, K.: *Regresiona analiza, objektivni pristup određivanju parametara funkcija,* Građevinski fakultet Univerziteta u Beogradu, Beograd 2002.

[21] WEISBERG, S.: *Applied Linear Regression*, 3rd Edition, John Wiley & Sons, Inc., Hoboken, New Jersey 2005.

[22] BROWN, N.; KALOUSTIAN, S.; ROECKLE, M.: *Monitoring of Open Pit Mines using Combined GNSS Satellite Receivers and Robotic Total Stations*. http://www.leica-geosystems.com/en/page_catalog.htm?cid=5311. Accessed 25 Oct 2009.

[23] Leica Geosystems: Leica GNSS Spider, Advanced GNSS Monitoring; Leica's internal material (provided upon request by manufacturer technical support in 2008).