Experimental Works on the Use of Kinematic GPS Positioning in Continuous Monitoring Applications

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Abstract
GPS techniques are now being used extensively in many monitoring applications such as engineering structures, landslides and crustal deformation. In most cases, the attainable accuracy of GPS measurements is dependent upon the presence of errors or noises in the measurements. Some of the errors can be eliminated or minimised by differencing techniques, but others require particular attention if a high accuracy result is sought. This paper presents various experiments on kinematic GPS surveys, from which a method to reduce GPS errors has been established. The method is based on transferring the error from one station to another where the two stations are highly correlated. Three GPS stations were involved: the first was located at a known reference station, the second at fixed station near the object being monitored and the third positioned on the object itself. It is the strong correlation between the latter stations that enables corrected co-ordinates to be determined. Results from the tests show that by applying the aforementioned method, the final GPS measurements are more reliable for use with continuous monitoring applications, particularly for structural monitoring. Based on the feasibility study of the kinematic GPS, the responses with tip displacement of 1 cm can be detected by GPS.

Keywords: Continuous Monitoring, Global Positioning System, Correlation and Error Correction.

1.0 Introduction

The Global Positioning System (GPS) is a satellite-based navigation system, which permits users to determine their position in three-dimensional space with a high precision capability. The precision of a few millimetres within a relatively short period of time can be guaranteed to all users through the use of developed techniques in GPS positioning. The principles and techniques of GPS were described in Hofmann-Wellenhof et al, (1997) and Leick (1995). Based on these capabilities, extensive efforts have been made in using GPS for deformation monitoring.

Basically, GPS offers two methods for monitoring applications. These can be described as repeated or episodic monitoring and continuous monitoring. In principle, repeated monitoring was accomplished by performing relative positioning at a certain epoch through static surveying technique. By repeating the measurement, any change in the estimated parameter between successive measurements is interpreted as a measure of geometrical displacement. Conversely, in continuous monitoring, the deformable bodies under study were continuously monitored through the use of two kinematic surveying techniques, i.e. either real time (Real Time Kinematic (RTK)) or post-processing techniques. One of the earliest practical examples of episodic monitoring is to monitor ground vertical movement (Steinberg and Papo, 1988). In this test, the capability of the GPS technique has been combined with conventional surveying technique by forming a mathematical model and adjusted using this combined model. Result show that it is promising in the sense that it can filter out certain errors and is therefore suitable for future application. The use of GPS in the previously mentioned test has been extended to other monitoring application such as dam deformation (Teskey & Porter, 1988), crustal deformation (Kleusberg et. al, 1988 and Hsu, 1996) land subsidence monitoring (Blodgett & Ikehara, 1989), detection of landslide movement (Barbarella et. al, 1989), landslide (Ananga et. al, 1997) and volcanic activity (Abidin et. al, 1998). On the other hand, continuous monitoring activities have included: engineering structures (Ashkenazi, et al 1997, , 1998, Brown et. al, 1999, Lovse et. al, 1995, , Guo and Ge, 1997), landslides (Kondo & Cannon, 1995 and Shimizu et. al, 1996) and crustal deformation (Genrich & Bock, 1992 and Chen 1998). In this research, the continuous GPS monitoring with kinematic post-processing is emphasized.

The attainable accuracy of GPS measurements are very much dependent upon the presence of errors or noises in the measurements. In general, GPS errors can be classified into three major groups, i.e. satellite-based, receiver-based and signal propagation-based. The satellite-based errors are those such as satellite clock and orbital errors. Examples of receiver-based errors are receiver clock, multipath and phase centre variation of the antenna. Finally, signal propagation errors are referred to as atmospheric errors, i.e. tropospheric and ionospheric effects. A detailed description of these errors can be found in many GPS textbooks (see for example Parkinson & Spilker, 1996, Hofmann-Wellenhof et. al, 1997, Strang & Borre, 1997 and Leick, 1995).

The troposphere and ionosphere parts of the atmosphere affect the GPS signal by delaying the time of receipt at the receiver. Trosposheric correction can be determined using different tropospheric models for example Hopfield, Modified Hopfield and Saastamoinen models (Hofmann-Wellenhof et. al, 1997) which are included in the GPS processing software. The ionospheric error on the other hand delays the GPS signal because of the amount of free electrons in ionosphere. This effect is proportional to the total electron content and inversely proportional to the square root of the signal frequency. The total electron content can be measured or estimated, thus one can estimate the ionospheric correction. However, the simplest technique to eliminate this effect is by using a dual frequency receiver i.e. by solving the delay between L1 and L2. For single frequency receivers, ionospheric correction is readily available in the navigation message transmitted by satellites.

Multipath affects the control signal in the receiver tracking loops this introduces an error equivalent to ranging errors. Geometrically, low elevation GPS satellites tend to be more susceptible to multipath interference compared to high elevation satellites due to low incident angle. In fact, Barnes et al, (1998) and Jaldelhag et al, (1996) have successfully demonstrated this effect. Furthermore, the multipath effect occurs on a day-to-day basis because the satellite position (or geometry) repeats daily (Leick, 1995). In addition this effect is temporally or spatially dependent upon the site environment. This repetition allows the removal of multipath effect by taking the difference between day-to-day solutions. This procedure has been shown to be viable for removing multipath effect in a permanent continuous GPS network (Chen, 1998). Although those errors are either removed or cancelled by GPS processing techniques, nevertheless, under certain conditions, there may still be errors present in the solution.

While some of the errors mentioned above can be eliminated or reduced using GPS positioning techniques, others can be ignored because they are not significant. For example, the results from the tests carried out by King et. al, (1995) have proven that for short baselines, the use of improved (precise) satellite orbit does not improve the overall estimate in position. For high accuracy positioning applications, such as monitoring of large engineering structures, the most demanding task is to eliminate these errors. Moreover, it is important to identify and remove features that are clearly not due to displacement and to separate between noise and true movement. In this paper, we will show that certain errors are correlated and lead to the development of a technique to detect and remove common-mode errors, which in turn improves the quality of GPS positioning especially for continuous monitoring applications.

2.0 Practical Works and Analysis

Two tests on kinematic GPS surveys have been carried out in order to achieve the objectives of the study. All the tests were conducted in accordance to different experimental procedures and purposes. A summary of the tests is given in Table 1.

No.	Test
1	Correlation analysis
2	Error Removal Technique

Table 1: Tests Summary

The data were collected with Leica GPS System receivers operating in stationary mode. The SKI Processing software was used to process the with the MATLAB software being used for further data analysis.

2.1 Correlation Test

The objective of this test is to examine the association or correlation between two roving stations in kinematic GPS environment. The correlation is the strength of relationship between two sets of random process measured by a correlation coefficient. It is always a number between -1 and +1. A value of -1 or +1 indicates a perfectly linear relationship**.** The closer the correlation coefficient is to 1.0 (or -1.0 for a negatively correlation), the better the correlation between the two processes. A coefficient of 0.0 means there is no relationship between the two random processes. The correlation coefficient is given by,

$$r = \frac{\sum\left(x-\bar{x}\right)\left(y-\bar{y}\right)}{\sqrt{\left[\sum\left(x-\bar{x}\right)^{2}\sum\left(y-\bar{y}\right)^{2}\right]}} \qquad (1)$$

where *x* and *y* are two sets of random process with mean values of *x* and *y* respectively and *r* lies between or equal –1.0 and +1.0 ($-1.00 \leq r \leq +1.00$).

In relative positioning, the GPS observations are highly correlated due to the similarity of the measurement and the environment associated with the observation. This type of correlation is referred to as physical correlation (Hofmann Wellenhoff et.al, 1997) which can be further classified into temporal and spatial correlation The importance of considering temporal correlation on the accuracy estimation has been investigated by El-Rabbany (1994), Han & Rizos (1995) and Robert and Cross (1993). Schweiger (1996) presented a derivation for the temporal correlation coefficient in GPS processing.

In the present study, spatial correlation based on two rover stations is determined. If one station was fixed at known position, the accuracy will improve by applying correction to the unknown station. As mentioned earlier, GPS errors such as multipath is highly correlated on day-to-day basis. This indicates that differencing the positions of the same stations on two consecutive days can eliminate this error. Nevertheless, for special applications such as the monitoring of large structures, which requires data in near, or real time, a rigorous error removal technique should be sought. This test undertakes an initial task of investigating this new technique by examining the correlation of two stations, which simultaneously observed the GPS satellites.

2.1.1 Test Description

Two tests with baselines of different sizes have been performed. Four stations (Reference, Rover1, Rover2 and Rover3) have been used to observe the GPS signals (see Figure 1). Table 2 outlines each test giving the selection of reference and roving station and baseline length between roving stations.

Test	Reference Station	Rover Station	Baseline Length
Short Baseline	Reference	Rover2-Rover3	1.5 m
Long Baseline	Reference	Rover1-Rover3	3.8 km

Table 2: Test Description

During the tests, GPS satellites above an elevation of 15 degrees have been continuously tracked. Each test session consisted of approximately six hours of tracking with measurements of carrier phase recorded once every 15 seconds.

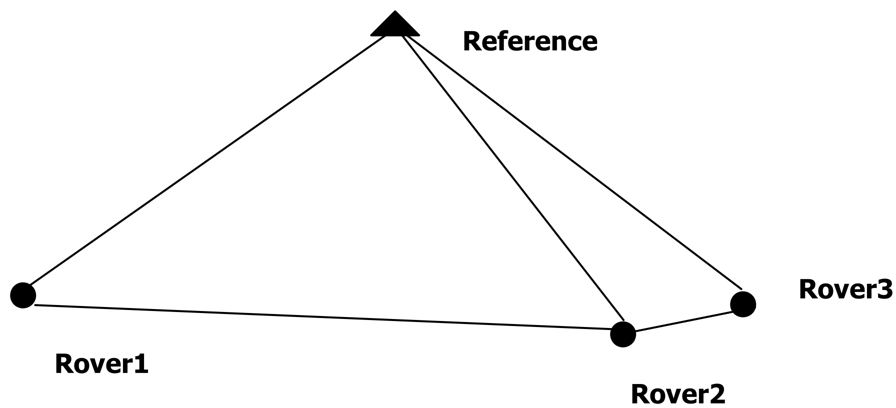

Figure 1: Configuration of Stations

2.1.2 Results

The GPS data processed in kinematic mode yielding time series of co-ordinates at an interval of 15 seconds. To verify the association between stations, correlation coefficients between two sets of measurement were computed. Table 3 presents correlation coefficients (r (from Equation 1)) for both baselines. These results are based on the Easting, Northing and Height components of both roving stations. The results show that for short distance between rovers, the measured components are highly correlated, except for Northing. In general, the results indicate the presence of correlating errors in the measurements. The results are one argument for establishing an error correction technique, which is discussed in the next section.

Baselines	Components		
	Easting	Northing	Height
Short	0.764	0.635	0.831
Long	0.479	0.639	0.542

Table 3: Correlation (r) between Measurements

2.2 Error Removal Analysis

The results achieved from the correlation analysis test mentioned above are the key for further analysis in improving position estimates. Following these results, a technique, which is appears to be viable for removing common-mode errors can be proposed. The technique is based on the application of correction from one roving station to the other roving station, which is simultaneously observing GPS signals. This is only true if the positions of one of the station are known. Then, the difference between the observed and known positions of that station can be written as;

$$c = l_k - l_o \qquad (2)$$

where c is the correction parameter, l_k and l_o are the known and observed positions. The corrected positions for other roving stations can be computed by applying the above correction using the expression,

$$X_c = X_o + c \qquad (3)$$

where X_c and X_o are the observed and corrected positions respectively.

Using the above technique, the root mean square error (RMSE) of the positions from previous test (long baseline) have been computed and shown in Table 4. The RMSE of the residuals (difference between the known positions and the corresponding observed positions) being computed as

$$RMSE = \pm\sqrt{\frac{\sum_{i}^{n}(x_i - x_k)^2}{n}} \qquad (4)$$

where:

x_i = measured positions

x_k = known positions

n = number of epoch

Table 4 shows the RMSE of the positions before and after applying the correction. The positions of Rover1 have been corrected from that of Rover3. From the table, there is almost a 100% improvement of the Rover1 positions using the above technique. In addition, the position (Easting and Northing), vertical (Height) and vector (Easting, Northing and Height) errors of the raw and reduced data sets were computed and shown in Table 5.

Components	RMSE	
	RAW (m)	REDUCED (m)
Easting	0.376	0.069
Northing	0.061	0.014
Height	0.492	0.090

Table 4: RMSE of Rover1 Positions Before and After Applying Corrections

Components	Error	
	RAW (m)	REDUCED (m)
Position	0.381	0.070
Vertical	0.492	0.090
Vector	0.622	0.114

Table 5: Position, Vertical and Vector Errors

The results shown in Table 4 and 5 suggest that the derived procedures can be adopted for removing common mode errors. For this reason, the technique has been used in analysing the results obtained in other simulation tests, which have been executed in conjunction with these tests. The tests involved the construction of a special device, which simulating the movement of the structures (Figure 2). Two stations mentioned earlier in Section 2.1.1 i.e. Reference and Rover1 have been used in this test. For the purpose of this test, the new station (Rover4) of about 30 m from Rover1 has been established. The reference antenna was located at the Reference station. One rover was stationed at Rover1 and the other one on the aforementioned device at Rover4. During the test, GPS data was acquired while translating the moving antenna in the horizontal plane for a specific duration of time.

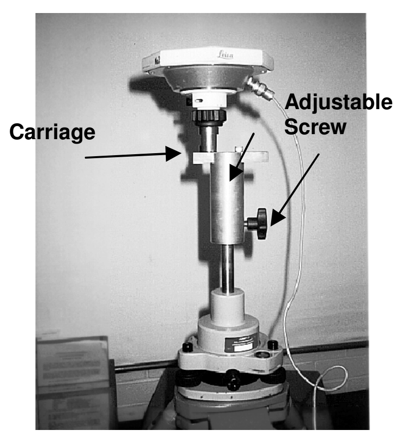

Figure 2: Device for the Test

In this test, the device was located on the moving station with its axis oriented along azimuth angle of approximately 49.445833 degrees. This angle was computed using the raw positions of point before and after translation in horizontal plane. In order to analyse the movements along the translation carriage, the raw positions should be transformed into the new co-ordinates system using the co-ordinates transformation. Positions generated with the SKI Processing software were firstly converted into Rectified Skew Orthomorphic co-ordinates system and finally the converted positions were transformed to a local apparatus co-ordinate system. With this new co-ordinate system, it allows the movement of the carriage to be analysed in longitudinal (along) and lateral (across) directions. Figure 3 illustrates the time series of co-ordinates before and after applying corrections i.e. the corrections from Rover1 to Rover4. The figure also shows the induced translations applied to the device.

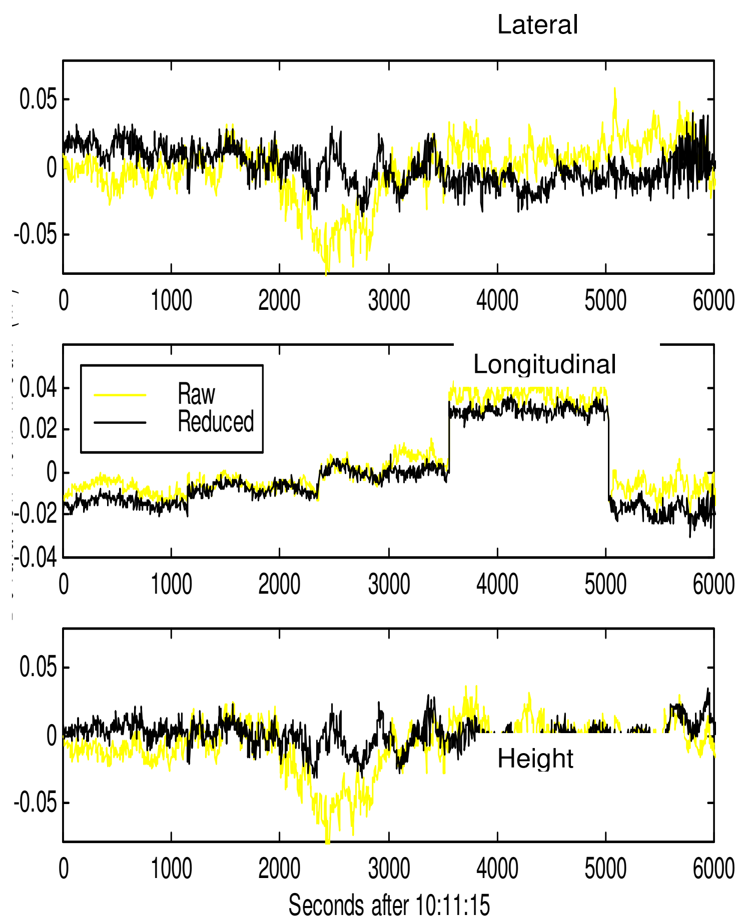

Figure 3: Time Series of Co-ordinates

3.0 Conclusions

The investigation has demonstrated the capability of kinematic GPS surveys for the continuous monitoring such as large engineering structures. A crucial finding in the test is the existence of a correlation between two roving stations in the kinematic GPS surveys. Depending on the baseline length and the components of co-ordinates, correlation coefficients of up to 0.831 has been obtained. Evidently, the error removal technique has been established to treat noise in GPS measurements. The technical feasibility of this technique is illustrated through the test conducted on a special apparatus that simulated movement. The test has demonstrated the power of this technique for the improvement of solution estimates. Results have shown that an increase of almost 100% in position estimates was achieved by applying this technique. The test conducted on the simulation device shows that the responses with tip displacement of 1 cm can be detected by kinematic GPS. This capability can be used for continuous monitoring applications particularly for structural health monitoring purposes.

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