The Use of Kinematic GPS to Monitor the Deflections and Frequencies of a 174m Long Viaduct under Traffic Loading

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SUMMARY

The Universities of Nottingham and Brunel have been collaborating into the use of GPS to monitor the deflections of structures for over a decade.

Recent tests were conducted on a 173.7m long viaduct that carries an 8 lane motorway in the UK. The tests included the use of two reference GPS receivers located some 1.5 km away from the structure, and a further 5 GPS receivers located at key locations on the viaduct. Leica SR530 and 1200 dual frequency code and carrier phase GPS receivers were used. Choke ring antennas were also used on all the locations in order to minimise the multipath effect. Data rates of 10Hz and 20Hz were gathered.

The results illustrate that movements with accuracy of the order of a couple of millimetres were detected. The movements themselves were of the order of up to 12cm in the vertical component.

Further to this, the results were analysed using spectral analysis techniques, which resulted in the fundamental frequencies of the deflections being determined. These were then compared to the Finite Element Models that exist for the structure.

The following paper describes the field tests and the data processing used as well as some of the movement and frequency results.

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1. INTRODUCTION

The use of GPS to monitor the deflection of bridges has been ongoing at the Universities of Nottingham and Brunel for about a decade [Ashkenazi et al, 1996], [Ashkenazi et al, 1997]. The work has focussed on suspension bridges, and usually those whose movements are in the decimetre to metre range, such as the Humber [Brown et al, 1999] and Forth Road Bridges [Roberts et al, 2006a], as well as the London Millennium Bridge that saw magnitudes in the order of centimetres [Roberts et al, 2006b].

The following paper outlines a field test carried out recently on a motorway viaduct in the UK, with a main span length of 173.7m. 5 GPS dual frequency receivers using choke ring antennas were placed at strategic locations upon the bridge, and two reference stations used, located 1.5km away. The data was all post processed in an on the fly manner, before converting it into bridge coordinates and careful analysis.

2. FIELD PROCEDURE

A two day assessment and feasibility trial for GPS monitoring of a concrete Viaduct with a main span length of 173.7m was conducted on the 29th and 30th of November 2007.

Five dual frequency GPS receivers were attached to the railings on the main span of the bridge at strategic locations and occupied for set durations at different times of the day. The GPS receivers were set to record data at 10Hz and 20Hz, and used light-weight choke ring antennas in order to mitigate multipath. Figure 1 shows the locations that were occupied. Point M corresponds to the midpoint of the main river span on the outer rail of the cycle track while point D is at the midpoint on the inner rail. Points A and B are approximately 40m away on either side of point M and point C is approximately 50m on the other side of the support at pier 9.

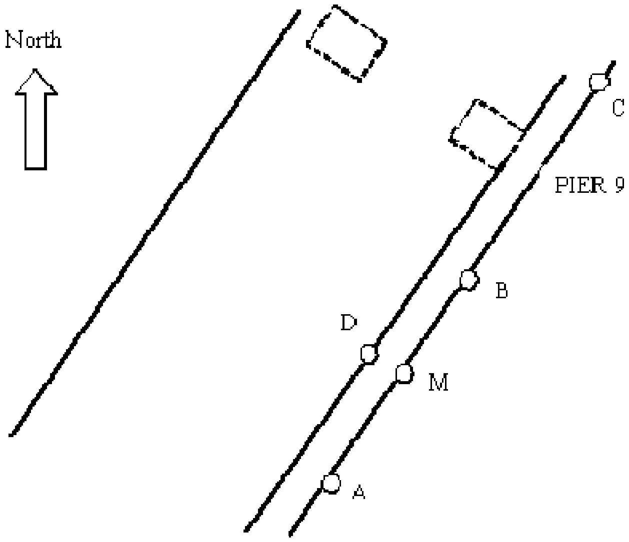


Figure 1. GPS Antenna Locations on the Viaduct.

Figure 2 illustrates the Google Earth image of the viaduct, illustrating its size and orientation. Figure 3 illustrates the location of 4 of the GPS antennas upon the bridge deck, and Figure 4 illustrates a close up of one of the light-weight choke ring antennas used, attached to the hand rail.

Figure 2. A Google Earth image of the viaduct.

Figure 3. Light-Weight Leica Choke Ring Antennas on Bridge Railings.

Figure 4. GPS Antenna Set up showing Clamp and Tribrach Attachment.

Two GPS reference stations were set up away from the main body of the bridge. One was set up in the adjacent harbour area, which is a secure site where the GPS receiver could be left unattended for some time. The second was set up on a disused granary building in the Avonmouth dock compound, which was located at approximately the same altitude as the bridge antennas, Figure 5.

Figure 5. Reference Stations at the Harbour (left) and on the Granary (right).

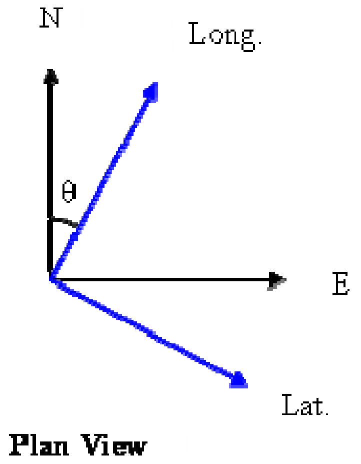
Data was downloaded to a laptop computer at the end of each day. The other reference receiver served as a backup, in case of any data loss from the main reference receiver. It also served to validate results obtained from the main reference station, allowing the authors to investigate the effect residual tropospheric error due to the altitude differences between the bridge receivers and the reference receiver. The granary site was not used as the main reference station as it is thought that the granary building would move due to solar expansion throughout the day.

A combination of Leica System 500 and System 1200 receivers were used for the trial, both at the reference stations and on the viaduct. The system 1200 receivers are able to collect data at a maximum rate of 20Hz while the System 500 receivers are able to collect data at a maximum rate of 10Hz. The main reference station at the harbour (Ground_Ref) was a System 500 receiver collecting data at 10Hz while Granary_Ref was a system 1200 receiver collecting data at 20Hz.

3. RESULTS

The data collected was post processed using Leica Geo-Office. This produced an epoch by epoch solution in the GPS WGS84 coordinate system. This was then converted to Ordnance Survey (OS) National Grid Coordinates using the software Grid Inquest.

In order to visualise the positions within the local context of the viaduct, the eastings and northings were then converted to a local coordinate system or the Bridge Coordinate System (BCS) whose lateral axis is across the width of the bridge and its longitudinal axis is along the length of the bridge.



$$\begin{pmatrix} Lat. \\ Long. \\ Vert. \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} E \\ N \\ H \end{pmatrix}$$

θ = Azimuth of Viaduct = 35°08’54”

Figure 6. Rotation of OS National Grid to Bridge Coordinate System (BCS).

Figure 7 illustrates the 3D movements of the midpoint on the bridge on day 2 over a 7 ½ hour period. The data shown has had a moving average filter passed through it with a 10s filtering average.

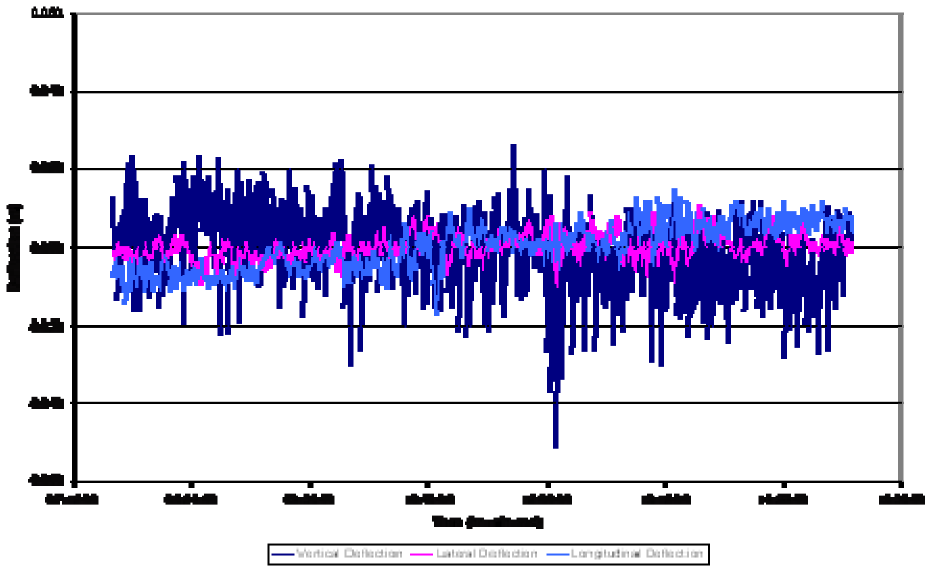


Figure 7. Midspan movements during day 2, with a 10s moving average filter applied.

The 10 seconds filtered data from all the receivers along the profile of the viaduct are shown together in Figure 8. The data from the second reference station on the granary building processed relative to the main reference station is also included in the graphs. The data from the granary was included in order to compare the bridge results with that of a relatively static point. The data for receivers A, M and C have been offset by +0.100m, +0.050m and -0.050m respectively. The data for the granary receiver was offset by -0.130m. It is evident from these results that the bridge's GPS results show larger movements than the granary. This helps to distinguish the movement and apparent movement due to the satellite geometry induced errors and residual tropospheric errors.

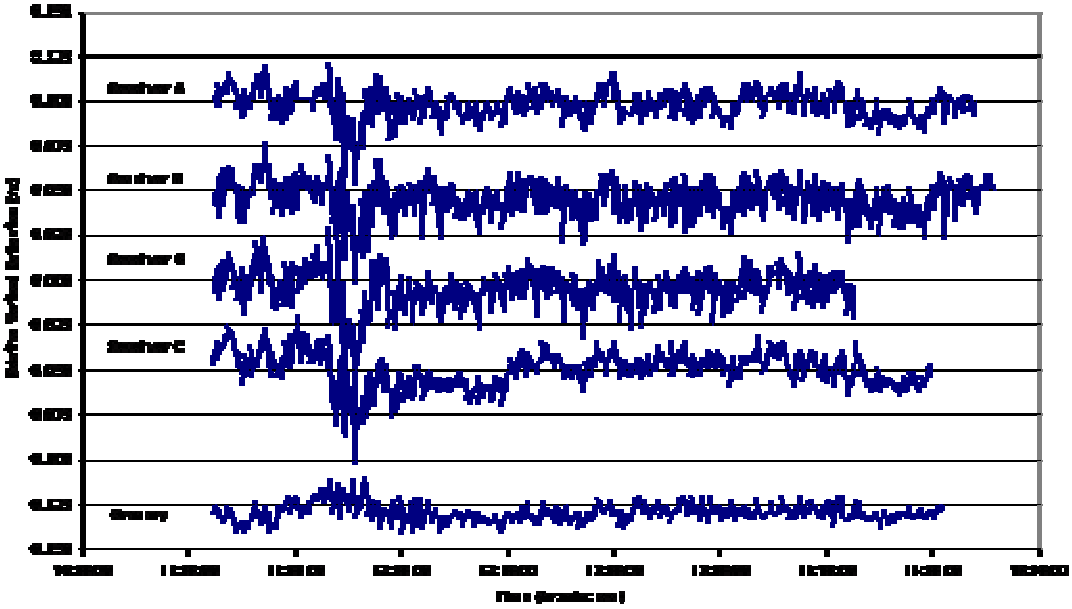


Figure 8. Vertical deflections of all points during day 2.

Bridge movements need to be identified and differentiated from variations caused by changes in the satellite constellation, errors from the reference and other error sources such as multipath and the effect of the troposphere. This is a focus of ongoing research.
The effect of the troposphere has to a large extent been mitigated by using a short base-line in the order of 1-2km between the reference and the receivers on the bridge. For distances less than 10km the troposphere at the reference and rover sites are similar and by using the differential algorithm most of this error is removed. Having another reference station at a similar height to the bridge also helped to check that there was no effect of relative tropospheric delay due to height difference.

Figure 9 illustrates the Eastings, Northings and Height deflections over a period of time for the granary (left) and midpoint (right). Again, it is evident that the bridge's movements are indeed greater than the granary's. However, not all this apparent movement is real, and Figure 9 illustrates the magnitude of noise experienced at the stationary granary site. This is most likely due to troposphere, satellite geometry and some multipath at the reference sites.

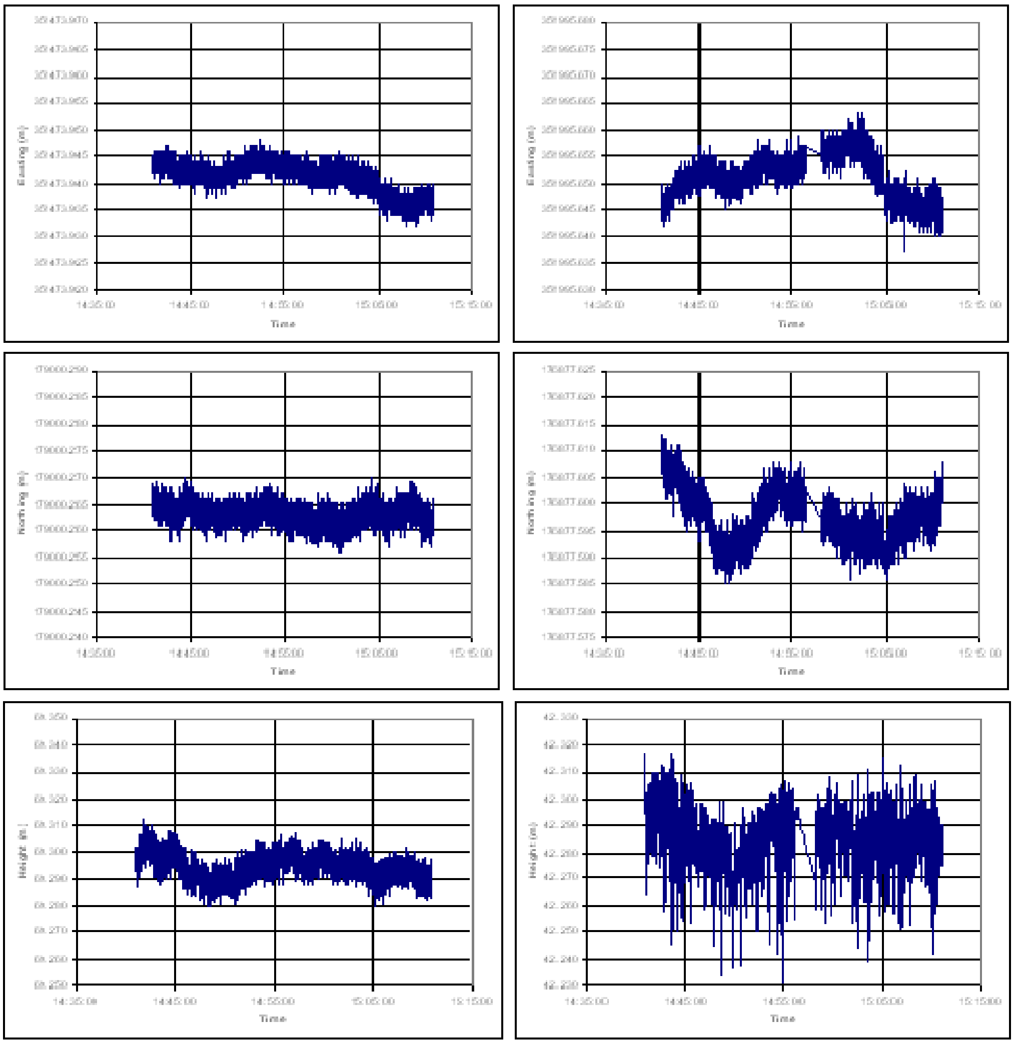


Figure 9. East, North and Height results for the granary (left) and bridge mid point (right).

Comparing the eastings, northings and heights of position M and B on the bridge with that of the granary at the same time period showed that the magnitude of the bridge movement are much larger than that of the granary. Also the position variation for position M and B on the bridge are similar while to a large extent that of the granary is different. However in the height component between 14:45 and 14:55 though the variation in the granary heights are much smaller, it has a similar dip pattern to that on the bridge. This suggests that any common pattern in the positions due to the variation in the satellite constellation is limited.

4. VIBRATIONS

A Fast Fourier Transform (FFT) was applied to the data in order to identify the frequencies in the time series. The results for the spectral analysis on the unfiltered (10Hz data rate) vertical deflections at midpoint on day 1 are shown in figures 10. Peaks representing frequencies of

less than 0.05Hz are not considered as these represent low frequency multipath effects or longer term effects.
The results show that significant frequencies were detected in the vertical direction, but not in the lateral or longitudinal; this is as expected.

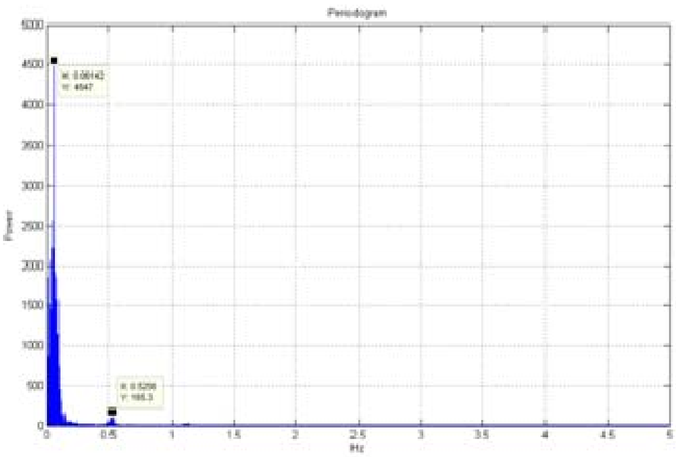


Figure 10. Spectrum for Vertical Deflection at Midpoint on Day 1.

The single sided Amplitude Spectrum was also computed, Figure 11. This was done because it is based on the same FFT values as the power spectrum, however because the power spectrum uses the square of the FFT values small peaks in the spectrum may be hard to identify.

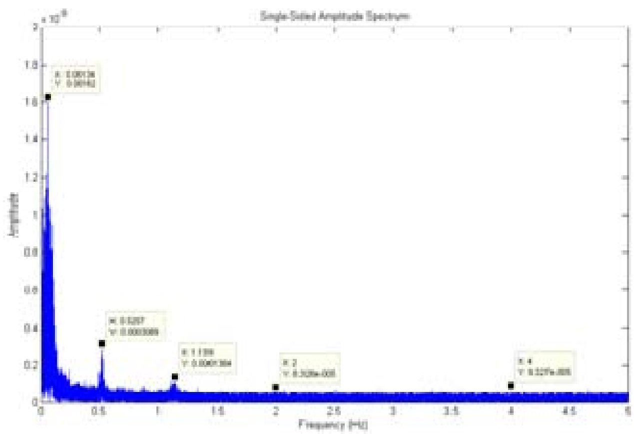


Figure11 . Amplitude Spectrum for Midpoint 1 Vertical Deflection.

Spectral analysis of the vertical deflections at the Midpoint on Day 2 from 07:35 to 15.00 are illustrated in Figure 12. Again, these results show that natural frequencies are obtained from the GPS results, and comparable on a daily basis, and agreed with the expectations of the bridge engineers.

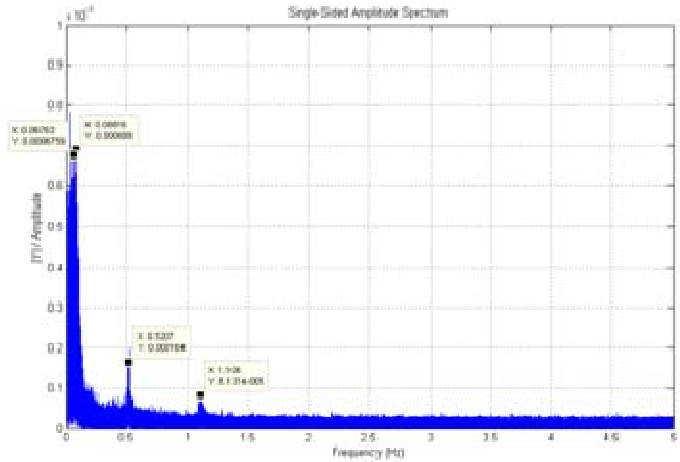


Figure 12. Amplitude Spectrum of the Vertical Deflections at Midpoint on Day 2.

5. CONCLUSIONS

GPS is a viable measurement tool in the viaduct environment. Adequate number of satellites required for positioning were visible both on the viaduct and at the reference station sites. Both sites were affected to a limited degree by multipath. Multipath filtering techniques developed at Nottingham could be used to reduce these. This however did not hinder the capability of the GPS to detect the bridge motion. Three main frequencies were clearly detected by the GPS in the vertical component. The previously known frequency of 0.5 Hz was identified as well as two other frequencies. The first frequency in the range of 0.056 – 0.088Hz (corresponding to a period of 17.8s – 11.4s) seem to vary in its peak value.

In terms of the receiver location, at the midpoint both on the outer rail (position M) and on the inner rail (position D), the three main frequencies where detectable. However, looking at the raw position data from the inner rail there are sharp spikes in the data, this is likely to be as a result of momentary passage of high-sided vehicles causing interference in the GPS signal for just an instant. The inner rail may not be the best location for the GPS antenna.

The report shows that mean movements of ±10mm in the lateral, longitudinal and vertical direction were evident, which could be due to diurnal effects.

The report also shows that the peak deflections in the vertical can lie anywhere up to the order of 50mm.

6. ACKNOWLEDGEMENTS

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BIOGRAPHICAL NOTES

Dr Gethin Roberts is an Associate Professor and Reader in Geospatial Engineering at the University of Nottingham. He is also Chair of the FIG's Working Group 6.4 "Engineering Surveys for Construction Works and Structural Engineering" as well as chair of the FIG Task Force "Measurement and Analysis of Cyclic Deformations and Structural Vibrations".

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