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Section: Technologies of Geodesy and Cadastre

Multi-GNSS measurement system for Structural Health Monitoring applications

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Abstract

This paper describes results of projects carried on by the Applied Geomatics Center at Military University of Technology since 2008. During this period different solutions were developed to use Global Navigation Satellite Systems as reliable source of construction geometry monitoring. This process is very important to provide studies of buildings and structures safety parameters. AGC MUT developed laboratory and field tests at different objects to create new efficient measurement solution for constructions geometry real-time monitoring with high accuracy. Results of first in Poland applications of GNSS based systems on real structures (bridges and high-rise industrial chimneys) are described in this paper. Basic measurement and telematics ideas are also shown in this paper in details.

Keywords: Global Navigation Satellite System (GNSS); Globalnaja Nawigacjonaja Sputnikowa Sistema (GLONASS); GALILEO; SHM (Structural Health Monitoring).

1. Introduction

Global Navigation Satellite System (GNSS) for monitoring displacements of engineering structures is relatively well known method used successfully around the world [1, 14, 16]. From the early beginning potential of this method becomes stronger with new hardware and software solution [2]. The first stage in this process was using Global Positioning System (NAVSTAR) to develop accurate tracking solutions related on post processing differential multiband signal computing [15]. At the end of 90' it was obvious that GPS is able to serve as a alternative sensor for Structural Health Monitoring Systems used in big scale building structures [3]. Today engineers are also able to use GLONASS (Globalnaja Nawigacjonaja Sputnikowa Sistema) satellite signal for positioning. In next few years Galileo satellite navigation system will be released as fully operational. It gives more possibilities for implementation of real-time GNSS solutions on different type of structures to provide continuously monitoring. The development of SHM systemsallowforthe practical use in cases where other measurement methods were not usable or not effective [6, 8, 10, 11]. All this can be done only under one condition – user has full knowledge about the quality of the data. Otherwise, it would be not possible to detect real deformations from the measurement noise. Standard noise level for GNSS real time solution should not exceed 1 cm for horizontal displacement [8, 18, 19]. Noise level as also unexpected errors related with GNSS observation conditions decreases accuracy of the measurement up to tens of cm. Information hit by such error might not be useful for diagnosis and analysis prurposes and may cause false interpretation. Based on the experienceof research teamsdealing withthis subject, the author conductedsince 2008 to study possible methods for complete characterization of GNSSas a method of measuring the displacement of highrise concrete structures.

2. Measurements description

After the end of 2012 an agreement on cooperation between the MUT and Vattenfal Heat Poland was signed. At that time Vattenfal Heat Poland (now PGNiGTermika) was amanaging institution of fivepower plants infrastructure in the Mazovia region. Under the agreement MUT was able to access facilities and build periodic laboratory on 300 m height concrete chimney in Kawęczyn Power plant (Fig. 1). According to sources contained in the online encyclopedia Wikipedia, the chimney is the second highest in Poland, the 18thin Europe and 50 in the world. Created laboratory was based on local server mounted in the technical rooms inside chimney construction.

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The scale of the object was a major obstacle in the construction of infrastructure to enable the implementation of the method of measurement RTN.RTK GNSS. At the top of the structure is installed GNSS antenna (Level 19 design). Use the 20 and 30 meter antenna cables adjusted signal from antennas to receivers located inside the mantle at the 18th level.

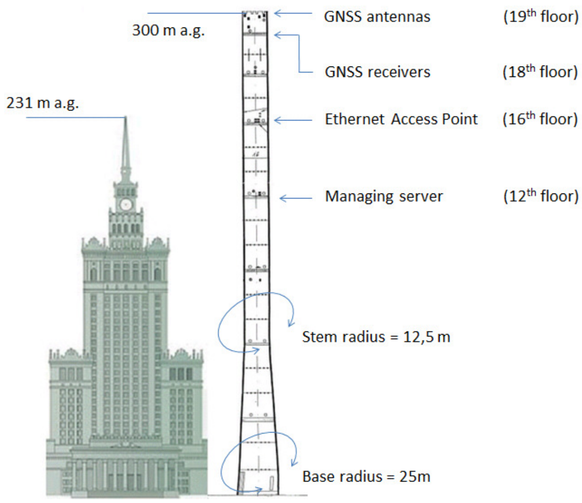

Fig. 1. Illustration of the levels of the concrete chimney in Kaweczyn Power Plant

Due to the use of Ethernet ports for data transmission (used receivers with built-in modem, Ethernet (Trimble SPS 851 and NetR9) or adapter Moxa RS232 to Ethernet (Receivers Trimble 5700) it was necessary to drag the copper cable to the server installation on a 12th floor. Due to the distance of about 80 meters separating the two points was necessary to use the device amplifying the signal – so-called repeater – at the 12th floor through consultation with the local Internet server provided realizing measured by the GNSS. Equipment mounted at the construction enabled it to provide continuous data for testing and operational purposes of Applied Geometics Center at MUT.

The main objective of developed system was to use real time GNSS methodsto obtain reliable information about the state of the geometric and dynamic characteristics of the structure to allow further health investigation [8]. Two key parameters to be measured is a method based on amplitude and frequency of vibration displacement of the structure with a known degree of reliability.

The task of the designed algorithm is:

- Acquisition of measurement data that meet accepted quality criteria
- Estimation of measurement errors
- Calculate the displacement amplitudes
- Calculation of the natural frequency

These tasks are defined on the basis of qualitative and quantitative requirements for measuring the geometry of structures for its diagnosis method of dynamic (2,4). As the literature the basic parameters helpful in diagnosing the condition of the structure by this method are about crossing warning and alarm levels of displacements values and frequency vibrations which change over time may be indicative of the occurrence of damage [1, 5].

3. Initial works

A characteristic feature and new -tech solutions contained in this work is the application of GNSS methods for detecting outliers adapted to the characteristics of the physical movements of the building during static wind loading [15].

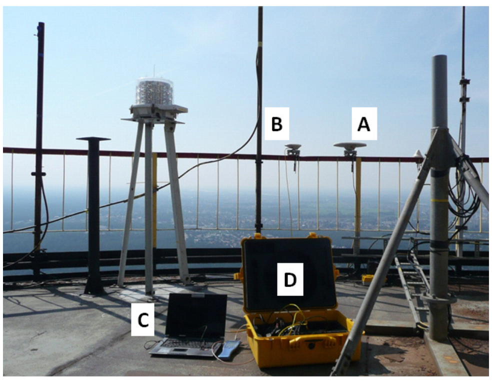

Fig. 2. Measurement equipement during first stage of tests. A – GNSS Trimble Zephyr Geodetic antenna; B – GNSS Zephyr antenna; C – spectrum analyzer Aaron AG HF- 6065 V4 and AaroniaLcs Analyzer software version 1.9.9.9; D – GNSS Trimble 5700 receivers

Procedure for determining displacement was divided into 4 parts. The first stage involveda control of the proper preparation of instruments for the measurements. This module applies to operations and technical conditions to be met to access a NMEAstream (National Marine Electronics Association) generated by the receiver operating in real time mode. During the control works electromagnetic signals that may affect degrading the quality of the GNSS signalquality were investigated. This is a very important problem, especially for high buildings which are often used to install antennas transceiver for various telecommunications systems. Therefore, in order to analyze the GPS system testing was performed using a spectrum analyzer Aaron AG HF- 6065 V4 and AaroniaLcs Analyzer software version 1.9.9.9 (Fig. 2). It was assumed that the attenuation resulting from the use of cabling is 0 dB. The Figure 3 shows the results of measurements for the L1 band.

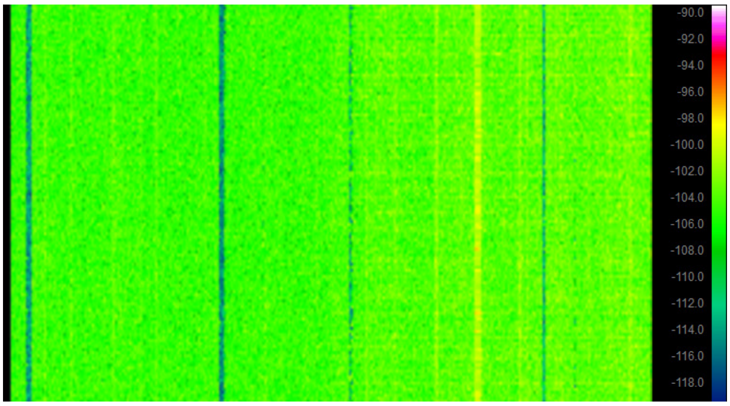

Fig. 3. Results of GPSL1signal spectrum (power for a given frequency)

It can not been seen any signs of the impact of other device operating on similar frequencies which may affect the quality of the received signal for the L1 carrier. What is more noteworthy the level of the received signal power was at very high level of up to 180pW/m2. The difference between the signal power and the power to noise ratio (S / N) in both cases is 22 dB and is housed in a standard described the Global Positioning System Standard Positioning Service Signal Specification [9]. The results allow for the conclusion that in the investigated range of the spectrum, there are no signals that could interfere with the work of GPS receivers placed on top of the 300 m concrete chimney in Kaweczyn Power Plant. The second step of the algorithm is described filtering data. At this stage the analysis of the quality of the observation and detection of outliers. After verification of the data followed by the penultimate step of the algorithm which determine the values of the amplitudes of displacement. The values are compared with the values for warning and alarm threshold. The final step is to determine the natural design frequency of the construction based on FFT analysis and comparison with the reference value obtained from the project documentation or results of numerical analysis [18, 19].

4. Data acquisition

This module algorithm is responsible for carrying out the measurement data used in the later stages of the displacement monitoring process. At the first step the NMEA GGA message is investigated about the key major factors influence at GNSS measurements quality as:

- The number of visible satellites

This parameter is taken into account as the first in the filtration process. The value of “0” will mean no satellite signal at the input to the receiver. This may be due to the complete screening of the antenna or the lack of connection between the antenna and the receiver. From our own experience and the literature [3] shows that for a correct determination of the position by real time GNSS is necessary to use the observation of a minimum of 5 satellites.

– Coefficient of PDOP (Percentage Dilution of Precision)

The PDOP is another parameter to be taken into account in the process of filtration. According to the recommendations of Polish Head Office of Geodesy and Cartography (Technical Guidelines G- 1.12) assumed that the maximum level of PDOP should not exceed 4 during precise measurements. In any other case, the information will be considered as unreliable.

– Solution status

This parameter is the information contained in the NMEA stream. This parameter assigns different operating modes of GNSS receiver corresponding number in the range 1–8. For the operation of geodetic measurements with high accuracy is essential work RTK (parameter = 4). Data do not meet this condition are considered unreliable. 6,7,8 -valued parameters are not used. Parameter with a value of “0” indicates the irregularities related to the visibility of satellites.

– The age of the telegram

Another condition that must be met to coordinate the measurement was made with centimeter accuracy is information on the age of the message, ie, the time (in seconds) elapsed since receipt of the last message from the navigation system to support the work of GNSS. Experience shows that a common problem when measuring method RTK / RTN is the need to ensure continuous access to the source of navigation messages from augmentation systems [3]. Disruption in the continuity of data stream transmission cause errors. The result of increasing age of the message is a dropping down the quality of GNSS solution [9].

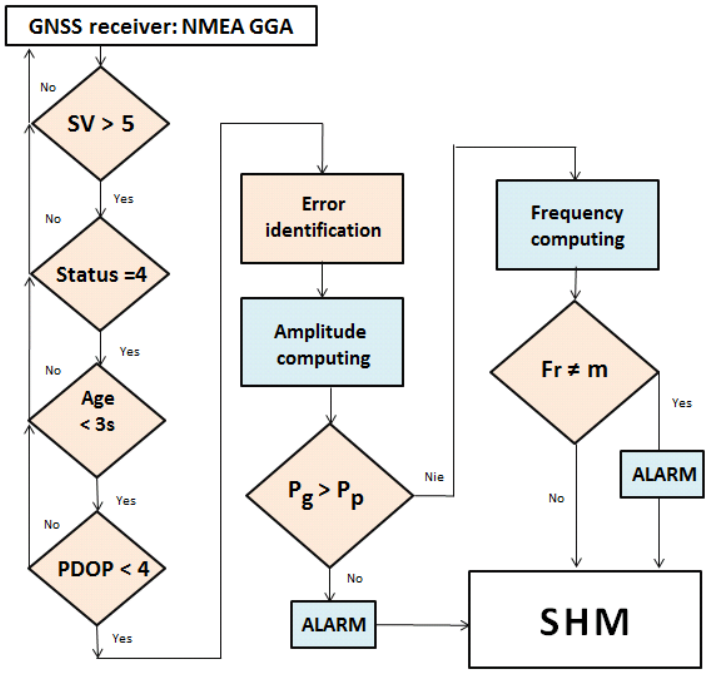

Fig. 4. Data quality check at data acquisition system

Figure 4 shows the main modules and the order of operations performed in data acquisition module. Data processing begins with a series of load data acquisition module. Range of data undergoing analysis stems from the need to register at least a few complete cycles of oscillation of the structure in order to properly determine the frequency of vibration. In the case of the use of data on the frequency of 5 Hz full oscillation period includes 25 points. Then the data are verified because of the quality of the observations in the following order (chosen because of the size effect on the final result designate the coordinates): the number of observed satellites, the status of solutions, age correction message, the coefficient of CIT. The order of these parameters was selected because of their impact on the quality of the obtained coordinates [8]. In the event of failure to comply with accepted criteria, the measurement data are marked as unreliable, ie not suitable as a source for reliable analysis of the structure. In a further step, the statistical analysis and data filtering are done to eliminate data outliers. This kind of errors are generally: multipath signal momentarily obscure the horizon or atmospheric disturbances that cause cycle slips [1]. Based on the data after filtering amplitudes are calculated in x and y direction in 2000 reference system. If the assumed threshold is exceeded, an alarm is signaled directed to the SHM or BMS (Building Management System). The last step of the algorithm is to determine the oscillation frequency to track the differences related to changes in the material structure [4]. If the change exceeds the established criteria, an alarm is triggered forwarded to the SHM. Obtained in this way, information can be collected and periodically removed after a certain time, such as one day. These data will be used in further works by the construction engineers during diagnostic process.

5. Results

Figure 5 shows a viewof the mains creen of the application developed in the Matlab environment. The largest window shows the implementation of the script window. On the right sideare visible three graphs showing thecourse of the coordinates before filtration, after filtration, and the differences between theoriginal and filtered signal. The left side of the bottom of the graph shows the frequency of displacements. The right side shows the result of calculating the amplitude of displacement with the calculated average error (red border).

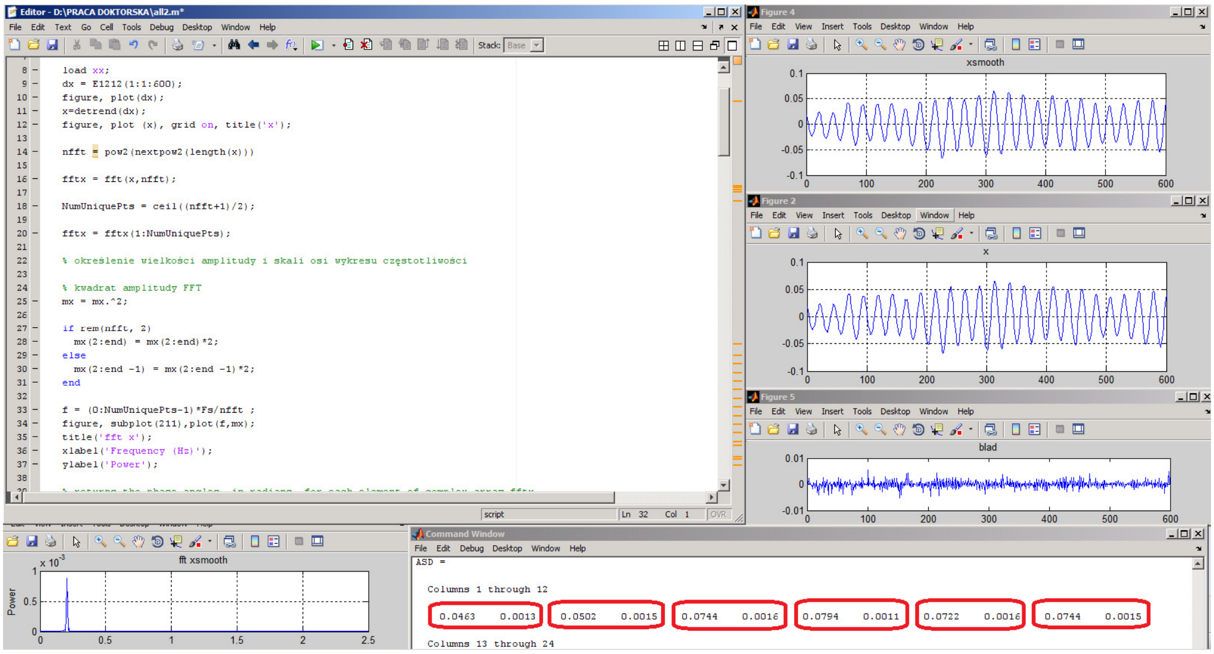

Fig. 5. Main window of the application

Figure 6 shows sample results of using designed system from period 11.01.2012 11:00:00–11:00:25. The average wind speed was approximately 15 m/s Frequency designate position – 5 Hz. First two data sets shows horizontal displacements in East-West and North-South directions. It is easily seen that in those weather conditions the Karman vortex effect can be easily seen and investigated.

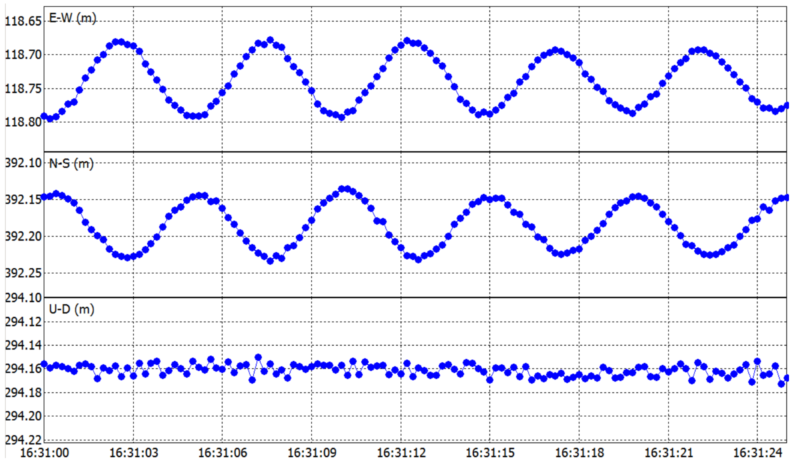

Fig. 6. Sample result of measurements took during 15m/s wind loading on the 300m tall concrete chimney

6. Summary

As a result of the described algorithm it was possible to develop tools that meet the required functionality and boundary conditions of diagnostics purposes. Fulfilling them is to ensure effective selection of data and reduce errors in their interpretation. For the purposes set out above analysis is based on data obtained during several measurement campaigns in the past five years. The results obtained from the comparison of two independent measurements indicate the possibility of measuring the amplitude of displacement of the structure with an average error not exceeding 1 cm. Observation characterized by large errors are possible to identify and remove in the process of appointment of the amplitude and frequency of vibration of the structure. Only apply full control to the extent described above algorithm allows the direct use of GNSS as a input for diagnostic systems.

The solution developed based on the experiences of the past five years can be implemented in practice. Confirmed experimentally [10, 11] utility measurements conducted by the GNSS allows to increase the efficiency of the diagnostic process design.

As a result, SWOT analysis of using GNSS in SHM systems is written below

- Strengths

- Determination of position changes in three directions – Positioning GNSS allows you to specify changes in the position ortho – cartesian defined by the user
- Automation of measurement – measurement is performed unattended automatically without operator intervention which allows unattended operation when the system starts.
- Fast measurement – the measurement result using RTK / RTN available immediately (if there are no adverse observing conditions affecting the implementation of the differential phase measurement) [2]
- High accuracy – Differential GNSS measurements allow you to specify the position of a single point with an accuracy of 0.5–1 cm in the "post-processing". Use of the method allows to achieve RTK accuracy of 1 cm for the horizontal components [2]
- High frequency of acquisition – the possibility of registering the data with a frequency of up to 20 Hz. Most of the current market geodetic GNSS receivers is based on the measurement card tracking satellite signal with a frequency of 20 Hz (www.geoforum.pl). Some of the producers (Javad, Novatel) provide solutions to determine the position of the frequency to 100 Hz (www.javad.com, www.novatel.com) (Doberstein, 2012)
- of distant reference base – through solutions NRTK network can be implemented measure to stable external reference system [4, 5]
- Without measurement of survey reference points – With the use of existing GNSS ground augmented infrastructure measurements of displacement can take place without the need for additional operations such as matrix measurement reference points or stabilization. All activities related to the setting of benchmarks carried the network administrator. The effective implementation of the provisions of the Law Surveying and Cartography and the accompanying guidelines ensures high reliability (accuracy) of the reference base constituting the control points of the base
- work at night and during the difficult (for the observer) weather conditions – thanks to this structure, it is possible to monitor continuously for longer periods casu daily allowing inference of geometry of the structure induced changesthermal loading [7].

- Weaknesses
  - of limited credibility – random errors necessitate ongoing follow-up and quality control services to support the process of designation position [14]
  - with limited accuracy – Dynamic change in the conditions of observation during the measurement results in a lack of stability of the results and change of coordinates in the range of + – 0,5 cm for the horizontal component [15]
  - The need to support the information from the outside – to achieve high accuracy requires the participation of additional information in the process of designation position [6, 11].
- Opportunities
  - The use of ASG- EUPOS – New opportunities creates launched in June 2008 Active Geodetic Network – EUPOS (European Position Determination System) support the work of mobile receivers operating GNSS RTK method. In 2012 began the construction of three private networks of reference stations to be met similar to ASG- EUPOS features for users GNSS specific brands. Increase of competitiveness contributes to the gradual improvement of the quality of services provided real-time and thus the quality of the measurement results of displacement.
  - The ability to use the method of RTK / RTN measurements of fast movements where the influence of errors due to the conditions of observation is smaller because of its long-term character. The examples from the literature and our own experience indicate the possibility of measuring the magnitude of the displacement amplitude of the average error of < 1 cm.
  - Verification of data quality – Current control observation allows for quick detection of gross errors caused by a momentary loss of status "fix".
  - Integration of the antenna, receiver and modem in one device – Trends in the construction of GNSS receivers allow today the use of instruments in one box containing all the necessary elements to implement measured by RTK or RTN.
- Restrictions
  - exposed horyzont – This requirement is crucial for the use of GNSS technology, regardless of the measurement method [9]
  - Susceptibility of observation conditions in a method for RTK / RTN – nature of errors in these embodiments prevent the real- time monitoring of the cyclic movements of a value below 0.03 m [11].

Acknowledgements

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