Monitoring Structural Deformations Using Network RTK

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***Abstract*—Physical infrastructure such as buildings and bridges may seem stable but in fact they experience a variety of perturbances. Such disturbances cause deformations in these structures. Analysis of these deformations is necessary because they may sometimes have fatal consequences. Deformations in such structures may vary from centimeter level to meter level. Techniques adopted to monitor structural deformations must therefore be capable of sensing as small as centimeter level variations.**

Usage of Network RTK positioning method to sense slight deviations in the structure can produce exemplary results. Such a network – known as Pak Rehber Precise Positioning Network – has already been developed in Karachi. The research covered in this paper highlights the utilization of Pak Rehber Precise Positioning Network to continuously monitor the structural deformation faced by bridges. The established system monitors the deviation form the original position each second and plots these deviations against time. If a threshold value od deviation is crossed in any of the three directions (east, north, vertical), an alarm can be generated and counter measures can be taken.

Keywords—structure; deformation; GNSS; RTK; NRTK; base; rover; tower; UHF.

I. Introduction

What makes the study and monitoring of deformation monitoring important is the fact that these studies are directly related to public safety. Other concerns include property damage and environmental protection. Any change – in the position, dimensions, structure or shape – that a non-rigid body undergoes is referred to as deformation.[1]

There is a need to monitor and measure the deformations produced in large engineering structures. This constant monitoring ensures that the safety of the structure is not compromised. Buildings of today are much higher than the buildings of the past. Structures designed in modern times have a high level of flexibility in their structure and the massiveness of these structures makes them prone to large deformations. Thus there is an innate requirement to withstand effects of large temperature fluctuations, high wind speed, floods and earthquakes. This gives rise to the need of highly reliable, robust, precise and effective methods to resolve the deformation concerns.[2] Safety can only be ensured by conducting a deformation survey. In the designing phase of a high rise building, the most important structural aspect to be kept in consideration is their dynamic behavior under external loads. Structure of a building is usually designed such that it can withstand the effects of primary loadings. Monitoring of deformation in a structure has previously been monitored using techniques involving geodetic surveys and equipments.[3]

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II. Conventional & Modern Techniques

Conventional tools to monitor structural deformations include strain gauges, photogrammetry [4], inclination and tilt measurements, pseudolites [5], lasers, Interferrometric Synthetic Aperture Radar (InSAR), accelerometers and total stations. Since the development in technology and applications of GPS, monitoring of structural deformations has become easier. Development and deployment of other GNSS (GLONASS, BeiDou and Galileo) has made GNSS applications more robust, reliable and effective. GNSS technology has directly enabled the measurement of position of a point (and hence the displacement from the reference).

Modern and effective techniques to monitor the deformations of engineering structures make use of the GNSS technology.[6] Deformations in bridges, dams, high rise buildings and walls etc can be effectively monitored using GNSS.[7] GNSS can be utilized in many ways for the subject purpose. Some trends include:

- GNSS receiver's integration with either of the following equipment; total station, accelerometers, inclinometers, laser levelers, digital levelers, strain gauge, etc
- GNSS RTK (Real Time Kinematic) surveying technique
- Low cost GNSS receivers (L1-only)
- Utilization of CORS Network (Network of Continuously Operating Reference Stations of GNSS)

There are some draw backs in utilization of GNSS as the core technology to monitor structural deformations. Bridges do not always offer clear sky visibility which is the prime requirement for GNSS receivers to work. The accuracy of the results produced by GNSS is dependent on the satellite geometry in space. Regions near the equator experience degraded GNSS operations at times of high ionospheric activity. The structure whose deformation is to be measured often becomes the biggest source of multipath.

The technique used in this research work is a combination of RTK and NRTK, making it one of the smartest, reliable and precise solutions to the problem at hand. Not only is this technique efficient in producing desirable results, but its cost-affectivity is one of the many other reasons that make this technique stand head and shoulders above the rest.

III. METHDOLOGY OVERVIEW

The common method, employed worldwide, for all types of surveying (such as cadastral surveying and engineering surveying) is RTK surveying using GNSS. RTK stands for Real-time kinematics. The utilization of RTK in the form of networks has increased vigorously throughout the last decade. The term dedicated for such networks is RTN and it stands for Real time network. Both public and private sectors are busy in deployment of such networks throughout the globe. Under the case of unavailability of the complete network, RTK serves as the only solution for precise positioning. Accuracy of position up to centimeter level accuracy can be achieved by using either RTK or RTN. Following terms need to be established before going through this paper:

- **User**: Person(s) performing survey using CORS Network.
- **GNSS**: Global Navigation Satellite Systems
- **RTK**: Real Time Kinematics (GNSS Survey)
- **CORS**: Continuously Operational Reference Stations
- **NRTK**: Network RTK (or RTN : Real-time Network) for GNSS Surveys

IV. WORKING SCHEME

Position determination using RTK is a technique employing the principles of relative positioning. In real time, position determination of two separate GNSS antennas is carried out relative to each other.[8] Antenna no. 01 is hoisted at a static place whose coordinates are fixed. This point is referred as base station. The user is this case carries the antenna no. 02 and is referred as the rover. The task of the RTK base station is to provide corrections to the rover's position by transmitting its raw observations. This all happens in real time. The rover then takes into account the base observations and consequently adjusts it's (rover's) position with respect to the base.[9] The line joining the base station with the rover is referred as the baseline. This process is depicted in the following figure:

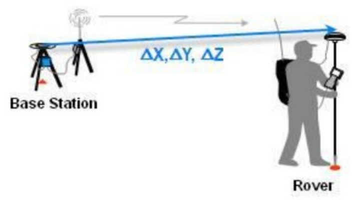

Figure 1: Base Rover Configuration in RTK

Initially, the rover needs a time to boot and collect positioning data. This initialization time is usually very low and in most of the cases, it takes less than a minute for the rover to determine its positions with respect to the base station. In order to transmit corrections from base station to rover, a non-stop communication link is required. Optimum conditions for conducting such a survey include open sky and good satellite visibility and geometry. Under these conditions, RTK produces results up with centimeter level accuracy. The basic shortcoming of this technique is the limited distance between the rover and the base station. When this distance exceeds 20 km, the accuracy decreases significantly because atmospheric errors and satellite orbit errors vary over large ground-distances. The general rule of thumb is that as the length of baseline increases, the precision decreases. To overcome this problem of baseline's length, Network RTK or NRTK is used for surveying. Network RTK employs a network of several base stations which independently collect GNSS observations. This information is then sent by all the base stations; in real time; to a master control center or a central server. The purpose of his server is to gather the incoming observation data from all the base stations, process it and calculate a general network solution. Using this network solution, errors in the observations are computed and their corrections are calculated. These corrections are then broadcasted to the rovers (users) who are within the coverage area of the network. Network RTK can employ different approaches to accomplish the same task such as VRS (Virtual Reference Stations), FKP (Flächen Korrektur Parameter) and MAC (master auxiliary concept).

V. RTK UP AGAINST NRTK

Surveying with RTK and surveying with NRTK have difference.[10] These differences will be the core of this section. Although accuracies of up to centimeter level can be achieved using either of the two techniques but they differ in terms of coverage, productivity and cost.

Base Station – Surveyors using RTK may need one or more base stations. This increases the cost of project, the maintenance tasks and the time for setup and monitoring; let alone the price of rover(s). For all user is general and new users in particular, some of the above mentioned drawbacks might become a real challenge. On the other hand, users of NRTK do not have to worry anything about the base station. Setting up of a base station and all of its related tasks are tasks of the CORS network developer. The user in this case will only have to purchase the services from the CORS network provider. As far as expert users are concerned, they can get more flexibility and control over the base stations' functions while working with the base of their own (i.e. RTK).

Communication – NRTK requires its users to receive corrections via cellular networks. Users who are out of the cellular network's coverage zone would not be able to receive corrections. RTK users receive corrections from the base station via UHF, VHF or other radio links. This means that RTK users; unlike NRTK users; are not dependent on any external entity for base to rover communication. However the baseline length in case of RTK becomes limited and is dependent on the range of radio link. Thus, over large surveying areas, RTK survey becomes challenging.

Quality of Solution – RTK precision is inversely proportional to the baseline length. Increase in baseline length result in decrement in precision and vice versa. NRTK is the solution for the limitation of baseline length. Survey carried out anywhere within the coverage area of the NRTK produces good results. Baselines in NRTK can be range from 50 to 100 km in length. In order to get NRTK's accuracy using RTK, one might have to use more than one base station or may have to set up a new base for every new measurement in order to cover long ranges. Both these techniques are challenging, time taking and cost ineffective, thus they are not that effective as NRTK.

VI. PAK REHBER PRECISE POSITIONING SERVICE

Pak-Rehber Precise Positioning Service is a network of continuously operational reference stations (CORS) that provides GNSS RTK correction data – consisting of carrier phase measurement of GPS, GLONASS and BeiDou – for usage in real time. This data is useful in a number of engineering and geo-spatial arenas like surveying, mapping, asset management, precision agriculture, mining, precise mapping and GIS etc. There are five CORS sites deployed in the outskirts of Karachi. Precision up to centimeter level can be achieved within and peripheral areas of Karachi. Pak Rehber precise positioning service is highly reliable, efficient and easy to use. It offers users a lot of convenience while being highly cost effective. Technical specifications and accuracy are summarized below.

Table 1: Specifications of Pak Rehber Precise Positioning Service

Parameters	**Mode**	**Technical Specifications**	
Service	Navigation	Navigation, GIS information collection and update	
	Position	Mapping & Surveying, cadastral inventory, urban planning, construction, deformation monitoring	
System Accuracy 1σ normal condition	Real-time	Horizontal ≤ 4 cm	Vertical ≤ 10 cm
	Post-processing	Horizontal ≤ 3 mm	Vertical ≤ 10 mm
	Navigation	Horizontal ≤ 2 m	Vertical ≤ 3 m
Note: Accuracy index is based on WGS-84 coordinate system. Terms and conditions apply			

The Master Control Center of Pak Rehber precise positioning network is established in SUPARCO HQs in Karachi where GNSS observation data from CORS sites is received and GNSS corrections are computed in RTCM format at a frequency of 1 Hz. These corrections can only be accessed by authorized users.

VII. EXPERIMENTAL SETUP

This research monitors the deformations produced in BTS Tower which is located in SUPARCO Headquarters and has a cylindrical structure with height of 237 feet and L/D ratio (Length to Diameter Ratio) of 11.54 which is very high. It can sufficiently duplicate the role of a high rise building. Major external loading is wind gust in this case as the tower is located near the coast line.

Pak Rehber Precise Positioning Service can be accessed by RTK enabled GNSS receivers via cellular network. At an altitude of 237 feet above ground level, the GPRS connectivity between the receiver and control server keeps on fluctuating. In other words, the quality of GPRS signals at the top of the tower is not good. Therefore network RTK technique can't be used in this case. This calls for a solution somewhere between RTK and NRTK. This is achieved by setting up the base station at the ground level with the help Pak Rehber Precise Positioning Service. Since NRTK is used to determine the coordinates of the base station, the precision level is in centimeters. The base station communicates with the rover station using UHF and hence the high precision in the base coordinates eventually gets transferred to the rover.

Base Station Setup – The test was conducted on March 17th, 2016. The temperature was 30°C and the wind speed was not less than 19 km/h. Maximum visibility was around 6.1 kms which was favorable for the whole experiment. A GNSS RTK-enabled receiver (Unistrong Hunter) was set up at the ground within SUPARCO Headquarters. The receiver was connected to the Pak-Rehber Precise Positioning Service and control point analysis was performed. In control point analysis, the receiver takes two sets of 10 fixed solutions and then computes the mean to calculate the coordinates. The control point survey produced precise coordinates of the base station receiver. The receiver was then switched to the base mode and the precise coordinates (computed from the control point survey) were fed in it. The base station (let's call it R_B) transmitted carrier phase measurements to the rover over UHF. Precise coordinates of the base station – as measured by the control point survey using Pak Rehber Precise Positioning Service – are as follows:

Table 2: Base Station Coordinates

Latitude	28°56'48.765370"
Longitude	67°08'09.814308"
Altitude	1.6107 m

Following figure shows the base station setting up process.

Figure 2: Base Station Setup

Rover Setup – A GNSS RTK-enabled receiver (Unistrong Hunter) was set up at the top of the tower. The top of the tower offers clear sky visibility.

Figure 3: Rover Setup

This receiver (let's call it R_R) was made to communicate with R_B over UHF. R_R was temporarily fixed on the tower using a tripod in such a way that it remained fixed over a particular point at the tower's roof throughout the experiment. The purpose is to have zero relative motion between R_R and the tower. R_R was left on for almost three hours.

VIII. Observations

Structurally safe limit for deviations in a high rise building is equal to 0.003 radians. But humans can feel the deviations not less than 0.005 radians. So for the building under discussion, the safe limit of horizontal deviation at the top of the building is 21.67 centimeters (0.71 ft). Occupants of this building would not be able to recognize any deviation if the top of the building deflects to any value below 36.12 centimeters (1.18 ft).

The data was collected for a time span of almost three hours. The movement in the north and east direction remained within an envelope of ±1 cm, while the variation in height remained within an envelope of ±2 cm. A few outliers have been observed but the deviation limit is still very acceptable. This means that the tower remained in the safe deformation limits during the test. On breaching the aforementioned threshold values, an alarm can be generated thereby promptly alerting the building crew. These results are very promising and are shown in the following figure:

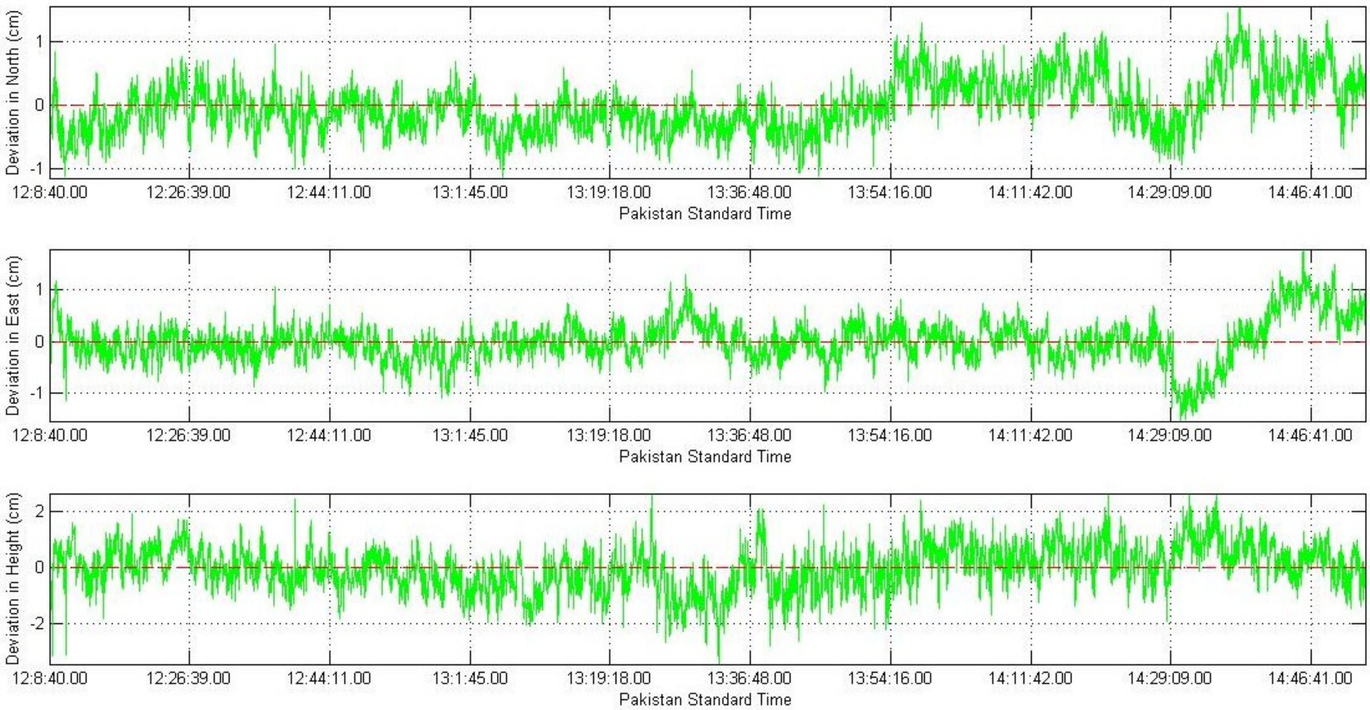

Figure 4: Displacement in North, East and Vertical Direction

IX. Conclusion

Identification and monitoring of deformations – caused by external disturbances such as earth quakes or wind gusts – need to be undertaken constantly and timely because not only can it save precious lives, but it can also help in avoiding financial and environmental damages. Gathering real time and conclusive information regarding structural deformation is compulsory and this can be achieved using GNSS. Conventional surveys and automated sensors lack this capability. Thus, this technology is a huge step forward in the direction of safety of people and infrastructure.

Keeping in view the results of the first RTK deformation monitoring test performed at BTS tower in SUPARCO Headquarters, the detailed time series analysis can be made available for deformation monitoring of other structures that experience high perturbance. Bridges, walls and other engineering structure can utilize the same technology to monitor their respective deformations.

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