Distance Limitations when using CORS Networks and GNSS Receivers for Deformation Monitoring

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ABSTRACT

Global Navigation Satellite Systems (GNSS) are currently widely used for deformation data collection.Numerous of receivers are installed on structures like bridges and dams, in order to monitor their operation and health conditions. The technological advancement and installation of many networks of permanent and continuously operated reference stations (CORS) have resulted in their extensive use for monitoring purposes. Each one of the GNSS receivers is connected with a reference station, to perform the measurements.

Although the use of GNSS receivers and a proper reference station has been scientifically proved that horizontal and vertical accuracies of about ±10-15 mm can be achieved, the distance limitations of using a permanent reference station for deformation monitoring, is a crucial parameter.

In this paper, the influence of the distance, between a monitor receiver and the reference station, to the achieved accuracy is investigated.The study involves measurements by single and dual frequency receivers at various conditions. These refer to the methodology being used for the measurements (Single Base and VRS), and the distance between the reference station and GNSS receiver, which fluctuates from 50m to 25km.

Regarding the results, the values of these distances are studied in order to examine the necessity and usefulness of using virtual stations, which are every time created at a different close distance to the monitored facility. Also, the least time between the different sets of measurements, in order for the deformation time series to be created, is concluded. Finally, the relation between the distance and the achieved accuracy is determined, through mathematical modelling.

I. Introduction

The deformation behavior and monitoring of engineering structures has been a subject of concern for many years.

Traditional methods for the monitoring of structural facilities refer to the used measurement techniques and systems, which could be geodetic or non-geodetic.

Geodetic survey techniques include conventional terrestrial observations (angle and distance measurements, precise levelling measurements), photogrammetric (aerial and digital photogrammetry) and satellite observations (Global Positioning System-GNSS, InSAR). (Erol et al., 2004)

Non Geodetic techniques refer to geotechnical / structural measurements, using accelerometers, lasers, tiltmeters, strainmeters, extensometers, joint-meters, plumb lines, micrometers. (Lovse et al., 1995)

In order to choose a certain technique, the expected accuracy is the main parameter to be considered.

Regarding the geodetic techniques, GNSS based measurements are currently widely used due to the technological advancement of the receivers and the simplicity of the procedure of the observations.

Nowadays the majority of GNSS measurement systems include a continuously operated reference station and a single rover GNSS receiver. Continuously Operating Reference Stations (CORS) can take the place of a traditional base station used in differential GNSS positioning. They can give an instant position to an accuracy of ±15 mm. (Wanninger, 2002)

The maximum distance between a base GNSS station and a rover GNSS receiver should be about 10 - 15 km. This is due to the effect of the atmosphere on the GNSS signals as they travel from the satellite towards the earth. (Janseen, 2009)

With the establishment of a network of reference stations, the distance between the base and rover receiver can be extended. The permanent stations can be spaced about 70 km apart, and by using at least 3 of them, the atmospheric effects can be modeled and corrected. (Vollath et al., 2002)

Due to the elimination of these types of errors, several GNSS receivers can operate as standalone, when they are installed on construction sites, in order to monitor either the health conditions or the deformation of them.

The main scope of this paper is to indicate the optimum values of the distance and the positioning methods, in order to use satellite based measurements for the detection of deformations of about ±1-2 cm.

II. State of the art

GNSS measurements are already used in common deformation studies under specific circumstances, which refer to the number of GNSS receivers used and the positioning methodology. GNSS receivers and satellites' provided observations can be used at both small and large scale studies.

For example regarding small scale studies, GNSS receivers were used in order to examine the dynamic deformation (structural vibrations) of tall or long structural facilities (Lovse et al., 1995) Three GNSS receivers were used for the measurements and the post processing relative static positioning method was used. Also GNSS observations were used to monitor the health conditions of a long suspension bridge when the temperature significally changed. (Roberts et al., 2017)

Regarding the large scale studies, several GNSS receivers were used in order to conclude about the crustal kinematic field of central Western Europe (Tesauro et al., 2006). GNSS measurements between the 55 receivers were used with complementary seismic data, in order to create velocity time series.

Also big data (20 years) of GNSS observations were used in order to preview the eruption behavior of an active volcano, by monitoring it in specific conditions. (Staudacher et al., 2016)

There are many other studies, where GNSS receivers were used in order to create three dimensional networks (Dong et al., 1989; Bock et al., 2004)

Also several experiments were implemented, where GNSS receivers were used in order to provide continuous real – time measurements which can be used to indicate displacements caused by temperature changes, wind loading, distant earthquakes, landslides, and other natural phenomena. (Ojaca, 2016)
These experiments were based to the category of real time kinematic positioning methods when two or more exact same GNSS receivers are used. The measurements are available on a continuous basis, or whenever a preset displacement threshold is exceeded. (Rizos et. al., 2010) From these experiments a conclusion about the optimum placement of the GNSS receivers on the structural facilities is being determined (Wieser et al., 2002).

The majority of these GNSS measurements were combined with other data and all of them were used in solutions based on conventional or more advanced mathematical models. (Kaloop et al., 2009; Ince et al., 2014)

III. GNSS networks and positioning methods

A. *CORS Networks*

The advantages of using a continuously operated reference station network refer to the elimination of base station and radio issues, the use of common coordinate system by all and the increase of the working range. The distance dependent errors are greatly reduced and a larger area is covered with few reference stations. (Rizos, 2002)

The only limitation of the use of continuously operating reference stations is the mobile coverage, in order to succeed the transmission of the corrections between the control center and the user, when using real time processing techniques. Several countries have developed their own reference stations network including Australia, USA, Canada, Dubai and Sweden. Each of these networks consists of an appropriate amount of stations. Many of these stations are participating in the International GNSS Service (IGS) network. (Lambrou et al., 2018)

Due to the technological advancement of GNSS receivers many positioning methods are currently used, like VRS and Single base RTK. (Janssen, 2009)

These methods relates to post – processing or real-time determination by using a single receiver and one or more permanent reference stations. These stations may be real (Single Base) or virtual (VRS). (Vollath et al., 2002)

B. *Positioning Methods*

The methodologies examined are the VRS and the Single Base positioning methods. Both of these methods can be used for real-time observations or post – processing solutions.

With respect to the VRS method, the virtual reference station is being placed every time at a close distance to the monitored location (approximately 50m). When the monitor coordinates are provided by the post processing procedure of the baselines, the location of the virtual station is being preliminary indicated by the user. When the coordinates are provided in real time, the location of the virtual station is obtained by the network's control center and does not exceed the distance limitation of 150m. (Landau et al., 2002)

As for the Single Base method each time one permanent reference station is used for the measurements. When the coordinates are provided by the post processing procedure of the baselines, the choice of the reference station is made by the user. When the coordinates are provided in real time, the choice of the reference station is limited to one or two of them, with the closest distance to the measurements' facility. (Vollath et al., 2002)

IV. CASE STUDY

A. *GNSS Observations - Measurement System*

Several experimental applications were carried out in order to examine the errors included to the measurements when either the distance between the receivers or the measurements' methodology changes.

All experiments were carried out at certain time where the DOP values, the number of the satellites and the atmospheric conditions were optimal. (Meng et al., 2004; Lambrou et al., 2018) These values were known by using planning software. Regarding the multipath effect, the surrounding area of the measurements' site was examined in order to eliminate obstacles near the GNSS receiver.

All the measurements refer to a specific point where the GNSS receiver is established. The GNSS receiver is placed successively at the same concrete position by using forced centering facility.

This point resembles to the monitored position where the GNSS receivers would be placed at a monitored construction structure.

Point positions are mainly the output of the evaluation of the measurements. During the deformation analysis phase, the coordinate changes in the point positions are investigated, by using the least – squares mathematical model. (Acar et al., 2006)

These point positions are provided at the datum, which is used by the CORS network, and usually refer to local grid coordinates. Usually this is the coordinate system, which is used, in order to eliminate the errors caused by the further transformation of the coordinates between several systems.

The scope of all the experiments was to detect deformations of at least ±1-2cm.

B. *Measurements' time series*

Deformation time series were created from the observations regarding each time exclusively the horizontal coordinates (x,y) and the vertical component (H: orthometric height).

These time series refer to the differences between the reference values (x_R, y_R, H_R) of the point position and the observations (x_{OBS}, y_{OBS}, H_{OBS}) made by the GNSS receivers, as described by the equations 1 to 3.

$$Dx_i = x_{OBS_i} - x_R \quad (1)$$

$$Dy_i = y_{OBS_i} - y_R \quad (2)$$

$$DH_i = H_{OBS_i} - H_R \quad (3)$$

where i= the number of each individual observation

The reference coordinates were known by the observations of a first class total station, and their determination accuracy fluctuated from ±1 to ±2mm.

Each of the three different time series was studied individually in order to conclude about the quality and reliability of the measurements. At the end, these three time series were compared in order to eliminate specific systematic errors and several noise - outliers from the observations.

C. *Hellenic Positioning System (HEPOS)*

The CORS network used for all the applications was the HEPOS (Hellenic Positioning System) network. This network consists of at least 98 permanent reference stations placed at various locations at all extents of Greece. It was picked due to the existence of at least four of these stations, in close distance to the monitored facility. Due to this inclusivity the Hepos network was already used in specific experiments referring to displacements. (Gianniou, 2011)

Regarding the VRS method when the observations were made in real – time, the network's processing system, was providing the location of the virtual station. The distance between the monitor receiver and the virtual station fluctuated from 56 to 64m.

As for the Single Base method two permanent reference stations were used at a distance of 5 and 25 km from the monitored location.

D. *GNSS Receivers – Positioning Methods*

In order to make the applications more conclusive, three different types of GNSS receivers were used.

One of them (Trimble 4600LS) is a single frequency receiver. The other two (Trimble 5800 and Trimble R8s) are both dual frequency receivers.

These receivers were picked because of their ability to perform observations with the preferred positioning methods as stated at Table 1. Also GNSS receivers like those, are the common equipment used for surveying.

Table 1. GNSS Receivers compatibility with Positioning Methods

	Single Base (PP)	Single Base RTK	VRS (PP)	VRS RTK
4600LS	√	-	-	-
5800	√	-	√	-
R8s	√	√	√	√

E. *Occupation time for each measurement*

In order to equally compare the results for each of the different positioning methods, considering the change of the distance between the monitor GNSS receiver and the stations, the time of each individual observation (occupation time) ought to be examined.

The occupation time is absolutely influenced by the coordinates' uncertainty. Each of the GNSS receivers used, have different values for them. In order to be able to detect deformations of about ±1-2cm, the GNSS receivers should determine the coordinates with uncertainty of 2-3 times better than these values (approximately at least ±4-6mm).

These facts were considered and combined with the coordinates' uncertainty, provided by the manufacturer of the GNSS receivers, in order to conclude about the proper observations' time.

Due to the fact that VRS positioning method is based at the creation of a virtual station at a very proximate position to the monitor GNSS receiver, the observations' time for the VRS Post – Processing method, was 5 minutes. It is stated that when using the VRS RTK positioning method the measurements' time series are continuous and the occupation time is 30 seconds.

As regards the measurements based at the Single Base Post - Processing methodology the observations' time fluctuates from 10 to 35 minutes. Approximately 10-14 minutes refer to the observations between the monitor receiver and the permanent station, which was spaced 5km from it. So, 28-35 minutes refer to the observations, when the distance was 25 km.

Observations' time greater than 35 minutes should not be used for deformation monitoring because the satellite formation would change and the time series would refer to different phases of measurements. Also, the observations' noise would be more and a modeling procedure should occur in order to eliminate them. (Williams et al., 2004;Lambrou et al., 2018)

It is stated, that when using the Single Base RTK positioning method the measurements' time series are continuous and the occupation time is 2 minutes, for either one of the distances.

F. *Results*

From the applications, it is concluded that both positioning methods can be used for deformation monitoring.

The GNSS receivers, which will be used as monitor, should not be single frequency due to the limitation of functions, the several noise and outliers on their observations and the inferior measurements' accuracy.

Also in order to examine thoroughly the exclusion of the single frequency GNSS receivers from the monitoring procedure, a comparison between them and dual frequency receivers was made. The comparison refers to the mathematical modeling of the differences of the measurements of distance (DS), as described by equation 4.

$$DS_{ij} = S_{DUAL_i} - S_{SINGLE_j} \quad (4)$$

where S_{DUAL} = the distance between the dual frequency receiver and the station

S_{SINGLE} = the distance between the single frequency receiver and the station

i,j= the number of each individual observation

From the mathematical modeling it is concluded that the relation between the measurements of the different types of GNSS receivers is not linear. In particular as it presented in Figure 1 the equation, which fits the data in the best way possible, is a 6th grade polynomial.

So it is concluded that there is no indication that there are any statistical and mathematical corrections, which can be used at measurements provided by single frequency GNSS receivers in order to quantify the differences and make the observations equal to the dual frequency ones.

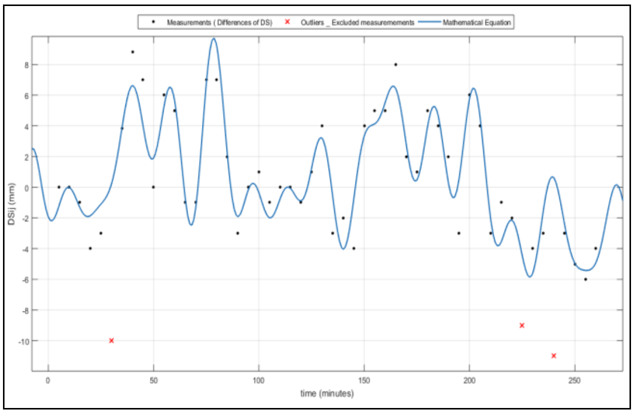

Figure 1. Mathematical modelling between Single and Dual Frequency GNSS receivers

The results refer to the possible detection of deformations of about ±1-2cm. That means that only the x,y coordinates are taken into concern. The measurement of the orthometric height, refer to an accuracy, which surpass the value of the wanted detected deformation. So any possible deformation on the vertical direction should be examined individually. (As regards the specific applications of this paper, the GNSS receivers used would detect vertical deformations of about ±6cm)

From Table 2 it is concluded that the virtual station and the permanent station at 5km would be more likely to be used for the deformation monitoring of ±1-2cm.

Table 2. Maximum value of the coordinates' uncertainty for each of the methodology used

	4600LS	5800	R8s	Methodology
50m	-	-	±4mm	VRS RTK
5Km	-	-	±6mm	SB RTK
5Km	±14mm	±9mm	±6mm	SB PP
25Km	-	-	±22mm	SB RTK
25Km	±23mm	±8mm	±8mm	SB PP

Also from Figure 2, which represents part of the overall measurements' time series of Dx for the R8s monitor receiver, it is concluded that the components of the VRS methodology (RTK and Post Processing) provide the same results. Also the same happens when the Single Base methodology (RTK and Post Processing) is implemented by using a permanent station at 5km.

When the station is at 25km the Single Base Post Processing methodology is more accurate. So, it is concluded that when the distance is increasing, the post processing methods, which require more observation time, are more efficient.

The same conclusions come up from the examination of the same data corresponding to Dy.

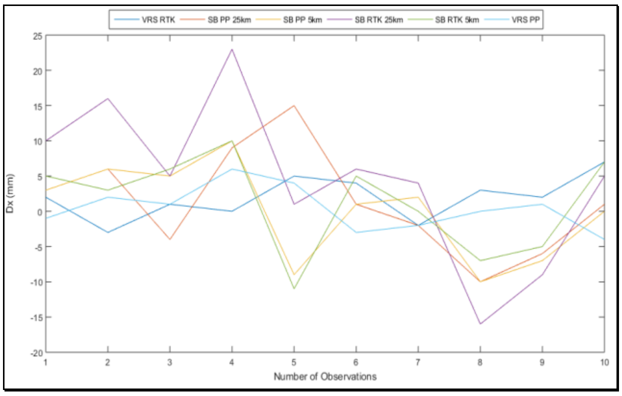

Figure 2. Differences of Dx between the methodologies by using the R8s GNSS receiver

V. Conclusions

Nowadays satellite based measurements are much more appreciated and widely used for deformation monitoring due to the simplicity of the observations' acquisition and the technological advancement of the CORS networks.

The use of CORS networks is mandatory in order to eliminate the error factors which refer to the modeling of the atmospheric conditions.

In this paper two methodologies (Single Base RTK and VRS) were examined, and both of them can be used for the deformation monitoring.

In order to conclude about the deformation of a structural facility by using GNSS measurements, proper measurements' time series ought to be created. These time series is advised to be sequential.

Many GNSS receivers can be used for deformation monitoring as long as they are dual frequency and have the ability to perform observations by using CORS Networks.

The least time between the different sets of measurements is concluded by considering the time needed in order to initialize the measurement system and the distance between the monitor and reference receiver (permanent or virtual).

Although the methods refer to real time observations, the distance between the monitor receiver and the reference station has to be taken into consideration. When the distance between the receiver and the station is increasing (Single Base method - PP) the occupation time of the observations should be greater than the time when using the VRS method, in order to maintain the same coordinates' accuracy.

So the distance between the monitor receiver and the reference station remains a crucial parameter. From the results of the external applications is concluded that the use of virtual reference stations is more beneficial. The virtual station is being placed at a very close distance to the monitored facility, thus the accuracy of the measurements is very similar to the manufacturers' values of the coordinates' uncertainty. This means that errors regarding the conditions during the measurements (atmospheric and site manufacturing), are eliminated from the observations because the receiver and the virtual station are at approximately very close distance and are equally influenced by them.

The only limitation to using virtual reference stations is the necessity of the existence of at least three other permanent reference stations of the same network at an area of approximately 50 km.

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