The Use of Single Frequency GPS to Measure the Deformations and Deflections of Structures

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Keywords:

SUMMARY

The Institute of Engineering Surveying and Space Geodesy (IESSG) at the University of Nottingham has been involved in deformation monitoring of structures for many years. This includes the use of terrestrial surveying equipment as well as GPS. In addition, for about 10 years the IESSG has been researching methods of allowing GPS to aid the deflection monitoring of structures. Structures not only exhibit long term deformation characteristics, but also short term deflections. The characteristics of such deflections are important to enable engineers to calculate and evaluate the health of such structures.

Currently, the IESSG is working in collaboration with Cranfield University, researching into the development of a technique based on integrating kinematic GPS integrated with accelerometers and pseudolites.

The following paper discusses an integrated approach using GPS accelerometers and pseudolites, as well as showing some of the results obtained. Trials are underway in Nottingham to evaluate the approach, both in a controlled environment as well as on a bridge.

The results show that the integrated approach has many advantages over GPS alone, and can gather data at a very high rate. The results obtained are of both the magnitude of the deflections as well as the frequencies, both of which are important in obtaining knowledge about the health of the structure.

The Use of Single Frequency GPS to Measure the Deformations and Deflections of Structures

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1. INTRODUCTION

Research at the University of Nottingham (UoN) into bridge monitoring with GPS has been underway for almost 10 years and dual frequency receivers have been used with good results (Ashkenazi, et al. 1996; Roberts, et al. 1999a; Roberts, et al. 2001b). The kinematic work started on the Humber Bridge in the north-east of England. The first experiments were conducted with Ashtech ZXII receivers measuring at 2 Hz and later receivers measuring at 5 Hz were used.

The work led to collaboration with colleagues at Brunel University, who had been previously commissioned by the Humber Bridge Board to provide a Finite Element Model (FEM) of the bridge. The FEM was to be used as a tool to assess whether the Bridge was safe to operate following any incidents, for example a car crash. The Humber Bridge Board needed the FEM to be evaluated and updated using real data, and so the two universities were brought together.

Various trials were conducted on this bridge, including one where 5 fully laden lorries were driven across the bridge in unison. The movements recorded by GPS were compared to those from the FEM with good results, showing that GPS could not only be used to measure the deflections of such structures, but also could determine the frequencies at which they move (Roberts, et al. 1999b). The bridge's first fundamental frequency was found to be 0.116 Hz by the GPS data, which compared extremely well with the value found by the FEM (Brown, et al. 1999). Further bridge trials were conducted on the Humber Bridge and trials were also conducted on the Millennium Bridge in London.

The UoN in collaboration with Cranfield University (CU) is currently undertaking a project entitled "A Remote Bridge Health Monitoring System Using Computational Simulation and GPS Sensor Data". In addition to the two universities the project also involves collaboration from Network Rail, Leica Geosystems and WS Atkins. The research goal is for a pilot remote condition monitoring system for bridges and other structures to be developed to provide health information in real-time. This is achieved by bringing together complementary research of FEM study conducted by CU and GPS monitoring work conducted by UoN.

CU's research has included the construction of a FEM capable of accurately replicating the behaviour of the test structure using the SAFESA^{TM} method and researching approaches for optimal sensor location (Meng, et al. 2003a).

The research by the UoN so far has involved integrating data from GPS and accelerometers to mitigate the errors of both systems, and increase the sampling rate compared to a GPS only solution (Roberts, et al. 2001a); using GPS and pseudolites to overcome problems with GPS satellite sky geometry (Meng, et al. 2003b); the development of adaptive filtering algorithms to mitigate multipath and integrate the position solutions from GPS and accelerometers (Dodson, et al. 2001); and also the use of single frequency GPS instead of more expensive dual frequency receivers (Cosser, et al. 2003).

This paper outlines the problems with single frequency integer ambiguity resolution in addition to a method to accelerate this in the context of measuring deflections on a bridge. The precisions achievable using single and dual frequency receivers are demonstrated as well as the method of adaptive filtering which can be used to mitigate multipath and hence improve the precision of the solution. Adaptive filtering is also used to integrate the position solutions from GPS with those from an accelerometer, which can improve the precision of the solution and increase the sampling rate. Satellite geometry issues are covered and the use of pseudolites as a means of overcoming these problems discussed. Finally the development of the FEM of the Wilford Bridge is briefly discussed and values are compared with results from real bridge monitoring data.

2. SINGLE FREQUENCY GPS

One of the specified aims of the current project is the use of single frequency receivers which typically cost about half as much as dual frequency receivers. Single frequency receivers have the obvious weakness that it takes longer to resolve integer ambiguities in an On The Fly (OTF) manner at the beginning of an observation session and after a cycle slip, compared to dual frequency receivers. Typically for single frequency receivers it can take anything up to 30 minutes (Sharpe 1999), whereas for dual frequency receiver this is reduced to under a minute in most cases. Some processing software does not even attempt to resolve integer ambiguities OTF for single frequency receivers. This is one of the reasons that the in-house software Kinpos, developed by the UoN, has been adapted to process single frequency data in an OTF manner and also using the information that the bridge site is semi-static to resolve ambiguities. A series of trials have been conducted, Figure 1, in order to investigate the use of GPS for such monitoring.

Figure 1 The two riverside reference stations with the Wilford Bridge in the background

It has been shown by Cosser, et al. (2003) that in the context of bridge monitoring, once the integer ambiguities have been resolved, single frequency receivers produce results that are as good and in some cases better than dual frequency receivers. The results showed that the 'best' solution when taking into account accuracy and cost was to have a dual frequency receiver as the reference station located close to the bridge, while the rovers on the bridge are single frequency.

Good results were achieved with a stop and go method of initialisation. However, there was one major problem, when the integer ambiguities were lost due to a cycle slip or a loss of lock, no further attempt was made to resolve the ambiguities again. The only option in this case would be to have another static initialisation, which would mean there would be an ‘outage’ of coordinates while integer ambiguity resolution was achieved.

Kinpos is GPS processing software developed at the IESSG to process dual frequency GPS data. Recently the software was adapted and it can now process single frequency data OTF. It takes between 11 and 15 minutes to resolve ambiguities in this manner compared to around 1 epoch for dual frequency data. If a cycle slip or loss of lock occurs it then takes a further 11 to 15 minutes to resolve the integer ambiguities again, and so coordinate ‘outages’ also occur with this software as it re-resolves integer ambiguities in an OTF mode. For the data from the May bridge trial outlined above there are periods of particular interest, due to the amount of activity on the bridge, where there is no ambiguity resolution for the single frequency receivers due to cycle slip. In this case the data is not accurate enough to draw any conclusions about the bridge movement during the period of interest.

Kinpos has therefore been further adapted to solve the problems with single frequency ambiguity resolution discussed above. A different method of ambiguity resolution which can be used in the context of bridge deformation monitoring based on a known average coordinate has been developed. Detailed explanation of the software and ambiguity resolution techniques will be the subject of future papers and is not discussed here. Using the method single frequency ambiguities can be resolved instantly and deformation data is made available for the whole of the observation period.

3. PRECISION ATTAINABLE

To compare the performance of single and dual frequency receivers, data from a bridge trial was processed in a number of different ways in Kinpos. This data was first processed as single frequency and then as dual frequency using L1 data only for positioning solutions. The results of the precision attained are given in Table 1. It can be seen from this Table that the results for the single and dual frequency processing are comparable with each other. No significant difference can be distinguished from the Table. The worst component in these cases is height, as expected, with a standard deviation of about 12mm.

Table 1 The standard deviations of the north, east and vertical components for the trials conducted on 15th May, 2003.

	Standard Deviations (m)		
	East	North	Height
Single Frequency	0.0054	0.0076	0.0120
Dual Frequency	0.0053	0.0077	0.0118

Figure 2 shows the relative vertical positions for the bridge trial data on the 15th May, 2003. It can be seen from this Figure that there is movement present in the data which could be attributed to multipath and means that it is difficult to identify real bridge movement. Bridge trial data from the 14th May were processed and the relative vertical positions for this data can be seen in Figure 3. Comparing Figure 2 and Figure 3 it can be seen that similar patterns can be identified within the two data sets and so these patterns are likely to be multipath.

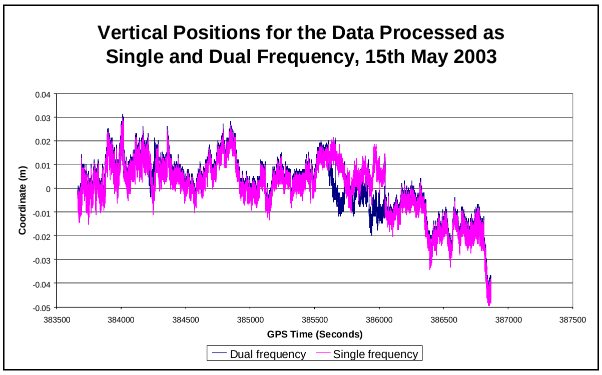


Figure 2 The relative vertical positions for the data processed as single and dual frequency from the bridge trial on the 15th May, 2003

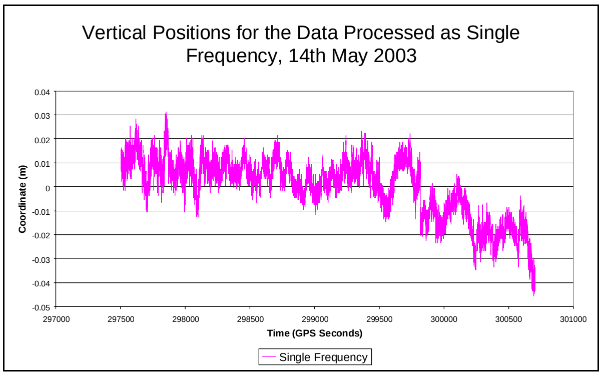


Figure 3 The relative vertical positions for the data processed as single frequency from the bridge trial on 14th May, 2003

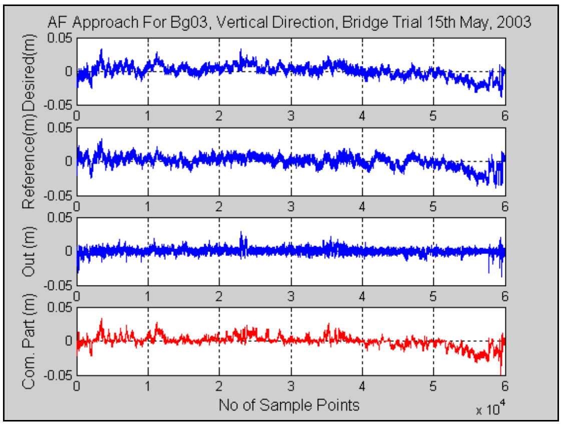


Figure 4 Vertical AF for two days time series for the data processed as single frequency. The desired signal is the coordinates from the 15th May, the reference signal is the coordinates from the 14th May,

the output signal is the bridge movement (plus receiver random noise) and the common part is the multipath signature.

Using adaptive filtering (AF) the multipath can be removed by comparison of the two days' data. The principle of AF and the Matlab script used for processing are introduced in Dodson, et al. (2001). The fundamental idea of this method of multipath mitigation is that the GPS constellation repeats daily but shifted by about 4 minutes due to the difference between sidereal time and Universal Time (Hofmann-Wellenhof, et al. 2001). Due to this repeatability, the multipath at static or semi-static sites should be the same on two consecutive days. Using this information the multipath can be extracted from the signal leaving behind the real bridge movement. In this example the desired signal is the time series from the 15th May, while the reference signal is the times series from the 14th May at the same location. These two signals are offset by 4 minutes. The results of AF for the vertical component can be seen in Figure 4 for the data processed as single frequency. The multipath signature is obvious in both days' data and it can be seen that AF removes this signature leaving behind bridge movement plus receiver random noise.

The cross-correlation levels of certain components are calculated to further verify the success of AF. Of particular interest are the correlations between the output signal and the common part and also the output signal and the reference signal, as both these correlations should be close to zero for successful AF. It was found that the correlation between the reference signal and the output signal was -0.0059 and between the output signal and the common part it was 0.0018. Both of these are small and so showed that there was only very slight correlation between these components. The correlation between the desired signal and the reference was found to be 0.7200, as they shared a common part which was the multipath, but the bridge movement in each case should be different. The desired signal's correlation with the output signal was 0.4202 and with the common part 0.9049, which shows that more of the desired signal was made up of the multipath than the bridge movement. All these results demonstrated that the AF was successful in this case.

After adaptive filtering the multipath has been removed. The standard deviation for the single frequency data in the vertical component has been reduced to 0.0053 metres which is a decrease of more than half. From the cleaned data real bridge movement can be detected.

4. GPS INTEGRATED WITH ACCELEROMETERS

To increase the sampling rate compared to a GPS only solution and also improve the positioning accuracy, a hybrid system of GPS receivers and accelerometers has been proposed by researchers at the UoN. The algorithms and data processing procedures can be found in Meng (2002). GPS has the major limitations of a slow sampling rate and multipath. Accelerometers can measure at high frequencies but have difficulty sensing very slow vibrations. Also, accelerometers have scale factor offsets and a drift caused by instrumental biases which increases over time. The proposed hybrid system can be used to overcome the biases of each individual system.

AF is also used to integrate data from GPS positions (after multipath has been removed) with positioning solutions from a triaxial accelerometer. The accelerometer data is integrated twice with respect to time to obtain displacement. The first time series in Figure 5 is the vertical GPS positions after multipath has been mitigated as described above. The second time series in this graph is the displacements from the accelerometer after the acceleration data has been integrated twice. The third row shows the random noise of the GPS receiver and the fourth row is the common part of the two input time series, which is the displacement sensed by the two kinds of sensors. This data is taken from a Wilford Bridge trial that was conducted in June, 2002. After this AF clear patterns of movement can be seen in the output signal, corresponding to periods where there was a large amount of activity on the bridge.

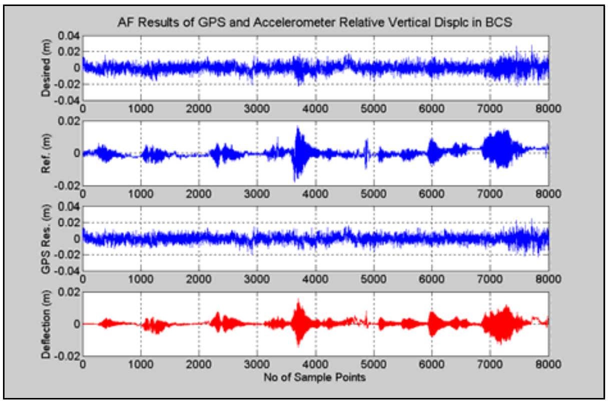


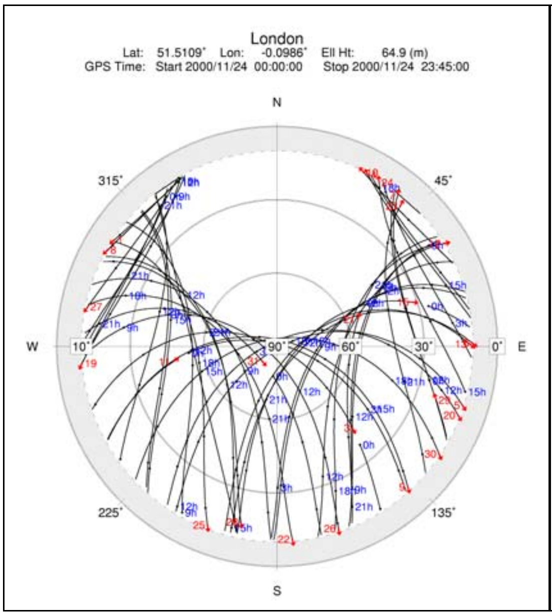
Figure 5 Vertical AF of GPS and accelerometer data from bridge trial on 20th June, 2002. The desired signal is the GPS positions (after multipath mitigation); the reference signal is the accelerometer positions; the third line is the GPS receiver random noise; and fourth line is the bridge deflections, the common part of both systems.

5. GPS SATELLITE CONSTELLATION AND ITS IMPLICATIONS FOR PRECISE ENGINEERING APPLICATIONS

Since the inclination of the GPS satellite orbits is 55°, simulation results 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 satellites close to the zenith, or near the horizon. In practice, no observations are possible when the cut-off mask is set to 10° or 15° (as is the usual case). There is therefore a lack of observable signals in the aforementioned areas, which leads to precision degradation in the north-south component in particular.

Figure 6 and Figure 7 depict the satellite sky distributions with 10° elevation mask for a period of 24 hours at two observed bridge sites in London and Nottingham, with latitude 51°30′ north and 52°56′ north respectively. In practice, to preclude the high level of errors caused by the propagation medium near the Earth’s surface and potential signal blockage by the surroundings, the elevation cut-off angle in both GPS trials was set to 10°. This excludes the possibility of tracking lower satellites in the northern quadrant. As a consequence, a big *immeasurable hole* is present. Such a satellite sky distribution results in poor DOP values and undoubtedly will lead to degradation in positioning accuracy even with good ranging accuracy.

The deficiency of GPS satellite geometry and its impact on the precise positioning for engineering applications are investigated using a simulation technique (Dodson *et al*, 2003). The precise ephemeris is used as the input file to the simulator and the user location and cutoff mask as the simulation parameters. The output from this simulator is a dilution of precision (DOP) file expressed in a local coordinate system, i.e. eastern DOP (EDOP), northern DOP (NDOP) and vertical DOP (VDOP), horizontal DOP (HDOP), etc. As the amplifiers, DOP values can be used to predict the obtainable positioning precision in three dimensions. The ratio between different axes in the local coordinate system can help the interpretation of the results. For example, in high latitude areas, the NDOP is larger than EDOP and this means a worse positioning solution in the northern coordinate than the eastern component. The horizontal positioning precision can even degrade to the same level as the vertical component at some times on the daily basis [*Meng et al.*, 2002a].



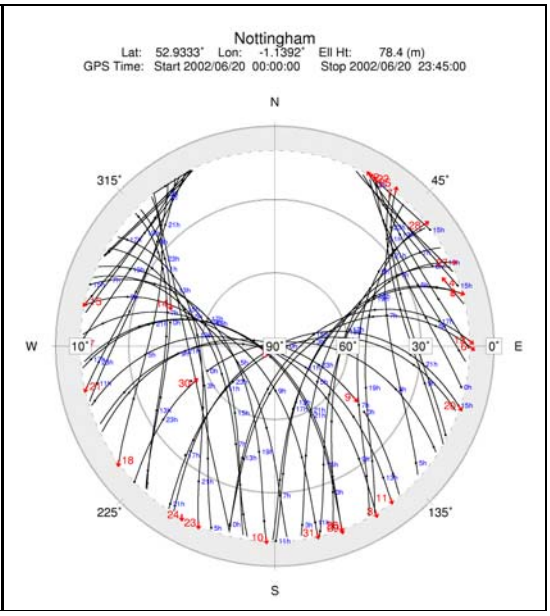


Figure 6 The Satellite Sky Plot at the Bridge Site in London on 24th November, 2000 (24 hours)

Figure 7 The Satellite Sky Plot at the Wilford Suspension Footbridge in Nottingham on 20th

	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

Table 2 Elevation, Azimuth and Distance to the Pseudolites from the Rover Site on the Bridge

The elevation and azimuth of each pseudolite were input into the simulator. Real GPS and pseudolite geometry is created and the DOP values are estimated. Also using the actual and simulated DOP values as well as the standard deviations (SD) in the GPS data processing, the augmented SD values with GPS/pseudolites constellation can be estimated.

Figures 8, 9 and 10 show the results of the actual and augmented SD values with the introduction of three pseudolites into GPS constellation. It can be seen from these figures that with the augmentation of pseudolites the positioning precision in 3D can reach millimetre level. The poor precision gaps for about 15 minutes in the northern and vertical coordinates caused by only four satellites being visible, are bridged by the augmented system. Significant improvements are achieved mainly in the eastern and vertical directions with these three pseudolites set up below the horizon of the rover station. However, except for the gap being bridged by augmented system, no other improvements can be expected in the northern direction, which is identical with the simulated results by *Meng et al.* [2002b]. As a general rule in the selection of pseudolite locations, pseudolites installed below the horizon of the rover station can be used to improve EDOP and VDOP, and pseudolites installed above the horizon can help improve NDOP [*Meng*, 2002]. Since the positioning accuracy is a function of DOP value and the measurement accuracy. Good DOP value cannot necessary guarantee a good positioning accuracy. Sometimes, a compromise should be made to achieve an optimal positioning accuracy. This will be discussed in the following examples with the real deformation data.

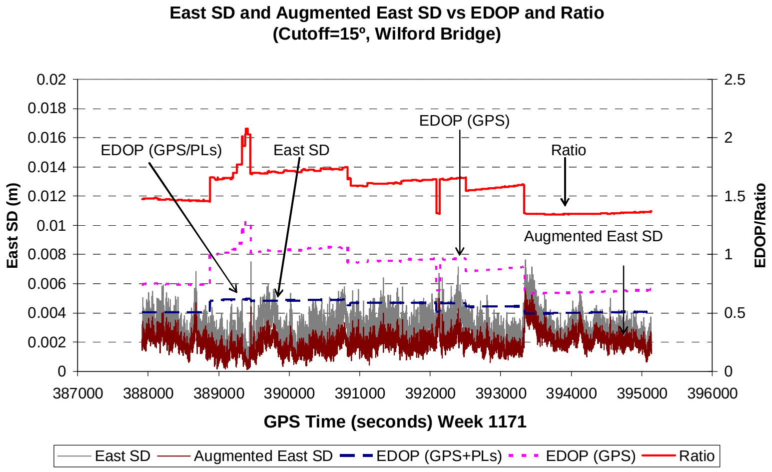


Figure 8 East SD Comparison with and with Pseudolite Augmentation

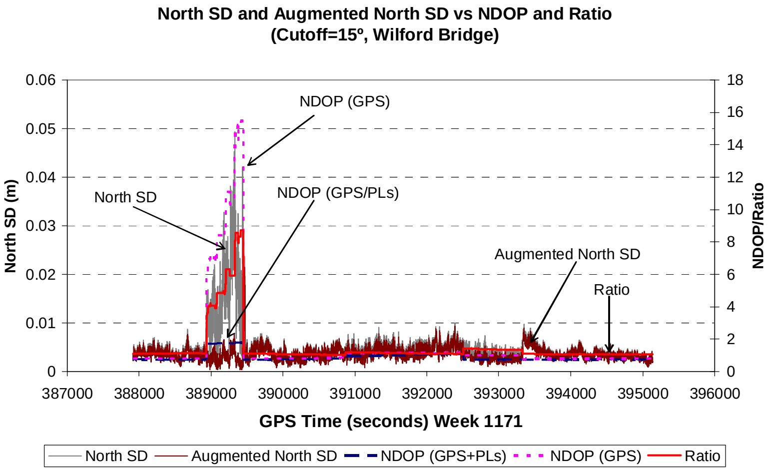


Figure 9 North SD Comparison with and with Pseudolite Augmentation

On 16 October 2002, a bridge trial was conducted. Two Canadian Marconi Allstar single-frequency GPS/pseudolite receivers were used as the reference and rover on the midspan of the bridge. This type of GPS receivers can track both GPS and pseudolite signals. Connected to two Leica AT502 antennas at the reference and rover stations via two 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 vibration of Wilford suspension footbridge which has a first natural frequency 1.75Hz. This trial was aimed at investigating the system feasibility.

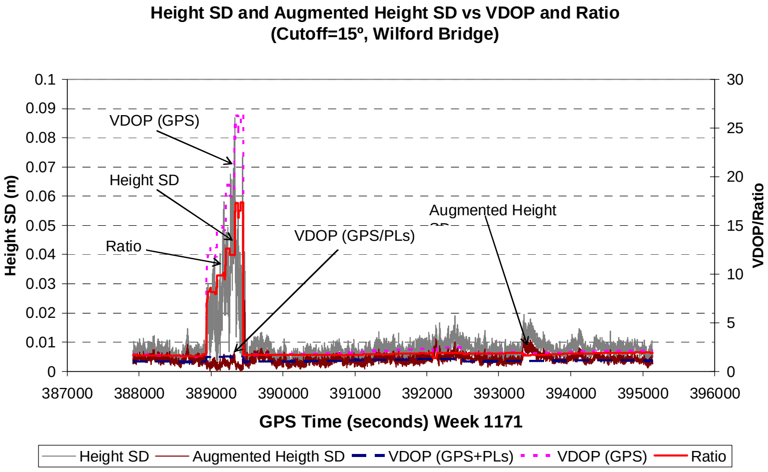


Figure 10 Height SD Comparison with and with Pseudolite Augmentation

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 calculated coordinates in the WGS84 datum were then converted to the OSGB36 coordinates, the UK datum. The following analysis is conducted in the local coordinate system.

Figures 11, 12 and 13 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 raw measurements from Allstar single-frequency receivers through selecting and deselecting three PLs.

Data processing reveals that 39% precision improvements in the east coordinate and 33% precision improvements in the vertical component were found when three pseudolites were included in the data processing. However, there was about 8% precision reductions in the north coordinate when three pseudolites with negative elevation angles are employed. The reason could be related to the error propagation scheme and is explained by *Meng et al.* [2002b], bearing in mind that the positioning accuracy is a function of the DOP value and the ranging accuracy. The latter is affected mainly by multipath and receiver noise, inaccurate location coordinates of the transmitters and other un-modelled biases. While three pseudolites were setup below the horizon of the rover station, the apparent improvement should be anticipated as being in the vertical direction and east coordinate component accordingly, 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 difficult to locate pseudolites with positive elevation angles on the northern side and close to the bridge. Further future effort will be made to find suitable sites for pseudolites.

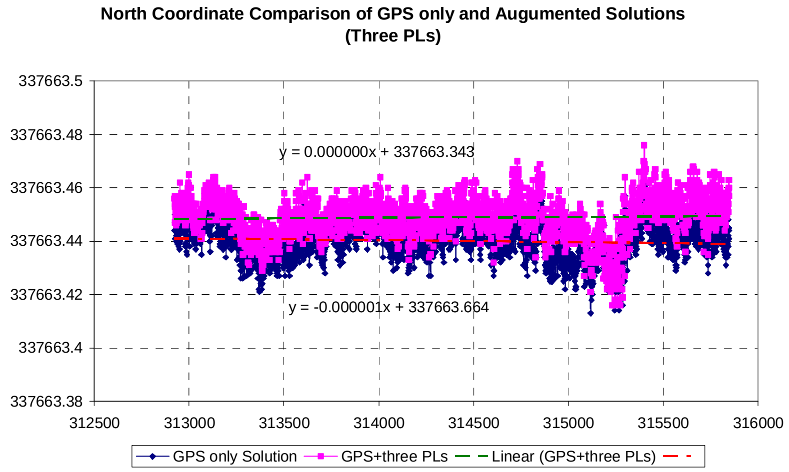


Figure 11 North Coordinate Comparison

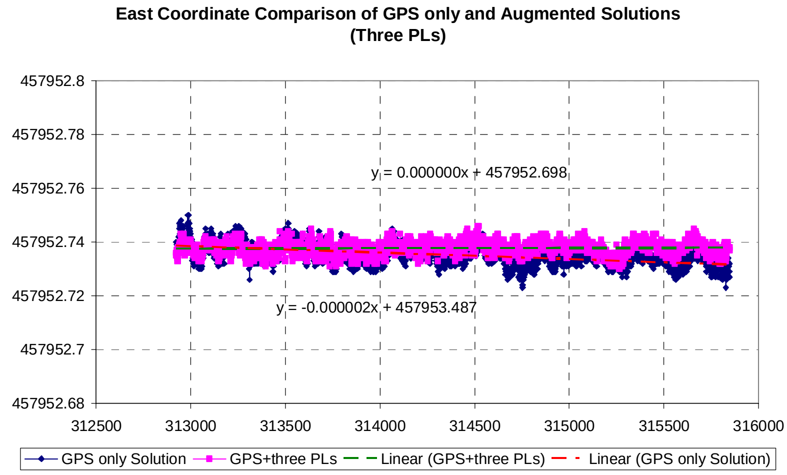


Figure 12 East Coordinate Comparison

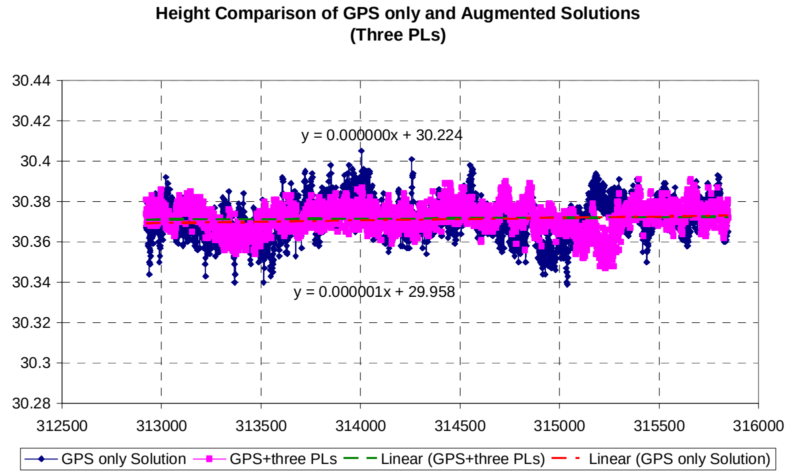


Figure 13 Height Comparison

6. DEVELOPMENT AND COMPARISON WITH FEM

The construction of an FEM was undertaken using the SAFESA^{TM} method; an FE algorithm developed a number of years ago at CU (Morris and Vignjevic 1997). The FEM that has been developed for the Wilford Bridge can be seen in Figure 14. It is known that to detect bridge dynamics the number and location of sensors is important. There needs to be minimum amount of sensors employed on the structure to be able to detect certain bridge dynamics. The amount of sensors is often limited by economical issues and their placement limited by accessibility on the structure. Many methods can be used to find the optimal location for the sensors. CU advises the UoN on the optimal locations of GPS sensors based on the Effective Independence-Driving-Point Residue (EFI-DPR) (Meng, et al. 2003a). . With this recommended instruments layout, sufficient information about the dynamics of the bridge can be detected.

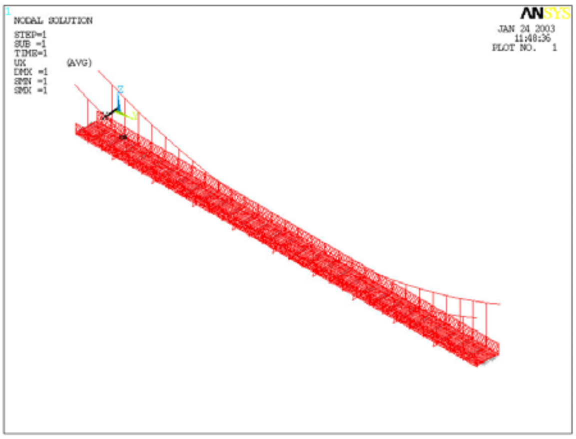


Figure 14 3D FEM for the Wilford Bridge

Table 3 FEM estimated natural frequencies

Mode	Frequencies
1	1.38
2	2.69
3	4.49
4	6.50
5	8.61
6	10.72

Table 3 lists the natural frequencies estimated by the FEM of the Wilford Bridge. Frequency data extracted by Fast Fourier Transforms (FFT) separately from the accelerometer and GPS data identify the first natural frequency of the bridge and match well, with this frequency being identified as 1.75 Hz. However, although close (to within 20%) this does not match very well with the first natural frequency identified by the FEM. This could be caused by the lack of detailed material and design descriptions of this bridge. At this stage the FEM is not accurate enough for health monitoring purposes. The FEM model needs to be further updated with field observations.

CONCLUSIONS

This paper discusses the problems caused by single frequency integer ambiguity resolution. In the context of measuring the deflections of a small suspension bridge a different method of integer ambiguity resolution is discussed. Once the ambiguities are resolved, the precision of the dual and single frequency data is compared with similar results for both.

Multipath signatures are identified in the data and adaptive filtering is used on two days' time series to remove the common multipath from the positions. Adaptive filtering is also used to combine the data from GPS with accelerometer data to increase the sampling rate and remove receiver random noise from the GPS solution.

An analytical FEM has been developed for the Wilford Bridge. Initial predicted results are compared with frequencies computed from field observations of GPS and accelerometer data. The compared frequencies match reasonably but not very well and the need to update the

FEM with the observation data is emphasised. This is an iterative process. The FEM is still being updated with results from the most recent bridge trials and new results will be the subject of future papers.

ACKNOWLEGMENTS

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