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REAL-TIME BRIDGE DEFLECTION AND VIBRATION MONITORING USING AN INTEGRATED GPS/ACCELEROMETER/PSEUDOLITE SYSTEM

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Abstract

GPS is used for various structural deformation monitoring, both for long-term deformations as well as instantaneous deflections. Due to the inherent deficiency in the GPS satellite geometry, multipath, residual tropospheric delay and cycle slips, GPS alone cannot provide the required positioning precision all the time to meet the requirements for such a system to detect subtle deformations of structures. The Integration of a triaxial accelerometer with the GPS could significantly increase the measurement production and improve the overall system reliability and performance. However, measurements from an accelerometer can only bridge short period positioning gaps caused by the GPS signal outrage. Also, a triaxial accelerometer cannot help the vertical precision improvement, which is normally two to three times worse than the plane precision as claimed.

In this paper, the authors explore the feasibility of introducing pseudolites or Galileo satellites into a previously developed hybrid bridge deformation system consisting of dual frequency GPS receivers and triaxial accelerometers. Data processing is conducted with the real deformation data gathered from two bridge trials to investigate the GPS satellite geometry and its impact on the precise engineering applications. Results from GPS satellite augmented system by pseudolites/Galileo are compared using the simulated data and real GPS/pseudolite based deformation monitoring data. It demonstrates that with such a system, millimeter 3D positioning precision can be maintained for the continuous deformation monitoring.

1. Introduction

A suspension bridge usually characterizes two kinds of distinct deformations, i.e. the long-term movement caused by foundation settlement, bridge deck creep and stress relaxation, and the short-term dynamic motion of the bridge, such as those induced by wind, temperature, tidal current, earthquake, and traffic etc. Unlike the long-term bridge deformation, which is irrecoverable, the latter deformation is called a deflection since the deformable object will recover to its original status with the release of loadings, unless under an extreme loading, permanent damage or deformation is caused.

Conventional instruments and analysis techniques used in bridge deformation monitoring usually have one drawback or another and hence they cannot serve as appropriate tools in monitoring those two kinds of bridge deformations simultaneously.

As an alternative, Global Positioning System (GPS) technology has shown its many merits in deformation monitoring in its earlier development stage over a conventional approach. The advance of GPS technology makes satellite positioning a more reliable and accurate technique. Like any other developing technology, GPS positioning has its defects when it is applied for precise engineering applications. Achievable accuracy of GPS positioning solution is recognized as a major barrier, which is affected by many factors and restraints. For example, GPS positioning accuracy depends on the number of satellites in view and the geometric distribution of satellites. It is very difficult to track enough satellites with well distributed geometry anywhere at anytime. Multipath is still one of the major limitations. Even though many efforts have been made in multipath mitigation, an effective solution is still elusive. Slow sampling rate is another major limitation when GPS positioning is employed to monitor short-term bridge deflections of high frequency vibrations. For a short span bridge the vibration frequency can be higher than 50 Hz (*Roberts et al.*, 2001). Currently maximum available sampling rate of GPS can only be about 20 Hz.

Accelerometers have been used extensively for bridge dynamic monitoring using the force measurements directly. These sensors are used to sense accelerations, and triaxial accelerometers could measure three orthogonal accelerations simultaneously. Compared with other surveying systems such as a surveying total station, triaxial accelerometers have some special advantages when they are used for bridge monitoring. The sampling rate of an accelerometer can reach several hundred Hz or even higher depending upon application requirements, which is a very important characteristic when monitoring a bridge with high dynamics. Triaxial accelerometers are also superior to other sensors since they are not dependent on the propagation of electromagnetic waves, and therefore avoid the problems of signal refraction, line of sight connections to the terrestrial or space objects, and do not have the visibility problems caused by the weather conditions. An accelerometer could form a completely self-contained system, utilizing only measurements of accelerations to infer the positions of the system, through integration based on the laws of motion. However, the drift caused by the instrumental biases and scale factor offsets can develop very fast over time. Hence, accelerometer cannot work alone to drive positioning solutions for a long period. Since the accelerometers are sensible to detect structures vibration with high frequencies, it has difficulty to sense very slow vibration with large deformation amplitudes accurately. In summary, either GPS or accelerometer alone cannot provide deformation monitoring measurements which can be used to detect deformation and extract vibration frequencies of the monitored structures. In his research, *Meng* (2002) presents the advantages of a hybrid system consisting of state of the art dual frequency GPS receivers and triaxial accelerometers. However, the proposed system still cannot fully cope with a long-term GPS signal blockage and augment the GPS satellite geometry. Since the overall system output mainly depends on the quality of GPS measurements, further investigation is need to result in more reliable deformation system.

In this paper, the deficiency of current GPS satellite geometry and its implications for precise deformation monitoring are analyzed. The need in the satellite geometry augmentation with a ground-based pseudo-satellite (pseudolite) or Galileo is emphasized with a simulated and real bridge deformation monitoring data.

2. GPS Satellite Geometry and Its Impact on Precise Engineering Applications

Because of the inclination of the GPS satellite orbits is 55°, simulations indicate that with the current GPS constellation the satellite distribution across the sky in mid and high latitude areas (>45°) is uneven. Observations in the northern sky quadrant (roughly between azimuths 315° and 45°) are only possible for the satellites close to the zenith, or near the horizon (*Santerre*, 1991). In practice, no observations are possible when the cutoff mask is set to 10° to 15° (as is the usual case). There is therefore a lack of the observable signals in the aforementioned areas. Figure 1 indicates the satellite sky distributions with 10° elevation mask for a period of 24 hours at a bridge site over the River Trent in Nottingham, with latitude 52°56′ north. The details about this bridge can be found in *Meng* (2002).

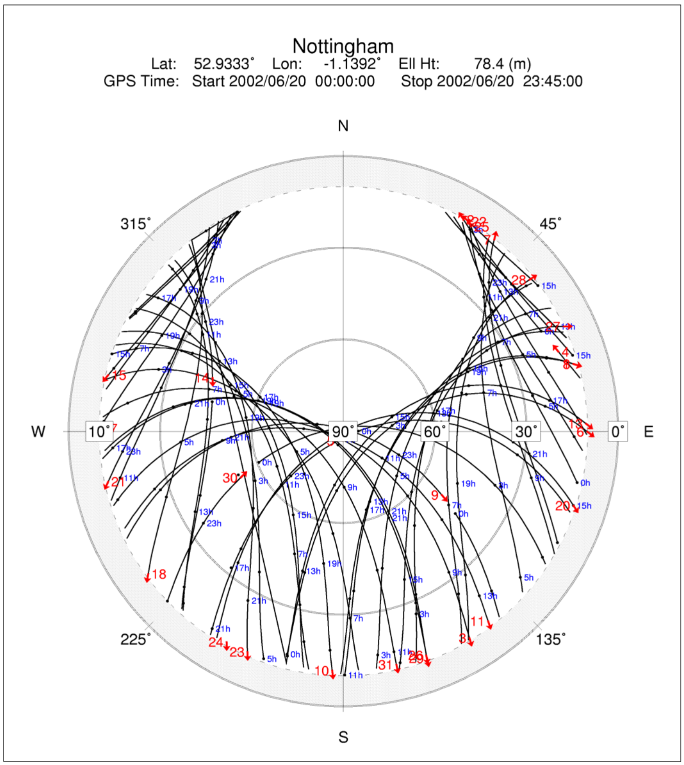

Fig. 1. 24 Hrs Satellite Visibility at Nottingham (20 June 2002)

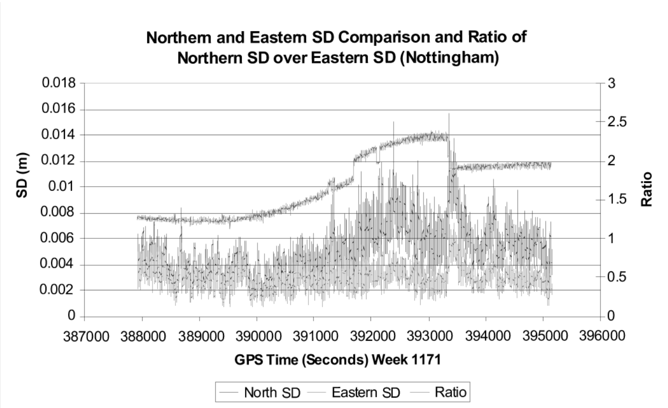

Fig. 2. Uneven SD in Horizontal Plane due to the Satellite

Due to this uneven satellite distribution, the 3D positioning precision at different areas will change according to their site latitudes in the local coordinate systems, which are the main datum frames used for data analyses. The direct impact of this deficiency in satellite orbit design is illustrated by Figure 2, where the northern standard deviation (SD) is worse than the eastern component as the ratio of northern SD over eastern SD is larger than 1. The data used were collected from a bridge trial on 20 June 2002 to Wilford suspension footbridge. The Wilford suspension footbridge is used as a test-bed by the IESSG at The University of Nottingham in the recent years.

Figure 3 is the 24-hour dilution of precision (DOP) value changes in a local coordinate system at similar latitude (50°). It shows that northern SD is worse than eastern SD. As a consequence of this, it will mislead the correct interpretation of deformation data. To calculate DOP values in a local coordinate system, precise ephemeris was used to calculate the DOP values in the WGS84 and then projected into the local coordinates using the formulas derived by *Meng* (2002). Figure 4 shows the 3D relative movements of the Wilford suspension bridge during a two-hour deformation monitoring trial. The coordinates are expressed in a bridge coordinate system (BCS). The main axis of this bridge offsets from northern direction for about 102°. According to the bridge design, the movement in the longitudinal direction should be less than that in the lateral direction since the two ends of the bridge are fixed by the abutments. The lateral wind loading should cause much larger lateral movements than in the longitudinal direction. However, due to the satellite geometry it seems that longitudinal direction experienced larger relative movements. Figure 5 is the 3D relative movements again in the BCS for a suspension footbridge over the River Thames in London. The main axis of this bridge faces exactly to the northern direction. Due to the satellite geometry effects, the longitudinal movements (northern direction in Figure 5) were much larger than lateral (eastern direction). It is apparent that the conclusions made based on these results will cause confused understanding to the real bridge deformation.

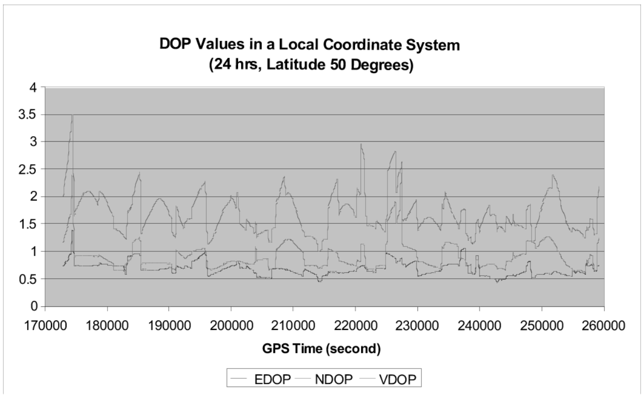

Fig. 3. 24 Hrs DOP Value Changes in a Local Coordinate System (Latitude: 50_)

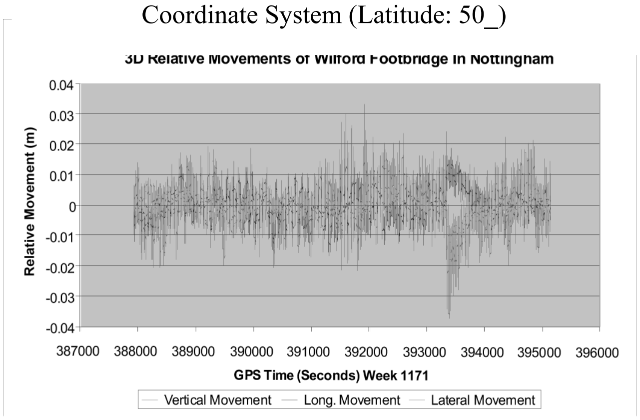

Fig. 4. 3D Relative Movements of Wilford Suspension Bridge in Nottingham

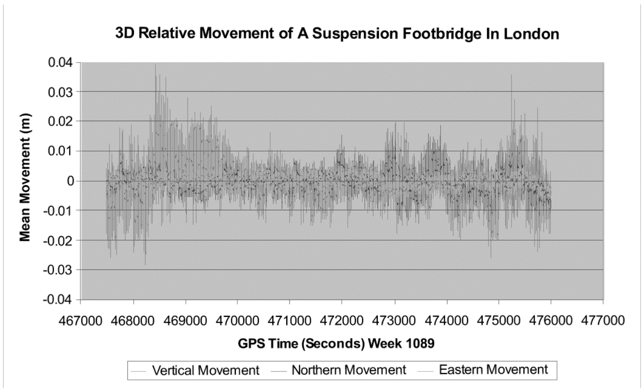

Fig. 5. 3D Relative Movements of a Suspension Bridge in London

This problem cannot be remedied by a hybrid system consisting of GPS receivers and triaxial accelerometers. The possible solution to this geometry deficiency is to augment GPS satellite with ground-based pseudolite, or by Galileo.

3. GPS Satellite Augmentation by Pseudolites/Galileo

Pseudolites transmit GPS-like signals, and are ideal for the deformation monitoring of a static or semi-static structure with limited movements such as a bridge. Pseudolite based deformation monitoring has been investigated by *Dai et al.* (2000). The effects of additional pseudolite signals on the ambiguity resolution and the improvement in the positioning accuracy have been investigated by the authors. The authors demonstrated that the accuracy of the height component can be improved to the same level as the horizontal components with appropriately located pseudolites.

Using the actual GPS satellite ephemeris for a time period demonstrated in Section 2 on 20 June 2002 when a GPS/accelerometer-based trial was conducted on the Wilford suspension bridge, the real locations of three pseudolites which were used in another bridge trial with pseudolites, a modified ephemeris was created with a simulator developed at the IESSG. This simulator is specially developed to investigate the satellite geometry and its augmentation with other systems, such as pseudolites and Galileo system. The DOP values are then estimated following the procedure as described by *Meng et al.* (2002) and compared with the DOP values associated with GPS-only solutions.

Figure 6 shows the actual layout of a GPS/pseudolite receiver and the locations of three pseudolites on 16 October 2002. Taking into account the actual GPS satellite geometry (only the geometry in the northern direction needs to be strengthened), as well as the topography of the area, several sites were chosen for the three pseudolites. PL1 was setup on the western embankment of the river, PL2 was setup on the eastern bank, and PL3 was also located on the eastern side. Table 1 lists azimuths, elevation angles and distances to these three pseudolite sites, using the rover site as the origin. In principle, there is no difference between GPS satellites and pseudolites having positive elevation angles when there is uniform GPS satellite geometry such as in low latitude areas. However, in mid- and high latitude areas, pseudolites installed on the northern side of receiver sites with positive and negative elevation angles will enhance geometry for the purpose of precise positioning.

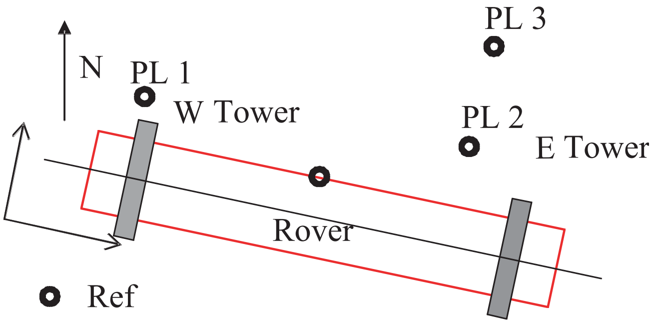

Fig. 6. Pseudolite and Receiver Layout for a Bridge Trial (Wilford suspension bridge)

Figure 7 is the comparison of the northern DOP values from the GPS alone solution and the pseudolite augmented result. The cutoff mask was set to 15 degrees. Since there were only four satellites available for a period time of fifteen minutes, the NDOP value rose to 15 and forced the accuracy to degrade to 4 cm. With the augmentation from three pseudolites, significant improvements in NDOP are evident, where the NDOP being less than 2 and the positioning precision better than 5 millimetres. Maximum NDOP value improvement of 8 times can be achieved in this case and also the positioning precision.

Table 1. Parameter of Three PLs

	Elevation (degrees)	Azimuth (degrees)	Distance (m)
PL1	-7.5	312.4	43.833
PL2	-4.2	71.4	59.866
PL3	-3.1	52.6	82.121

Since the geometry in the South-East direction is strong enough for positioning already, there are no big changes in the associated values for the east coordinate component (Figure 8).

As anticipated, such a temporary blockage in the satellite availability resulted in very bad vertical positioning solutions, where VDOP degraded to 27 and the vertical accuracy to 7 cm (as illustrated in Figure 9). Figure 9 also shows the significant improvements in VDOP, and hence the positioning accuracy, by inclusion of the extra signals transmitted from below the horizon.

Using the pseudolites set up at three sites close to the Wilford suspension bridge, GPS and pseudolites based bridge trial was conducted on 16 October 2002 to test the feasibility of the proposed system.

Two Canadian Marconi Allstar single-frequency GPS receivers were used as the reference station (Ref in Figure 6) and the rover on the midspan of the bridge (Rover in Figure 6). This type of GPS receivers can track GPS and pseudolite signals. Connected to two Leica AT502 antennas at the reference and rover stations (with signal splitters) are two Leica dual-frequency SR530 GPS receivers logging only the GPS measurements at the same time as the Allstar receivers were logging both the GPS and pseudolite measurements. The sampling rate for both types of receivers was set to 1 Hz. It is worth pointing out that this sampling rate is not fast enough to detect the bridge vibration in this feasibility test stage. This trial was aimed as a prototype for investigating system feasibility.

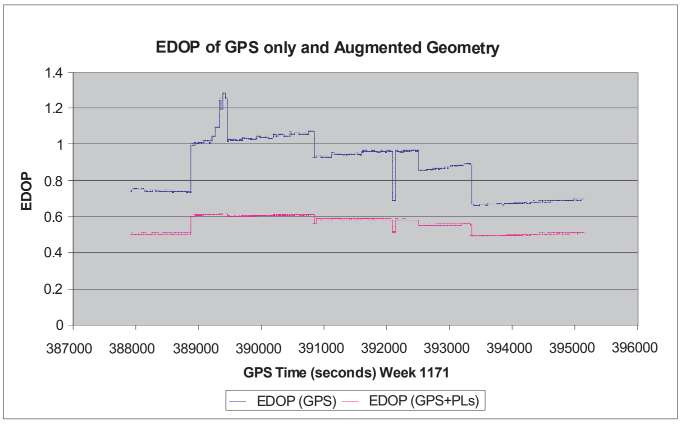

Fig. 7. EDOP Comparison of GPS only and Augmented System

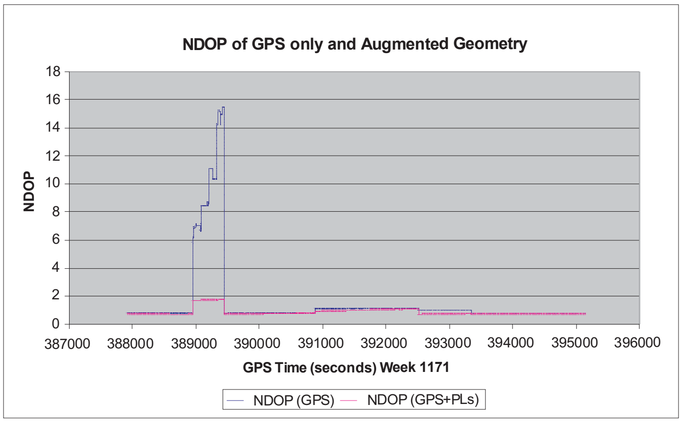

Fig. 8. NDOP Comparison of GPS only and Augmented System

The data from the dual-frequency receivers were post-processed. The integer ambiguity fixed coordinates were then used as the initial known coordinates for processing the GPS and pseudolite measurements from the single frequency receivers. The software employed for processing GPS and pseudolite measurements was developed by the researchers from the University of New South Wales in Australia. The derived coordinates in the WGS84 datum were then converted to OSGB36 coordinates, the UK datum. The following analysis is conducted in the local coordinate system.

Figures 10, 11 and 12 are the comparison of the coordinate pairs of the GPS-only solutions with the GPS/pseudolite solutions. The coordinate pairs were obtained by processing the measurements from Allstar single-frequency receivers through selecting and deselecting three PLs.

Data processing reveals that 39% precision improvement in the east coordinate and 33% precision improvement in the vertical component were found when three pseudolites were included in the data processing. However, there was 8% precision reduction in the north coordinate when three pseudolites with negative elevation angles are employed. The reason could be related to error propagation scheme and explained by *Meng et al.* (2002), bearing in mind that the positioning accuracy is a function of the DOP value and the ranging accuracy. The latter is affected by multipath and receiver noise, inaccurate location coordinates of the transmitters and other un-modelled errors. While three pseudolites were setup below the horizon, the apparent improvement should be anticipated as being in the vertical direction and east coordinate component according, which are true (see Figures 11 and 12). To improve the positioning accuracy in the north direction, pseudolites should be installed at locations with positive elevation angles on the northern side of the rover sites. However, at this particular bridge site, it is impossible to locate pseudolites with positive elevation angles on the north side and close to the bridge. Further effort will be made to find suitable sites for the pseudolites.

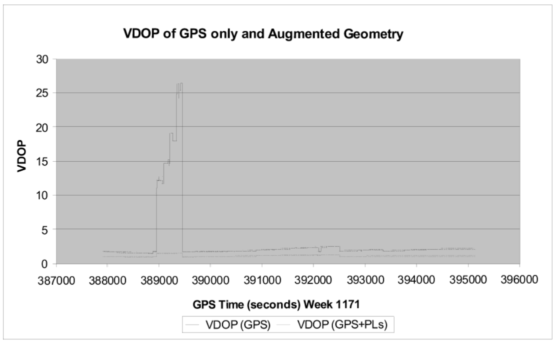

Fig. 9. VDOP Comparison of GPS only and Augmented System

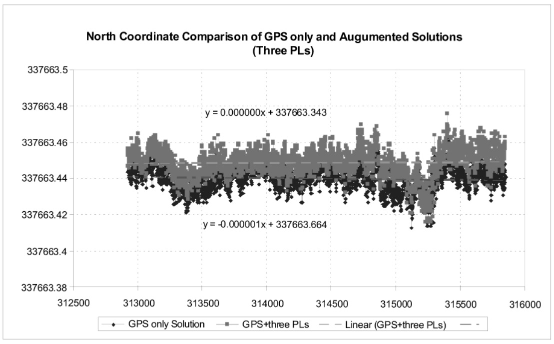

Fig. 10. North Coordinate Comparison

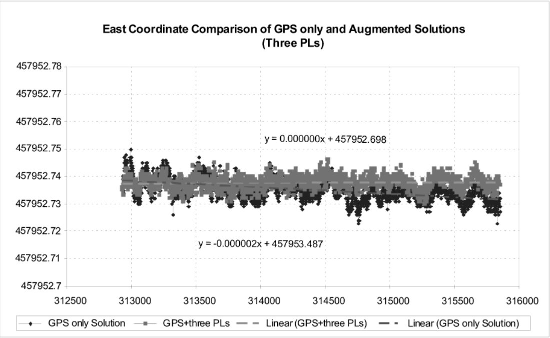

Fig. 11. East Coordinate Comparison

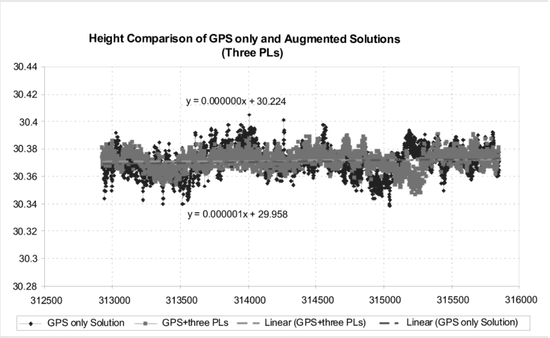

Fig. 10. North Coordinate Comparison

Further research has been carried out to investigate the relationship of the plane DOP according to the geographical locations. Precise GPS ephemeris is used as the input to the simulator to calculate EDOP and NDOP values. The cutoff angle was set to 10° in all simulations. The worst DOP within 24 hours is shown by Figure 13. Results show that there are problems for positioning in the areas with latitudes between 60° and 70°, where the worst NDOP can reach 37 and VDOP 124.

Galileo orbit has been created according to its design specifications using Keplerian orbital parameters (*Benedicto et al.*, 2000). The modified ephemeris including GPS and Galileo satellites was then created by the developed simulator. The detailed description of the simulator will be available in future papers. Figure 14 shows the EDOP and NDOP results. Significant improvements are also evident both for HDOP and VDOP (see Figure 15).

In the hybrid deformation monitoring system, the final coordinates largely depends on the quality of GPS/pseudolite/Galileo measurements and derived coordinates. Using these high quality coordinates, further data fusion can help mitigate multipath and other satellite borne errors.

4. Data Fusion

The Adaptive filtering (AF) technique was used to integrate the data from GPS based positioning solutions and the positioning solutions from a triaxial accelerometer by double integrals. For the principles of AF approach readers can be directed to *Dodson et al.* (2001). Time series one in the Figure 16 is the vertical movement of Wilford suspension bridge after multipath mitigation proposed by *Meng* (2002). Time series two in this graph is the relative displacement calculated by the acceleration double integrals. The third row is the random noise output of the GPS receiver and the fourth row is the common part of two input time series to the AF system (row one and row two). It is apparent that after the AF procedure, the clear movement pattern caused by the forced movement is evident.

Using the positioning solution as the desired signal to an AF system obtained by the augmented satellite systems, either GPS plus pseudolite, or GPS plus Galileo, uniform highly precise 3D positioning solutions can be achieved since the dada fusion procedure with the solution from an accelerometer can further reduce receiver random noise and residual multipath. Software development for this purpose is underway at the IESSG. Further trials will be conducted to test the developed concepts and software.

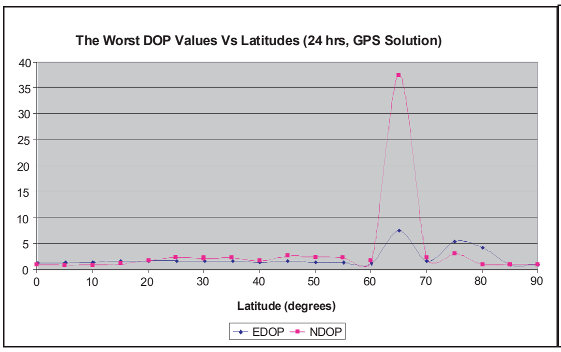

Fig. 13. The Worst Plane DOP Values from the Equator to the North Pole

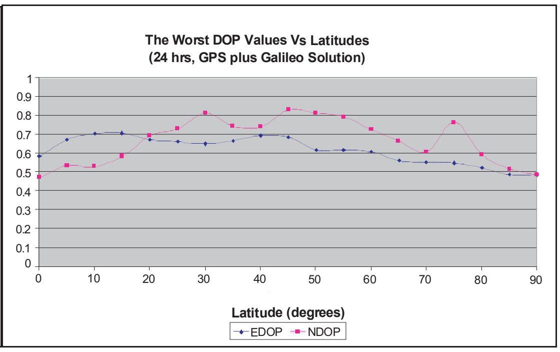

Fig. 14. The Plane DOP Values from a GPS/Galileo System

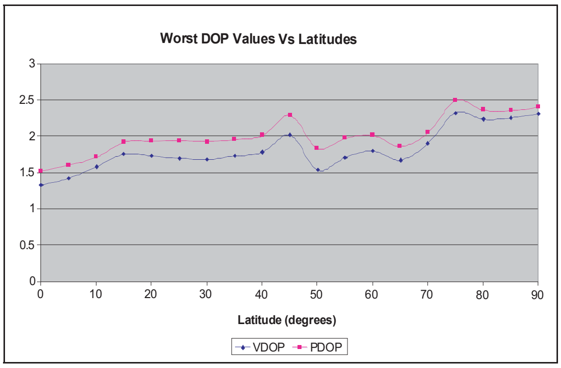

Fig. 15. HDOP and VDOP from a GPS/Galileo

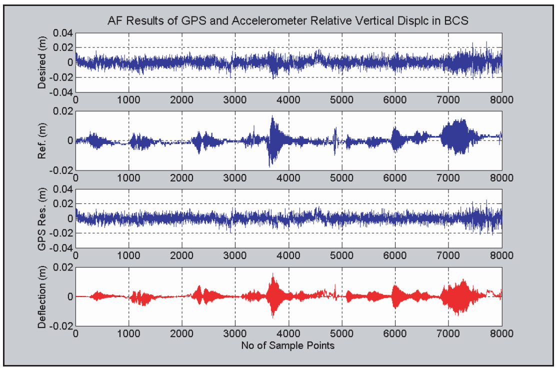

Fig. 16. GPS Data Fusion with Accelerometer Data

5. Conclusions

In this paper, the authors discuss the deficiencies of the sensor systems used for precise structural deformation monitoring. The previous proposed sensor system consisting of dual frequency GPS receivers and triaxial accelerometer is further augmented with ground based pseudolites. Simulated results are compared with positioning solution from a real GPS/pseudolite based bridge deformation trial. About 40% positioning precision improvements are evident for both eastern and vertical coordinates. The reason for the precision reduction in northern coordinate is analyzed. The research reveals with an appropriate layout of pseudolites it is possible to achieve mm level 3D positioning precision for continuous structural deformation monitoring. The functionality allocations of different sensor and possible scheme for a hybrid system comprising GPS, pseudolite and accelerometers are proposed. Also the future Galileo for deformation monitoring is investigated with the simulation tool. With the launch of future Galileo, a robust deformation system will become possible for anytime and anywhere.

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