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PRELIMINARY RESULTS OF COMBINED GEODETIC METHODS IN MONITORING

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Subject review

The actual object movements can be examined by well designed and carefully performed observations and measurements. The processed and adjusted data are a precondition for analysis and interpretations of short and long-term predictions of object functionality. Beside periodic deformation observations, experimental measurements could be performed on selected objects. The purpose of such work is to determine the accuracy and improve the applied methods of measurement based on the analysis of theoretical errors and actual values of the facility shifts on a daily basis. On the business tower "Zagrepčanka" the GNSS measurements in relation to the nearest reference station from CROPOS (Croatian Positioning System) network were performed, combined with geometric levelling and gravity measurements. Analysis of measurement results that are presented in this paper provides an answer to the question to what extent one method can be controlled by another, or to what extent the application of a combination of different surveying methods affects the quality of the interpretation of the results.

Keywords: *deformations; GNSS; gravity; levelling; shifts*

Preliminarni rezultati kombiniranih geodetskih metoda u monitoringu

Pregledni članak

Stvarno ponašanje objekta može se ispitati samo dobro osmišljenim i brižljivo izvedenim opažanjima i mjerenjima te na osnovu toga obradom i izjednačenjem mjerenja što je preduvjet za izvođenje analize i interpretacije kojom se daju kratkoročne ili dugoročne prognoze funkcionalnosti objekta. Pored periodičnih opažanja pomaka, izvode se i eksperimentalna mjerenja na odabranim objektima. Svrha takvih radova je u određivanje točnosti i poboljšanju primijenjenih metoda mjerenja na bazi analize teorijskih pogrešaka i stvarnih veličina pomaka na dnevnoj bazi. Eksperimentalna mjerenja na poslovnom tornju Zagrepčanka obuhvatila su GNSS mjerenja prema najbližoj referentnoj stanici iz CROPOS mreže, u kombinaciji s geometrijskim nivelmanom i gravimetrijskim mjerenjima. Analiza rezultata mjerenja koji su prikazani u ovom radu daje odgovor na pitanje u kojoj mjeri jedna metoda može kontolirati drugu, odnosno u kojoj mjeri primjena kombinacije različitih geodetskih mjerenja utječe na kvalitetu interpretacije rezultata.

Ključne riječi: *deformacije; GNSS; ubrzanje sile teže; nivelman; pomaci*

1 Introduction

Every object, whether built or under construction is exposed to the constant and variable effects. Constant effects are those that are considered likely to affect the construction of the entire life cycle in which is expected a change of the intensity of action, but these changes are negligible compared to the average [1]. The constant effects result from its own weight construction, weight superstructure including any permanent lining, the forces from the effects of soil pressure, strain due to the way of construction, the forces due to water pressure, etc. The variable effects are those which are not likely to act in a given budget situation and will have a change of intensity over time. Variable effects are loads that result from active and passive use of the object, due to the effects of weight of the structure of individual parts that operate only in certain phases of construction, due to mounting stress, due to temperature changes, due to wind, snow, ice, rain, effects that occur as a result of changing groundwater levels, etc. Actually, three main causes for the occurrence of deformation can be distinguished [2]: tectonically and seismically induced processes; changes in the foundations of a building and the surrounding area that is affected by building (static change of pressure, hydrological processes) and processes in the body of building that lead to its own deformation. The forces that can affect buildings are divided into [3]: outer forces on the building (own weight, water pressure, sole water pressure, wind loads, traffic loads); inner forces on the building (temperature differences in the structure, voltages of concrete constructions, which are caused by the curing process of the concrete and reaction forces in foundation of the building (artificial interventions (loading and unloading), natural (soil chemical and physical processes). For each analysis are required deformation and monitoring measurements. These are all measurements that should be executed [3] for determining the elastic or permanent deformation of objects (which was produced under the influence of external and internal forces). The purpose of deformation measurements is discovering and recording the geometric changes of buildings or between parts of buildings [4]. The following geometric changes can be distinguished [4]: vertical (uplift, shrug, sinking) and horizontal displacements; twists; tilts and deformations (change in length, bending, torsion).

Thanks to the rapid technology development the movements monitoring of the buildings are no longer limited to the monitoring of static and slow shifts, but the object of interest moves towards dynamic, and rapid shifts of buildings caused by the action of variable effects. Geodetic monitoring of dynamic shifts until recently was focused only on flexible structures such as suspension bridges, skyscrapers and towers. For the purpose of the movement monitoring of such facilities GNSS equipment is generally used with the measurement frequency of 10-20 Hz [5]. For the displacements of over 2 cm and natural frequency of 2 Hz or less real time kinematic (RTK) method [6] can be used. Different types of engineered structures such as dams, bridges, and high-rise buildings can feasibly be monitored using continuous GNSS. Continuous data recording from the GNSS satellites, using ground-based receivers can be used for monitoring the health of engineered structures, and can thereby be useful for the public safety aspects of civil, structural, and earthquake engineering [7].

The task of a deformation survey is to determine whether or not movement is taking place and subsequently whether the structure is stable and safe.

Movement can be further analyzed to see if it is due to seasonal factors, daily variances etc. and then the information used to determine future movement of the structure. For the purpose of the numerical expression of the movement of the already built facilities the experimental measurements on a business tower "Zagrepčanka" were carried out using the data from the national network of reference stations CROPOS [8], combined with local GNSS, geometric levelling (reference point R outside the influence zone of the building) and gravity measurements. The points position are determined directly in relation to the nearest Continuously Operating Reference Station (CORS) from the CROPOS network, Fig. 1. In order to assess the maintenance of security of high-rise building at the stage of its full exploitation, different geodetic measurements were carried out with which it is possible to monitor three-dimensional shift of the selected characteristic points, which is caused by the combined effects of various external and internal forces. The basic aim of this research of the combination of different geodetic techniques was focused on the possibility of integrating them into a hybrid measurement system that can be used to determine the displacements caused by constant and variable effects and not on an analysis of the size of individual impact.

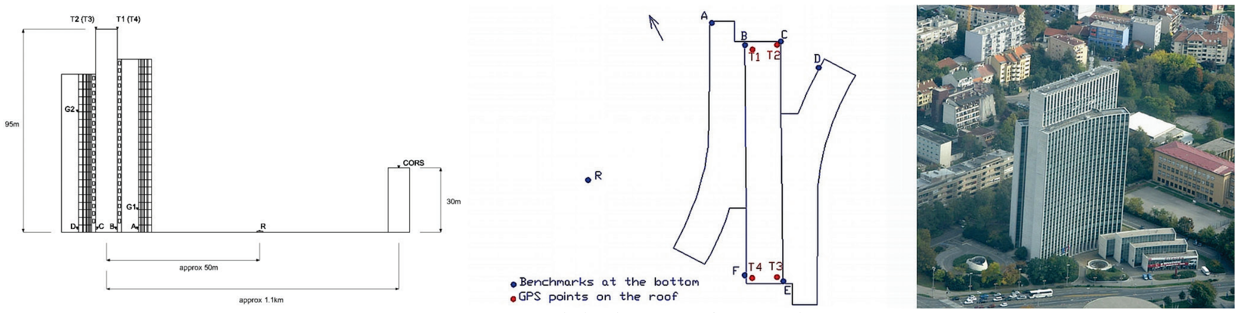

Figure 1 Relation between reference points

2 Processing and adjustment of measurements

GNSS observations and measurements of geometric levelling were conducted at time interval of 17th to 19th June 2010. The GNSS measurements were carried out in continuity. Geometric levelling measurements at discrete points in the bottom of the business tower were performed twice a day. In order to properly interpret daily movement of the business tower the GNSS measurements are divided into intervals of 1 hour.

The established points on the roof of the business tower, Figure 1, were calculated in relation to the nearest CORS from CROPOS network in Zagreb using GPPS (Geodetic Precise Positioning Service) service. The distance from the reference station to the business tower is about 1,1 km.

The points which were used for observing the business tower of Zagreb were placed on top at the edge of the roof while the benchmarks were placed at the bottom of the tower about 1,5 m above ground level.

The accuracy of the coordinates obtained in relation to the CORS reference station in Zagreb is expressed as a root mean square value (rms) for each axis. Almost all the hourly intervals have the longitude and latitude accuracy less than 1 mm, while the height accuracy is predominantly less than 1 mm. The average value of standard deviation per axis is 0,7 mm in latitude, 0,6 mm in longitude and 0,9 mm in height. The expected movement of the "Zagrepčanka" tower is higher and so obtained precision will be sufficient for the expression of the point's displacements.

In order to define values of the tower settlement the benchmarks were stabilized in the bottom of the tower and by the precise levelling connected to the benchmark outside the zone of influence without being connected to the benchmarks from the national height network, Fig. 1. The achieved precision of local settlement defining in this process is up to 0,6 mm. Levelling measurements are made according to specifications for the precise levelling. Digital level Leica DNA03 with pair of coded Invar rods, whose accuracy is 0,3 mm/km, were used. For the GNSS measurements 4 receivers Trimble R7 with Zephyr Geodetic L1/L2 antennas were used. On the roof of the office tower is the armature in which are embedded a special screws that are mounted GNSS antenna, thus to ensure the immutability of position during the measurement. The changes in coordinates so stabilized discrete points on the roof are showing only the actual daily shift of the object. Gravimetric measurements were carried out with two Scintrex CG-3M gravimeters, Fig. 2.

Figure 2 Used equipment

3 Analysis of GNSS and levelling results

The monitoring of the business tower "Zagrepčanka" was more concentrated on the variable effects because they can already be seen on a daily basis. To monitor the continuous effects the time interval between each measurement epoch should be much bigger.

Based on the height changes of the GNSS roof points, it is evident that the tower has its own daily rhythm which depends primarily on the atmospheric conditions and the daily load variations in the building. Daily changes of atmospheric condition are shown in Fig. 4.

Most building materials during temperature changes are not stable. Specifically, when heated, building materials are subjected to physical and chemical changes that cause the transformation of their microstructure, and thus change their characteristics [9]. The trend of increasing volume of the building, Fig. 3, correlated with increasing of the air temperature, Fig. 4, is evident in the early morning hours on June 17th on the basis of increasing the height of the GPS points on the roof.

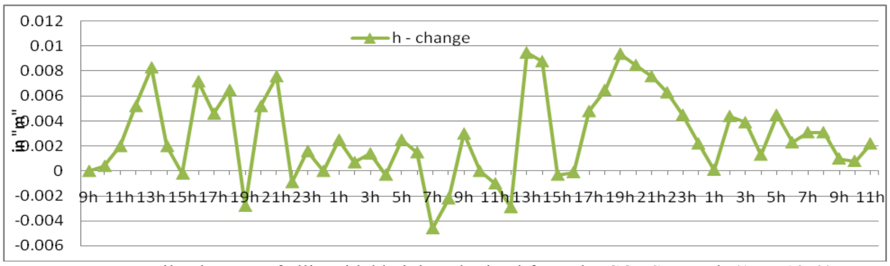

Figure 3 Daily changes of ellipsoidal heights obtained from the CORS Zagreb (17. - 19.6.)

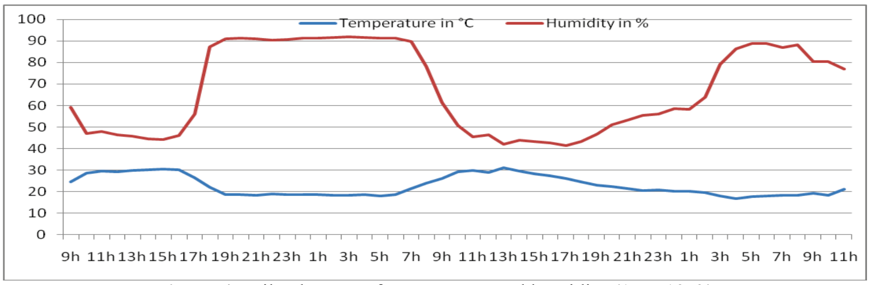

Figure 4 Daily changes of temperature and humidity (17. - 19.6.)

A sudden jump in volume of the building occurs as a result of micro-seismic reactions caused by the release of employees from the business tower during the lunch break. Equally evident is the compression of the building after returning of the employees. The repeated change in the trend occurs at the end of working hours when employees leave the building. In the late afternoon there is a stabilization of temperature and humidity, resulting in inactivity of the business tower to the morning hours when employees come to work, which is manifested by reducing the height of the building. After that comes an increase in the temperature which changes the direction of the trend, and again there is an increase of the building volume. A sudden drop in the volume of the building at about 19 h is more the result of extremely harsh weather conditions in this interval that hit the Zagreb city. The rain of high intensity correlated with a sudden drop in temperature led to a cooling of the building that may lead to squeezing of the building. The stabilization of the weather condition in the night results in inactivity of the building until the beginning of a new day when the employees come to work again. At that time there is a sudden drop of the building volume. Business tower is about 100 m high and has 25 floors. Assuming that on each floor there are about 50 employees with an average weight of 80 kg it can be a fascinating amount of around 100 000 kg daily load change. Of course such a load change must leave a mark on the daily fluctuations of the building volume and especially in the intervals of arrivals and departures from the building [10].

If one looks at the behaviour of the building volume in the morning of June 19th, no sudden drop in the time between 7 and 9 o'clock can be seen, and the reason is that it is Saturday, a day in which only a small number of employees comes to work. The minor height changes in this time interval are the result of unstable atmospheric conditions.

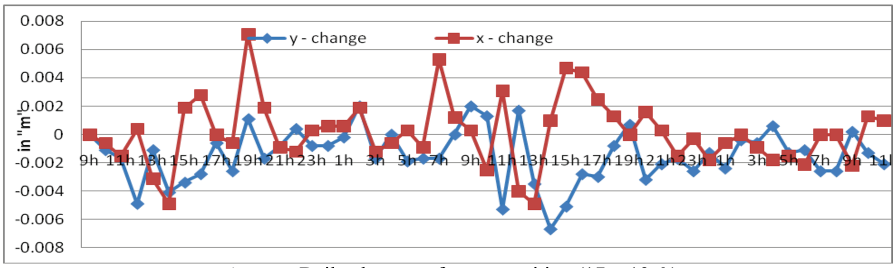

Figure 5 Daily changes of tower position (17. - 19.6.)

Daily coordinate changes of the observed points are continuously influenced by load changes in tower, simultaneously with the atmospheric conditions. Therefore, only a cumulative impact of these actions could be seen on the behaviour of the observed points on the roof for the time interval June, 17th - 19th. Daily monitoring of the tower by the temperature difference of about 12 °C and daily load changes of about 100 000 kg recorded a change of 9 mm in the y-axis, 12 mm in the x-axis and 14 mm per height of the GNSS observed points established on the roof. Graphic indicator of the daily displacement of the tower, Fig. 5, shows that the load changes and a dynamic alteration of the atmosphere, result in jumps in individual axes. In particular, it is evident by the behaviour of the points in the time interval between 11 and 20 hours.

If we would like to specifically define the particular atmospheric conditions and daily load changes the measurements should be extended for several days with steady and alternating atmospheric conditions, and certainly on a weekend when a high frequency of the employees in the business tower does not exist.

For monitoring and state description of the buildings or the local area movements the relative altitude changes become detected in real-time by precise levelling methods [11]. The comparison of height marks in the bottom of the building measured at different times of day suggests that the daily movement of the business tower is mainly manifested in the body but not on the foundation of the tower, Fig. 6.

It should be noted that the reported displacements, which are smaller than 1 mm, may be partly a result of lack of good sight "drawn lines" on the facade elements which have served as benchmarks because it was not allowed to embed the benchmarks in the foundations of the building. The thickness of drawn lines is about 1 mm, so the error of sighting the middle of the line is actually built into the final results.

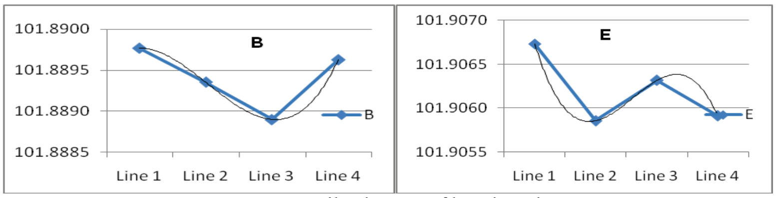

Figure 6 Daily changes of benchmarks

The above-ground part (body) structures of this type will not react so sensitively to the impact of the wind which, in the cases of the towers (chimneys), can cause mild or strong bending. The warm sun radiation leads here to the temperature gradient change of the building. The concrete is unevenly stretched due to the temperature differences of the sunny and shaded side causing minor changes in the building geometric shape. Buildings (structures) whose stability affects only the atmospheric influences, as a rule, tend in the opposite direction of the solar radiation. [12], so the observed points shift during the day can define the shape like an ellipse or circle.

This fact is especially important to know during construction as errors caused by construction could differ from errors that occurred by changing of the building geometry. In the case of business tower Zagrepčanka the simultaneous atmospheric conditions and the daily load changes of the building simultaneously influence the behaviour of the daily movement of the building, so that the expected shape like an ellipse (circle) is missing, but can be foreboded, Fig. 7. It can be assumed that the daily movement, when there are no employees in the building, followed the proper form as is the case with the towers. During regular daily monitoring of the television tower in Dresden, at the temperature difference of 8 °K, using a simple static model and the expansion coefficients of the reinforced concrete, were recorded tilt tower movements of 9,5 cm at a height of 150 m [13].

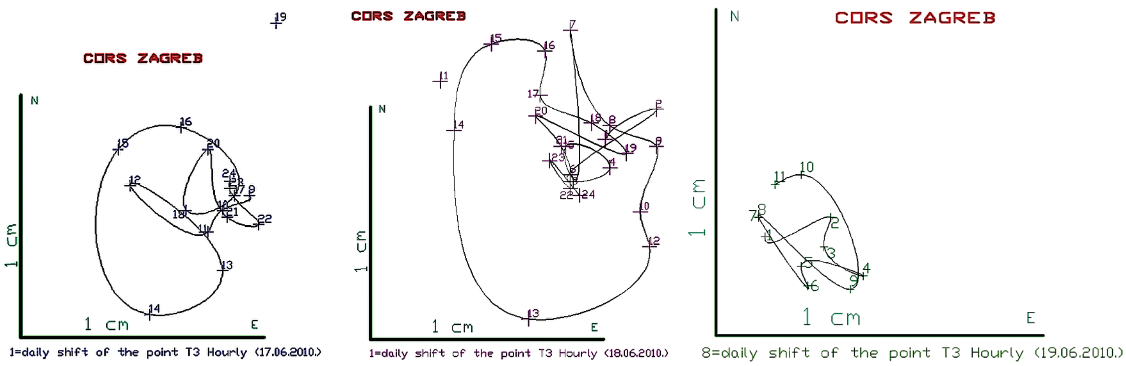

Figure 7 Daily shift of the point T3 (17. - 19.6.)

4 Gravity measurements

Geodetic monitoring of large buildings and determination of their dynamic shifts mainly was based so far on the use of GNSS technology [14]. In order to examine the daily shift of the tower, except GNSS and leveling measurements the continuous gravimetric measurements were performed also in the same time frame as the GNSS measurements. As a location where the gravimeter will be located the room in 3rd floor of tower was selected where measurements are normally performed for the purpose of regular gravimeters monitoring. To perform the gravimetric measurements Scintrex CG-3M gravimeter was used.

Principle of operation of relative gravimeter Scintrex CG-3M is based on vertical spring balance of zero length. Its sensing element is a fused quartz elastic system [15]. Equilibrium position of the proof mass is balanced by a spring and electrostatic counterforce, whose magnitude reflects the change (or difference) of the gravity. Since the changes of position of the proof mass are extremely small, spring gravimeters are extremely sensitive to instrumental influences.

Measurement process of Scintrex CG-3M is completely automatized [15]. Measurement signal is converted in gravity samples on the basis of user defined (in general linear) calibration function. Each gravity reading comprises specific number of one-second samples defined by user (in this study 60), automatically averaged by the meter. Instrumental corrections, i.e. stationary (long term) drift correction, tilt correction and temperature compensation are automatically applied by the meter, as well as gravimetric tidal reduction according to Longman formula [15].

4.1 Processing and adjustment of gravity measurements

Given a reading of 60 second samples and time required to process the reading by the instrument, one reading is taken every 77 seconds. For this study series of such reading that lasted continuously from June 17th to 19th are used. Gravity readings are stored by the instrument together with its standard deviations, tidal correction and other quantities on the basis of which instrumental corrections are calculated (including x and y tilts of the instrument).

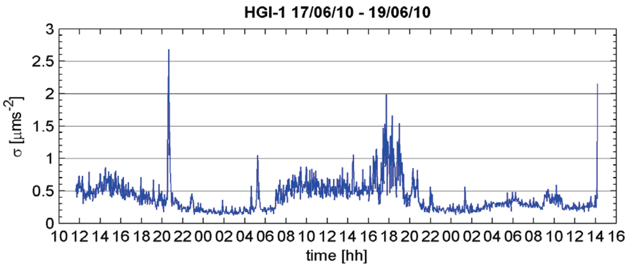

Figure 8 The standard deviation of gravimeter readings

Standard deviations being a measure of signal noisiness, which includes the instrumental and ambient seismic noise [15], mainly reflect the influence of micro-seismic made by the employees, Fig. 8.

Specifically, on business hours the level of the noise is significantly raised. In addition, one can notice irregular occurrence of sharp peaks (on June 19th around 20 h, June 20th around 5 h and at the end of the series) that coincides with the disturbances in the gravity readings, Fig. 9. There could be several causes for such disturbances: close or distant earthquakes, shaking of the building due to thundering, or noise maid by the operator while ending the measurements. Processing gravity readings involved correction for linear daily drift, calculation of hourly mean readings and barometric reduction. Specifically, spring gravimeters exhibit a temporal variation in the display of the zero positon, which is denoted as gravimeter drift, caused by the fading of spring tensions and by uncompensated or unshielded external influences [16]. In general, modelling of the gravimeter drift is made by a polynomial (ibid):

$$D(t) = d_1(t - t_0) + d_2(t - t_0)^2 + \dots, \quad (1)$$

where $D(t)$ is a drift correction at time t, d_1, d_2 … are the coefficients of daily drift and t_0 is reference time of the respective measurement epoch.

Gravity reading can thus be corrected for daily drift as follows:

$$z(t_0) = z(t) - D(t) . \quad (2)$$

In this study drift is modelled as a linear function by least squares fitting. To eliminate instrumental noise, from 77 seconds readings, weighted mean for one hour period that coincides with GNSS data is calculated with weights inversely proportional to reading variances. Also, barometric reduction, to account for gravity variations due to pressure change during the measurements, were applied [16]:

$$\delta g_P = 3(p - p_n)\,[\text{hPa}]\,\text{nms}^{-2} , \quad (3)$$

where p is actual atmospheric pressure and p_n is normal pressure at station computed from station height using the standard atmosphere.

In this study arbitrary value of p_n is used, since only relative changes of gravity readings are concerned. Thus, processing of gravity readings was necessary in order to remove (or diminish) variations in gravity readings caused by instrumental influences and temporal variations of gravity caused by pressure changes. Processed readings can then be analysed in order to detect possible shifts of the observed object. Specifically, difference in gravity readings occurs as a result of the micro-seismical impact of the observed object stability. On the basis of variations in gravity readings and gravimeter tilt readings, the daily changes of subsidence, uplift and tilting of the observed object are analysed.

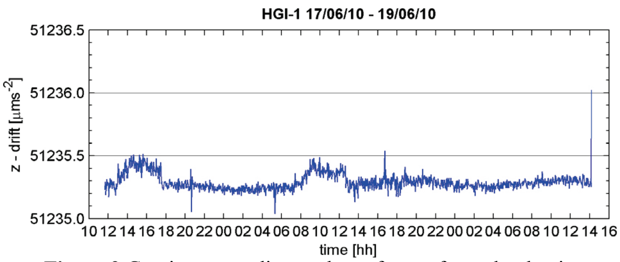

Figure 9 Gravimeter readings values after performed reduction

The analysis of the gravimeter readings on the 3rd floor in the time interval between 17th and 19th June shows that the biggest changes in the building occurr at the time of arrival to work, during lunch time between 12 and 13 hours, and at a time when employees leave from work, Fig. 9. In the time interval between 17 pm June 17th and 7 am June 18th gravimeter readings show very stable behavior of the tower. After that, there was recorded increase in gravimeter readings values until the end of the arrival of employees to work. A sudden drop in the gravimeter readings values appeared when the employees left the tower at lunch time. In the afternoon, June 18th, were very unstable weather conditions that result in minor fluctuations in the gravimetric readings. Gravimeter readings suggest the same trend which is obtained by analyzing the processed GNSS measurements.

In order to determine the variation of the inclination of the office tower the gravimeter inclination values of the *x* or the *y* axis are automatically recorded. The values of gravimeter inclination are shown in the arc seconds, Fig. 10.

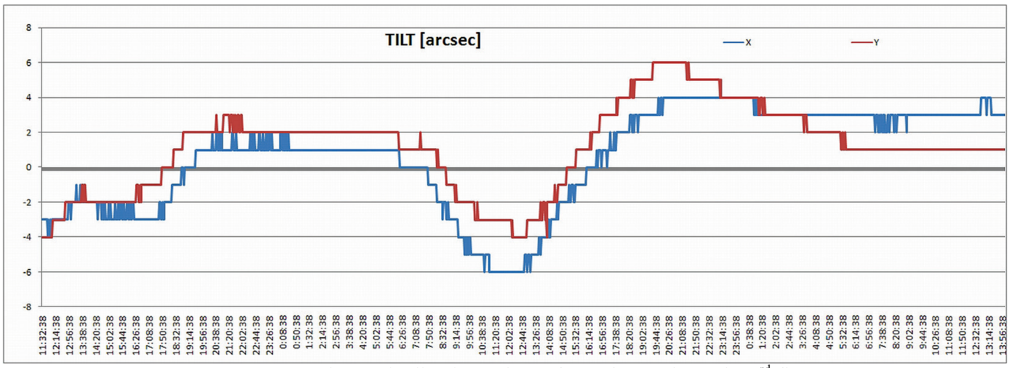

Figure 10 Gravimeter inclination values of *x* or the *y* axis on the 3rd floor

The monitoring of inclination changes of the tower in metric values is a function of the gravimeter height within the tower and observed values of the gravimeter inclination in arc seconds. Based on the recorded value of the gravimeter inclination which was set on the 3rd floor at the height of about 20 m it can be shown that the tower is moving along the value of the *x* and the *y* axes in the range of about 1,5 mm.

Apart from gravimetric measurements on the 3rd floor the gravimetric measurements were performed on the 16th floor. Because of the perceived technical problems on the 16th floor, the gravimeter placed there was re-leveled on the June 18th. Fig. 11 shows the inclination after the gravimeter re-leveling.

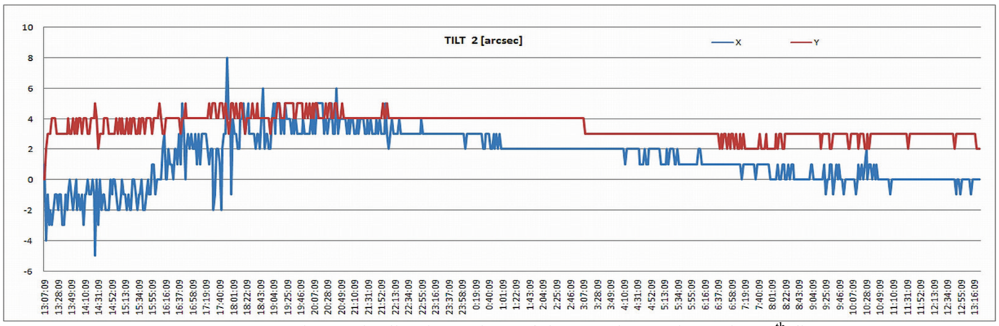

Figure 11 Gravimeter inclination values of the *x* or the *y* axis on the 16th floor

The recorded values of the inclination of the gravimeter which was set on the 16th floor at the height of about 75 m show that the tower is moving along the value of the x and the y axes in the range of about 6 mm, Fig. 11.

Based on the inclination values recorded on the 3rd and 16th floor, proportional increase can be expected of the inclination values along the *y* and the *x* axis on the tower roof at a height of about 100 m, where the GNSS measurements were carried out. Accordingly, changes in the y and the x axis on the tower roof are estimated to be in the range of about 8 mm. These values are slightly smaller than those resulting from the processing of GNSS measurements.

Neither the gravimeter on the 3rd floor nor the one on the 16th floor have recorded significant changes in the inclination for the June 19th at a time when there were no employees in the building because it was Saturday (day off). It follows that a greater part of the building inclination is caused by daily load changing in the building and a smaller part due to atmospheric effects.

Correlation coefficients have been calculated for gravity readings and GNSS heights on all four points at the roof, as well as the regression function [17, 18]:

$$z = ah + b \tag{2}$$

where z is the gravity reading, h is an ellipsoidal height and a and b are coefficients of the regression function.

No significant correlation has been found, apart from correlation coefficients amounting from 0,50 to 0,58, regarding specific point, for second part of gravity readings on 16th floor (from 14 h, local time 18th to 19th June). Diagrams 12 and 13 show dependence of gravimeter readings, corrected for gravimeter daily drift and the change of pressure, on the ellipsoidal height at T3 point.

However, since this is really a short period of time, the found correlation can be merely a coincidence. Moreover, correlation coefficients are of positive signs, while change of gravity should be negative with increase in height. In general, increase in height of 1 cm should cause decrease in gravity of about 0,03 μms^{-2}, while declared accuracy of Scintrex Autograv CG-3M gravimeter is 0,05 μms^{-2} [15]. Therefore, variations in height of a couple of centimetres are hard to detect from gravity readings of the Scintrex CG-3M gravimeter, especially in highly micro seismic environment caused by employees on working days.

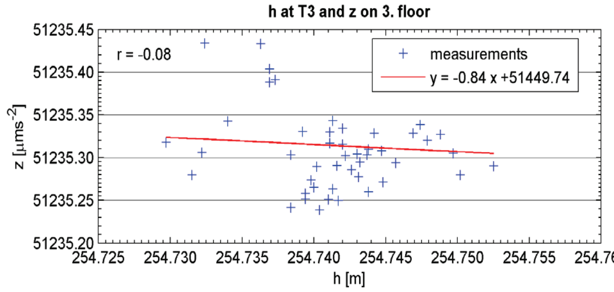

Figure 12 Correlation coefficients for gravity readings and GNSS heights for T3 on the 3rd floor

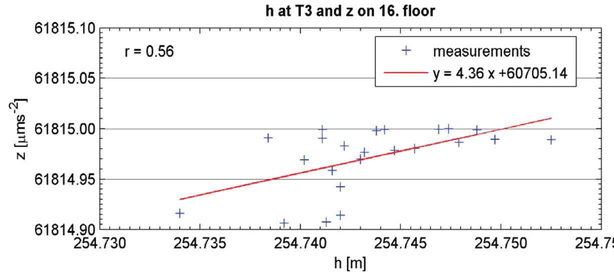

Figure 13 Correlation coefficients for gravity readings and GNSS heights for T3 on the 16th floor

Recently, independent of conventional surveying methods used to monitor the movements and deformations, thanks to the new technological solutions the inclinometer can be used to measure the slope of the high buildings, with the possibility of the automated data storage in the optionally user defined time interval, wherein the slope is recorded in two orthogonal directions. For the purpose of the mutual comparison and analysis of the results from different measurement methods it is necessary that results from all measurement are expressed in the unique metric system [19].

5 Conclusion

If one examines the daily volume change of the business tower, which shows significant changes caused by atmospheric conditions and the daily load changes in the building, he should be aware of the fact that the spatial definition of the reference station in Zagreb is probably subject to slight changes for the same reasons as in the case of the business tower. The reference station has been established on an isolated, detached, office building that is sensitive to the daily movement in all directions since there are no objects on which it leans. Such objects would be building on which is placed a reference station, which is leaning on them, anchored and held tentatively fixed. Since the building with a reference station in Zagreb is much lower, and has almost regular shape, the expected daily movements of the building are much smaller. Awareness of the daily coordinate changes of the reference stations is very important since it is one of the CROPOS services intended for scientific research works.

Daily movement of the business tower "Zagrepčanka", based on the results of the CORS Zagreb, recorded a change of 9 mm in the *y*-axis, 12 mm in the *x*-axis and 14 mm per height of the GNSS observed points established on the roof by the temperature difference of about 12 °C and daily load changes of about 100 000 kg.

From the analysis of the gravimeter readings values on the 3rd and 16th floor cannot be confirmed the same point's displacement trend which is obtained by analyzing of the processed GNSS measurements, but may suggest the same trend shift. The recorded values of the gravimeter inclination show that the tower is moving along the value of the x and the y axes in the range from about 8 mm which confirmed the results obtained from GNSS measurements.

By combining gravimetric and GNSS measurements the interpretation of the daily tower inclination gets on the reliability and accuracy, especially if we consider the errors sources in the GNSS measurements processing and adjustment. The inclusion of gravity measurements to the tower monitoring purpose could contribute to a better estimation of the daily tower inclination, especially in critical daily periods when the GNSS processing weaknesses could adversely affect the quality of the result interpretation. The daily height variations in the range of a couple of centimetres are hard to detect from gravity readings of the Scintrex CG-3M gravimeter.

The result of precise levelling shows that the daily movement of the business tower is mainly manifested in the body but not on the foundation of the tower.

Based on the processing, analysis and interpretation of test measurements carried out on the business tower "Zagrepčanka" the main goal of the research was achieved, which consisted in proving that the geodetic measuring equipment has the ability to determine the daily walk of the buildings in their full exploitation.

The successful implementation and management of the conceptual inception to the end of the demanding and complex projects involves an interdisciplinary approach surveyor, structural engineers, architects and all others who in any way participate in them.

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